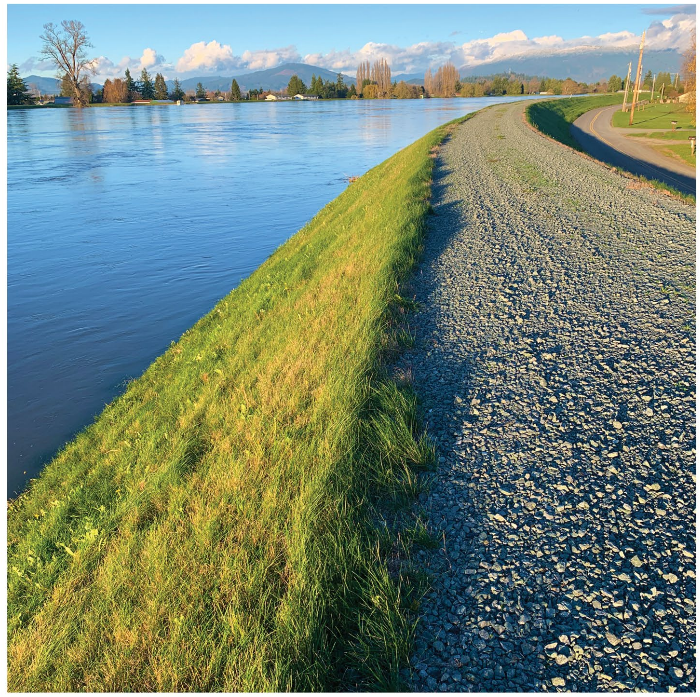
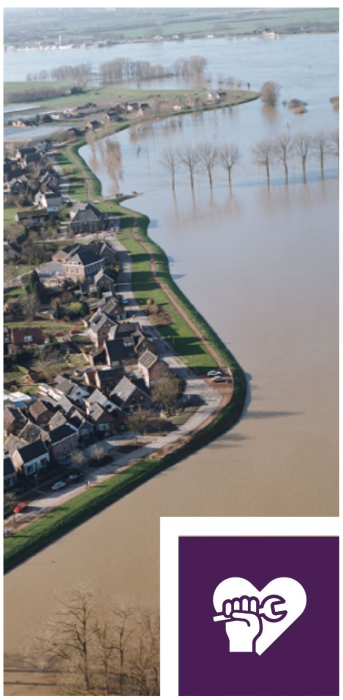
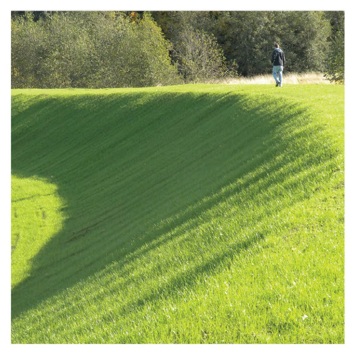
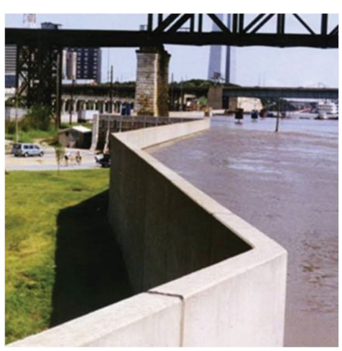
NATIONAL LEVEE SAFETY GUIDELINES









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Preface

National Levee Safety Guidelines—A Step Towards A More Aware, Prepared, and Flood Resilient Nation

The Challenge of Managing Flood Losses

Floodplains have served important functions in human livelihoods for over 200 years. Early settlements in the United States frequently occurred along waterways due to the many benefits offered such as navigation for transporting goods and supplies, fertile soils for growing crops, and access to water for irrigation and household purposes. Developing lands near waterways had many benefits, but also came with the risk of flooding. For many decades, there have been public policy discussions and national level studies to identify best practices to mitigate flooding, while being able to afford the benefits floodplains had to offer.

The principles of the best practices involved:

- Creating a national approach.
- Improving awareness and understanding of flood risk.
- Having timely and relevant data.
- Integrating roles and responsibilities.

These basic principles remain applicable today. Over time, progress has been made in these areas, and the National Levee Safety Guidelines are another successful step towards a more aware, prepared, and flood resilient nation.

The Importance of Levees in Managing Flood Risk in the U.S.

As flooding continued to result in economic losses and risk to public safety, physical barriers such as levees became a common measure to help manage the impacts of flooding. From the early colonial period through the 1920s, levee construction was crude and occurred without the benefit of modern engineering and maintenance practices. Devastating floods on the Mississippi and Ohio Rivers spurred congressional response, resulting in the Flood Control Acts of 1917, 1928, and 1936. What followed was the construction of thousands of miles of the nation's largest and most robust levee systems.

Today, flooding continues to be a regular hazard faced by many communities. According to the Federal Emergency Management Agency (FEMA), 99% of U.S. counties were impacted by a flooding event between 1996 and 2019.[1] There are about 2,400 communities with over 23 million people who depend on levees to help manage the impacts of potential flooding to assets such as hospitals, fire and police stations, roads, water treatment plants, and power stations. The value of properties being protected by flood control measures is approximated at nearly $2.4 trillion (Figure 1).[2]

[1] https://www.fema.gov/data-visualization/historical-flood-risk-and-costs.

[2] The numbers in Figure 1 have been rounded based on data obtained from the National Levee Database in October 2023.

Figure 1: People and Infrastructure Behind Levees

BEHIND THE LEVEES

Quick Takes (Approximated) **Source: National Levee Database – October 2023**

Total number of levee systems **6,825**	Total miles of floodwalls **590**	Number of levee systems with unknown owners **2,000**	Average age of levees **57** Years
Total miles of levees **24,020**	Oldest levee system recorded in NLD **105** Years	Total miles of other features (roadways/ railroads) **348**	Total miles of earthen embankment **23,000**
Longest single levee system **360** Miles	Most closures in a single levee system **317**	Total miles along the coast **1,800**	Population **23M**
Schools, K-12 **5,900**	Universities **417**	Major sport venues **38**	Property value **$2.4T**
Hospitals **330**	Airports **700**	Police stations **1,320**	Oil and gas wells **83,380**
Fire stations **1,960**	Wastewater treatment plants **534**	Religious buildings (all faiths) **2,240**	Major power generators **430**

Although levees are built for the same overall purpose of flood risk reduction, they vary in scale and level of benefits provided—with some providing secondary benefits such as recreation in the form of walking and biking trails. For example, some levees were built to benefit urban communities such as the 35-mile Sacramento Levee, which reduces flood risk to over 380,000 people and $6.7 billion of property value.[3] Other levees provide benefits to smaller, rural communities such as the 2.29-mile Red Oak Levee in Iowa, where there are just over 2,300 residents.[4]

Levees located along the Mississippi River provide flood risk reduction benefits to millions of acres of farmland that produce billions of dollars' worth of agricultural commodities.

WHAT IS A LEVEE?

A levee is defined as:

- A human-made barrier with the primary purpose to provide flood risk reduction to a portion of the floodplain.
- Infrastructure that does not constitute a barrier across a watercourse (i.e., is not a dam).

Whether simple or complex, levees provide important flood risk benefits across the nation and will continue to do so as the climate changes and the need to remain adaptive to the dynamic nature of floodplains continues to evolve.

Why We Need a Common Approach

Periodic flood events continue to highlight the importance of levees. The understanding of the state of levees today is:

- Much of the levee infrastructure is decades old and was built without the benefit of modern engineering practices.
- Levees are designed, constructed, and managed by various entities, utilizing different processes and standards.
- Development continues to intensify behind levees, putting more reliance on the levees' ability to perform and the consideration of other means, such as evacuation and land-use planning, for managing flood risk.
- There is no central resource for evolving engineering practices, training, or technology related to levees.
- Much of the public remains unaware of their flood risks and the important role a levee plays in their community's resilience.

To address the need to improve the awareness and management of levees across the U.S., Congress enacted 33 U.S. Code Chapter 46, entitled the National Levee Safety Program. The foundation for moving the nation towards a common understanding and practices for levees starts with the National Levee Safety Guidelines.

NATIONAL LEVEE SAFETY PROGRAM

For more information about the National Levee Safety Program, including tools and resources being developed for all stakeholders across the nation in promoting consistent levee management, reducing flooding impacts, and increasing community resilience in areas behind levees, visit www.leveesafety.org.

[3] National Levee Database, 2022: https://nld.sec.usace.army.mil/levees/5205000441.

[4] National Levee Database, 2022: https://nld.sec.usace.army.mil/levees/4705000023.

Guidelines: A Significant Step Towards National Consistency

Overview of the National Levee Safety Guidelines

The National Levee Safety Guidelines, which are part of the larger National Levee Safety Program, are a resource of best practices to help achieve nationwide consistency in improving the reliability of levees and resilience of communities behind levees throughout the U.S. The intent of the guidelines is for:

- Levee owner/operators to have a common resource of best practices for all phases in the life of a levee.
- Local officials and communities to have a common resource for best practices in levee risk management in the context of broader flood risk, emergency management, and enhanced community resilience.
- The private sector to have an available reference document for levee-related activities.
- Federal, state, regional, and tribal organizations to use in association with their levee safety programs.

The guidelines are intended to apply to all aspects of traditional levee management: planning, site investigation, design, construction, operation and maintenance, and potential setback or removal. The content ranges from explaining basic terminology to more complex engineering concepts. Each chapter is expressed as a series of best practices that include an explanation of the underlying principles and how the best practices contribute to levee safety using examples, case studies, methodologies, and tools. These best practices were collected and consolidated from a review of publications that were broadly used and accepted, along with input from subject matter experts and practitioners.

The guidelines attempt to present the most current and advanced information in a manner that is as useful as possible to the widest number of stakeholders and situations. Many of the practices are somewhat general in nature or are presented with different options to be scalable and adaptable to each unique circumstance.

Guidelines Scope and Principles

The scope of the National Levee Safety Guidelines is intentionally broad, including not only best practices for activities on the levee itself (e.g., design, construction, maintenance), but best practices associated with other important opportunities for flood risk management as they exist within a larger community context. The guidelines recognize the following:

- Where life safety is a concern, effective emergency planning and evacuation is crucial.
- Flood risk is not equally distributed across the nation. Some communities behind levees or in areas historically prone to flooding face disproportionate burdens in preparing for, responding to, and recovering from flooding.
- Managing land use behind a levee, floodproofing, or elevating buildings or critical infrastructure may be effective if considered in conjunction with levees, especially where they can be expected to overtop.
- Education and outreach help people know what to do in case of an emergency, reduce potential flood damage to their property, and support investment in levee maintenance.

These important concepts were considered along with the following guiding principles when developing the best practices in the guidelines:

- Life safety is the most important consideration.
- Levee safety is a shared responsibility. This means all levels of government (federal, state, tribal, local) work together to assist communities with reducing flood damages and promoting sound flood risk management using policies, programs, and inclusive engagement. In addition, individuals have a responsibility to know their flood risk and if possible, take action to reduce that risk.
- Levees should exist in balance with social, environmental, cultural, and economic interests within the floodplain.
- Levee risk should not contribute significantly to the overall flood risk.
- Transparent, proactive, and continuous communication and engagement is essential.

In addition to these principles, the guidelines rely on risk-informed approaches, taking into consideration all available information related to the likelihood of a hazard occurring, the anticipated performance of the levee in the face of a hazard, and the susceptibility of people and property that may be in harm's way.

It is important to determine all the potential ways a levee might breach or overtop, how likely these scenarios are to occur, and the potential impacts on the community. This level of knowledge and understanding can help inform the prioritization of activities leading to more complete, transparent, and informed decisions.

Cross-Cutting Topics

Throughout the development of the guidelines, three cross-cutting topics of national importance were identified and incorporated across every chapter, as applicable.

Adapting to Climate Change

The U.S. has seen significant shifts in large weather patterns over the last decades, and levees are vulnerable to these shifts in a variety of ways. It is critical that levee owner/operators, regulators, and professionals evaluating and designing levees understand the shifting trends in climate threats in their region, monitor those trends over the life of the levee, and adapt to evolving conditions. This publication considers various climate threats, their potential to impact levees, and projected national trends for each phase of the levee lifecycle. Best practices are conveyed in relevant chapters of the guidelines to highlight situations where traditional levee management actions might be altered because of climate threats.

Considering Underserved Communities

Disasters like floods do not affect all communities or individuals in the same way. Due to a variety of social, economic, or other factors, communities can face different barriers to preparing for, responding to, or recovering from flooding. Often, these barriers include not having access to relevant services or information or not having meaningful opportunities to participate in the decision-making processes. Throughout the guidelines, best practices promote fair treatment and meaningful involvement during various stages of the life of a levee, including engaging communities and developing community-based flood resilience strategies.

Incorporating Natural and Nature-Based Solutions

Floodplains are lowlands adjacent to natural water sources and serve important functions by providing habitat for wildlife, hosting spawning areas for many species of fish, improving water quality, controlling water temperature, and helping recharge underground aquifers. To the extent practicable, the guidelines incorporate best practices to retain these floodplain functions, reduce environmental impacts, and reduce the impacts of flooding.

Updating the Guidelines

Over time, it will be necessary to update the National Levee Safety Guidelines. Periodic updates may be based on any of the following:

- Suggested improvements from stakeholders, including the need for additional tools or materials.
- Advances in science and technology, including when the profession adopts a new best practice or updates an existing best practice.
- Changes in legislation.

As technical advancements, publications, and applications of levee-related work continue to grow, the National Levee Safety Program is committed to updating these guidelines and developing additional technical aids and tools, as necessary, to further advance the state of the practice and implementation of the National Levee Safety Guidelines. To provide feedback on the guidelines, visit www.leveesafety.org.

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Navigating the Guidelines


SUPERMARKET
WATER PLANT
LEVEETOWN, USA

Contents

1 Navigating the National Levee Safety Guidelines 1
1.1 Intended Users 1
1.2 Structure and Content 4
1.2.1 Chapter Themes 4
1.2.2 Graphics, Images, and Key Messages 6
1.2.3 Callout Boxes and Case Studies 7
1.2.4 References 8

List of Figures

Figure 1: Example Community Watershed Graphic/Key Messages for Chapter 1 6
Figure 2: National Levee Safety Guidelines Iconography 7
Figure 3: Example Chapter Content with Callout Boxes and Case Studies 8

List of Tables

Table 1: National Levee Safety Guidelines—User Topics of Interest 3
Table 2: Chapter Descriptions and Themes 4

1 Navigating the National Levee Safety Guidelines

1.1 Intended Users

The intended users of the National Levee Safety Guidelines are intentionally broad, recognizing that it takes a community approach to manage levee risk. Because levees are visible in the community landscape and integrated into floodplain management, land use, and emergency management activities at the state and community level, the entities that need to be involved in managing levee risk in a community can be numerous.

The expansive scope of the guidelines is intended for use by many different people, each with their own unique mix of authorities, responsibilities, and capabilities. The distribution of levee risk management responsibilities varies significantly across the nation. For example, some owner/operators have narrow authorities focused only on daily maintenance, while others are states, cities, and counties with broad responsibilities in land use, floodplain planning, and delivery of public services. For this reason, users of the guidelines are described mainly by their responsibilities.

The target audience for the National Levee Safety Guidelines includes:

- **Levee owner/operators**: Those typically responsible for the operations, maintenance, and management decisions on levees. These owner/operators may be federal, tribal, state, territorial, regional, or private operators. For simplicity, the guidelines refer to these professionals as owner/operators, though it is recognized that not all owners have the responsibility for the day-to-day operation and maintenance (O&M) of levee infrastructure, and likewise not all those responsible for O&M have ownership of the infrastructure.
- **Emergency managers**: An interconnected group of local, state, tribal, and federal professionals responsible for flood preparedness, response, recovery, and/or mitigation near or behind levees.
- **Local community officials**: This group includes those with responsibility and authority for land use and floodplain management, overall public safety, and emergency planning and management.
- **Levee planners**: Professionals who conduct or provide services to support owner/operators, agencies, and communities in formulating a levee project.
- **Levee designers**: Professionals who conduct or provide services to support owner/operators, agencies, and communities in the full-scale design of a levee project and associated features.
- **Levee constructors**: Professionals who conduct or provide services to support owner/operators, agencies, and communities through the entire construction process including preparation, construction, and closeout.
- **Risk estimators**: Professionals with the expertise, knowledge, and experience to perform a levee risk assessment (e.g., qualitative, semi-quantitative, quantitative).

- **Land use managers**: Those with responsibility for ensuring land use is compliant with regulations, making suggestions for sustainable use, and researching the impact of development.
- **Floodplain managers**: Those with responsibility for administering local flood damage reduction regulations, as well as promoting and ensuring sound land use development in floodplain areas to promote the health and safety of the public, minimize loss of life and property, and reduce economic losses caused by flood damages.
- **Permit reviewers/issuers**: Federal, tribal, state, territorial, regional, and local agencies with regulatory authority for activities related to levees or floodplains.
- **Professional communicators**: A wide range of individuals who may have a role in communicating and engaging with communities about flood and/or levee-related risk (e.g., public affairs/outreach professionals, local leaders, floodplain managers, emergency managers, regulators, levee owner/operators, governmental officials, technical professionals, non-governmental, and non-profit organizations).

The guidelines cover every aspect of the levee—from deciding whether a levee is the right choice for a flood risk reduction strategy to operating and maintaining a levee to removing a levee that no longer meets a community's needs. Some readers will be interested in certain chapters more than others depending on their role in levee safety. To assist the reader in knowing what chapters are the most important to them, the following table was developed based on common roles (Table 1).

Table 1: National Levee Safety Guidelines—User Topics of Interest

	Managing Flood Risk	*Understanding Levee Fundamentals*	*Engaging Communities*	*Estimating Levee Risk*	*Managing Levee Risk*	*Formulating a Levee Project*	*Designing a Levee*	*Constructing a Levee*	*Operating and Maintaining a Levee*	*Managing Levee Emergencies*	*Reconnecting the Floodplain*	*Enhancing Community Resilience*
Chapter	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Audience • Reader • Role												
Levee owner/ operator	Moderate	High	Moderate	High	High	Low	Low	Low	High	High	Moderate	Low
Emergency manager	Moderate	Moderate	Moderate	Moderate	Moderate	Low	Low	Low	High	High	Low	Moderate
Local community officials	High	Moderate	High	Low	High	Moderate	Low	Moderate	Moderate	Moderate	Moderate	High
Levee planner	Low	Low	Moderate	Moderate	Moderate	High	Moderate	Low	Low	Low	High	Low
Levee designer	Low	Low	Moderate	Moderate	Low	High	High	Moderate	Low	Low	High	Low
Levee constructor	Low	Low	Moderate	Moderate	Low	Low	Moderate	High	Low	Low	High	Low
Risk estimator	Low	Low	Low	High	Moderate	Low	Low	Low	Low	Low	Low	Low
Land use manager	High	Low	Low	Low	Moderate	Moderate	Low	Low	Low	Low	Low	High
Floodplain manager	High	Low	Moderate	Low	High	Moderate	Low	Low	Low	Low	Moderate	Moderate
Permit reviewer/ issuer	High	High	Low	High	High	Low	Low	Low	Low	Low	Moderate	Low
Professional communicator	Moderate	High	High	Low	Moderate	Moderate	Low	Low	Low	Moderate	Low	Moderate

Importance/interest/relevance *High* *Moderate* *Low*

1.2 Structure and Content

Throughout the guidelines, various features have been added to increase the ease of navigation and readability for users. Features include color-coded chapter themes; graphics, images, and key messages; and callout boxes and case studies.

1.2.1 Chapter Themes

Each chapter within the guidelines focuses on a specific topic and is represented by a colored icon. The icon colors represent themes and allow the reader to quickly determine which chapters are similar in topic.

- Purple: Communities and resilience
- Orange: Risk concepts
- Green: Levee infrastructure
- Yellow: Levee management

Table 2 provides a high-level description of each chapter within the guidelines and its associated theme.

Table 2: Chapter Descriptions and Themes

Chapters	Description	Theme
Chapter 1: Managing Flood Risk	Describes the sources of flooding and the contribution of various measures, including levees, to reduce risk. Explains the basic steps in a flood risk management strategy and describes the relationship between flood and levee risk.	Communities and resilience
Chapter 2: Understanding Levee Fundamentals	Provides basic terminology and background information that is pertinent to all other topics within the guidelines. It helps provide consistency for public awareness efforts and training materials.	Levee infrastructure
Chapter 3: Engaging Communities	Explains the approach for engaging communities during the life of the levee.	Communities and resilience
Chapter 4: Estimating Levee Risk	Explains basic risk concepts and describes principles and best practices related to risk assessments.	Risk concepts

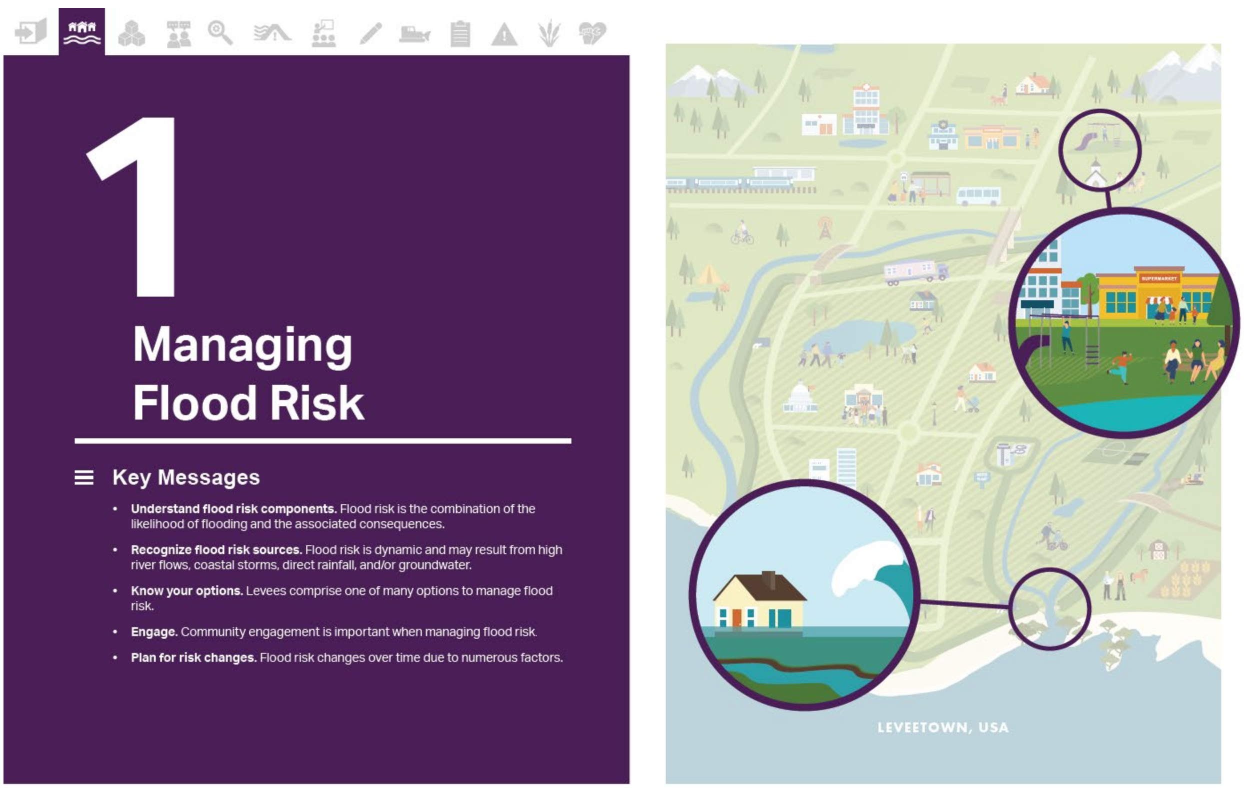
Chapters	Description	Theme
Chapter 5: Managing Levee Risk	Outlines levee risk management principles, highlighting responsibilities, and providing guidance on key decisions and management actions for each phase of the life of the levee.	Risk concepts
Chapter 6: Formulating a Levee Project	Describes the principles and practices of planning any levee project (new, repair, rehabilitation, modification, removal).	Levee infrastructure
Chapter 7: Designing a Levee	Describes the underlying principles and design procedures for any levee project.	Levee infrastructure
Chapter 8: Constructing a Levee	Addresses the levee construction process including best practices to use prior to, during, and at the end of levee construction. It emphasizes practices that promote good levee performance, resilience, and serviceability.	Levee infrastructure
Chapter 9: Operating and Maintaining a Levee	Provides guidance for operating and maintaining levee features and developing an operations and maintenance plan.	Levee management
Chapter 10: Managing Levee Emergencies	Provides information on preparing, managing, operating, and recovering from a levee emergency.	Levee management
Chapter 11: Reconnecting the Floodplain	Describes the reasoning behind levee setback or removal and provides information on factors that should be considered during the planning, design, and construction phases.	Levee infrastructure
Chapter 12: Enhancing Community Resilience	Provides a roadmap to improve a community's resilience to flooding through an iterative process.	Communities and resilience

1.2.2 Graphics, Images, and Key Messages

Each chapter begins with an illustration showing the interconnectedness of the community within a watershed. Certain features or concepts that are discussed within the chapter are highlighted on the community watershed graphic. For example, Chapter 1 discusses the sources of flooding and consequences; therefore, these elements are highlighted on the community illustration (Figure 1). Throughout each chapter, additional graphics and images have been carefully designed and selected to help visually reinforce key concepts for the reader. It should be noted that graphics and illustrations used throughout the guidelines are intended to describe levee features and processes at a high level and should not be used for detailed design or construction purposes.

In addition, each chapter provides a series of key messages. These short, concise statements reflect important points of information that readers can expect to learn or understand after reading the chapter (Figure 1).

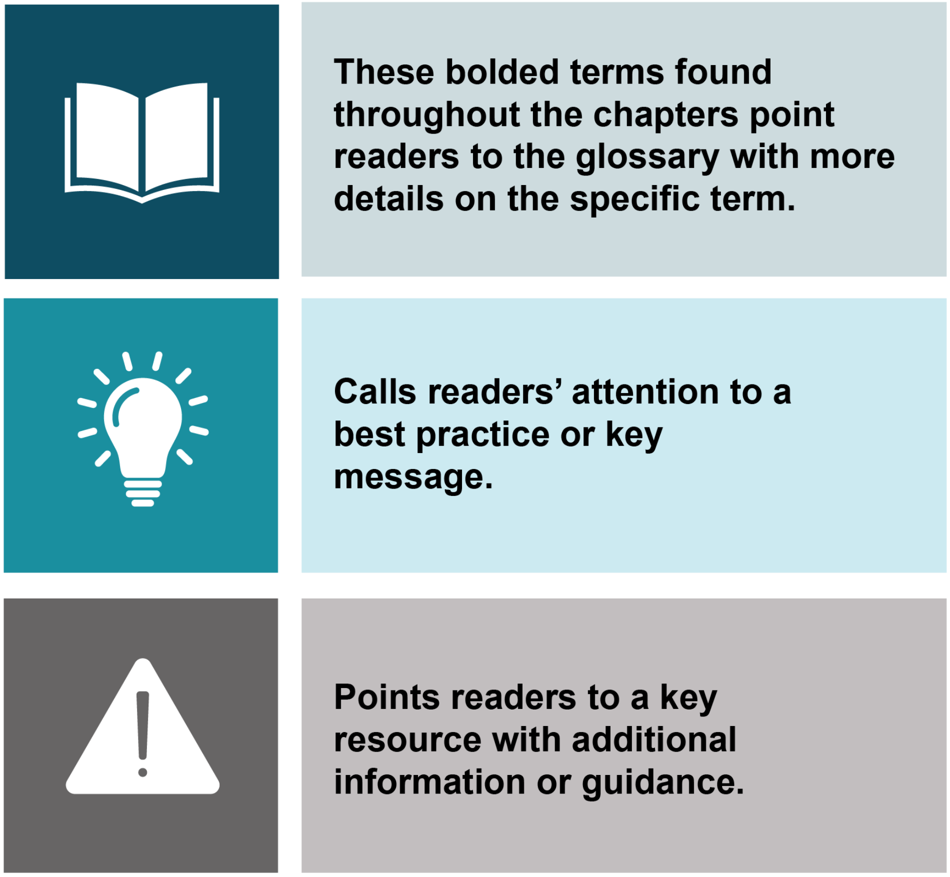
Figure 1: Example Community Watershed Graphic/Key Messages for Chapter 1



1.2.2.1 Iconography

In the final, interactive version of the guidelines, readers will notice several reoccurring icons to highlight specific content or provide additional information (Figure 2). Please note, these icons will not be present in this draft delivery.

Figure 2: National Levee Safety Guidelines Iconography



1.2.3 Callout Boxes and Case Studies

Throughout the guidelines, there is wide use of callout boxes and case studies to help enhance the reader's understanding of principles and best practices (Figure 3). Callout boxes provide supplemental resources such as websites, programs, and guidance. Case studies highlight best practices that are being successfully implemented by stakeholders across the country.

Figure 3: Example Chapter Content with Callout Boxes and Case Studies

CASE STUDY

CASE STUDY: IMPORTANCE OF PIPE MAINTENANCE AND REPAIR

Failure to adequately maintain, or quickly repair gravity pipes can lead to dangerous situations, as the following sequence of events illustrates. During high water in 2013, a 54-inch diameter corrugated metal pipe failed on a levee that runs along a tributary of the Mississippi River. The first sign of a potential breach was the appearance of a sinkhole formed mid-slope on the levee embankment, paired with a whirlpool/vortex.

Early attempts to stabilize the situation involved several dangerous situations. A truck attempted to approach the sinkhole with repair materials but sunk into the damaged levee and was pulled back out. Rock trucks then arrived on site and began placing rock at the crown, while a bulldozer pushed material into the vortex area. While this was successful in choking off the flow, by the next morning a sinkhole had formed in the crown, just where the numerous dump trucks and bulldozers had been working the previous day. The new sinkhole was rock-filled to the top elevation of the crown. During these efforts, a third sinkhole formed near the crown.

Due to limited funding and weather restrictions, replacement of the failed pipe did not begin until the fall of 2015. The excavation for this replacement was open when a flood began that winter, creating a second emergency management situation. Material was quickly placed in the excavation to restore the levee, but the material quickly began to slough and erode. Plastic sheeting was used to protect the riverside slope and regular surveys of crown height were completed to assess the likelihood of overtopping. The levee was maintained throughout the flood and the 54-inch corrugated metal pipe was successfully replaced in the fall of 2016.

Appropriate and timely pipe inspections and maintenance could have prevented the emergency situation in 2013. Prioritization of the pipe replacement could have prevented the second emergency which occurred in 2015.

(a) Sinkhole caused by a buried pipe failure. (b and c) 2013 emergency levee repairs at a pipe failure along the Mississippi River. (d) The second pipe failure a few years later at the same Mississippis River site.

48 National Levee Safety Guidelines

3.5.1.1.1 | Joint Integrity

Joints along gravity pipes resist infiltration and exfiltration, accommodate lateral and longitudinal movements, and provide hydraulic continuity. Pipe joints include concrete joints, neoprene sleeves, rubber O rings, gaskets, and steel end rings.

Joint inspections look for damage to joint filler material, signs of pipe separation, and root intrusion through the joint.

Joint maintenance and repair will vary by joint type, accessibility, and pipe material. In general, exposed joints that fail may need to be disassembled and replaced. Refer to levee O&M manuals and manufacturer's instructions for specific maintenance and replacement considerations, but a few good practices include:

- In addition to routine inspections, in regions that experience freezing ground, schedule pipe joint inspections to look for signs of pipe separation during cold periods.
- Root intrusion through joints should be repaired by removing all roots that have penetrated the joints, addressing associated vegetation on the levee embankment above the impacted joint areas, in addition and repairing defects in the pipe.
- In concrete pipes, joint separation may require complete pipe replacement. When the degree of separation is minimal, slip lining using trenchless technology or pressure grouting may be adequate to limit further deterioration. Open cut methods may be needed if the degree of separation is large or erosion of pipe backfill materials is occurring.

RECOMMENDED REFERENCES

CORRUGATED METAL PIPE LIFE SPAN

It's important to understand that corrugated metal pipes, frequently used in rural areas or where potential risks to life are low, have a typical life span of 50 years. Replacement of the pipe is therefore expected during the levee's service life, and inspections are as critical to identify the timing of that replacement as maintenance is to delaying it. Certain environmental conditions may expedite pipe corrosion: in regions with salinity intrusions, acidic soils (such as those high in peat moss), or high use of pesticides or fertilizers, inspection and rehabilitation may be needed more frequently than in less corrosive environments. Signs of deterioration in metal pipes include rust, corrosion holes, tearing, and cracks. Conduct maintenance at the first sign of issues to extend the pipe's usable life and avoid more intensive repairs. In order of priority:

- Restore protective coatings (either bituminous or polymer) when corrosion is noted on the inside of a pipe.
- Establish a pipe inspection strategy to regularly evaluate coatings.
- Weld new metal sections in place as patches.
- Cover holes with a cement grout or concrete.
- Open cut and replace or slip line the pipe using trenchless technology.

Examples of corrosion on a pipe's surface and corrosion leading to pipe damage.

Index | CHAPTER 9 | Operating and Maintaining a Levee 49

1.2.4 References

Many reference materials are provided to readers to serve as guidance throughout the guidelines. These sources are cited within the body of the chapter with the name of the author(s) followed by the date of publication. All other publication details will be provided in the references list at the end of the guidelines. Regardless of the manual or document cited, readers should always use the latest version available, as applicable.

In addition to the references list, a repository of select resources will be available for download at an external website in the final, interactive version of the guidelines.

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1 Managing Flood Risk

Key Messages

This chapter will enable the reader to:

- **Understand flood risk components.** Flood risk is the combination of the likelihood of flooding and the associated consequences.
- **Recognize flood risk sources.** Flood risk is dynamic and may result from high river flows, coastal storms, direct rainfall, and/or groundwater.
- **Know your options.** Levees comprise one of many options to manage flood risk.
- **Engage.** Community engagement is important when managing flood risk.
- **Plan for risk changes.** Flood risk changes over time due to numerous factors.


SUPERMARKET
LEVEETOWN, USA

Other chapters within the National Levee Safety Guidelines contain more detailed information on certain topics that have an impact on managing flood risk, as shown in Figure 1-1. Elements of those chapters were considered and referenced in the development of this chapter and should be referred to for additional content.

Figure 1-1: Related Chapter Content

CH 1	CH 2	CH 3	CH 4
Managing Flood Risk		Engaging to build knowledge and awareness	Estimating hazards Estimating consequences
CH 5	**CH 6**	**CH 7**	**CH 8**
Flood risk versus levee risk	Levee-related alternatives for reducing risk	Resilient levee design approaches	
CH 9	**CH 10**	**CH 11**	**CH 12**
			Flood risk reduction strategies for community flood resilience

Contents

1 Introduction 1-1
2 Understanding the Basics of Flood Risk 1-2
2.1 Watersheds 1-2
2.2 Floodplains 1-4
2.3 Flood Hazards 1-5
2.3.1 Riverine Flooding (Fluvial) 1-6
2.3.2 Coastal Flooding 1-7
2.3.3 Rainfall Flooding (Pluvial) 1-8
2.3.4 Groundwater Flooding 1-9
2.3.5 Compound Flooding 1-9
2.3.6 Evaluation of Flood Hazards and Resultant Flooding 1-9
2.4 Consequences of Flooding 1-10
3 Applying Flood Risk Management Principles 1-11
3.1 Overview of Flood Risk Management 1-11
3.2 Developing a Flood Risk Management Strategy 1-13
3.2.1 Community Flood Resilience 1-14
3.2.2 Flood Risk Management Process 1-17
4 Managing Flood Risk with Levees 1-23
4.1 Foundational Concepts and Definitions 1-23
4.2 Interconnectivity of Risk Management Activities 1-25
5 Recognizing Changes in Flood Risk 1-27
5.1 Drivers of Changed Conditions 1-27
5.2 Challenges with Adaptation 1-29
5.3 Climate Change Implications 1-30
6 Summary 1-31

List of Figures

Figure 1-1: Related Chapter Content 1-i
Figure 1-2: Components of Risk 1-1
Figure 1-3: Sample Watershed 1-3
Figure 1-4: Water Resource Regions to Watersheds 1-3
Figure 1-5: Example of Coastal Floodplain 1-4
Figure 1-6: Floodplain Layout 1-5
Figure 1-7: Sources of Flooding 1-5
Figure 1-8: Riverine Flooding 1-6

Figure 1-9: Example of Riverine Flooding....1-7
Figure 1-10: Coastal Flooding....1-7
Figure 1-11: Example of Coastal Flooding....1-8
Figure 1-12: Rainfall Flooding....1-8
Figure 1-13: Groundwater Flooding....1-9
Figure 1-14: Flood Risk Reduction....1-12
Figure 1-15: Resiliency Expressed as Functionality Over Time Following an Event....1-14
Figure 1-16: Flood Risk Management Process Diagram....1-17
Figure 1-17: Types of Coastal Flood Risk Reduction Measures....1-19
Figure 1-18: Flood Risk Management Options....1-20
Figure 1-19: Relationships Between Flood Risk, Levee Risk, and Non-Breach Risk....1-24
Figure 1-20: Flood and Levee Risk Management Overlap....1-26
Figure 1-21: Contributors to Changes in Flood Risk....1-28
Figure 1-22: Drivers of Change in Flood Risk and Responses....1-29

List of Tables

Table 1-1: Related Content....1-32

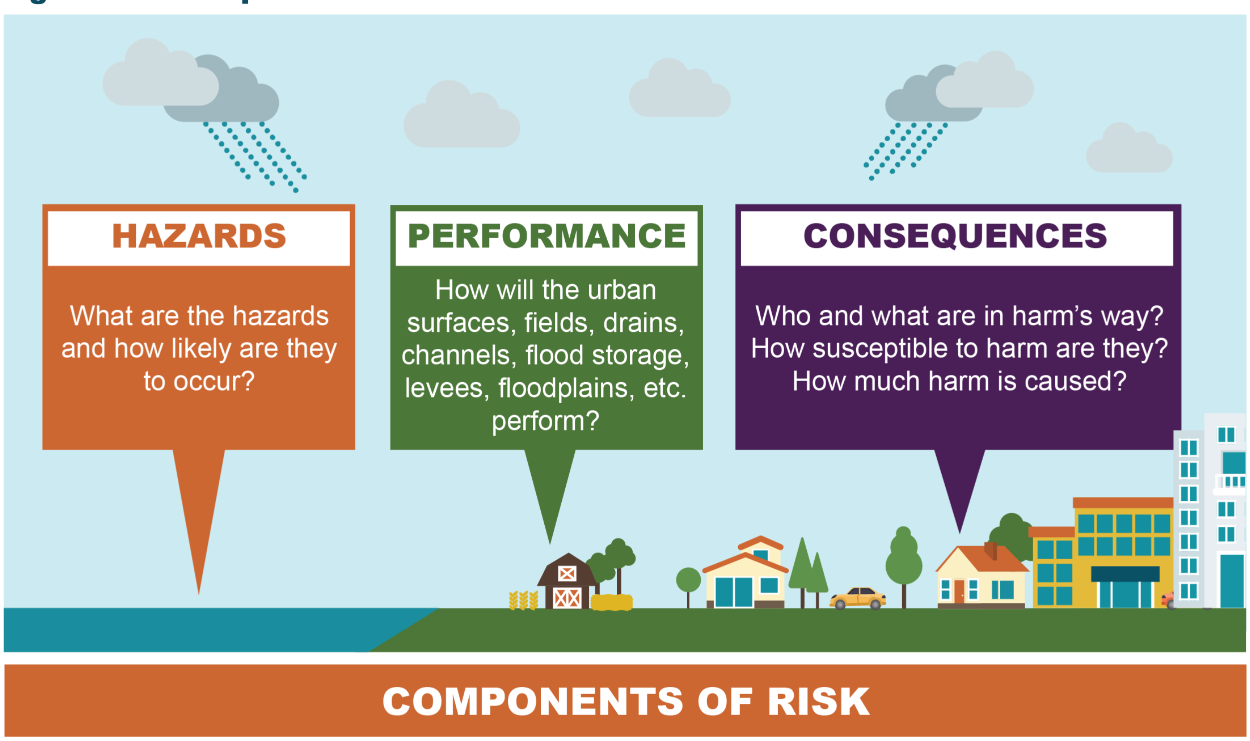
1 Introduction

As communities, industry, and people in the United States build, work, live, and play in and around our nation's rivers and coastlines, flooding results in flood loss and flood damage. Nearly 25 million properties are at risk to flooding with over 5 million structures situated behind levees or other flood risk reduction infrastructure. With almost $2 trillion in damages due to flooding in the U.S. since 1980 (Smith, 2020), a better understanding of the risks to flooding along streams, rivers, lakes and coastlines must be gained and a national approach is needed. This national approach should seek to raise awareness, increase preparedness, and create a more resilient nation. This chapter serves as a primer for those interested in the concepts of flood risk and its management, with a target audience of not only leveed communities at risk of flooding, but also levee owners/operators and stakeholders impacted by levees and other flood risk reduction infrastructure. Flood risk management is described within the chapter in a manner such that a reader who is unfamiliar with the topic is able to understand the concept.

> **RISK**
>
> Risk = the measure of probability and consequences

Risk is therefore one of the main concepts presented in this chapter, more specifically flood risk. **Flood risk** can be understood as the combination of the probability (or likelihood) of a location being flooded and the associated consequences (life loss, property damage, etc.). The probability of flooding includes the likelihood of hazard occurrence combined with the likelihood of the performance of the flood reduction infrastructure against that hazard. Thus, there are three key components of flood risk: hazard, performance, and consequence, as shown in Figure 1-2.

Figure 1-2: Components of Risk



Flood risks resulting from high river flows, coastal storms, direct rainfall, and/or groundwater are faced by many communities in our nation. Communities employ different methods to identify and manage the impacts of those risks through various risk reduction strategies. These include:

- Structural measures such as dams, levees, floodwalls/seawalls, diversion channels, and other physical modifications which alter the characteristics of floods and are designed to reduce the probability of flooding in the location of interest.
- Nonstructural measures such as floodproofing or zoning which are generally aimed at altering the impact or consequences of flooding and may have little impact on the characteristics of the flood itself.

Levees are one of many ways to manage flood risk. This chapter sets a broad context for the use of levees as a flood risk reduction measure, describing how levees fit into the bigger picture. The decision to build a levee should be based on the knowledge that a levee does not eliminate the risk of flooding, but if implemented well, it can reduce the risk of flooding.

Flood risk is dynamic over time and influenced by many factors, including climate change, aging levees, and community growth. Communities should continually re-evaluate their flood risk and the effectiveness of the methods they have chosen to manage it, including levee maintenance and improvement.

These guidelines focus on the flood risk management option of designing, constructing, and maintaining levees with complementing topics described in Figure 1-1. The remaining chapters guide the reader through each phase of the levee lifecycle and address essential activities such as engaging the community and enhancing community resilience.

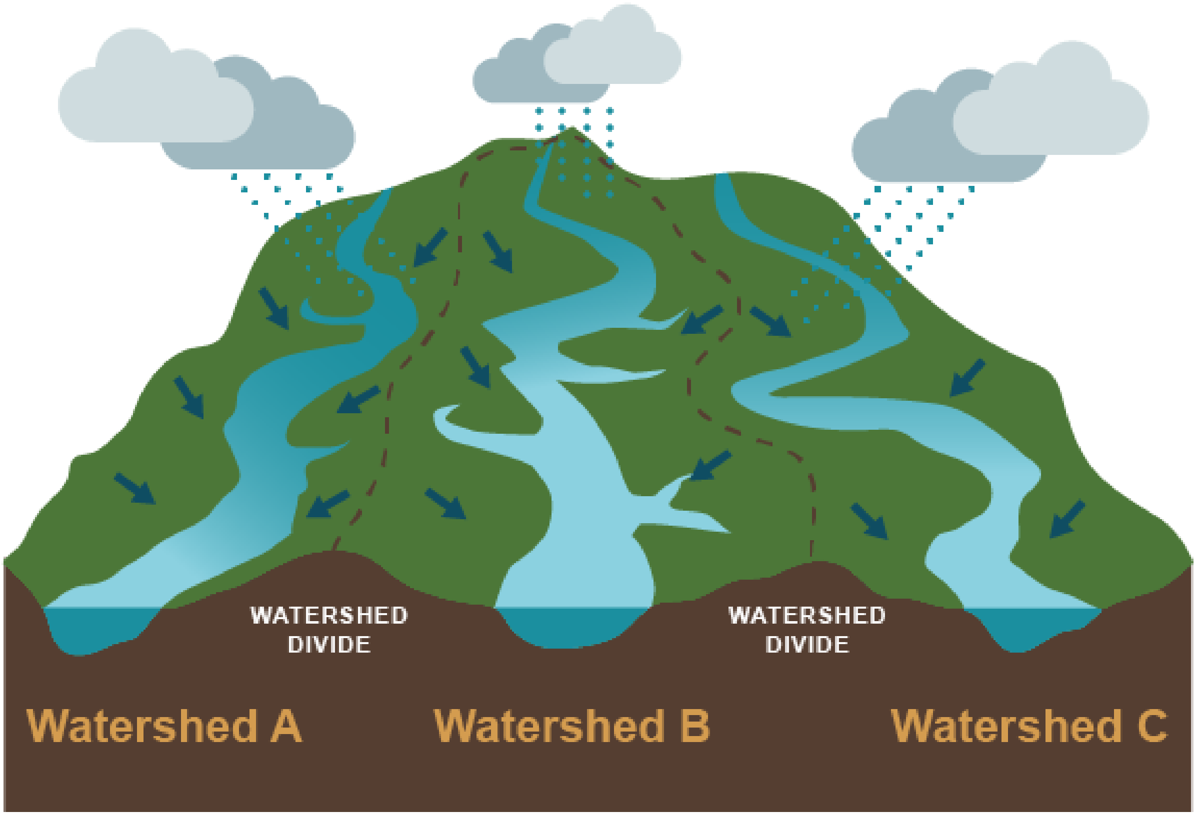
2 Understanding the Basics of Flood Risk

Floods can negatively affect communities in many ways, including disruption of essential services like roads, power stations, healthcare facilities, and water/wastewater treatment facilities; closure of businesses leading to economic losses; and damage to homes causing displacement of residents either temporarily or permanently, depending on the severity of damage. For communities to better prepare for potential flooding with the overall goal of reducing these effects, it is important to understand the connection of the various types of flooding (e.g., from rivers, direct rainfall, groundwater, or from the sea) to the larger context. Since these guidelines are related to the use of levees to manage flood risk, the focus is mainly on river and coastal flooding.

2.1 Watersheds

To understand the potential flooding risk posed to the community, it is important to understand the impact localized activities and drainage area characteristics may have on the watershed or watersheds that encompass a community. A **watershed** is a land area that channels rainfall and snowmelt to creeks, streams, rivers, and eventually outflow points such as reservoirs, bays, and the ocean. The size of a watershed (also called a drainage basin or catchment) is defined via a heirarchy of scales. Depending on the scale of interest, watersheds can be small, such as that of a single small creek, or they can be very large, such as the watershed of a big river that includes many streams, tributaries, and reservoirs. The separation between watersheds is known as the watershed divide (Figure 1-3).

Figure 1-3: Sample Watershed



Individual watersheds within the U.S. may be located through an interactive U.S. geological survey map starting with the selection of a water resource region (Figure 1-4). The U.S. and Caribbean are currently divided into 22 regions, 223 sub-regions, 387 basins, 2,318 sub-basins, 18,586 watersheds, and 101,534 sub-watersheds.

Figure 1-4: Water Resource Regions to Watersheds

The flooding potential for a community near a river or other bodies of water, is influenced by the characteristics and the activities within its respective watershed(s). Having knowledge of development activities within the watershed, while understanding how human influences are changing the watershed's characteristics, is important because localized activities may impact other areas. For riverine watersheds, impacts may be realized upstream or downstream of a community or point of interest. For example, increased development and urbanization within a watershed may decrease the ground's ability to retain water and subsequently increase flooding downstream of the development. Additionally, the construction of a new levee may reduce flood storage within the floodplain and increase water surface elevations upstream of the levee. Reducing storage will also pass higher peak discharge rates and discharge volumes downstream which could also increase flood elevations downstream of the levee.

Some watersheds ultimately outlet to coastal areas including oceans and large lakes. For these instances, impacts within the watersheds should also take into account the interaction between the coastal floodplain and the rest of the watershed. Coastal floodplains comprise the areas adjacent to the water body affected by the upstream extent of tidal influence, including estuaries, beaches, nearshore waters, and offshore waters (Figure 1-5). They traditionally encompass a large area, the focus being the shorelines that are subject to high water, waves, and winds. Coastal floodplains warrant their own field of study describing coastal processes and dynamic changes. Smaller units within these areas are defined in other ways, for example linked to the commonality of coastal behaviors or to adjoining riverine watersheds and associated riverine flooding. Additional discussion of coastal flooding and coastal floodplains is included in section 2.3.2.

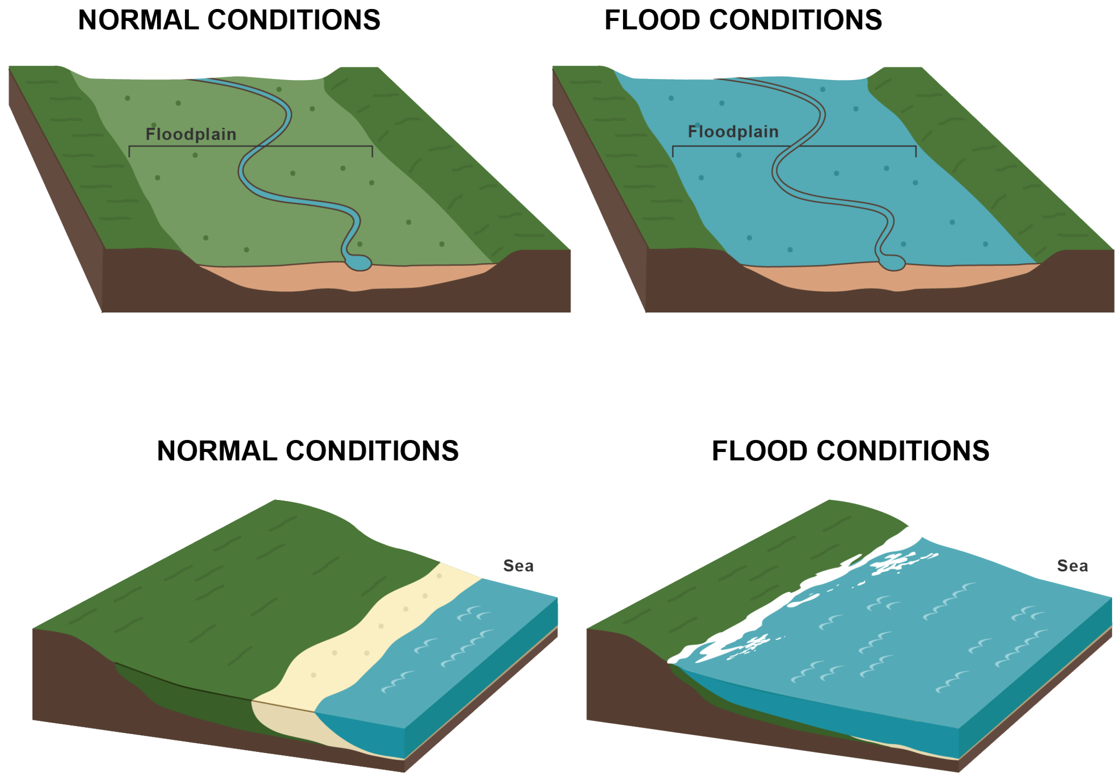
Figure 1-5: Example of Coastal Floodplain

(a) Watershed along California's central coast in Carmel, California; March 2023. (b) Carmel River flowing to the Pacific Ocean in Carmel, California; March 2023.

2.2 Floodplains

During a flood, rainfall, snowmelt, and groundwater will naturally accumulate at the lowest points within the watershed that coincide with streams, rivers, lakes, and estuaries. These bodies of water can retain a set amount of flow or volume with excess accumulations overflowing into adjacent floodplains. A floodplain is any land area susceptible to being inundated by floodwaters from any source. Communities should be aware of the location and characterization of the floodplains within their jurisdictions to minimize development thereby decreasing future flood risk. Representative floodplain layouts for rivers and coasts are shown in Figure 1-6.

Figure 1-6: Floodplain Layout

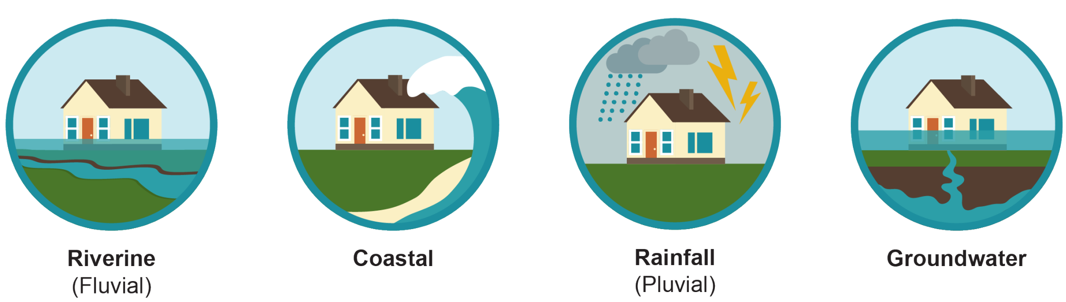


Determination of the floodplain boundary can be challenging and subject to judgment in areas of flat terrain. Some federal, state, and local agencies have identified floodplains as regulatory and their delineation of the boundary serves as the best available data for use in identifying and mitigating developments in floodplains. For example, the Federal Emergency Management Agency (FEMA) has published several products including Flood Insurance Rate Maps, which identify floodplains for the areas that will be inundated during flood events equal to or greater than the events having a 1% or 0.2% chance of occurring in any given year.

2.3 Flood Hazards

The flood hazards that may impact a community can be broken down into four categories, as shown in Figure 1-7:

Figure 1-7: Sources of Flooding



These flooding sources may act independently or in conjunction with one another (i.e., compound flooding). Though compound flooding is not itself an independent source of flooding, it is prevalent where two flooding sources intersect. Compound flooding is described further in section 2.3.5.

2.3.1 Riverine Flooding (Fluvial)

The most commonly understood and quantified source of flood inundation is riverine flooding. When rain falls on land, it either infiltrates into the ground or it runs off along the surface, which is commonly referred to as surface runoff. Surface runoff will naturally seek the lowest elevation of the terrain to continue to flow, or in some cases pool in low-lying areas. Rivers form from the collection of surface runoff with water moving from a higher elevation to a lower elevation due to gravity. **Riverine (or fluvial) flooding** is defined as an event that occurs when the water level in a river, lake, or stream rises and overflows onto the surrounding banks, shores, and neighboring land (Figure 1-8 and Figure 1-9). The water level rise could be due to excessive rain, snowmelt, or ice jams. Riverine flooding can also be in the form of overland flooding or flash flooding.

Lakes may be categorized as riverine or coastal depending on the size and flooding characteristics of the lake. Most lakes are considered riverine flooding sources, but larger lakes (e.g., Great Lakes) where wave action and setup are impactful, are considered coastal flood hazards.

Figure 1-8: Riverine Flooding

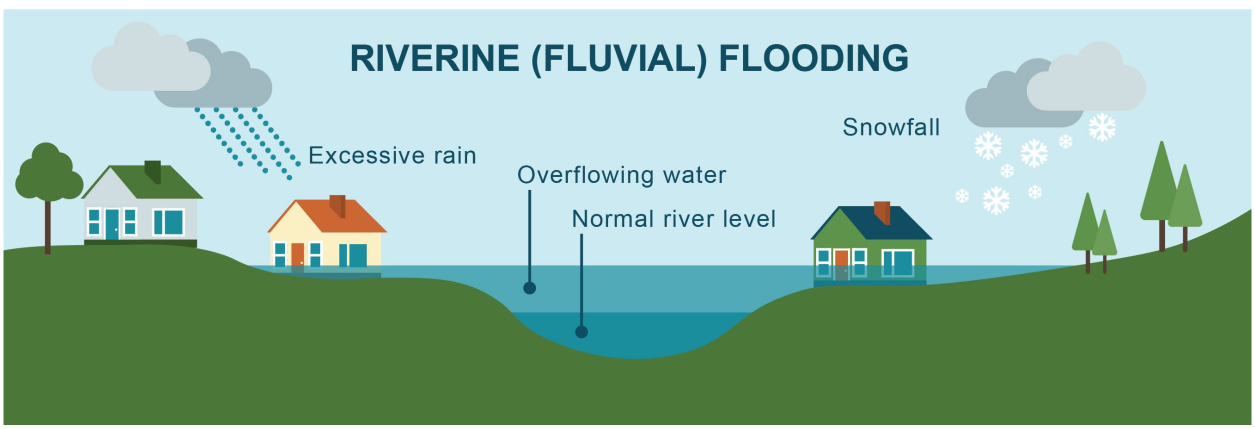


Figure 1-9: Example of Riverine Flooding

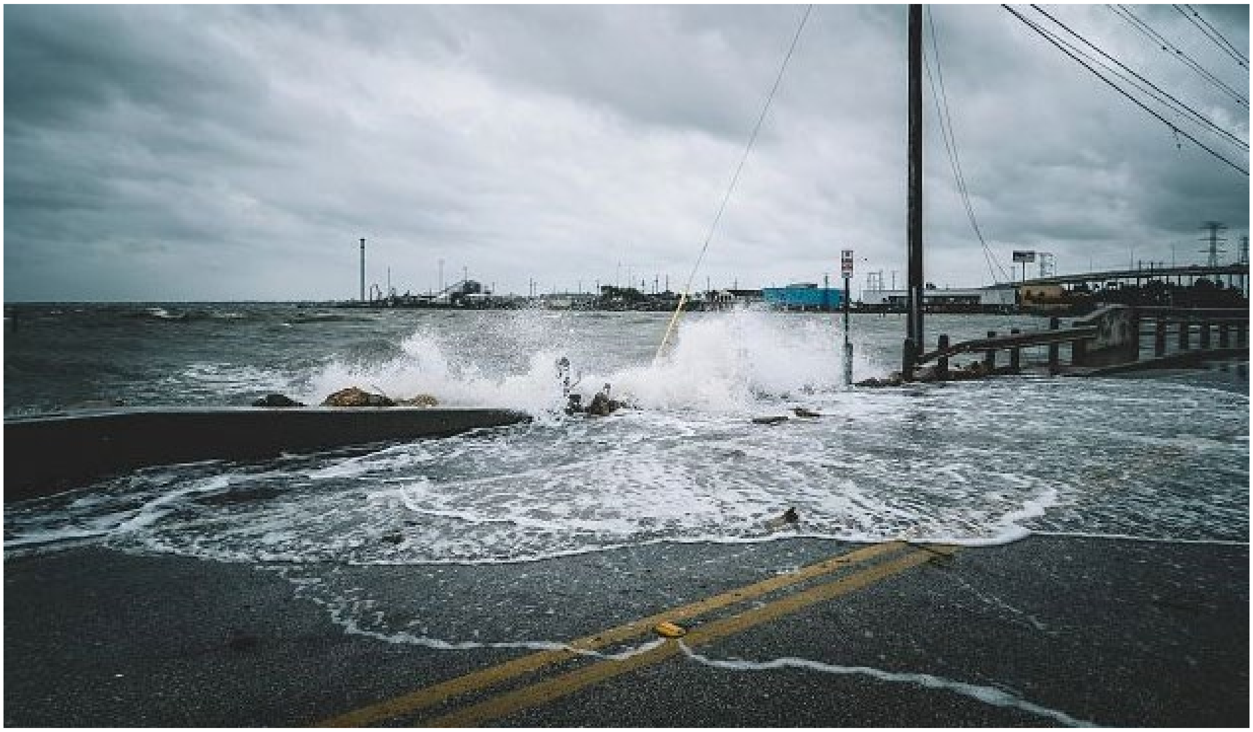
Riverine flooding in the community of Hardin, Illinois, looking east to the area that flooded from the Nutwood Levee breach during the spring 2019 flood on the Mississippi River.

2.3.2 Coastal Flooding

Coastal flooding occurs when exposed coastlines are submerged by water from large bodies of open-water such as oceans, gulfs, bays, or large lakes (Figure 1-10). Common causes include high water levels, wind, waves, storm surge, sea level rise, and tsunamis (FEMA, 2023). The degree and severity of flooding depends on the intensity of the event in combination with other factors. As an example, if a storm surge coincides with a high tide event, the resulting coastal flooding is extensive (Figure 1-11). Likewise, most coastal storm events are comprised of multiple contributors (e.g., waves, surge, rainfall, wind, etc.) creating a more severe flood situation.

Figure 1-10: Coastal Flooding

Figure 1-11: Example of Coastal Flooding

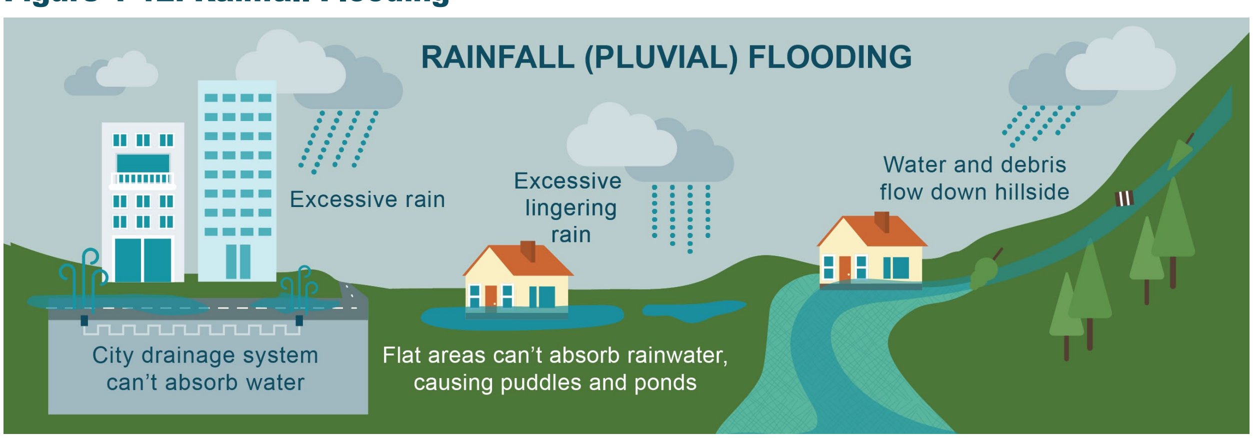


Destructive impact of coastal storm surges resulted from Hurricane Harvey in Kemah, Texas; August 2017.

2.3.3 Rainfall Flooding (Pluvial)

Rainfall (pluvial) flooding can be defined as an event that is caused by persistent, heavy rainfall and independent of an overflowing water body, occurring when the ground cannot absorb rainwater effectively or when drainage systems are overwhelmed by excessive water flow (Figure 1-12). These events can sometimes be categorized as urban flooding or flash flooding. This flooding source is normally independent of a water body with occurrence dependent on storm intensity and therefore not always easily identifiable or understood. Areas of rainfall flooding are traditionally associated with localized topographical depressions, poorly drained soils, areas with poor or undersized drainage systems, or areas with high water tables.

Figure 1-12: Rainfall Flooding

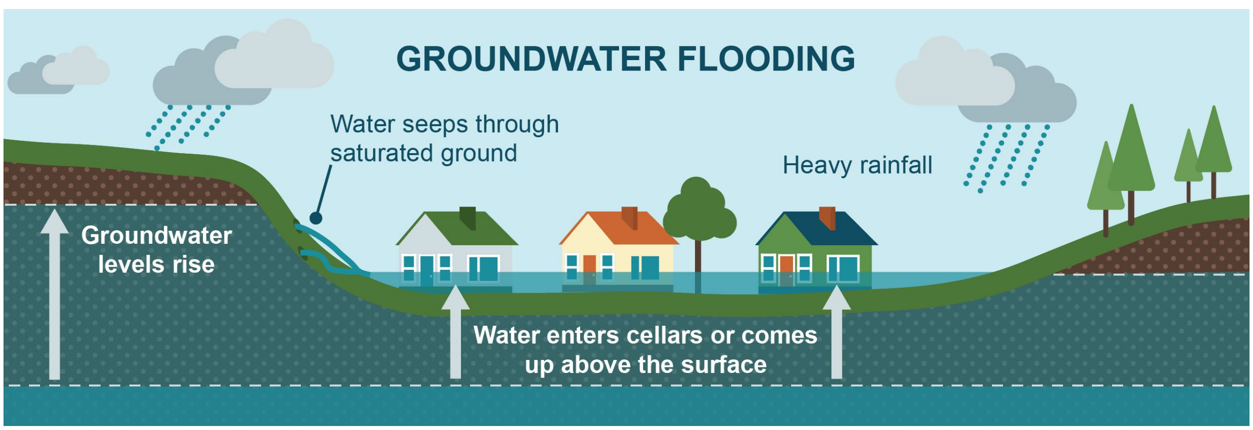


Rainfall flooding is most prominent in urban areas with higher percentages of impervious surfaces which do not allow the penetration of water, and inadequate drainage and/or drainage systems. These conditions may not always be obvious until the flooding occurs. Anticipating and quantifying the areas at risk of rainfall flooding leverages similar tools as riverine flooding, including historical observation and modeling described in section 2.3.6. One challenge identifying urban flooding is that it can be exacerbated locally due to storm drain obstructions or other problems that are difficult to predict.

2.3.4 Groundwater Flooding

Groundwater flooding is the emergence of groundwater at the ground surface (Figure 1-13). It can occur in a variety of geological settings including valleys in areas underlain by permeable rocks (such as chalk), and in river valleys with thick deposits of alluvium (e.g., clay, silt, sand, and gravel deposits left behind by flowing streams) and river gravels. Groundwater flooding happens in response to a combination of already high groundwater levels—usually during mid or late winter due to snowmelt and higher precipitation—and intense or unusually lengthy storms. Groundwater flooding often lasts much longer than flooding caused by a river overflowing its banks. It may last many months and can cause significant social and economic disruption to the affected areas.

Figure 1-13: Groundwater Flooding



2.3.5 Compound Flooding

Compound flooding refers to a phenomenon in which two or more sources contribute to inundation, simultaneously or within a short period of time (*Characterization and Modeling of Compound Flooding Events and Their Environmental Impacts*, 2021). Typical examples include inundation as a result of coastal storm surge, riverine and rainfall flooding (i.e., flash flood), and coincident flooding at the confluence of two rivers or streams. When identifying and quantifying the sources of flooding, it is helpful to take into account the interaction of these different sources.

2.3.6 Evaluation of Flood Hazards and Resultant Flooding

Once the flood hazards have been identified, comprehending the subsequent risks posed on the community requires further understanding of the magnitude and frequency associated with each flooding source. Methods to understand and evaluate the resultant flooding of the community are described in **Chapter 4**, but generally involve the use of historical observations of past flooding occurrences along with hydrologic and hydraulic modeling to simulate the likely range of future events.

- **Historical observations** include results from dedicated instruments strategically placed in or near a flooding source, such as stream or tidal gauges, high water marks on buildings, and photographs of flooding or debris lines. Trends in these observations can also inform flood modeling and mapping activities. Historical observations can be utilized to calibrate hydrologic and hydraulic models to historic rainfall events, thereby improving model accuracy. However, historical events are not necessarily good predictors of the future, given factors such as climate change, hydrologic variability, channelization, changes in development or land use, and geomorphic processes.
- **Hydrologic and hydraulic modeling** simulates the conditions of a flood event involving various parameters to estimate the flood risk for a given area. Hydrologic modeling pertains to the analysis of the rainfall and surface water, in particular its movement in relation to land. Hydraulic modeling evaluates how flood water will move within a system in response to flood hazards of differing magnitudes, taking account of the performance of the flood risk management infrastructure. Models should account for the full range of expected flood conditions and may need to account for changes in flood magnitudes under future climate regimes.

2.4 Consequences of Flooding

Consequences of flooding may be either direct or indirect. Direct consequences are readily observed and specific, such as flood damage to residences or other structures. Indirect consequences may be less tangible, such as short- or long-term health or quality of life impacts borne by displaced community members. Consequences are exacerbated when zoning allows low lying, flood prone areas to be zoned residential. They are also exacerbated in low lying areas when mixed zoning—residential with commercial and/or industrial—is allowed. Whether direct or indirect, flood consequences are often times inequitably distributed with those populations most at risk bearing the most consequence. Consequences may commonly be grouped into several broad categories, including, but not limited to:

- **Life, health, and safety impacts** including loss of life, short- or long-term physical or mental health effects, and issues such as raw sewage, leaked toxic chemicals, runoff from farms/hazardous waste sites, and/or contamination and mold.
- **Monetary and economic impacts** including loss of or damage to property, business, and wages.
- **Environmental impacts** such as those arising from contamination or loss of critical habitat.
- **Social and cultural impacts** to include historic/archeological sites, or where entire communities are uprooted.
- **Agricultural impacts** including the loss of or damage to valuable crops in neighboring fields.

- **Critical infrastructure impacts** such as power generation, water and wastewater treatment plants, military facilities, nuclear power plants, interstates, hospitals, police stations, and fire and rescue stations.

It should also be noted that these consequences will likely be exacerbated in underserved communities and among socially vulnerable populations. For example, historical policies such as redlining forced minorities, particularly African Americans, to live in areas more prone to flooding. These areas often have limited resources for capital improvements for flood risk reduction infrastructure, and are more likely to contain industrial facilities such as refineries, superfund sites, or other toxic waste sites that can lead to severe environmental, health, and economic impacts if flooded.

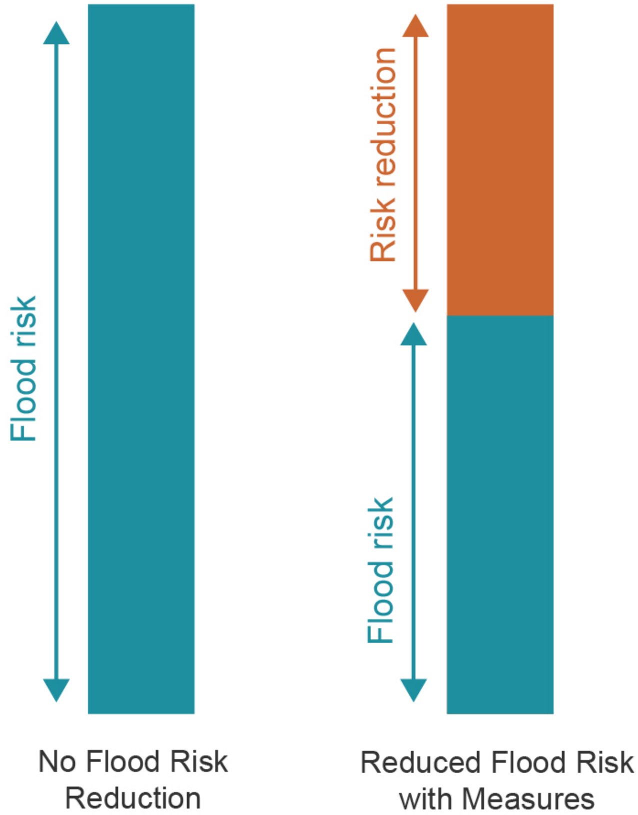
Consequence evaluation requires an understanding of who and what is at risk (asset inventory), the degree to which those assets come in contact with the hazard (exposure) and the extent of the impact to the asset (vulnerability) based on that exposure. Each of these aspects of the consequence evaluation are described in **Chapter 4**, alongside approaches used to develop the consequence estimate.

3 Applying Flood Risk Management Principles

3.1 Overview of Flood Risk Management

Flood risk management encompasses activities (risk reduction measures) that aim to reduce the likelihood and the impact of floods from the various sources (Figure 1-14). Every community is unique in the flood risk they experience. No one method or solution may be suitable for all instances, though application of common principles and best practices can support efficient and effective **risk-informed decision making**. This is the process of using qualitative or quantitative risk information, in conjunction with other considerations, to lead to more complete, transparent, and informed decisions.

Figure 1-14: Flood Risk Reduction



Flood risk management principles align with the vision and mission for the National Levee Safety Program:

- **Life safety is paramount**. Prioritizing actions to reduce the risk to life loss is the most important responsibility for flood risk management.
- **Flood risk management is a shared responsibility**. To be effective, it must include all levels of government, businesses, and the public working together in a coordinated fashion.
- **Transparent, proactive, and continuous engagement with all community members is essential**.
- **Flood risk should be periodically reevaluated and proactively managed** due to dynamic and changing environments influenced by natural and human impacts.
- **Floods do not affect all communities and individuals equally**. Flood risk management practices should strive to achieve equity by addressing unique challenges and barriers that may be experienced by any community member.

NATIONAL LEVEE SAFETY PROGRAM

Vision: Reduce the impacts of flooding and improve community resilience in areas behind levees.

Mission: To manage reliable levee systems as part of an integrated approach to protect people and reduce property damage from floods.

For effective flood risk management decisions to be made, a holistic approach considering environmental, social, and economic factors, should be undertaken after the risk of flooding is fully understood. Estimating flood risk requires: (1) the consideration of all types of floods, and (2) the evaluation of the probability of flooding and potential adverse consequences. Section 4.1 provides more information on foundational concepts related to flood risk and **Chapter 4** has been dedicated to details on estimating levee risk.[1]

3.2 Developing a Flood Risk Management Strategy

A comprehensive flood risk management strategy is important because it helps to achieve the primary goals of reducing flood risk and promoting community resilience through an integrated and collaborative approach. When developing a comprehensive strategy there are several overarching best practices to consider:

- **Communicate risk in meaningful ways to the public**. People need accurate, timely, understandable, and actionable information (e.g., risk maps, property specific vulnerabilities, real time news/updates about events, technical information in layperson's terms, translation, education). Special consideration should be given to communicating risk to those who are non-English speaking, disabled populations, underserved communities including those with high poverty rates, and those who have not been engaged in previous community actions which have directly impacted their risk of flooding, health, or economic opportunities.
- **Promote the sharing of responsibilities**. Multiple groups within the local government have a stake in reducing the risk of flooding in their communities, but that does not mean flood risk management responsibilities solely exist at the local government level. Effective flood risk management cuts across disciplines, departments, and levels of government (local, state, federal, tribal).
  - Public and private sectors working together. The portfolio of tools should seek an equitable balance among the needs and circumstances of individuals, businesses, and government, as well as the community's economic, social, and environmental resources (National Research Council and National Academies, 2012, p. 61). Public and private sectors play different roles in response and recovery. Thus, they should have different, but complementary, strategies prior to a disaster, sharing a role in reducing risk through preventative strategies. They share a responsibility for the performance of the built environment, and thus share an interest in resilience goals.
- **Support community values**. For flood risk management to be effective, it must be rooted in the community's values and long-term vision, while adhering to the existing capabilities and recognizing limitations. In other words, flood risk management needs to protect what the community prioritizes through a sustainable program. Ideally, flood risk management activities are fully integrated into the fabric of a community—a risk reduction mindset—that influences policy, capital spending, insurance participation, and

[1] Other resources within the industry that focus on overarching flood risk concepts include FEMA 480—Floodplain Management Requirements (FEMA, 2005) and the Association of State Floodplain Managers, Inc. ("The Association of State Floodplain Managers, Inc. | ASFPM," 2024).

land use decisions including future development and takes into account the needs of underserved populations.

- **Engage the whole community in disaster policy making and planning** (National Research Council and National Academies, 2012, p. 117). Organize communities, neighborhoods, and families to prepare for disasters and prioritize investments, advancing community goals. Flood risk management strategies should provide for equity across the various populations impacted by the actions taken to:
  - Prevent or reduce losses (i.e., costs and human suffering caused by flooding).
  - Protect the natural and beneficial function of floodplains.
  - Ensure a more resilient community, both now and in the future.

The first step in developing a strategy to reduce flood risk is to generate goals that align with the risks. Goals are typically broad statements that promote community values and align with its long-term vision related to residential and commercial development and the protection of assets. Goals can be grouped by themes, such as sustainability or type of flood hazard, by critical assets at risk, or by location. Existing plans and policies, such as a community's comprehensive plan or capital improvement program, should be reviewed to identify opportunities for overlapping goals. Additionally, hazard mitigation plans that assess an area's vulnerability in relation to the effects from hazards and existing regional watershed or stormwater plans may support the strategic alignment of goals for future funding and partnerships.

3.2.1 Community Flood Resilience

Concepts related to enhancing a community's flood resilience should be interwoven into the flood risk management strategy. **Community resilience** to flooding (see also **Chapter 12**) is the ability of a community to anticipate, prepare for, respond to, and recover from floods with minimal damage to social well-being, the economy, and the environment. Resilience is a responsibility shared by the whole community. It is delivered by a continuous process of strengthening and adapting, and takes into account the changes in flood risk that may arise (see section 5).

Figure 1-15: Resiliency Expressed as Functionality Over Time Following an Event

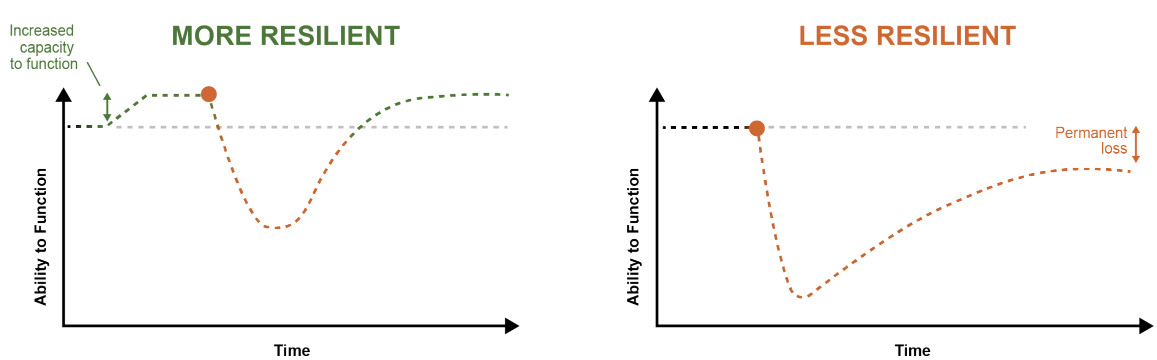


Figure 1-15 illustrates two levels of resilience for a system. A system can be considered either a community, an asset, or service within the community. On the right, a system operates at a steady state (business as usual) until an acute hazard occurs (orange dot). If the level of service drops below a tipping point—the level of performance during pre-hazard conditions—the system attempts to recover, but experiences a permanent loss. On the left, actions taken to improve overall conditions prior to an acute hazard increase the system's functional level. From this higher baseline, the same acute hazard still requires a period of recovery, but no irreversible damage occurs. Building resilience means improving conditions so that the system can accommodate future disruptions.

Approaches used to enhance community resilience should be grounded by the principles of including and listening to the whole community, understanding risk, exploring options to reduce risk, prioritizing and implementing those options based on the unique characteristics and needs of the community, and then monitoring and adapting to changing conditions. Tools and case studies are available for communities to help implement resilience activities, such as the U.S. Climate Resilience Toolkit. Additional approaches to design-in resilience—in the context of robustness, redundancy, and recoverability of levee projects—are discussed in **Chapter 7**.

U.S. CLIMATE RESILIENCE TOOLKIT

The U.S. Climate Resilience Toolkit provides resources and steps that communities can take to create a resilience framework for reducing climate-related risks. Communities can use the framework to help identify valuable assets, determine their climate-related hazards, prioritize options for reducing risk, and implement effective actions to reduce risk.

The toolkit is available at https://toolkit.climate.gov.

1. **Understand exposure**
2. **Access vulnerability and risk**
3. **Investigate options**
4. **Prioritize and plan**
5. **Take action**

CASE STUDY: FLOOD RISK REDUCTION IMPROVEMENTS AT A WASTEWATER TREATMENT FACILITY (FENTON, MISSOURI)

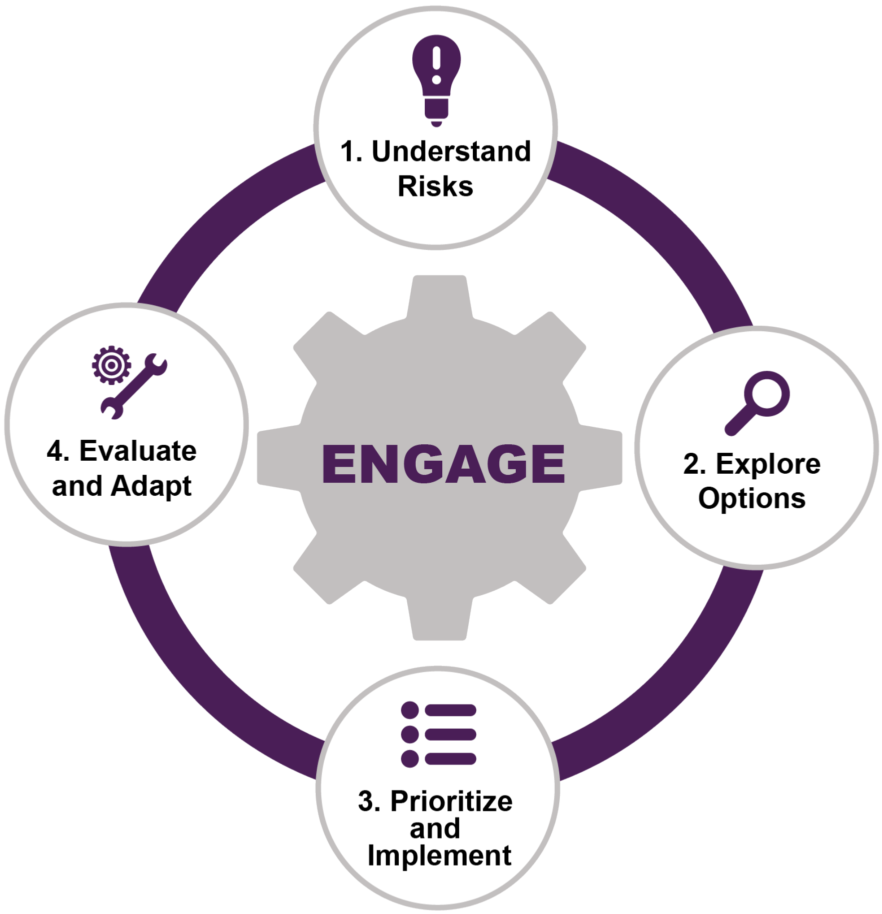
The Fenton Wastewater Treatment Facility is situated near the confluence of Fenton Creek and the Meramec River in south St. Louis County, Missouri. Despite the existence of a levee surrounding the facility, it was overrun with flood waters during the historic flooding of the Meramec River on Dec. 30, 2015. The damage caused by this flooding prompted the Metropolitan St. Louis Sewer District to look at options for improving the levee surrounding the facility and increasing the resilience of this vital community infrastructure. A second flood event occurred on May 3, 2017, prior to the implementation of the levee improvements, which would have flooded the facility if not for emergency floodfight efforts.

In 2018, a 3,000 linear foot, 3.5-foot riverside levee raise, and a 150-foot long floodwall were constructed. As seen in the image below, flooding from a 2019 event, the flood of record for this location, did not impact the facility.

3.2.2 Flood Risk Management Process

Once the flood risk management goals have been identified, a best practice is to proceed through a stepwise approach of supporting activities, as depicted in Figure 1-16. The center of the figure signifies perpetual engagement activities associated with each phase to include discussing risk, defining options, prioritizing and implementing the most effective options, evaluating the results and planning for future activities. The sequential steps around the outer portion of the figure are briefly described below but further detailed in **Chapters 4, 6, and 12**.

Figure 1-16: Flood Risk Management Process Diagram



3.2.2.1 Engage the Community

An essential step in flood risk management is ensuring the engagement and buy-in of the entire community, particularly those who have previously not been included in community decision making such as underserved populations. Communities commonly include residences, industrial buildings, critical facilities, or farmland vulnerable to hazards such as flooding. Organizing a collaborative planning process that engages the whole community requires understanding and incorporating community values and priorities into resilience building activities. A full discussion of best practices for community engagement can be found in **Chapter 3**.

CASE STUDY: PUBLIC EDUCATION AND OUTREACH (DOWNERS GROVE, ILLINOIS)

The Village of Downers Grove, Illinois, is a bustling suburb 22 miles outside of Chicago where existing flood vulnerabilities are compounded by the reality of increasing storm frequency and intensity combined with an increase in impervious surfaces. The village adopted a comprehensive public outreach and education campaign which it used to gain community consensus to employ a full suite of stormwater and flood risk management tools to minimize both riverine flooding and urban flooding (see “Tools in the Toolbox”). Examples include:

Stormwater Utility Fee. The initial attempt at a monthly stormwater utility fee based on the total square footage of impervious area on a parcel (e.g., roofs, driveways, gravel, pools, decks, parking lots) received a mixed reaction from both commercial and residential property owners. An intense educational campaign “Stormwater YOUtility” utilized multiple communications platforms (i.e., short videos, social media, the village website, local television, print advertisements) to raise awareness about the Stormwater Utility Referendum. A fully interactive GIS-based map provided comparisons between stormwater utility fees and property taxes for each property within the village. Reductions in utility fees were also available for residents using green infrastructure solutions like rain barrels, permeable pavers, or detention basins. After years of reinforcing the need for a fee, and the control it gives residents over their own bills by decreasing the amount of Imperviousness on their lot, in 2016, Downers Grove voters approved a referendum to keep the stormwater utility fee.

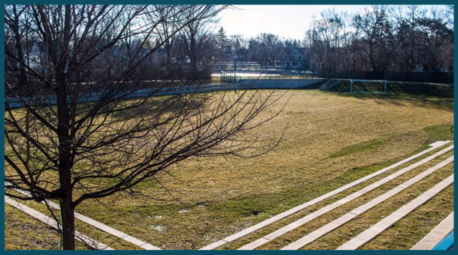
Policy Regulation. Localized poor drainage areas are bowl-shaped areas of the village where stormwater runoff cannot infiltrate the ground and tends to accumulate, creating flooding or standing water. Filling in a portion of one, similar to filling in a portion of a floodplain, may increase the flood elevation, potentially leading to a higher chance of flooding to properties. Although localized poor drainage areas are not recognized by FEMA, village codes were modified, after engagement with the community, to regulate them in a similar way to FEMA special flood hazard areas. The regulations ensure any new construction is reasonably safe from flooding and does not adversely affect other properties.

To view the Downers Grove public education website related to its stormwater utility fee initiative, visit Downers Grove Stormwater Utility Page.

TOOLS IN THE TOOLBOX

Downers Grove has implemented the following tools within the community to help reduce the impacts of flooding to people and property within the community:

- Set elevations for new development at least 1 foot above the 1% water surface elevation in special flood hazard areas and localized poor drainage areas.
- Acquire properties and return areas to open space.
- Record drywells with a deed.
- Promote rain gardens and natural wetlands on small city lots.
- Require large developments to establish “special service areas” with the village for continued maintenance of stormwater detention.
- Review all permits and development plans for changing imperviousness and stormwater consequences.
- Collect stormwater utility fees.
- Regulate localized poor drainage areas similarly to special flood hazard areas.
- Participate in the FEMA Community Rating System to develop a plan for undertaking activities that result in increased resilience to flooding in the community.



Washington Park in Downers Grove, Illinois before and after extreme rain. The park was designed to allow for storm water detention after rain events.

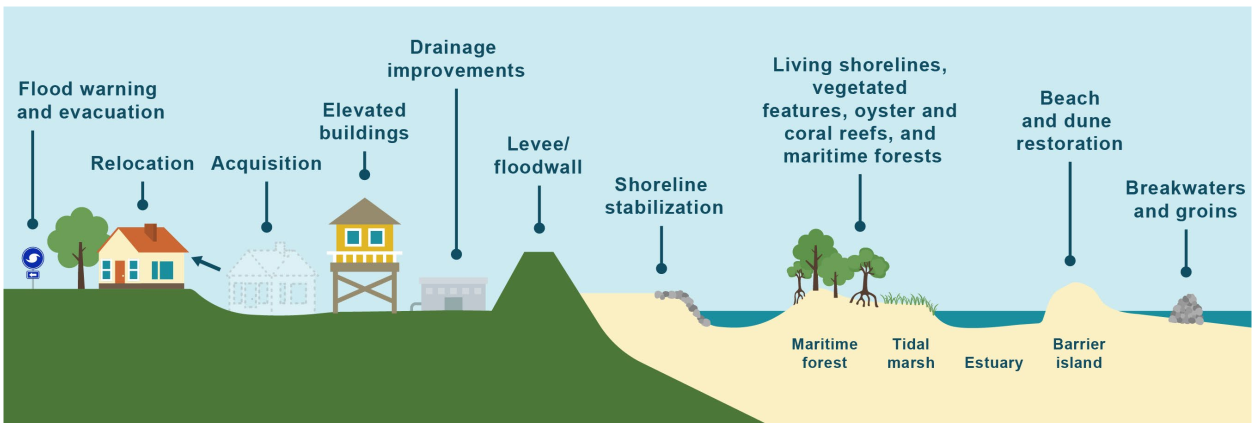
3.2.2.2 Understand Risks

As illustrated in Figure 1-16 and described in section 2, understanding risks is the first step in a community's flood risk management process. Understanding flood risk involves evaluation of flood hazards, the flooding process from those hazards (including the performance of any exisitng flood risk managament infrastructure) and the consequences of the resulting flooding. Additional details pertaining to levee risk estimation may be found in **Chapter 4**.

3.2.2.3 Explore Options

Flood risk is rarely simple. A multitude of actions may be required to reduce risk to life, health, and property and restore natural floodplain resources and functions (Figure 1-17).

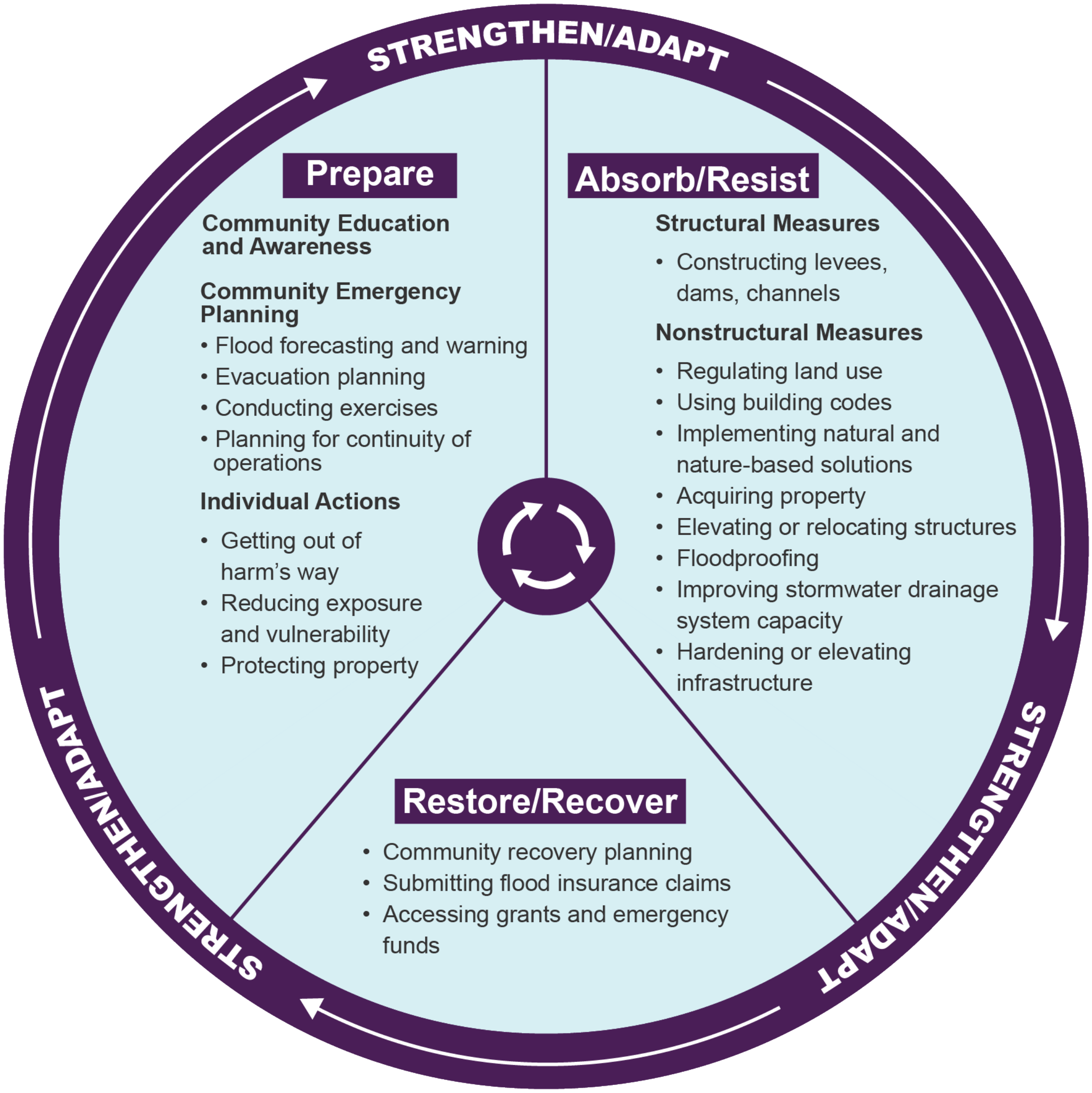
Figure 1-17: Types of Coastal Flood Risk Reduction Measures



Finding ways of reducing flood risk can be a complex dance between competing priorities and limited regulatory capabilities. It requires consideration of risk exposure, vulnerable populations and assets, resources/funding, and local community priorities, but can provide an opportunity to align seemingly unrelated community goals and achieve multiple benefits. Solutions that embrace a variety of techniques to promote multiple benefits across a community can result in additional funding sources and staffing by municipal and/or non-governmental organizations. These solutions may be better poised to retain long-term community-wide support, as shown in the example about the use of nature-based approaches in Toledo, Ohio.

Numerous options (Figure 1-18) may be considered for use by a community, with the primary categories relating to the steps commonly employed to deliver **resilience**. Reducing flood risk through levee infrastructure is the main subject of this guidance, however the use of other mitigation options is briefly discussed in **Chapter 12**.

Figure 1-18: Flood Risk Management Options



CASE STUDY: NATURE-BASED SOLUTIONS (TOLEDO, OHIO)

The city of Toledo, Ohio was built on a low-lying area formerly known as the Great Black Swamp. The city's relatively low elevation and its proximity to so much water makes it highly susceptible to flooding. Recently, the city has experienced more frequent and intense rains, with annual precipitation rates rising by more than 40% in some areas.

To help address recurring flooding issues, the city explored the use of nature-based strategies initially with small demonstration projects, followed by large-scale projects in high-profile areas. The construction, operation, and maintenance of these projects helped to promote local buy-in.

An economic assessment of green infrastructure was undertaken by the city for Toledo's Silver Creek watershed, a 15-square-mile area in the northwest part of the city. A framework later formalized in a 2016 publication entitled “A Guide for Assessing Green Infrastructure Costs and Benefits for Flood Reduction,” was used to compile information about current and future flooding. Results indicated that the green infrastructure plan could reduce the estimated flood damages by $290,000 under current conditions and $400,000 under future scenarios.

The project's analyses indicated that precipitation and damage from flooding is expected to increase in the Silver Creek watershed over the next 20 years. The following strategies were recommended to reduce future flooding damages:

- Look for opportunities to increase flood storage and reduce runoff with green infrastructure including natural functions restoration, blue rooftops, pervious pavement, curb cuts to direct runoff into vegetated areas, and bioretention areas and swales.
- Remove buildings from the floodplain where flooding is severe (buy-outs) and incentivize shifting future development away from the most flood-prone areas.
- Promote community acceptance of green infrastructure by building on past successes and showcasing benefits (e.g., previously installed bioretention areas, parks, and open space).
- Consider revising stormwater policies to incorporate more stringent requirements for onsite retention.

A key factor in the success of Toledo's green infrastructure planning was the collaboration. "Partners are a critical part of the success of this project," explained Lori Cary-Kothera, Operations Manager with the National Oceanic and Atmospheric Administration's Office for Coastal Management, in 2014. "I think the take-home message is that these projects are complicated, and you really need to build partnerships that supplement the skills, take advantage of the network and the resources that are out there, and figure out how to leverage those.” She added, "It takes time to implement green infrastructure, so give yourself a break. It's not going to happen overnight and build that into your implementation plans” (U.S. EPA Office of Wastewater Management, 2014).

Since 2014, Toledo has implemented green infrastructure projects throughout the city, with the understanding that beneficial impacts will not happen immediately, but will be the result of consistent application of projects within the framework of the project.

The city of Toledo used sustainable management of stormwater to create rain gardens as one aspect of the overall project.

3.2.2.4 Prioritize and Implement

The third step of the flood risk management process is to select the risk reduction best suited for the community. A community should select the best feasible solution unique to their specific needs and resources. If applying for a grant or funding to a specific agency, the decision about the risk reduction activity should also consider the specific criteria established by the grant requirements. Best practices for selecting the most appropriate option include:

- Identifying a broad selection of options before, during, or after a disaster situation to improve resilience and promote effective risk management. Redundancy of mitigation strategies, should one measure fail or not perform as expected, increases the likelihood that flood risk will be reduced.
- Determining the risk reduction benefits for each option. This will include the need to question whether or not the mitigation ideas are in line with the community's risk reduction goals. This approach will lead to a true indication of the performance of a particular strategy. At the end of the day, it is important to know if the goals are achievable, if they promote the long-term community vision, and if they maximize benefits (direct, indirect, compounded).
- Having a method for prioritizing the options through an action plan that describes: the prioritization of factors, assignment of a lead, anticipated timeframes, and financing methods.

When selecting the best flood risk management solution, whether it be a levee or some other option, it is important to formulate, evaluate, and compare all options. These steps are discussed in more detail in **Chapter 6**. Although that chapter is focused on formulating a new levee project, the generalized planning process can be applied to any potential flood risk management solution.In addition to striving to reduce flood risk, the following factors should be considered:: cost, environmental impacts, necessary land acquisition, laws or regulations, equity among community members, public support, and community resilience. It may be feasible to implement multiple strategies to enhance resilience. For example, the construction of a large flood risk reduction project may provide opportunities for enriching the community through the inclusion of multi-purpose facilities (i.e., parks, trails). **Chapter 12** discusses various options other than levees that a community may elect to implement, grouped within one of the broader categories depicted in Figure 1-18.

3.2.2.5 Evaluate and Adapt

After implementation, it is important to evaluate the strategies that have been implemented. During the decision-making process for implementing the particular strategies, a process for evaluating the effectiveness of each strategy—both during the project and after the project—should have been identified which addresses the following questions:

- How is the levee working now?
- How have conditions changed, or how do we anticipate conditions to change in the future? The conditions include not only the potential flood risks, but also the social and economic conditions for the community.

- Do these changes require a change in the project that was implemented or an entirely new project by the community? Are there new partners that have been identified that need to be brought into the discussion?

Throughout the entirety of this process, it is essential to document all of the alternatives considered, decisions made, and stakeholders involved so that future evaluations can take these factors into account.

4 Managing Flood Risk with Levees

4.1 Foundational Concepts and Definitions

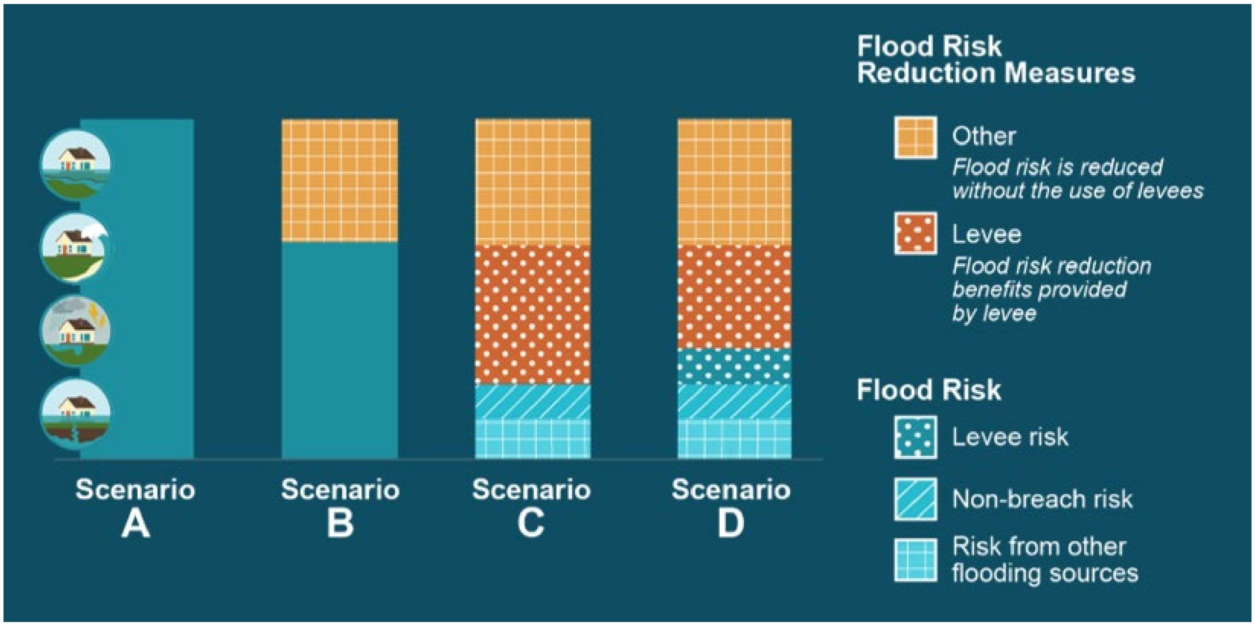
As explained in the previous section, there are multiple combinations of structural and nonstructural measures that can be used to achieve the desired level of flood risk reduction. The selection depends on many factors, including flood risk drivers and the effectiveness of a given measure in addressing them, project physical constraints, availability of funding, and existing policies and practices, among others. The purpose of flood risk management is to reduce flood risk to as low as practical through the integrated implementation of the selected measures. Levees are just one of many tools that may be used when implementing a flood risk management strategy.

Decisions associated with levees should be made in the context of flood risk management, and therefore, it is important to understand the relationship between flood risk and levee risk. The definitions below are fundamental concepts that help establish the foundation for these guidelines.

- **Flood risk**: The probability and consequences of flooding in an area. For areas with flood risk reduction infrastructure (e.g., levees), it accounts for how the infrastructure impacts the subject area, including life, health, and safety impacts; monetary and economic impacts; environmental impacts; and social and cultural impacts. It also includes all sources of flooding.
- **Non-breach risk**: The risk associated with the scenario of the still-water level and/or associated waves, wind runup, or surge exceeds the top of the levee system, but does not result in a breach of the levee system. This is also known as overtopping without breach risk.
- **Levee risk**: The likelihood of occurrence and potential consequences for the following three inundation scenarios: levee breach prior to overtopping; overtopping with breach; and component malfunction or misoperation of levee features.

As depicted in Figure 1-19, flood risk within the leveed area is a sum of non-breach risk, levee risk, and flooding from other sources. Flood risk may be addressed by implementing measures singularly or in combination with other measures. Once strategies are implemented, the flood risk for a community is changed and some level of risk is replaced by the benefits of that strategy. When a levee is chosen as a flood risk reduction strategy, a typical levee will transform some amount of flood risk to levee risk. This is because all levees have some potential to fail before overtopping. The scenarios shown in Figure 1-19 help to further illustrate the relationship between the terms defined above, and additional scenarios described in **Chapter 5**.

Figure 1-19: Relationships Between Flood Risk, Levee Risk, and Non-Breach Risk



- **Scenario A: No flood risk reduction strategy**. Flooding in the area may occur from any and all potential sources and through the full range of flood events.
- **Scenario B: Risk reduction measures other than levees**. Measures may include nature-based solutions, floodproofing, or zoning. In Scenario B, the flood risk is reduced compared to Scenario A, without the use of levees.
- **Scenario C: No levee breach**. A levee is constructed to provide additional flood risk reduction benefits compared to Scenario B. In this fictional scenario, the likelihood of breach or improper operation is zero for the full range of flood events, and the only potential for adverse consequences is due to inundation from floods that exceed the top of the levee (overtopping without breach, also known as 'non-breach risk'). In Scenario C, flood risk in the leveed area—an area behind the levee—is the sum of non-breach risk and flooding from other sources not associated with the levee. For example, for a community with a riverine levee, the riverine (fluvial) portion of the flood risk will go down but flooding in the leveed area may still occur from groundwater recharge or heavy rain and surface water runoff (pluvial).
- **Scenario D: Typical levee**. Building on Scenario C, this situation recognizes the reality that the levee can breach, thereby increasing flood risk. In this case, the flood risk reduction provided by the levee is less than in Scenario C and the flood risk is higher.

It should be noted that the height of the bar, which indicates the overall flood risk potential, was kept the same for all scenarios. This is an oversimplification made for illustrative purposes. It is important to recognize that flooding without a levee is likely to be different in terms of frequency, magnitude, and severity of damages when compared to the risk of flooding with a levee in place. Levees fundamentally change the floodplain and transform flood risk. On one hand, levees reduce the likelihood of flooding in the leveed area for relatively frequent floods up to the levee crown. On the other hand, while a natural flood often results in gradual but widespread inundation, a levee breach could be rapid. A levee breach may also come with little or no warning and could result in greater depth and velocity of floodwaters, especially near the breach, potentially resulting in higher consequences for people who did not evacuate. For additional discussion, see **Chapter 5**.

4.2 Interconnectivity of Risk Management Activities

Levee risk management activities are a subset of flood risk management activities. For example, flood emergency action plans for a community behind a levee would include procedures for all potential flooding scenarios, including floods that significantly exceed levee height and rainfall flooding. These plans would also include developing specific provisions for managing levee-related emergencies. Those provisions are part of levee risk management and help manage consequences of levee failure.

Further, levee and flood risk management activities are interconnected. Decisions to adopt good flood risk management could improve levee risk management. For example, zoning restrictions near the levee and strong community awareness of flood risks can help manage consequences of levee failure. Conversely, allowing development in the leveed area without proper emergency planning and provisions for evacuations can hinder the ability to get people out of harm's way in the event of levee breach.

It is important to understand the contribution of levees to the overall flood risk management. For new levees, this means developing project objectives and formulating the levee design in terms of desired life safety, economic, and other flood risk reduction metrics. Intended flood risk reduction in terms of annual probability of overtopping or "frequency of overtopping," as well as locations of controlled overtopping and breach, should be consistent with the overall flood risk management strategy.

In situations when the flood risk management plan is developed around existing levees, the first step is to estimate the maximum flood risk reduction the levee can provide (**Chapter 4**). Once the maximum risk reduction is understood, the overall strategy can be formulated by either considering other measures to supplement flood risk reduction benefits provided by the levee, setting new objectives for the existing levee and modifying the levee accordingly, or both. Details associated with levee removal and/or setback can be found in **Chapter 7**.

Examples of flood risk management and levee risk management activities are provided in Figure 1-20. In general, flood risk management activities are broader and deal with overall strategies and floodplain management, while levee risk management activities focus on the levee itself, including potential consequences a levee breach could cause. As shown in Figure 1-20, some activities require joint decision making.

Figure 1-20: Flood and Levee Risk Management Overlap

While flood risk management and levee risk management are closely related, and in some instances are implemented by the same entity, it is important to clearly communicate what levee risk management includes, as well as what is not in its purview. Clear goals and objectives can help inform effective risk management approaches that are aligned with roles, responsibilities, and authorities associated with levees. The National Levee Safety Guidelines provide direction for managing levee risk, and as such, they should not be viewed as comprehensive flood risk management guidelines.

It is also important to recognize that while understanding the interrelationship between levee risk and flood risk is critical for decision making, the general public is not aware of nor generally concerned about such differentiation. Their primary expectation is adequate protection from flooding and other hazards. Therefore, communication strategies should be formulated accordingly.

5 Recognizing Changes in Flood Risk

5.1 Drivers of Changed Conditions

Flood risk is not static, so flood risk management practices must adapt to changing conditions. Past flooding events should not be relied upon as good predictors of future flood risk. There are several drivers of flood risk change (Figure 1-21 and Figure 1-22):

- Changes in **hazards**. Climate change alters precipitation patterns and soil moisture, sea level, and resulting risk of flooding from riverine, coastal, rainfall, and compound sources. New development in the floodplain may lead to increased imperviousness of the land, which influences both the quantity and velocity of stormwater run-off.
- Reductions in the **performance** of land regions impacted by the hazard (including levees). One example may be subsidence from natural occurrences (repetitive soil expansion and contraction, soil decomposition, tree roots, or earthquakes) or human-influenced factors (damaged pipes or improper construction practices). Land-use decisions between the water source and the adjacent community result in having more or less capacity to store rainfall and snowmelt.
- Changes in the **consequences** of flooding. Development along the river or coastline may increase the number of residential and commercial structures, as well as population. Land-use decisions directly impact what may be in harm’s way.

Figure 1-21: Contributors to Changes in Flood Risk

5.2 Challenges with Adaptation

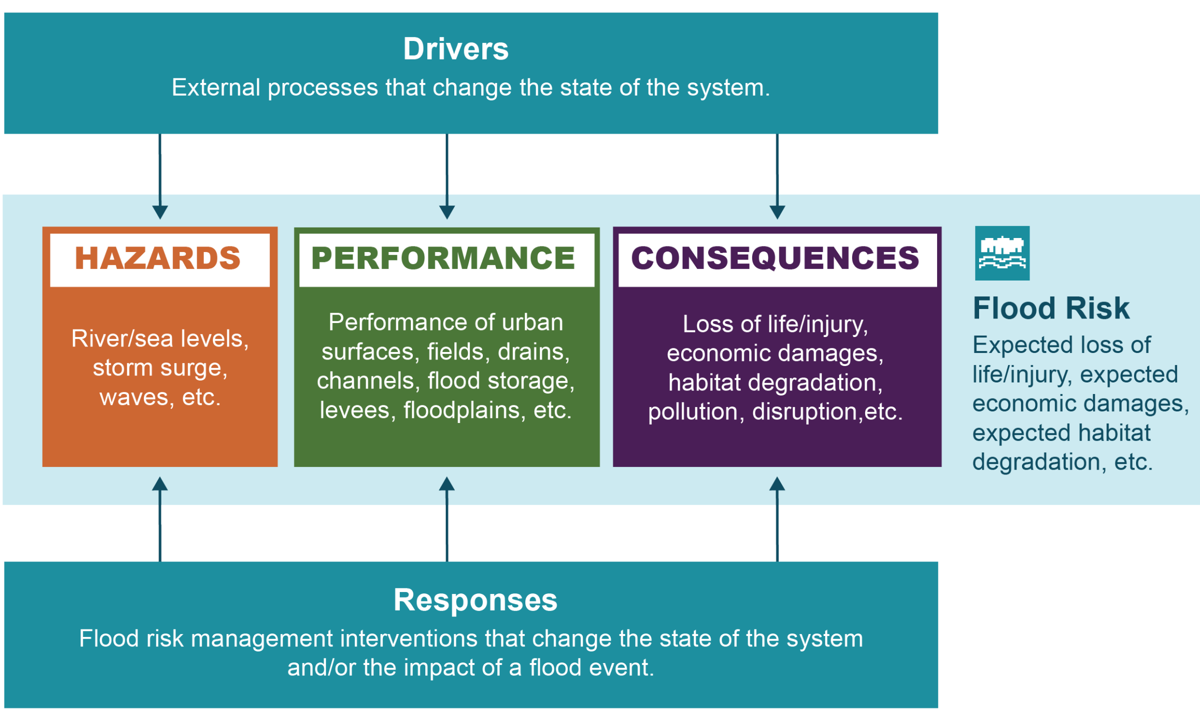
There are several reasons that adapting to changes in hazards, performance, and consequencesmay be difficult. These include:

- The existing built environment. It may be more difficult to retrofit existing structures than to establish regulations promoting the resilience of new infrastructure (i.e., coordination with existing owners, cost of risk reduction measures, limited municipal authority to implement upgrades).
- Misalignment of policies (i.e., local plans and regulations may reflect different priorities than those from state or federal levels of government).
- Limitations in individual or societal capability to adapt (e.g., low income, elderly, non-English speaking) increases both the difficulty of adapting to risk and the seriousness of consequences in failing to do so. Under-resourced communities often suffer the greatest impacts.

However, best practice in flood risk management is to use an appropriate combination of the various measures identified earlier (Figure 1-18) as responses to the increases in flood risk. Responses (Figure 1-22) should target hazards, performance, or consequences as appropriate for the driver of change being addressed.

Figure 1-22 demonstrates the reality that drivers exist—and they have the potential to change the state of the system—while there are corresponding measures that may be employed in response.

Figure 1-22: Drivers of Change in Flood Risk and Responses



5.3 Climate Change Implications

Climate change is changing risk in ways that are often difficult to understand and quantify. As greenhouse gases accumulate in the atmosphere, global average temperatures continue to rise and climatic patterns continue to change, resulting in non-intuitive and less consistent regional weather events. Current models and data suggest that changes in climate increasingly affect the overall risk and impacts to communities across the country from destructive weather events, such as more frequent and more intense heavy snow, rainstorms, heatwaves, and drought. These events increase flood risk and in many locations that risk extends beyond the most severe flooding observed to date.

Communities can assess climatic changes using multiple data sources maintained by government agencies which provide climate change projections at the state, regional, and county level. Climate change projects can be found using the assessment tool on the Climate Mapping for Resilience and Adaptation, part of the U.S. Climate Resilience Toolkit. These projections can assist with making decisions and designing flood risk management options that account for future conditions.

Several of the most common sources of changes to flood hazards are:

- Changes in rainfall and riverine flood hazards:
  - Changes in precipitation.
  - Changing snowpack.
  - Compound impacts: rain on snow, rain on rain, and rain on drought events.
- Changes in coastal flood hazards:
  - Sea level rise.
  - Increased storm surge.
  - Increased wave height.
  - Increased compound coastal flood hazards.
- Changes in groundwater flood hazards:
  - Rising groundwater tables from rising seas.
  - Inundation of surface areas from increased precipitation.
  - Lowering of groundwater due to drought and heat events.
  - Degradation of freshwater due to saline intrusion.

6 Summary

This chapter is centered on aspects associated with managing flood risk, the efforts communities take to reduce flood risks to people and property, and to enhance their resilience to flooding. Flood risks can take the form of rainfall, riverine, coastal, or groundwater flooding, or a combination of any of the four. A discussion is necessary regarding the evaluation of flood risk and how methods to reduce these risks often times results in a change in risk along with a reduction in risk.

As the climate changes and as flood risks change, communities should continue to evaluate the methods they have chosen to manage their flood risk. They should maintain or improve the structures that have been built and evaluate the effectiveness of any nonstructural methods that have been adopted.

Just as important as continued evaluation of the flood risk reduction measures, whether they are structural or nonstructual, is community engagement pertaining to what is being done to manage flood risk and how circumstances are changing. An in-depth discussion about engagement and a community's continued steps towards resilience can be found in **Chapters 3 and 12**.

The decision to build a levee as a flood risk reduction measure should be based on the knowledge that a levee does not eliminate the risk of flooding, but implemented well, it can reduce the risk of flooding. Once a community understands the need to manage the risk associated with a levee, it can be an effective tool and steps can be taken to further reduce the risk. For communities that have chosen a levee as either the main means of flood risk reduction, or as part of a suite of methods, levee risk will remain a focal point of any discussion about flood risk management. A more detailed discussion about levee-related flood risk, including design considerations, can be found in **Chapter 4**.

For the purposes of the National Levee Safety Guidelines, it is assumed that one of the flood risk management options selected is the design and construction of a new levee. The remaining chapters guide the reader through each phase of the levee lifecycle and address essential activities such as engaging the community and enhancing community resilience The remaining chapters guide the reader through each phase of the levee lifecycle and address essential activities such as engaging the community and enhancing community resilience.

Related content associated with this chapter is included in detail in other chapters of the National Levee Safety Guidelines as described in Table 1-1.

Table 1-1: Related Content

Chapter	Chapter Title	Related Content
1	**Managing Flood Risk**	
2	Understanding Levee Fundamentals	
3	**Engaging Communities**	• Engaging to build knowledge and awareness
4	**Estimating Levee Risk**	• Estimating hazards • Estimating consequences
5	**Managing Levee Risk**	• Flood risk versus levee risk
6	**Formulating a Levee Project**	• Levee-related alternatives for reducing risk
7	**Designing a Levee**	• Resilient levee design approaches
8	Constructing a Levee	
9	Operating and Maintaining a Levee	
10	Managing Levee Emergencies	
11	Reconnecting the Floodplain	
12	**Enhancing Community Resilience**	• Flood risk reduction strategies for community flood resilience

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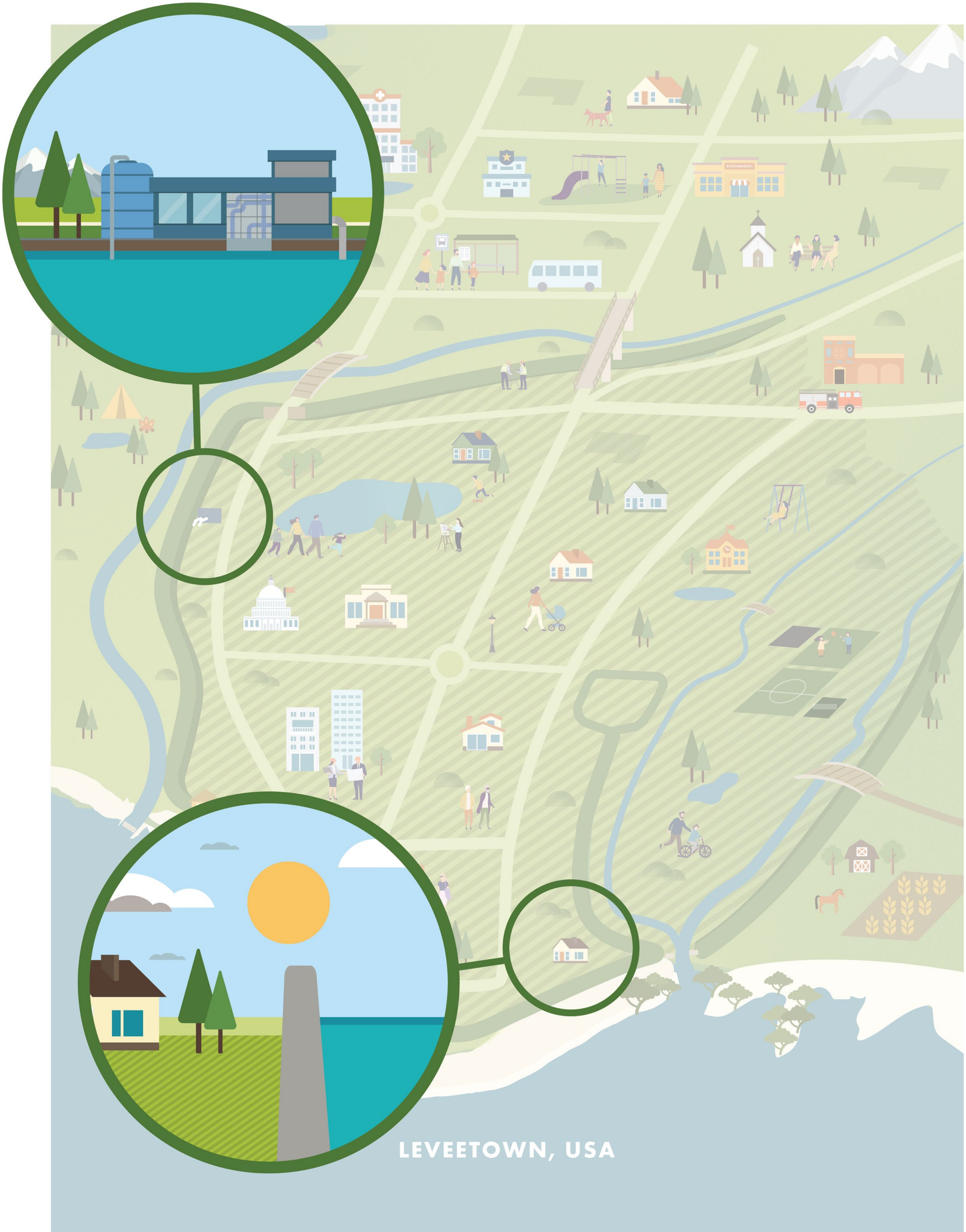
2

Understanding Levee Fundamentals

Key Messages

This chapter will enable the reader to:

- **Know levee terminology.** A levee is a human-made barrier with the primary purpose to provide flood risk reduction to a portion of the floodplain and does not constitute a barrier across a watercourse.
- **Understand levee function.** The function of a levee is to exclude floodwater from a defined area, channel water away from a defined area, or control the release of water into a defined area.
- **Understand levee features.** Levees are composed of various features that are spatially arranged to meet its intended function.
- **Understand ways levees can breach.** A levee breach could develop in different ways; therefore, it is important to understand why and how a breach may occur.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LEVEETOWN, USA

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Other chapters within the National Levee Safety Guidelines contain more detailed information on certain topics that have an impact on understanding levee fundamentals, as shown in Figure 2-1. Elements of those chapters were considered and referenced in the development of this chapter and should be referred to for additional content.

Figure 2-1: Related Chapter Content

CH 1	CH 2	CH 3	CH 4
Strategy to manage flood risk	**Understanding Levee Fundamentals**	Engaging to build knowledge and awareness	Potential failure modes
CH 5	**CH 6**	**CH 7**	**CH 8**
Levees transform the floodplain	Types of levee projects	Design of levee features	Construction of levee features
CH 9	**CH 10**	**CH 11**	**CH 12**
Perform regular inspections	Emergency preparedness and response Practicing emergency action plans	Promote floodplain restoration	Community resilience to reduce risks

Contents

1 Introduction 2-1
2 Levee Basics 2-1
2.1 What is a Levee? 2-1
2.2 Levee Projects 2-2
3 Levee Function 2-3
3.1 Levees' Role in Reducing Flooding 2-3
3.2 Configuration of Levees 2-6
4 Levee Features 2-9
4.1 Embankment 2-10
4.2 Floodwalls 2-13
4.2.1 T-Wall 2-14
4.2.2 L-Wall 2-14
4.2.3 I-Wall 2-15
4.2.4 Mass Gravity 2-16
4.2.5 Demountable 2-17
4.3 Closure Structures 2-18
4.3.1 Movable Gates 2-19
4.3.2 Structural Assembled Closures 2-26
4.3.3 Earthen Assembled Barriers 2-27
4.4 Transitions 2-30
4.5 Seepage Control Features 2-31
4.5.1 Cutoff Walls 2-31
4.5.2 Seepage and Stability Berms 2-33
4.5.3 Relief Wells 2-34
4.5.4 Drains 2-35
4.6 Channels, Floodways, and Controlled Overtopping 2-36
4.6.1 Channels and Floodways 2-36
4.6.2 Controlled Overtopping Sections 2-38
4.7 Interior Drainage Systems 2-39
4.8 Pump Stations 2-42
4.9 Instrumentation 2-43
5 Levee Breach 2-44
5.1 Levee Breach Scenarios 2-44
5.2 Levee Potential Failure Modes 2-46
5.2.1 Breach from Overtopping 2-46

5.2.2 Breach Prior to Overtopping 2-47
5.2.3 Malfunction or Improper Operation of a Feature 2-47
6 Example of a Levee 2-50
7 Summary 2-55

List of Figures

Figure 2-1: Related Chapter Content 2-i
Figure 2-2: Examples of Riverine and Coastal Levees 2-2
Figure 2-3: Levee Projects 2-2
Figure 2-4: Function of Levees in Reducing Flooding 2-5
Figure 2-5: Typical River Levee 2-6
Figure 2-6: Typical Coastal Levee 2-7
Figure 2-7: Example Setback Levee 2-8
Figure 2-8: Example Ring Levee 2-8
Figure 2-9: Offline Storage Area 2-9
Figure 2-10: Typical Homogeneous Embankment 2-11
Figure 2-11: Typical Zoned Embankment 2-12
Figure 2-12: Typical Coastal Embankment 2-13
Figure 2-13: Typical T-Wall 2-14
Figure 2-14: Typical L-Wall 2-15
Figure 2-15: Typical I-Wall 2-15
Figure 2-16: Examples of Floodwalls 2-16
Figure 2-17: Typical Mass Gravity Wall 2-17
Figure 2-18: Example Mass Gravity Wall 2-17
Figure 2-19: Example Demountable Walls 2-18
Figure 2-20: Typical Roller Gate 2-20
Figure 2-21: Roller Gate Details 2-21
Figure 2-22: Typical Swing Gate 2-22
Figure 2-23: Swing Gate Details 2-22
Figure 2-24: Example Swing Gates 2-23
Figure 2-25: Example Trolley Gate 2-24
Figure 2-26: Example Vertical Lift Gate 2-24
Figure 2-27: Example Sector Gate 2-25
Figure 2-28: Example Miter Gate 2-26
Figure 2-29: Typical Stoplog Closure 2-27
Figure 2-30: Example Stoplog Closures 2-27
Figure 2-31: Example Sandbag Closure 2-28
Figure 2-32: Example Soil/Gravel Basket Closures 2-29
Figure 2-33: Example Earthen Fill with Plastic 2-30

Figure 2-34: Typical Types of Transitions 2-31
Figure 2-35: Typical Cutoff Wall 2-32
Figure 2-36: Cutoff Wall Under Construction 2-32
Figure 2-37: Typical Seepage Berm 2-33
Figure 2-38: Example Seepage Berm 2-34
Figure 2-39: Typical Relief Well 2-34
Figure 2-40: Example Relief Well 2-35
Figure 2-41: Typical Drain Systems 2-36
Figure 2-42: Typical Floodway Channel 2-37
Figure 2-43: Examples of Channel Erosion Control 2-37
Figure 2-44: Typical Controlled Overtopping Section 2-38
Figure 2-45: Essential Function of Interior Drainage System 2-40
Figure 2-46: Typical Interior Drainage System 2-41
Figure 2-47: Detail of Pipe Passing Floodwall 2-41
Figure 2-48: Typical Gates for Interior Drainage Systems 2-42
Figure 2-49: Example Pump Station 2-42
Figure 2-50: Typical Levee Instrumentation 2-44
Figure 2-51: Levee Breach Scenarios 2-45
Figure 2-52: Graphical Representation of Levee Breach Scenarios 2-46
Figure 2-53: Typical Embankment Potential Failure Modes 2-48
Figure 2-54: Typical Floodwall Potential Failure Modes 2-49
Figure 2-55: Example of Features Along a Riverine Levee 2-50
Figure 2-56: Example of Floodwall and Tie-in to High Ground 2-51
Figure 2-57: Example of Interior Drainage Features 2-51
Figure 2-58: Example of Embankment Tie-in to Floodwall 2-52
Figure 2-59: Example of Railway and Roadway Closures 2-52
Figure 2-60: Example of Floodwall 2-53
Figure 2-61: Example of Interior Drainage System 2-54

List of Tables

Table 2-1: Tpyical Levee Features 2-10
Table 2-2: Categories and Types of Closures 2-19
Table 2-3: Related Content 2-56

1 Introduction

The purpose of this chapter is to introduce the basic concepts and terminology associated with a levee, which provides the necessary foundation for information presented in the remaining chapters.

Two main types of levees are discussed in this chapter—those that reduce flood risk from riverine hazards and those that reduce risk from coastal hazards. The various features that comprise these levees are described and illustrated, with examples showing how they are arranged along a selected alignment into a spatial form to create a leveed area.

In addition, different potential failure mechanisms that lead to breach and flooding of the leveed area are presented.

These are essential concepts for understanding the role of levees in flood risk management.

2 Levee Basics

2.1 What is a Levee?

A **levee** is a human-made barrier with the primary purpose of reducing the frequency of flooding to a portion of the floodplain, sometimes referred to as a 'levee system'. Basic characteristics of a levee include the following:

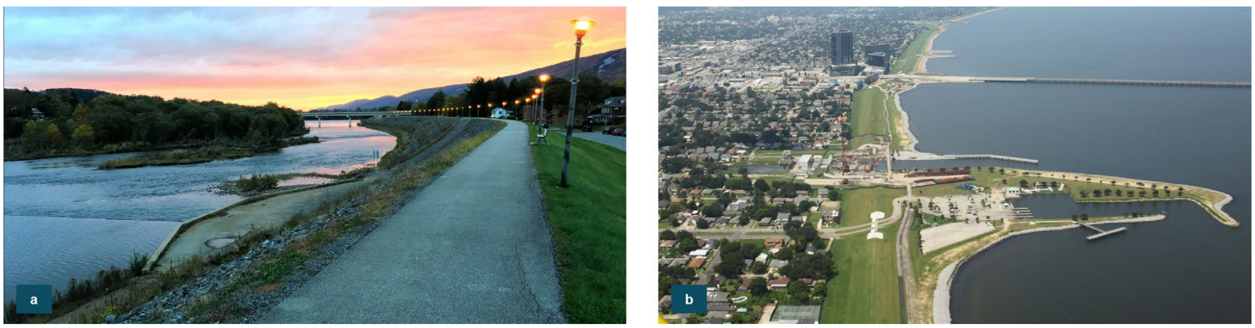
- Typically constructed along a watercourse (not across a watercourse like a dam), such as rivers, tributaries, coastlines, canals, or other waterways.
- Designed to exclude flooding from a limited range of flood events. Levees do not eliminate the risk of flooding.
- Usually subjected to flood loading of a limited duration (days or weeks); however, some levees are continuously loaded.
- Typically comprised either of earthen embankments, concrete floodwalls, or a combination of both.
- Can have other features such as pedestrian gates, traffic closures, and pump stations.
- Will usually tie into high ground (elevated land that is higher than the floodplain, above the design flood event for the levee, and less likely to flood) on either end, but some levees do exist that are open-ended; or could form a ring.
- Can be designed to be compatible with a designed channel or canal.
- May be linked to or comprised of other engineered structures that are integral to the levee performance but were not designed specifically for a flood risk reduction purpose, such as roadway, railroad, or canal embankments.

- May be linked to dam-related structures and coastal barriers, which can also be integral to a levee or can function like a levee.

The term levee does not include a stand-alone roadway or railroad embankment, shoreline, or riverbank erosion projects, nor does it include a canal or channel constructed completely within natural ground without an embankment or retaining wall to constrain the flow of water.

Levees can be broadly categorized as either riverine or coastal, based on the primary source of the hazard and resulting floodwaters being excluded, and their environmental setting. Natural features (dunes, barrier islands, mangroves) and engineered structures (jetties, spur dikes, groins), often support the function of the levee, typically by attenuating the flood loading, but are not considered to be a part of the levee. Figure 2-2 illustrates both riverine and coastal levees.

Figure 2-2: Examples of Riverine and Coastal Levees



(a) Riverine levee in Lock Haven, Pennsylvania. (b) Coastal levee in New Orleans, Louisiana.

A levee generally goes through various stages throughout its life (**Chapter 4**), referred to as the levee lifecycle. This lifecycle consists of project formulation, design, construction, operation and maintenance, modifications, and levee removal (if needed). Certain activities such as community engagement, emergency preparedness, and response occur at all stages of the lifecycle. See **Chapters 3 and 10** for additional information.

2.2 Levee Projects

Levee-related activities necessitating any aspect of planning, design, or construction should be considered levee projects. There are five different types of levee projects that are discussed in greater detail in subsequent chapters. These projects are shown in Figure 2-3.

Figure 2-3: Levee Projects

- **New:** Building a new levee as part of a flood risk reduction strategy.
- **Repair:** Restoring a levee to its original (e.g., as intended in design) operation and function after isolated damage has occurred and a structure's functionality has been reduced. Repair can also be thought of as normal maintenance and routine in nature.
- **Rehabilitation:** Restoring a levee to its original operation and function due to extensive deterioration or deficiencies from design/construction. Rehabilitation is more substantial than normal maintenance and repair and is not routine in nature.
- **Modification:** An activity that changes the original operation and function of a levee. It includes raising a levee, modifying its alignment, or changing features. Modification is not routine in nature.
- **Removal:** An intentional activity that effectively eliminates the flood risk reduction benefits provided by a levee. Removal is a form of modification and is not routine in nature.

3 Levee Function

3.1 Levees' Role in Reducing Flooding

Levees are just one element of a community's flood risk management strategy, which may include nonstructural and structural measures, as discussed in **Chapter 1**. As a structural measure, levees can have one to three primary functions:

- **Exclude water**: Levees reduce the risk of inundation of an area by keeping floodwaters out of the leveed area (riverine and coastal). They may also manage stormwater in the leveed area when storm drainage systems are closed off from natural gravity drainage during floods.
- **Divert water**: Levees direct floodwater, storm surge, and wave run-up either downstream (riverine only) or into a non-leveed area to avoid inundation of the leveed area (riverine and coastal).
- **Controlled release**: Levees can be designed or operated to release water in a designated area in order to remove a portion of flow upstream, which within a watercourse reduces flood loading downstream (riverine only).

In addition to flood risk reduction, levees often serve as sites for riverine habitat corridors, regional trails, recreational parks, transportation corridors, and other public amenities. These supplemental benefits can be vitally important to those living and working nearby and to those visiting the region. When designed with this multi-purpose use in mind, levees provide important social, economic, agricultural, recreational, and environmental benefits. However, care should be exercised to ensure other uses of the levee do not take priority over the flood risk reduction function or compromise levee performance.

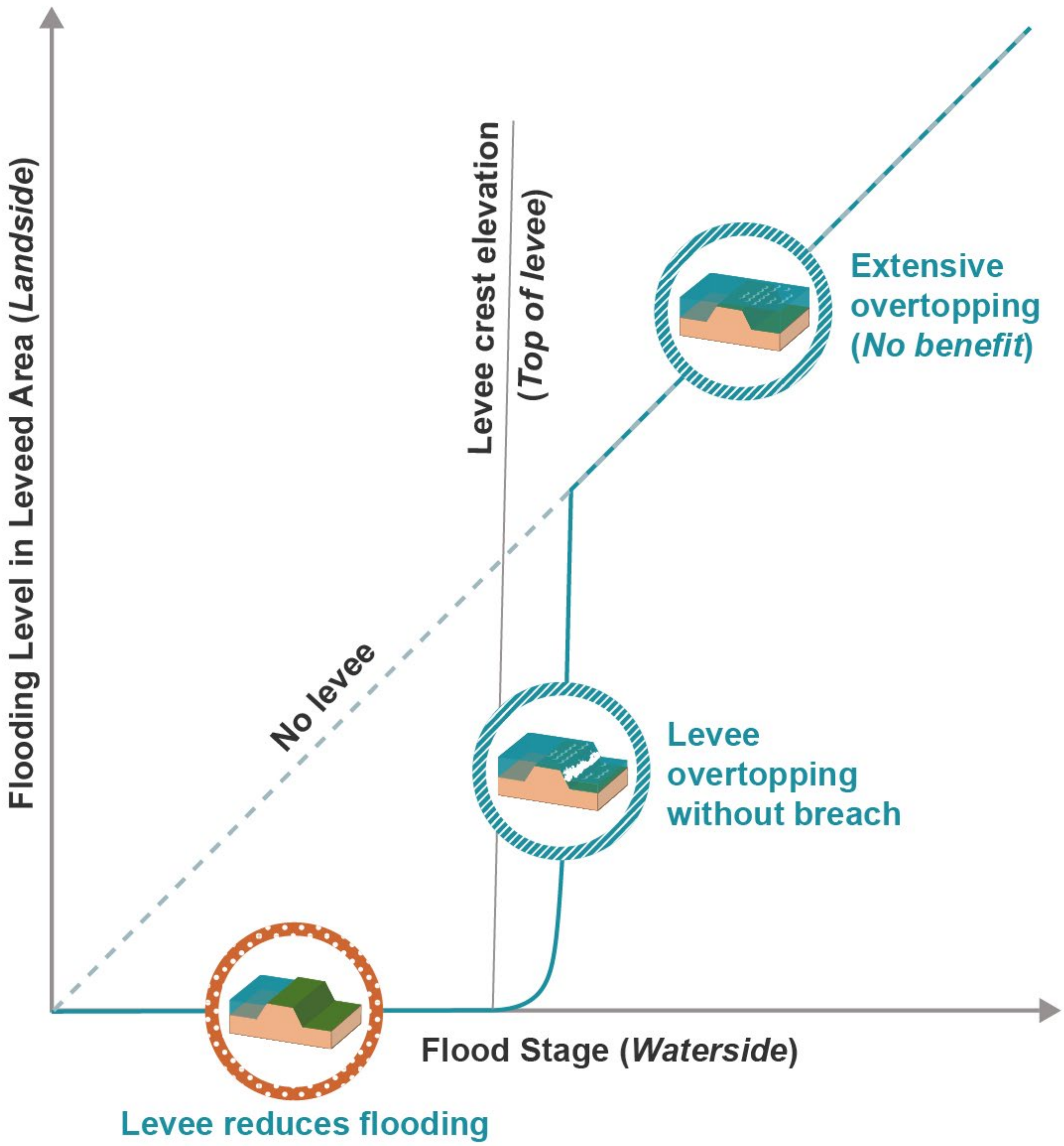
The function of levees in reducing flooding in the leveed area is illustrated in Figure 2-4, which portrays flood stage on the waterside of the levee versus flooding elevation in the leveed area (landside). When there is no levee (dashed line), the flooding elevation in the leveed area is equal to the flood stage on the waterside. The introduction of a levee and the resulting flood risk reduction is depicted as a solid line. The solid line traces the flooding on the waterside of the levee from the levee toe to the levee crest and beyond. Following the line from left to right illustrates that there is no flooding in the leveed area for flood stages on the waterside of the levee up to the levee crest elevation when the levee performs as intended. As water exceeds and overtops the crest of the levee, the levee continues to provide some benefits during **overtopping**, until a point where there is so much water in the leveed area that the levee no longer provides any flood risk reduction benefits (solid line meets and follows dashed line).

Figure 2-4 illustrates a levee that is functioning as intended by providing flood risk reduction benefits including:

- Excludes flood waters from the leveed area for flood levels up to the levee crest.
- Allows time for orderly evacuation of individuals within the leveed area.

This figure is a simplification to illustrate the general function of levees to exclude floodwaters. It should be recognized that levees transform the floodplain, as described in **Chapter 5**.

Figure 2-4: Function of Levees in Reducing Flooding



The intended level of flood risk reduction can vary significantly for different levees. For some communities, a shorter levee providing less flood risk reduction combined with zoning restrictions and evacuation planning for larger events may be a preferred strategy, while other communities may opt for higher levees as their strategy to achieve the same overall flood risk reduction.

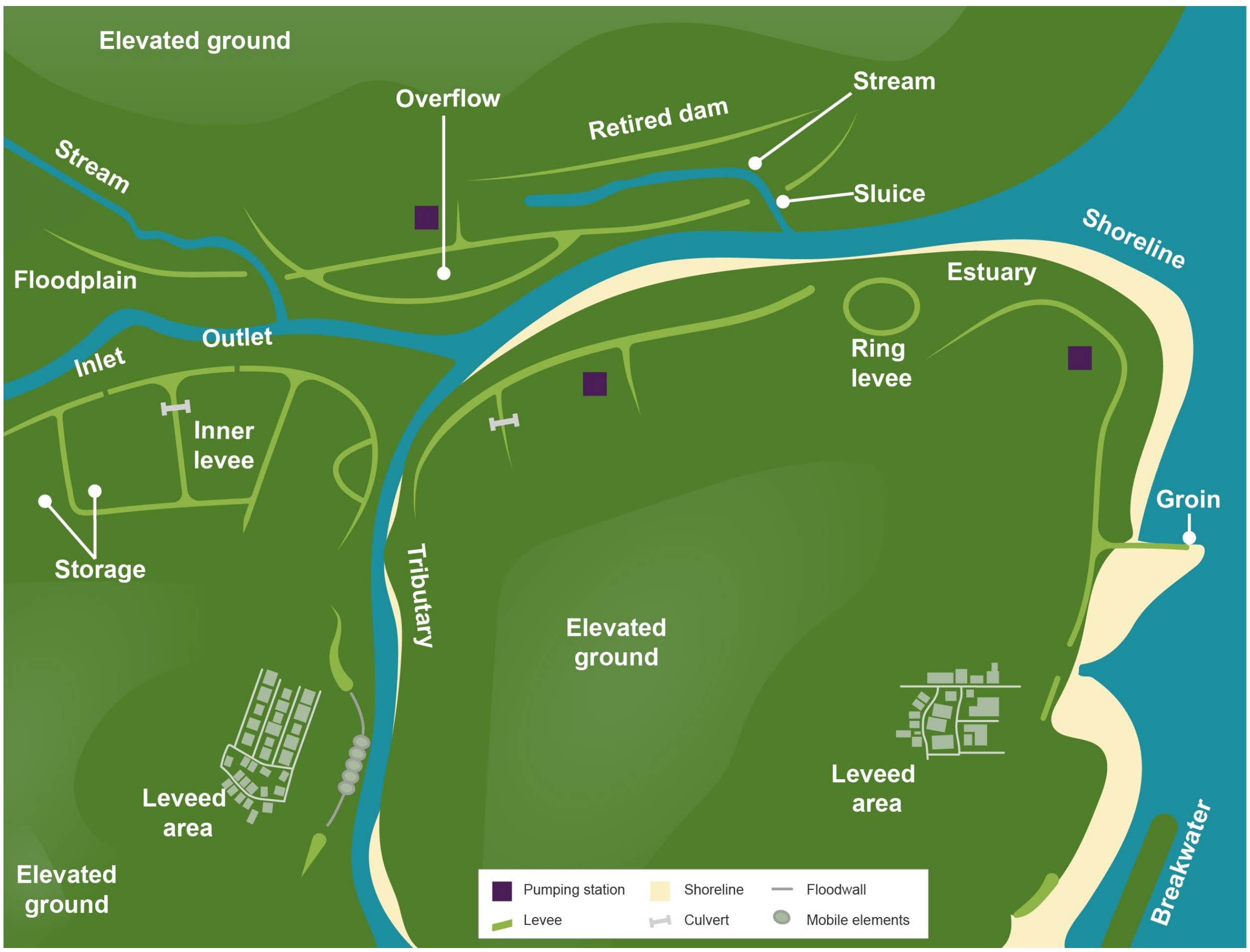
Flood awareness and emergency preparedness play an important role in flood risk management for individuals and communities behind levees. Involved, informed individuals and communities behind levees will be better prepared to take meaningful actions to reduce risks to loss of life (e.g., practicing emergency action plans, warnings, and evacuations) or property (e.g., flood-proofing, purchasing flood insurance, or elevating structures). See **Chapters 1, 3, 10, and 12** for additional details.

3.2 Configuration of Levees

The overall levee configuration is primarily based on the level of flood risk reduction that the levee is intended to provide and its environmental setting; however, other natural and human-made factors influence the configuration (e.g., right-of-way constraints), as discussed in **Chapter 6**.

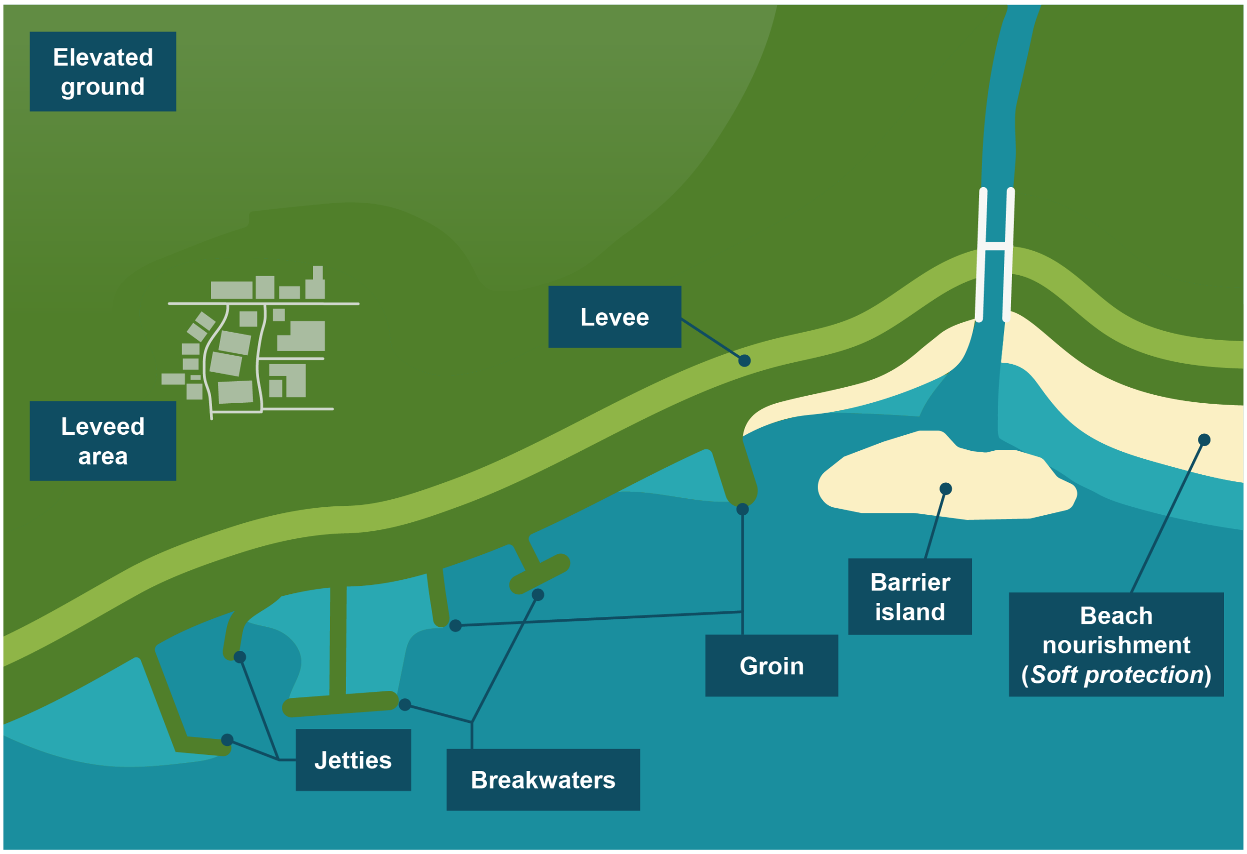
In a riverine environment (Figure 2-5), levees are generally placed parallel to a river channel in order to help pass floodwater downstream. Levees may be constructed along both banks of a watercourse, often set back from the channel to provide added storage capacity during high water. Under normal, non-flood conditions, secondary use of this area may be allowed for farming operations, recreation, or other approved uses. Because levees are expected to overtop for floods greater than the designed level of risk reduction, the levee may include location(s) with a lower crest for intentional overtopping to control and understand where flooding will first occur.

Figure 2-5: Typical River Levee



In a coastal environment (Figure 2-6), levees are typically aligned with the coastline; therefore, are generally situated perpendicular to the incoming flow from the sea. Levees function to temporarily retain storm surge and moderate wave overtopping. Coastal systems may also include other human-made or natural structures such as offshore breakwaters, groins, mangroves, and dunes to reduce erosive forces on the beaches and levees. Coastal areas may also be subject to flooding due to the rise in sea level during a storm event causing backwater flooding of drainage features that flow to the sea. To prevent this, levees may be needed along these drainage features.

Figure 2-6: Typical Coastal Levee



Levees that are built landward of existing levees, usually because the existing levee has experienced distress or is in some way being endangered, are typically referred to as setback levees (Figure 2-7). When the existing levee is removed, setback levees can promote floodplain restoration by giving space for riparian and aquatic habitats in the floodplain (**Chapter 11**). Setback levees are generally loaded less frequently than levees positioned directly adjacent to main river channels.

Figure 2-7: Example Setback Levee

Setback levee construction at the Southport Levee in west Sacramento, California.

Levees typically tie to (abut) natural high ground in order to exclude floodwaters from a leveed area. Where it is not feasible to abut natural high ground, a ring levee (Figure 2-8) may be constructed to enclose a leveed area, to help reduce the risk of flooding to isolated, vulnerable infrastructure.

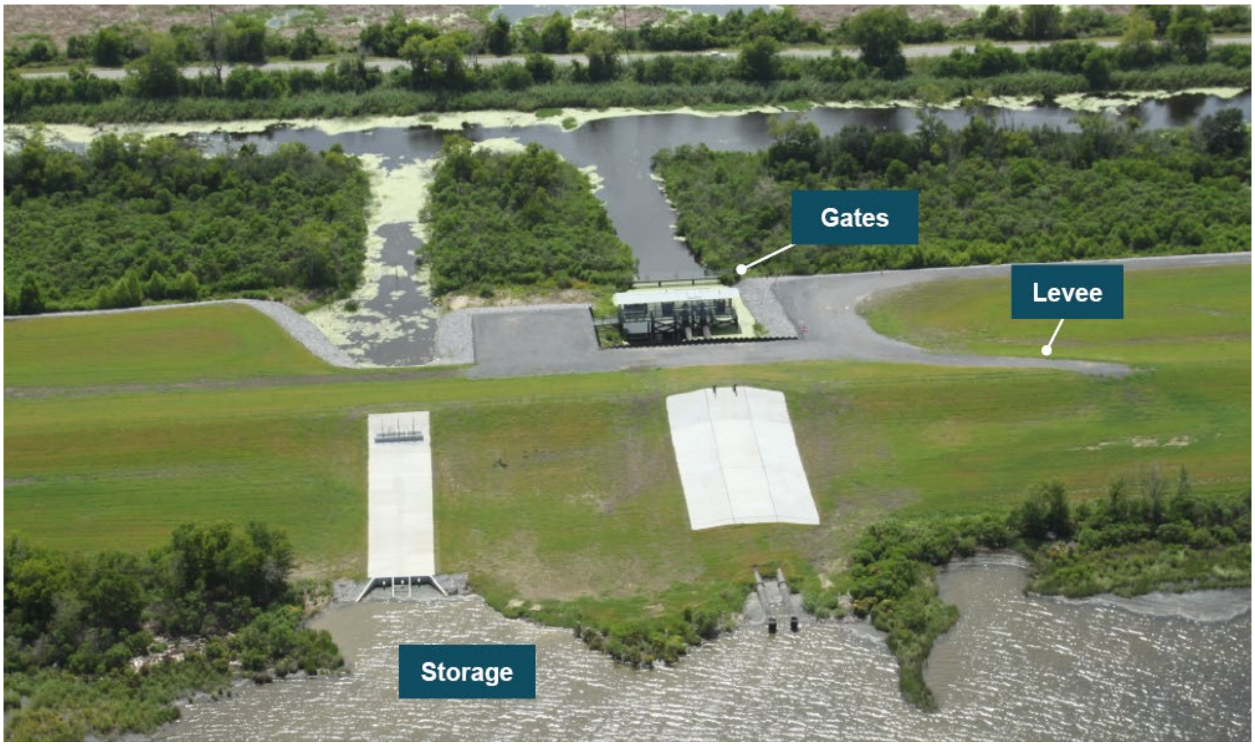
Figure 2-8: Example Ring Levee

A ring levee surrounds the Fenton Wastewater Treatment Facility near the confluence of Fenton Creek and the Meramec River in south St. Louis County, Missouri.

Offline storage areas (Figure 2-9) are often created to complement the use of levees, floodways, natural structures, and topography. Such storage areas are normally empty for long periods of time and are only used during flood events, providing for secondary uses and benefits, including public access, recreation, and opportunities for environmental habitat.

Levees often work together with dams to manage floods and in these cases, the infrastructure where they coexist within a watershed, should be considered as one integrated system. Dams attenuate and regulate flood flows while levees exclude flood water from the leveed area.

Figure 2-9: Offline Storage Area



Structure used to move water from the river to an offline storage area in New Orleans, Louisiana.

4 Levee Features

A levee may be composed of multiple features acting as a physical barrier to prevent floodwater from entering the leveed area. Utilizing complementary structures beyond the levee structure may be necessary for activities that promote proper functionality. Examples of related activities include managing interior stormwater within the leveed area or reducing the loading on the primary feature (floodways). Features can be thought of as the major elements or building blocks that comprise the levee. The form of the levee is the spatial arrangement of features to provide flood risk reduction within the leveed area.

Table 2-1 presents the typical levee features and some key types. There are a limited number of features and variations of feature types, but there are numerous ways they can be formed into an arrangement to create a levee. The sections that follow illustrate some of the various levee features and their typical types that provide benefits to the leveed area.

Table 2-1: Tpyical Levee Features

Feature	Types	Function
Embankment	Zoned, homogeneous	Exclude water from leveed area.
Floodwall	T-wall, L-wall, I-wall, mass gravity, demountable	Exclude water from leveed area.
Closure structure	Roller gate, swing gate, trolley gate, vertical lift gate, sector gate, miter gate, stoplog (wooden or metal), sandbag, soil/gravel baskets, earthen fill with plastic	Exclude water from leveed area during floods, while allowing water to pass the rest of the time.
Transition	Embankment/hard structure, embankment/high-ground, embankment/revetment	Exclude water from leveed area by joining different features of the system.
Seepage control systems	Cutoff wall, seepage berm, relief well, trench and blanket drains	Exclude water from or manage water in the leveed area as a result of seepage.
Channels and floodways	Natural, concrete lined, armored	Manage floodwater outside the leveed area.
Interior drainage systems	Canals, pipes	Manage primarily surface water inside the leveed area.
Pump stations	Permanent, temporary	Manage primarily surface water inside the leveed area.
Instrumentation	Settlement cells, staff gages, piezometers, inclinometers	Provide operational and performance data.

4.1 Embankment

An earthen **embankment** is the most typical feature associated with a levee, and for many levees it can be the primary (or even only) physical feature. However, they often work in concert with other features which support the function of excluding floodwaters (e.g., a floodwall along the watercourse or relief wells for seepage control). Supporting features are sometimes required to ensure levee integrity, such as erosion protection, stability berms, and **seepage** control features.

Embankments are common features incorporated into both riverine and coastal levees. However, their geometric configuration and the components incorporated into an embankment typically differ based on the environment they are situated in and the loading to which they are subjected to due to the hazard (see Figure 2-10 and Figure 2-12).

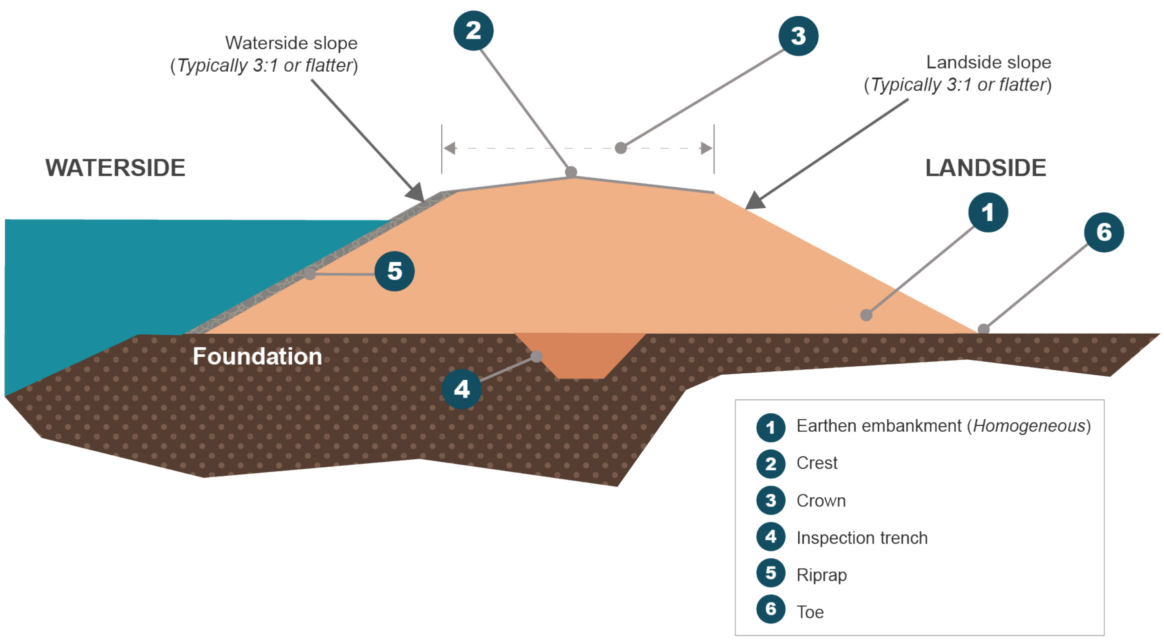
The function of an embankment is to act as a barrier to restrict the intrusion of floodwaters into the leveed area. The embankment must be designed and constructed to function under the required flood loading without loss of its structural integrity and stability. Its successful integration as a levee feature needs to consider potential failure mechanisms that could compromise its ability to function as designed. The performance of the embankment must consider the performance of the underlying embankment foundation when subjected to the flood load, because the performance of the levee is greatly impacted by the conditions below the levee. Embankment design considerations are presented in more detail in **Chapter 7**.

A number of embankment types may be developed to meet unique functional requirements, such as:

- Characteristics and duration of flood loading
- Components incorporated into the levee
- Geomorphic and geologic setting
- Locally available materials
- Construction access
- Right of way

The most common type of embankment levee is a homogeneous earthen (i.e., one soil type) compacted embankment, as shown in Figure 2-10. Common geometric characteristics include a 10-15-foot-wide crown and 3:1 side slopes for riverine levees and flatter slopes for coastal levees (typically 5:1 or greater on the waterside).

Figure 2-10: Typical Homogeneous Embankment



Several factors impact the geometry of the embankment, including the allowable steepness of the **waterside** and **landside** slopes, and often the minimum levee crown width. The steepness of the embankment slopes depend on the evaluation of the stability of the levee, which is influenced by the loading, foundation conditions, and type of soil used in the embankment. The width of the embankment crown may be established based upon the anticipated or predicted stability of the embankment, seepage considerations, accessibility needs (e.g., vehicular access, provisions for bike paths, or other recreational elements), or by regulatory minimum requirements. The crown may consist of simple grass cover, gravel, pavement, or other surface cover based on the expected allowable use. Provisions to incorporate roads and/or ramps for vehicular access to the levee crown may be needed and stairways or ramps for pedestrian access may also be included. An exploration or inspection trench is typically constructed into the foundation below all earthen embankments to provide direct visual observation of the subsurface foundation conditions continuously along the alignment of the levee. See **Chapters 7 and 8** for more details.

A slight variation to the homogeneous earthen levee embankment shown in Figure 2-10 is the zoned earthen embankment shown in Figure 2-11. The central portion of the embankment is constructed with a less pervious soil type to address potential seepage issues through the embankment. Note that the location of this less pervious zone is beneath the levee crown but may be shifted towards either the waterside or landside slopes, as necessary. Also, there are examples where a thick (typically 3-5 foot) impervious layer is located on the waterside slope and crown, with the remainder of the levee being composed of more pervious material.

This schematic also shows scour protection on the waterside slope, which is typically riprap or some other hard armored surface. Such treatment is required when the flow velocities under the flood event are substantially high, or when the levee is subject to wave or wake action, which could undermine the stability of a simple grassed waterside embankment slope.

Figure 2-11: Typical Zoned Embankment

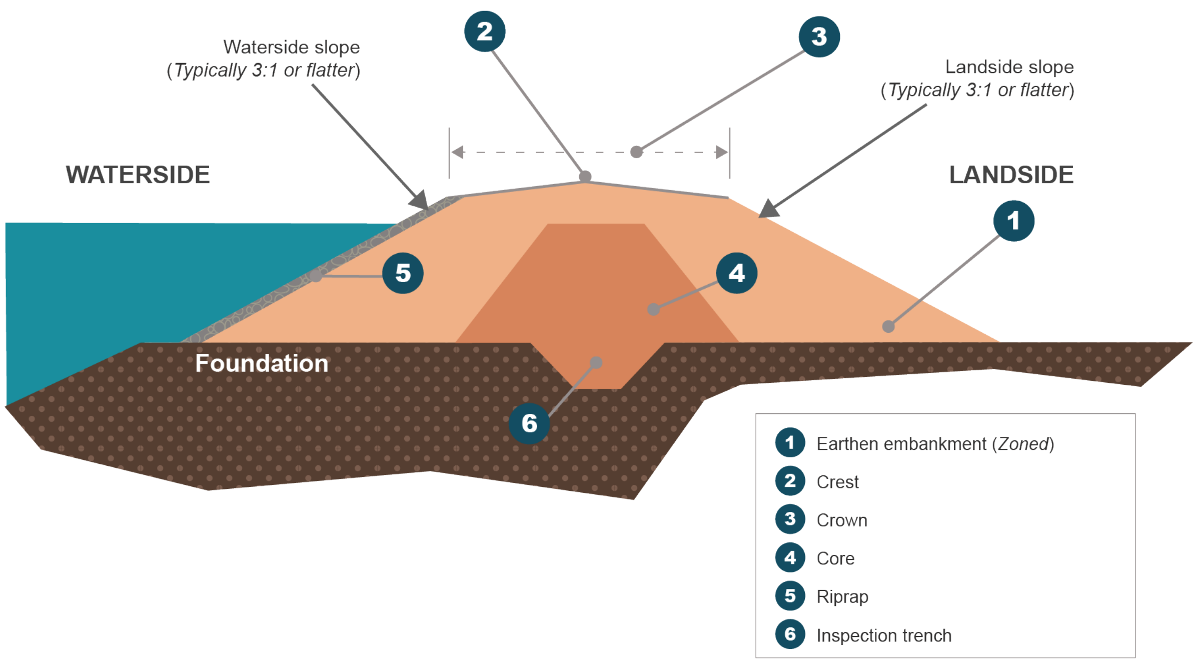
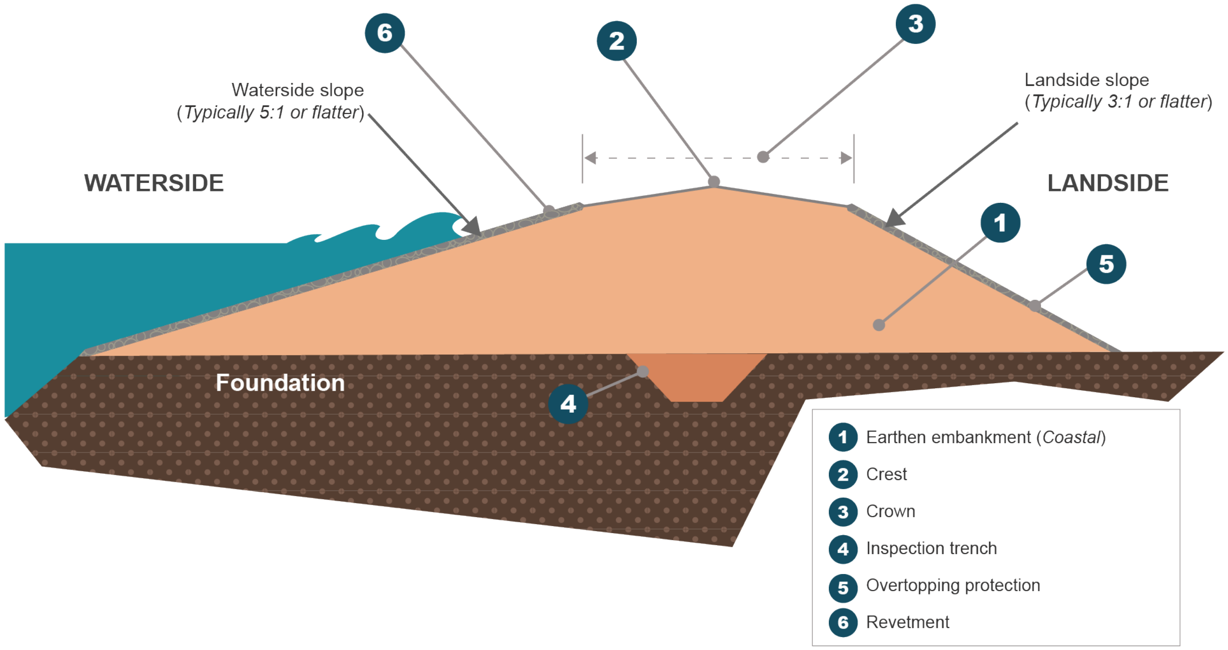


Figure 2-12 shows a coastal levee embankment and some additional components that may be incorporated due to unique coastal hazards. For coastal levees, the loading is primarily attributed to storm surge (often combined with tidal effects and high winds) resulting in higher water levels and wind/wave action. There are a wide variety of options for the materials used to construct the embankment as well as surface treatments of the waterside embankment slope and crown. The geometry of the waterside slope is generally flatter and can incorporate revetments to minimize the impact of wave action. Due to potential for wave overtopping, it is also possible that scour protection may be required on the landside.

Figure 2-12: Typical Coastal Embankment



Structures such as groins and revetments may be incorporated as vital elements to attenuate storm surge and/or wave action loading on the levee. Natural features—such as marshes or mangroves, sand bars, or barrier islands—can also reduce loading impacts. While these elements are potentially vital to levee performance, they are not considered levee features.

4.2 Floodwalls

Floodwalls are commonly used where earthen levees are not considered a viable alternative, typically either due to limited real estate space for the levee's alignment or a need to tie into other structural features. They are commonly used in both riverine and coastal levees.

The function of a floodwall is to act as a barrier to restrict the intrusion of floodwaters into the leveed area. As with the earthen embankment, the floodwall must be able to function under the required flood loading without compromising its structural integrity and stability. The performance of the floodwall should consider the underlying foundation (typically soils) and support of the structure using either a deep or shallow foundation system. These considerations are described in more detail in **Chapter 7**.

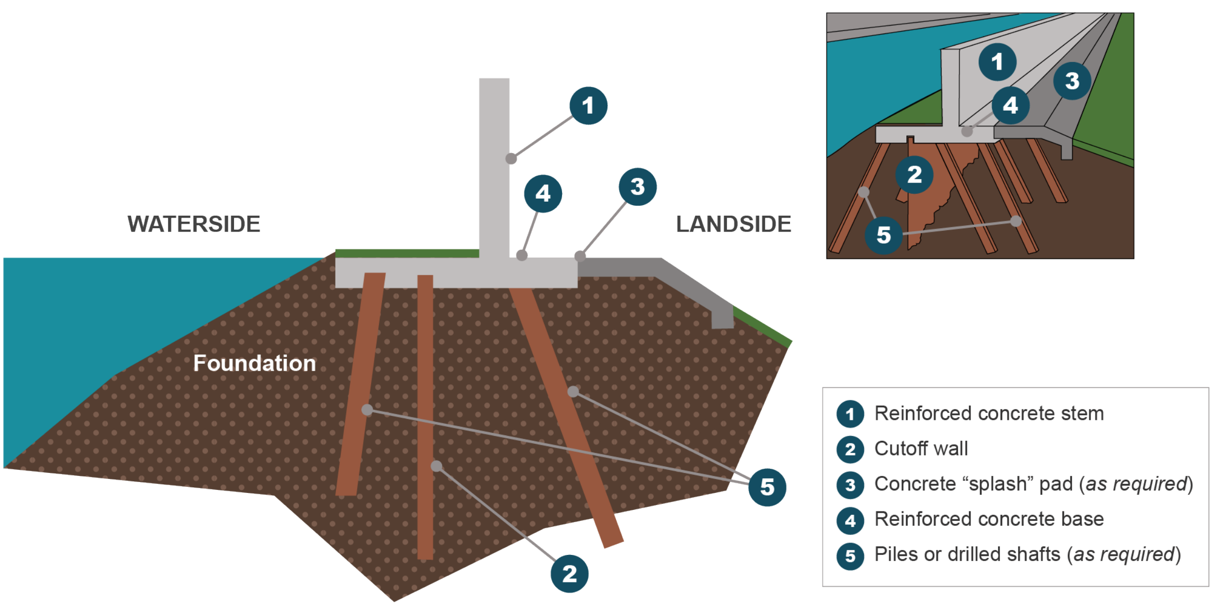
There are a variety of floodwall types that consist of a stem that protrudes above the ground surface to act as the barrier to the intrusion of floodwater into the leveed area. The stem consists of a linear arrangement of discrete sections or monoliths typically constructed with reinforced concrete. Some walls also incorporate a reinforced concrete base within foundation soils to provide stability. The type of wall selected is based on the type of loading, the foundation conditions, and the foundation system required to resist that loading. In most floodwalls, a cutoff is typically provided to control underseepage (i.e., water flowing through the soil in the foundation beneath the levee) because the distance between the flood loading and the landside floodwall toe where underseepage may surface is typically very short. A component often incorporated—particularly for coastal levees—is a concrete 'splash' pad to protect against overtopping wave action. This can be accommodated by exposing the base on the landside or providing a separate component. These components can also be incorporated as a buttress on the landside of the floodwall, as shown in Figure 2-13, Figure 2-14, and Figure 2-15, which can function to aid in either stability or seepage control. Depictions of these types of floodwalls are described in sections 4.2.1 – 4.2.3, with examples shown in Figure 2-16.

Other types of floodwalls that exist are gravity monolith floodwalls (Figure 2-17), demountable floodwalls (Figure 2-19), and less common sheetpile cellular walls, buttress/counterfort walls, and other unique types of walls.

4.2.1 T-Wall

The designation as a T-wall originates from the shape of the stem and base (Figure 2-13). The stem is structurally connected to a reinforced concrete base. The base serves as the foundation of the floodwall, acting as a cap for deep foundation elements (steel pile sections, and/or drilled shafts) or simply acting as a shallow foundation bearing on the underlying foundation soils without a deep foundation.

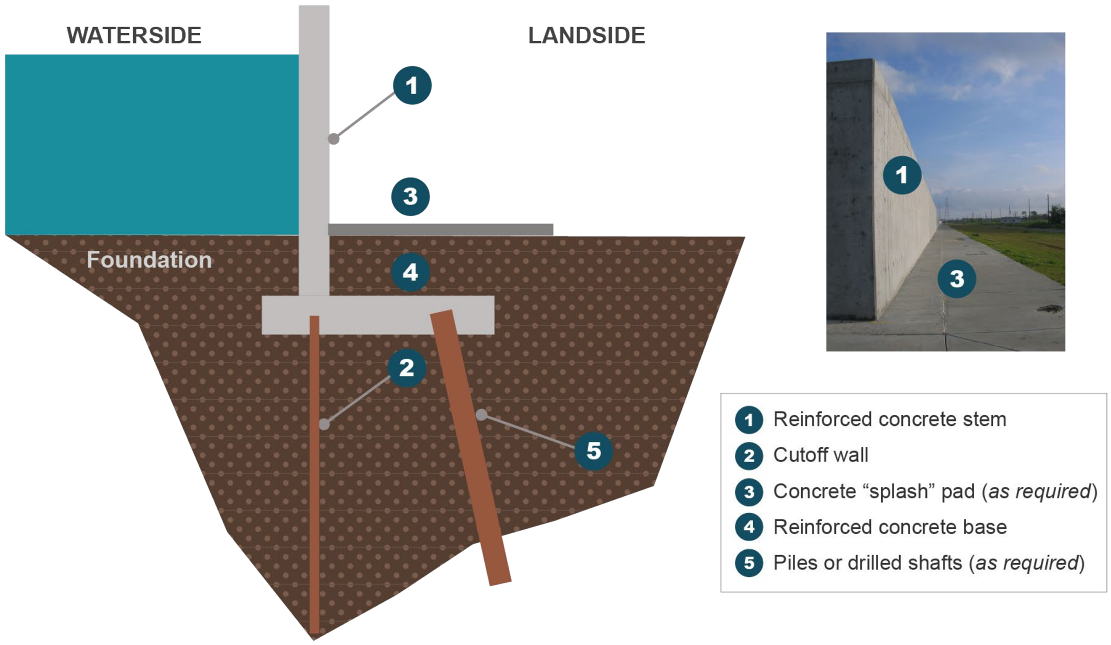
Figure 2-13: Typical T-Wall



4.2.2 L-Wall

The designation as an L-wall originates from the shape of the stem and base (Figure 2-14). The stem is structurally connected to a reinforced concrete base. The base serves as the foundation of the floodwall, acting as a cap for deep foundation elements (steel pile sections, and/or drilled shafts) or simply acting as a shallow foundation bearing on the underlying foundation soils without a deep foundation.

Figure 2-14: Typical L-Wall



4.2.3 I-Wall

An I-wall has no base and is essentially a vertical structural element consisting of the stem, which is commonly supported by a sheetpile cutoff (Figure 2-15), which can serve as the flood barrier and underseepage cutoff feature. I-walls are primarily for use where construction access is limited or for transition elements.

Figure 2-15: Typical I-Wall

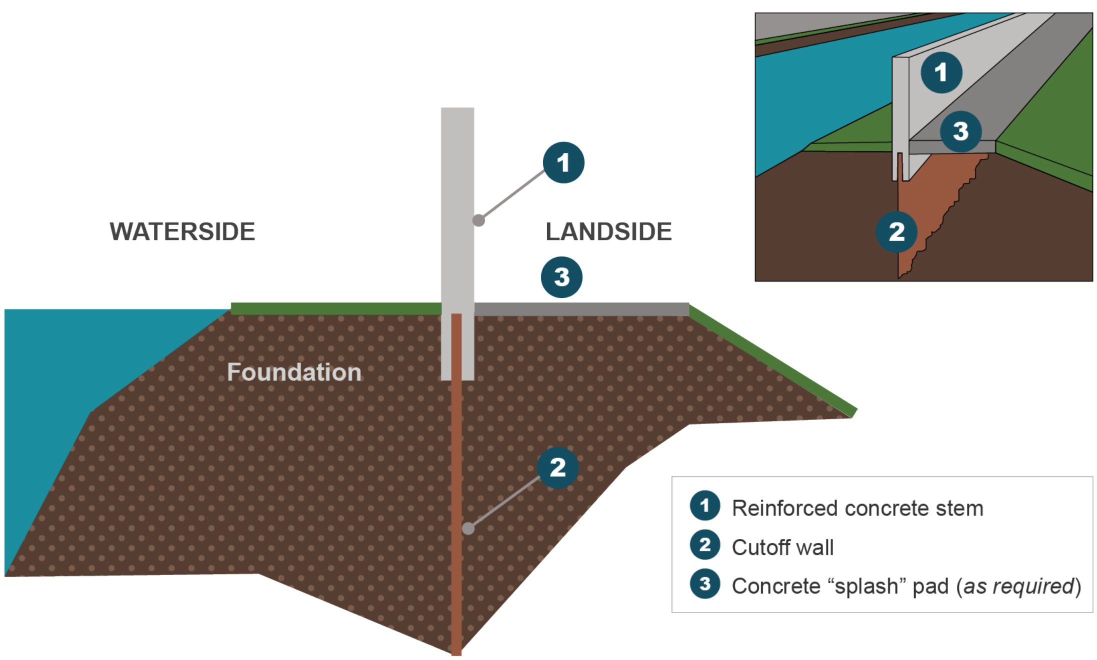


Figure 2-16: Examples of Floodwalls

(a) L-wall being constructed in St. Louis, Missouri. (b) I-wall being constructed in New Orleans, Louisiana. (c) T-wall being constructed in New Orleans, Louisiana.

4.2.4 Mass Gravity

Mass gravity structures (Figure 2-17 and Figure 2-18), often found in coastal environments, are concrete structures where the flood loading is resisted by the sheer mass of the structure, and the structure acts as the barrier to exclude floodwater from the leveed area. A unique element of this type of feature is the geometric design of the waterside face, which is often tailored to deflect the incoming waves.

Figure 2-17: Typical Mass Gravity Wall

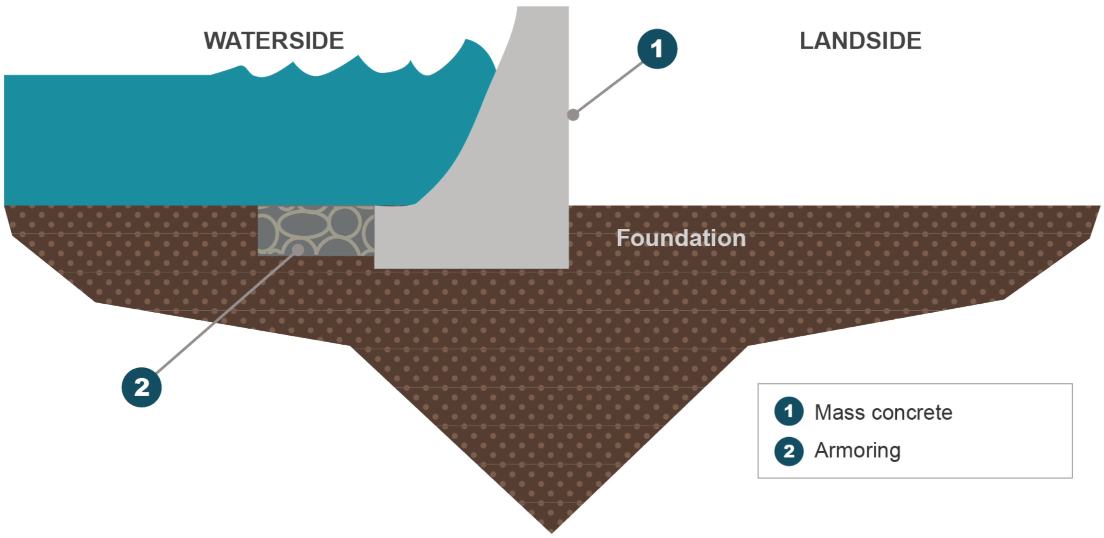


Figure 2-18: Example Mass Gravity Wall

Coastal mass gravity seawall in Galveston, Texas.

4.2.5 Demountable

In certain situations where a permanent structure is undesirable because of aesthetics, accessibility, or required vertical clearances during non-flooding conditions, a demountable floodwall system (Figure 2-19) may be employed. Key considerations for demountable walls include the ability to safely store the components and having sufficient time and trained personnel to reliably deploy the system prior to a flood. Typical demountable floodwalls use a series of posts that are embedded into a reinforced concrete sill that extends along the levee alignment. Spans between the posts are filled with panels or stoplogs that mechanically interlock with the posts. Additional structural supports may be required to support the lateral flood loading. Many of these structures are functionally similar to closure structures, which are also only deployed prior to a flood. The key difference between demountable floodwalls and closure structures is the size of the opening. Closure structures typically have a limited opening length along the alignment of the levee to accommodate the required access corridor. The opening length of a demountable floodwall can extend considerably further along the levee alignment.

Figure 2-19: Example Demountable Walls

Placement of the 17th Street demountable wall in Washington, D.C.

4.3 Closure Structures

Closure structures are required where access across or through the alignment of a levee is needed during non-flood periods. This may be where roadways, railways, walkways, waterways (including both navigable and non-navigable types), and runways transect the alignment of a levee. Closure structures addressed in this section do not include gates, valves, or other controls for pipes, and other penetrations through a levee that are meant to convey channelized water flow. Those types of structures are detailed in section 4.7.

During non-flood periods, access typically remains open. When flood conditions are forecasted, the opening must be closed on a temporary basis to restrict the intrusion of floodwaters into the leveed area. When closed, the structure essentially acts as a floodwall or embankment;

therefore, many of the key concepts and considerations are identical or similar to those previously discussed.

Closure structures can be broadly classified based on:

- Whether they transect the levee over a land course (e.g., roadways, railways, walkways) or watercourse (when the watercourse closure is part of the levee).
- Whether the opening is mechanical/structural (may be automated), or requires human assembly (sandbags, earthen fill).

Table 2-2 presents the three main categories of closure systems with a listing of various types under each category. Although there are other commercially available, temporary closure systems which are proprietary in nature that are used throughout the nation, they are not described within this publication.

Table 2-2: Categories and Types of Closures

Category	Types
Movable gates	• Roller gate • Swing gate • Trolley gate • Vertical lift gate • Sector gate • Miter gate
Structural assembled closures	• Stoplog (wooden, metal, concrete)
Earthen assembled closures	• Sandbag • Soil/gravel baskets • Earthen fill with plastic

The selection of a specific type of closure typically depends on two primary factors: (1) the physical constraints associated with deploying/installing or removing the structure that is used to close the opening, and (2) the operational constraints (i.e., warning time before deployment is required and time/resources required to deploy the system). Additional details are provided in **Chapter 7**.

4.3.1 Movable Gates

Movable gate closures are usually the simplest type of closure to set and the most reliable. They are gate structures that are moved into place by either manual or mechanical means. The gates are permanently attached to the closure superstructure (i.e., adjacent closure wall section) in the recessed or open position and then simply moved into place ahead of the rising floodwaters. Once moved into their final position (recessed or closed), they are secured by some type of locking mechanism. There are a variety of styles of movable gate closures, which are highlighted in the following sub-sections. These closures are easy to set, require no inventory of parts, and can quickly be moved into place by maintenance personnel.

However, they are not used more frequently because of the high initial cost to construct the gate and supporting closure structure. Not only does the heavy steel gate require a higher initial cost, but the wall, any supporting frame (overhead trolley slide gates), and sill structure must be designed into the closure structure. This increases the initial construction costs considerably when compared to using other types of closure systems.

The most influential risk factor affecting the ability to successfully set movable gate closures is the operating plan and experience. Movable gate closures are frequently used in urban areas where there are numerous closures that should be set in place ahead of rising floodwaters. Sometimes different entities are responsible for setting closures; therefore, it is imperative there is a well-practiced operating plan for the 'who, what, and when' of how each closure is to be set. Other less influential risk factors include vandalism and general structural condition. Deficiencies resulting from either can easily be checked as part of an active inspection program, described in **Chapter 9**.

4.3.1.1 Roller Gate Closure

Roller gate closure structures (i.e., movable transect over land) move on wheels or casters that travel on a set of tracks on its foundation to slide the gate in and out of position (Figure 2-20). They frequently require a mechanical system (e.g., a cable winch) to move the gate. These gates can often be deployed rapidly and may be incorporated into levees that transition into either floodwalls or embankments on the flanks of the opening (Figure 2-21). The tracks are attached to a sill bearing on a foundation system to structurally support the entire closure system. The performance requirements, and thus design and construction of the foundation system, is nearly identical to that for supporting a floodwall and could be either a deep or shallow foundation system. However, a key, unique component consideration for closures is providing a mechanism to seal the gate when it is deployed. The frame of the closure structure typically consists of end supports that tie in and transition to the levee features on either side of the levee, which could be either earthen embankments or floodwalls.

Figure 2-20: Typical Roller Gate

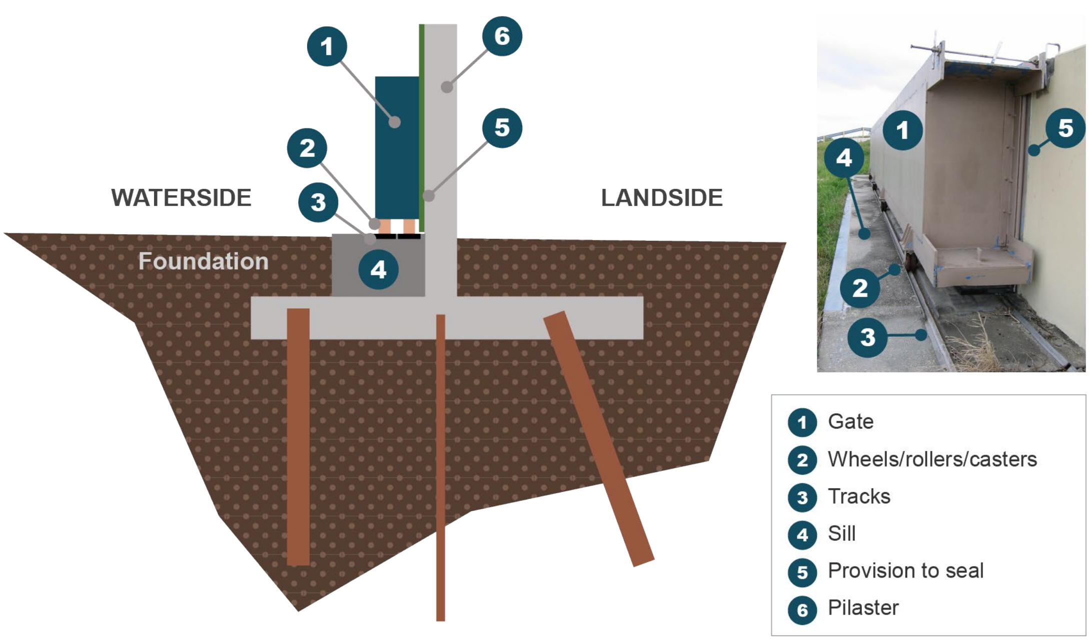
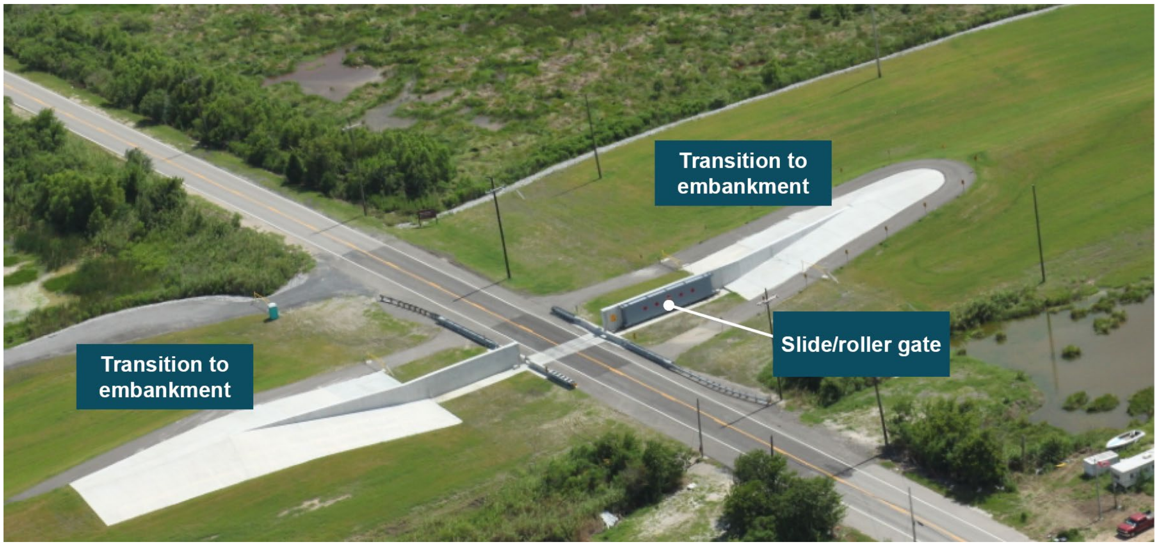
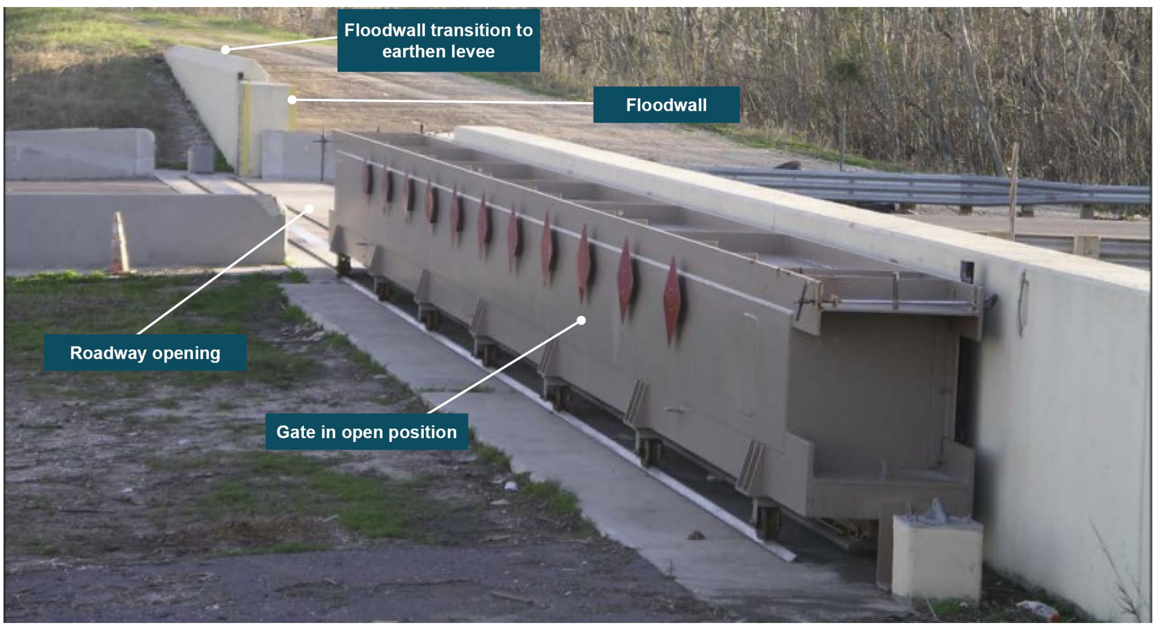


Figure 2-21: Roller Gate Details





View of a typical roller gate and transitions to embankment, with the main roller gate components identified.

4.3.1.2 Swing Gate Closure

Swing gate closures are typically steel gates with hinges that are attached to an adjoining concrete floodwall (pilaster) and swung into place to make the closure. They are structurally latched in place to keep them stationary when either in the open or closed position. Swing gate closures are usually the easiest closures to set in place. Wider openings that utilize a swing gate require two gate leaves with a center support section to close the gap, while smaller width openings only require a single gate leaf. Typical swing gate closures are shown in Figure 2-22, Figure 2-23, and Figure 2-24.

Figure 2-22: Typical Swing Gate

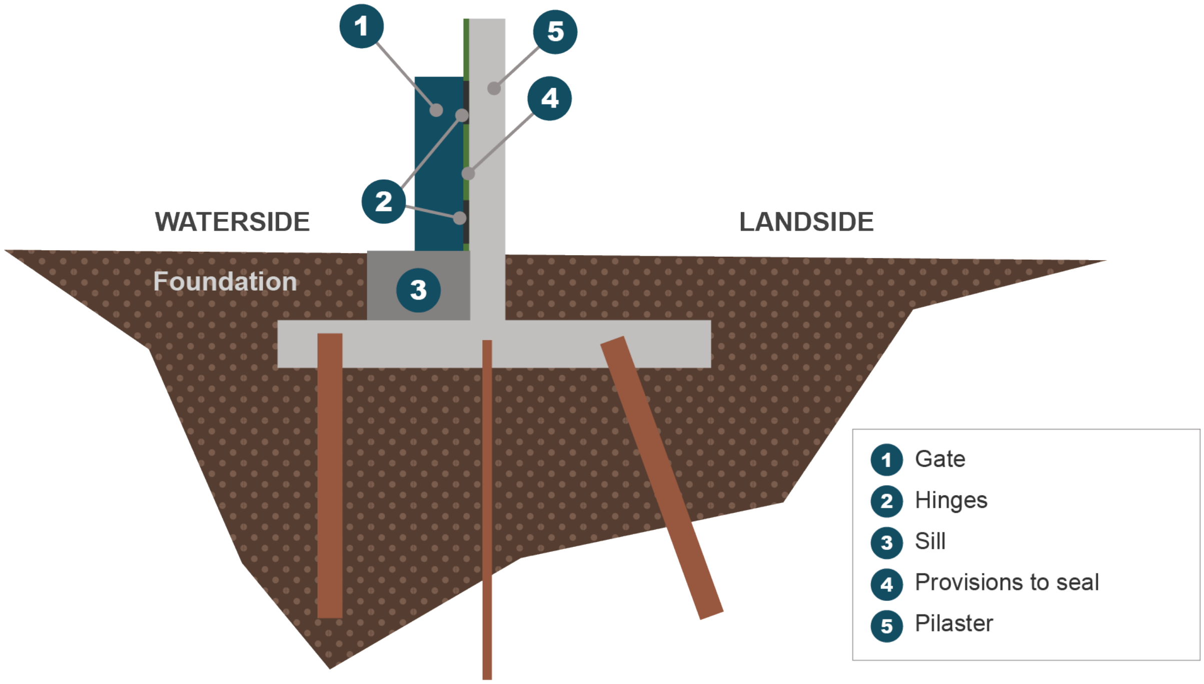
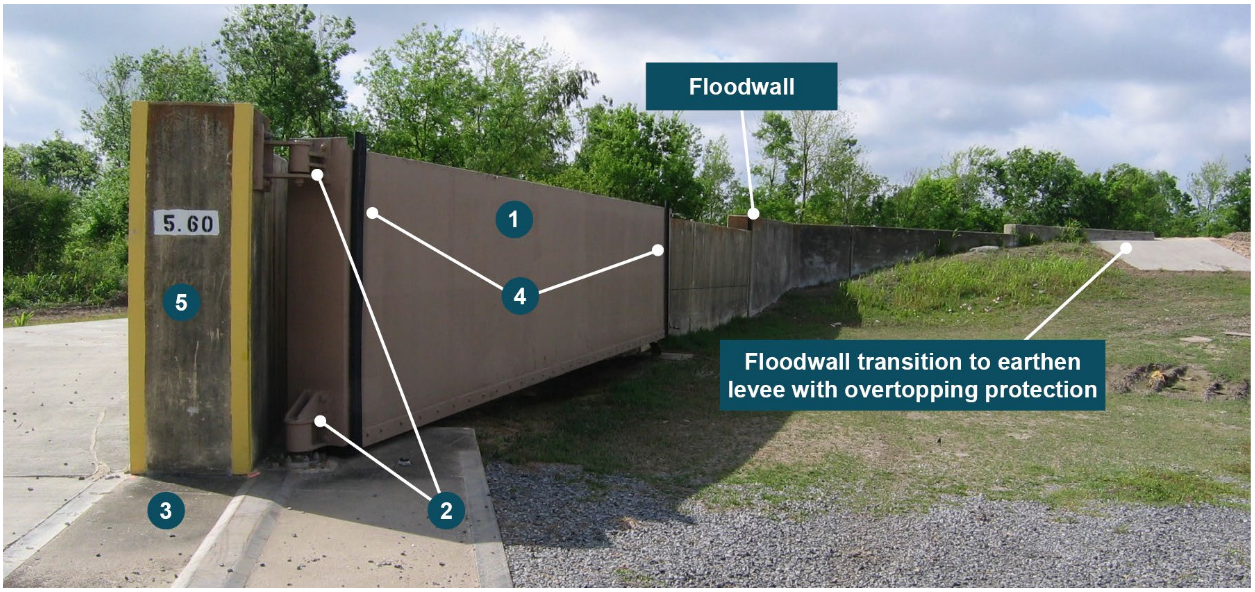


Figure 2-23: Swing Gate Details



View of a swing gate and transition to embankment, with the main components identified.

Figure 2-24: Example Swing Gates

(a) Swing gate that provides a closure to the railroad line crossing the levee. (b) View of a typical swing gate with the transition to embankment.

4.3.1.3 Trolley Gate

A trolley gate closure structure is a steel gate that is suspended from an overhead rolling track and is pulled across the opening in the levee. Once the trolley gate is set in place, it is latched/locked in place to keep it stable under hydraulic loading. A structural frame or other support mechanism connects the rollers and track to the gate leaf. A typical trolley gate closure structure is shown in Figure 2-25. These closures are usually utilized in more urbanized areas where floodwalls are present. When these gate closures are present in a levee embankment, a supporting concrete transition structure is used.

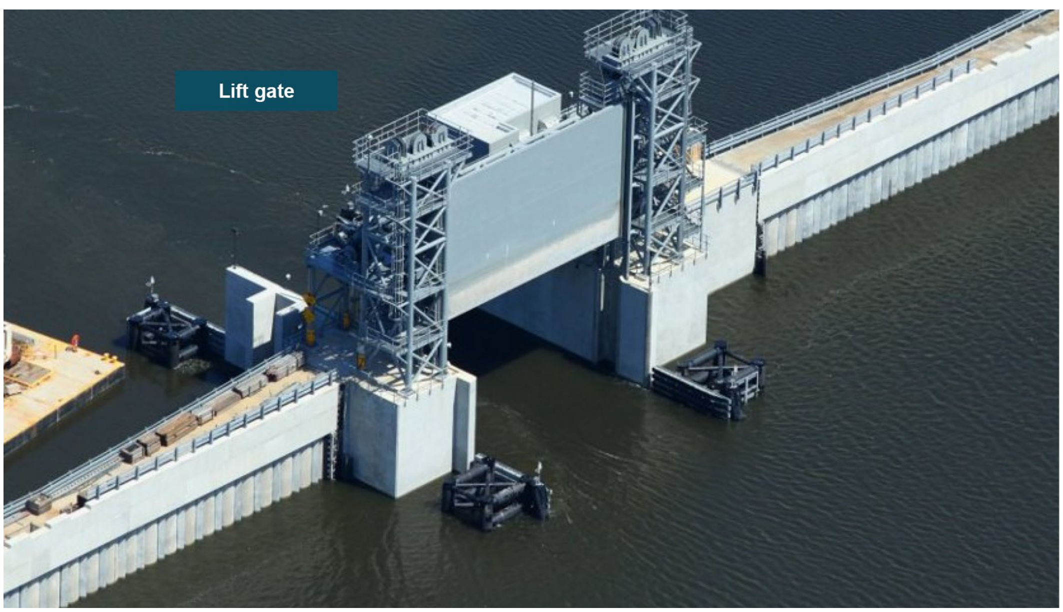
Figure 2-25: Example Trolley Gate

View of a trolley gate in New Orleans, Louisiana, in both the open and closed positions; March 2023.

4.3.1.4 Vertical Lift Gate

A vertical lift gate closure is a large gate that is moved downward along an embedded guide track to close a gap in the levee. Vertical lift gates require specially designed operating equipment for moving the heavy gates into and out of place. They are typically used for special applications where other gate types would not work due to loading or operation conditions. A vertical lift gate closure is depicted in Figure 2-26.

Figure 2-26: Example Vertical Lift Gate

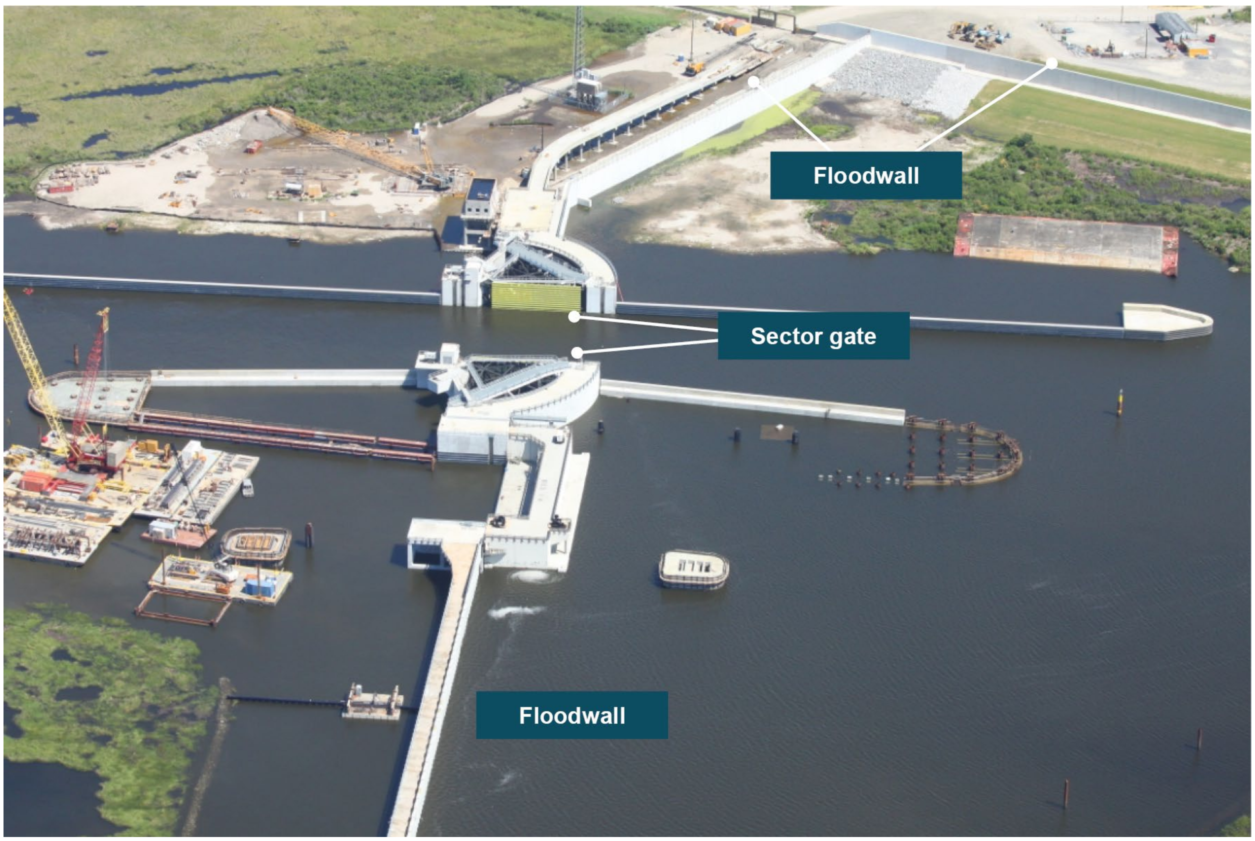


Open lift gate in New Orleans, Louisiana.

4.3.1.5 Sector Gate

Sector gate closures utilize two gates that are swung into place to provide a positive closure. Sector gate closures are commonly used along waterways and canals where the closure has the potential to be loaded from both directions. This usually occurs in coastal areas where tropical storms/hurricanes can result in surge and wave-induced loadings from one direction, whereas day-to-day operations load the gates in the opposite direction. When sector gates are not in use, they sit in large recess openings built as part of the supporting structure. A typical sector gate closure in the levee is shown in Figure 2-27.

Figure 2-27: Example Sector Gate



Sector gate open to allow for waterborne traffic in New Orleans, Louisiana.

4.3.1.6 Miter Gate

A miter gate closure consists of two individual gate leaves that close to form a three-hinged arch. The gate closes at a mitered angle, hence, the name. The three-hinged arch (miter gate) is designed to withstand loading in one direction (waterside to landside). Most miter gates are constructed of steel, but there are wooden miter gates that may exist in very old systems. Figure 2-28 shows a typical miter gate installed in a levee embankment with a supporting concrete closure structure. Miter gates can be horizontally framed or vertically framed, with the framing of the miter gate determining the load transfer. Common applications for miter gate closures are for providing closures across canals that cross a levee, but they can also be used to temporarily close off taller road/railroad openings. When the gate leaves are not in use, they sit in recesses that are built into the supporting concrete structure. When recessed, the gate leaves should be structurally tied in place, commonly referred to as pinned, so they cannot inadvertently be moved by wind, vandalism, or other causes. Miter gates for small openings can be moved manually, but larger ones require specialized equipment or machinery to set in place.

Figure 2-28: Example Miter Gate

Fully closed miter gate.

4.3.2 Structural Assembled Closures

These types of closures utilize metal or wooden beams—known as stoplogs—that are placed in guide slots in an opening of a floodwall or in an opening of a levee embankment where a transition has been constructed specifically for the closure structure (Figure 2-29 and Figure 2-30). Many erectable barrier structures include an on-site storage vault to store the stoplogs and supporting materials. These closures are very popular because of their versatility. They can be used to close various size openings and typically do not require much, if any, specialized equipment. Utilizing stoplogs with wider openings or very tall openings may require an interior support post. In the case where stoplogs are not fitted with seals, other means like plastic sheeting or sandbags can be used to reduce leakage through the stoplog closure. Stoplogs should be secured (held down and tight against any seals) in the installed condition.

Figure 2-29: Typical Stoplog Closure

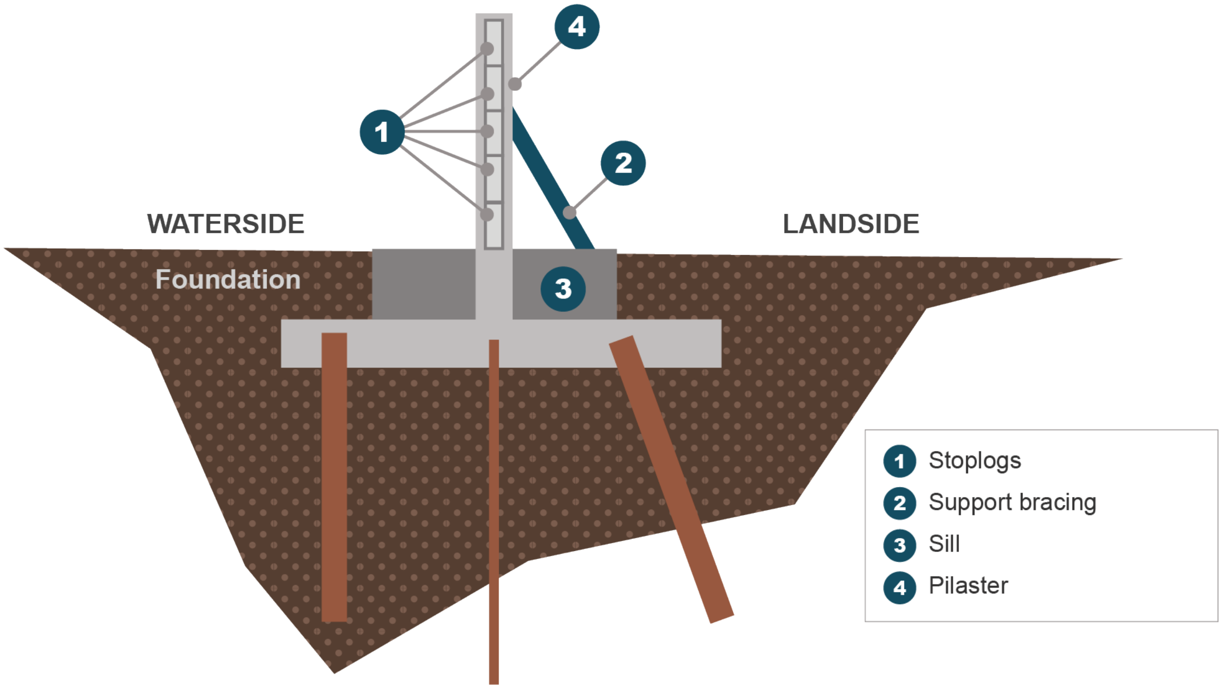


Figure 2-30: Example Stoplog Closures

(a) Levee closure across a roadway using metal stoplogs. (b) Levee closure across a roadway using wooden stoplogs in Vicksburg, Mississippi. (c) Levee closure using concrete stoplogs.

4.3.3 Earthen Assembled Barriers

Earthen assembled barriers as detailed in the following sub-sections are some of the most common types of closures due to the low cost of implementation and simplicity. However, there are several factors that should be considered with these closures. The most important consideration is the operating plan and experience of the personnel responsible for setting the closure. These closures take time to set, require various equipment and personnel to install, and may require experience or knowledge to properly set the closure. Another factor that needs to be considered with respect to these closures is storage and stockpiling of material. Additionally, the use of heavy equipment may be needed, so damaging the levee should be considered when assessing the risk of placing these types of closures.

4.3.3.1 Sandbag Closure

A sandbag closure is an opening along the levee alignment that is closed by a sandbag wall, as shown in Figure 2-31. Sandbag closures are common due to their low initial cost and simplified construction. They require sufficient time to set in place (ample advance warning) and a large enough workforce of personnel/volunteers as it is labor intensive. Closures usually require numerous sandbags to be placed in a particular arrangement. Sometimes a permanent concrete sill is included with the original construction of the levee for identification of where to build the sandbag wall, as well as for deterring seepage underneath the sandbag wall. In addition, individual sandbags are commonly placed at the base of other closure structure types to help deter seepage along the structure/foundation base.

Figure 2-31: Example Sandbag Closure

Levee closure across a roadway using sandbags in Washington, D.C.

4.3.3.2 Soil/Gravel Baskets

This type of closure utilizes wire baskets that are put together on-site and then are structurally connected to one another to form a water barrier, as shown in Figure 2-32. The lining placed inside the basket provides the water barrier while the soil or gravel used to fill the basket provides the necessary weight for stability. Plastic sheeting can also be used to provide a secondary measure to reduce throughseepage. The baskets are designed so they can be vertically stacked to close taller openings. When vertically stacked, the base must be widened with additional baskets. The weight on the foundation is an important consideration when using these types of closures, particularly when they are vertically stacked. While there is no formal guidance on the stacking limits, experience has shown that they should not be stacked more than three high when used for floodfighting purposes.

Figure 2-32: Example Soil/Gravel Basket Closures

(a) Levee closure using sand-filled baskets in Walla Walla, Washington. (b) Levee closure using sand-filled baskets in New Orleans, Louisiana.

4.3.3.3 Earthen Fill with Plastic

Probably the simplest concept for closing a gap in the levee is the use of a soil pile closure. A soil pile closure is earthen material that is placed with construction equipment across the closure. It should be at least minimally compacted when being placed. The earthen material should be covered with plastic sheeting and then anchored down to prevent the soil from eroding. If plastic sheeting is not used, then some other erosion protection measure should be applied. The sheeting and anchoring system (usually sandbags) should extend beyond the opening onto the adjoining embankment section to prevent excessive seepage along the contact between the embankment and soil pile. Soil pile closures are sometimes used as an emergency measure when an attempt to set a different closure type is unsuccessful. An example of a soil pile closure with plastic sheeting along the waterside face is shown in Figure 2-33.

Figure 2-33: Example Earthen Fill with Plastic

Example of a levee closure across a roadway using earthen fill.

4.4 Transitions

A levee consists of an arrangement of features along an established alignment, which creates a need to transition between different feature types. Several types of transitions between different features are illustrated in Figure 2-34.

If not designed and constructed properly, transitions can become a vulnerable point of the levee due to the intrinsic dissimilarity of the structures. Each feature will likely respond differently during and after construction. For example, a floodwall and embankment may impose separate loads on the foundation, which can cause the transition to be prone to performance issues due to differential settlement. Foundation treatments such as surcharging or preloading are often implemented to address these concerns. Often, the transition must be more robust than the individual features being joined, with careful consideration of how they overlap and are incorporated within the transition section. Issues due to differences in geometry can arise if not carefully evaluated and addressed in the design. For example, eddy currents or flow concentrations where floodwalls tie into earthen embankments can cause erosion of soils.

Figure 2-34: Typical Types of Transitions

(a) Transition from floodwall to high ground in New Orleans, Louisiana. (b) Transition from embankment to infrastructure in New Orleans, Louisiana. (c) Transition from embankment to the gate in New Orleans, Louisiana.

4.5 Seepage Control Features

The difference in water surface elevations on the waterside and landside of the levee and the associated seepage can cause performance issues with structural integrity and stability of the feature. Seepage through or under the levee may produce water flow that exits at some point on the landside of the levee, which may require collection with filters and drains, and ultimately be conveyed and discharged with interior drainage. The movement of water under or through a levee from high energy to low energy can result in erosion of foundation or embankment soils. To mitigate these effects, seepage controls may be employed.

Seepage controls provide a mechanism to reduce, collect, filter and/or discharge seepage through the levee or its foundation. They may be used as individual features or used in combinations to mitigate potential seepage issues for levees. They can address potential issues through either diversion or interception of the water flow.

4.5.1 Cutoff Walls

Cutoffs (Figure 2-35) divert seepage below the structure, extending the seepage path length to reduce the amount of energy within the flow of water and reduce the force with which it exits on the landside of the levee. Cutoffs can be constructed through, below, and riverside of earthen embankments (Figure 2-36) by excavating the soils and filling the excavation with a material that has lower permeability (soil-bentonite, cement-bentonite, or soil-cement-bentonite). Careful consideration is needed to determine the necessary depth of cutoff, as discussed in **Chapter 7**.

Figure 2-35: Typical Cutoff Wall

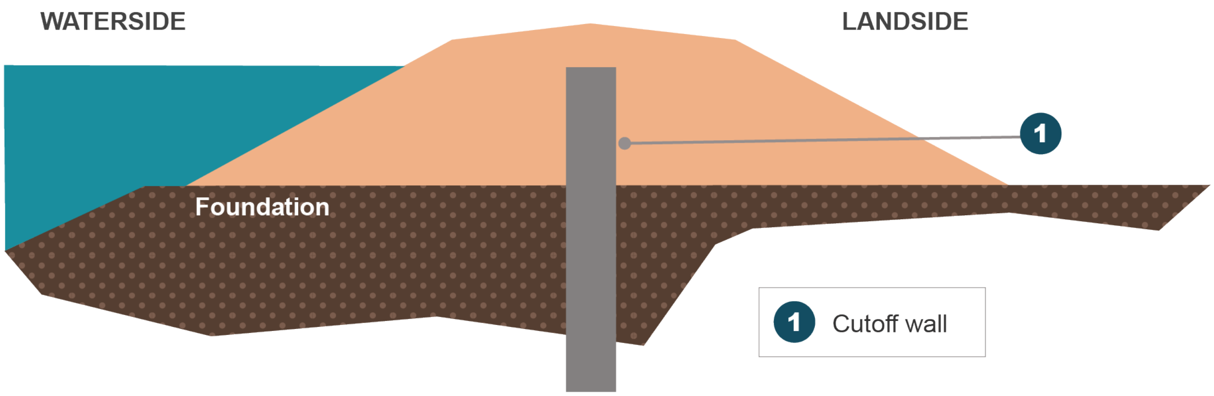


Figure 2-36: Cutoff Wall Under Construction

Slurry trench cutoff wall under construction in Sacramento, California.

4.5.2 Seepage and Stability Berms

Seepage berms and stability berms have similar appearances because they consist of prisms of soil immediately to the landside of an earthen embankment (some stability berms may be constructed waterside). And while both provide some level of stability and seepage improvement, seepage berms are primarily intended to counter underseepage and high uplift pressures in the levee foundation, whereas stability berms are meant to provide predominantly counterbalancing weight to prevent slope instability and address **throughseepage** (water moving through the soil that comprises the levee embankment) issues. Seepage berms can be constructed from either impervious or pervious soils, depending on the specific seepage issue that needs to be addressed based on the site-specific foundation conditions. Seepage berms lengthen the seepage path such that seepage water emerges further from the levee toe where it is less likely to cause damage to the levee. For this reason, seepage berms extend much farther out from levee embankment than stability berms, typically 150 to 400 feet. An example of a seepage berm is shown in Figure 2-37 and Figure 2-38.

Figure 2-37: Typical Seepage Berm

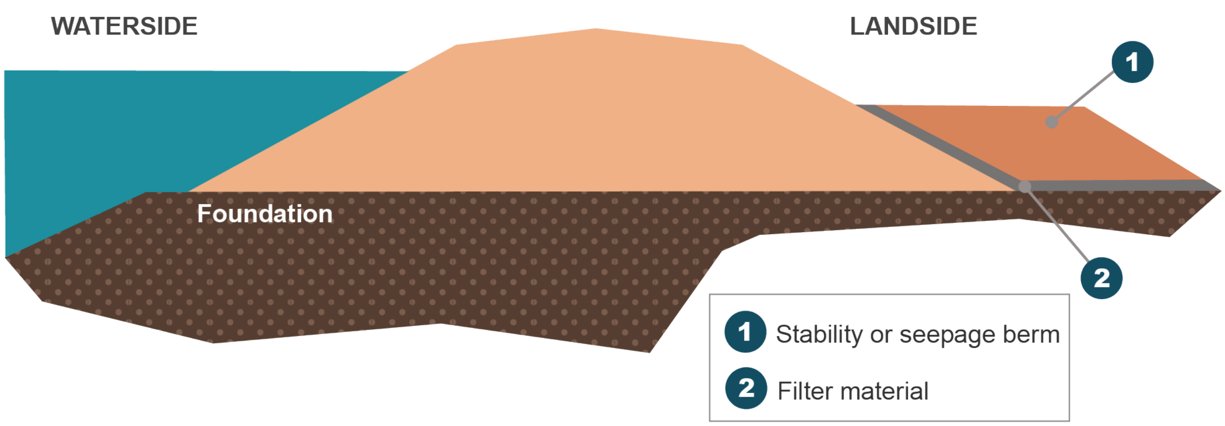
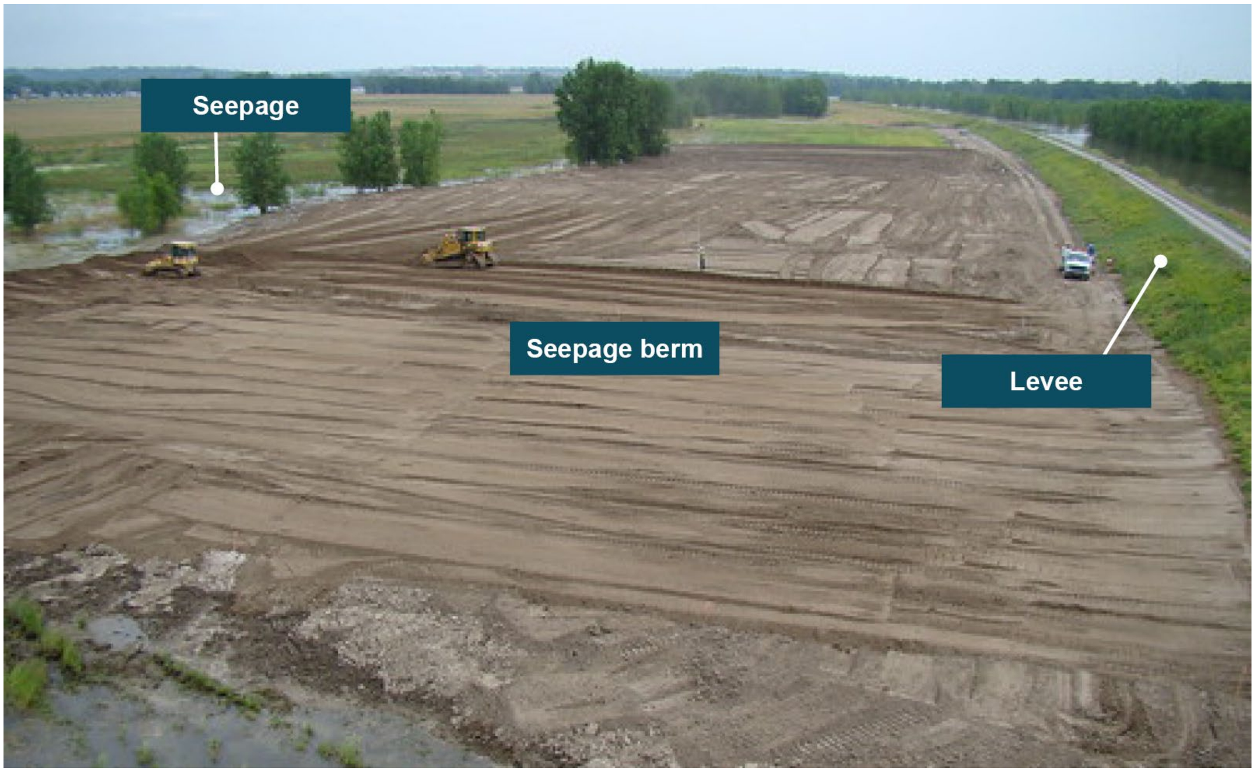


Figure 2-38: Example Seepage Berm

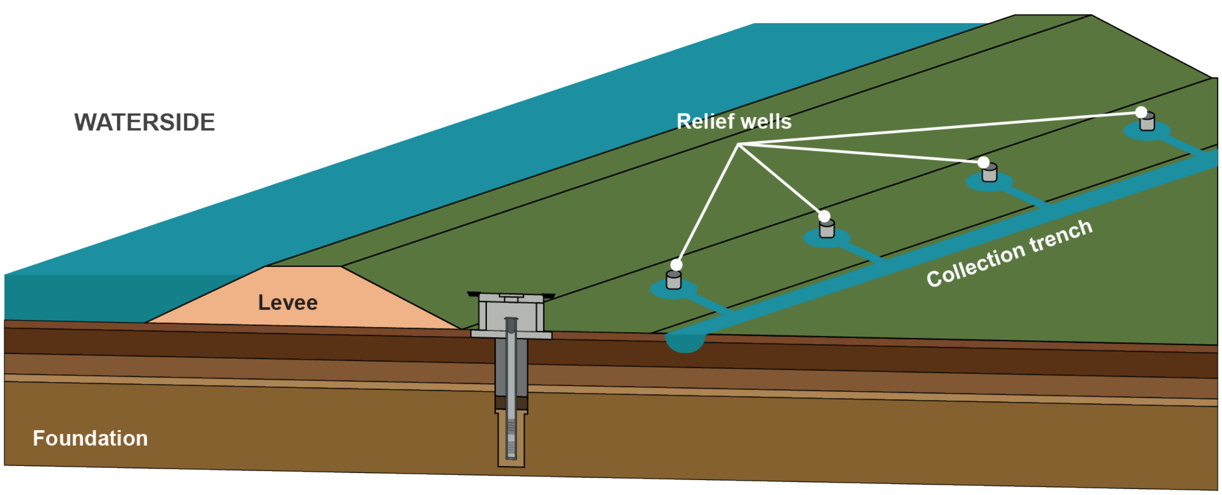


Seepage berm under construction in Elwood, Kansas.

4.5.3 Relief Wells

Relief wells (Figure 2-39) are installed landside of levees to reduce uplift pressure which may otherwise cause sand boils and internal erosion of foundation materials. Wells accomplish this by intercepting and providing properly filtered, controlled outlets for seepage.

Figure 2-39: Typical Relief Well



Generally, relief wells are used where space for landside berms is limited or where the permeable soil layer in the foundation is too deep to be penetrated by toe drains or cutoff walls. However, wells require periodic maintenance and frequently suffer loss in efficiency with time, due to clogging of well screens by muddy surface waters, bacteria growth, or mineral build-up. Relief well systems also require a means for collecting, conveying, and disposing of the discharge from the wells as shown in Figure 2-39. Typical relief wells at the toe of an embankment are shown in Figure 2-40.

Relief wells may also be installed around structures, such as pump stations and drainage structures, to reduce uplift pressures and improve stability.

Figure 2-40: Example Relief Well

Relief wells installed at the toe of a levee, along with a close up view of the relief well cover.

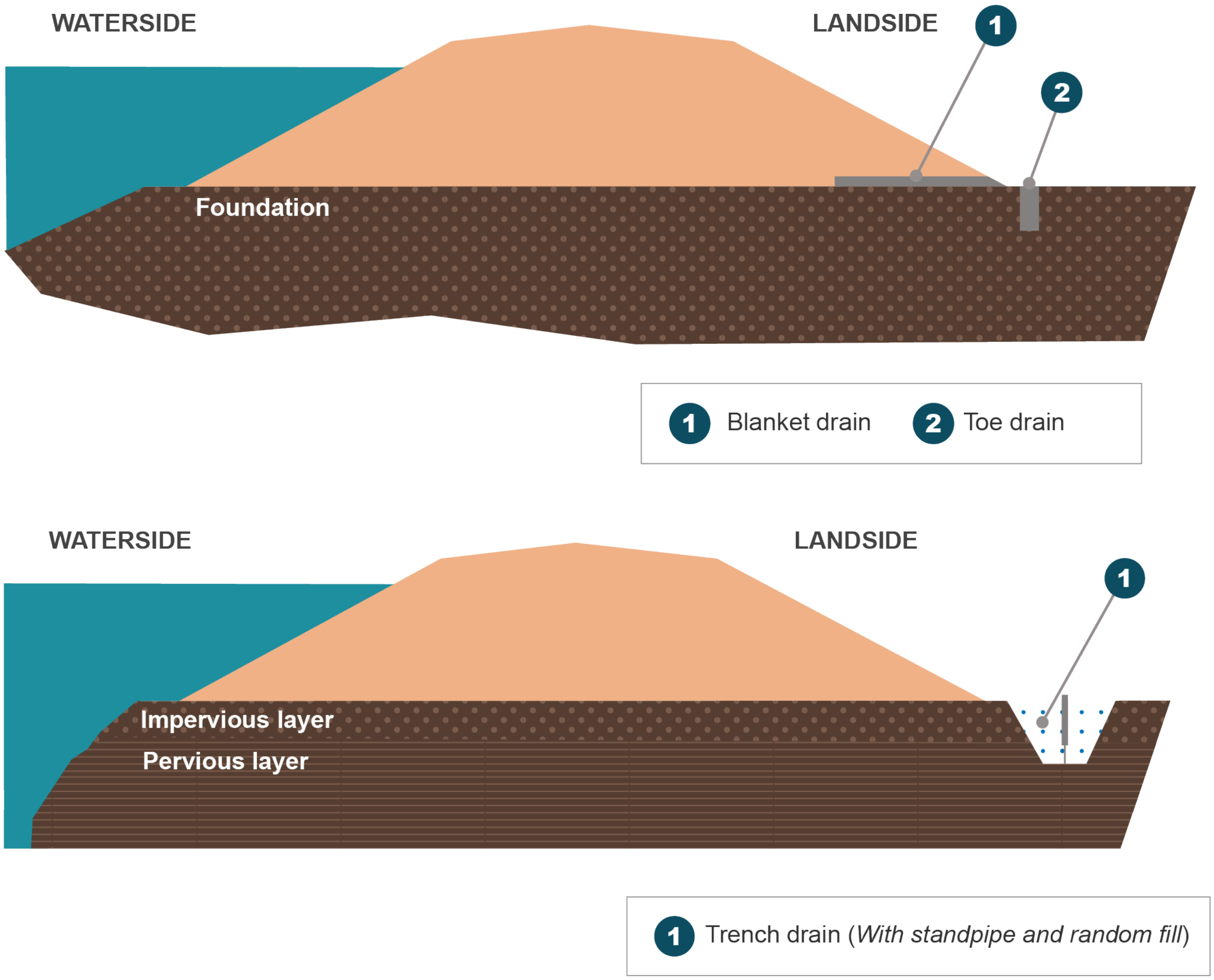
4.5.4 Drains

Drain systems collect the seepage through the levee embankment or in the shallow foundation soil at the levee toe to control throughseepage flows in the levee. There are a number of drain systems that work in conjunction to capture seepage.

- **Blanket drains**: Layer of filter material placed at the contact between the embankment and foundation material to capture throughseepage at the levee toe.
- **Toe drains**: Located at the landside toe of the levee, extending a shallow depth into the foundation to reduce high exit gradients.
- **Trench drains**: Can be used to control underseepage where the top stratum is thin and the pervious foundation is relatively shallow, so the trench substantially penetrates the aquifer.

These drain systems are shown in Figure 2-41.

Figure 2-41: Typical Drain Systems



4.6 Channels, Floodways, and Controlled Overtopping

4.6.1 Channels and Floodways

Floodways consist of an engineered, diversion channel and/or adjacent land designated for flood inundation during certain flood events with the intent of diverting floodwater flows in a river to prevent increase in river stages during these flood events. Figure 2-42 shows a typical floodway with an engineered diversion channel. Floodways are similar to spillways for dams and function to remove a portion of flood waters and lessen the flood load on the levee. They consist of floodwater diversion locations, which allow certain floodwater flows within a river to be diverted through an engineered channel and, ultimately, an area where the consequences of flooding are deemed an adequate trade-off for reduced flood risk to a levee.

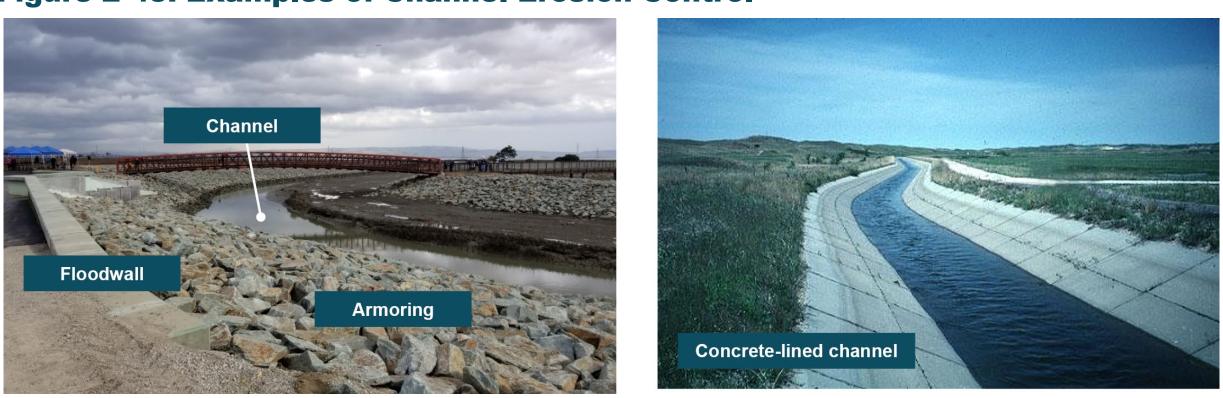
Floodwater diversion locations can either be controlled with gates that must be operated, or uncontrolled, meaning that diversion of floodwater flows initiate once the river water surface reaches a specific elevation to overflow a structure. Fuse gates may also be incorporated to control the release. Fuse gates are designed to be overtopped. Once the overtopping flow reaches a critical depth, the fuse plug is designed to 'wash away,' thereby creating a larger release opening to accommodate higher bypass discharges.

Engineered diversion channels can be natural (e.g., grass-lined, natural soil, or rock), concrete-lined, riprap, or other armoring to prevent erosion or loss of foundation material in the channel. An engineered channel can exist between two levee systems with proper functioning of the channel being required to prevent impacts to the flowline that could overtop the levee before the design flood. Figure 2-43 shows an armored and a concrete-lined engineered channel.

Figure 2-42: Typical Floodway Channel

Sacramento Weir floodway channel in both non-flow (top left) and flow condition in Sacramento, California.

Figure 2-43: Examples of Channel Erosion Control

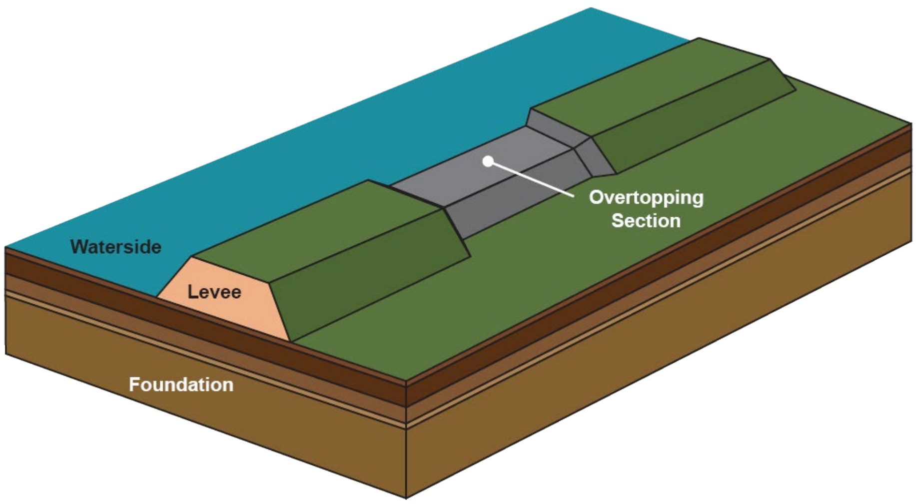


Protection of earthen channel using armoring (left) and concrete lining (right).

4.6.2 Controlled Overtopping Sections

A controlled overtopping section (1) typically allows the levee to overtop in a location that minimizes consequences, (2) has some type of reinforcement that decreases the likelihood that breach will occur during a flood that overtops the section, and (3) allows the leveed area to fill up slowly, providing more time for warning and evacuation. A controlled overtopping section on a levee is typically a long notch covered with overflow-resistant material such as masonry, concrete, gabions, or concrete riprap. In some cases, the section may be a gravity structure abutted to earthen levees. A typical controlled overtopping section is shown in Figure 2-44.

Figure 2-44: Typical Controlled Overtopping Section



This is an overtopping section along the Los Angeles River.

4.7 Interior Drainage Systems

Levees should not impede stormwater collection and drainage within the leveed area. During non-flood periods, interior drainage systems allow interior stormwater to flow out of the leveed area under gravity drainage through pipes. These pipes create penetrations through the levee. It is important to ensure such pipes are regularly inspected to prevent them from introducing a weak point in the levee (**Chapter 9**).

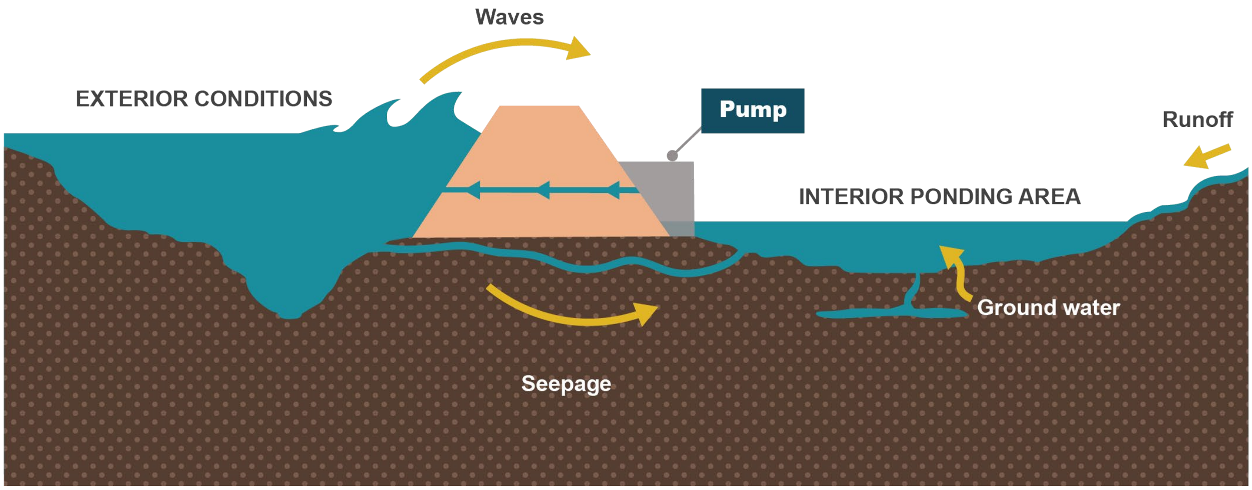
To prevent floodwater from entering the leveed area through these drainage systems, various controls can be employed that can be closed during floods. Because interior stormwater cannot be discharged through the pipes when the controls are closed, pump stations can be employed to remove the water from within the leveed area. This may be accomplished through the use of pressurized pipes or making provisions for a sufficient ponding area to allow stormwater to collect within the leveed area without inducing damages to improved property.

Figure 2-45 shows a diagram for the essential function of an interior drainage system and pumping. The diagram shows schematically the key elements of the system, which is to:

1. Allow interior storm drainage to flow out through pipes that extend from the landside to the waterside of the levee.
2. Provide outlet control so stormwater can flow out of the leveed area during non-flood periods, and be closed to prevent floodwater flows into the leveed area during floods.
3. Provide the energy and means to remove interior stormwater that can no longer flow out when the interior drainage controls are closed.

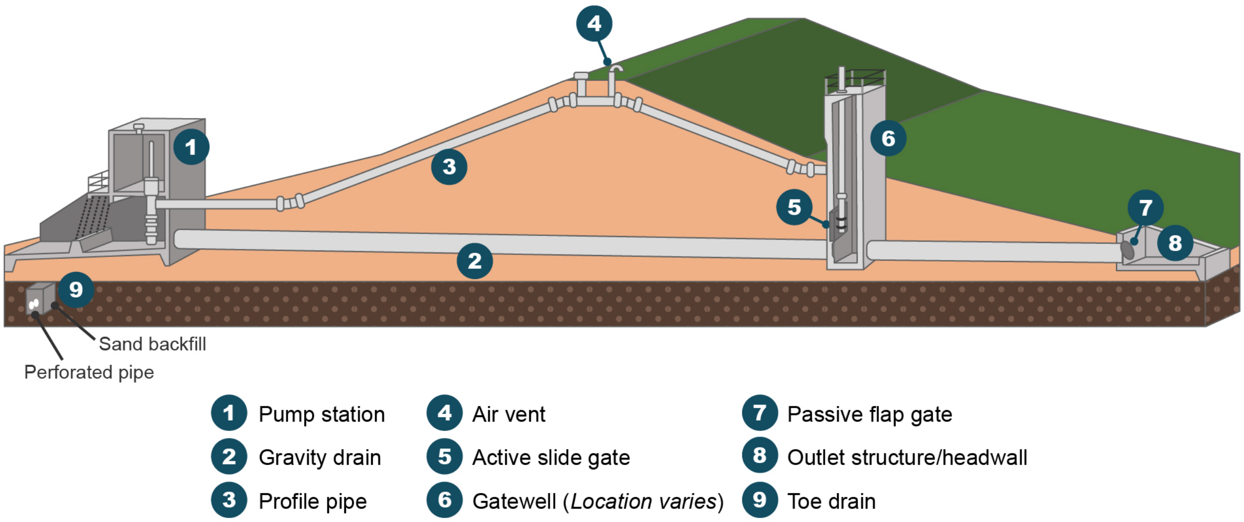
Interior stormwater is diverted to an area near the pumping station (interior ponding area) to be removed by the pumping system. Figure 2-46 shows details of a typical interior drainage system.

Figure 2-45: Essential Function of Interior Drainage System



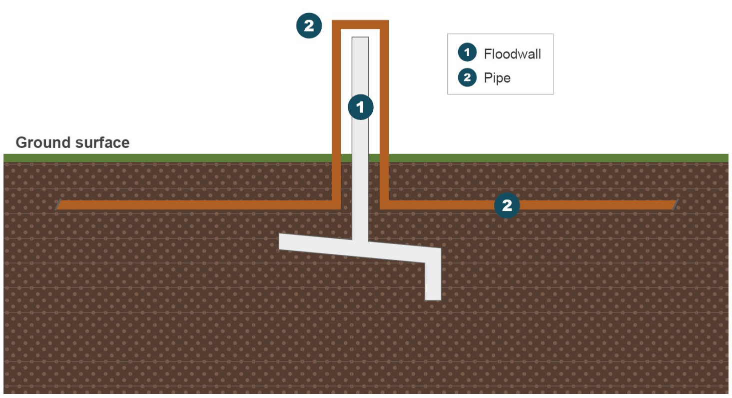
Interior drainage system showing the pump station and gate house on a levee in Cedar Rapids, Iowa.

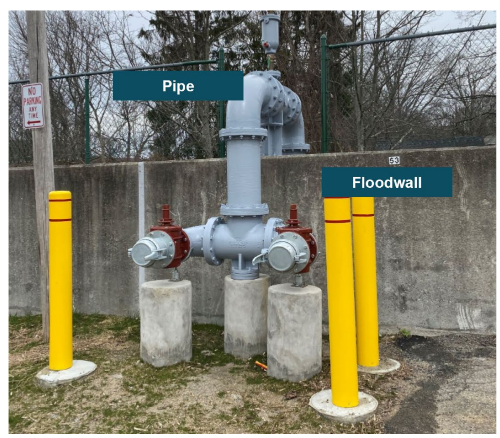
Figure 2-46: Typical Interior Drainage System



As shown in Figure 2-47, when interior drainage is required through a floodwall, the preferred path to route the pipe is over the floodwall or through the floodwall foundation. Figure 2-48 shows some of the more common gates used for interior drainage systems. The gates are either manually operated (sluice gate) or designed to remain closed until a certain pressure builds up behind the gate, at which point it opens (flap gate and duckbill). Once the pressure relieves the gate closes.

Figure 2-47: Detail of Pipe Passing Floodwall





View of a pipe passing over a floodwall, rather than through the levee under the floodwall.

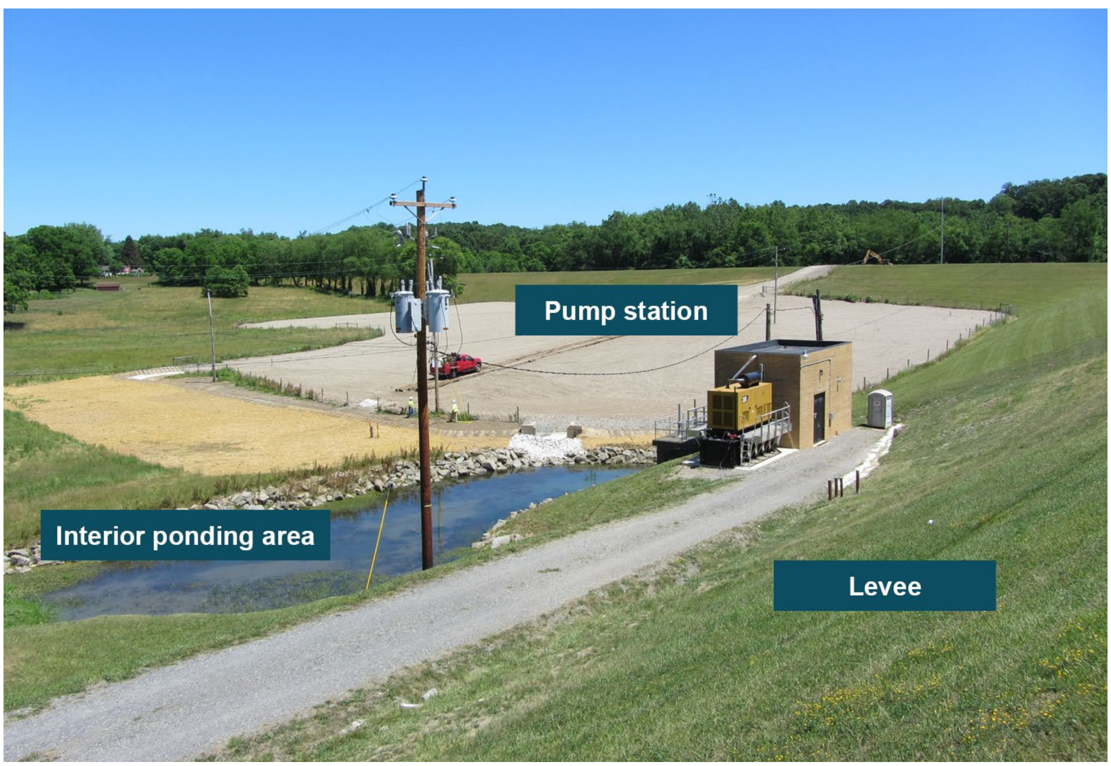
Figure 2-48: Typical Gates for Interior Drainage Systems

(a) Sluice gate being used for interior drainage. (b) Use of a flap gate for interior drainage. (c) Duckbill being used for interior drainage.

4.8 Pump Stations

Figure 2-49 shows a pumping station example. The scale and configuration of pumping stations can vary tremendously based on the pumping rates required. Regardless of the scale of the system, the key components consist of (1) an area to collect the diverted interior storm drainage (ponding area); (2) the pumps to create sufficient energy and capacity to remove the stormwater out of the leveed area, and (3) pipes to discharge the pumped water out from the leveed area.

Figure 2-49: Example Pump Station



Pump station and ponding area located at toe of Zoar Levee in Tuscarawas County, Ohio.

4.9 Instrumentation

A number of different instruments and technologies can be used for levee monitoring. Instrumentation may provide an indication of conditions on a relatively discrete portion of the levee or provide an understanding of the levee conditions on a broader scale. Instrumentation can broadly be classified according to the parameter it is used to detect and measure, which generally falls into one of the following three main categories:

- Hydraulic head (pore water pressure)
- Seepage
- Displacements (vertical and lateral)

Instrumentation can provide useful performance and operational data. A variety of instruments can be used to monitor performance including observation wells, piezometers, weirs, staff gages, displacement gages, settlement cells, and inclinometers. Some instrumentation examples are shown in Figure 2-50.

Observation wells are the simplest device for measuring water pressures in soils. Piezometers are used to measure the pore pressures (head) in levees and their foundations under both unconfined and confined conditions. The elevation of the water in both wells and piezometers can be determined manually by using a water level indicator, or the readings can be automated by installing a pressure transducer.

Direct measurement of seepage through a levee or its foundation can be a challenge if the seepage path is not known or if the seepage water cannot be collected and directed to a measurement location. When the opportunity exists to channel seepage water into a ditch or channel, weirs or flumes installed in the ditch or channel can be used to quantify the seepage flow. Water levels at weirs or flumes can be read visually using staff gages or using instruments.

A number of methods and types of instrumentation are available to measure settlement and vertical displacements. The methods vary depending on what type of displacement is to be measured, and what sort of measurement methods are feasible. The simplest form of displacement measurement (apart from just a qualitative visual observation) is the total displacement at the ground surface of a fixed location or marker, determined by surveying. Other traditional methods can be used to provide the relative displacement of a location compared to a specific reference point, but these methods generally require installation of instrumentation within the body of the levee.

While surveying monuments can detect lateral displacements at the surface of the levee, inclinometers can monitor for lateral displacements or offsets within the body of a levee embankment and/or within its foundation. For structures such as floodwalls, inclinometer casings can be installed in the backfill adjacent to the structure, or within the concrete floodwall itself. Also, tiltmeters can be installed on floodwalls to infer the lateral displacement from rotation of the face.

This section details some of the traditional types of instrumentation. There are several modern methods for monitoring displacements, including fiber optic cables, shape acceleration arrays, and synthetic aperture radar.

Figure 2-50: Typical Levee Instrumentation

(a) Use of a staff gage in a stream for flow level measurements. (b) A displacement gage is used between concrete panels of a floodwall to measure vertical movement. (c) Piezometer at the toe of earthen embankment used to measure pore water pressure. (d) V-shaped weir used to measure outflow at the landside of an embankment.

5 Levee Breach

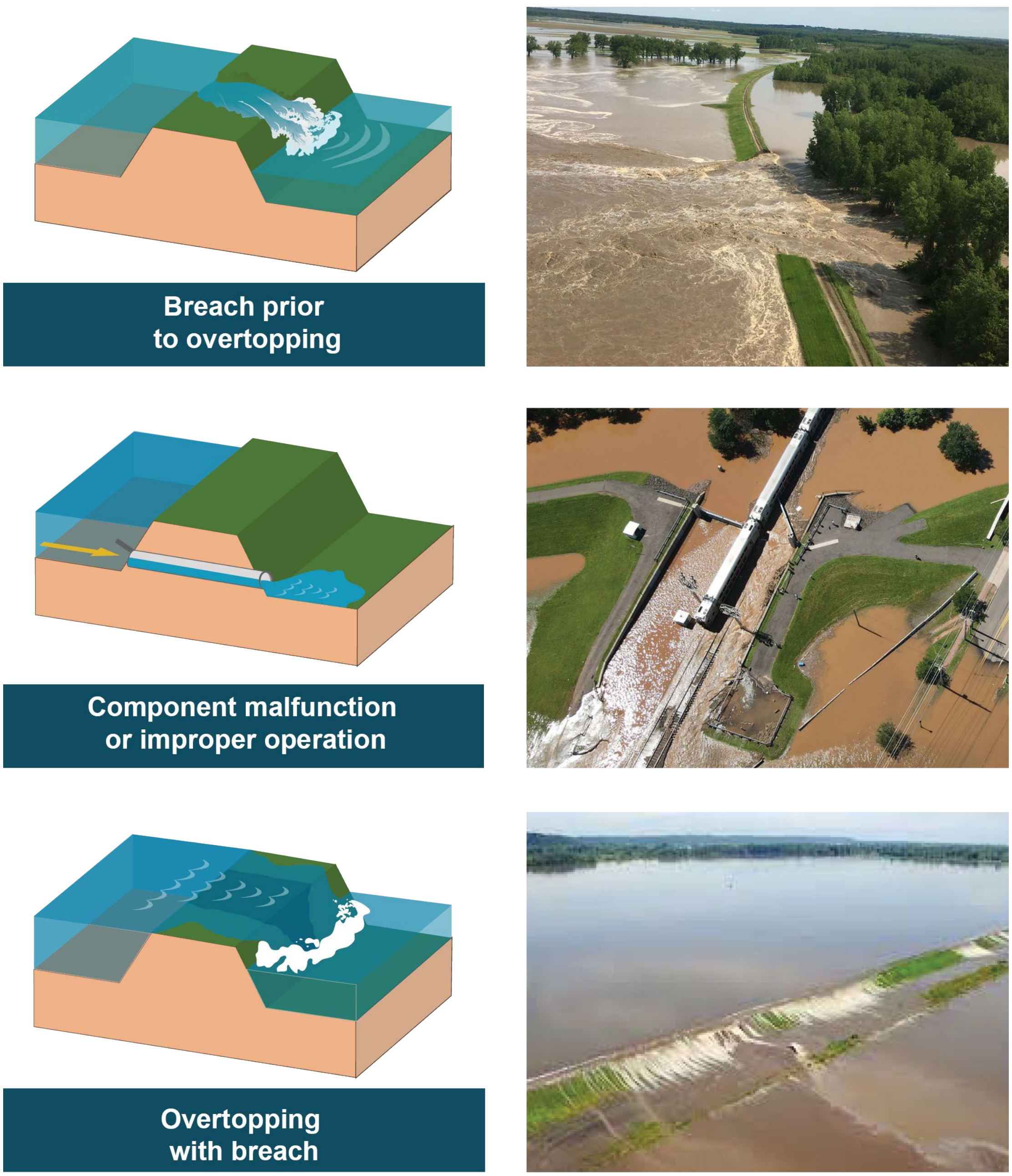
Levee **breach**, or sometimes referred to as levee failure, is the formation of a gap in the levee through which water may flow uncontrolled into the area intended to receive flood risk reduction. A breach may occur prior to water reaching the top of the levee or subsequent to overtopping. Levee breaches may occur due to an unknown defect or the malfunction or misoperation of a levee feature. It is important to be aware of some of the common breach mechanisms of a levee so they can be identified and mitigated to ensure successful levee performance. The following sections describe levee breach scenarios and breach mechanisms, commonly referred to as potential failure modes.

5.1 Levee Breach Scenarios

Levee breach scenarios include the following, also illustrated in Figure 2-51:

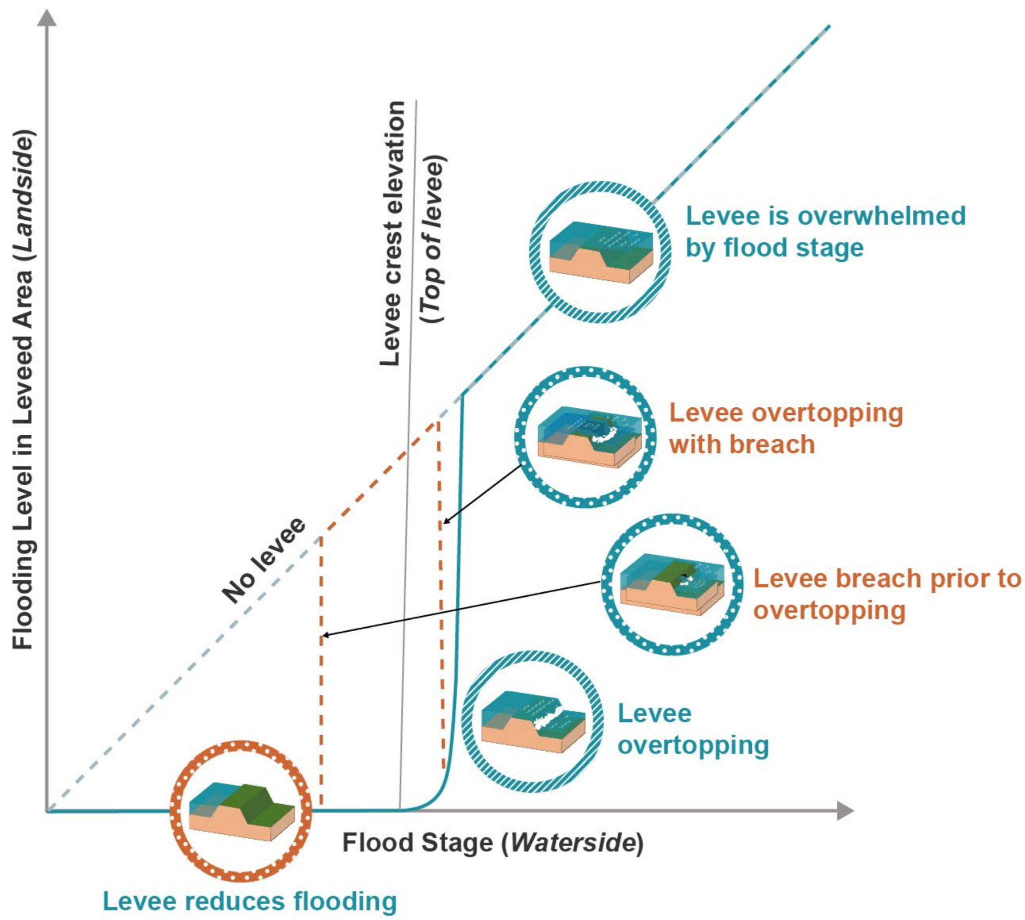
- **Breach prior to overtopping**: In this scenario, the levee breaches and floodwaters flow uncontrolled into the leveed area before the levee is overtopped.
- **Malfunction or improper operation**: In this scenario, a levee feature either malfunctions or does not properly operate. These failures can result in an uncontrolled release of floodwater into the leveed area or can lead to more constricted and constrained inundation (higher flow velocities).
- **Overtopping with breach**: This scenario occurs when water overtops the levee, and the flows cause erosion sufficient to breach the levee with rapid inundation of the leveed area.

Figure 2-51: Levee Breach Scenarios



Using the same concept as Figure 2-4, Figure 2-52 illustrates how the leveed area (landside) could be flooded with each of these breach scenarios. The solid blue line illustrates the levee functioning as intended, including inundation resulting from overtopping of the levee without breach. The orange dashed lines illustrate the levee breach prior to and from overtopping.

Figure 2-52: Graphical Representation of Levee Breach Scenarios



5.2 Levee Potential Failure Modes

These guidelines describe five general categories of potential failure modes considered most common to levees. These include breach from overtopping, external erosion, internal erosion, instability, and malfunction or improper operation of a feature, which are illustrated in Figure 2-53 and Figure 2-54, followed by a description.

5.2.1 Breach from Overtopping

Breach from overtopping is typically the result of progressive erosion of the landward slope from the flow over the levee. Overtopping may cause concentrated flows that, with sufficient velocity, can erode rills and channels on the landside embankment or of a floodwall toe. With time, this can either cause landside embankment slope or floodwall instability (or progressive erosion) and downcutting through the levee embankment. Overtopping without breach is not considered a levee failure because the levee was intentionally designed for an anticipated loading or flood event.

5.2.2 Breach Prior to Overtopping

Breach prior to overtopping is typically the result of sudden progression of one or a combination of external erosion, internal erosion, or instability as described below.

- **External erosion**: Occurs when water flow or wave action causes loss of surface protection (vegetative, riprap, mat armoring, or fabrics) that results in undercutting the levee toe or loss of the levee prism. Once exposed, riverine or coastal forces can progressively and catastrophically continue to erode the levee, leading to levee instability and breach.
- **Internal erosion**: Occurs when seepage exits on the landside levee face or foundation at or beyond the levee toe with sufficient force to erode and carry soil particles from within the levee foundation or embankment prism. This can occur through one of several mechanisms such as concentrated leak erosion, backward erosion piping, and suffusion. Specifics of these mechanisms are extensively studied and described in technical literature, including best practices for dam and levee risk analysis (USACE, 2000).
- **Instability**: Occurs when the levee includes slope stability failures (slides) or excessive settlement due to foundation issues. This can lead to loss of the crest and, during a flood, result in overtopping and breach at the location of the instability. Instability also includes sliding or overturning failure of structural elements such as floodwalls.

5.2.3 Malfunction or Improper Operation of a Feature

This potential failure mode includes the inability to deploy removable flood risk reduction features or operate closure gates or walls; failure of a closure component; failure of a pump to operate; or the installation of a closure does not occur in time for the structure to properly exclude floodwaters. This typically leads to inundation of the leveed area prior to overtopping.

Figure 2-53: Typical Embankment Potential Failure Modes

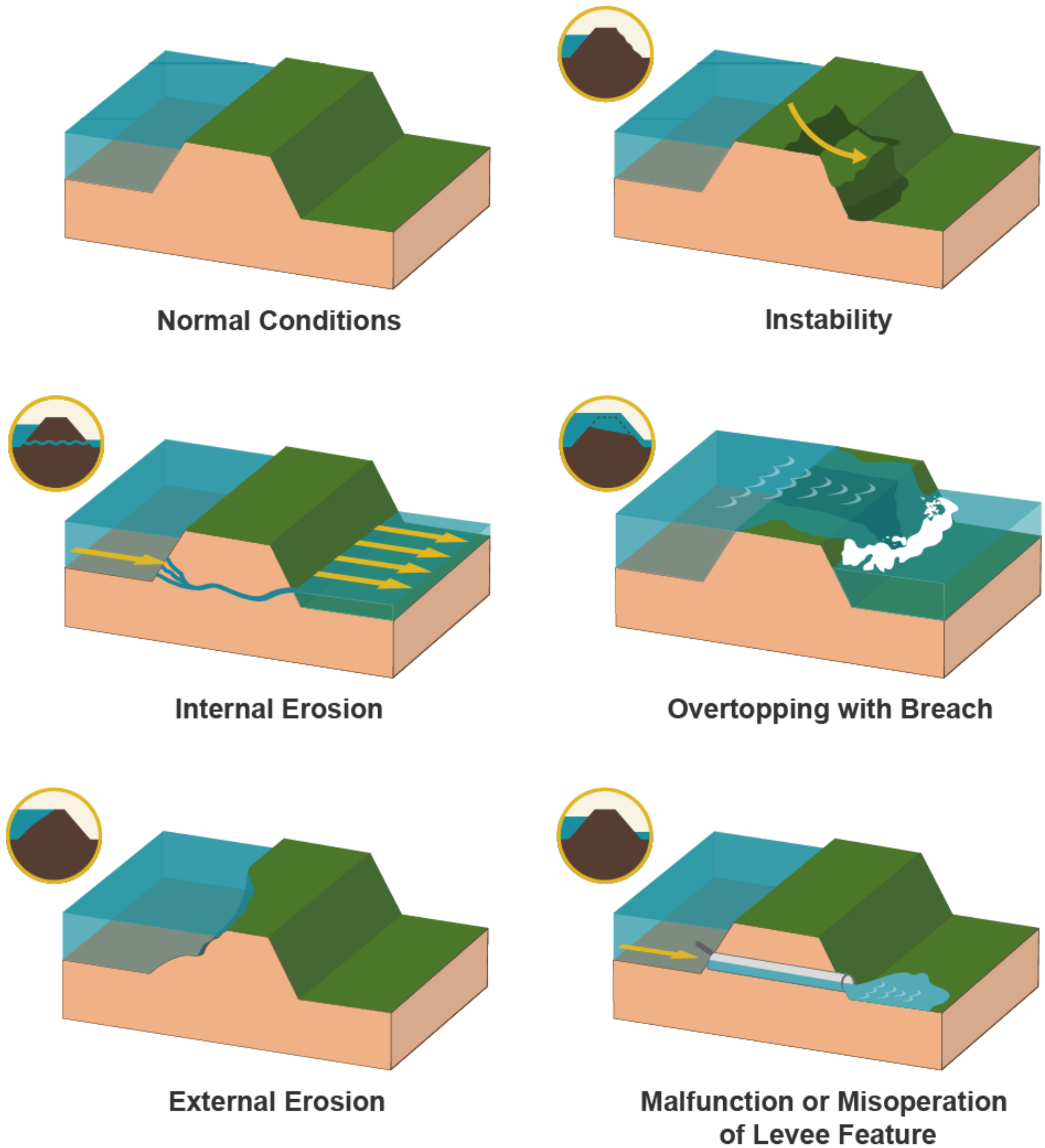
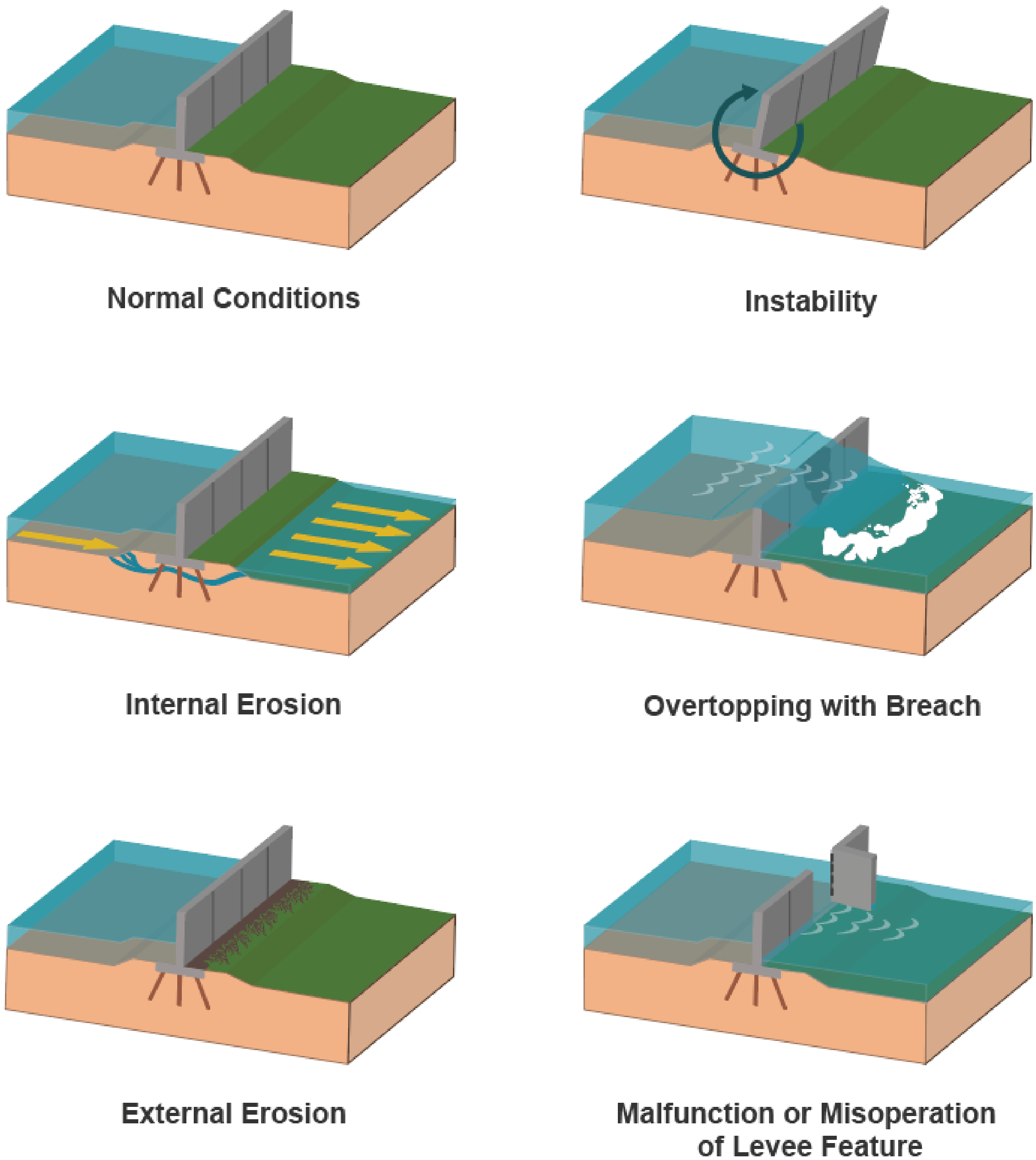


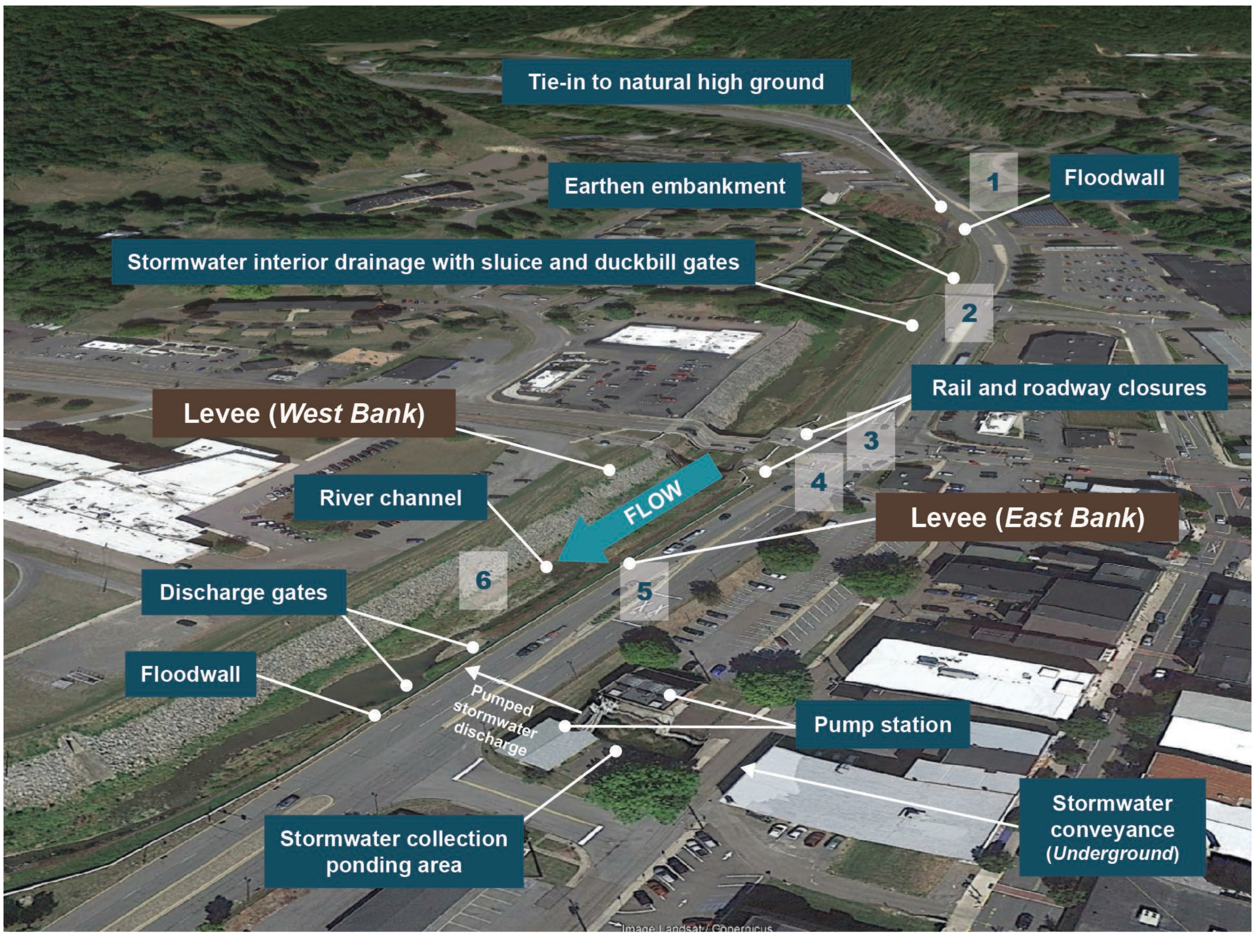
Figure 2-54: Typical Floodwall Potential Failure Modes



6 Example of a Levee

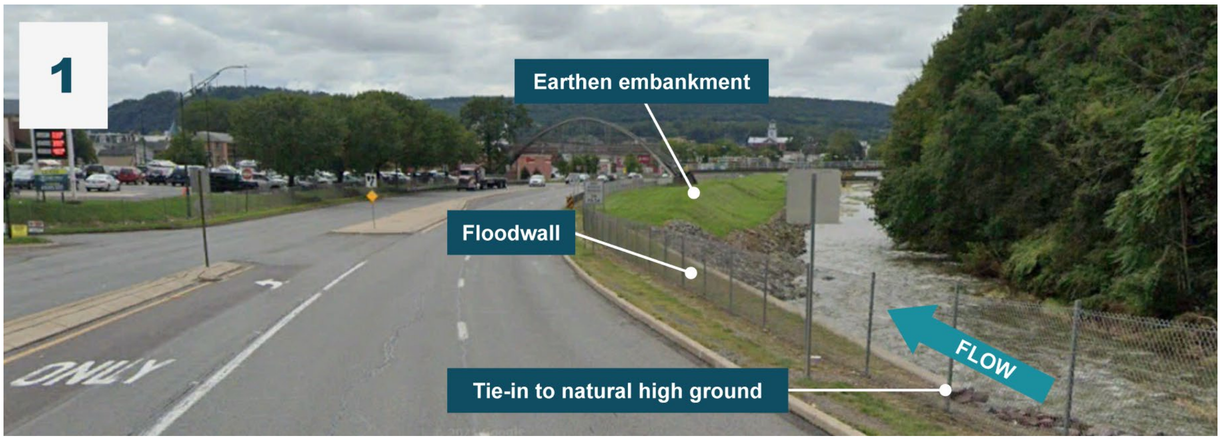
To illustrate how levee form and function coincide to achieve the intended flood risk reduction objective of a levee, the following material describes a real levee example with a discussion pertaining to individual features. Figure 2-55 displays a portion of a riverine levee in a semi-urban area in central Pennsylvania. The levee extends from the north to the south along either side of the Mahoning Creek, which is a natural drainage feature in a watershed north of the Susquehanna River (West Branch). For the purposes of this example, the focus will be the levee on the east bank.

Figure 2-55: Example of Features Along a Riverine Levee



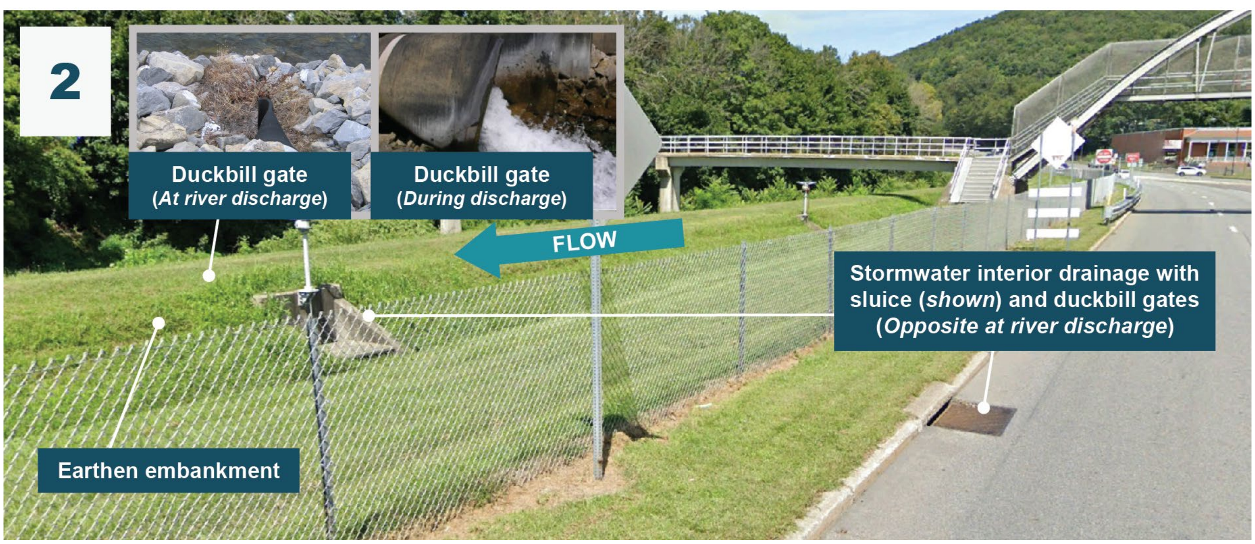
Area 1: The east bank levee begins at the northern terminus with a short length of low-profile floodwall that ties into natural high ground (Figure 2-56). A floodwall was used in this area due to the limited right of way available between the creek bank and adjacent roadway (State Route PA-54). The tie-in of the floodwall with natural high ground represents a transition between two different features. Erosion protection in the form of large diameter stone (riprap) was placed around the wall at the high ground contact.

Figure 2-56: Example of Floodwall and Tie-in to High Ground



Area 2: On the landside portion of the levee, there are a variety of interior drainage features to manage stormwater within the leveed area (Figure 2-57). Catch basins along the curb line of the roadway and inlets within swales on the landside of the levee capture surface runoff into stormwater collection pipes. During non-flood periods, control structures (gates) are open and allow the stormwater to drain into the creek by gravity.

Figure 2-57: Example of Interior Drainage Features



During floods, these controls are closed to keep floodwater from backing into the stormwater collection system and entering the leveed area. The gravity discharge is bypassed with the control structures, and stormwater that collects within the leveed area is conveyed to areas where it can be temporarily ponded with provisions to pump out of the leveed area and into the waterside (in this case the creek).

Areas 3 and 4: The earthen embankment continues south to the intersection with a transportation corridor consisting of a major roadway (US Route 11) and railway (SEDA-COG Joint Rail Authority). The earthen embankment transitions into a floodwall (Figure 2-58) and two stoplog closure structures extending across the roadway and railway (Figure 2-59). During the 2011 flooding, sandbags were used to transition from the earthen embankment to the closure structures. Stormwater is ponded on the landside of the closures, and a mobile pumping station is used to divert the stormwater from within the leveed area back into the creek.

Figure 2-58: Example of Embankment Tie-in to Floodwall

Figure 2-59: Example of Railway and Roadway Closures

Areas 5 and 6: The railway closure transitions into a floodwall to the south, dictated by the limited footprint between the adjacent roadway (PA-54) that runs parallel to the creek and levee (Figure 2-60). Further south along PA-54 lies the main interior drainage ponding area to which a large portion of the stormwater within the leveed area is conveyed (Figure 2-61).

Gates control the discharge of the interior drainage from culverts extending under the roadway, which can be released under gravity drainage into the creek during non-flood periods or discharged using the pumping station during flooding events.

Note that the levee continues beyond what has been shown in this example.

Figure 2-60: Example of Floodwall

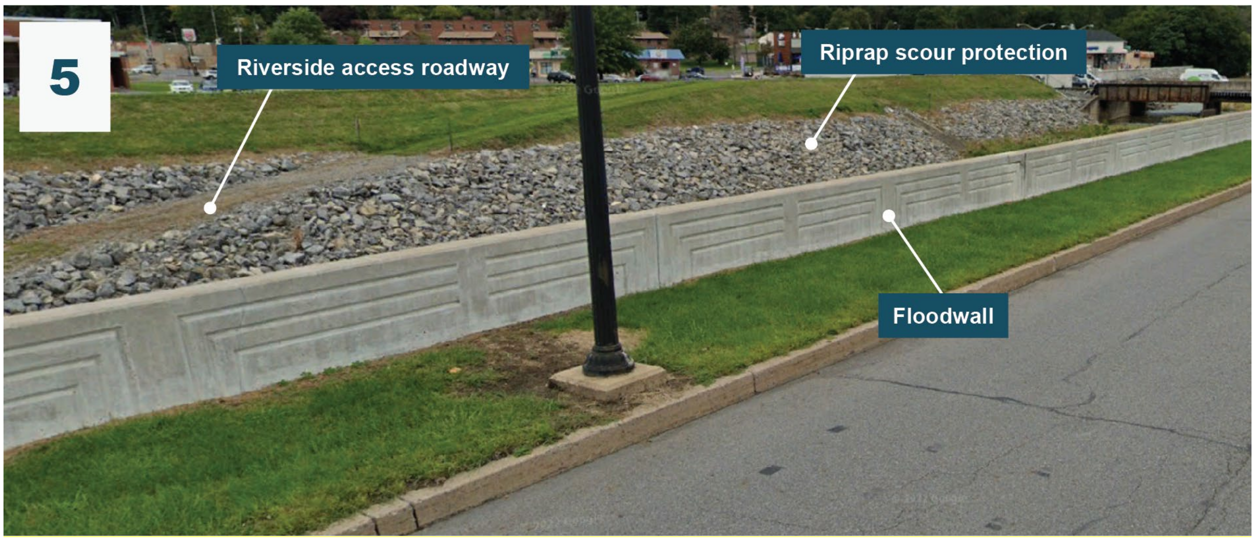


Figure 2-61: Example of Interior Drainage System

7 Summary

Understanding the basic concepts and terminology associated with a levee provides the reader with the necessary foundation for information presented in the remaining chapters. A levee—defined as a human-made barrier with the primary purpose of reducing the frequency of flooding to a portion of the floodplain—generally goes through various stages throughout its lifecycle, including project formulation, design, construction, operation and maintenance, modifications, and levee removal, if needed. Levee-related activities necessitating any aspect of planning, design, or construction are demonstrated through five different types of levee projects.

Following the concepts presented in **Chapter 1**, levees are just one element of a community's flood risk management strategy, which may include nonstructural and structural measures. As a structural measure, levees can have one to three primary functions—exclude water, divert water, or control the release of water. Therefore, the overall levee configuration is primarily based on the level of flood risk reduction that the levee is intended to provide and its environmental setting.

This chapter also discusses and provides examples of how a levee may be composed of multiple features acting as a physical barrier to accomplish the intended function. Features can be thought of as the major elements or building blocks that comprise the levee. The main features of a levee include embankments, floodwalls, closure structures, transitions, seepage control systems, channels and floodways, interior drainage systems, pump stations, and instrumentation.

Just as understanding the levee structure is important for managing flood risk, so is the comprehension that levee breach, or levee failure, can occur. Familiarity with levee breach scenarios—breach prior to overtopping, malfunction or improper operation, and overtopping with breach—can improve levee performance and help reduce consequences. The application of the concepts provided in this chapter are further explained through the evaluation of a typical levee highlighting numerous levee features.

Related content associated with this chapter is included in detail in other chapters of the National Levee Safety Guidelines, as described in Table 2-3.

Table 2-3: Related Content

Chapter	Chapter Title	Related Content
1	**Managing Flood Risk**	• Strategy to manage flood risk
2	**Understanding Levee Fundamentals**	
3	**Engaging Communities**	• Engaging to build knowledge and awareness of levees
4	**Estimating Levee Risk**	• Potential failure modes
5	**Managing Levee Risk**	• Levees transform the floodplain
6	**Formulating a Levee Project**	• Types of levee projects
7	**Designing a Levee**	• Design of levee features
8	**Constructing a Levee**	• Construction of levee features
9	**Operating & Maintaining a Levee**	• Perform regular inspections
10	**Managing Levee Emergencies**	• Emergency preparedness and response • Practicing emergency action plans
11	**Reconnecting the Floodplain**	• Promote floodplain restoration
12	**Enhancing Community Resilience**	• Community resilience to reduce risks

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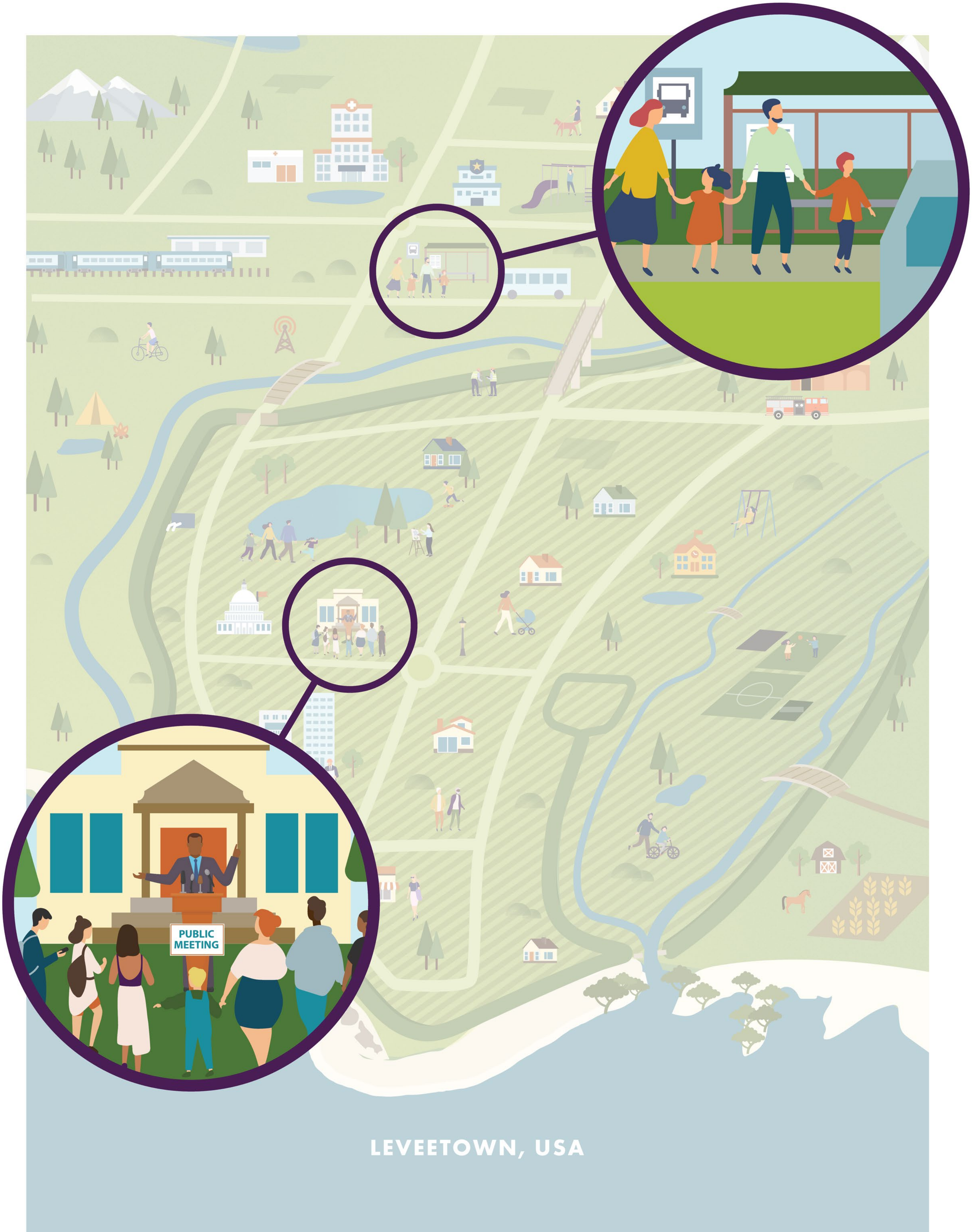
3

Engaging Communities

Key Messages

This chapter will enable the reader to:

- **Build trust.** Successful engagement is built on a foundation of relationships and trust.
- **Raise awareness.** Raising knowledge and awareness of flood risk and how levees play a role can be the first step towards creating a more flood resilient community.
- **Continue dialogue.** Community engagement is not a one-time event—it is an ongoing process.
- **Embrace differences.** Every community is different and the way you engage with them will vary based on their unique circumstances.


PUBLIC MEETING
LEVEETOWN, USA

Other chapters within the National Levee Safety Guidelines contain more detailed information on certain topics that have an impact on engaging communities, as shown in Figure 3-1. Elements of those chapters were considered and referenced in the development of this chapter and should be referred to for additional content.

Figure 3-1: Related Chapter Content

CH 1	CH 2	CH 3	CH 4
Flood risk management strategies Climate change impacts	Understanding how a levee functions	**Engaging Communities**	Estimating consequences Social vulnerability
CH 5	**CH 6**	**CH 7**	**CH 8**
Understanding risk	Understanding levee projects at various phases of lifecycle		Engagement during levee construction
CH 9	**CH 10**	**CH 11**	**CH 12**
Levee-related activities	Emergency preparedness Evacuation planning	Engagement for floodplain restoration activities	Community involvement in flood resilience planning

Contents

1 Introduction 3-1

1.1 Communication and Engagement Basics 3-2

2 Engaging Throughout the Life of a Levee 3-3

2.1 Engaging to Build Knowledge and Awareness 3-3

2.2 Engaging About Routine Levee Activities 3-6

2.3 Engaging for Levee Emergencies 3-9

2.3.1 Engaging Before a Flood 3-10

2.3.2 Engaging During a Flood 3-12

2.3.3 Engaging After a Flood 3-14

2.4 Engaging for Future Levee Projects 3-15

3 Best Practices for Engaging with Communities 3-18

3.1 Community Assessments 3-18

3.2 Communication and Engagement Goals 3-20

3.3 Level of Engagement 3-22

3.4 Partnering with Trusted Messengers 3-24

3.5 Key Messages 3-27

3.6 Communication and Engagement Techniques 3-28

3.6.1 Reaching Underserved and Vulnerable Populations 3-28

3.7 Evaluating Engagement Results 3-29

4 Putting it All Together–Engagement Plan 3-30

5 Summary 3-31

List of Figures

Figure 3-1: Related Chapter Content 3-i

Figure 3-2: Opportunities for Engaging People Throughout the Life of a Levee 3-1

Figure 3-3: Communication versus Engagement 3-3

Figure 3-4: Building Knowledge and Awareness 3-4

Figure 3-5: Engaging about Routine Levee Activities 3-6

Figure 3-6: Engaging for Levee Emergencies 3-10

Figure 3-7: Engaging for Future Levee Projects 3-16

Figure 3-8: SMART Method of Goal Setting 3-21

Figure 3-9: International Association of Public Particiation Spectrum of Public Participation 3-22

Figure 3-10: Example of Engagement Level Based on Levee Footprint 3-23

Figure 3-11: Best Practices for Engaging Communities 3-31

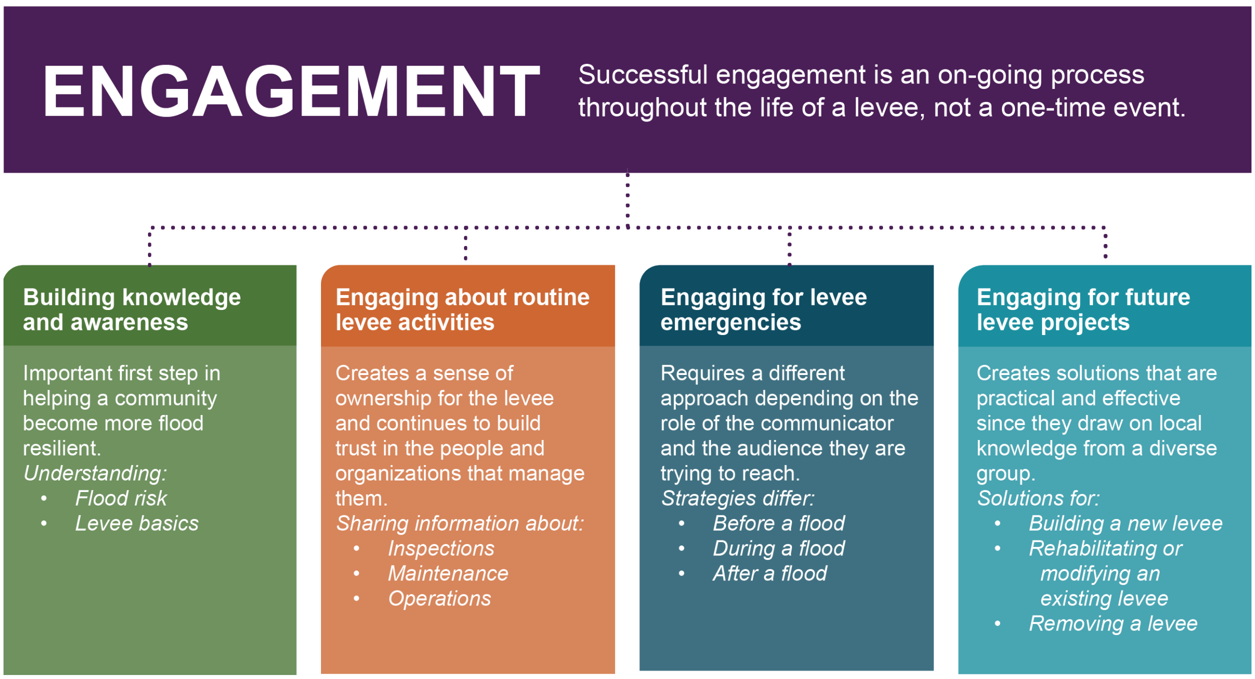
List of Tables

Table 3-1: Ongoing (Routine) Levee Activities and Potential Engagement Topics 3-7
Table 3-2: Communication Tools for Use During an Emergency 3-13
Table 3-3: Federal Recovery Tools for Disaster Assistance 3-15
Table 3-4: Sources of Trusted Messengers 3-25
Table 3-5: Example Communication and Engagement Techniques 3-28
Table 3-6: Related Content 3-32

1 Introduction

Levee systems play a critical role for managing flood risk for many communities. Raising awareness about levees and flood risk and providing engagement opportunities for everyone in the community are important steps in helping a community become more resilient to flooding. Resilient communities are likely to have fewer disruptions to community functions and recovery can be expected to occur more quickly. Raising awareness can be accomplished by communicating with and engaging people throughout the various phases of the life of a levee (Figure 3-2).

Figure 3-2: Opportunities for Engaging People Throughout the Life of a Levee



This chapter is intended to support a wide range of individuals who may have a role in communicating and engaging with communities about flood and/or levee-related risk during any phase or activity shown in Figure 3-2. These individuals may include:

- Local leaders and officials
- Floodplain managers
- Emergency managers
- Regulators
- Levee owners/operators
- Federal, state, tribal, territorial, regional, and local governments
- Technical professionals (e.g., scientists, engineers, private consultants)

- Non-governmental organizations
- Non-profit organizations

Moving forward in this and other chapters, the term **community** refers to a network of individuals and families, businesses, governmental and non-governmental organizations, and other civic organizations that reside or operate within a shared geographical boundary and may be represented by a common political leadership. Communities also include stakeholders who are individuals, groups, organizations, or businesses that have an interest in, can affect, or be impacted by the proposed project and other decisions.

Within a community, **underserved populations** may also exist that have limited or no access to resources or have historically been marginalized and excluded from decision-making processes. These groups could include people who are:

- Socioeconomically disadvantaged.
- Have limited English proficiency.
- Geographically isolated or educationally disenfranchised.
- Those of color as well as those of ethnic and national origin minorities.
- Women and children.
- Individuals with disabilities and others with access and functional needs.
- Seniors.

It is vitally important for community leaders to ensure that tools and resources exist for everyone, including those who may be underserved, to participate in the communication and engagement process in order to build a more flood resilient community overall.

1.1 Communication and Engagement Basics

Communication is the practice of developing and sharing information with others and is most typically thought of as one-way—giving a presentation at a public meeting, issuing a press release, posting information on a website, or providing evacuation information during a flood emergency. It is an effective technique for reaching many people at once and in some instances, such as an emergency, is exactly what is needed to keep a community informed. It is important to keep in mind however, that certain communication barriers can potentially lead to disengagement. Communication barriers can be physical (e.g., relaying too much information at once, unclear messages), emotional (e.g., fear, mistrust), or linguistic (e.g., not relaying messages in different languages).

When communication leads to a conversation with others, engagement begins to happen. Successful **engagement** is built on active dialogue that allows for meaningful interactions where all those involved feel heard and know their opinions matter. Over time, this can lead to relationships and build trust (Figure 3-3).

Figure 3-3: Communication versus Engagement

COMMUNICATION	ENGAGEMENT
Intent is "Hear Me"	**Intent is "Listen"**
One message to many people	Targeted messages based on audience
Can begin to lack meaning over time	Can become more meaningful over time
Can lead to overall **disengagement**	Can lead to relationships **built on trust**

Throughout this chapter, references are made to flood and levee risk communication; however, the best practices presented are intended to go a step further than simply communicating with communities. They are intended to promote engaging (i.e., building relationships and trust) with others.

Successful engagement is an ongoing process not a one-time event (Figure 3-2). The more individuals know and trust the source of their flood and levee information, the more effective interactions can be between everyone involved.

2 Engaging Throughout the Life of a Levee

2.1 Engaging to Build Knowledge and Awareness

Building knowledge and awareness of flood risk can be the first step towards creating a more resilient community. There can sometimes be a disconnect between community members and leaders over why flooding occurs, and what is being done to address it. Engaging in a dialogue about peoples' experiences during and after a flood event (experiential knowledge) and identifying what is currently known about the community's flood risk (local knowledge), including what has worked in the past and what has not, can be beneficial to developing a foundational understanding of flood risk (Figure 3-4).

Figure 3-4: Building Knowledge and Awareness

It is also important, particularly if engaging with tribal nations to address flooding on tribal lands, to consider traditional ecological knowledge—which is the body of observations, oral and written knowledge, innovations, practices, and beliefs that promote sustainability and responsible stewardship of cultural and natural resources through relationships between humans and their landscapes (Daniel *et al.*, 2022).

In addition to experiential, local, and traditional ecological knowledge, tools such as flood maps and inundation maps can be used to help build knowledge and awareness of flood risk. These maps show possible (or historical in some cases) flooding and can help answer questions like, what areas will flood, how deep will flood waters get, and when will the flood arrive? They can also be used as planning tools, particularly before a flood to help inform the development of emergency action and evacuation plans (**Chapter 10**).

Federal agencies such as the United States Army Corps of Engineers (USACE), Federal Emergency Management Agency (FEMA), National Oceanic and Atmospheric Administration, and U.S. Geological Survey produce flood and inundation maps to help show a variety of conditions including possible flooding near infrastructure such as dams and levees (**Chapter 4**), community exposure to the 1-percent-annual-chance flood, expected or imminent flooding based on forecasting and precipitation data, and at-risk areas based on real-time stream data and flood forecasts.

COMMUNITY ENGAGEMENT LEADS TO INCREASED FLOOD RISK AWARENESS

Examples of how community engagement can lead to increased flood risk awareness and the development of community-based solutions can be found on the University of Iowa/Iowa Flood Center's Iowa Watershed Approach Initiative website at: https://iowawatershedapproach.org/programs/resilience/.

The "2021 Flood Resilience Action Plan: Guidebook for Planners" was also developed under the Iowa Watershed Approach which focuses on engagement techniques used in rural and underserved communities to increase overall flood risk awareness (De La Torre, Hauss and Fixmer-Oraiz, 2021).

Once there is a foundational awareness of flood risk, it is important to continue the dialogue to help a community understand how a levee fits into the overall flood risk picture (**Chapter 1**). Helping community members become aware of the existence of a levee—along with the benefits and limitations associated with that levee, including how a levee functions or could fail during a flood event (**Chapter 2**)—can provide them with the information needed to help make decisions on reducing their personal risk (e.g., follow evacuation orders during a flood event, purchase flood insurance, floodproof home and valuables).

Engagement efforts can also focus on increasing community knowledge about issues that could impact the safe function of a levee and potentially put them at risk. For example, community members can be encouraged to communicate levee issues to local officials, such as signs of burrowing rodents, which are a known source of damage that can cause seepage issues, encroachments (e.g., sheds built into or on top of levees), or unauthorized use of a levee (e.g., off-road dirt bikes and all-terrain vehicles). Shared responsibility for levee systems proves valuable in keeping levees in good condition. Shared responsibility includes all levels of government (federal, state, tribal, and local) working together to assist communities in reducing flood damages and promoting sound flood risk management using policies, programs, and inclusive engagement. In addition, individuals have a responsibility to know their flood risk and, if possible, take action to reduce that risk.

CASE STUDY: INCREASING PUBLIC AWARENESS OF THE DANGERS OF ALL-TERRAIN VEHICLES ON LEVEES

The Fort Bend Levee Improvement District 15, located in Sugar Land, TX, uses the power of social media and its website to routinely educate residents about the importance of staying off the levee and reporting unauthorized use (e.g., all-terrain vehicles and other motor vehicles) to local authorities. In addition to being against the law at the local level, the levee district explains how all-terrain vehicles strip away grass which can lead to erosion, cause ruts that can collect water and lead to flooding, and affect federal levee inspections. The district stresses the importance of these levee inspections because the information is used in risk assessments, which support the prioritization of levee-related activities.

Through this campaign, the levee district is raising resident awareness about the levee and, in turn, is encouraging residents to share in the responsibility of keeping the levee safe by reporting unauthorized activities.

More information can be found at: www.fblid15.com/latest-news/all-terrain-vehicles-cause-unwanted-levee-damage/.

Ultimately, building knowledge and awareness is the foundation for all other communication and engagement that occurs throughout the life of a levee. It allows for:

- A shared understanding of challenges/vulnerabilities that exist in the community.
- Improved knowledge of flood risk and the role that levees play.
- Relationships and trust to be built with the community.
- Setting the context for more complex topics (e.g., understanding overall flood risk may lead to greater understanding of future flood risk reduction projects).

It is important to keep in mind that dams can also be present in the watershed, often working together with levees as a system to provide flood risk reduction benefits. When engaging with communities about their flood risk and levees, raising awareness of the benefits and risks of dams, if applicable, should also be included in the conversation.

2.2 Engaging About Routine Levee Activities

As explained in **Chapter 9**, the day-to-day management of a levee includes providing for, overseeing, and following up on activities, such as inspections and maintenance. Every engagement with community members offers an opportunity to share information about these ongoing activities and the current state of the levee, including routinely operating certain levee features, such as pumps and closure structures, to keep them ready for use in the event of a flood.

Figure 3-5: Engaging about Routine Levee Activities

Routine sharing about levee operations creates a sense of ownership for the levee and continues to build trust in the people and organizations that manage them. Knowledgeable community members can help alert those responsible for the levee about any problems they may notice or advocate for necessary funding to help operate and maintain the levee.

During this phase of a levee's life (Figure 3-5), community members may have an interest in the ongoing activities listed in Table 3-1.

Table 3-1: Ongoing (Routine) Levee Activities and Potential Engagement Topics

Activities	Potential Engagement Topics

ROUTINE INSPECTIONS:
Inspectors visually observe the condition and physically operate the levee and associated features, to gather information on the location, type, and severity of deficiencies.
	• The physical presence of inspectors on or near a levee, what they are doing, and why they are there.
	• The preventative and routine nature of the inspection, features inspected, how the information is used, and where it can be found (if information is shared publicly).
	
	Examples:
	• The city of Auburn, Washington, works with local news outlets to keep residents informed of routine inspections that occur on the King County Levee along the Green River.
	    ○ Information includes number of inspectors, what they are wearing (city-issued clothing and identification), and why it is important to conduct routine levee inspections.
	    ○ The city also encourages residents to participate in shared responsibility for the safe operation of the levee by reporting issues (e.g., seepage) or unauthorized activity around the levee.
	• The California Department of Water Resources has an entire section of its public website dedicated to levee inspections to include inspection reports on federal levees in the Central Valley.

MAINTENANCE: Activities include repairing minor deficiencies identified during inspections, clearing encroachments, maintaining the levee system (e.g., mowing embankment slopes, removing weeds and debris), and cleaning and checking operational readiness of levee components (e.g., pumps, drainage systems, stoplogs, gates, and valves).	• The physical presence of workers and equipment on the levee, what they are doing, and why they are there. • Work schedules that could impact community members (e.g., closure of walking/bike trails on a levee). • Potential conflicts or impacts to other uses of the levee or areas adjacent to the levee. ○ In some locations, removal of vegetation or encroachments (including incompatible uses) may be a source of controversy. Additional engagement approaches may be needed to address these concerns. ***Example:*** • See "Case Study: Community Learns about Levee Maintenance with the Help of Goats."
OPERATIONS: Activities include installing closure structures, closing gates on gravity drainage pipes, and operating pump stations during flood events, as well as performing test operations of these features prior to flooding.	• The physical presence of workers and equipment on the levee, what they are doing, and why they are there. • How operable features help reduce flood risk. ***Example:*** • Each year, the National Park Service and USACE perform a test installation of the 17th Street levee in downtown Washington D.C. The annual test installation is necessary to ensure the levee closure can be erected properly in the event of high water and is also a requirement of USACE, which constructed and regulates the levee system and closure. Because the test impacts a highly trafficked area used by motorists, bikers,

	and pedestrians, the two agencies use this as an opportunity to educate the community and visitors about what is involved in the test and the flood risk reduction benefits it provides to the area known as the Federal Triangle.  *Test closure of the 17th Street levee in Washington, D.C., provides an opportunity to engage the public on the importance of the test and the benefits the flood risk reduction structure provides.*

CASE STUDY: COMMUNITY LEARNS ABOUT LEVEE MAINTENANCE WITH THE HELP OF GOATS

Goat grazing is often a cost-effective and environmentally friendly method of keeping vegetation on levees under control. In some areas of the country, bringing in goats for vegetation management on levees can cost a fraction of the amount it costs to bring human crews in several times a year to mow. In addition, goats are more environmentally friendly than using traditional methods to remove vegetation such as herbicides, burning, gas-powered mowers and trimmers, and heavy equipment.

When using goats, it is important that they are carefully managed to ensure no damage to any of the levee features. Electric fencing can be used to keep goats confined to the target area, and professional shepherds can manage the timing, intensity, and duration of grazing to achieve the desired results with minimal impact.

People are often curious about what the goats are doing and many entities with levee responsibilities use this as an opportunity to educate the community about the importance of levee maintenance and the role that goats play.

One example is the city of Pendleton, Oregon's "Goat Watch 2022." This unique social media campaign provided the community with weekly information on where the goats could be seen grazing on the Umatilla River Levee in the summer of 2022 and encouraged people to post their own pictures of the goats hard at work. At the same time, the city discussed how grazing allows levee inspectors to find and address issues in a timely manner, as well as how the annual goat grazing program is funded.

2.3 Engaging for Levee Emergencies

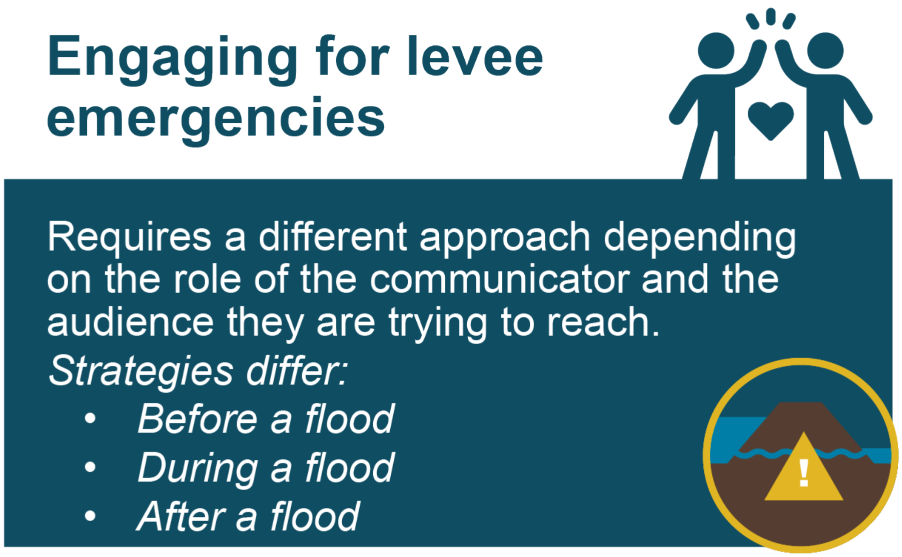
Effective emergency response depends on communication, in this case, the ability to maintain situational awareness through the constant flow of accurate information.

When a community experiences a flood, members of that community are usually the first on scene and typically carry out much of the initial disaster recovery efforts. The social, economic, and environmental fabric of a community can be greatly impacted after a flood and often there is a strong motivation to rebuild and return to normal. A changing climate leads to an increase in extreme weather events (e.g., hurricanes, floods, wildfires) that can result in significant damages to communities and their levees. Consequently, financial assistance to rebuild after a flood may become harder to obtain or may be less than what is needed to adequately cover the community's losses, due to competition for resources across the U.S.

For communities looking to rebuild, it is more important than ever to incorporate resiliency into that plan (**Chapter 12**). This helps to reduce flood impacts and make overall flood recovery efforts less expensive, therefore reducing the amount of additional financial assistance needed.

Engaging communities before, during, and after a flood requires a different approach, depending on the role of the communicator and the audiences they seek to reach, as shown in Figure 3-6. Engagement activities are likely to be more robust during a flood, particularly if the community is also facing a levee emergency. **Chapter 10** provides more detailed information on the engagement roles and responsibilities of various stakeholders, including levee owners/operators, emergency management agencies, and others in the community.

Figure 3-6: Engaging for Levee Emergencies



Chapters 10 and 12 also explain the need for an emergency action plan and how these plans are most effective if developed and implemented in close coordination with all entities, jurisdictions, agencies, and regulators with responsibilities associated with an incident at a levee or that have statutory responsibilities for warning, evacuation, and post-emergency actions. They also discuss information on disseminating levee emergency action plans to appropriate stakeholders, including which stakeholders to engage in routine training and exercises. Frequent engagement with stakeholders—including annual meetings between levee owners/operators and emergency management agencies—can facilitate a better understanding of roles and responsibilities and enhance emergency readiness.

2.3.1 Engaging Before a Flood

Engagement before a flood begins with educating the public about the need for preparedness (**Chapter 12**). Despite the frequency of stories seen on the news that prove the devastation a community may experience from a flood, communicating the importance of preparedness can be difficult. There are many reasons these messages may not resonate. For some, there is an optimistic hope that an unexpected disaster could never destroy one's home or hurt one's family. Other community members may explain that they have been in the area for years and never experienced any flood-related consequences (**Chapter 4**). Others may lack the necessary financial resources to prepare. Even in the context of a changing climate and more extreme flood events, it is often difficult to overcome these views and realities.

Despite this difficulty, as discussed in section 2.1, building knowledge and awareness early on about flood risk—and the role levees play—can help open the lines of communication and build trust between local officials, community members, and other stakeholders such as levee owner/operators and emergency management officials. According to Scott Roberts, past president of the International Association of Emergency Managers, "Trust is built on community and some type of fellowship or engagement, whether that's going for coffee, having a one-on-one meeting, or publicly addressing a community on foot. The desire to genuinely engage in relationship building with community members and other professionals in the emergency management sector reduces the barrier to entry to understanding each other. It levels the playing field to holistic decision making."

SPECIALIZED ENGAGEMENT

Individuals in need of specialized engagement and additional assistance may include those who:

- Have disabilities—temporary and/or lifelong.
- Live in institutionalized settings (e.g., nursing homes, prisons).
- Experience poverty.
- Are elderly or living alone without any assistance.
- Are medically fragile and/or mobility impaired.
- Are unhoused.
- Are from diverse cultures unfamiliar with local practices.
- Have limited proficiency in or are non-English speaking.
- Have sight or hearing losses (impairments).
- Lack access to transportation.
- Have limited access to technology.
- Live in remote areas.

Engagement efforts aim to maximize residents' awareness of the importance of proactive planning and encourage participation in disaster preparedness activities. It is important to remember, however, that not all community members have access to the resources, tools, or information in order to participate.

Several best practices for engaging community members before a flood include:

- Identify partners able to share resources and responsibilities. Contact local organizations such as the Red Cross, homeless shelters, food banks, faith-based organizations or other community leaders and ask them to be part of the education and planning efforts.
- Recruit residents for assistance with educational campaigns. Homeowners and other civic groups are often willing to support engagement activities.
- Educate residents on individual home preparedness. Create and promote educational materials that offer residents tips and best practices for protecting their individual homes. Ensure that these materials are accessible to everyone including those who lack technology, have disabilities, or do not speak English. For example, the Santa Clara Valley Water District, with input from community members and other stakeholders, develops an annual floodplain mailer that is sent to homes and businesses located in the FEMA special flood hazard areas (i.e., high-risk flood zones). The mailer provides information on flood risks, flood insurance, flood safety tips, and resources in four different languages including English, Spanish, Chinese, and Vietnamese.

- Establish and communicate evacuation procedures. Communicate the location of evacuation routes and shelters. Include a map and list of facilities that are accessible to everyone, including those who lack technology, have disabilities, or do not speak English.
- If not already present, implement an emergency notification system and encourage people to sign up. Ensure the system and sign-up process is accessible to everyone, including those who lack technology, have disabilities, or do not speak English.

Additional implementable strategies for engaging with underserved and socially vulnerable populations before a flood are available from the Natural Hazards Center at the University of Colorado Boulder.[1] The strategies are based on decades of research by social scientists and experts in the field of risk communication and work with community leaders to understand the needs of socially vulnerable populations in the face of hazards and disasters.

Ultimately, engaging beforehand allows for building connected networks and testing approaches and tools for all segments of the community—including those who are vulnerable or underserved. A well-informed and prepared community is less likely to be negatively impacted by flooding or a levee emergency.

2.3.2 Engaging During a Flood

During a flood and/or levee emergency, interactions with the community are potentially focused more on communication (one-way information out) rather than engagement (two-way dialogue) due to the necessity for quick action—often known as crisis communication. Emergency (i.e., crisis) communications may include alerts and warnings; evacuation and curfew directives, and information that may impact response and recovery such as status of response efforts and community services (e.g., roads, power, water); and assistance available for critical needs.

The extent to which people respond to emergency communication is influenced by many factors, including individual characteristics and perceptions, whether the message comes from a credible source, how the message is delivered, and the message itself. In addition, the level of community interaction is likely to affect the extent to which emergency messages are received, comprehended, and heeded. Therefore, engaging with community members long before an emergency occurs can help build the networks and trust necessary to encourage action during an emergency.

FACTORS THAT AFFECT EMERGENCY RESPONSE

Keep in mind that several factors can influence the extent to which emergency alerts and warnings are received, understood, and followed. These include community, experiential, and individual factors.

Community – Community type (rural vs. urban), the interconnectedness of community members, and family composition (proximity of extended family, children, and pets).

Experiential – How people interpret messages, their previous experiences, observations (i.e., taking cues from others), and their perception of risk (i.e., if their perception of personal risk is high, people will act quickly. When the perception is low, they will delay acting.)

Individual – Age, language, residency status, access and functional needs, and level of individual preparedness.

(FEMA, 2021)

[1] https://hazards.colorado.edu/news/research-projects/risk-communication-and-social-vulnerability.

During an emergency, there are many communication tools to choose from, each with their own advantages and limitations, depending upon the communication objective and the intended audience. Table 3-2 presents several communication tools that can be used during a flood or levee emergency, including the speed at which information can be released and how widespread the coverage is.

Regardless of which communication tool or combination of tools are chosen, it is vitally important that key messages during an emergency are clear, specific, and consistent. Messages that are well crafted and delivered effectively can help protect public safety and property, facilitate response efforts, prevent confusion and rumors, elicit cooperation from community members, and instill public confidence. For example, a warning message of, “a 10,000 cubic feet per second flow, moving at 20 feet per second,” is unlikely to spur the same kind of action as, “a wave of water 20 feet high moving faster than a person can run” (*PrepTalks: Dr. Dennis Mileti ‘Modernizing Public Warning Messaging’*, 2018).

Specifically, one should:

- Present the information in sequence (i.e., reason for the message, supporting information, and conclusion).
- Word the message precisely, making every word count.
- Avoid jargon, codes, and acronyms.
- Use common terminology for all personnel and facilities.
- Omit unnecessary details.
- Speak in sync with other related authorities.
- Keep messages consistent across various media.
- Ensure messages are released in a timely manner.

Table 3-2: Communication Tools for Use During an Emergency

Communication Tools	Speed	Coverage
Communications technology		
Wireless Emergency Alerts	Very fast	Widespread
Loudspeakers and public address (PA) systems	Fast	Limited
Message boards	Fast	Limited
Social media	Fast	Widespread
Broadcast media		
Radio	Moderately fast	Widespread
Television broadcast	Moderately fast	Widespread
Television message scrolls	Moderately fast	Widespread
Newspaper	Very slow	Widespread
Tone alerts		
Dedicated tone alert radios	Very fast	Limited
Tone alert and National Oceanic and Atmospheric Administration weather radio	Fast	Widespread
Audio sirens and alarms	Fast	Limited
Broadcast sirens	Fast	Limited

Telephone systems		
Wireless communications (SMS)	Very fast	Widespread
Text telephone (Telecommunications Device for the Deaf/Teletypewriters)	Fast	Widespread
Reverse telephone distribution systems	Fast	Limited

It is important to remember the audience when selecting appropriate emergency communication tools, particularly if there are underserved or vulnerable groups of people within the community. For example, people living in rural or remote communities may lack access to reliable mobile or internet technology; people with visual or hearing impairments may lack the ability to see or hear warning signals; people living in extreme poverty may lack access to television, phone, or internet and therefore rely on inter-personal networks for flood warning information.

Determining who these groups are, where they live, and the most effective way to communicate with them during an emergency is information that can be gathered during an initial community assessment (section 3.1), by reaching out to trusted partners and messengers (section 3.4), and by simply asking members of these groups what is most effective.

These and other best practices for communicating with underserved and socially vulnerable populations during a flood are available from the Natural Hazards Center at the University of Colorado Boulder.[2]

2.3.3 Engaging After a Flood

A primary responsibility for those involved with engagement after a flood is to provide messages that support the public in safely managing the outcomes of the emergency. Messages may include information regarding road conditions and status of essential services such as power, potable water, and wastewater treatment, as well as, in the case of flood inundation, safely recovering from and remediating flood damaged buildings, belongings, and other human-made and natural assets.

This phase of engagement also supports individuals seeking financial or other assistance by communicating how to apply for services. It may be necessary to partner with community officials to reach out to community members and work with those who may need additional assistance to ensure they have access to available funds, resources, etc. Keep in mind that all audiences may not feel comfortable or know how to reach out for this aid; reaching out to people where they are remains critical.

Engaging with communities after a flood also helps determine what worked and what did not work in the emergency communication. The lessons learned can inform future response efforts with the goal of reducing life loss and impacts to businesses, property, and essential community infrastructure, such as water and wastewater treatment plans, energy facilities, police/fire stations, and hospitals.

[2] https://hazards.colorado.edu/news/research-projects/risk-communication-and-social-vulnerability.

Table 3-3 lists several FEMA recovery programs worth exploring when developing a post-disaster engagement strategy. In addition to FEMA, several other federal and state agencies offer resources for recovery assistance.[3]

Table 3-3: Federal Recovery Tools for Disaster Assistance

Resource	Audience	Description
Assistance programs	Individuals, governments, non-profits	This resource provides contact information and descriptions for post-disaster assistance for individuals and families, governments and private non-profits, and non-English speaking individuals. • https://www.fema.gov/assistance
Disaster recovery checklist	Individuals	Engaging communities with a FEMA disaster recovery checklist can be helpful in initiating the post-flood communication process. This checklist provides all steps necessary to properly document the disaster, qualify for insurance or loans, receive floodproofing information, request rental assistance, etc. Helping community members complete the necessary checklists and assistance forms can play a key role in building trust. • https://www.fema.gov/fact-sheet/disaster-survivors-checklist
Community emergency response team (CERT)	Volunteers, professional responders	The community emergency response team is a FEMA program that offers volunteer training and a framework for professional responders to follow in disaster situations, including floods. In addition to post-flood assistance, these trained volunteers can play an active role in helping the community with flood preparedness activities. • www.fema.gov/emergency-managers/individuals-communities/preparedness-activities-webinars/community-emergency-response-team

2.4 Engaging for Future Levee Projects

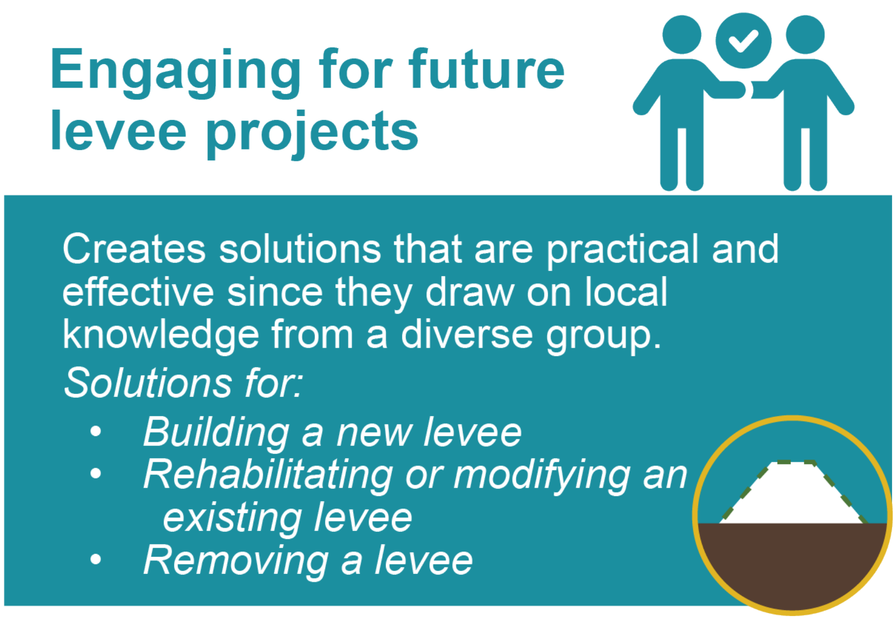
Community members are fully engaged when they play a meaningful role in the discussions, decision making, and/or implementation of projects or programs affecting them (**Chapter 6**). In addition, as shown in Figure 3-7, there are numerous benefits to robust community engagement (Bassler, 2008) when it comes to future levee projects such as:

- Increases the likelihood that projects will be widely accepted. Community members who participate in these processes show significant commitment to help make the projects happen.
- Creates solutions that are practical and effective since they draw on local knowledge from a diverse group.

[3] Additional recovery assistance resources can be found at https://www.disasterassistance.gov/.

- Improves knowledge and skills in problem solving. Participants learn about the issues in-depth, and greater knowledge allows them to see multiple sides of the problem.
- Integrates people from different backgrounds. Groups that typically feel ignored can gain greater control over their lives and their community. When people from different areas of the community work together, they often find that they have much in common.
- Creates local networks of community members. The more people who know what is going on and who are willing to work toward a goal, the more likely a community is to be successful in reaching its goals.
- Creates several opportunities for discussing concerns. Regular, on-going discussions allow people to express concerns before problems become too big or out of control.
- Increases trust in community organizations and governance. Working together improves communication and understanding. Knowing what government, community citizens, leaders, and organizations can and cannot do may reduce future conflict.

Figure 3-7: Engaging for Future Levee Projects



In addition, engaging with the community on a new project can allow for shared understanding of (Bassler, 2008):

- Differing values and priorities.
- Different ways that citizens view the community or a particular project.
- Various alternatives and consequences.
- Different ideas and potential solutions and actions.
- Perceptions of the benefits and risk.

Presenting the potential benefits and risks of a levee project—whether planning for (**Chapter 6**), constructing (**Chapter 8**), rehabilitating/modifying, or removing a levee (**Chapter 11**)—can help people understand the tradeoffs of the decision being made. For example, building a new levee can help reduce flood risk; however, if increased development behind the levee is permitted, then exposure to flood risk is essentially increased over time, rather than decreased (**Chapters 4 and 5**).

CASE STUDY: SUCCESSFUL COMMUNITY ENGAGEMENT LEADS TO NEW LEVEE SETBACK PROJECT

Atchison County, located in the northwest corner of Missouri along the Missouri River, suffered significant damages as a result of the 2019 flood in which the levee was breached in seven locations. This flood event inundated 56,000 acres within the county, flooded 166 homes, and cost $25 million in agricultural revenue, among other impacts.

Because damage to the levee and surrounding agricultural community was so extreme, and the risk of the levee breaching again was likely if built back in the same alignment, the Atchison County Levee District wanted to take a more proactive approach to possible future flooding. Partnering with community members—who were also affected landowners—and numerous state and federal agencies, the levee district and USACE looked at several solutions including repairing the existing levee to its pre-flood condition and setting the levee back, which would allow more room for the river to flow. Ultimately, setting the levee back proved to be more favorable from a cost standpoint but created a significant challenge, as it would place many landowners on the water side of the levee—owners who had been farming the land for decades.

The Atchison County Levee District enlisted the help of The Nature Conservancy to bring together all parties to identify barriers to success and develop potential solutions. This strategy proved to be successful in that establishing and understanding the common goal—to protect the landowners on the water side of the levee by offering fair compensation and support for relocation—allowed the group to identify and develop a unique funding and implementation strategy.

The strategy utilized a permanent easement program from the Natural Resources Conservation Service which allowed landowners to receive fair compensation for their previously flooded land and move to a less vulnerable location. The permanent easement also established conservation land which provides numerous ecological benefits, such as increased floodplain habitat for fish and wildlife, increased groundwater recharge, and water quality improvements.

By engaging with others and creating the space for collaboration, the Atchison County Levee District found a cost-effective strategy for flood mitigation that benefits landowners, the community, and the environment well into the future.

3 Best Practices for Engaging with Communities

The following best practices are applicable to any phase of the life of a levee (as discussed in section 2) and can be scaled up or down depending on community size and available resources such as staffing or funding.

3.1 Community Assessments

A **community assessment** is the process of identifying the strengths, needs, and challenges of a community.

- Strengths are the skills and abilities of individuals, as well as resources provided by the community such as political, religious, educational, recreational, and youth organizations; community, civic, and service groups; local businesses, nonprofit organizations, and volunteer groups. Simply put, strengths are any element that improves the way a community works.
- Needs are gaps in policies, programs, community services, etc., and represent areas that can be improved upon to strengthen the community as a whole.
- Community challenges are problems that arise as a result of its needs.

Conducting a community assessment can help provide a better understanding of who might be impacted by flooding and levee activities and their understanding, interests, and perceptions of flood and levee risk. It can also help identify peoples' ideas or expertise for solutions and resources available to enhance levee-related activities and emergency planning.

An assessment helps determine how wide the audience for engagement should be, and depending on the activity, certain groups of people may need more direct engagement than others. For example, people who are engaging on a future levee project may need more targeted engagement if they are concerned about construction impacts to roadways, the movement of buildings to a new location, or environmental impacts. If the goal is to build knowledge and awareness of flood risk and basic levee information, the target audience may be extremely broad, but the timing, level of detail, and method of engagement might be quite different.

It is also important to note that there may be community members who are vulnerable to flood risk or impacted by a levee activity but do not know they are; therefore, they are not engaging. Lack of engagement does not imply that they do not care or are not interested. It is equally important to consider these groups of people when conducting a community assessment as part of developing the overall engagement strategy.

In order to gather information about the audience to be engaged, the following questions can be asked:

- Who is invested in the topic?
- Who should be involved in the levee-related effort?
- What are the locations and demographics of these groups?

As part of this research, it is also important to learn the potential risks within the community, the magnitude of recent floods, the impact of previous flood events on the community, and how levees played a role in the outcome.

In many cases, previous studies and/or risk assessments exist which may provide insight into past circumstances and reduce the time needed for additional research. It is important to keep in mind, however, that these documents may not have considered social, cultural, economic, or other impacts to people in underserved communities. Emergency managers and federal, tribal, state, regional, and local partners are often reliable sources of information. In addition, trusted leaders in the community, the academic community, and technical professionals (i.e., scientists, engineers, geologists, and floodplain management professionals), may be able to provide guidance on locating specific information.

Internet research can often provide additional useful information such as population demographics, community information sources, popular local activities, and gathering places. Even potential vulnerabilities or factors that may prevent an individual from receiving or acting on information (e.g., lack of mobility, transportation, technology, or non-English speaking) are available through this type of research. The following sources may be useful:

- U.S. Census Bureau: Provides regional information such as racial diversity, income, educational attainment, and employment.
- National Levee Database: Assists in determining what is located behind a levee such as buildings, population, and property values.
- Historical documents: Provides information on important events, previous communications, and previous levels of stakeholder involvement. The online availability of these documents is growing. Again, it is important to remember that past levels of involvement do not always indicate the true number of people who were interested in or impacted by the project. For example, those who are non-English speaking may not have been able to understand information that was disseminated about the project or those living in extreme poverty or lacked transportation may not have been able to attend community meetings about the project.
- Underserved community information is available from the following:
  - Centers for Disease Control’s Social Vulnerability Index website.
  - Environmental Protection Agency’s Environmental Justice Screening and Mapping Tool (U.S. EPA, 2023) website.
  - Council on Environmental Quality’s Climate and Economic Justice website.
  - FEMA’s National Risk Index website.
  - State-specific environmental justice websites (examples include California, New Jersey, and North Carolina).

After gathering basic demographics, leaders or other respected members of the community can provide more information about suggested communication preferences. This is also a time to learn more about who they think might be other interested individuals and groups, determine who the community views as a trusted source of information, and identify those able to make contributions to the flood and levee risk engagement effort. As discussed further in section 3.4, identifying and engaging trusted partners and messengers is an essential component in building effective engagement.

This type of early outreach helps to establish longer-term relationships with key individuals and the community at large. These same people are often able to help develop on-going communication and engagement strategies and identify important next steps to fulfill the engagement goals.

While community assessments are a recommended first step, they only reflect a particular point in time and would benefit from updates as community circumstances or levee activities change.

CASE STUDY: COMMUNITY VULNERABILITY ASSESSMENT PORTFOLIO

The National Centers for Coastal Ocean Science, a research arm of the National Oceanic and Atmospheric Administration focused on coastal ocean science, has undertaken an initiative to develop locally-based solutions to “better protect, advance and manage climate change impacts within local communities, specifically those communities with high hazard probability and high social vulnerability.”

Through the Community Vulnerability Assessment Portfolio, every year the National Centers for Coastal Ocean Science identifies one community or region and works with local partners and stakeholders to assess community climate vulnerability (e.g., social vulnerability, flood hazard). Priority is given to those communities that are often omitted from national screening tools, such as U.S. territories and Alaska. Each project starts with a community assessment to understand the demographics of the community, social and economic factors, level of vulnerabilities and hazards, local knowledge of past flooding, etc. This information is gathered from national datasets and extensive engagement with stakeholders and others in the community.

When incorporated with risk analysis, the information garnered from a community assessment serves as an important foundation for developing solutions that are locally tailored and provide for effective, equitable planning.

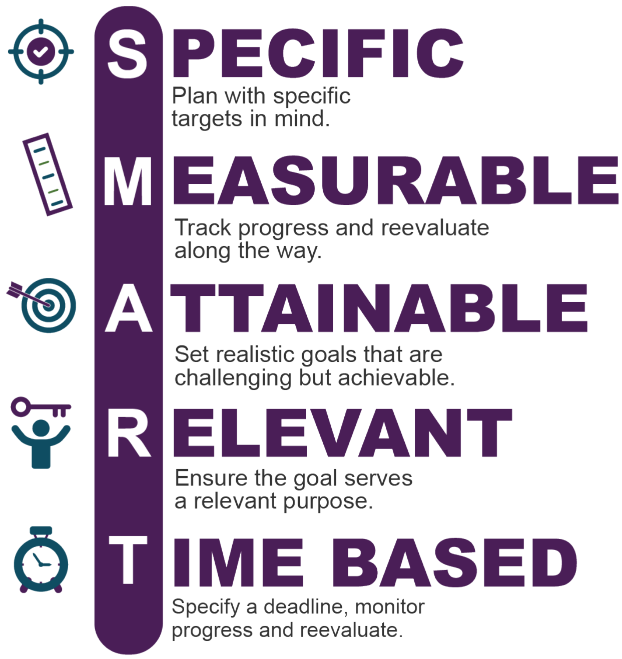
National Centers for Coastal Ocean Science is currently focusing its efforts on the U.S. Virgin Islands, which according to the agency, are home to some of the nation’s most disadvantaged and underserved populations in harm’s way. More information about the Community Vulnerability Assessment Portfolio, including past assessments, can be found at https://coastalscience.noaa.gov/project/programmatic-execution-of-nccos-vulnerability-assessments/.

3.2 Communication and Engagement Goals

A community assessment provides a better understanding of the people to be engaged and informs the development of communication and engagement goals.

To begin developing the goals, it is important to understand the intent of the engagement. Is the intent to inform, influence, inspire, or motivate? Or is it to build relationships, learn, and/or advance or socialize ideas? After determining the intent, the desired outcome should be defined. The outcome describes what community members might do or gain because of the engagement. Communication and engagement goals may differ depending on the levee activity; however, goals should be achievable. If resources are limited, goals may have to be scaled back to ones that are achievable. Using the SMART method (Figure 3-8) can help set goals that are achievable.

Figure 3-8: SMART Method of Goal Setting



Some example engagement goals may include:

- Increase awareness of the community's flood risk.
- Promote awareness of levees, including their benefits and risks.
- Promote an understanding of the levee's purpose.
- Provide tools that allow community members to be stewards and advocates for their own levee system.
- Encourage people to take actions to reduce their risk like creating a readiness kit or purchasing flood insurance.
- Enhance community readiness to respond to emergencies.
- Gather input on a proposed levee project.
- Develop solutions in collaboration with community members.

3.3 Level of Engagement

Community engagement can be complex and labor-intensive and require dedicated resources such as time, funding, and people with the necessary skills. Those who have a role in engaging with the community may not have the resources necessary to carry out a wide-scale engagement effort or hire a private firm to develop and execute an engagement plan; therefore, it is critical to determine the appropriate level of engagement based on the goals that are set.

One useful tool developed by the International Association of Public Participation is the spectrum of public participation (Figure 3-9). This spectrum can assist with the selection of the most appropriate level of participation relative to the engagement goals, including the role communities need to play in the decision-making process.

Moving through the spectrum from left to right—from inform to empower—there is a corresponding increase in expectation for public participation and impact. 'Inform' represents a relatively low level of public participation and 'empower' represents an increase in expectations and an increased level of public impact on the decision. It is not uncommon for agencies to promise the public more potential influence than what is possible. For instance, many agencies are not legally able to promise decision-making authority (i.e., empower). Despite this, it is important to choose the highest level of engagement possible that aligns with the established goals.

Figure 3-9: International Association of Public Particiation Spectrum of Public Participation

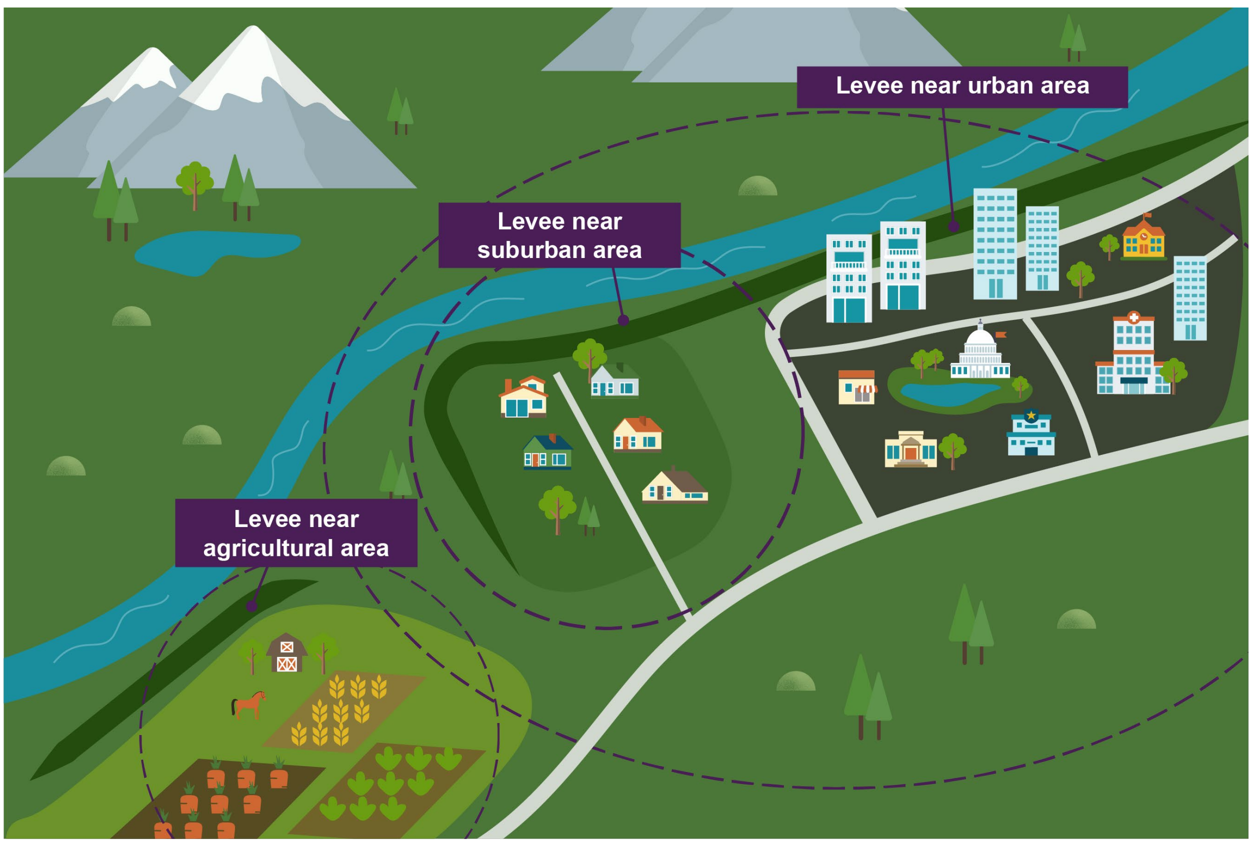
Increasing Impact On The Decision

	Inform	Consult	Involve	Collaborate	Empower
Public participation goal	To provide the public with balanced and objective information to assist them in understanding the problem, alternatives, opportunities, and/or solutions.	To obtain public feedback on analysis, alternatives and/or decisions.	To work directly with the public throughout the process to ensure that public concerns and aspirations are consistently understood and considered.	To partner with the public in each aspect of the decision including the development of alternatives and the identification of the preferred solution.	To place final decision making in the hands of the public.
Promise to the public	We will keep you informed.	We will keep you informed, listen to and acknowledge concerns and aspirations, and provide feedback on how public input influenced the decision.	We will work with you to ensure that your concerns and aspirations are directly reflected in the alternatives developed and provide feedback on how public input influenced the decision.	We will look to you for advice and innovation in formulating solutions and incorporate your advice and recommendations into the decisions to the maximum extent possible.	We will implement what you decide.

In the case of a levee project, the scale of engagement may be limited to just the locations where the activity will occur. Although, if a change to one part of the system impacts some other aspect of the system, there may be a need for greater engagement. The level of engagement may also be greater if trying to raise knowledge and awareness about flood risk and the levee (section 2.1).

As an example of determining an appropriate level of engagement, Figure 3-10 illustrates three areas that are behind levees: an agricultural area, a suburban area, and an urban area. In the case of a large storm event, all the dotted circle areas in the illustration may experience some flood impacts and heightened risks to levees. The breadth of communication in this situation may include all the locations that receive flood risk reduction benefits from the levee; however, the depth of the engagement may be scaled to give more emphasis to the areas of highest concern. This decision may be based on population, location of other critical infrastructure (e.g., fire and police stations, hospitals, water/wastewater treatment facilities), levee condition, and other circumstances specific to the location.

Figure 3-10: Example of Engagement Level Based on Levee Footprint



CASE STUDY: INCREASED LEVEL OF ENGAGEMENT LEADS TO SUCCESS IN FUTURE PROJECTS

Over the past 20 years, Delaware County, New York, has experienced major flooding, including from Tropical Storm Irene. In 2011, the community experienced increased flood damages to homes, farms, and businesses along the Delaware River, due to filling of the floodplain with flood waters. Despite these losses, the community continued to redevelop the floodplain. The Delaware County Soil and Water Conservation District, municipal leaders from surrounding communities, and other stakeholders decided it was time to do something different. With the help of a consultant, the team modeled various flooding scenarios, past and present, to show community members what flooding in the floodplain looked like and how they were being impacted and would continue to be impacted if development in the floodplain continued. Community members were also shown various floodplain restoration solutions and the benefits of each solution to include reduced damages, environmental benefits, and lower flood insurance rates.

Armed with this information, community members were then asked to help choose the most appropriate solutions. As a result of this collaborative level of engagement, two major floodplain restoration projects have been completed and the community is supportive of looking at future projects to include relocating businesses, acquiring land, demolishing buildings, restoring native vegetation and removing invasive species, correcting the elevation and slope of the floodplain, creating a riparian buffer, and restoring wetlands where possible. More information about this project, including lessons learned, can be found at https://coast.noaa.gov/digitalcoast/training/walton-village.html.

(a) The West Brook site before restoration. (b) The West Brook site after fill was removed and graded to the correct elevation and slope to allow water to spread out onto the floodplain.

3.4 Partnering with Trusted Messengers

Past experiences and on-going events can affect how receptive an audience is to an engagement effort. For example, any of the following concerns could contribute to a community's lack of trust when officials reach out to them:

- General distrust of government.
- Uncertainty or confusion regarding one's flood risk, especially as compared to neighbors in nearby communities.
- Language barriers.
- Rumors and urban myths.

- Inability to access information due to lack of technology.
- Varying political and economic perspectives.
- Lack of trust due to historical injustices to members of racial and ethnic minority communities, including Native American communities.

Successful engagement requires trust and shared understanding. One way to begin building this trust is to collaborate with trusted community messengers. Trusted messengers help develop and provide the four key elements needed to build trust—empathy, honesty, commitment, and expertise. The use of trusted messengers can be particularly important in establishing engagement with hard-to-reach communities, under-represented populations, or those who face barriers in receiving traditional communications.

Knowing an audience's needs will help with identifying those trusted partners. For example, after Hurricane Sandy severely impacted New York and New Jersey in 2012, the local veterans' health care center was a reliable source of disaster information for the veteran community. In the 2013 floods in Boulder, Colorado, county officials connected with senior living organizations to foster information transfer and engage the community in addressing long-term risks to their elderly population. In this case, these senior living organizations were essential trusted messengers for reaching a socially vulnerable portion of the population.

To identify a trusted messenger, consider who the audience respects and to whom they will listen. The community assessment is one source of this information. Other methods to help build familiarity with the community include local media and key community service providers, such as places of worship, businesses, nonprofits, social services, advocacy organizations, or mutual aid groups. If these individuals cannot be immediately identified, it may be helpful to check with other local agencies, visit local events, conduct community interviews, or distribute a survey to gather more information.

Local government representatives, such as floodplain managers or zoning officials, may also help to identify trusted messengers. These representatives often have a strong familiarity with and connections to the target population and their trusted leaders and may be a helpful first connection. State, regional, and even federal representatives, including state hazard mitigation officers, university extension offices, Council of Government Resource Conservation District personnel, FEMA personnel, and state and tribal historic preservation officers, may also have familiarity with trusted groups and serve as trusted messengers.

Table 3-4 describes types of trusted messengers that may be potential partners in engaging with the community.

Table 3-4: Sources of Trusted Messengers

Source	Potential Partners
Institutions	• Local public schools, universities, and community colleges • Public hospitals or clinics • Centers for independent living • Any publicly funded or private educational institution • State or federal agencies • Municipal libraries

Source	Potential Partners
	• Police officers and other emergency personnel • Local parks department
Grassroots or citizens' associations	• Local neighborhood organizations • Community centers • Seniors' groups • Veterans' groups • Local officials, politicians, and leaders • Local social media influencers or bloggers • Applications, such as Nextdoor
Community-based organizations	• Non-profit housing organizations • Homeowners' associations • Food kitchens and emergency housing shelters • Halfway houses, substance abuse homes, domestic violence shelters • Churches • Clinics and counseling centers • Advocacy groups for environmental, safety, drug abuse reduction, etc.
Private sector	• Banks • Chambers of commerce • Businessmen/businesswomen associations • Local businesses
Media	• Commercial and nonprofit news and editorial providers • Bloggers and influencers

IDENTIFYING POTENTIAL ENGAGEMENT CHALLENGES

In addition to language, there can be other challenges to engagement that trusted messengers can help identify and develop strategies to address them. The following questions support the identification effort:

- What cultures and languages are prevalent in this community, and how may these cultural and linguistic differences impact message receipt and interpretation?
- Is there a distrust of government or other authoritative bodies? Is there a way to ease distrust?
- Do any community members have disabilities, such as hearing or vision impairment? What resources are in place to communicate information to these groups or individuals?
- Are there pockets of the community or community members living without access to the internet?
- Are any community members living in remote locations?
- Where do most community members receive information about important events?
- Have any community members experienced a flood event previously, and how may this impact their perception of risk or receipt of levee risk communication?
- Who and where are leaders within the community (both formal and informal)?
- Does a portion of the community work night shifts or unconventional hours? If so, what are alternative ways to communicate?

After identifying a potential trusted messenger, determine if that individual (and their associated organization) has an existing relationship with the community, or how to create a new connection to this person/organization. While some messengers are happy to provide feedback and share the messages with the target audience, others may require an investment of time to build a relationship. Building these relationships early will pay dividends later.

By gathering information about the community and establishing a relationship with trusted messengers, special communication needs will become more transparent; needs such as communication requirements for individuals with disabilities or languages other than English.

For example, in Los Angeles, California, there is an identified need to provide county services in 12 different languages and provide limited services for another six languages. Even in less urban settings, significant numbers of individuals may require language support. According to U.S. Census data, close to 8% of Nebraska's residents speak Spanish, Vietnamese, and Amharic, Somali, or other Afro-Asiatic language. Some documents produced by FEMA and other agencies are already available in different languages. If needed outreach materials are not yet available in the desired languages, consider obtaining the support of a translator. Many state and local governments already have access to these types of services.

3.5 Key Messages

Key messages are main points of information in bite-sized pieces that an audience can hear, understand, and remember when they are learning about or engaging in a levee-related effort. Effective key messages can help get people on the same page—messages that begin with what people care about can be a powerful tool for overcoming differences in opinion and finding common ground. This is as true for engagement with residents and community leaders as it is for conversations with elected officials or colleagues in other municipal departments. Using effective messages that resonate will help make flood risk relevant to community members and build a wider consensus for taking actions to reduce risks.

Effective key messages are:

- **Concise**: Bite-sized information that is easy to understand and remember (ideally three to five key messages per topic and one to three sentences for each key message).
- **Strategic**: Define, differentiate, and address benefits. Key messages addressing the benefits and risks of levees can help support understanding for future levee-related projects.
- **Relevant**: Balance of what needs to be communicated with what the community needs to know.
- **Compelling**: Provide meaningful information to stimulate action.
- **Simple**: Easy-to-understand language with no technical jargon and acronyms.
- **Memorable**: Messages are easy to recall and repeat.
- **Tailored**: Not all audiences access or regularly consume information in the same way. Pictures are not helpful to vision-impaired people, and messages in English may not reach all audiences. The meanings of words and concepts may differ across cultural groups. This is where the knowledge gained in the community assessment and the survey of trusted partners may become invaluable.

An example of one of the most recognized key messages related to flooding consists of all the elements of an effective message and contains just four words—Turn Around Don't Drown® (National Weather Service and NOAA, 2003).

3.6 Communication and Engagement Techniques

Table 3-5 presents examples of communication and engagement techniques that can be used depending on the level of engagement chosen (refer to section 3.3).

Table 3-5: Example Communication and Engagement Techniques

Inform	Consult	Involve	Collaborate	Empower
▪ Website ▪ Email ▪ Fact sheets ▪ Videos ▪ Infographics ▪ Social media ▪ Advertisements ▪ Posters ▪ Information hotlines ▪ Presentations/ live streaming ▪ Expert panel ▪ Displays/exhibits ▪ Site visits/tours ▪ Media coverage ▪ Public meeting	▪ Polls ▪ Voting ▪ Surveys ▪ Interviews ▪ Focus groups ▪ Workshops ▪ Online forums ▪ Online commenting ▪ Social media discussion/ town halls ▪ Voicemail commenting ▪ Open houses ▪ Comment boxes	▪ Workshops ▪ Mapping ▪ Digital storytelling ▪ Design charette ▪ Scenario testing ▪ Citizen panels	▪ Large group meetings ▪ Document co-creation ▪ Citizen advisory committees	▪ Decision-making platform ▪ Citizen juries ▪ Community projects

3.6.1 Reaching Underserved and Vulnerable Populations

While **vulnerability** to flooding typically refers to the susceptibility of exposed persons, property, or the environment to harm from an identified hazard, there are factors beyond physical exposure to flooding that may make some populations more vulnerable than others when a flood occurs.

Section 2.3.1 in this chapter and **Chapter 12** explain certain characteristics that may exist for a person or group—in terms of their capacity to anticipate, cope with, resist, and recover from the impact of a natural hazard—and it is the combination of these factors that determines social vulnerability. Historically underserved groups may be vulnerable due to economic situations, racial discrimination, or lack of access to education or other opportunities. A person or group may also be vulnerable due to age or disability. In any case, it is important to be aware of social vulnerabilities that exist within a population of concern and to account for these differences in the engagement process (**Chapter 4**).

Working with trusted messengers may be particularly important in addressing the needs of vulnerable groups, as these populations may rely more heavily on trusted messengers than other portions of the community do. Engaging advocacy groups, organizations that assist underserved populations, and leaders within socially vulnerable groups is fundamental for successful engagement.

In addition to working with trusted messengers, it is essential to consider how each vulnerable individual or a larger population will receive information and be able to adapt or respond when a disaster occurs. For example, if emergency communication involves notification to evacuate regions with potential flooding, consider if individuals within these neighborhoods would have the means to evacuate safely and effectively. If few individuals within certain neighborhoods own cars, consider how bus routes or other public transportation methods may stop during a flood event and how to communicate this ahead of time.

In reaching underserved and socially vulnerable populations, it is vital to use clear and concise language, to repeat information, and to deliver messages through a range of information channels and methods. Use of community networks, technology, and trusted messengers may be particularly important.

3.7 Evaluating Engagement Results

Evaluating the results of engagement is an essential best practice done iteratively throughout the life of the levee. Feedback from evaluations helps improve the effectiveness of future engagement by building on successes and avoiding pitfalls. It helps encourage effective audience participation and helps with adaptation to unique situations or the allocation of resources. New evaluations should occur after major events or times of change to reassess strategies as needed.

No matter how one decides to evaluate and measure the engagement effort, it is important to remember that evaluations should be done regularly during any levee activity. Each engagement effort should be evaluated with the goal of continuous improvement.

Ultimately, evaluation is about understanding if communication efforts led to an intended outcome. Outcomes such as:

- Did the information or message reach the target audience?
- Has there been a change in media coverage, the types of questions asked, or the level of participation?
- Is the needed information reaching all target audiences equally?
- Did the target audience act in response to the communication?
- Were interactions sufficient to allow for two-way discussion and learning?
- Did the process for engagement ensure everyone was heard and understood?
- Were audience needs (food, childcare, schedules) accommodated?
- Did engagement build trust?

The evaluations should directly correlate to the goals of the overall engagement and the goals of each key task and event. Formal evaluations and reports may not be necessary.

Simple methods exist to help evaluate the effectiveness of communication and engagement efforts such as looking for readily available information:

- Find out how many other reputable media sources are sharing the intended information. Evaluate:
  - The extent and tone of press coverage.
  - The accuracy and completeness of key information disseminated.
- Assign designated observers at a meeting to provide feedback.
- Ask community members and stakeholders what they think (verbally through evaluation forms and non-verbally through the use of surveys).

The iterative process of communicating and engaging on flood risk and levee-related activities, evaluating results, and then adjusting allows for an improved engagement strategy over the life of the levee.

4 Putting it All Together–Engagement Plan

One effective tool that can help document engagement efforts is a community engagement plan. The engagement plan is essentially a roadmap for how to work collaboratively with the community over the course of planned levee activities. A community engagement plan does not have to be elaborate; however, at a minimum should contain some of the tools and strategies discussed in this chapter including results of the community assessment, engagement goals, level of engagement, identification of trusted messengers, key messages, engagement techniques, and strategy for evaluating results. More detailed information such as specific tasks, schedule, budget, and responsible staff can also be included as part of an engagement strategy.

Developing a community engagement plan can help ensure that engagement goals are aligned with the community's goals, as well as provide clarity of effort, increase accountability among everyone involved in engagement, and allow for a more well-developed approach before interacting with the community. It can also serve as a valuable resource for new staff who may have a role in the engagement process.

There is no one standard template for a community engagement plan. Each plan will look different depending on the scenario and community; however, it should be developed to meet the needs of the plan's users, as well as the audience being engaged. In addition, a community engagement plan can focus on general hazard mitigation strategies of which a levee may be a small part. There are numerous resources to assist with developing a community engagement plan—one of which is the FEMA Flood Risk Communication Toolkit for Community Officials.[4] This comprehensive resource includes templates and guides for developing a communication plan along with engagement strategies for addressing flood risk.

[4] The toolkit is available at https://www.fema.gov/floodplain-management/manage-risk/communication-toolkit-community-officials.

5 Summary

Raising awareness about levees and flood risk and providing engagement opportunities for everyone in the community are important steps in helping a community become more resilient to flooding. The best practices described in this chapter (Figure 3-11) can help anyone who may have a role in engaging with the community begin to build trust and continue the dialogue throughout the entire life of the levee, from increasing knowledge of levee and flood risk basics to including community members in decisions related to current and future levee projects as well as other flood risk reduction measures.

When implementing any of these best practices, it is important to consider areas of the community where people face barriers or vulnerabilities that can prevent successful engagement from happening. In these instances, a shift in strategy may be necessary to ensure everyone has equal opportunity to participate.

Ultimately, successful engagement is an ongoing process, not a one-time event. The more individuals know and trust the source of their flood and levee information, the more effective interactions can be between everyone involved.

Figure 3-11: Best Practices for Engaging Communities

1. Conduct Community Assessment

- *Helps identify strengths, needs, and challenges of a community.*
- *Provides understanding of who might be impacted by flooding and levee activities.*
- *Conduct internet research (Census Bureau, NLD, Environmental Justice websites) and have conversations with community leaders and members.*

2. Develop Communication and Engagement Goals

Goals should be achievable. Examples:

- *Increase awareness of community's flood risk.*
- *Promote understanding of levee's purpose.*
- *Enhance community readiness to respond to emergencies.*

3. Determine Level of Engagement

- *Engagement is scalable depending on resources and the impacted community.*
- *Levels of engagement range from inform, consult, involve, collaborate, to empower.*

4. Partner with Trusted Messengers

- *Helps build trust, empathy, and commitment with the community.*
- *Serves as an important resource to engage with hard-to-reach and underserved communities.*

5. Identify Potential Engagement Barriers

- *Examples include language, cultural differences, disabilities, lack of access to technology, or remote locations.*
- *Strategies can be developed to overcome these barriers.*

6. Develop Key Messages

- *Provide main points of information in bite-sized pieces that people can hear, understand, and remember.*
- *Ensure messages are concise, strategic, relevant, compelling, simple, memorable, and tailored.*

7. Decide Communication and Engagement Techniques

- *Varies depending on level of engagement and audience.*
- *Examples include fact sheets, social media, workshops, and/or citizen advisory committees.*

8. Evaluate Engagement Results

- *Methods can be simple or formal.*
- *Can help improve the effectiveness of future engagements.*

9. Create an Engagement Plan

- *Serves as a roadmap for how to work collaboratively with the community over the course of planned levee activities.*

Related content associated with this chapter is included in detail in other chapters of the National Levee Safety Guidelines as described in Table 3-6.

Table 3-6: Related Content

Chapter	Chapter Title	Related Content
1	Managing Flood Risk	• Flood risk management strategies • Climate change impacts
2	Understanding Levee Fundamentals	• Understanding how a levee functions
3	Engaging Communities	
4	Estimating Levee Risk	• Estimating consequences • Social vulnerability
5	Managing Levee Risk	• Understanding risk
6	Formulating a Levee Project	• Understanding levee projects at various phases of lifecycle
7	Designing a Levee	
8	Constructing a Levee	• Engagement during levee construction
9	Operating and Maintaining a Levee	• Levee-related activities
10	Managing Levee Emergencies	• Emergency preparedness • Evacuation planning
11	Reconnecting the Floodplain	• Engagement for floodplain restoration activities
12	Enhancing Community Resilience	• Community involvement in flood resilience planning

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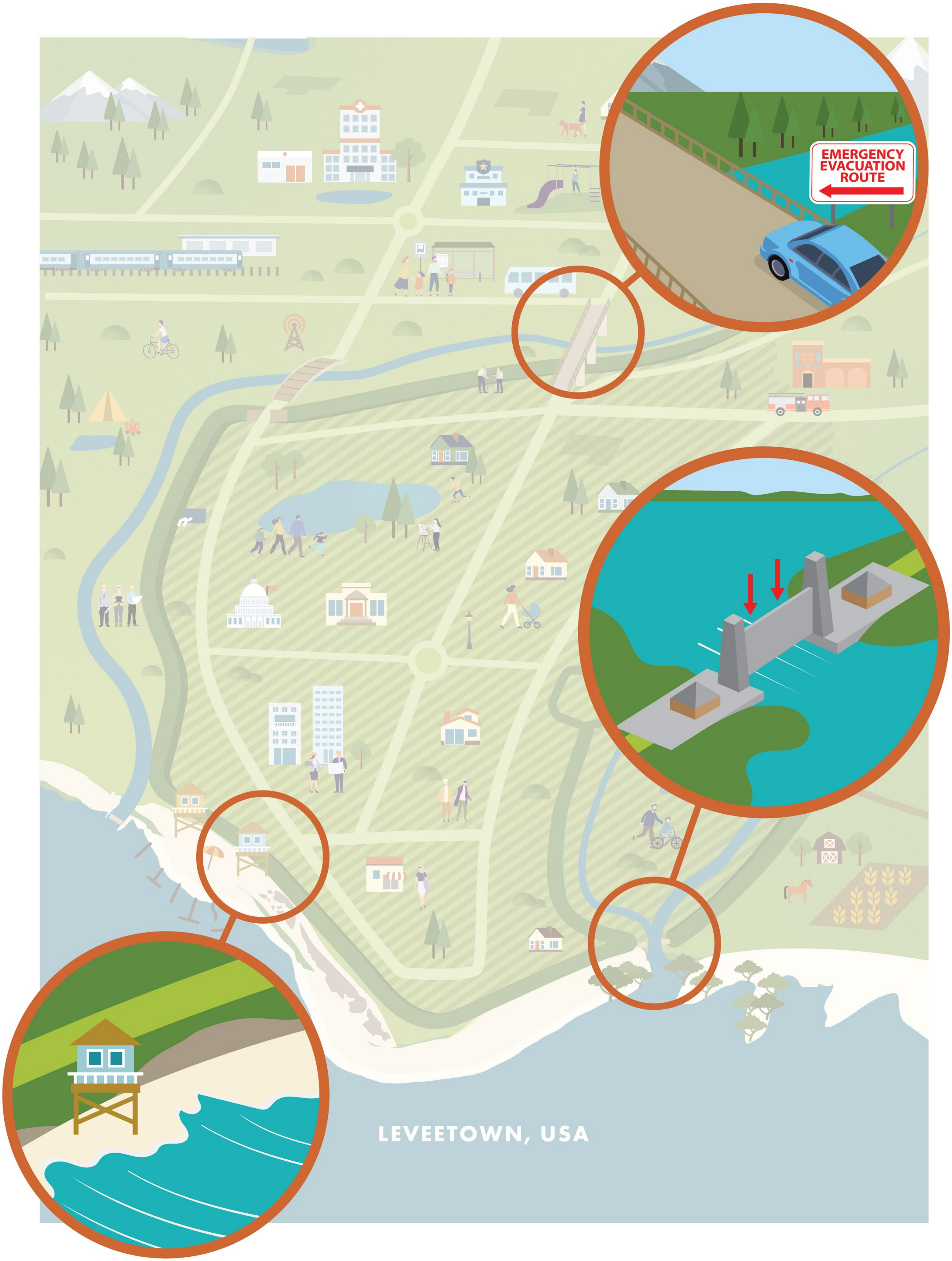
4

Estimating Levee Risk

Key Messages

This chapter will enable the reader to:

- **Understand levee risk.** Levee risk is the likelihood of occurrence and potential consequences of levee breach or malfunction of levee features. Hazard loading covers a full range of possible hazards.
- **Prepare scalable risk estimates.** Risk estimating techniques are scalable and should be commensurate with the purpose of the risk estimate and the decisions that are informed by the risk estimate.
- **Understand risks.** Levees shift risk from one area to another, especially along rivers where they impact the capacity of the river conveyance. They also have a capacity that can be exceeded by larger floods.
- **Evaluate risk.** Life safety is paramount, but economic and other considerations also influence decision making.


EMERGENCY
EVACUATION
ROUTE
LEVEETOWN, USA

Other chapters within the National Levee Safety Guidelines contain more detailed information on certain topics that have an impact on estimating levee risk, as shown in Figure 4-1. Elements of those chapters were considered and referenced in the development of this chapter and should be referred to for additional content.

Figure 4-1: Related Chapter Content

CH 1	CH 2	CH 3	CH 4
Estimating hazards Estimating consequences	Potential failure modes	Communicating risk Social vulnerability	**Estimating Levee Risk**
CH 5	**CH 6**	**CH 7**	**CH 8**
Levee risk classification	Analysis preparation	Scalability of project design Performing site characterization	Understanding construction activities
CH 9	**CH 10**	**CH 11**	**CH 12**
Conducting levee inspections	Emergency preparedness		Understanding potential consequences

Contents

1 Introduction 4-1
2 Risk Concepts 4-1
2.1 Definition of Risk 4-1
2.2 Uncertainty 4-3
3 Risk Assessment Overview 4-4
3.1 Best Practices for Conducting Risk Assessment 4-5
3.2 Risk Assessment Scalability 4-7
3.3 Risk Assessment Process 4-10
3.4 Risk Assessment Team 4-11
3.5 Review and Approvals 4-12
4 Scoping and Data Preparation 4-12
4.1 Scoping Risk Assessment 4-12
4.2 Data Preparation 4-13
4.3 Considering Changing Conditions 4-14
5 Assessing Hazard, Performance, and Consequences 4-15
5.1 Hazards 4-15
5.1.1 Flood Hazards 4-16
5.1.2 Seismic Hazards 4-29
5.1.3 Impact Loads 4-31
5.2 Performance 4-31
5.2.1 Understanding Levee Condition 4-32
5.2.2 Potential Failure Mode Analysis 4-34
5.2.3 Estimating Probability of Levee Breach 4-36
5.2.4 Changing Conditions 4-38
5.3 Consequences 4-39
5.3.1 Levee Breach and Inundation Modeling 4-39
5.3.2 Estimating Life Loss 4-45
5.3.3 Estimating Direct Economic Damages 4-47
5.3.4 Indirect Consequences 4-50
5.3.5 Considering Changing Conditions 4-51
6 Computing a Risk Estimate 4-51
6.1 Levee Risk 4-51
6.1.1 Breach Prior to Overtopping or Component Malfunction/Misoperation 4-52
6.1.2 Overtopping with Breach 4-54
6.2 Non-Breach 4-57

6.3 Flood Risk ... 4-59
6.4 Considerations for Levee Risk Calculation ... 4-59
6.4.1 Length Effects ... 4-59
6.4.2 Combining Risk ... 4-60
7 Risk Characterization ... 4-60
7.1 Risk Narrative ... 4-61
7.2 Risk Portrayal and Communication Aids ... 4-62
7.2.1 Risk Matrices ... 4-62
7.2.2 Flood Risk Maps ... 4-63
8 Summary ... 4-64

List of Figures

Figure 4-1: Related Chapter Content ... 4-i
Figure 4-2: Components of Risk ... 4-2
Figure 4-3: Scalability of Risk Assessments ... 4-10
Figure 4-4: Steps in a Risk Assessment Process ... 4-11
Figure 4-5: Flood Hazard Function at a Specific Location Along the Levee ... 4-18
Figure 4-6: Levee Profile with River Stage Profiles for Various Flood Events ... 4-22
Figure 4-7: Coastal Flood Hazards ... 4-24
Figure 4-8: Coastal Flood Hazard Map ... 4-25
Figure 4-9: Example Seismic Hazard Curve Combined from Various Sources ... 4-30
Figure 4-10: Example Event Tree ... 4-36
Figure 4-11: Sample Levee System Response Curve ... 4-38
Figure 4-12: Example Inundation Map ... 4-42
Figure 4-13: Stability Thresholds Based on Flood Severity ... 4-43
Figure 4-14: Consequence Zones and Flood Severity ... 4-44
Figure 4-15: Example Flood Force Map ... 4-44
Figure 4-16: Hazard Detection and Warning Delay Timeline ... 4-46
Figure 4-17: Use of Stage Damage Curve to Develop a Probability-Damage Relationship ... 4-49
Figure 4-18: Example Probability of Inundation Map ... 4-49
Figure 4-19: Example f-N and F-N Charts ... 4-63
Figure 4-20: Example Flood Risk Map ... 4-64

List of Tables

Table 4-1: Hydrologic Analysis for Levees ... 4-20
Table 4-2: Verbal Mapping Scheme Adopted for Quantitative Nodal Event Tree Risk Estimates ... 4-37
Table 4-3: Sources of Flood Fatality Data ... 4-47
Table 4-4: Related Content ... 4-65

1 Introduction

The purpose of this chapter is to present risk concepts and describe how to estimate, characterize, and portray flood risk reduction benefits provided by the levee, the non-breach risk, and the risk associated with levee breach or misoperation. The chapter discusses various types of risk assessments and provides guidance on scaling the level of effort commensurate with decisions to be made. The intent is to highlight considerations for evaluating each part of risk—hazard, performance, and consequences—while acknowledging that risk assessment is an evolving field and computational approaches may vary depending on the situation. The focus of this chapter is on developing a credible risk estimate and building a well-supported case for levee risk management decisions (**Chapter 5**).

The intended audience are those practitioners performing the risk assessment calculations and decision makers who should be familiar with the benefits and limitations of risk assessment. Stakeholders who review risk estimates, characterization, and/or decisions drawn from them may also benefit.

2 Risk Concepts

2.1 Definition of Risk

There are many definitions of risk. The International Risk Governance Center defines risk as a measure of the uncertain outcome of an event with respect to something of value (Renn, 2005). **Risk** has the following three components: (1) a scenario (e.g., levee breach), (2) a probability estimate for the scenario, and (3) the consequences of the scenario. In these guidelines, risk is defined as the measure of the probability (or likelihood) and consequence of uncertain future events. The evaluation of risk is needed for decision making under uncertain circumstances to help answer the following questions:

- What can go wrong?
- How can it happen?
- What are the consequences?
- How likely is it to happen?

Decision makers face two broad categories of risk—risk of loss and the chance of unrealized benefits. A risk of loss could be due to flood, storm damage, infrastructure failure, disruption of services, bad weather, or economic setbacks. Types of losses include loss of life, adverse impacts to health and safety, property damage, environmental degradation and ecosystem damage, interruption of transportation services, and reputation damages, among others. A risk of loss is sometimes referred to as a pure risk because there can only be a loss. The risk of an unrealized benefit is sometimes called a speculative risk because there can be a loss or a gain. Examples of unrealized benefits include transportation cost savings that do not occur, ecosystem restoration benefits that do not materialize, operation and maintenance efficiencies that are not realized, or an investment that does not produce the expected returns.

Risk is described by the following general expression:

- Risk = Probability x Consequence

This is not a literal formula for calculating risks. Most risk calculations are more complex. It is instead a conceptual expression that helps one think about risk.

If there is no chance of an event occurring (i.e., probability is zero), then there is no risk. Likewise, if there are no consequences resulting from an event occurring, then there is no risk.

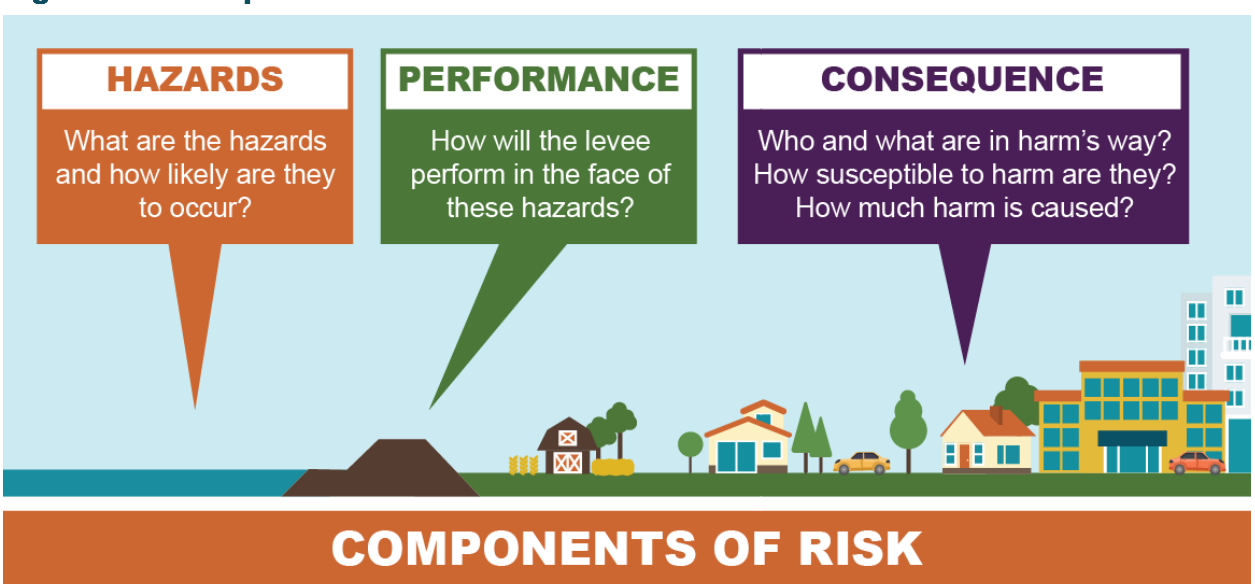
Understanding what is driving the risk estimate is just as important, if not more important than the estimate itself. There could be two situations that seemingly have the same risk, but what is driving the risk for each of the two situations can be very different. A high consequence/low probability event and a low consequence/high probability event may have the same risk estimate in terms of the product of the probability and consequences. However, these seemingly identical risk estimates have very different characteristics and may lead to different decisions. Risk has a social context, and it is multidimensional. It cannot be described completely by a single number.

Risk is dynamic and can increase or decrease due to changes in any and/or all parts of the risk equation. The term risk, when used in the context of levee safety, is calculated in three parts, shown schematically in Figure 4-2:

- Hazard: The likelihood of occurrence of a load (e.g., flood event).
- Performance: The likelihood of an adverse structural response (e.g., levee breach).
- Consequence: The magnitude of the impacts resulting from the adverse event (e.g., life loss, economic damages, environmental damages, loss of critical functions).

Levee Risk = Probability (Hazard x Performance) x Consequences

Figure 4-2: Components of Risk



2.2 Uncertainty

Uncertainty is the result of imperfect or missing knowledge related to risk or components of risk. It reflects a lack of awareness, knowledge, data, or evidence about circumstances related to an event, including its consequence and/or likelihood. To make an informed decision, it is important to separate what is known from what is not known. One of the fundamental principles of risk assessment is to base assessment of risks on the best available science and evidence. A second foundational principle is to focus appropriate attention on the unknowns that could impact decisions.

Uncertainty, as used in these guidelines, comprises limitations in knowledge and natural variability. Limitations in knowledge (also referred to as epistemic uncertainty) is attributed to a lack of knowledge on the part of the observer. It stems from a lack of or inadequate information and arises from incomplete theory, incomplete understanding of a system, modeling limitations, and/or limited data. It is reducible in principle, although it may be difficult or expensive to do so. For example, there is often significant uncertainty about geologic conditions along the levee because levees are long linear features that span variable terrain. The understanding of subsurface conditions could be improved with additional drilling, better modeling of geologic processes, or additional laboratory testing. In theory, investigations with close enough coverage could completely remove this uncertainty, but it is not practical.

Certain parameters that influence risk estimates have natural variability (also referred to as inherent uncertainty or random variation). For example, random variations naturally occur in weather patterns and resulting hydrologic characteristics from year to year. This uncertainty cannot be reduced by obtaining more information; however, more data may improve estimation of the natural variability that exists. Significant natural variability could impact the understanding of risk and make decisions more challenging because the decisions will need to account for a potentially large uncertainty that cannot be reduced.

Uncertainty may influence decisions. Both the magnitude of uncertainty and the sensitivity of a decision to that uncertainty are important. In some cases, decisions can be made with confidence despite large uncertainty. In other circumstances, additional data collection and analyses are required to reduce uncertainty and refine the risk estimate before a decision can be made. Well-supported decisions account for factors driving the risk, the sensitivity of risk estimates to individual input parameters, and the main sources of uncertainty. In assessing the need for additional studies, it helps to identify those uncertainties with the potential to have a significant impact on decision criteria and consider the following questions: Could more information lead to a different outcome in the estimate? Would it change the decision? If the answer to these is "yes," the next question is: What specific data or studies are needed to obtain this information and reduce uncertainty? The goal is to have sufficient evidence and information so that the decision maker can be confident in their decision.

Considerations for incorporating uncertainty in decision making include (Yoe, 2017):

1. Identify the specific things that are uncertain and the sources of that uncertainty.
2. Identify those uncertainties with the potential to have a significant impact on the decision.

3. Apply tools and techniques that may help quantify, better understand the scale of, or address the uncertainty.
4. Develop a risk estimate.
5. Understand the uncertainty of the inputs (scenarios, modeling, knowledge) to the risk estimate.
6. Identify options for reducing sources of uncertainty.
7. Evaluate the risk estimate and significance of uncertainty with decision makers to determine if effort to reduce uncertainty should be taken or a decision can be made.

EXAMPLE OF CONSIDERING UNCERTAINTY IN MAKING DECISIONS

SETTING: Hydrologic setting of this levee is such that the peak flood level and time of arrival can be accurately forecasted several days in advance. At the same time, there is little information about the levee materials and construction history in the area of expected overtopping. Soil erodibility is highly dependent on compaction and material type. Hydraulic sensitivity modeling shows that the rate of breach widening impacts how much time is available for evacuation and potentially the incremental life loss. Once a key evacuation route is flooded, many people are trapped in the leveed area, placing them in life threatening conditions.

CONSIDERATIONS: The high level of uncertainty in breach rate could lead to large uncertainty in the consequence estimates; critical information about the material properties could have significant impact on the estimated life loss. Conversely, the overtopping scenario may be definitively forecasted in advance, allowing ample time for evacuation and higher confidence in the life loss estimate; more material data and breach analysis would have little impact on the life loss.

DECISIONS: In this example, additional data gathering may help refine consequences of levee breach prior to overtopping and improve confidence in the associated decisions. At the same time, decisions related to levee overtopping with breach can be confidently made with the existing information.

3 Risk Assessment Overview

Risk assessment is a systematic, evidenced-based approach for evaluating and characterizing the nature, likelihood, and magnitude of risk. Levee risk assessments focus on identifying the most likely ways a levee might breach and evaluating how likely these scenarios are to occur and their impacts, describing factors driving the risk and developing a risk estimate. Risk characterization is an integral part of risk assessment and provides context for the estimated risks.

Risk estimate is the combination of the probability of inundation of the leveed area and the associated consequences and portraying the results as a combined risk estimate typically portrayed in a risk matrix. Risk estimate requires identifying and estimating the hazards, levee performance, and adverse consequences. Risk estimates should include all relevant aspects of the risk, which may encompass existing, future, historical, reduced, transformed, or transferred risks.

Making informed levee safety decisions requires estimating levee risk, including risk due to breach prior to overtopping, risk associated with levee breach due to overtopping, as well as malfunction or misoperation of levee features. In addition, because levee safety decisions should be made in the context of the flood risk management strategy, it is necessary to estimate non-breach risk and flood risk. Levee risk estimates compared to non-breach risk estimates and flood risk estimates can serve as the basis for most levee risk management actions and decisions (**Chapter 5**).

3.1 Best Practices for Conducting Risk Assessment

Estimating levee risk will involve the consideration of three different scenarios: breach prior to overtopping, breach due to overtopping, and malfunction or misoperation of levee features. In addition, non-breach risk will be considered in order to understand the total flood risk a community may face. This information can help inform levee risk management actions (**Chapter 5**). Each levee is unique, and each community is different in the way they experience and recover from flooding. Risk assessments should recognize these differences, yet produce repeatable and consistent results. No one method or tool for assessing risk may be suitable for all situations, but application of common principles and best practices described below can support efficient and effective risk-informed decision making.

Planning to start:

- **Frame the questions that need to be answered.** A good risk assessment should begin with formulating the questions that need to be answered by the risk assessment to support effective decision making. Clearly state the questions and confirm questions have been answered through the risk assessment process. Examples of questions risk assessments may strive to answer include:
  - Are there opportunities to reduce risk in the leveed area?
  - Is the observed levee distress a major levee safety issue or a minor maintenance concern?
  - Are additional features needed to improve levee reliability?
  - Which part of the community should be evacuated first, in the event of a breach?
  - What priorities should be set in terms of investments and actions to efficiently reduce risks?
- **Make risk assessment a team effort.** Risk assessments work best when conducted with a team. Evidence-based analysis requires subject matter experts qualified to evaluate levee risks. It is unusual for a single person to possess all the knowledge required to complete a risk assessment. Refer to section 3.4 for additional details on the makeup of the team.

The process:

- **Scale the effort to match the magnitude of the problem or decision needed to be made.** The risk assessment effort should be commensurate with the problem or decision. The effort will also be driven by the resources available.

- **Follow a risk assessment process.** The process is often as important as the result. Following a credible, transparent, and repeatable risk assessment process brings many benefits and aids the understanding of the problem and its solutions. Benefits include:
  - Providing a framework for quantifying professional judgment.
  - Delivering technical concepts in a non-technical manner for communicating levee risks to the public. Providing a basis for development of a safety case or safety demonstration for owners and regulators.
  - Systematically identifying and better understanding potential failure modes.
  - Identifying, justifying, and prioritizing investigations and analyses to reduce uncertainties in risk estimates for individual levees and an inventory of levees.
  - Strengthening the formulation, justification, and prioritization of risk reduction measures.
  - Justifying expenditures on levee safety improvements, as well as levee risk management activities.
- **Keep the assessment unbiased and objective.** Effective risk assessments are unbiased and objective. Risk assessments should be transparent, logical, and clear.
- **Keep risk assessment and decision making separate.** Risk assessments provide information and insights; they do not produce decisions. Qualified technical professionals complete risk assessments, while risk managers make decisions.

The analysis:

- **Use science to describe uncertainty.** Effective risk assessments separate what is known from what is not known. It then focuses special attention on what is not known. Recognizing uncertainty helps better understand the confidence in the risk estimate.
- **Tie the analysis to the evidence.** Good science, good data, good models, and the best available evidence are integral to effective risk assessment. Leverage data, facts, and physical evidence to develop a risk estimate.
- **Identify assumptions.** In an effective risk assessment, all assumptions are clearly identified for the benefit of members of the assessment team, risk managers, and others who will read or rely on the results of the risk assessment.
- **Conduct sensitivity analyses.** Evaluating how much the results change when a change to input parameters is made (i.e., sensitivity analysis) should be a part of every risk assessment. Testing the sensitivity of assessment results is important for every assessment, qualitative or quantitative. It helps identify key parameters and factors driving the risk estimate, and inform the need for additional analyses and investigations.
- **Consider multiple dimensions of risk.** Consider risk broadly and focus on the risks of interest. These may include risk reductions, as well as existing, future, historical, transferred, and transformed risks. In addition, risks of interest could also be defined in terms of types of consequences (e.g., life safety, environmental damages, economic impacts, loss of critical functions, and/or reputational harm). Further, some assessments

may only focus on direct losses while others might also consider indirect losses. It is not always necessary to consider each of these kinds of risk, but it is rarely adequate in decision making to consider only one dimension of a risk. See **Chapter 5** for guidance on risk-informed decision making.

The outputs:

- **Clearly describe the limits of knowledge discovered during an assessment.** Risk assessments can have educational value for use in future assessments. They often identify the limits of current knowledge and in doing so guide future investigations and studies. Completed risk assessments may be conducive to learning about similar or related risks.
- **Document the assessment.** Documentation is an important part of the risk assessment process. Effective documentation tells a good story well. It lays out the answers to the risk manager's questions clearly, correctly, and simply. It provides a basis for understanding the context of the outputs and can be used for knowledge transfer and as a foundation for future assessments.

3.2 Risk Assessment Scalability

Risk assessments are **scalable**. The level of effort should be commensurate with the decisions the risk assessment is intended to support. In a general sense, the need or level of effort for a risk assessment is based on the amount of uncertainty and the adverse impacts of a wrong decision. For example, if there is rutting on the crest of the levee that requires minor routine repairs, an in-depth risk assessment is not needed. If there needs to be a decision of how to prioritize a major investment in levee improvements, then a more detailed risk assessment would help inform that decision.

In the context of levees, some situations may exist where there is significant uncertainty about overall levee performance, but certain decisions can be made without extensive additional analyses because consequences of a decisional mistake are relatively minor. Examples of such 'no regrets' decisions include selection of specific equipment to use for control of grass vegetation, or an approach to minor repairs such as filling animal burrows or riprap replacement. This could also include well-established and understood aspects of project design (e.g., reinforced concrete structural analysis), common construction activities (e.g., placement of earth fill for levee rehabilitation), and routine emergency management activities (e.g., testing emergency action plans), discussed further in **Chapters 7, 8, and 10**.

As the consequences of a mistake grow more serious, there is increasing need for more rigorous risk estimation and assessment. Levee risk management inherently necessitates decision making in the face of significant uncertainty; therefore, risk assessment is required to support most levee safety activities and decisions, as discussed in **Chapter 5**.

Risk assessments can be grouped into the following three types, from least to most detailed: qualitative risk assessment, semi-quantitative risk assessment, and quantitative risk assessment.

- **Qualitative risk assessment**: This results in non-numerical expressions for probability of breach and consequence that allows risk ranking or risk discrimination into classes.

They depend on risk descriptions, narratives, and relative values often obtained by ranking or separating risks into descriptive categories like high, medium, low, and no risk. Qualitative risk assessments can be useful for simple, routine decisions; as an initial screening for prioritization; or when time and data are limited. Qualitative risk assessments provide a relative characterization of risk. They can inform whether a levee risk is higher or lower relative to other levee risks. However, a qualitative risk assessment cannot tell whether a levee risk is high or low in an absolute sense.

- **Semi-quantitative risk assessment**: This uses a combination of limited numerical estimates with qualitative descriptions that result in risk estimates based on orders of magnitude. This can be used to inform decisions based on both the relative and absolute value of the risk estimate. The level of effort for a semi-quantitative risk assessment will vary depending on the purpose. For these guidelines, two levels have been defined—basic and detailed—however, the level of effort is a sliding scale and there will be variations between these two semi-quantitative risk assessments.
  - Basic semi-quantitative risk assessment is intended to develop an overall risk characterization of the levee and initiate prioritization of activities to manage and reduce risk. A basic assessment considers a set of most common potential failure modes (section 5.2.2) and historical levee performance data related to those potential failure modes as a starting point for a risk estimate. The estimate is then refined using project-specific information from visual inspections and readily available engineering analyses. A small team of qualified professionals may be sufficient to complete a basic semi-quantitative risk assessment.
  - Detailed semi-quantitative risk assessment is often conducted to evaluate a specific issue of concern or refine a risk estimate from a basic assessment and may be conducted on a few select potential failure modes. It may also be used to support design decisions related to levee modifications. A detailed semi-quantitative risk assessment is supported by a site-specific potential failure modes analysis and may use event trees to describe these potential failure modes. Additional engineering analyses/investigations are typically required to support risk estimates. The effort can vary greatly depending on potential failure modes and levee safety issues, and should be completed in a team setting with a qualified facilitator.
- **Quantitative risk assessment**: This is a risk assessment that results in numerical calculations for probability of breach and consequences over a full range of possible scenarios, combined with full characterization of uncertainty. A quantitative risk assessment may be needed to support costly investment decisions, detailed designs, or when the uncertainty has significant impact on the decision. Generally, they may be needed when the risk needs to be more precisely quantified. A quantitative risk assessment explicitly considers the distribution of probability and uncertainty through the use event trees or fault trees and typically involves detailed modeling and analyses.

LEVEE SCREENING TOOL

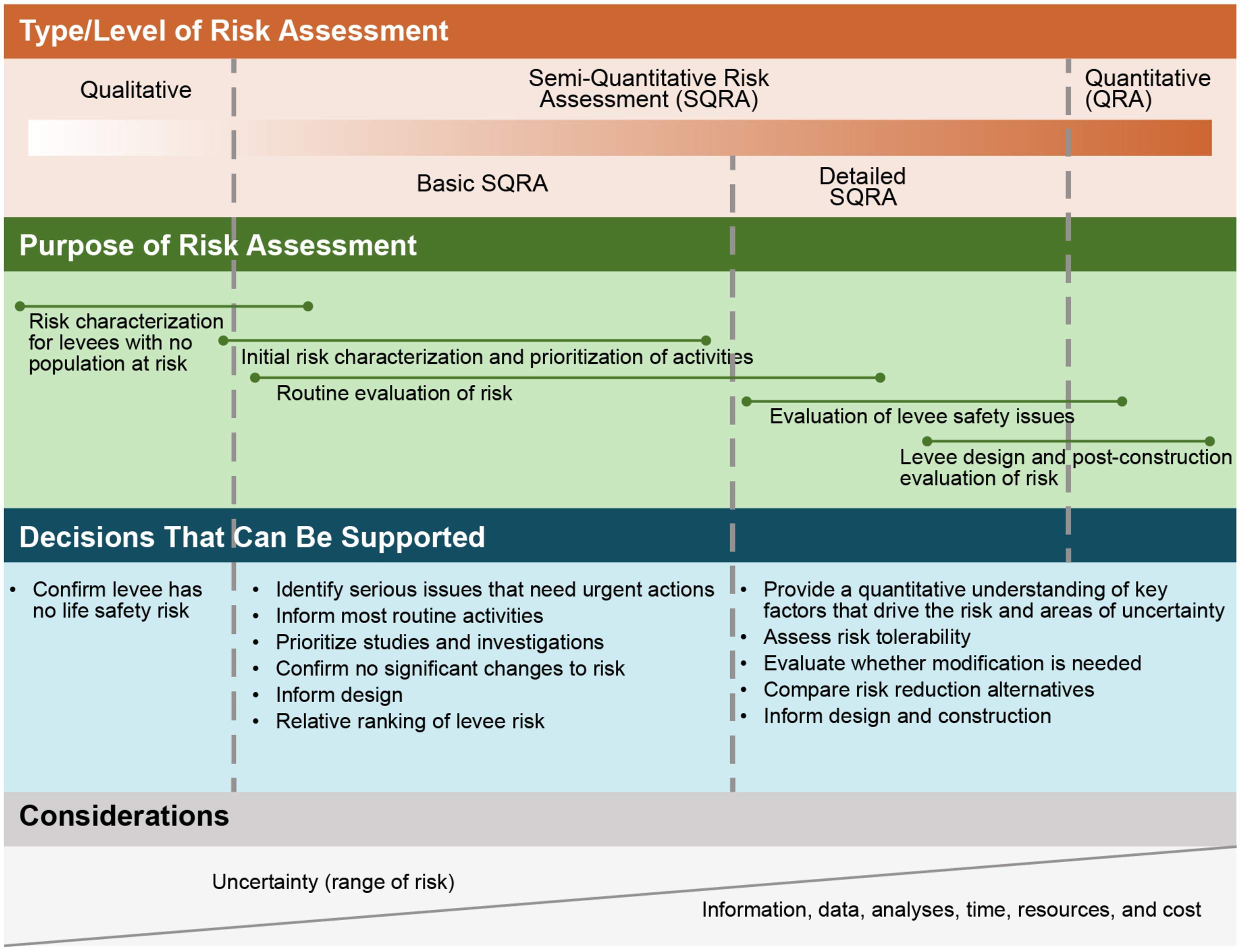
The Levee Screening Tool is a web-based tool developed and maintained by the U.S. Army Corps of Engineers (USACE). Initially developed to facilitate screening of the USACE levee portfolio, the Levee Screening Tool now has additional capabilities to facilitate basic and detailed semi-quantitative and fully quantitative risk assessments.

USACE uses the Levee Screening Tool to obtain an initial understanding of levee risk, prioritize risk management activities, and identify levees which require more detailed assessments. USACE intends to make this tool available to partners with levee management responsibilities to gain understanding of levee risks. The benefit of the tool is that it provides an effective structure to collect, assess, and document data needed to conduct a minimum level semi-quantitative risk assessment. Existing data in the National Levee Database (NLD) and Levee Screening Tool can be leveraged to understand components of risk and inform prioritization of action if levee-specific information is lacking. As with all risk assessments, better quality data will produce more reliable risk estimates.

Figure 4-3 shows the types of risk assessment along with the typical purpose and decisions they support. Each type of risk assessment uses a different set of tools and methods that are proportionate in terms of level of effort required, details considered, and confidence in their outcomes. As the risk assessment becomes more detailed, the uncertainty is reduced, while the level of effort and the associated time and cost tend to increase. Generally, more detailed risk assessments require more comprehensive supporting engineering analyses and investigations.

Within each risk assessment type, individual components of risk can be assessed with varying levels of detail. For example, there may be substantial information available to inform the understanding of consequences, but limited data with regards to performance. There may be engineering analyses to support the evaluation of floodwall instability, but no studies to inform probability of breach due to erosion. Therefore, it is helpful to think of the types of risk assessment being represented along a sliding scale, rather than in distinct bins, as illustrated in Figure 4-3.

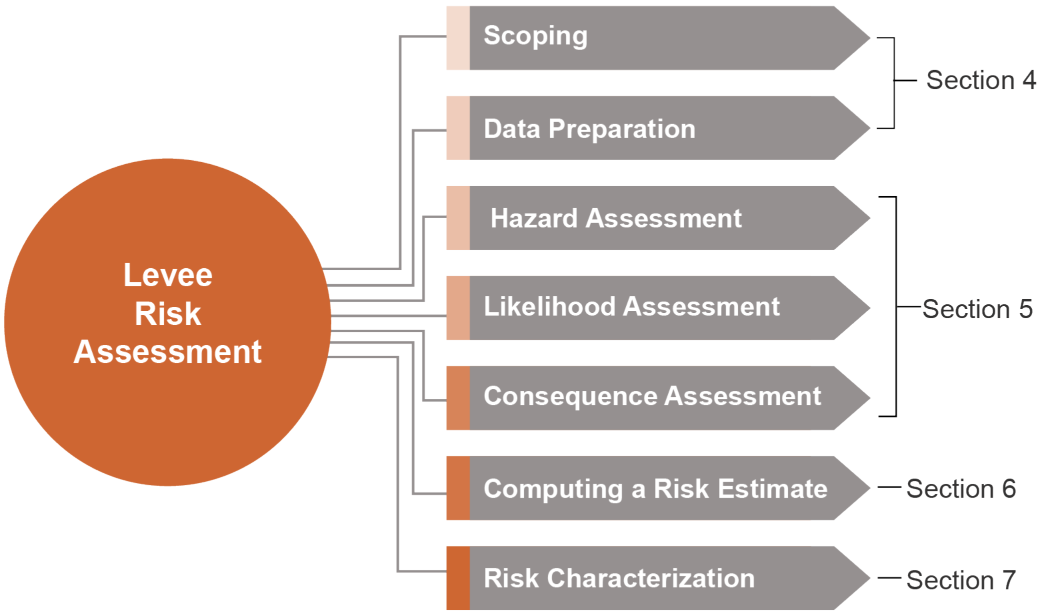
Figure 4-3: Scalability of Risk Assessments



3.3 Risk Assessment Process

Figure 4-4 illustrates typical steps of a risk assessment and maps them to the sections of this chapter which provide more detail. The first six steps together are often referred to as risk analysis. Risk analysis stops at developing a risk estimate. Risk characterization builds on that estimate to develop a risk narrative and prepares the case for risk-informed recommendations for managing levee risk. Risk assessment steps are scalable and may be iterative and/or combined.

Figure 4-4: Steps in a Risk Assessment Process



3.4 Risk Assessment Team

Risk assessments should be led by a trained facilitator with experience conducting them and guiding multidisciplinary teams. The supporting team members should be selected considering the unique features of the levee being assessed. For example, a levee with a floodwall and a pump station would require a team with a different set of expertise than a coastal embankment levee with a sector gate closure structure.

Estimating risk requires consideration of each element of the components of risk. Characterization of the hazard is the domain of hydrologic and hydraulic engineers, who estimate the likelihood of the river or sea reaching flood stage, and experts in geology and seismology, who can help estimate seismic hazards. Performance is evaluated by geotechnical, geological, mechanical, civil, hydraulic, and structural engineers, who analyze the reliability of the levee features to estimate the probability of levee breach or misoperation. Evaluation of consequences is the domain of consequence experts. These experts include hydraulic engineers, who estimate the extent, depth, and timing of inundation, as well as planners, economists, and environmental and social scientists, who are charged with understanding and quantifying the adverse impacts that will be experienced in a community once water enters the floodplain. The team should be augmented as necessary to provide insights into specific aspects of the project.

While qualitative and basic semi-quantitative risk assessments can be performed by an individual, there are distinct advantages to engaging a small team. For detailed semi-quantitative and quantitative risk assessments, a multidisciplinary team that is trained in the current risk estimation methodologies and led by an independent facilitator is recommended.

Each team should include the levee owner/operator and personnel involved in the day-to-day operation and maintenance of the levee. It may also include levee inspectors, emergency management, and construction experts as appropriate. Team members will provide information for input into the analysis, verify the reasonableness of analysis assumptions and results, and assist in answering questions posed during the process. While separate components of the risk assessment are typically led by specific disciplines, this is a team effort that requires interdisciplinary discussion and coordination.

3.5 Review and Approvals

Risk assessments should include a formal review to confirm that the evidence provided supports the results and that a credible risk assessment process was followed. Review is an important component to help ensure consistency across risk assessments. The review process should be scaled considering the complexity of the risk assessment and the decisions it informs. The more impactful or difficult the decision, the more the supporting risk assessment should be scrutinized. Certain risk assessments may require multiple levels of reviews and approvals. Reviews should be completed by independent experts qualified in risk assessments for levees.

4 Scoping and Data Preparation

4.1 Scoping Risk Assessment

Scoping a risk assessment should include:

- Framing the questions that the risk assessment is intended to answer (section 3.1).
- Selecting the type of risk assessment appropriate to the decisions.
- Identifying the team to perform the risk assessment, including both the required technical disciplines and level of experience of the members. Risk assessment reviewers should also be identified.
- Reviewing the available data and evaluating the additional data needs to perform the risk assessment.
- Selecting the tools and methods to be used in performing the risk assessment.
- Identifying the risk assessment deliverables.
- Developing the budget and schedule for the risk assessment.

A well-established scope will set expectations with regard to outcomes of the risk assessment, including necessary review and approvals. This is important in setting the stage for levee risk management activities, as described in **Chapter 5**.

In preparation for risk assessment, it is helpful to divide the levee into analysis reaches (see discussions in **Chapter 6 and 7**). A levee **reach** is a portion of a levee system (usually a length of a levee) that may be considered for analysis purposes to have approximately uniform representative properties (levee geometry, materials, foundation, hydraulic loading). Reaches may also be defined for other reasons of convenience, such as different jurisdictions, owners, or phases of the project. Delineation of reaches provides structure for assessing hazards, consequences, and performance.

4.2 Data Preparation

Data preparation involves identifying and gathering pertinent information to be used for estimating risk. Ideally, risk estimates should be informed by the most recent inspections, analyses, and condition assessments. Section 5 of this chapter provides a more detailed discussion of the data required for each part of the risk estimate. Gaps in information should be noted to help decide whether more data collection and/or further analysis is needed to answer the questions formulated during the scoping step. Risk estimating requires input from several disciplines that collectively inform hazard loading levels, levee reliability, breach formation, inundation, and consequences. In assessing data gaps, it is important to consider general compatibility and the relative level of details of various supporting analyses.

The following is the minimum geospatial-related information for a levee risk assessment. This information, among other levee data, is readily available in the NLD.

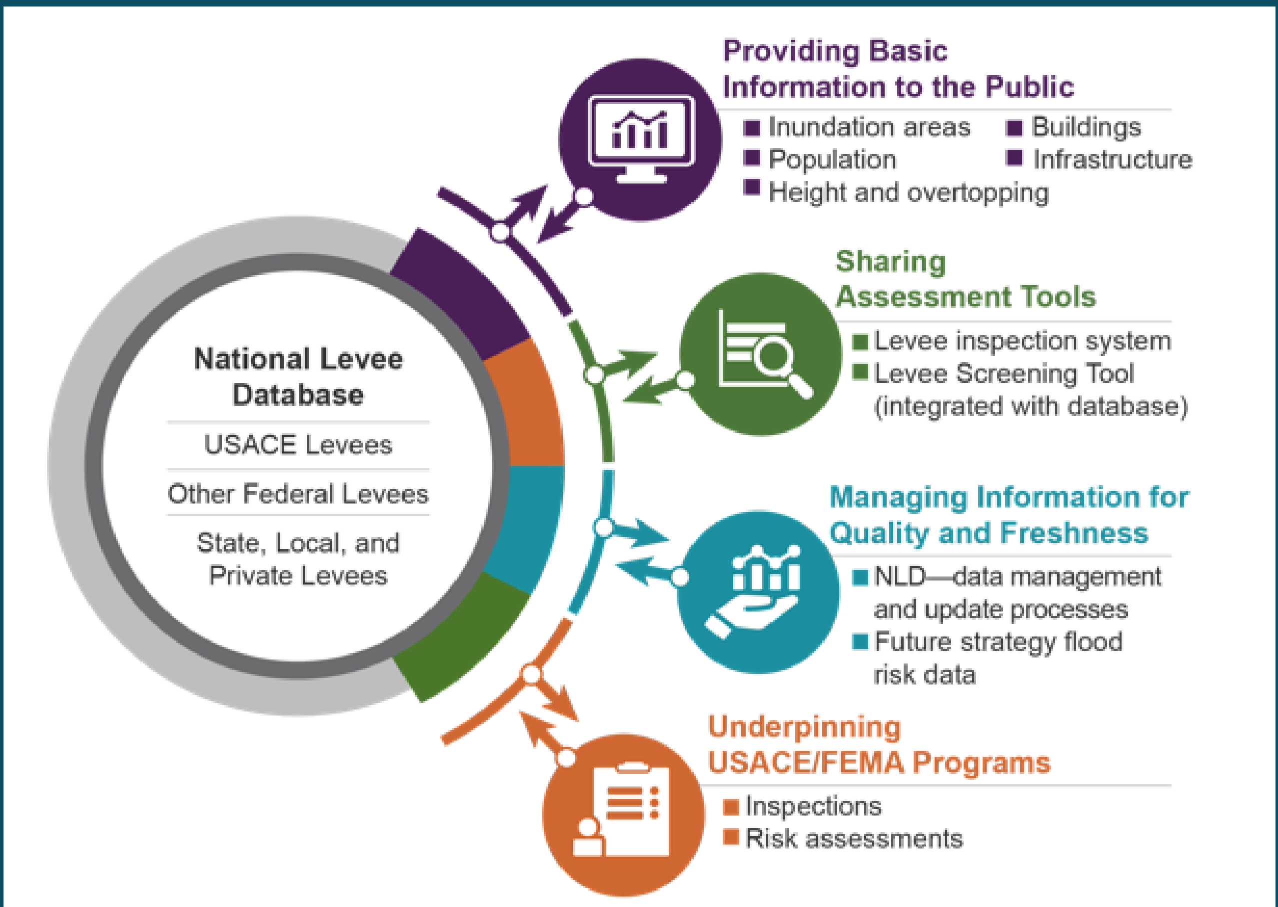
- Levee location and alignment
- Levee profile, including levee crest and landside toe
- Feature types and location
- Leveed area

This list is considered a starting point for the levee risk assessment. There will likely be a need for additional information to complete the analyses and evaluations described in the subsequent sections of this chapter.

NATIONAL LEVEE DATABASE

The NLD (https://nld.sec.usace.army.mil) is a public-facing website, managed through a partnership between USACE and the Federal Emergency Management Agency (FEMA) , that captures all known levees in the U.S. It is designed to provide a variety of users the ability to search for specific data about levees and serves as a national resource to support awareness and actions to address flooding. The information generally available for all levees includes location, responsible organization for the levee, levee length and height, and a summary of what is behind the levee. For levee owners/operators, the database can store documents, photos, levee performance history, risk assessments, and more.

The NLD can be used in tandem with other data sets and tools, such as the Levee Inspection System and Levee Screening Tool developed by USACE.



4.3 Considering Changing Conditions

Risk assessments typically depict a snapshot in time of the risk. However, risk management requires consideration of potential changing conditions that would impact the risk estimate. Therefore, it is important to include additional future scenarios that reflect these changing conditions. See section 5 for additional information on changing conditions that should be accounted for in assessing hazard, performance, and consequence.

5 Assessing Hazard, Performance, and Consequences

Methodology for assessing risks continue to evolve. Current state-of-the-practice approaches should be implemented regardless of the type of risk assessment being performed. The following sections provide existing best practices for evaluating the hazard, performance, and consequence components of risk.

Developing a risk estimate is an iterative and collaborative process that benefits from close coordination across disciplines. For example, hydrologic analyses conducted for the flood hazard assessment may identify a critical location along the levee for scour potential where performance should be analyzed. Similarly, potential failure mode analysis conducted as part of performance assessment may identify a critical flood scenario or a location for which hydraulic modeling should be refined. It may also be valuable to identify flood load levels where a slight increase in water level or wave energy results in a large increase in either the likelihood of breach or consequences. Identifying these 'tipping points' may require iterating between the hazard, performance, and consequence assessments.

5.1 Hazards

A **hazard** is an event that causes the potential for an adverse consequence. Each hazard is described by a magnitude and characteristic of loading, as well as the probability of occurrence.

Floods are the primary hazard that levees are subjected to. Levees that are loaded frequently and are in high-to-moderate seismic areas should also be evaluated for seismic hazards. This evaluation should consider the potential for coincidental occurrence of different water levels on the levee and earthquakes. Sequences of events where an earthquake occurs followed later on by a flood are typically not evaluated for a levee risk assessment.

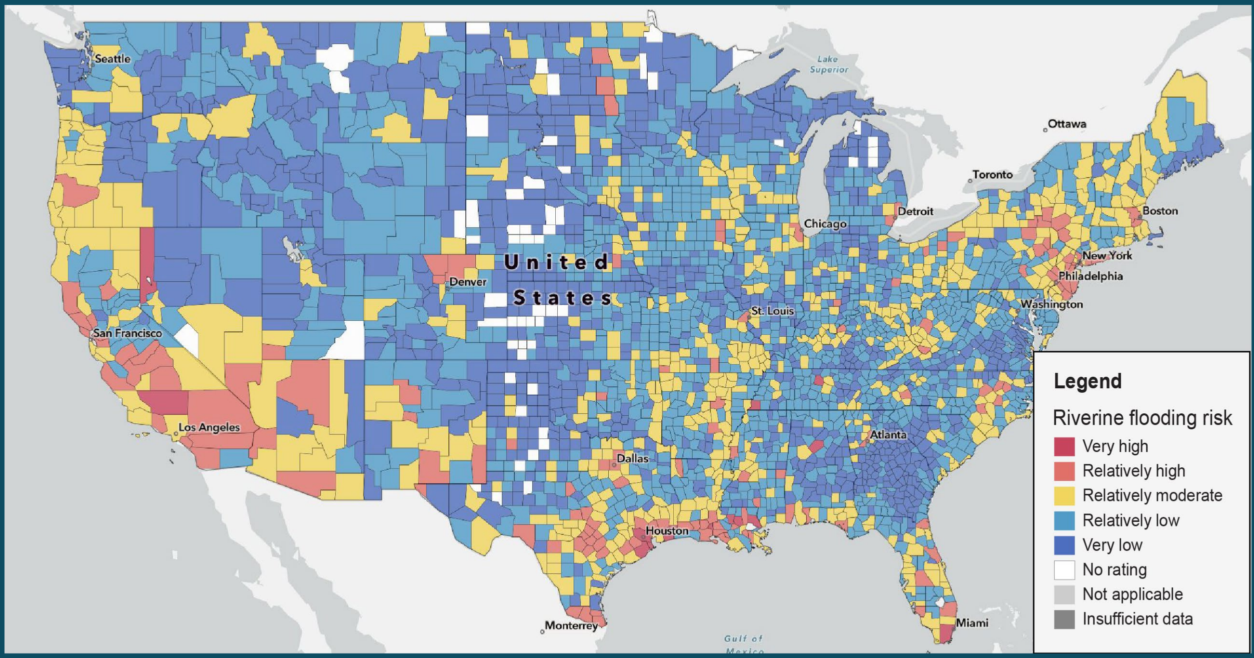
Other hazards that can damage levees are impacts from ice, debris, and boats, and should be considered when applicable.

Steps to assessing hazards are as follows:

- Identify all hazard sources and consider the potential for coincidental and correlated loading.
- Collect historic data on occurrences of the hazard (e.g., flood, record high water marks).
- Conduct frequency analysis of hazard loading (e.g., stage, ground acceleration) and supporting engineering analyses to estimate hazard characteristics (e.g., storm surge duration).
- Apply a range of hazard loadings to the levee to identify locations of critical loading (e.g., first overtopping location, location of maximum wave runup).
- Document uncertainty in data and results.

HAZARD IDENTIFICATION TOOLS

There are nationwide tools available to help identify hazards. One is the American Society of Civil Engineers 7 Hazard Tool, which depicts FEMA flood, tsunami, and seismic zones. Another is FEMA's National Risk Index, which is an online mapping application that identifies communities at risk to 18 natural hazards including: coastal floods, riverine floods, hurricanes, ice storms, winter weather, earthquakes, and tsunamis. It also includes data about expected annual losses, social vulnerability, history of losses, and community resilience. Caution must be used when looking at areas behind levees. The National Risk Index does not take into consideration probability of levee failures. The earthquake risk in both the American Society of Civil Engineers 7 Hazard Tool and the National Risk Index is tied to buildings and population vulnerability, but may indicate where additional attention should be paid to levees under seismic loads.



Source: FEMA National Risk Index Map (Riverine Flood Risk) (FEMA, 2023).

5.1.1 Flood Hazards

As described in **Chapter 1**, there are four categories of flood hazards and corresponding sources:

- Riverine (fluvial) flooding is from a river or stream.
- Coastal flooding is from large bodies of water—oceans, gulfs, bays, and large lakes.
- Rainfall (pluvial) flooding is runoff related to heavy rainfall that occurs independent of a water body.
- Groundwater flooding occurs when groundwater levels rise and emerge at the surface.

A community may be at risk from all four categories of flood hazard and flood risk management decisions should take into account all potential sources of flooding. However, levee risk management decisions and activities are primarily focused on the flood sources the levee is intended to protect against, typically riverine and/or coastal flooding. Therefore, assessing levee and non-breach risks focuses on these two flood hazards.

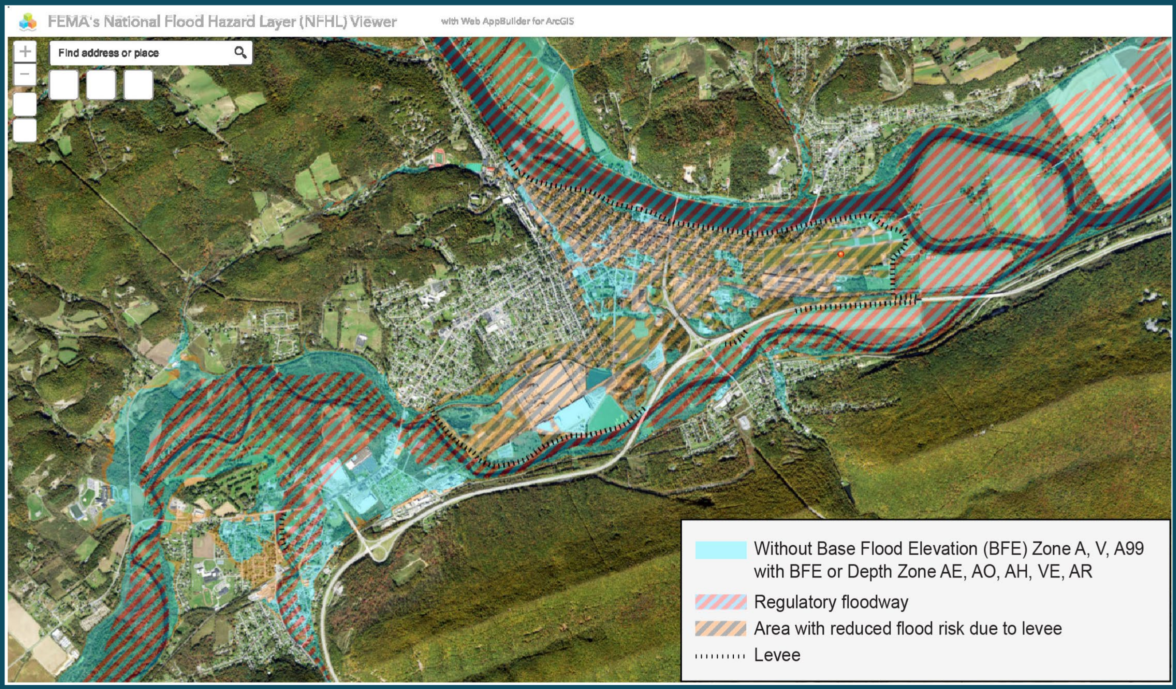
Rainfall and groundwater hazards are only included in the levee risk estimate if they could lead to a malfunction or misoperation of a levee feature. However, while not typically part of the levee risk estimate, rainfall and groundwater flooding should be evaluated in sufficient detail to ensure the levee does not make conditions in the leveed area worse. As discussed in **Chapter 2**, rainfall flooding within the leveed area can be exacerbated by the levee if it blocks a drainage course. To compensate, levees often include interior drainage conduits and pump stations. During floods, when interior drainage conduits are closed, stormwater is typically pumped over the levee or allowed to pool in the leveed area until it can drain by gravity outside of the leveed area.

An interior drainage analysis should consider the potential correlation between interior runoff (rainfall flooding) and exterior stage (coastal or riverine flooding). This analysis can inform pump station capacity requirements and help establish operational procedures for interior drainage systems and closure structures.

FLOOD INSURANCE STUDIES

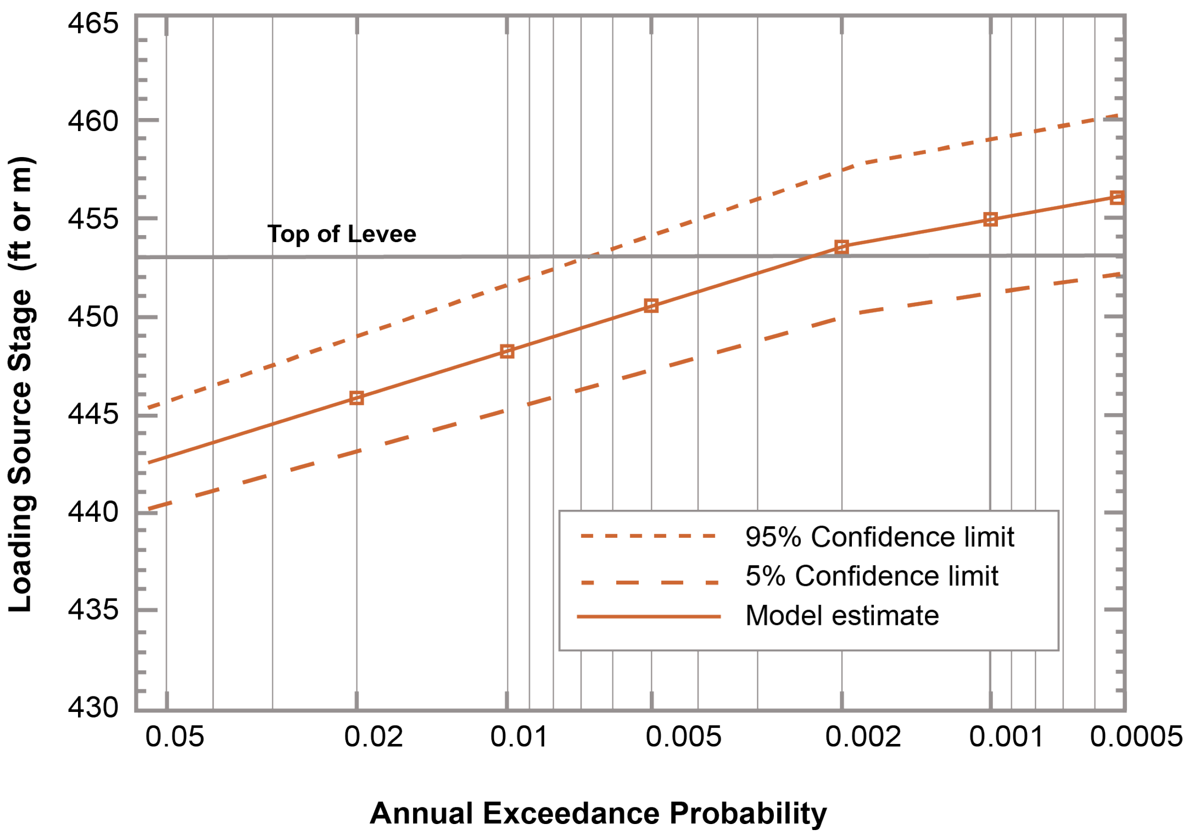
When a flood study is completed for FEMA's National Flood Insurance Program, the information and maps are assembled into a flood insurance study. The flood insurance study report contains detailed flood elevation data in flood profiles and data tables. Flood insurance rate maps are the official community maps that show special flood hazard areas. Special zones depict areas behind levees that are determined to be reliable for a 1/100 or 1/500 annual chance exceedance event.

The 1/100 and 1/500 annual chance exceedance floodplains are shown, which indicate the extent of flooding from interior drainage (rainfall flooding) or if the levee overtops for that event (riverine flooding) and the elevation of the flood levels. The flood insurance rate map layers are also available in GIS. If no other data exists, flood insurance studies and associated flood insurance rate maps, like the one shown here, can give an indication of the potential flood hazards for a community.



No matter the source of the flood hazard, it is necessary to estimate the probability of the flood loading. To properly estimate and characterize levee risk requires the consideration of a full range of possible flood loading conditions, including flood levels well beyond design loads and above the levee crests. Flood hazard studies relate the magnitude of discharge, stage, or volume to the probability of occurrence or exceedance. Figure 4-5 is a stage probability graph, which portrays the likelihood of reaching or exceeding a particular flood level (water surface elevation), often as it relates to the top of the levee. The graph also conveys the uncertainty in the estimated probability of the various flood stages by using lower and upper confidence bounds at 5% and 95% respectively. This means there is 90% confidence that the flood stage will fall within this range. In Figure 4-5, the best estimate of probability of a flood large enough to reach or exceed the top of the levee is approximately 0.002 (1/500) in any given year. There is 90% confidence that this probability is between 0.006 (1/170) and 0.0005 (1/2,000).

Figure 4-5: Flood Hazard Function at a Specific Location Along the Levee



Estimating flood hazard relies on hydrologic and hydraulic modeling supported by historical data and observations from past flood events, along with readily available sources of information such as flood insurance studies. In addition, there are several unique considerations when estimating flood hazards for levees:

- The need to extrapolate hazard probability functions to predict extreme events larger than those that have been observed.
- The need to account for changing hydrologic conditions when forecasting future trends.

- The potential for coincidental loads. This includes coincidental loading from multiple flood sources, or the need to estimate loading from floods combined with other hazards (i.e., earthquakes and impact loads).
- The potential for failure of upstream dams or levees that could result in either more or less flooding at the levee being evaluated.

5.1.1.1 Historical Data and Observations

Historical data and observations from past floods can be used as a starting point for determining the type of critical storms for the area of interest. Federal agencies such as the United States Geological Survey and the National Oceanic and Atmospheric Administration collect and store multitudes of hydrometeorological information that is relevant to risk assessments.

U.S. Geological Survey: Most major rivers and streams located near populated areas have stream gages installed to measure the height of flow and other characteristics of the river. The agency installs and maintains a network of stream gages across the nation that can be leveraged for this information. Over time, these gages collect enough data to depict a historical trend of local floods and droughts that can be referenced to understand how the watershed responds to severe weather events. The following data types, which are particularly relevant for hydrologic hazard studies, are available: instantaneous data, daily discharge, daily stage, field measured stages and discharges, and annual maximum peak discharges. The frequency and associated magnitude of floods can be determined using statistical analysis, such as the methodology described in Bulletin 17C (England *et al.*, 2019).

National Oceanic and Atmospheric Administration: Similar to riverine flooding, one of the best ways to understand trends in coastal flooding is through the capture of historic data from tidal gages. A network of gages is operated and maintained by the agency. These gages are placed along the coasts, including the Great Lakes, and are typically placed in areas that are not impacted by wave action, such as harbors or other protected areas. Location and information regarding tidal gages, including sea level trends, can be found in the National Oceanic and Atmospheric Administration’s tide and currents website. In some areas, wave gages are leveraged to inform the wave setup and wave height. These are typically farther offshore and are not as prevalent as tidal gages. Information regarding the location and information associated with wave gages can be found on the agency’s Data Buoy Center or similar websites. The agency’s Climate Data Center contains multiple data sets relevant for flood hazard assessments, including precipitation, temperature, wind direction, wind speed, and snow water equivalent, among others, for various locations in the U.S. In addition, Atlas 14 can be used to collect rainfall frequency estimates using the precipitation frequency data server.

Observed high water marks from major historical floods and local records are an important source of information for flood hazard assessment. They can help calibrate hydraulic models, identify critical locations within a leveed area, and assist with evaluating trends over time. Commonly, during and following large floods, federal agencies such as U.S. Geological Survey and FEMA collect relevant flood data to inform flood modeling and mapping, and in some cases, to aid in disaster recovery. These historical flood reports can be helpful in identifying large storms in the area of interest.

Historical observations are also useful in understanding rainfall and groundwater flooding. Repeated flooding in an area that is not associated with known water bodies can indicate localized flooding from other sources that requires study of their contribution to flood risk. While high water marks may not be feasible to collect, local records documenting the timing, location, and depth of flooding in these areas could help understand historical trends. The National Oceanic and Atmospheric Administration publishes estimates of precipitation frequency for the U.S., which can be used as inputs to an assessment of rainfall flooding.

5.1.1.2 Hydrologic and Hydraulic Modeling

Hydrologic modeling is a numerical analysis used when assessing riverine flood hazards to estimate the quantity of runoff that flows into a watershed, basin, channel, or human-made structure. The analysis uses a combination of historic and present-day data to evaluate the precipitation intensity and duration, in addition to the runoff characteristics within the study area or watershed. These characteristics may include land use, slope, impervious cover, and flow path to estimate a flow quantity that is collected in a drainage point, such as a lake or a river.

Hydrologic analyses estimate flows for a range of floods of different annual exceedance probability, or frequency. Discharge hydrographs are produced representing the variation of water levels and flows with time during a particular flood event. Details of hydrologic analyses required for levee projects are shown in Table 4-1.

Table 4-1: Hydrologic Analysis for Levees

Component	Determinants	Provides/Influences
Catchment runoff	Topography (steepness or slope), land use, soil type (infiltration rates), vegetation, climate (precipitation), basin shape, basin orientation relative to prominent weather patterns, stream network development.	Rate, duration, and volume of water derived from the catchment.
Groundwater interaction	Soil stratigraphy and permeability, presence of aquifers.	Base flow, loss of water from surface flow in losing streams.
Flood routing	Channel and floodplain characteristics, change in available volume within floodplain due to levee project, presence of storage or detention features as part of project (e.g., provisions for overflow of some levees to reduce loadings on other levees).	Changes in rate, duration, and volume of water due to the influence of stream, floodplain, and project components.
Statistics	Observed stream data, synthetic data derived from long-term simulation using catchment characteristics and models, transposition of data from similar catchments, statistical method used.	Understanding of extreme events through discharge-probability relationship, duration curves, understanding of basin response through plots of water level and flow hydrographs at one or more points along stream of interest.

Note to table: Adapted from the International Levee Handbook (Eau and Fleuves, 2017).

Hydraulic modeling is a numerical analysis that estimates the depth and velocity of flow, the height period, the direction of waves, and the resulting forces including at levees and hydraulic structures. In the case of riverine situations, the hydraulic modelling is based on input flow rates determined from a hydrologic model. Hydraulic modeling is performed for the waterside of the levee to estimate loading on the levee. It is also used to estimate flooding in the leveed area for sizing and evaluating the interior drainage.

The approach to modeling and portraying the results is different for the different types of flood hazard (e.g., riverine, coastal, rainfall). However, regardless of the type of modeling implemented, it is good practice to calibrate and validate hydrologic and hydraulic models to observed conditions, when sufficient data is available.

5.1.1.2.1 Riverine (Fluvial) Modeling

Hydraulic modeling of streams and rivers estimates the conveyance and routing of water through streams, rivers, natural channels, and lakes along with pipes and pumps. The modeling considers the characteristics of the flow in the river and the geomorphic behavior of the stream channel. Typical outputs include water surface profiles, flow depth, velocity, and lateral extent at any point in the river as a function of time. It is common to visualize the flood loading along the riverine levee with a water surface profile, as illustrated in Figure 4-6.

Figure 4-6 shows the levee profile (top of the levee and landside levee toe) along with river water surface profiles for various flood events. Each of these flood events has an associated probability of exceedance. Presenting the flood loading using a profile helps identify critical locations along the levee, including:

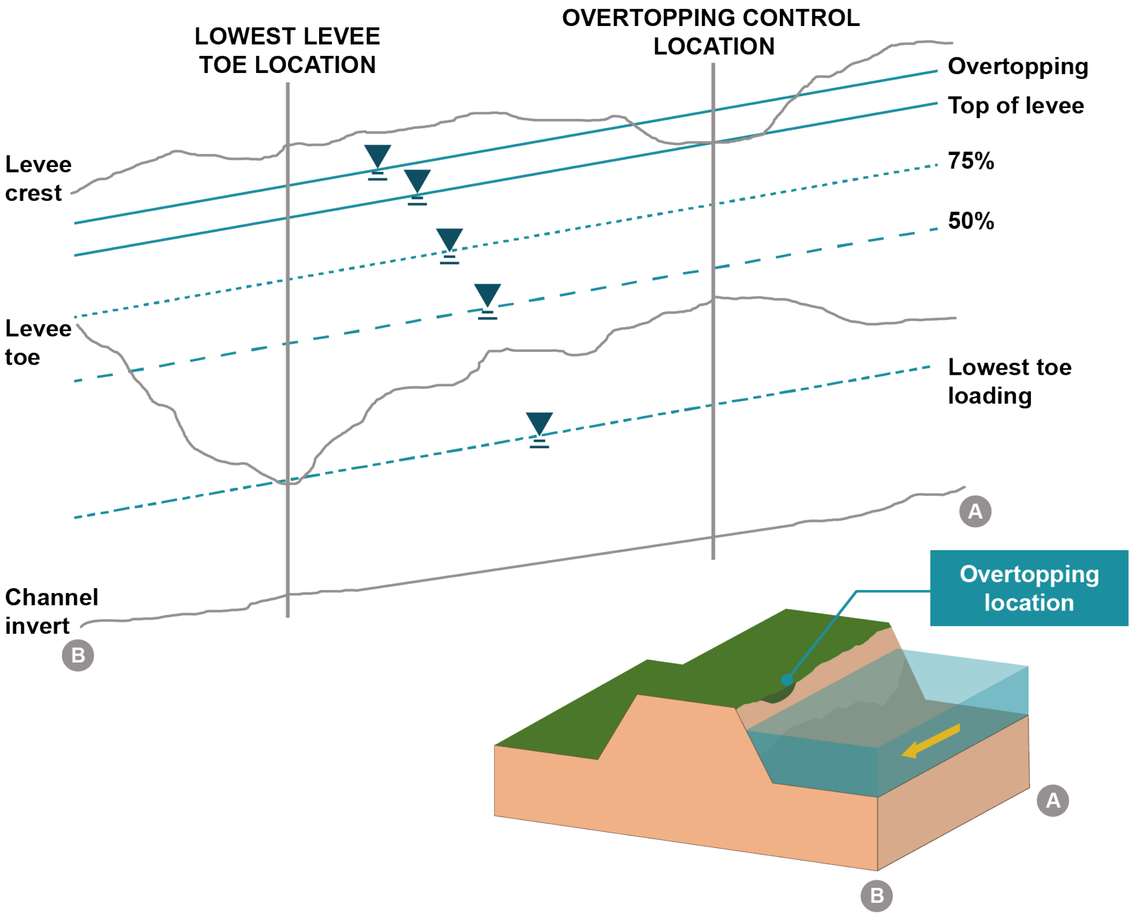
- Location where the levee is loaded first.
- Location of first overtopping.
- Location subject to the maximum loading.

Other factors that influence the selection of locations of interest or specific flood loading scenarios that require more detailed flood hazard modeling include:

- Proximity to the largest population in the leveed area.
- Vulnerability to a particular failure mode.
- A flood level at which levee performance or consequences change markedly (e.g., probability of breach significantly increases or there is a loss of a key evacuation route).

Once critical locations along the levee are identified, additional hydraulic modeling may be needed to estimate the likelihood and characteristics of flood events that load the levee to a particular level (e.g., 25%, 50%, and 75% of the levee height) and develop a flood hazard function (Figure 4-5) for each location.

Figure 4-6: Levee Profile with River Stage Profiles for Various Flood Events



In terms of the practicalities of the river hydraulic modeling, depending on the system being evaluated, one-dimensional or two-dimensional versions of a hydraulic model may be used. Generally, a one-dimensional steady state, fixed-bed model will be sufficient if:

- Flow does not spread laterally significantly and generally flows in one direction.
- It is a well-defined channel.
- Detailed bathymetric and/or terrain data are unavailable.

More complex models may use two-dimensional hydraulic analyses, which provide more detail related to flow conditions (depth and velocity at a specific location). Generally, a two-dimensional model will be more appropriate where:

- The channel or floodplain is wide, and water is flowing in several directions.
- The floodplain includes an urbanized area.
- The effect in the floodplain of levee breaching is being modeled.

Many hydraulic models now have the capability of simulating a combination of one-dimensional and two-dimensional areas. Results from these analyses include:

- Discharge-probability curve

- Stage-probability curve
- Stage-discharge relationship
- Water surface profile
- Floodplain extent

Further complexities that may need to be introduced into the modeling include:

- Unsteady (time dependent) flow modeling. Usually adopted where there is a need to understand the flooding development and progression over time.
- Mobile bed modeling. Usually adopted when significant effects are expected from bed erosion and sediment transport.

Additional information related to river hydraulic modeling can be found in Engineer Manual (EM) 1110-2-1416 (USACE, 1993) and on the Hydrologic Engineering Center River Analysis System (also known as HEC-RAS) website (Hydrologic Engineering Center, 1995).

When still water surface elevations have been determined, if waves are also present, the effects of water level setup and the runup of waves as they impinge on a levee also need to be assessed, as discussed in the following sections.

5.1.1.2.2 Coastal Flood Modeling

Coastal flooding is typically caused by a combination of elevated water levels and high energy wave action. A primary driver of elevated water levels is storm surge, which in general terms, is an increase in water levels (due to low atmospheric pressure) pushed toward shore by storm winds. The height of the storm surge (a few feet to tens of feet) is affected by many factors, including the intensity, path, and speed of the storm; the presence of waves; the depth of water offshore; and the shape of the shoreline.

Waves are important because they increase the flooding and have the potential to cause significant structural damage. In addition, waves will propagate with greater magnitude inshore during storm surge events because of the increased water depth.

Modeling coastal flooding requires first understanding the increased water level through a storm surge analysis, which is used to estimate the stillwater elevation for a given flood. This storm surge stillwater elevation does not take into account all effects from waves coming ashore during a storm event.

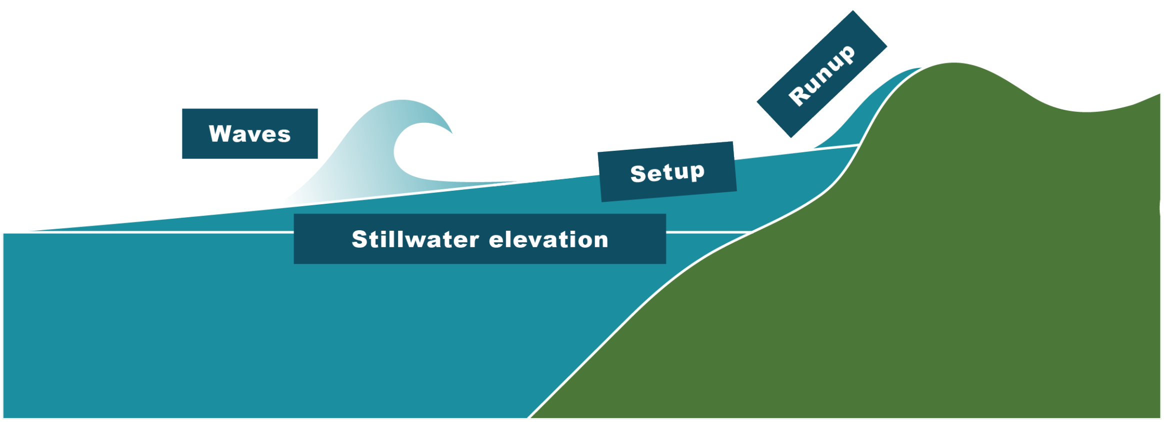
Coastal models are used to predict storm surge and flooding, model tides, and wind driven circulations. The models focus on the amount of water that is pushed towards the shore during a storm, combined with tidal effects. However, due to the regional nature of coastal hydraulic conditions used for design scenarios, estimating water levels during hurricanes and tropical events requires large-scale two-dimensional hydraulic models to estimate storm surge scenarios. It is also helpful to pair the two-dimensional hydraulic model with a wave model to develop a suite of storm scenarios for both water levels and wave conditions. This suite of storm scenarios and model results can then be used to develop a joint probabilistic model for water level and wave conditions for a range of annual exceedance probabilities, or return periods.

LEVERAGING FEMA REGULATORY STUDIES

Coastal hydraulic modeling at large scale can be costly and time consuming, and for the majority of locations, existing analyses can be leveraged. FEMA regulatory studies can be leveraged for identifying basic components such as water levels and wave conditions based on their regulatory transects. While these are likely not at the detail necessary for levee design, they can be used for initial planning and identification of likely water levels and wave heights at the 0.01 and 0.002 annual exceedance probabilities. It should be noted coastal base flood elevations shown on FEMA regulatory maps include water levels and wave heights combined, and additional information for them independently is often available in the flood information study report.

Once the nearshore wave conditions (i.e., wave height, period, and direction) are known for the given surge stillwater depth, the effect of the waves may be evaluated, considering wind and wave setup, wave runup, and overtopping and overland wave propagation, as shown in Figure 4-7. The setup is water forced to pile-up against land by wind blowing over the sea surface or by momentum of the waves resulting in increases in the average water level. The runup results from individual waves breaking against the shore or levee and its magnitude is affected by the roughness of the seaward face of the levee. During storms, runup may lead to overtopping of the levee.

Figure 4-7: Coastal Flood Hazards



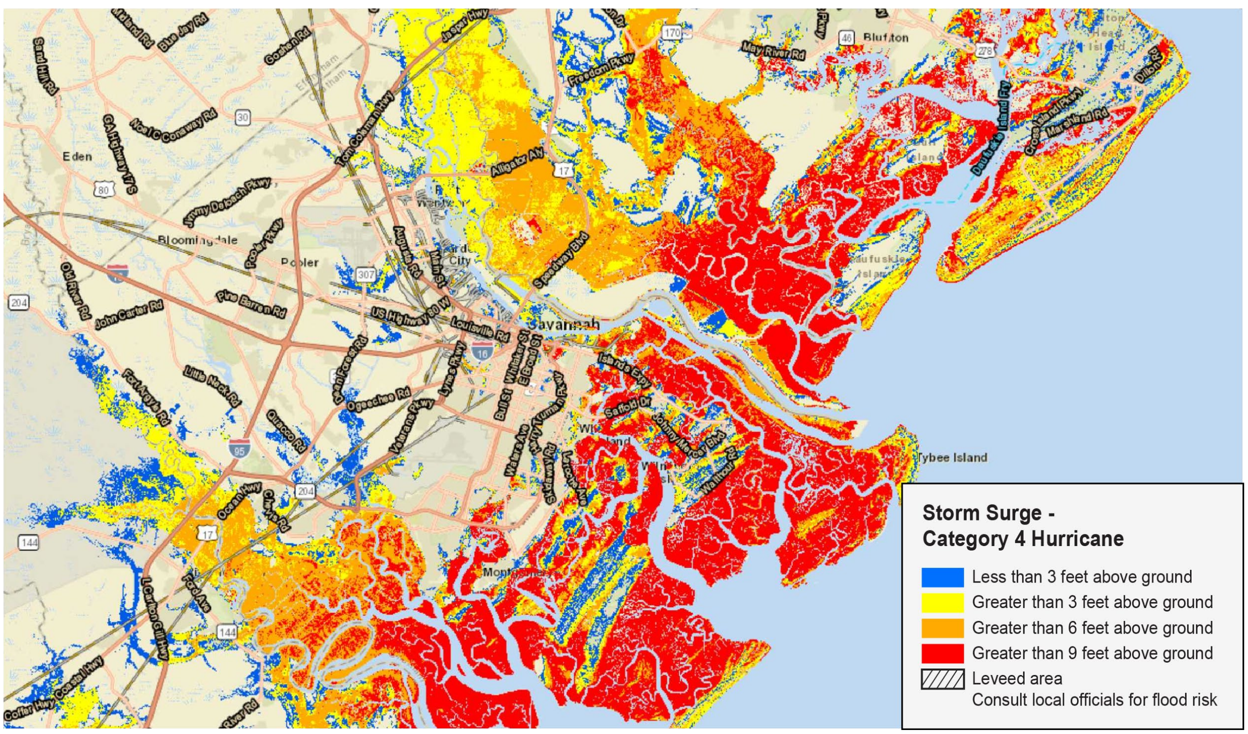
Setup and runup computation methods are provided in USACE's EM 1110-2-1100 (USACE, 2002), and Engineer Circular (EC) 1110-2-6067 (USACE, 2010). Additionally, Guidance for Flood Risk Analysis and Mapping: Coastal Wave Runup and Overtopping (FEMA, 2018) provides support requirements and recommends approaches for effective and efficient implementation. An additional widely used tool for estimating wave impacts, including setup and runup, is EurOtop (van der Meer *et al.*, 2018), which also estimates the rates of wave overtopping for levees.

Coastal levees are evaluated against three primary loadings:

- The stillwater plus setup level is used often for geotechnical seepage and stability analysis because the runup is intermittent and typically does not have a long enough duration to significantly impact seepage and stability.
- The calculated wave action at the flood risk reduction infrastructure is used for waterside erosion analysis and design of erosion protection.
- The contribution of all elements to overtopping flow rates is used for landside erosion analysis and as an input to the modelling of landside flooding.

To identify locations that may be most vulnerable to flooding, modeling of overland propagation of storm surges and wave conditions is required, both on the waterside and the landside of the levee alignment. The resulting coastal flood hazards are often visualized using maps or plan views, since the flooding levels are influenced by wind direction, tides and currents, along with the nearshore bathymetry, coastline shape, and features. Figure 4-8 is an example of a flood hazard map for storm surge.[1]

Figure 4-8: Coastal Flood Hazard Map



5.1.1.2.3 Rainfall (Pluvial) and Groundwater Flood Modeling

Rainfall flooding is caused by localized surface water runoff and not typically associated with flow in rivers or streams. Therefore, the modeling should focus on simulating the response of the drainage area to rainfall. These models assume a specific rainfall amount and intensity applied over a defined area with considerations for storm drains, ground absorption and

[1] Map from the National Oceanic and Atmospheric Administration Coastal Flood Exposure Mapper.

overland flow to estimate ponding areas, and associated depths. There are numerous modeling programs available through both public agencies and private vendors.[2]

Interactions between groundwater and surface water may need to be considered for poorly draining areas. Conditions at the beginning of the storm (antecedent conditions) play an important role in modeling rainfall flooding. For example, infiltration may be expected in sandy soil when conditions are dry, but a high-water table could prevent that infiltration in pervious soils or even push groundwater to the surface, adding to the flooding.

In addition to modeling, review of terrain information can help identify localized depressions that do not drain and may be at risk of flooding. This information, supplemented with historical observations of areas that typically have standing water during severe rainfall events can help calibrate and validate models.

5.1.1.3 Extreme Event Modeling and Changing Conditions

Risk assessments often require estimating flood events larger than any previous storms. Probabilistic flood assessment methods can be used to extrapolate available historical data to larger, more remote events. Information from a larger region could support the efforts (i.e., transplanting an extreme storm that impacted a neighboring watershed). Given the difficulties in extrapolating from existing data, it is important to convey the uncertainty in the probability estimates for these very large flood events.

Using historic observations may also lead to inaccurate predictions of future flooding if the conditions producing those floods are changing. The life of a levee often extends decades beyond the originally planned lifespan. On those timescales, long-term changes in conditions can have an impact on the risk estimate. Changes to the watershed, such as land use and impacts resulting from climate change, may result in higher or lower than anticipated flood flows and elevations. When utilizing historical data for future flood forecasting, the potential changes in the watershed and climate should be considered. For example, if significant development has recently taken place in a watershed, historical data may underestimate future flooding potential. Sea level rise and coastal subsidence can also increase the frequency of flooding. As with any future prediction, there is uncertainty in the estimates. The uncertainty should be documented and conveyed with the results.

The following is a list of some climate-related drivers that may change the hazard.

- Sea level rise.
- Changes to hydrology (more rainfall versus snow, higher intensity events, longer droughts, more frequent floods).
- Stronger wind loading (storm surges and waves).
- Higher frequency of tropical storms.

[2] Several modeling programs include: ICM (InfoWorks Catchment Modeling), https://www.autodesk.com/products/infoworks-icm/overview?term=1-YEAR&tab=subscription&plc=IWICMS; TUFFLOW, https://www.tuflow.com/products/tuflow/; HECRAS 2D (Hydraulic Engineering Center River Analysis System), https://www.hec.usace.army.mil/software/hec-ras/; XPSWMM (Stormwater and Wastewater Management Model), https://help-innovyze.refined.site/space/xps/19660802/XPSWMM+and+XPStorm+Help+Documentation.

- Slower moving tropical storms (more rainfall accumulation, longer duration of surge).
- More frequent or severe ice jams in northern climates.
- Larger and more frequent wildfires increase the rate and magnitude of flood runoff and produce debris that can reduce channel capacity.

Loading conditions can change with time due to the dynamic nature of riverine and coastal environments driven by geomorphology and human activities. For example, urbanization of areas along coasts and river channels may change site characteristics drastically. Less natural vegetation and more impervious surfaces and drainage networks leads to an increase in the amount of stormwater runoff and the rate at which it is flowing. These changes are often inter-related. For example, urbanization drives geomorphic changes to the river such as bank erosion. Changes driven by morphology or human factors include:

- River morphology and meandering effects (changing angle of erosive attack, changing bed elevation).
- Coastal morphology effects (loss of surge dampening vegetation, movement of sediment in barrier islands, dunes, sandbars, etc., that impacts surge and wave levels).
- Subsidence of foundation and/or the leveed area with respect to the flood hazard.
- Urbanization, increase in drainage (tiling, ditching), forest harvesting.

5.1.1.4 Coincidental Loading and Correlated Events

Characterization of flood hazards often requires estimating joint probability of two or more conditions occurring at the same time, which may result in more flood loading than if only one occurred. For example, it may be necessary to estimate a joint probability of:

- Total coastal water levels as a result of storm surge and astronomic tide.
- Combinations of wave heights, periods, and directions with total water levels.
- Extreme water level and extreme wave conditions.
- High river stage and ice loading.
- River stage and stormwater runoff in the leveed area.

In some cases, it may also be necessary to consider the probability of more than one coincident breach forming. This is more common on long levees that could be overtopped at multiple locations and those where the breach outflow volume has little impact on the river stage. The evaluation of compounding impacts should take into account potential dependencies and correlations among parameters.

Correlation is the degree to which the probabilities for two or more events are related. For correlated events, the occurrence of one event is an indication that the other event is also likely to occur or likely to not occur. For example, performance of levee features of similar character, such as multiple closure structures or floodwall monoliths, may be positively correlated. Correlation can be quantitatively accounted for in the risk estimation using correlation matrices or more qualitatively accounted for by applying expert judgment to the estimated probabilities associated with the responses of groups of similar components.

For levees subject to both riverine and coastal flood hazards, probability of critical conditions from both the coastal and tributary river should be evaluated. A levee that protects against multiple flood sources may be positively or negatively correlated. For example, in an estuary, high river flows may not be correlated with storm surge, or a levee at the confluence of two rivers may have positive or negative correlation between the two sides.

Methods for estimating joint probability are described in the International Levee Handbook, FEMA Guidance for Flood Risk Analysis and Mapping Statistical Simulation Methods (FEMA, 2016), and Hydrologic Engineering Center's Statistical Software Package (Hydrologic Engineering Center, 2023).

In addition to coincidental flood loads, earthquakes (seismic hazard) are often evaluated as a loading that occurs coincidentally or shortly after the primary flood loading. This is primarily applicable to levees that are loaded frequently and are in high-to-moderate seismic areas. The approach to estimating coincidental seismic and flood loadings is discussed further in section 5.1.2.

5.1.1.5 Flood Hazard Impacts from Upstream Infrastructure Failures

Individual levees are often part of larger flood risk management infrastructure systems within a watershed. Estimating and attributing risk to an individual levee can sometimes be complicated by system effects. For example, failure of an upstream dam might result in overtopping of a downstream levee. The default assumption should be that the upstream dam or levee functions as intended and if it overtops, it does not breach. This assumption may be conservative or unconservative, depending on the circumstances. For instance, if an upstream levee breaches, it can act as a 'relief valve' by redirecting flows into another part of the floodplain, reducing flood loading on the downstream levee. On the other hand, the breach of an upstream dam would likely create a flood wave that increases the loading on the downstream levee. In other words, the impacts of upstream infrastructure failures could either reduce or increase flood loading on the levee being evaluated.

Risk is attributed to the specific infrastructure that is the source of the risk; therefore, impacts of upstream failures on the flood loading of the levee being assessed are typically not considered. Conversely, if breach of the levee being assessed would result in overtopping and subsequent breach of another structure, the risk associated with these cascading failures would be attributed back to the levee being assessed. In other words, cascading failures should only be considered when the subsequent failures are directly caused by a breach of the levee being evaluated. These impacts should be considered in the consequence assessment, further discussed in section 5.3.

To support flood risk management decisions and to communicate the flood risk from multiple sources, there may be a benefit to estimating the risk from a systems perspective. This could include consideration of cascading impacts of failures in both the upstream and downstream direction.

5.1.2 Seismic Hazards

Seismic hazard is often defined as a natural phenomenon (such as ground shaking, fault rupture, or soil liquefaction) that is generated by an earthquake, although these phenomena could also be produced by human activities (e.g., oil and gas extraction, mining processes).

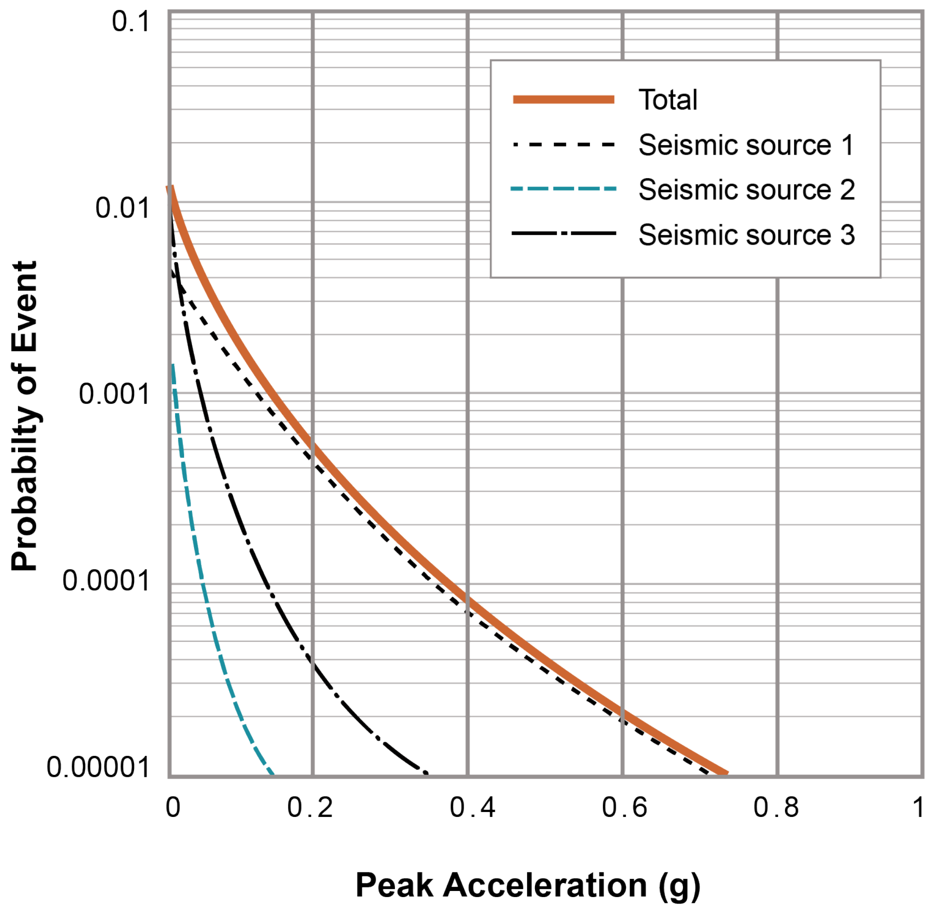
Seismic hazard information is used to evaluate levee performance under earthquake loading. It usually applies to levees that are continuously or frequently loaded, such as those at the coast or in an estuary or bay. They can also apply when there is insufficient time to repair or rebuild the levee after the seismic event and before the next flood. However, sequences of loadings, such as an earthquake followed later by a flood, are usually not considered for levee risk assessments.

Levee breaches from earthquakes are typically caused either by loss of soil strength due to liquefaction or exceedance of the structure's strength capacity through dynamic loading leading to settlement or sloughing. Features such as pump stations or other conveyance structures could be damaged from seismic loads, which can impact levee performance and lead to misoperation or failure.

Seismic hazard analysis for risk assessment typically refers to the estimation of earthquake-induced ground motions having specific probabilities over a given time period. Additional seismic hazard information includes the magnitude of ground acceleration, duration, time history, and amplification periods. It may also be useful to evaluate the relative contributions of the various sources to the total seismic hazard. Probabilistic seismic hazard curves (Figure 4-9) are used to convey probability of exceeding a particular peak ground acceleration for different seismic sources that may affect a given levee. A web tool[3] developed by U.S. Geological Survey can serve as a starting point for developing seismic hazard curves for levee risk assessments (USGS, 2022). Detailed risk assessments may require additional, site-specific probabilistic seismic analyses.

[3] Unified Hazard Tool: https://earthquake.usgs.gov/hazards/interactive/.

Figure 4-9: Example Seismic Hazard Curve Combined from Various Sources



Similar to the flood hazard, it is important to understand the probability of a wide range of potential seismic loadings. Unlike the flood hazard, the seismic loading does not typically change significantly along the levee length; therefore, a single seismic hazard assessment can be applied to the entire levee.

The evaluation of levees located in seismically active areas may require the estimation of joint probability of the seismic and flood events. If the levee is expected to perform poorly under a seismic event (e.g., experience widespread liquefaction and excessive deformations) and damage to the levee is expected to be so extensive that restoring the flood risk reduction benefits cannot be achieved before it experiences a flood, both loadings should be considered. In this scenario, the timing of the repair is included in the probability estimates. This requires estimating (1) annual chance of a seismic event capable of significantly damaging the levee to the point it cannot be quickly repaired; and (2) a chance of flood occurring before repairs can be completed. The joint probability of earthquakes and floods can be estimated using the USACE Risk Management Center Event Combination Toolbox.[4]

[4] The RMC Event Combination Toolbox: https://www.rmc.usace.army.mil/Software/RMC-Toolboxes/Risk-Calculations-Suite/. This web-based tool was developed based on The Joint Occurrence of Earthquakes and Floods, USACE Miscellaneous Paper GL-80-10 (Haynes-Griffin, 1980) and Event Combination Analysis for Design and Rehabilitation of U.S. Army Corps of Engineers Navigation Structures, USACE Contract Report ITL-95-2 (Ellingwood, 1995).

5.1.3 Impact Loads

Levees can also be damaged or breached from an impact load. Impacts can be from debris or ice floating in the river, vessels, or wind-toppled trees. For example, the consideration of impact loads may be appropriate for floodwalls along a navigable canal or an area where barges or ships are moored that have the potential to break loose during flood/hurricane events. Stray barges/vessels can become unmoored due to high winds, surge, or excessive flow and strike floodwalls located in the vicinity of the barge/vessel. Another example would be when a large tree near a floodwall is uprooted and overturns onto a floodwall. A large enough tree toppling onto a floodwall can cause a wall failure.

It is not possible to develop failure sequences for every scenario. When a unique situation arises as part of the levee risk assessment that warrants the consideration of impact loads, the assessment should be handled on a case-by-case basis with site-specific factors.

5.2 Performance

The performance of the levee under load will be influenced by the geologic conditions, the levee design and construction details, the current condition of the levee, how long water will be present on the levee, and the ability to detect issues as they arise and successfully intervene. **Performance** is the measure of how a levee functions when subjected to a hazard. It is evaluated by identifying credible potential failure modes that could lead to adverse impacts when the levee is loaded and estimating the probability of each occurring. **Chapter 2** explains that **potential failure modes** are mechanisms that could progress to breach of a levee or inundation of the leveed area. For a given levee, all relevant loadings should be considered when evaluating potential failure modes.

The performance assessment relies on expert judgment supported by the best available information. Existing information might include studies and investigations, past inspection reports, construction plans and photos, engineering analyses, observed performance during past flood events, and national publicly available datasets, such as the national elevation dataset.

Knowing how a levee has performed under previous flood events (whether it was good or poor), including understanding any floodfighting activities that took place, is critical evidence that helps reduce uncertainty about expected levee performance. The best available historic performance information is often held by those who work on the levee daily; therefore, the perspective of levee operators, inspectors, and maintenance personnel is invaluable for levee performance assessments. If critical potential failure modes are overlooked or misjudged, the risk estimate will be incomplete and misleading.

Typical steps of the process of assessing levee performance are as follows:

- Collect and review pertinent data, including design and construction records, previous studies, historic performance, and inspection results.
- Compare design and construction against current practice to identify potential vulnerabilities.
- Identify, describe, and screen potential failure modes.

- Conduct supporting analyses, investigations, or modeling as needed.
- Estimate probability of failure given the hazard loading for individual potential failure modes.
- Document sources of uncertainty and key factors driving the estimate, including sensitivity of the results to specific input parameters and/or assumptions.

5.2.1 Understanding Levee Condition

The risk assessment should identify the best available information to answer the following questions with a focus on understanding the main vulnerabilities of the levee:

- What loads and conditions was the levee designed to resist?
- Was the levee well-constructed and is there good documentation of construction?
- What is the current condition of the levee?
- How has the levee responded to previous loadings?

Answering these questions may require additional investigations and collecting samples for laboratory or in situ material testing to better characterize the levee or its foundation. It may also be valuable to perform supplemental engineering analyses such as seepage, stability, or erosion resistance to inform the assessment of different potential failure modes. **Chapter 7** provides guidance for performing site characterization and engineering analyses.

5.2.1.1 Design and Construction Records

Design and construction practice has improved over time through lessons learned, new technology, and capabilities. The review of design and construction records seeks to understand the design standard and the level of care taken during original construction and/or modifications to levee features. A levee that was not designed or constructed to current state of practice could indicate potential problems (refer to **Chapters 7 and 8**). For example, the use of an old design standard, poor construction techniques, or inadequate monitoring of the construction can increase uncertainty about a potential failure mode or indicate it is more likely to occur. However, it should be noted a levee design that does not meet a current state of practice does not necessarily mean there are performance issues or that the risk is higher when compared to a levee that does meet modern standards.

The design and construction review answers the questions:

- What was the original condition of the levee?
- What was the intended performance level?
- Are the design and construction consistent with modern practices?
- Could poor design or construction practice result in worse than expected performance?

Sources of this information includes plans and specification, design reports, and construction documentation (field reports and photos), as well as past studies and investigations. If this information is not available, records from levees designed and constructed during the same era, in the same region, and/or by the same designer/constructor can be used to inform performance assessments.

5.2.1.2 Visual Observations and Monitoring Data

Risk assessments rely on levee inspections and visual observation records as a primary source of information related to levee condition and performance. Therefore, it is important that levee inspection documentation provides sufficient details to answer the following questions:

- What is the current condition of the levee?
- How has the levee responded to previous loadings?
- What/where are the levee's biggest vulnerabilities?

There is often limited information relative to the entire length of the levee (e.g., there may only be a handful of borings and a few engineering cross sections for a 5-mile levee). Therefore, risk estimates also rely on visual observations and past performance to better understand potential levee performance. This fact highlights the importance of robust levee inspection documentation, flood performance data collection, and comprehensive operation and maintenance records. Gaps in this information should be taken into account as part of the uncertainty analysis. See **Chapter 9** for guidance on conducting levee inspections. Another important source of information is instrumentation readings over time, which can reveal long-term trends in levee performance. Another important source of information is instrumentation readings over time, which can reveal subtler, long-term trends that may indicate levee deterioration and/or slowly developing potential failure modes.

5.2.1.3 Past Performance

Possibly the most important data for estimating levee performance is documentation of how the levee has performed over its history and under flood loads. Accurate and detailed historic records of previous levee loadings, damage, or breach incidents and repairs are good sources of information for estimating levee performance and probability of breach. However, the evaluation of levee performance should not rely solely on past performance or lack of physical evidence when completing the performance assessment if the project has not been hydraulically loaded near the top in its current condition. This is particularly true when considering situations that worsen with time, such as vegetation growth and deterioration of culverts/discharge pipes that are within the embankment or under floodwalls. Historical records help answer the following questions:

- What has the levee endured in the past?
- What has caused damage and how was it addressed?
- Is the levee performance exhibiting worsening trends under repetitive loadings?

Expected levee performance can also be informed by reviewing historical failure rates and details of the failure of similar levees under similar loading conditions.

5.2.2 Potential Failure Mode Analysis

The goals of a potential failure mode analysis are to: (1) identify the site-specific credible potential failure modes for a given levee; (2) provide complete descriptions of the potential failure modes, including the initiating event and the progression of steps leading to a breach; and (3) provide a general description of the magnitude of the breach, including identifying and recording the factors that make the potential breach more or less likely, and the consequences more or less severe.

Potential failure modes generally fall into five categories, as discussed in **Chapter 2**. There are numerous failure mechanisms in each category. Site-specific conditions and levee configuration will help to identify the set of potential failure modes to consider with in the following general categories:

- External erosion
- Internal erosion
- Overtopping
- Instability
- Malfunction/misoperation of levee feature

A potential failure mode analysis is performed by experts with experience in levee design and construction who are familiar with case studies of levee failures and incidents. A potential failure mode analysis begins with the review of available data. This review informs the brainstorming of potential failure modes that could impact the levee. It should be recognized that each levee is unique in terms of features, geologic setting, design, construction, loading it is subjected to, and consequences in the leveed area.

For a basic semi-quantitative risk assessment, potential failure modes can be evaluated by screening a list of common potential failures and applicable case studies of historical levee failures and considering whether and how these potential failure modes impact the levee being evaluated. Detailed semi-quantitative and quantitative risk assessments require a levee-specific analysis of potential failure modes.

MALFUNCTION OR MISOPERATION: POTENTIAL FAILURE MODES

The malfunction or misoperation of a levee feature could result in flooding in the leveed area. In general, malfunction is a failure of an automated system or equipment, while misoperation typically involves a human error. Examples of levee misoperation include failure to close flood gates, failure to install a stop-log closure structure, or failure to deploy demountable barriers. Malfunction is often associated with a mechanical failure that renders a component inoperable. For example, overtopping of the levee could damage pump station equipment and take it out of service. Another example is a failure of flap gates that prevent flood waters from entering the leveed area through interior drainage conduits.

In addition, some levee systems may be susceptible to security failures, such as vandalism or intentional/malicious harm. Security of sensitive features should be considered (physical and cyber) in the risk assessment. Risks associated with levee misoperation should be quantified and characterized similarly to the risks associated with levee breach prior to overtopping.

Potential failure mode analysis should identify scenarios that could lead to levee breach prior to overtopping, as well as overtopping erosion that would result in breach due to overtopping. For levees with a controlled overtopping section, it is important to consider both the controlled overtopping location, as well as the next lowest location along the levee crest that is likely to overtop first based on the levee grade and water surface profiles. This is not necessarily the lowest point along the levee crest. Understanding where overtopping will occur helps inform the selection of breach locations for consequence assessment.

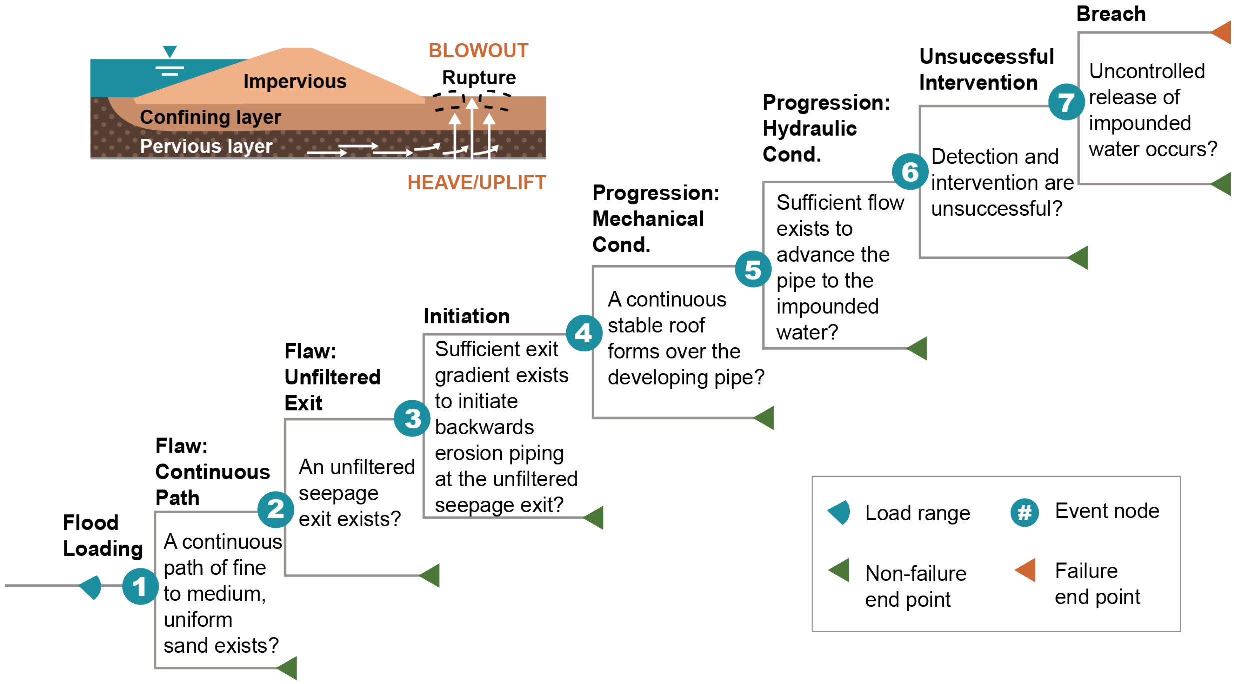
Potential failure modes should be described with enough detail to adequately estimate the probability of failure or justify screening out the potential failure mode. The team should consider each failure mode in increasing levels of detail until it is either screened out (i.e., excluded) or carried forward to risk estimation. A failure mode may be screened out because it is too remote of a possibility, it does not result in consequences, it is physically impossible, or it is not actionable.

For each potential failure mode, the team should develop and describe the progression of events from initiation (the hazard loading) through the end state that results in consequences (typically levee breach). Event trees and fault trees can be constructed to illustrate the independent nodes (steps) of a specific failure progression. Event trees describe failure mechanism from loading to breach formation, while fault trees describe various causes of a particular failure type. Fault trees are typically used for potential failure modes associated with mechanical/electrical systems, and event trees are commonly used for all other potential failure modes. For guidance on conducting potential failure modes analysis and developing event trees and fault trees, see Best Practices in Dam and Levee Safety Risk Analysis Risk Management.[5] Figure 4-10 is an example of an event tree for internal erosion through a levee foundation. The level of detail used to define the failure progression is scalable depending on the level of risk assessment; if quantitative estimates for each step are not needed, several nodes of the event tree can be combined.

Most event trees will include a node for detection and intervention that could prevent a failure from progressing before it causes a breach. Emergency intervention techniques are discussed in **Chapter 10** and could include measures such as sand bagging at the crest of the levee (overtopping with breach) or an emergency seepage berm (prior to overtopping potential failure mode). Understanding the impacts of intervention on the risk estimates can be important in developing specific risk reduction actions. Therefore, risk should be estimated with and without intervention.

[5] Best Practices in Dam and Levee Safety Risk Analysis: https://www.usbr.gov/damsafety/risk/methodology.html.

Figure 4-10: Example Event Tree



5.2.3 Estimating Probability of Levee Breach

Probability estimates can range from an order of magnitude best estimate to a probability distribution function with fully quantified uncertainty. The estimates should be informed by case histories and data collected from past incidents and levee breaches. The probability of breach for individual potential failure modes is typically estimated using one or more of the following approaches.

- Historical levee failure/incident rates that are adjusted to reflect the understanding of specific conditions related to the levee being evaluated.
- Expert elicitation informed by information and engineering analyses.
- Expert elicitation information by statistical modeling considering a range of input parameters to estimate reliability based on the underlying physics of failure.

The first method is appropriate for basic semi-quantitative risk assessments and is built into the Levee Screening Tool.[6] The other two methods are generally reserved for detailed semi-quantitative and quantitative risk analyses and require a trained team of risk estimators. Many risk assessments use a combination of these approaches and different potential failure modes may be evaluated using different approaches and combinations of tools.

Expert elicitation is the process of obtaining probabilistic belief statements from experts about unknown quantities or parameters and involves carefully defining the target questions to properly capture experts' beliefs. Expert elicitation should be led by a trained risk facilitator with

[6] Levee Screening Tool: https://www.rmc.usace.army.mil/Reference-Center/Risk-Assessment/.

experience eliciting and aggregating expert judgments. In addition, both the facilitator and the estimators should beware of potential biases and trained to recognize and overcome them.

Elicited probabilities can be provided as an order of magnitude best estimate, which may be appropriate for a semi-quantitative risk assessment, as conditional probability for each node in an event or fault tree (nodal estimate) to be used as inputs to statistical risk modeling, or as adjustments to a system response curve. For nodal estimates, Table 4-2 is often used to help turn expert opinion into a numeric probability estimate. Verbal descriptors in Table 4-2 serve as a general guide and estimators are not limited to the specific numerical values listed in the table.

COMMON ESTIMATING BIASES

Overconfidence: The tendency to be more confident than the evidence warrants.

Anchoring: The tendency to keep an estimate near a specific value such as a base frequency.

Availability: The tendency to overemphasize easily recalled or vivid evidence.

Motivational: The tendency to steer an estimate toward an outcome of one's vested interest.

Representativeness: The tendency to overemphasize similarities and neglect other information.

(Adapted from Vick, 2002.)

Table 4-2: Verbal Mapping Scheme Adopted for Quantitative Nodal Event Tree Risk Estimates

Descriptor	Assigned Probability
Virtually certain	0.999
Very likely	0.99
Likely	0.9
Neutral	0.5
Unlikely	0.1
Very unlikely	0.01
Virtually impossible	0.001

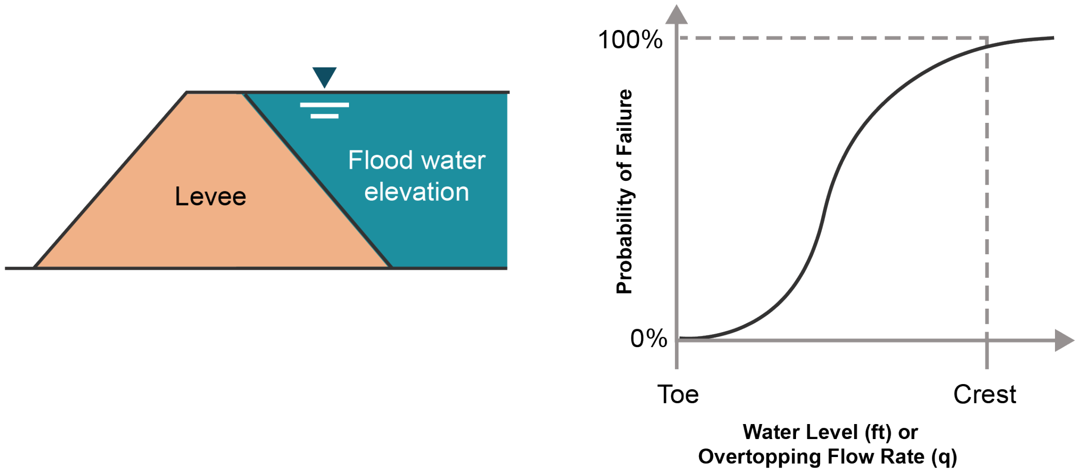
One tool that can be used in conjunction with expert elicitation or as a statistical model input is a system response curve established from case studies.

To assess the potential for failure, it can be helpful to develop system response curves (sometimes referred to as fragility curves) to portray probability of levee breach over the range of anticipated loadings, from normal conditions to various flood events. As illustrated in Figure 4-11, system response curves portray conditional probability of breach, given the load. A system response curve for a more reliable levee would be one that is shifted to the right on the axis in Figure 4-11, indicating a lower probability of failure at higher loading levels. A system response curve for a less reliable levee would be shifted to the left, indicating there is a higher probability of failure prior to the levee being fully loaded.

System response curves may be developed from statistical modeling supported by engineering analyses and case studies. Databases containing information regarding historic levee performance can also be used to generate system response curves.

System response curves can help identify critical loading levels, for which levee performance is expected to change, which could inform emergency action thresholds.

Figure 4-11: Sample Levee System Response Curve



Levee performance should be evaluated for all loading conditions, including normal. Normal loading is a loading that is assumed to happen at least once annually and may be present for the entire year resulting in 100% annual chance exceedance for the hazard. Adverse impacts to the levee under normal conditions could occur as a result of the following:

- Internal erosion, particularly associated with levee foundation and levee penetrations
- Shoreline wave erosion
- Boat wake erosion
- Riverine erosion
- Surface runoff erosion
- Vegetation (windthrow of trees or rotting)
- Settlement
- Deterioration of levee protrusions (e.g., pipes, concrete, or masonry structures)
- Intentional or unintentional excavations of the levee prism
- Security breaches of operational computer networks
- Physical security breach and tampering or vandalism

5.2.4 Changing Conditions

Changing conditions can affect the probability of potential failure modes developing and/or could initiate a new potential failure mode. For instance, more frequent and longer droughts can generate cracking within the levee, leading to an increased risk of levee breach due to internal erosion. Ground subsidence could lower the levee crest, leading to increased probability of overtopping. Larger and more frequent wildfires could increase flood runoff and add debris to the system, increasing the risk of overtopping and scour. The locations along the levee vulnerable to a particular potential failure mode may also change due to changing conditions.

For example, river morphology and meandering can change the angle and intensity of erosive forces.

5.3 Consequences

Consequence estimates for levee risk assessments aim to quantify: (1) who and what can be impacted in the event of flooding inside the leveed area; (2) the degree to which those people and assets come in contact with the flooding; and (3) the extent of the impact to the people and assets based on that exposure.

Flood **consequences** are the direct or indirect outcome of inundation, as reflected in the potential loss of life, economic losses, and adverse environmental impacts. They are broadly referred to as the short- and long-term impacts attributable to the flood. Consequences may be readily observed and specific, such as a flooded residence, but could be less tangible and distributed, such as long-term quality of life impacts borne by displaced community members. The consequences may also have ripple effects over time and outside of the leveed area resulting in regional, national, or international economic losses and indirect life loss (including an ability to provide services to the community at large with the potential for disproportionate impact to underserved populations).

For levee risk, it is typical to focus on direct life loss and property/economic damage from flooding. Other consequences are considered qualitatively and should be discussed as part of the risk assessment. These include environmental, social, and cultural impacts, along with community recovery and resilience (**Chapter 12**). There are instances when these other damages are estimated due to the significance of their impacts (e.g., flooding a nuclear waste disposal site).

Sources of uncertainty in consequence estimates include hydrology, hydraulics, breach location, breach parameters, warning communication delays, time to recognize a developing failure, evacuation delays (e.g., traffic or flooded roads), and fatality rates.

Incremental (sometimes referred to as excess) consequences are used to estimate levee risk. Incremental consequences are defined as the consequences that can be attributed to the failure of the structure and are typically estimated by subtracting the consequences of levee overtopping without breach (non-breach) from the total consequences of the flooding from levee overtopping with breach. It is typically assumed that consequences without levee breach for a flood below the levee crest are zero.

5.3.1 Levee Breach and Inundation Modeling

Estimating consequences typically relies on a hydraulic model to estimate inundation extent, flood depth and velocity, as well as duration and timing. The first step in estimating the inundation is to model the levee breach and the resulting outflow.

In consequence estimating, it is important to model various breach scenarios to align with the hazard and performance estimates. Consequence estimates should be based on scenarios identified in the potential failure mode analysis regarding the location of weak points in the levee and the type of breach to be modeled. Sometimes there may be additional critical locations along the levee that were not identified or specifically analyzed in the potential failure mode analysis, but that result in much higher consequences. A common example is a long levee reach with a community clustered in one section of the leveed area. The probability of failure is roughly the same for the whole reach, but a breach near that community could result in much higher consequences than one farther away, due to lack of warning time and more dangerous flood conditions. In this case the critical consequence location should be considered in the risk assessment.

Several breach scenarios may need to be modeled for a risk assessment. For prior to overtopping breach, different flood loading levels could be selected depending on the potential failure mode being considered. Similarly, levee breach modeling for more than a single overtopping depth may be needed.

In addition to modeling levee breach scenarios, overtopping without breaching the levee should be modeled so that the incremental consequences can be estimated.

5.3.1.1 Breach Modeling

The outflow from a levee breach is a function of breach geometry and the timing of the breach formation. This is the width, depth, and shape of breach, along with the time of the breach initiation relative to the levee loading level and the time it takes for the breach to fully develop.

Breach parameters depend on several factors, including but not limited to the type of structure that is breached (embankment, concrete floodwall, gate/closure structure); the breach scenario (prior to overtopping versus overtopping); and the flood loading level on the levee when it breaches.

Methods to estimate embankment breach parameters and the resulting breach outflow include:

- Physics-based erosion methods predict the development of an embankment breach and the resulting breach outflows using an erosion model based on hydraulics, sediment transport, and soil mechanics.
- Parametric regression equations developed from case study information are used to estimate the time-to-failure and ultimate breach geometry. The breach can then be simulated to proceed as a time-dependent linear process with the computation breach outflows using hydraulics.
- Predictor regression equations estimate the dam breach peak discharge empirically based on case study data of peak discharge and hydrograph shape.

It is important to note that the majority of parametric and predictor regression equations were developed based on dam breach case histories and may not be applicable for modeling levee breaches. One notable difference is that for dams, the water level through the breach drops as the storage in the reservoir is released. In the case of levees, the incoming flow volume and duration are often sufficient to maintain the water level through the breach. This often results in continued widening of the levee breach after it reaches full depth. Therefore, the breach width to height ratio for levees is typically larger than for dams. For these reasons, it is generally recommended that physically based methods be used to model levee breaches.

Several computer models have been developed that attempt to physically model the breach process using sediment transport theories, soil slope stability, and hydraulics. These methods are summarized in the report *Prediction of Embankment Dam Breach Parameters* (L. Wahl, 1998). The USACE Hydrologic Engineering Center River Analysis System computer program uses a ‘Simplified Physical Breach Method’ that estimates the breach width based on the velocity of flow through the breach and the erodibility of the embankment materials.

Floodwalls and gates or closure structures are typically more brittle, and failure occurs more rapidly. The size of the failure can often be estimated based on the structure’s construction geometry. For example, a floodwall breach may occur between construction joints in the structure.

5.3.1.2 Inundation Modeling and Mapping

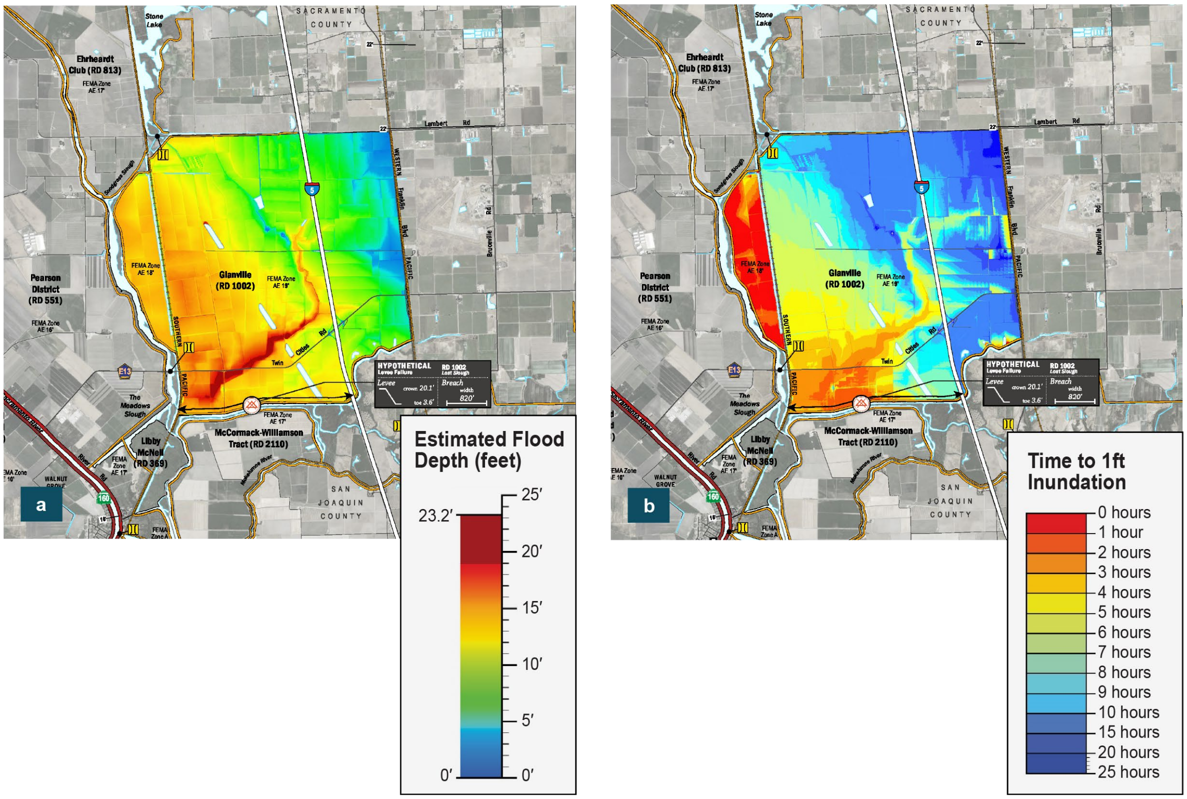
The levee breach modeling is an input to hydraulic modeling used to estimate inundation in the leveed area. For some levees, the configuration of the levee and topography of the leveed area may be such that overtopping or breaching of the levee would fill up a finite volume, similar to a bathtub or pond, making inundation modeling relatively simple. However, for many levees the water flows through the leveed area rather than ponding and a hydraulic model may be needed to estimate the flooding. Flooding in the leveed area could be modeled similar to riverine flooding or rainfall flooding (discussed in section 5.1.1.2). Two-dimensional hydraulic modeling is often most appropriate for levees, since the flow from the levee breach tends to spread out in all directions as opposed to being channelized.

The inundated area from the levee breach can be mapped based on the output from the hydraulic model. Inundation maps visually convey information about a flood’s extent, depth, and/or time of arrival. This information can be used to estimate the assets and population that could be exposed to the flooding.

The hydraulic model will also provide estimates on velocity through the breach and timing of the breach hydrograph as it propagates over the terrain. This information can be included as contours on the inundation maps. Arrival time contours and depth data are very useful for assessing potential consequences, including potential life loss and economic damage estimates (sections 5.3.2 and 5.3.3). They can also inform emergency preparedness activities (**Chapter 10**) and help communicate risk to decision makers, community members, and stakeholders (**Chapter 3**). Inundation maps should portray realistic scenarios identified during the performance assessment (section 5.2).

The inundation map in Figure 4-12 shows maximum depth of flooding due to a levee breach and also arrival time of the flood wave (beginning after the breach initiation).

Figure 4-12: Example Inundation Map



5.3.1.3 Flood Severity

The output from the levee breach and inundation modeling/mapping are used to characterize the severity of the flooding, which is used in estimating life loss and direct economic damages. Both the depth and velocity of the flood waters are important. Deep flooding with low velocities can cause damage and life loss, as can more shallow, high velocity flooding. Flood severity is often expressed in terms of the product of depth and velocity (also referred to as DV). There are also depth and velocity relationships with thresholds for the stability of structures, vehicles, and people that are used in consequence estimating, as illustrated in Figure 4-13. In the figure, different stability thresholds are established to represent low to high potential for damage and/or life loss.

Figure 4-13: Stability Thresholds Based on Flood Severity

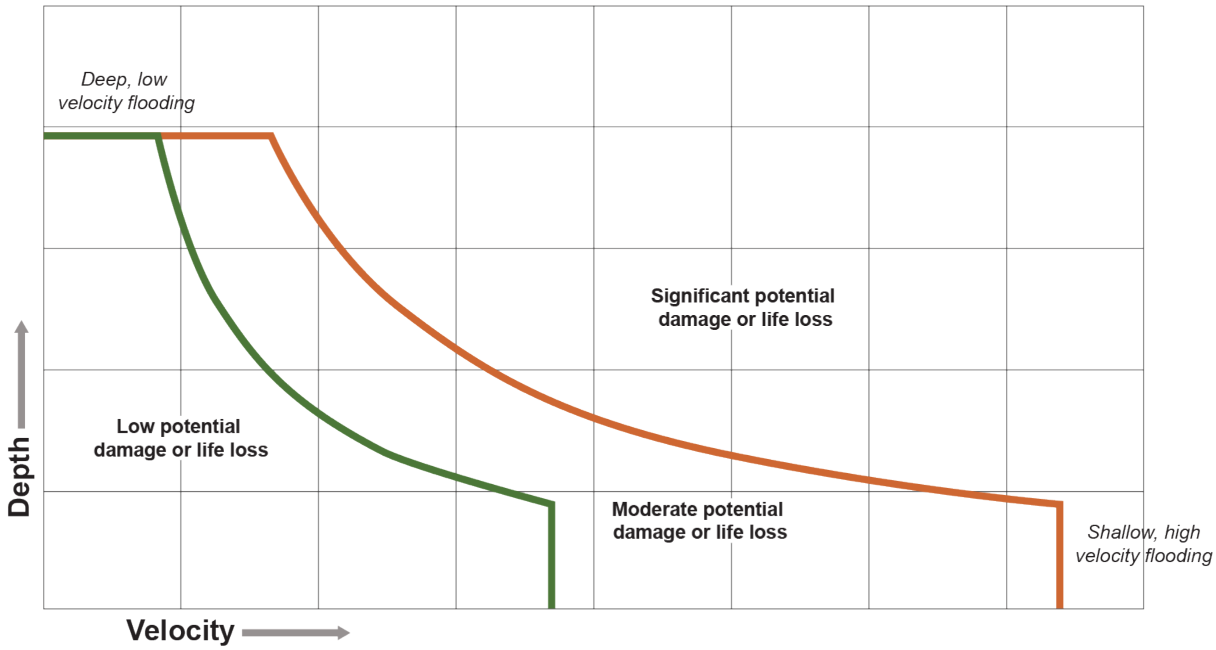
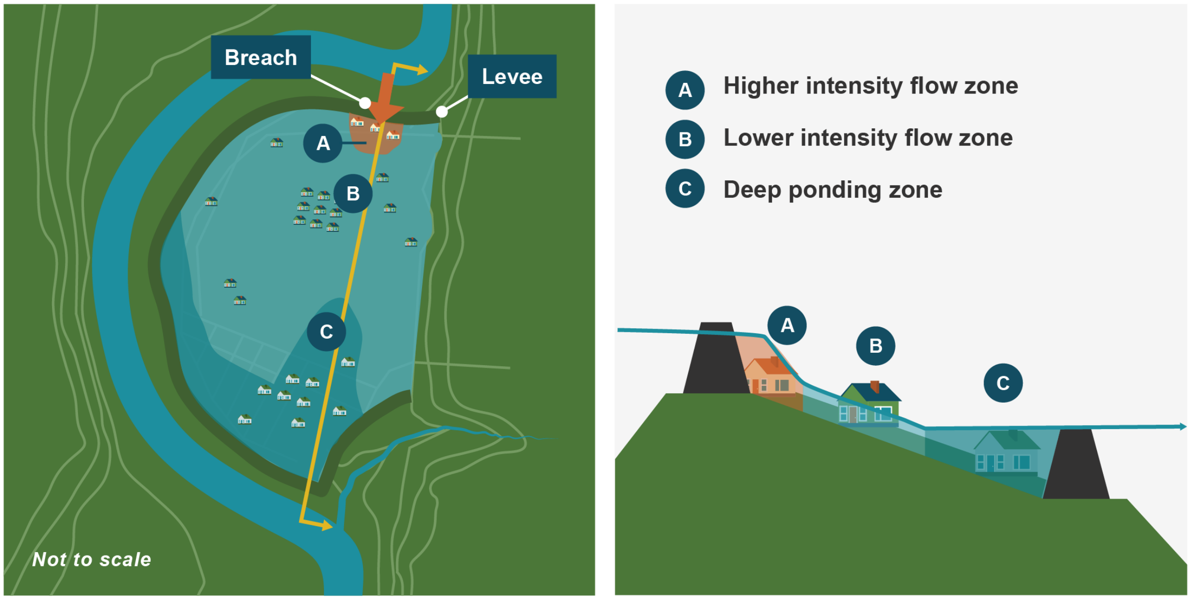


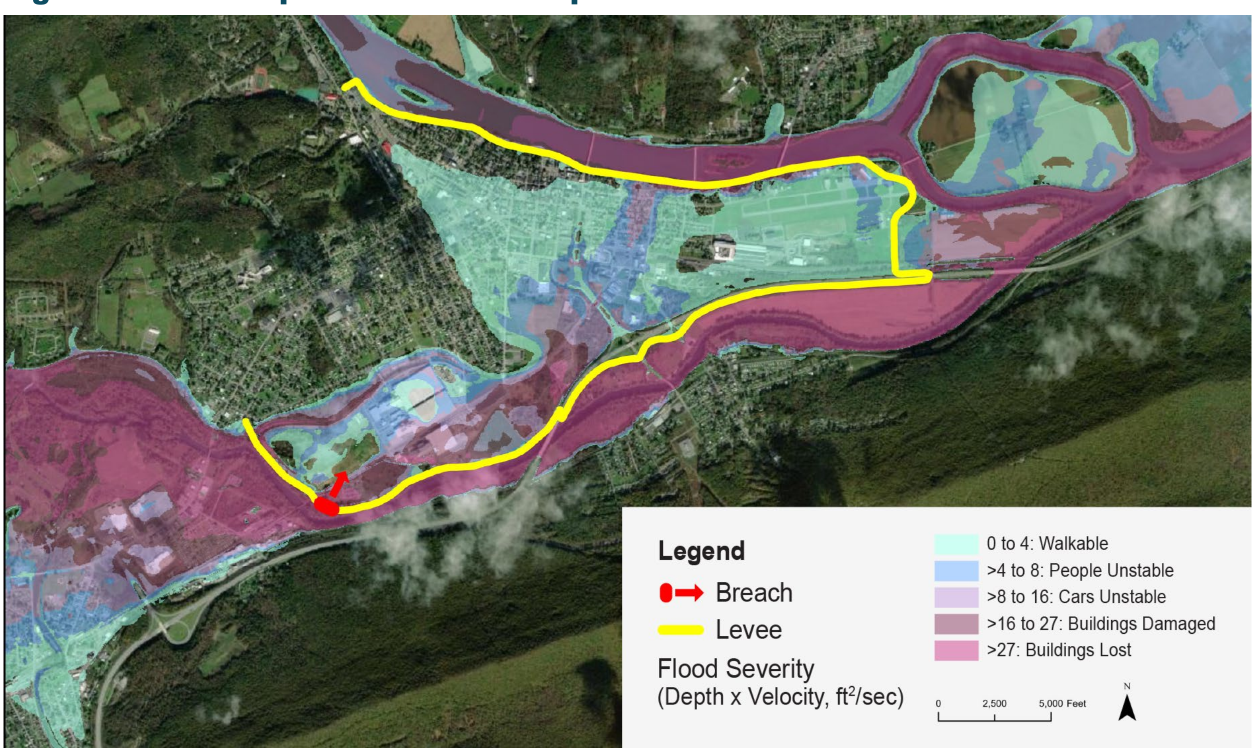
Figure 4-14 illustrates how the same levee breach results in different flood severities depending on location. Zone A is near the breach and is typically not a large area, but has the most damaging flood conditions and is the first to be impacted. Zone B is the next area to be flooded as the water spreads out. The majority of the population may be in this area, but the flood severity is less than in Zone A. Zone C is an area where ponding occurs against the landside of the levee, further downstream. velocities in this area may not be sufficient to destroy buildings and the water rises slowly, but people trapped in this zone may not be able to seek refuge in a structure, even if it is unmoved by the flood due to excessive flooding depths. This figure also illustrates how different locations within the leveed area may have different warning and evacuation times (discussed further in section 5.3.2). The population in Zone A may have very little warning while those in Zone C may have sufficient warning to evacuate.

Figure 4-14: Consequence Zones and Flood Severity



A flood force map can help illustrate flood severity and display additional information beyond flood depth and arrival times. These maps depict the danger associated with flood water by relating the depth and velocity of flow to its damage potential (Figure 4-15). For example, a depth and velocity less than 4 feet per second (ft^2/s) is considered walkable by most people, but above 27 ft^2/s causes buildings to float off their foundations or crumple under the hydraulic load (exact thresholds may differ).

Figure 4-15: Example Flood Force Map



Flood severity and consequence estimates can be useful in informing emergency preparedness and response. For example, there is a tipping point in flood exposure conditions where the chance of surviving a flood drops dramatically. This is typically when water levels are deeper than people can walk through and/or the velocity is fast enough to move vehicles or buildings. The hydraulic thresholds for higher fatality rates will vary depending on a person's circumstances when they come in contact with the flood water (e.g., in a strong building versus a weak one, in a car, or on foot). When this tipping point occurs at different locations, it can help prioritize warnings and evacuations within the leveed area. See **Chapter 10** for guidance on managing levee emergencies.

5.3.2 Estimating Life Loss

Life loss from flooding is a function of many factors and is primarily driven by:

- The extent of flooding and number of people impacted.
- The efficiency of the warning and evacuation within the time before flood arrival.
- The severity of the flood (depth and velocity).

In other words, how many people are in harm's way, how many can get out, and how severe is the flooding? A generic process for estimating life loss includes the following steps:

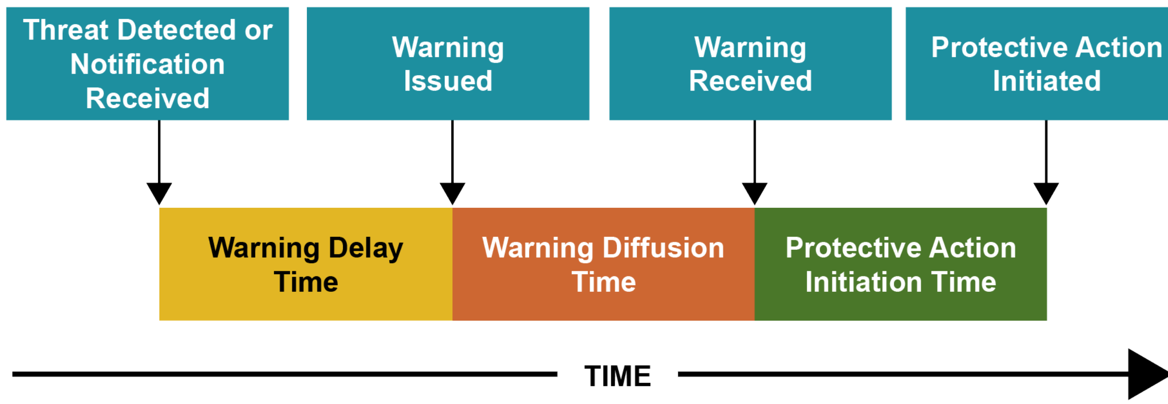
1. Define the leveed area.
2. Model the flood/breach scenarios (based on hazard and performance).
3. Estimate the population impacted by the flood.
4. Estimate the time required for warning and mobilization of the population.
5. Estimate the evacuation efficiency (based on warning time, evacuation time, arrival time).
6. Estimate fatality rates (based on hydraulics).
7. Apply fatality rates to the population in the leveed area.

Considerations when evacuating those within the leveed area include the potential for delays in identifying a potential flood and/or a lapse in the chain of communication which leads to miscommunication from decision makers to individuals in the leveed area. Figure 4-16 shows the flow of information from discovery of a hazard to the people at risk and their delay in taking protective action.

LIFE LOSS: IT IS NOT JUST A NUMBER

While current approaches for consequence estimating result in a specific number of lives that would be lost, the factors that drive life loss estimates are most important to the risk estimating team and to inform emergency planning for a levee breach. These factors include the severity of the flooding (depths and velocity), the ability of buildings in the leveed area to withstand the flooding, the population in the leveed area (number of people and characteristics, such as age and vulnerability), and warning and evacuation of this population (including communications, evacuation routes). This information can be used for both estimating risks and developing approaches to reduce consequences through emergency planning.

Figure 4-16: Hazard Detection and Warning Delay Timeline



5.3.2.1 Population Data and Structure Inventories

Estimating the population can be as simple as counting the structures in the inundation area and multiplying by an assumed number of people per structure. For larger populations and areas, inundation maps can be overlaid on census block data to obtain an estimate. Geographic information systems (GIS) and available datasets can facilitate these processes.

One resource for estimating populations in an inundation area is the National Structure Inventory,[7] which was developed by USACE in coordination with FEMA. The National Structure Inventory database contains information on structure location, building type, economic value of structure and contents, and most importantly on estimating life loss for the population in each structure. Population by structure is provided for day (2 p.m.) and night (2 a.m.), along with the population over and under 65 years old. The data can be imported into GIS or consequence estimating software.

5.3.2.2 Fatality Rates

A fatality rate is the percent of a given population that would lose their lives during a flood. To estimate life loss, the fatality rate is multiplied by the population in the leveed area. Depending on the consequence estimating method, this could be the entire population or only that portion of the population that does not evacuate (also known as the exposed population).

Flooding case histories—including those resulting from a dam or levee breach—are a valuable source of information for estimating fatality rates. Case histories have shown correlation between flood severity and fatality rates. Table 4-3 lists various sources for case histories that could be used for estimating fatality rates.

[7] National Structure Inventory: https://www.hec.usace.army.mil/confluence/nsi.

Table 4-3: Sources of Flood Fatality Data

Source	Link
Academic literature	Various
Reclamation Consequence Estimating Methodology case histories	https://www.usbr.gov/ssle/damsafety/documents/RCEM-CaseHistories2015.pdf
Association of State Dam Safety Officials	http://Damfailures.org
Estimating Life Loss for Dam Safety and Risk Assessment: Lessons from Case Histories (McClelland *et al.*, 2002)	USCOLD 2000 Lecture[8]
Centre for Research on the Epidemiology of Disasters emergency events database	https://www.emdat.be/
Base de Données Historiques sur les Inondations (historical flood database)	https://bdhi.developpement-durable.gouv.fr/
Technische Universiteit Delft flood fatality database	http://floodfatalities.tudelft.nl/floodfatality/

5.3.2.3 Methods and Tools for Estimating Life Loss

The level of detail and resolution of the life loss estimates are scalable to the purpose of the risk assessment and availability of data. The simplest method is to estimate population in the leveed area and multiply it by an approximate fatality rate, informed by applicable case studies. More detailed approaches rely upon information obtained from hydraulic modeling of various scenarios, consideration of uncertainty, and/or soliciting input from the community, emergency managers, and other stakeholders. Where appropriate, the inundation area should be separated by locations having similar characteristics related to flood severity, warning time, and other factors. More detailed consequence estimates consider factors such as the change in population with a time of day or season, the opportunities for people to shelter in place on higher floors of buildings, the ability of buildings to withstand flood impacts, the redistribution of population along evacuation routes as well as traffic congestion, and the specific challenges a particular population may face related to warning and evacuation (e.g., language barrier).

Two of the more common approaches for estimating life loss consequences from flooding that are used in the U.S. are the Reclamation Consequence Estimating Methodology and the USACE LifeSim computer model.

5.3.3 Estimating Direct Economic Damages

In general, direct economic consequences include damages to buildings and their contents, vehicles, public and private infrastructure, utilities, agricultural crops and capital, erosion loss to land, costs associated with responding to the emergency, cleaning up contaminates, and repairing or rebuilding the levee. Some levee owners may also consider less quantifiable things such as reputational harm, loss of environmental habitat, or impacts to historically significant resources. After life safety, the importance of various damage estimates is at the discretion of the regulator and/or levee owner.

[8] This lecture and similar publications by these authors were used in the development of the LifeSim program.

A generic process for estimating direct economic damages is similar to estimating life loss and includes the following steps:

- Define the leveed area.
- Model the flood/breach scenarios (based on hazard and performance).
- Estimate the assets that are impacted by the flood and assign economic value to these assets.
- Estimate levels of damage to the assets (based on hydraulics).
- Apply damages to the assets and estimate economic losses.

5.3.3.1 Asset Inventories

The inventory of the floodplain should include a comprehensive list of the assets in the defined inundation area. Assets may include property—and the built and natural environment—as pertinent to the types of consequences being considered. Advances in GIS databases have made this effort more streamlined, with the ability to obtain most of the asset data necessary for the consequence analysis from local, state, and federal agencies charged with maintaining such information. When a community or floodplain contains unique assets at risk of flooding, some field inspection or primary data collection may be warranted to develop an understanding of the potential losses.

The National Structure Inventory contains asset information that can be used to estimate economic damages, including structure type and size (square footage and number of stories), foundation height, value of the structure and its contents, and value of vehicles at the structure.

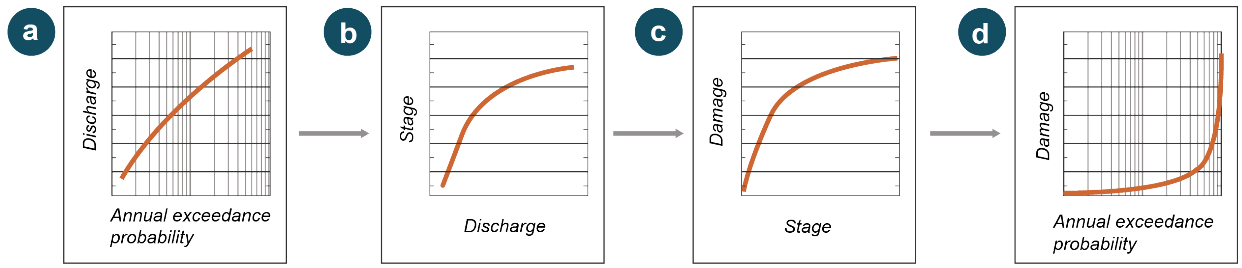
5.3.3.2 Asset Damage and Loss Functions

The quantification of vulnerability for the built environment usually relies on loss functions that relate depth of flooding to dollar loss. A loss function quantifies the consequences (damages or impacts) as a function of hazard exposure (e.g., depth, velocity, recurrence interval) and asset vulnerability (e.g., dollar loss, percent damaged, jobs lost).

Vulnerability of buildings is relatively well understood, and industry-standard loss functions (also referred to as stage damage curves) are available that relate depth and dollar loss by building type (e.g., single-family home, restaurant, hospital). Building/property damages are driven by the ultimate depth of flooding experienced, typically defined by a stage-damage function. Several factors impact this calculation including where a structure is located in the floodplain and the overall structure height (inclusive of the foundation and the number of stories). Flow velocity can also be a factor leading to collapse of a structure. This analysis requires information about the construction materials and size of the building. Damage to the contents of buildings should also be considered and in some cases, the value of these contents may outweigh the value of the building itself.

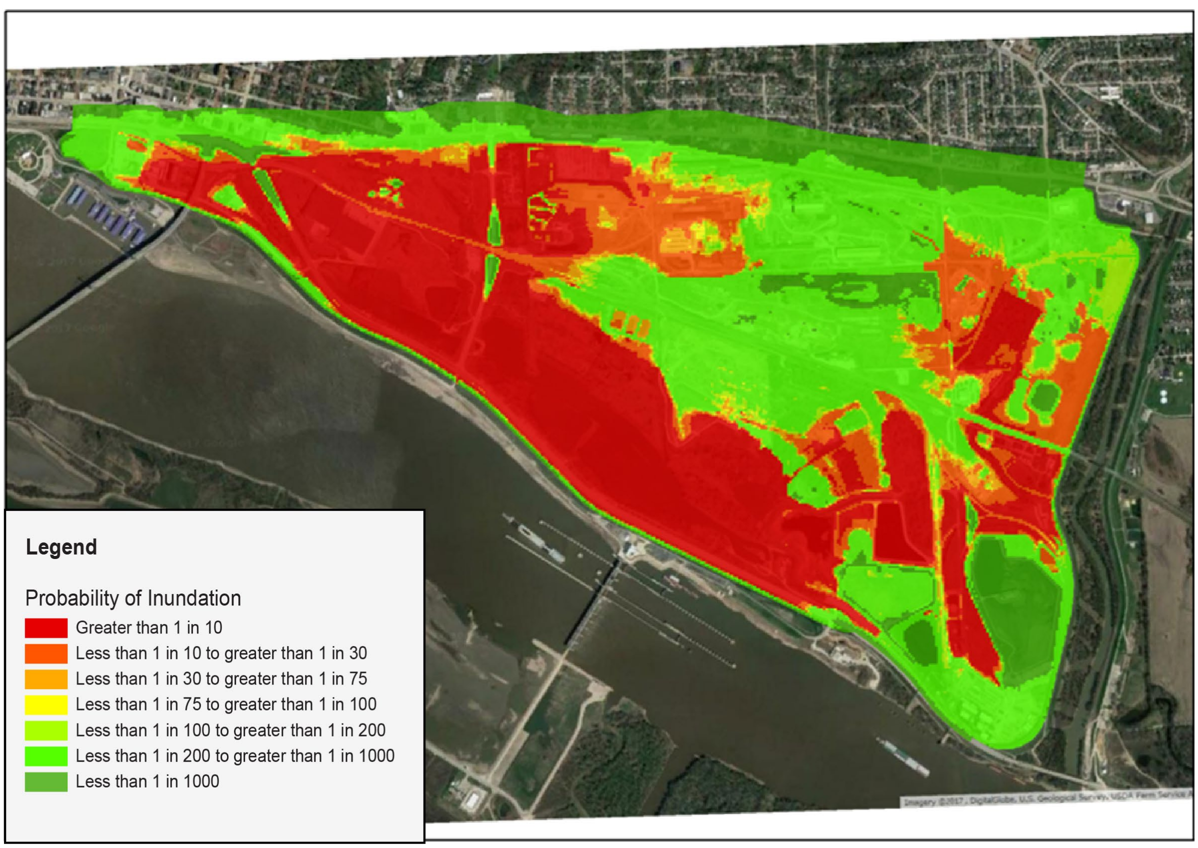
Depth damage curves can be developed for damage to structures, a structure's contents, vehicles, roads, and agricultural crops. Standard curves have been developed by FEMA and USACE for several structure types and vehicles. In detailed consequence models, they can be applied to each structure in the flooded area geographically to estimate flood damages by structure. Various relationships (probability-discharge, discharge-stage) can be combined with the stage damage curve to estimate the probability of exceeding a particular level of flood damage for a particular asset, as schematically illustrated in Figure 4-17. These results could be used to spatially illustrate the potential for damages in the leveed area.

Figure 4-17: Use of Stage Damage Curve to Develop a Probability-Damage Relationship



Flood depth frequency maps (Figure 4-18) can help visualize the potential for damages. These maps display the probability of flooding exceeding a given depth (e.g., 0.1 or 2 feet) for an area, which can then be used to estimate expected damages. Their advantage is in their capability to account for the probability of levee failure in expressing the resultant variation of the probability of inundation of various areas.

Figure 4-18: Example Probability of Inundation Map



5.3.3.3 Methods and Tools for Estimating Direct Economic Damages

Specialized software packages are available that support economic consequence estimation such as Hydrologic Engineering Center Flood Damage Assessment, FEMA Hazards U.S., Risk Management Center LifeSim, and other tools. These tabular or GIS-enabled software packages allow exposure data (e.g., flood depth or depth-velocity maps) to be overlaid on asset inventories. Given user-specified stage-damage or loss functions, the software will compute individual asset-level consequence estimates, as well as aggregate floodplain-level consequence estimates for the flood event being modeled.

5.3.3.4 Community Vulnerability

A community’s vulnerability to flooding is important in estimating and understanding consequences. While avoiding loss of life is of paramount concern, consideration is also given to health effects, as well as employment and social impacts that diminish one's quality of life. Understanding disparities in human vulnerability within communities and floodplains that may result in underserved populations bearing a disproportionate share of adverse flood impacts or experiencing disproportionately severe effects from flooding is essential in consequence assessment. For example, flooding in low-income neighborhoods is likely to have more substantial indirect effects on families, as they may lack the economic resources to make rapid home repairs or may be at greater risk of job loss due to missed workdays or loss of transportation. Similarly, flood damage to a major local or regional employment facility could have significant impacts on vulnerable populations. Another example is a retirement community, where the older residents may be at greater risk of life loss—compared to other populations with similar flood exposure—due to reduced evacuation speed or ability. These and many other demographic, economic, or social indicators may be useful in developing a nuanced understanding of vulnerable populations within a floodplain. Such information is often available from the U.S. Census Bureau-American Community Survey, as well as from state and local health departments. By considering these factors, the consequence analysis may expand the characterization of risk beyond consideration of only dollar losses, adding consideration of population vulnerabilities and spatial distribution of impacts within the community.

5.3.4 Indirect Consequences

Indirect consequences may extend to people, regional economics, or the environment beyond the leveed area. They include indirect life loss and indirect damages. Some examples of indirect consequences are fatalities due to evacuation stress or lack of medical care, business losses, and disrupted navigation. Typically, indirect consequences are considered qualitatively in the risk assessment, but there are some methods in development to quantitatively assess the ‘ripple effects’ of a levee failure.

INDIRECT CONSEQUENCE EXAMPLE

The 2011 Tohoku earthquake and tsunami caused a meltdown at Tokyo Energy and Power Company's Daiichi #2 nuclear power plant. A seawall designed to prevent coastal flooding was overtopped by the tsunami and allowed the plant to flood. The incident at the reactor led to additional evacuations for people living near the plant due to airborne radiation emissions. The earthquake and tsunami caused many thousands of direct fatalities and damages to infrastructure and the environment. The extended evacuation and environmental contamination also caused indirect fatalities and damages. In a 2020 estimate, over 40,000 people were still not able to return to their homes nearly a decade later. More than 3,000 evacuees had died, which is partially attributable to the stress of the evacuation and lack of adequate medical care. It is typically elderly people or those who need medical/psychological care that become indirect victims of a flood or other disaster. In addition to indirect life loss, other indirect damages and losses have occurred. Storm debris and radiation have been spread by oceanic currents causing pollution far from the impacted area. The loss of power generation and radiation containment has resulted in significant costs to Tokyo Energy and Power Company and the government.

5.3.5 Considering Changing Conditions

Over time, the land and population within the leveed area can change, impacting consequence estimates. One of the largest drivers of risk change over time is additional development in the leveed area, which leads to higher potential consequences, both for levee breach or non-breach scenarios. See **Chapter 5** for potential strategies for managing potential increases of levee risk.

6 Computing a Risk Estimate

The following sections provide guidance on combining various outputs of hazard, performance, and consequence assessments to estimate levee risk and flood risk in the leveed area.

The discussion of computing each type of risk is followed by an example calculation using semi-quantitative approaches for risk estimates. This calculation would be similar for a quantitative risk assessment. The purpose of the examples are to illustrate the overall logic, rather than specifics of a particular risk assessment. The calculations are intentionally simplified, and several estimates are considered 'given' without providing details of how to calculate them.

6.1 Levee Risk

Levee risk is the portion of flood risk associated with the levee itself, also known as incremental risk. **Levee risk** is defined as the likelihood of occurrence and potential consequences for the following three inundation scenarios: prior to overtopping, overtopping with breach, and component malfunction or misoperation of levee features. It is calculated by combining the risk due to breach prior to overtopping—which may be the combination of multiple potential failure modes, including component malfunction or misoperation—with the risk due to overtopping with breach. As discussed in section 5.3, only incremental consequences are used to estimate levee risk.

It is common to focus risk estimating on potential failure modes that are suspected to be **risk drivers**—those that contribute significantly to the total risk estimate and may require taking a risk management action. Therefore, a potential failure mode may be excluded from further consideration as soon as it is understood to be significantly lower risk than another failure mode. The assumptions to that point and comparison to the risk driver should be clearly documented.

6.1.1 Breach Prior to Overtopping or Component Malfunction/Misoperation

Breach prior to overtopping could result from a variety of potential failure modes, discussed in section 5.2.2. Typically, more than one potential failure mode contributes to the risk.

The total annual probability of breach prior to overtopping ($APF_{\text{breach prior OT}}$) is calculated by adding together the annual probability estimates for all individual potential failure modes. This calculation assumes the potential failure modes are mutually exclusive, which is not always true. If this assumption is incorrect for the levee in question, individual estimates should be combined using alternative methods. These options include assuming joint failure modes or competing failure modes (section 6.4.2).

The expected annual consequences due to levee breach prior to overtopping is calculated by summing the average annual life loss estimates for all the individual potential failure modes. The same principles apply as with combining the annual probability of failure. Average annual life loss is equal to the product of the failure probability and the average consequences.

MALFUNCTION OR MISOPERATION OF A LEVEE FEATURE—CONTRIBUTION TO LEVEE RISK

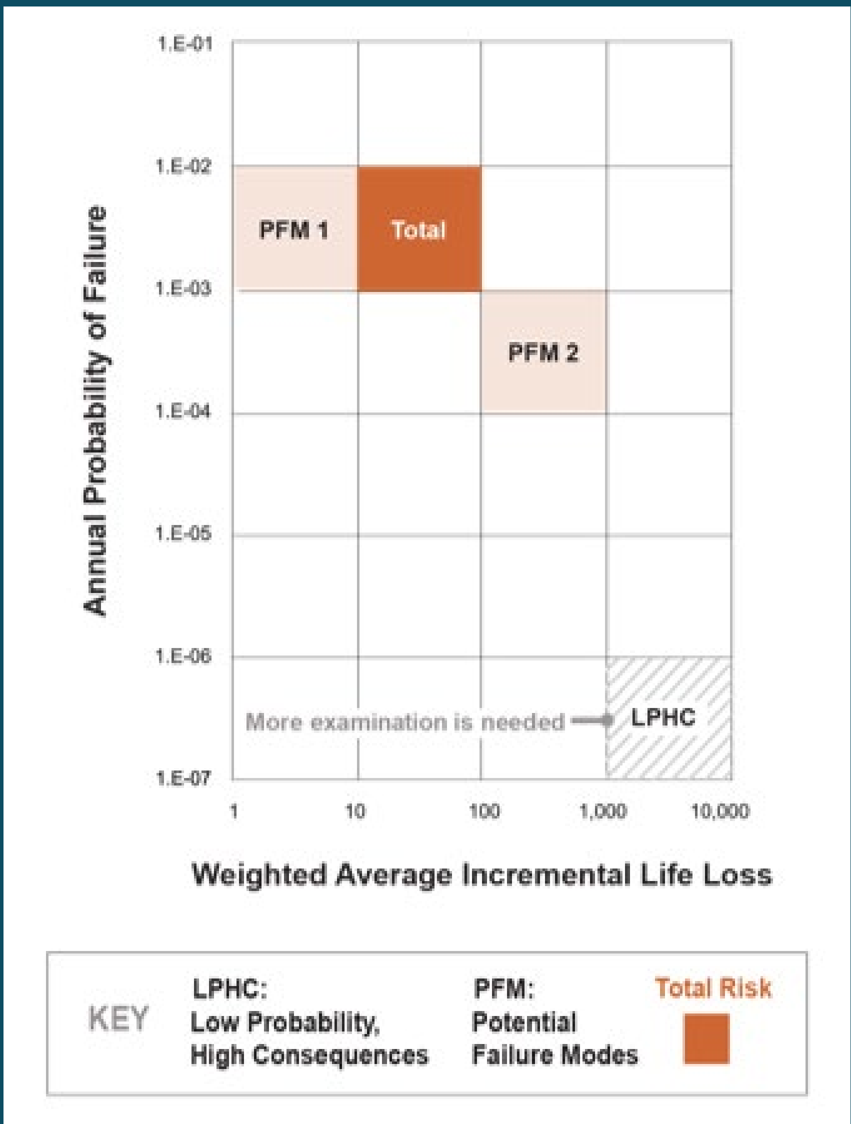
Component malfunction or misoperation could occur prior to or following levee overtopping. An important distinction should be made about how the risk of misoperation/malfunction contributes to levee risk based on the flood source. The levee is designed to prevent flooding from a certain source (or perhaps multiple external sources). Misoperation of a closure that allows this water to enter the leveed area is part of the levee risk from the same source as the levee and should be included in the breach prior to overtopping risk. However, if the levee induces flooding by failure to remove interior water, that levee risk should be portrayed and characterized separately from the main source of flooding. Interior drainage flooding is typically less damaging than flooding from the primary source, due to lower depths and velocities, but life loss and economic damages are possible. Interior flooding that exceeds the design level of the gate or pump station would be considered part of the non-breach risk.

BREACH PRIOR TO OVERTOPPING: EXAMPLE CALCULATION IN A DETAILED SEMI-QUANTITATIVE RISK ASSESSMENT

In detailed semi-quantitative risk assessment, where probability and consequences are estimated using order of magnitude boxes, the center of the order-of-magnitude box is used as a point estimate. Because risk estimates are portrayed and evaluated in logarithmic space, a geometric mean is used to calculate the point estimate at the center of a box.

Given:

	Annual Probability of Failure, APF (failures/year)	$\bar{N}$ (Average Incremental Life Loss, lives/failure)
Potential Failure Mode (PFM) 1	$1 \times 10^{-3} - 1 \times 10^{-2}$	1-10
Potential Failure Mode (PFM) 2	$1 \times 10^{-4} - 1 \times 10^{-3}$	100-1000



BREACH PRIOR TO OVERTOPPING: EXAMPLE CALCULATION IN A DETAILED SEMI-QUANTITATIVE RISK ASSESSMENT (CONTINUED)

Step 1: Calculate the $\boldsymbol{APF}$, using the geometric mean.

$$APF_{PFM\ 1} = \sqrt{1 \times 10^{-2} * 1 \times 10^{-3}} = 3.16 \times 10^{-3}$$
$$APF_{PFM\ 2} = \sqrt{1 \times 10^{-3} * 1 \times 10^{-4}} = 3.20 \times 10^{-4}$$

Step 2: Calculate the $\overline{\boldsymbol{N}}$, average incremental life loss, using the geomean.

$$\overline{N}_{PFM\ 1} = \sqrt{1 * 10} = 3.2$$
$$\overline{N}_{PFM\ 2} = \sqrt{100 * 1000} = 320$$

Step 3: Calculate the total probability of breach prior to overtopping ($\boldsymbol{APF_{POT\ (prior\ to\ overtopping)}}$).

$$APF_{POT} = APF_{PFM\ 1} + APF_{PFM\ 2}$$
$$APF_{POT} = 3.48 \times 10^{-3}\ {}^{failures}/_{year}$$

Step 4: Calculate the total societal risk for breach prior to overtopping.

$$Average\ Annual\ Incremental\ Life\ Loss = AALL_{POT} = (APF_{PFM\ 1} * \overline{N}_{PFM\ 1}) + (APF_{PFM\ 2} * \overline{N}_{PFM\ 2})$$
$$AALL_{POT} = 1.00 \times 10^{-1}\ {}^{lives}/_{year}$$

Step 5: Calculate the average life loss.

$$\overline{N} = Average\ Incremental\ Life\ Loss = {}^{AALL_{POT}}/_{APF_{POT}}$$
$$\overline{N} = 29\ lives/failure$$

6.1.2 Overtopping with Breach

Levee overtopping for floods that exceed the design capacity will result in flooding of the leveed area, but a levee breach from overtopping (also called overtopping with breach) can exacerbate this flooding. The additional (incremental) consequences may be due to increased flood depths and velocity, increased flood forces, and/or faster arrival time that reduces the ability to evacuate.

The consequences of overtopping with and without a levee breach often converge at some large flood event such that the incremental consequences become zero, meaning the levee is not providing flood risk reduction for those events. This is an important scenario for the risk estimate because the risk posed by the levee is negligible for larger, less frequent floods. In some cases, interpolation or extrapolation of consequence information is necessary to estimate the probability for this flood event.

Whether incremental consequences become smaller and smaller for larger and larger floods can be influenced by the size of the leveed area, volume of the leveed area, rate of rise in the leveed area, depth of overtopping, overtopping discharge, duration of overtopping, overtopping volume, breach formation time, breach size, and shape of the flood hydrograph. Some questions to consider might include:

- Is there sufficient overtopping volume to fill the leveed area with and without a levee breach?

- Is there sufficient overtopping volume to fill the leveed area prior to reaching the critical overtopping elevation?
- Will overtopping flow pooled at the downstream end of the leveed area overtop back into the river, causing a breach that limits the flood depths?
- Does the extent and depth of flooding progress at a similar rate with and without a levee breach?
- At what flood magnitude does the levee become overwhelmed?
- Do consequences continue to increase with increasing flood magnitude, or do they begin to taper off?

The consequences of overtopping with and without a levee breach do not converge for every levee. The incremental consequences could continue to increase with increasing flood magnitude. In these cases, it is necessary to estimate an overtopping flood that captures the majority of the societal risk. This flood should produce widespread flooding of the leveed area such that larger floods would not substantially change the average consequence estimate. This flood should also be infrequent enough, such that the probability contribution of the flood does not substantially impact the risk estimate.

The probability of failure for overtopping erosion can be estimated by combining the loading (annual probability of overtopping) and performance (conditional probability of breach given overtopping) over a range of overtopping events. This is typically done in 1 foot or similar increments of overtopping depth that adequately captures the risk estimate from the maximum (most frequent) annual exceedance probability of overtopping (AEP_{TOL}) up to a critical location where breach is estimated to occur.

For a semi-quantitative risk assessment, a single probability of failure estimate (p(f) = 1) at a critical location and critical overtopping depth is typically used for a simplified and sufficient estimate. The critical overtopping elevation approach assumes the probability of breach is 0% below this level and 100% above this level. The consequences however should still be estimated for a range of overtopping depths to properly estimate incremental consequences. Estimating incremental consequences based on a single flood (e.g., the critical overtopping elevation) typically results in overestimating the societal risk posed by the levee.

OVERTOPPING WITH BREACH: EXAMPLE CALCULATION

Step 1: Calculate the average annual incremental life loss, $\bar{N}$.

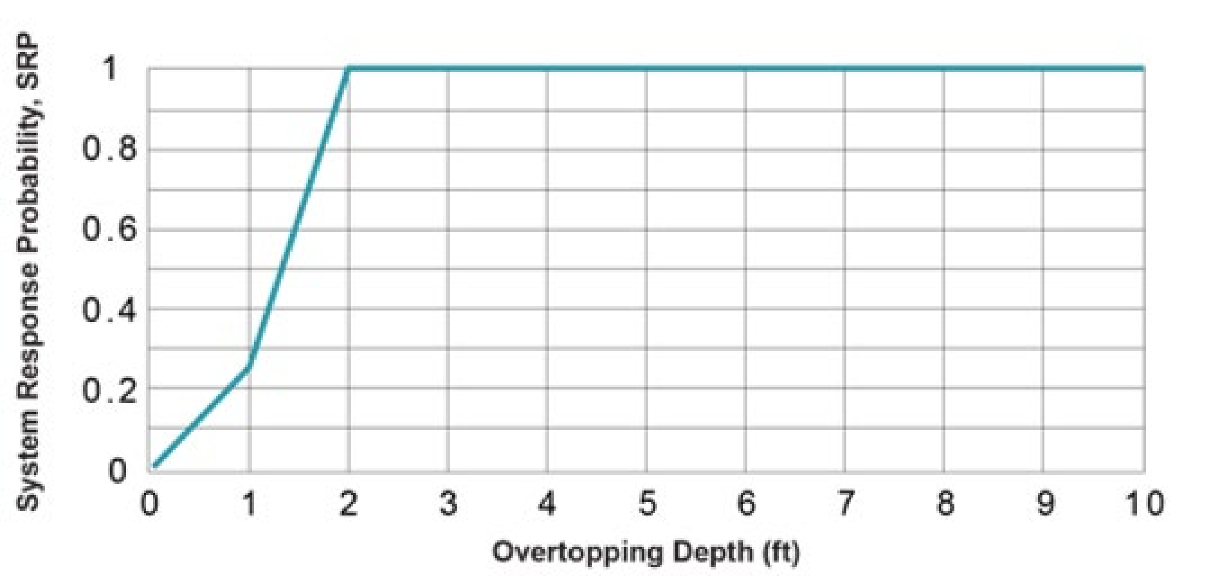
Calculation	$\bar{N}$
$\frac{(4.0\times10^{-3}-3.8\times10^{-3})\times(\frac{0+0.25}{2})\times(0+595)}{2}$	0.007
$\frac{(3.8\times10^{-3}-3.5\times10^{-3})\times(\frac{0.25+1}{2})\times(595+700)}{2}$	0.121
$\frac{(3.5\times10^{-3}-3.0\times10^{-3})\times(\frac{1+1}{2})\times(700+800)}{2}$	0.375
$\frac{(3.0\times10^{-3}-2.5\times10^{-3})\times(\frac{1+1}{2})\times(800+400)}{2}$	0.300
$\frac{(2.5\times10^{-3}-2.0\times10^{-3})\times(\frac{1+1}{2})\times(400+0)}{2}$	0.100
$2.0\times10^{-3}\times1\times0$	0

Step 2: Calculate the societal risk due to levee overtopping with breach.

$$\sum Average\ Annual\ Incremental\ Life\ Loss\ for\ all\ scenarios, AALL_{OT\ (overtopping)} = 0.9\ lives/year$$

Step 3: Calculate APF_{OT},.

Given:



$$Incremental\ Probability = AEP_{OT\ depth\ A} - AEP_{OT\ depth\ B}$$

; where OT depth A < OT depth B

$$Incremental\ APF = SRP \times Incremental\ Probability$$

OVERTOPPING WITH BREACH: EXAMPLE CALCULATION (CONTINUED)

Using information from the plot and equations above, the following table can be populated:

Overtopping Depth (feet)	System Response Probability, SRP	Incremental Probability	Incremental APF Overtopping
0-1	0.125	$\mathbf{2.0 \times 10^{-4}}$	$\mathbf{2.50 \times 10^{-5}}$
1-2	0.625	$\mathbf{3.0 \times 10^{-4}}$	$\mathbf{1.88 \times 10^{-4}}$
2-3	1	$\mathbf{5.0 \times 10^{-4}}$	$\mathbf{5.0 \times 10^{-4}}$
3-6	1	$\mathbf{5.0 \times 10^{-4}}$	$\mathbf{5.0 \times 10^{-4}}$
6-10	1	$\mathbf{5.0 \times 10^{-4}}$	$\mathbf{5.0 \times 10^{-4}}$
>10	-	$\mathbf{2.0 \times 10^{-3}}$	$\mathbf{2.0 \times 10^{-3}}$

$$\sum Incremental\ APF_{OT} = APF_{OT} = \mathbf{1.7 \times 10^{-3}}$$

Step 4: Calculate $\overline{N}$, average life loss.

$$\overline{N} = Average\ Incremental\ Life\ Loss = \frac{APF_{OT}}{AALL_{OT}} = 242\ lives/failure$$

6.2 Non-Breach

Non-breach risk is a risk estimate that assumes the population in the leveed area is not exposed to the potential for a levee failure. The non-breach risk can be calculated by assuming the probability of levee failure is equal to zero and estimating the consequences of flooding associated with levee overtopping. In a typical levee risk assessment, these are the consequences associated with flood waters exceeding the top of the levee without the levee failing. The non-breach risk can be calculated by increasing overtopping depths until maximum consequences occur.

NON-BREACH: EXAMPLE CALCULATION

Given:

Overtopping (OT) Event	OT Depth (feet)	AEP	Non-Breach Life Loss
Top of levee (TOL)	0	$\mathbf{4.0} \times \mathbf{10^{-3}}$	0
1-ft overtopping	1.00	$\mathbf{3.8} \times \mathbf{10^{-3}}$	5
2-ft overtopping	2.00	$\mathbf{3.5} \times \mathbf{10^{-3}}$	100
3-ft overtopping	3.00	$\mathbf{3.0} \times \mathbf{10^{-3}}$	800
6-ft overtopping	6.00	$\mathbf{2.5} \times \mathbf{10^{-3}}$	2,000
10-ft overtopping	10.00	$\mathbf{2.0} \times \mathbf{10^{-3}}$	3,100
Infinite OT	>10	~**0**	3,100

Step 1: Extract $AEP_{\ TOL\ (top\ of\ levee)}$ and $AEP_{life\ loss\ initiation}$ from table:

$$AEP_{TOL} = AEP_{\ life\ loss\ initiation} = 0.004$$

Step 2: Calculate average annual life loss for non-breach.

Calculation	Average Annual Life Loss
$\frac{(\mathbf{4.0 \times 10^{-3} - 3.8 \times 10^{-3}) \times (0+5)}}{\mathbf{2}}$	0.0005
$\frac{(\mathbf{3.8 \times 10^{-3} - 3.5 \times 10^{-3}) \times (5+100)}}{\mathbf{2}}$	0.02
$\frac{(\mathbf{3.5 \times 10^{-3} - 3.0 \times 10^{-3}) \times (100+800)}}{\mathbf{2}}$	0.23
$\frac{(\mathbf{3.0 \times 10^{-3} - 2.5 \times 10^{-3}) \times (800+2000)}}{\mathbf{2}}$	0.70
$\frac{(\mathbf{2.5 \times 10^{-3} - 2.0 \times 10^{-3}) \times (2000+3100)}}{\mathbf{2}}$	1.28
$(\mathbf{2.0 \times 10^{-3} - 0) \times (3100)}$	6.20

$$\sum Average\ Annual\ Non\text{-}Breach\ Life\ Loss = 8.4\ lives/year$$

Step 3: Calculate number of lives non-breach (NNB).

$$N_{NB} = \frac{\sum Average\ Annual\ Non\text{-}Breach\ Life\ Loss}{AEP_{\ life\ loss\ initiation}} = \frac{8.4}{0.004} = 2{,}100\ lives$$

6.3 Flood Risk

Flood risk associated with a levee is the sum of levee risk and non-breach risk from the same flood source. The calculation example below combines the levee risk and non-breach risk from earlier calculations to determine the total flood risk.

FLOOD RISK: EXAMPLE CALCULATION

From previous calculations above:

Risk Type	Average Annual Life Loss
Breach Prior Overtopping, $\boldsymbol{AALL_{POT}}$	0.1
Overtopping with Breach, $\boldsymbol{AALL_{OT}}$	0.8
Non-Breach, $\boldsymbol{AALL_{NB}}$	8.4

Step 1: Calculate levee risk.

$$Levee\ Risk, AALL\ = \sum AALL_{POT} + AALL_{OT}\ = 0.9\ lives/year$$

Step 2: Calculate flooding risk.

$$Flood\ Risk, AALL_R = \sum AALL +\ AALL_{NB} = 9.3\ lives/year$$

6.4 Considerations for Levee Risk Calculation

6.4.1 Length Effects

Systems fail at locations where loads are high and strengths are insufficient to resist the load. If these critical locations are known or can be identified ahead of time, the overall length of the system is usually immaterial because the performance of the system is dominated by the performance of the weak spots. The more common situation is that the system is not characterized with enough detail to know the weakest spots with reasonable certainty. In this case, any section of the system has some probability of experiencing higher than average loads and/or lower than average strengths. Because these locations cannot be uniquely identified before a failure occurs, a longer system length results in a greater probability of a failure.

There is currently no standard practice identified for dealing with length effects directly, although some research in the Netherlands has attempted to combat the issue by considering prior levee performance (Roscoe *et al.*, 2020). Overestimation of the risk can be combatted by use of logic trees to characterize the uncertainty of levee fragility to optimize the reach length (National Research Council, 2013, Appendix I).

A detailed discussion of length effects is beyond the scope of these guidelines. Risk estimators should consult with appropriate experts when estimating risks for long levees or for levees with many components (e.g., a levee with many pipe penetrations).

6.4.2 Combining Risk

There is typically more than one potential failure mode that could lead to a levee breach. To properly estimate levee risk, it is necessary to combine risks due to individual potential failure modes. An often-reasonable approximation for screening is to simply add all probabilities together to estimate the overall probability of failure. However, it could lead to an overestimation of risk. There are two methods to prevent overestimation of the risk.

One such method is the competing risk model where each failure mode competes to be the first failure. The weakest failure mode will occur first, at which point subsequent failures are not possible. The following statements must be reasonably true in order to use the competing risk method.

- Each failure mechanism leading to a particular type of failure (i.e., failure mode) proceeds independently of every other one, at least until a failure occurs.
- The levee fails when the first of all the competing failure mechanisms reaches a failure state.
- Each of the potential failure modes has a known consequence estimate.

This method is used in the USACE Levee Screening Tool (see Levee Screening Tool call out box in section 3.2).

The second method is the joint risk model where more than one failure mode can occur during the same hazard event. The following statements must be reasonably true in order to use the joint risk method.

- Each failure mechanism leading to a particular type of failure (i.e., failure mode) proceeds independently of every other one, at least until a failure occurs.
- Multiple failures can occur during the same hazard event.
- When multiple failures occur, consequences must be explicitly estimated, or a simplifying assumption must be made such as taking the maximum, sum, or average of the consequences for each failure mode.

7 Risk Characterization

Risk characterization describes the levee in the context of risk by considering the key drivers of likelihood of performance, potential consequences, and sources of uncertainty. In other words, it is used to portray and describe the risk associated with the levee, as well as flood risk reduction benefits it provides. Risk characterization builds on a risk estimate and requires developing a risk narrative, supported by a risk portrayal and preparing the case for risk-informed recommendations. A good risk characterization converts the scientific evidence-based information and the remaining uncertainty into a statement of risk that informs levee risk management activities (**Chapter 5**).

7.1 Risk Narrative

A risk narrative is an explanation that bounds and depicts a risk estimate for decision-making purposes. It's the story that accompanies the risk estimate that places it in a proper context for levee risk managers and others to understand. This means understanding the benefits the levee provides, as well as the limitations of its ability to manage flood risk in the leveed areas. Understanding the basis of the risk estimates and the context is as important as the risk estimates themselves.

The risk narrative should cite the most compelling information that supports the risk estimates and the overall findings regarding levee risk, flood risk, and non-breach risk. The risk narrative should provide a logical and objective set of arguments that string together key evidence for the three basic components of the risk estimate. The goal of the risk narrative is to convince decision makers that the portrayal of a levee's condition and its ability to withstand future loading are all adequate for justifying the decisions.

The arguments should also address main sources of uncertainty. The risk narrative should not be used as a means of backfitting an argument for design or business decisions that have already been made.

Information that may be included in a risk narrative includes:

- General description of the levee, including length, height, and features.
- General description of the leveed area including population, critical infrastructure, and the value of economic activities. It is helpful to present this information in terms of flood risk reduction benefits provided by the levee (e.g., annual economic damages avoided).
- Estimated critical flood events:
  - Flood that is expected to overtop the levee. For levees with a controlled overtopping location, include annual exceedance probability of a flood that is expected to activate it. This quantifies annual probability of inundation due to overtopping without breach.
  - Flood that results in the highest incremental consequences.
  - Flood above which incremental risk associated with the levee is negligible, which sometimes is referred to as ultimate overtopping flood.
- Estimated levee risk, including a discussion of whether the risk is driven by breach prior to overtopping or overtopping with breach.
- Non-breach risk and flood risk.
- Sources of uncertainty, sensitivity of risk estimates to key input parameters, and confidence in the risk estimates.

7.2 Risk Portrayal and Communication Aids

The levee risk is primarily shown on a **risk matrix**, which is a graph depicting the relationship between the probability of inundation (shown on the vertical axis) and consequences (shown on the horizontal axis) to help one's understanding of the risk. Other outputs of a risk assessment can accompany the risk narrative to help communicate the understanding of risk with stakeholders and decision makers, such as inundation maps (section 5.3.1.2), flood hazard maps (section 5.1.1.2) and flood depth frequency maps (section 5.3.3.2). Inundation maps that show depth of flooding and arrival time for flood waters discussed in section 5.3.1 are the most common maps used to portray the potential for flooding in a community and are often used in emergency preparedness plans for evacuation planning. These products do not truly represent flood risk because they do not account for probability.

SOCIETAL RISK GUIDELINES

A probability-weighted average annualized life loss guideline of less than 0.001 (1/1,000) lives per year and an annual exceedance probability of life loss less than 1/N * 10^{-3} are considered reasonable risk neutral guidelines for societal risk by many levee and dam safety organizations in the U.S. and internationally. It is important to note that these societal guidelines are not limited lines of tolerability but guidelines or reference lines to inform and justify risk management actions, further explained in **Chapter 5**.

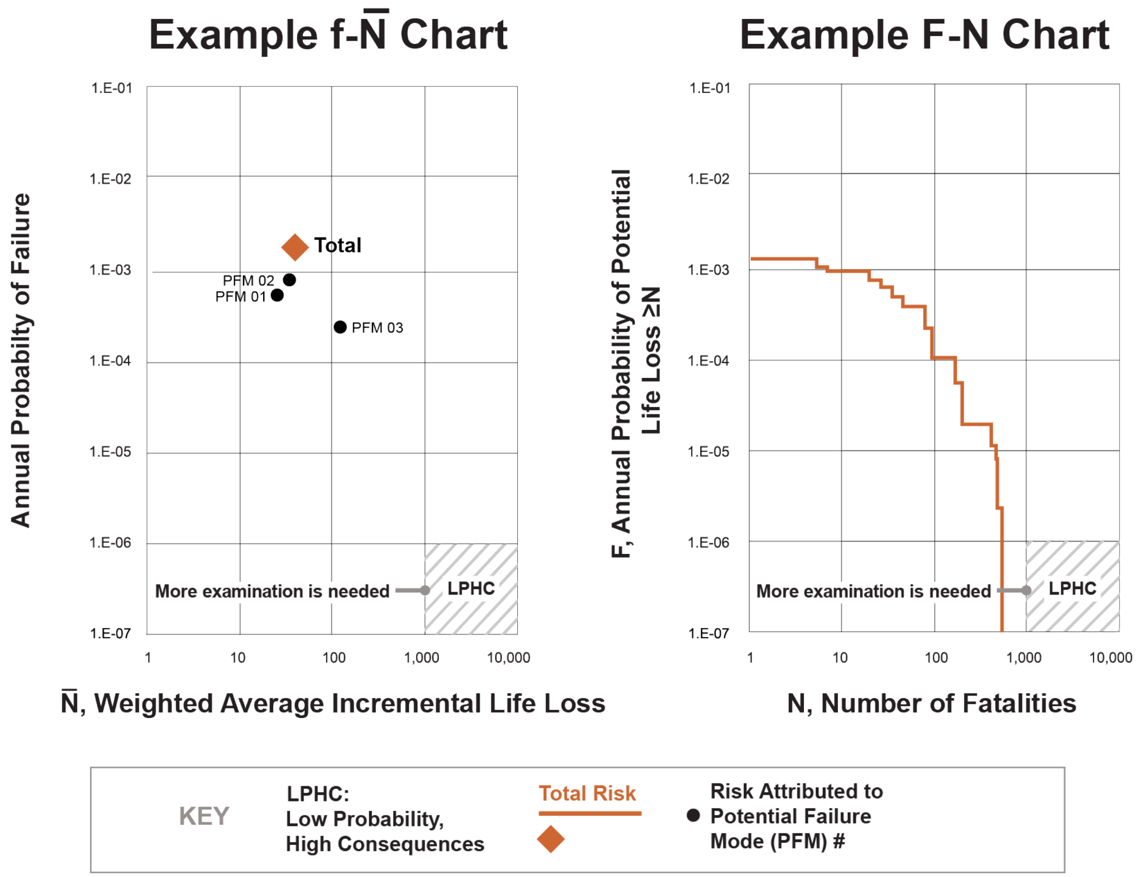
7.2.1 Risk Matrices

Risk estimates are typically shown on either an f-$\bar{N}$ or F-N plot. On an f-$\bar{N}$ plot, a risk estimate is shown as a pair (f, $\bar{N}$) while on the F-N plot, the same risk estimate is portrayed as a curve. Figure 4-19 shows examples of both types of charts. While f-$\bar{N}$ or F-N charts may look similar, they are distinctly different.

In an f-$\bar{N}$ plot, the vertical axis (f) is the annualized probability of inundation resulting from levee performance and $\bar{N}$ is the expected (mean) value of life loss conditional upon on that inundation. This means that $\bar{N}$ is the probability-weighted sum over all possible fatality numbers that could result from the failure event. For any point on the chart, the probabilities (on the vertical axis) and conditional expectations (on the horizontal axis) must relate to the same event. On an f-$\bar{N}$ plot, estimates with differing levels of detail may plot as a box covering an order of magnitude (semi-quantitative risk assessment), a single point, or a cloud of points showing the distribution of uncertainty (quantitative risk assessment). The results must be quantified to some degree in order to plot.

In an F-N plot, the vertical axis (F) is the annual exceedance probability of life loss N, plotted on the horizontal axis. Note, this N is not a conditional expectation. An F-N plot portrays the full range of potential life loss.

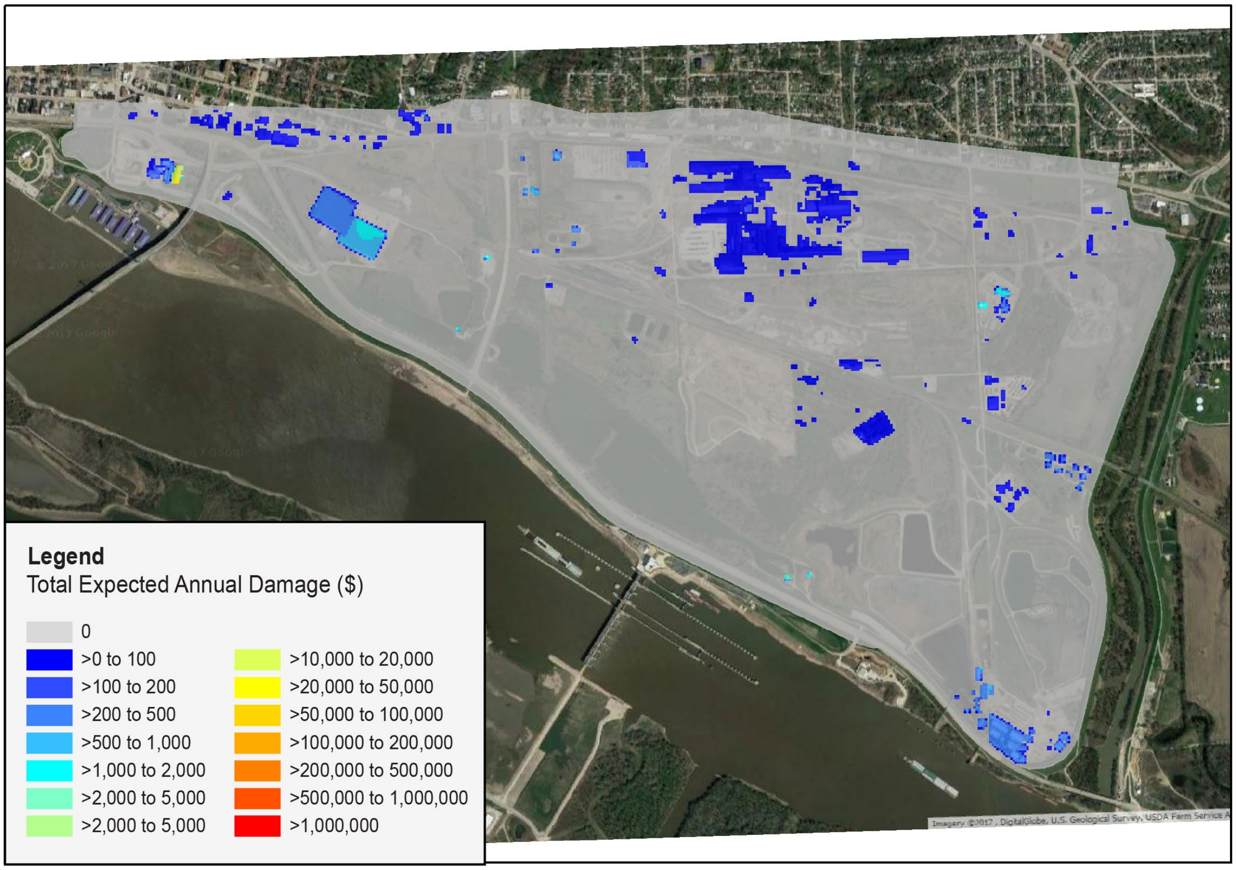
Figure 4-19: Example f-N̄ and F-N Charts



7.2.2 Flood Risk Maps

Although not commonly used in the U.S., it is possible to generate maps which take account of consequence as well as hazard. Essentially, they combine information from system response curves for a given levee across all return periods with that from the relevant stage damage curves. These maps display the variation in expected annual average damages across the flooded area (Figure 4-20).

Figure 4-20: Example Flood Risk Map



8 Summary

This chapter presents basic risk concepts and describes how to estimate, characterize, and portray flood risk reduction benefits provided by the levee, including the non-breach risk and the risk associated with levee breach or misoperation.

A risk assessment overview provides the best practices for conducting assessments, explaining how to allow for scalability in determining the type of assessment to perform and decisions made, and scoping and preparing for the assessment.

The chapter also details methodologies for assessing risks to evaluate the hazard, performance, and consequence parts of the components of risk, as well as provides guidance on combining various outputs of hazard, performance, and consequence assessments to estimate levee risk and flood risk in the leveed area. The discussion of computing each type of risk is followed by an example calculation using semi-quantitative approaches for risk estimates.

Finally, the chapter details risk characterization, which describes the levee in the context of risk by considering the key drivers of likelihood of performance, potential consequences, and sources of uncertainty. It is used to portray and describe the risk associated with the levee, as well as the flood risk reduction benefits it provides. Risk characterization builds on a risk estimate and requires developing a risk narrative, supported by a risk portrayal, and preparing the case for risk-informed recommendations. A good risk characterization converts the scientific evidence-based information and the remaining uncertainty into a statement of risk that informs levee risk management activities.

Related content associated with this chapter is included in detail in other chapters of the National Levee Safety Guidelines as described in Table 4-4.

Table 4-4: Related Content

Chapter	Chapter Title	Related Content
1	**Managing Flood Risk**	• Estimating hazards • Estimating consequences
2	**Understanding Levee Fundamentals**	• Potential failure modes
3	**Engaging Communities**	• Communicating risk • Social vulnerability
4	**Estimating Levee Risk**	
5	**Managing Levee Risk**	• Levee risk classification
6	**Formulating a Levee Project**	• Analysis preparation
7	**Designing a Levee**	• Scalability of project design • Performing site characterization
8	**Constructing a Levee**	• Understanding construction activities
9	**Operating and Maintaining a Levee**	• Conducting levee inspections
10	**Managing Levee Emergencies**	• Emergency preparedness
11	**Reconnecting the Floodplain**	
12	**Enhancing Community Resilience**	• Understanding potential consequences

5

Managing Levee Risk

Key Messages

This chapter will enable the reader to:

- **Monitor.** Risk is dynamic and evolves with time necessitating continuous and proactive monitoring.
- **Consider benefits.** Levee risk management should deliver the benefits of the levee safely and equitably in consideration of the overall flood risk management strategy.
- **Promote an integrated approach.** Managing levee risk requires collaborative action.
- **Be risk-informed.** Levee safety decisions should be informed by risk.
- **Ensure scalability.** Levee risk management activities should be scalable in terms of rigor, frequency, and focus.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Other chapters within the National Levee Safety Guidelines contain more detailed information on certain topics that have an impact on managing levee risk, as shown in Figure 5-1. Elements of those chapters were considered and referenced in the development of this chapter and should be referenced for additional content.

Figure 5-1: Related Chapter Content

CH 1	CH 2	CH 3	CH 4
Flood risk management strategies		Engagement for risk awareness Engagement for levee-related activities	Estimating and characterizing levee risk Levee risk classification
CH 5	**CH 6**	**CH 7**	**CH 8**
Managing Levee Risk	Guidance on levee project formulation	Levee design considerations	Construction phases
CH 9	**CH 10**	**CH 11**	**CH 12**
Routine O&M activities and inspections	Emergency preparedness and planning	Flood risk management strategies	Strategies for community flood resilience

Contents

1 Introduction 5-1
2 Levee Risk Management Overview 5-1
2.1 Levee Risk Management Principles 5-2
2.2 Risk-Informed Decisions 5-3
2.3 Levee Risk Concepts 5-4
2.3.1 Routine Activities are Essential for Managing Levee Risk 5-6
2.3.2 Levee Risk Cannot be Eliminated 5-7
2.3.3 Risk is Dynamic 5-8
2.3.4 Risk Transfer and Transformation 5-10
3 Levee Risk Management Responsibilities 5-10
3.1 Understanding Risks Associated with Levees 5-11
3.2 Taking Actions to Reduce Risk 5-13
3.2.1 Categories of Actions 5-13
3.2.2 As Low as Reasonably Practicable 5-14
3.2.3 Equity and Efficiency 5-16
3.2.4 Investment Strategies 5-16
3.3 Building Risk Awareness 5-18
3.4 Fulfilling Day-to-Day Responsibilities 5-19
4 Risk Management in the Levee Lifecycle 5-19
4.1 Levee Project Formulation, Design, and Construction 5-21
4.1.1 Project Formulation 5-22
4.1.2 Design 5-22
4.1.3 Construction 5-23
4.2 Routine Activities 5-24
4.2.1 Operation and Maintenance 5-24
4.2.2 Inspections 5-24
4.2.3 Monitoring 5-25
4.2.4 Risk Assessment 5-25
4.2.5 Data Management 5-26
4.2.6 Emergency Preparedness 5-26
4.2.7 Sharing Information 5-26
4.2.8 Training 5-27
4.2.9 Triggers from Routine to Non-Routine Activities 5-27
4.3 Non-Routine Activities 5-27
4.3.1 Is There a Levee Safety Issue? 5-28

4.3.2 Evaluate Levee Safety Issues 5-28
4.3.3 Is Action Justified to Reduce Levee Risk? 5-28
4.3.4 Evaluate Structural and Nonstructural Alternatives 5-29
4.3.5 Prioritize and Implement Risk Reduction Actions 5-29
4.3.6 Return to Routine Activities 5-29
5 Rigor, Frequency, and Focus of Levee Risk Management Activities 5-30
6 Summary 5-32

List of Figures

Figure 5-1: Related Chapter Content 5-i
Figure 5-2: Levee Risk Management 5-2
Figure 5-3: Flood Risk Reduction Strategies 5-4
Figure 5-4: Levee Risks Increase Without Routine Activities 5-6
Figure 5-5: Flood Risk Reduction Benefits Decrease Without Routine Activities 5-6
Figure 5-6: Change in Levee Benefits/Risk Resulting from a Lack of Maintenance 5-6
Figure 5-7: Levee Modifications Result in Increased Levee Benefits 5-7
Figure 5-8: Non-Breach Risks Decrease with Levee Modifications 5-7
Figure 5-9: Change in Risk with Modified Levee 5-7
Figure 5-10: Economic Development Causes Levee Benefits to Increase 5-9
Figure 5-11: Economic Development Causes Flood Risk to Increase 5-9
Figure 5-12: Increase in Flood Risk over Time 5-9
Figure 5-13: Risk Matrix Displaying Levee Risk Estimates 5-13
Figure 5-14: Scenarios Informing Levee Risk Management Activities 5-17
Figure 5-15: Routine and Non-Routine Levee Risk Management Activities 5-21

List of Tables

Table 5-1: Additional 'As Low As Reasonably Practicable' Considerations 5-15
Table 5-2: Investment Strategy Considerations 5-18
Table 5-3: Activities Informed by Levee Risk 5-31
Table 5-4: Related Content 5-33

1 Introduction

Risk management is a decision-making process in which risk-reducing and resilience-increasing actions are identified, evaluated, implemented, and monitored. The overall purpose is to take actions to safeguard benefits and effectively reduce and manage risks. Assessing and communicating risks are key to proactive risk management.

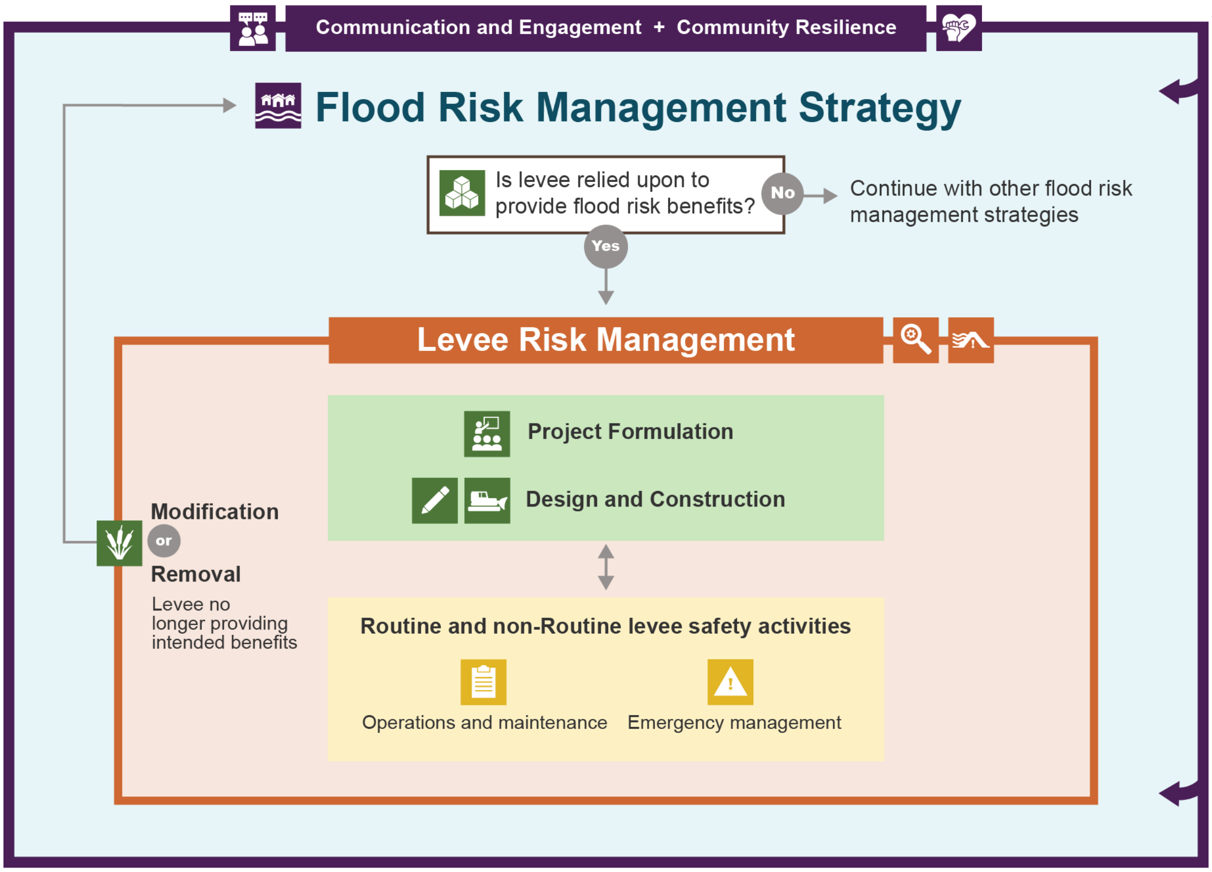
This chapter provides guidance on levee risk management. The goal is to assist those with roles, responsibilities, and authorities for managing levees with making sound decisions regarding whether actions are needed and the type of actions to take. This chapter also presents strategies for addressing levee risk and considerations of urgency and prioritization of actions.

While the chapter's primary audiences are levee owner/operators, regulators, and community decision-makers, the contents are intended to be informative guidance for all.

2 Levee Risk Management Overview

As illustrated in Figure 5-2, levee risk management is part of an overall flood risk management strategy. Levee risk management encompasses all activities described in these guidelines. The objective of levee risk management is to ensure the levee provides intended flood risk reduction benefits and that levee risk is tolerable (see section 3). This is achieved by ensuring reliable performance of the levee and managing potential consequences of levee breach or misoperation. It is important that levee risk management activities be scalable and flexible.

Figure 5-2: Levee Risk Management



2.1 Levee Risk Management Principles

The following principles apply to levee risk management:

- **Life safety is paramount**. Prioritizing actions to reduce the risk of life loss is the most important responsibility within levee risk management.
- **Levee safety is a shared responsibility**. To be effective, levee risk management should include all levels of government, businesses, and the public working together in a coordinated fashion.
- **Levees should exist in balance** with social, environmental, cultural, and economic interests within the floodplain.
- **Levee risk should be commensurate with the benefits** and not contribute significantly to the overall flood risk in the leveed area.
- **Transparent, proactive, and continuous engagement** with community members and other relevant stakeholders is essential.
- **Levees exist within a dynamic environment**, influenced by natural and human factors. Levee risk should be periodically re-evaluated and proactively managed.

- **Floods do not impact all communities and individuals equally**. Levee risk management practices should strive to achieve equity by addressing unique challenges and barriers that may be experienced by underserved communities behind levees.

2.2 Risk-Informed Decisions

Decisions related to managing levees should be informed by risk, which requires estimating and characterizing risk, as described in **Chapter 4**. A good risk management process is ongoing, iterative, and flexible, providing opportunities to adapt to new information and requirements. Risk management considers uncertainty during decision making and conveys the significance of uncertainty to relevant decision makers and other audiences. Risk management occurs throughout the levee lifecycle.

Independent review is critical to the credibility of risk management decision making and actions. They help ensure that biases and individual preferences do not dominate the decision-making process. Independent reviews are also valuable when there are controversial or unique challenges and approaches in the risk management action. For managing a portfolio of levees, it is critical to perform centralized reviews of risk estimates to ensure consistency of results across the inventory and improve consistency of decisions and actions.

Managing risk requires setting priorities. Factors to consider in setting the priorities are the:

- Magnitude of levee risk and benefits at a given levee.
- Impact of uncertainty on the understanding of the risk.
- Costs and benefits of implementing risk management actions.
- Timeframe required to achieve risk management objectives.

Prioritizing work is typically a dynamic process. While priorities may be revisited on a regular schedule (e.g., annually), levee issues that have a higher urgency of action may develop between scheduled activities, requiring flexibility in prioritizing work.

A transparent, documented process for establishing priorities to complete levee risk management actions should exist and the community should be engaged to provide input into the priority-setting process. The process should equally weigh the significance of risk reduction activities to the community with impacts on the community.

Concepts for risk management and prioritization are applicable to both a single levee and a portfolio of levees. Actions should be prioritized to efficiently reduce risk for an individual levee and where applicable, across an entire portfolio of levees. Efficient risk reduction generally means achieving the largest risk reduction for the smallest investment of time and money. Life safety is the primary factor to consider in prioritizing actions. Other considerations may include understanding interim steps to reduce risks, prioritizing actions that are relatively easy and quick to implement, prioritizing actions or projects with available funding, or understanding measures that are ready to be implemented.

It is helpful to establish multiple prioritized queues that are informed by risk. For example, queues may be set for additional studies or data collection, operations and maintenance (O&M) activities, emergency response planning, risk assessments, modifications, and/or construction projects.

Ongoing communication and engagement with stakeholders and the community creates the foundation for successful levee risk management. Establishing a shared understanding of the benefits of levees—along with their limitations—supports better decision making and improves the community's ability to respond to critical events. The goal is to promote a common and shared understanding of the risks and inform risk management decisions. Community engagement should begin early and continue throughout the entire lifecycle of a levee. It should provide meaningful opportunities for input and feedback related to decisions. For guidance on engagement activities and practices, see **Chapter 3**.

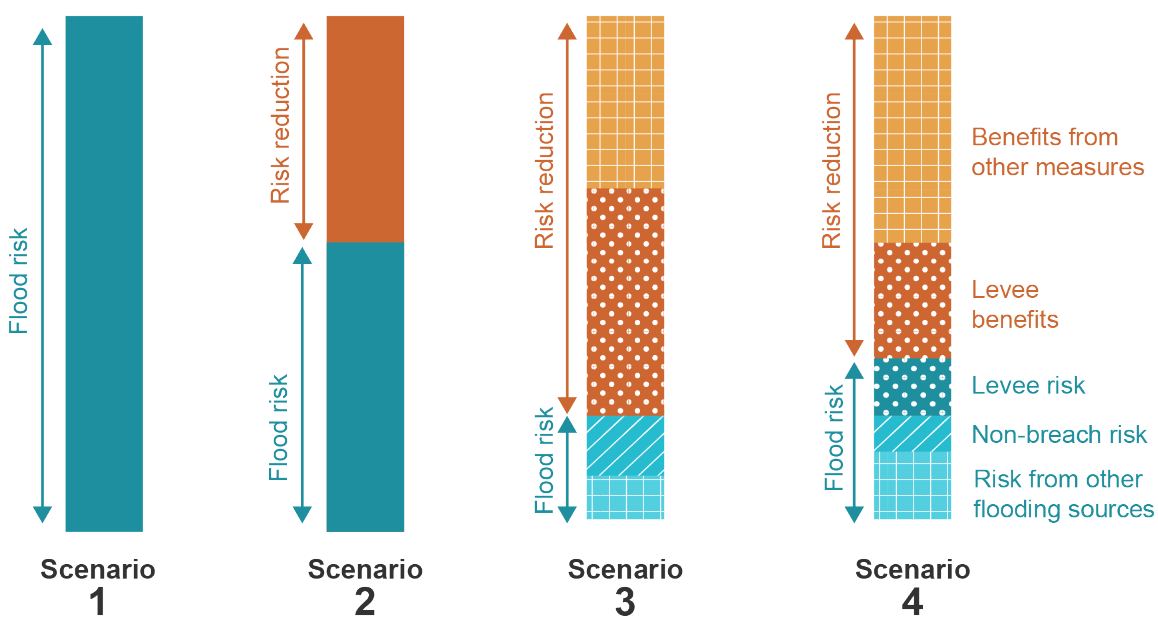
2.3 Levee Risk Concepts

The objective of levee risk management is to provide the intended flood risk reduction benefits and ensure that levee risk is tolerable. Figure 5-3 illustrates four distinctive scenarios that include:

- Scenario 1: No flood risk reduction strategies employed.
- Scenario 2: Flood risk reduction strategies employed but not including a levee.
- Scenario 3: Flood risk reduction strategies employed including a levee subject to overtopping only (no levee breach).
- Scenario 4: Flood risk reduction strategies employed including a levee subject to breach.

For all four scenarios, flood risk is shown in blue and flood risk reduction benefits are shown in orange.

Figure 5-3: Flood Risk Reduction Strategies



Scenario 1 depicts a case where no flood risk reduction measures are being employed to reduce flood risk to a particular area; therefore, there is only flood risk with no risk reduction benefits.

Scenario 2 depicts a case where strategies have been employed to reduce the flood risk without the help of a levee. As discussed in **Chapter 1**, strategies could include zoning restrictions, elevating buildings, moving critical infrastructure away from the floodplain, nature-based solutions, and evacuating people during a flood. Scenario 2 reduces flood risk, compared to Scenario 1.

Scenario 3 depicts a situation when a levee is added to the suite of risk reduction measures to further reduce flood risk. This scenario acknowledges that all levees have their limitations. Most levees are constructed to reduce flood risk up to a particular level and large enough floods will overtop them. It is impractical to construct levees high enough to eliminate any chance of overtopping, no matter how remote. Further, this scenario recognizes that levees only reduce flood risk from a particular source (e.g., riverine flood), and other sources of flooding (e.g., groundwater rise) can still cause flooding in the leveed area. This scenario assumes that even when overtopped, the levee would not breach. In this case, flood risk in the leveed area is due to levee overtopping without breach (blue diagonal pattern) and other sources of flooding that are not associated with the levee (blue square pattern). It should be emphasized that this scenario is a purely theoretical construct to help illustrate the concept and such a levee can never exist in real life.

Scenario 4 recognizes that no levee is perfect and there is always a chance that levees, as with any structure, may breach and impact the leveed area. Therefore, the flood risk in the leveed area includes the levee risk (blue dot pattern), plus risk due to levee overtopping without breach (blue diagonal pattern), and risk from other sources of flooding that are not associated with the levee (blue square pattern). For more detailed discussion on levee risk, non-breach risk, and flood risk, see **Chapter 1**.

Other scenarios associated with managing levee risk are provided in the following sections using similar conceptual graphics to Figure 5-3.

2.3.1 Routine Activities are Essential for Managing Levee Risk

Regular inspections, monitoring, and timely maintenance helps prevent levee deterioration and promote proper function. Without these routine activities, levee risk can increase over time, as shown in Figure 5-4.

This, in turn, diminishes the flood risk reduction benefits associated with the levee (Figure 5-5), even if all other factors, such as leveed area population, remain unchanged.

Figure 5-4: Levee Risks Increase Without Routine Activities

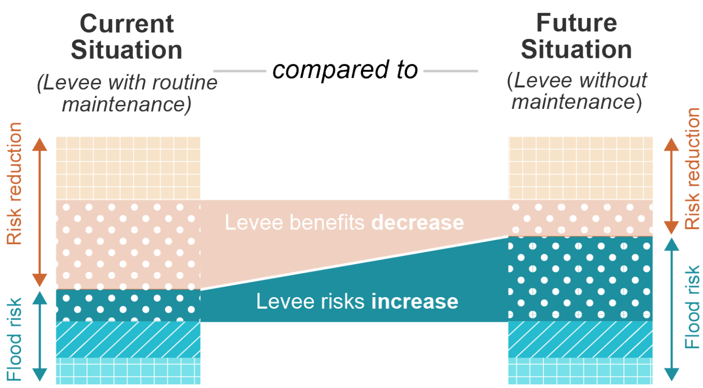
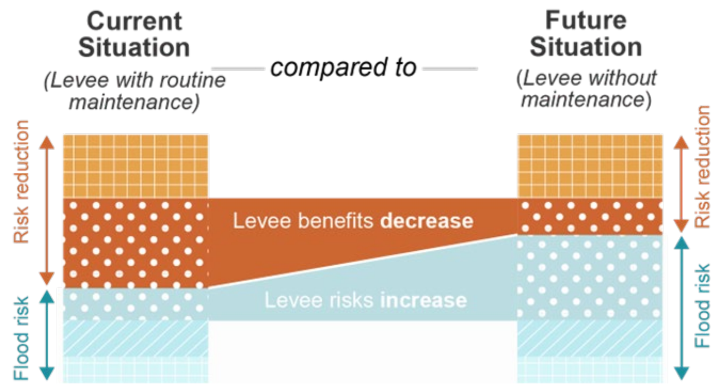
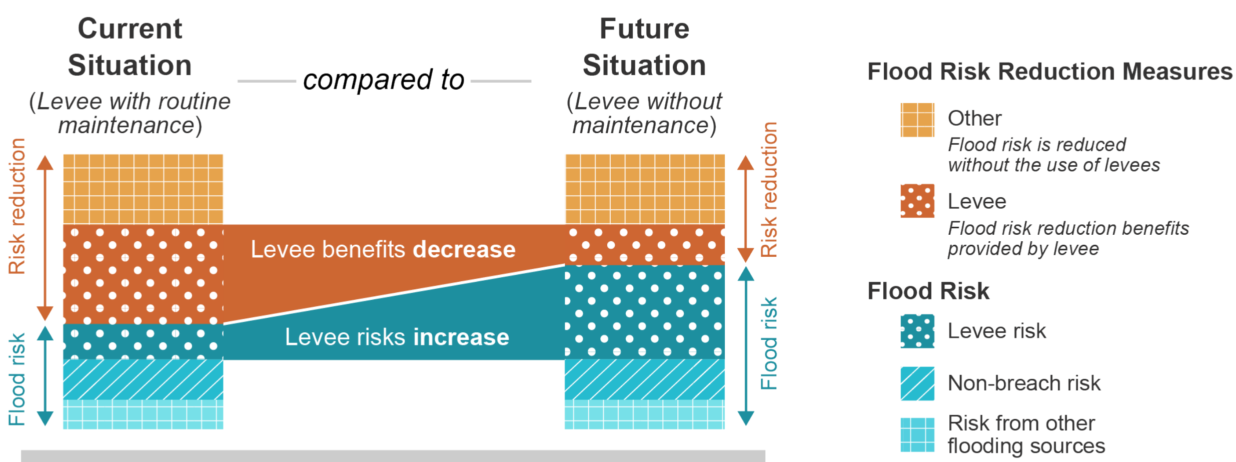


Figure 5-5: Flood Risk Reduction Benefits Decrease Without Routine Activities



The entirety of this concept is illustrated in Figure 5-6 where the current situation is compared to a future situation and where the levee has deteriorated due to lack of proper maintenance, resulting in a loss of benefits and an increase in levee risk.

Figure 5-6: Change in Levee Benefits/Risk Resulting from a Lack of Maintenance



2.3.2 Levee Risk Cannot be Eliminated

Levees can be modified (e.g., raised) to provide additional flood risk reduction benefits, shown in Figure 5-7. Although raising a levee will decrease the risk of overtopping, it is not feasible to make a levee tall enough to eliminate all non-breach risk or to make a levee strong enough to eliminate all levee risk (Figure 5-8). Further, a levee raise does not reduce flooding in the leveed area from other sources not managed by the levee. Levee risk typically remains about the same. The levee risk could be reduced further by strengthening the levee and constructing additional flood risk reduction measures—such as retrofitting the levee with a seepage berm—but it can never be eliminated.

Figure 5-7: Levee Modifications Result in Increased Levee Benefits

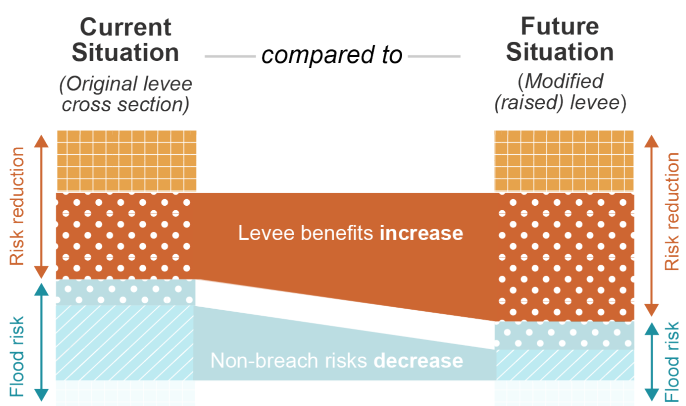
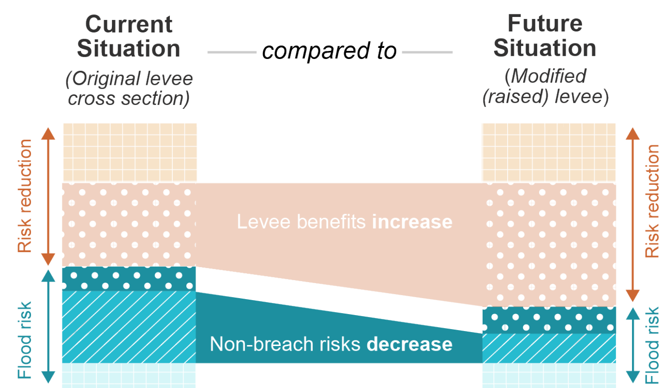
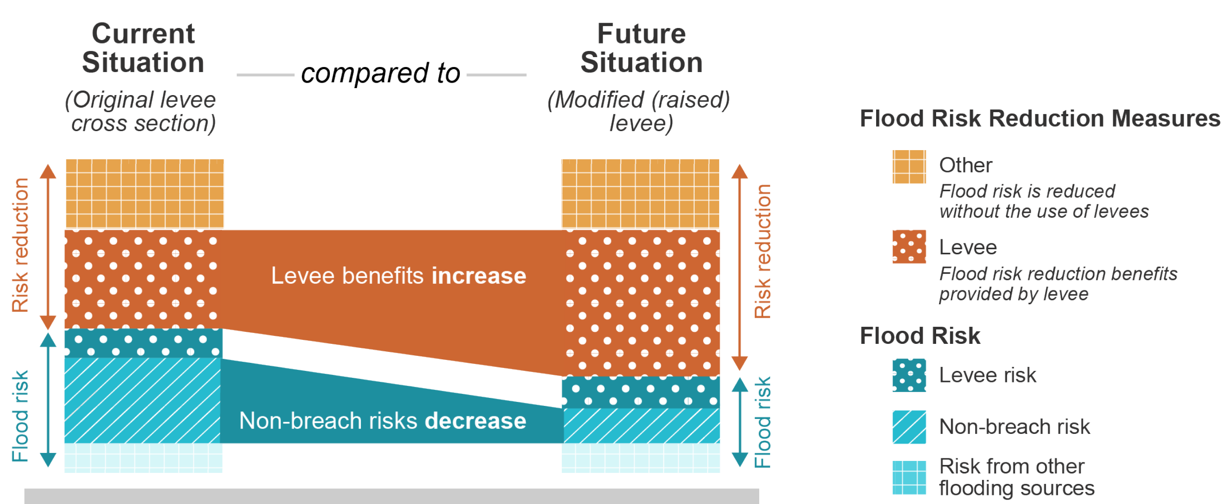


Figure 5-8: Non-Breach Risks Decrease with Levee Modifications



The entirety of this concept is depicted in Figure 5-9 where the current situation with an existing levee is compared to a future situation with a modified (raised) levee. With the modification, the levee risk reduction benefits increase and the overall flood risk in the leveed area is reduced, primarily due to the reduction in the non-breach risk (i.e., risk of the levee overtopping).

Figure 5-9: Change in Risk with Modified Levee



The potential exists to inadvertently increase levee risk from the current situation when modifying a levee. This increase could be from the introduction of a new potential failure mode or by increased consequences associated with a breach of a taller levee (e.g., higher depth and velocity of flooding). Actions should be taken to recognize and manage potential levee risk creep.

2.3.3 Risk is Dynamic

Both flood and levee risks are dynamic and can evolve with time due to changes in the frequency and magnitude of flood loading, levee condition, and changes in land use and development in the leveed area. In addition, knowledge about the levee risk can change through collection of new information or advances in engineering approaches. All these changes should be periodically assessed and the corresponding risks proactively managed.

Even with proactive levee risk management that prevents levee risk from increasing, the flood risk in the leveed area can increase with time. For example, economic development in the leveed area—causing an increase in the population living and working behind the levee—would result in the levee providing more benefits (Figure 5-10), but also increases flood risk (Figure 5-11) due to higher potential consequences of failure.

Figure 5-10: Economic Development Causes Levee Benefits to Increase

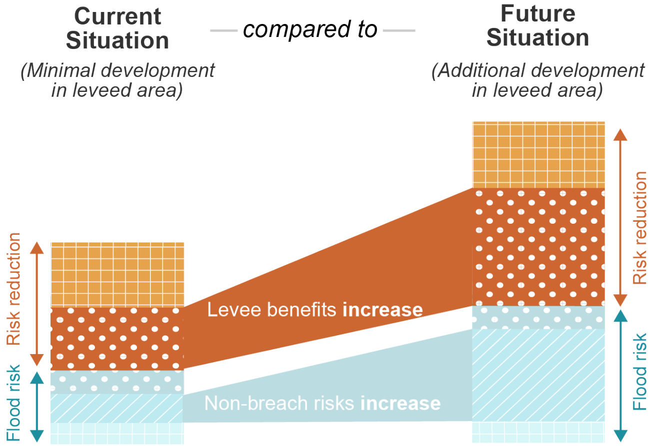
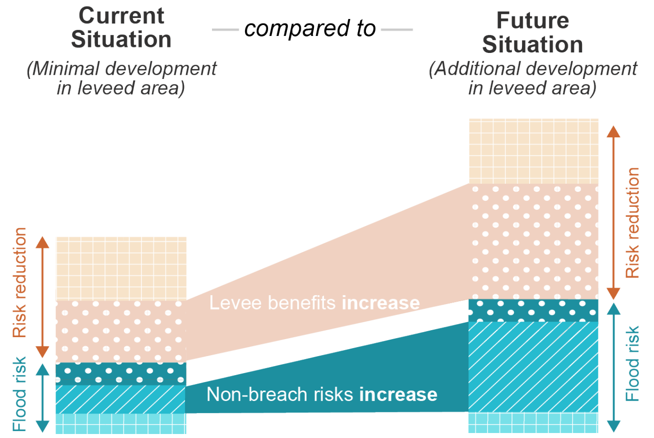
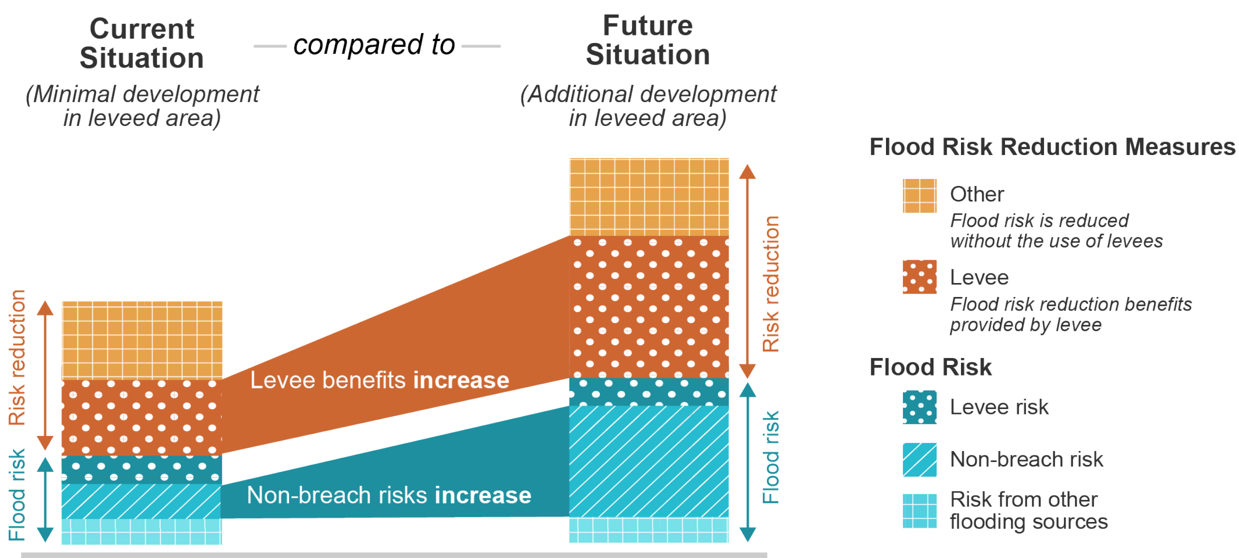


Figure 5-11: Economic Development Causes Flood Risk to Increase



This scenario is fully illustrated in Figure 5-12, which compares current and future situations. The future situation consists of additional development in the leveed area, resulting in increased non-breach risk, along with increases in risk reduction benefits provided by the levee. For the illustration purposes, it is assumed that the levee risk remains unchanged.

Figure 5-12: Increase in Flood Risk over Time



For this scenario, there are approaches to compensate for an increase in levee risk, primarily by improving evacuation effectiveness, strengthening the levee to reduce the probability of breach or slowing down breach development, and designating a controlled overtopping location. However, without additional measures (not associated with the levee), the non-breach risk will still increase since consequences of levee overtopping without a levee breach are greater.

Because community needs change over time, strategies for flood risk management should also evolve. For example, with the desire to shift to nature-based solutions or to provide additional storage in the floodplain, existing levees may need to be removed and new setback levees constructed to meet the revised flood risk management strategy (**Chapter 11**). Conversely, with additional development in the leveed area and the associated increase in flood risk, the strategy may shift to more robust structural measures combined with improved emergency response planning. This scenario may constitute a levee modification.

Strategies for managing this increase are considered flood risk management decisions. These decisions should be made jointly between levee owners and those responsible for flood risk management. See **Chapter 1** for additional discussion on levee risk and flood risk decisions.

2.3.4 Risk Transfer and Transformation

Levee risk management decisions, particularly decisions to construct or modify a levee, should consider the potential for risk transfer and risk transformation. Risk transfer and/or transformation should be avoided, unless agreed to by all affected parties. For additional information on formulating a levee project, see **Chapter 6.**

Transferred risk occurs when an action shifts the risk burden from one entity to another or from one location to another. For example, if a levee is constructed or an existing levee is raised along one bank of the river to provide additional risk reduction for that leveed area, that action could increase flooding up or downstream or to areas along the other bank, putting other communities at higher risk. Risks can also be transferred within a single levee system. Raising an existing low spot on a levee could transfer overtopping risk to another, more populated location within the leveed area.

Transformed risk is risk that is altered because of changing conditions, including risk management actions. For example, the nature of the flood risk with a levee is different than without a levee. A levee reduces the likelihood that flood-prone property will be inundated, but in some cases, the levee may transform the severity of flooding from gradual and observable without the levee to sudden and catastrophic with the levee if the levee were to breach. Levees may also lead to risk transformation by inadvertently encouraging development within the leveed area that can increase economic and life safety consequences.

3 Levee Risk Management Responsibilities

Within any given community, it is common for multiple individuals or organizations to have responsibilities for different aspects of levee risk management. It is important for these entities to coordinate, interact, and communicate to fulfill their responsibilities in accordance with their respective roles. For example, one entity may be responsible for the operation and maintenance of the levee, but different entities may be responsible for land use decisions or evacuation planning. Further, roles and responsibilities can change through the levee lifecycle. This requires an integrated approach of aligned programs, regulations, policies, incentives, and activities.

Responsible levee risk management requires continuous and proactive monitoring of risk and taking actions to reduce it as practicable. Levee risk management responsibilities are:

1. Understanding risks associated with levees.
2. Taking actions to reduce risk.
3. Building risk awareness.
4. Fulfilling day-to-day responsibilities.

Fulfilling these responsibilities throughout the levee lifecycle is essential for ensuring levee risk is tolerable and the levee continues to serve its intended function. Tolerable risks are defined as:

- Risks that society is willing to live with to secure certain benefits.
- Risks that society regards as negligible or something that it might ignore.
- Risks that society is confident are being properly managed.
- Risks that are kept under review and reduced further if and as practicable.

Levee risk is considered tolerable if it is understood to be commensurate with the benefits provided by the levee, the risks are being communicated to those affected, routine activities are being performed, and risks have been reduced to as low as reasonably practicable. The evaluation of tolerability is subjective and is not intended to be a checklist or a pass/fail grade.

The activities described in section 4 are intended to collectively fulfill the four levee risk management responsibilities. They are organized as follows: levee project formulation (planning), design and construction, routine activities, and non-routine activities.

3.1 Understanding Risks Associated with Levees

A **risk characterization** documents and depicts risk for use in risk management and decision making. It can be supported by various products portraying the risk. Understanding the risk includes:

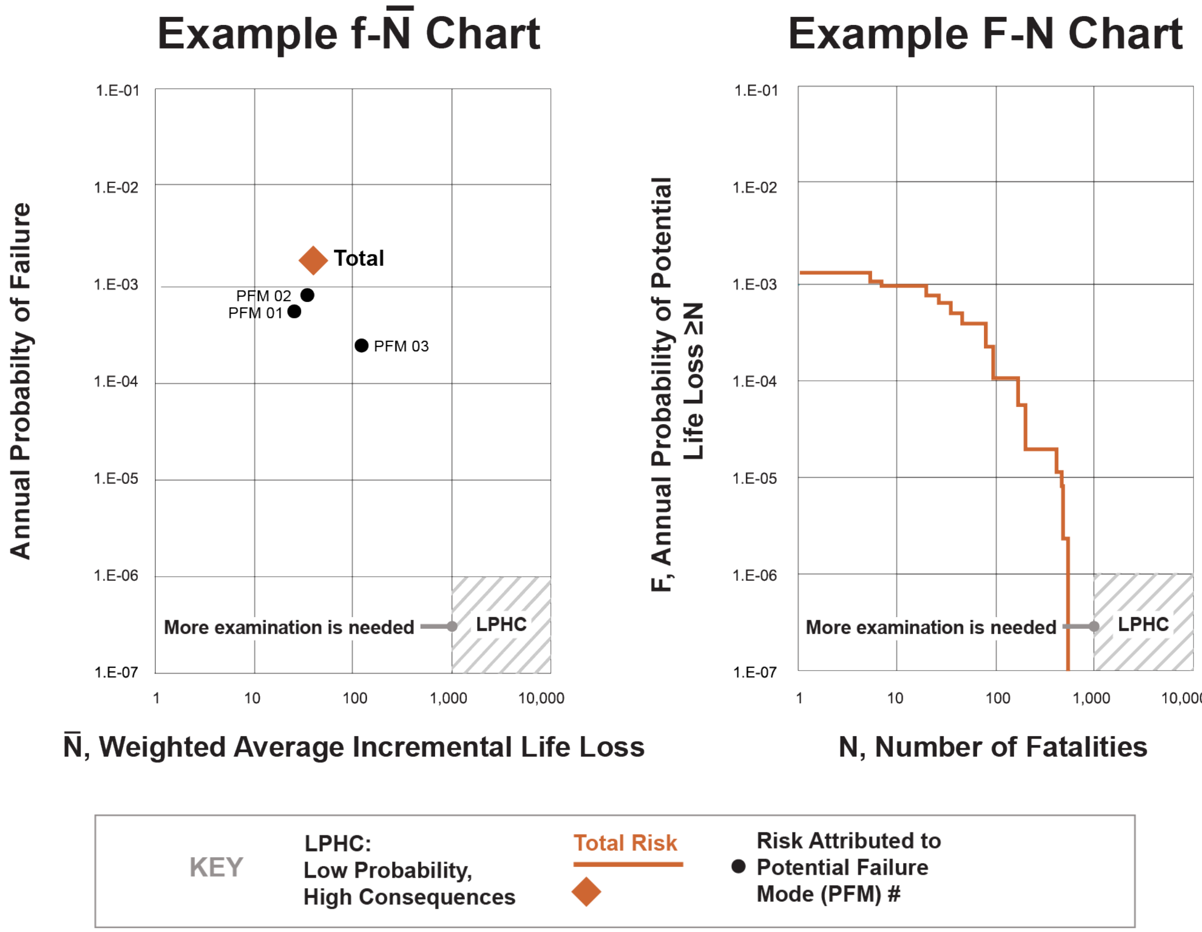
- **Understanding the basis for risk estimates**, including primary sources and impacts of uncertainty. It is important to recognize that it is difficult to estimate annual failure probabilities more remote than 1 in 1,000,000 and there is inherently significant uncertainty in risk estimates below this level. It is also important to understand that a failure producing more than 1,000 fatalities would be considered catastrophic to society. For levees where the annual failure probability is less than 1/1,000,000 and the potential exists for more than 1,000 fatalities, there are special considerations to ensure all reasonably practicable risk reduction efforts have been implemented. A particularly thoughtful and careful examination of risk reduction activities is required.
- **Knowing where a levee risk estimate plots on the risk matrix** and other ways risk is portrayed and visualized. It is important to understand risk imposed on a particular (most vulnerable) individual in the leveed area by the existence of the levee compared to the background risk to life, which the person would live with on a daily basis. This reflects society's expectations of equity and fairness (i.e., a person living in a leveed area should

not be exposed to significantly greater risk than any other person). Refer to section 3.2.3 for additional discussion on equity. It is also important to consider the potential for harm to society as a whole that a levee breach could cause. In general, society has a lower tolerability for events that result in higher casualties. In addition, society is generally more averse to human-made technological disasters (i.e., failure of engineered structures, facilities, public transportation), as opposed to natural disasters such as hurricanes or earthquakes which by themselves result in life loss (Rasmussen, 1975).

- **Understanding what is driving the risk**, such as a specific potential failure mode, a particular loading condition, the most vulnerable location along the levee, or specifics of warning and emergency response procedures affecting evacuation effectiveness. In addition to evaluating life safety, it is important to consider other benefits and potential impacts associated with the levee. Consideration should be given to potential economic damages, disruption of critical infrastructure and essential services that serve residents and businesses in the leveed area (e.g., energy, water, medical care, communications, and transportation lifelines), environmental risks (e.g., impacts to endangered and non-endangered species habitat), impacts to historic or culturally significant sites, and exposure of people and the ecosystem to hazardous and toxic material. Some of these impacts may be quantified, while others are described qualitatively as part of the risk assessment.
- **Understanding how levee risk compares to flood risk reduction benefits** provided by the levee, the non-breach risk, and the flood risk in the leveed area. Because levee safety decisions must be made in the context of overall flood risk management, the evaluation should consider the flood risk reduction benefits a levee is intended to provide. This is done by comparing the levee performance prior to overtopping with the overtopping frequency. Generally, the probability of levee breach prior to overtopping should be at least one order of magnitude below the overtopping frequency. For instance, if the levee overtopping probability is 1/500, then the probability of levee breach prior to overtopping should be less than (more remote than) 1/5,000. This requirement recognizes that there is little benefit to reducing the likelihood of overtopping (non-breach risk) if there are prior to overtopping concerns that are driving levee risk.

Levee risk estimates can be portrayed on various charts discussed in **Chapter 4**. The two main charts typically used within the industry today are shown in Figure 5-13.

Figure 5-13: Risk Matrix Displaying Levee Risk Estimates



The f-N̄ chart on the left side of Figure 5-13 plots the annual probability of a levee breach (f) (or misoperation) against the weighted average incremental life loss (N̄), which is the expected (mean) value of life loss, given that failure event. The average annualized life loss is equal to the product f and N̄.

The F-N chart on the right side of Figure 5-13, also referred to as a loss exceedance curve, portrays annual exceedance probability (F) of life loss (N).

On an f-N̄ plot, a risk estimate is shown as a point defined by a pair (f, N̄) while on the F-N plot, the same risk estimate will be portrayed as a curve that describes the full range of potential consequences and the probability of exceeding them. For additional details on these approaches for portraying and evaluating levee risk estimates, refer to **Chapter 4.**

3.2 Taking Actions to Reduce Risk

3.2.1 Categories of Actions

In addition to basic levee repairs, which are considered part of routine O&M activities, risk-informed levee safety actions can be categorized as described below. These categories of actions may be undertaken in concert with one another; one category of action does not preclude other actions from occurring.

Temporary (interim) risk reduction measures. These are risk reduction measures that are intended to be temporary until risks are better defined or more permanent risk reduction measures are implemented. These measures could include temporary construction of seepage berms or overtopping resiliency features. If determined feasible, such measures could later be incorporated into a permanent solution. Temporary measures could also be nonstructural in nature. Examples include changes in levee operation, improvements to evacuation procedures training, and implementation of a communication plan. It is important that temporary measures do no harm and do not make it more difficult to implement a permanent solution.

Levee rehabilitation, modification, or removal. This action often involves longer-duration projects and major investments. Risk-informed decision making is used to compare risk reduction alternatives and select a preferred alternative based on many factors, including risk reduction, cost, and other community objectives (e.g., environmental goals). Additional studies or analyses may be needed to better understand the risk and reduce uncertainty.

Engineering investigations, studies, and analyses. Engineering investigations, studies, and analyses are intended to reduce uncertainties and better understand risks to support levee safety decisions.

Critical or elevated O&M actions. Risk assessment processes sometimes identify specific O&M activities that help reduce uncertainty and potentially lower the chances for breach. These activities should be highlighted for consideration. Examples of levee safety-related O&M actions may include floodwall concrete repairs, surface erosion repairs on the levee embankment, or enhanced observations, inspections, and instrumentation monitoring.

Nonstructural risk management strategies. Implementation of nonstructural actions is often an option to reduce levee risk temporarily or permanently. Emergency action plan improvements and engaging with communities about risk are intended to improve levee risk awareness and benefit evacuation capabilities of the population in the leveed area, reducing life loss potential.

3.2.2 As Low as Reasonably Practicable

To achieve flood risk reduction benefits and manage levee risks, cost effective and socially and environmentally acceptable approaches should be identified and implemented. Even if risks are judged to be generally low, actions may still be justified to reduce risk further, as appropriate.

WHAT IS MEANT BY AS LOW AS REASONABLY PRACTICABLE?

In essence, making sure a risk has been reduced ‘as low as reasonably practicable’ is about weighing the risk against the investments needed to further reduce it. The decision is weighted in favor of life safety because life safety is paramount. The risk reduction benefits achieved with additional expenditures should be compared to the costs. If the costs are grossly disproportionate to the benefits, it may be concluded that additional expenditures are not warranted, and risks have been reduced as low as reasonably practicable. Thus, the process is not one of balancing the costs and benefits of measures but, rather, of adopting measures except where they are ruled out because they involve grossly disproportionate investments. Extreme examples might be:

- To spend $1 million to prevent a few staff members from potential minor injuries is grossly disproportionate.
- To spend $1 million to prevent a serious accident potentially harming hundreds of people is proportionate.

(Examples adopted from UK Health and Safety Executive website (HSE, 2019).)

The fulfillment of the 'as low as reasonably practicable' considerations is usually assessed as a matter of judgment based on the following:

- The level of risk compared to other levees.
- The cost-effectiveness of the risk reduction measures.
- Any relevant recognized good practice and a precedent of comparable decisions on other projects.
- The chance of success of an action.
- Societal concerns as revealed by engagement with the community and other stakeholders.

The following are questions for 'as low as reasonably practicable' considerations. The questions presented in Table 5-1 are adapted from the State of Queensland Guidelines on Safety Assessments for Referable Dams (Queensland Government, 2021).

Table 5-1: Additional 'As Low As Reasonably Practicable' Considerations

Questions to Consider	Comments
• Is the appropriate duty of care to manage levee risk being exercised? • Is the public sufficiently informed? • Are the actions reasonable and what a reasonable person would do?	These questions address the generic definition of what is reasonably practicable and what would be regarded as a minimum standard of care.
• Are best practices being implemented? • Are there industry guidelines that suggest a safer levee would be appropriate? • Is an explanation of the difference in safety from other guidelines appropriate?	"…Those standards for controlling risk […] judged and recognized as satisfying the law, when applied to a particular relevant case, in an appropriate manner." One measure of identifying best practice is that "it is either written down or is a well-defined and established practice adopted by an industrial/ occupational sector."
• How is the levee being managed compared to other levees? • Are levee safety management practices for this levee consistent with or better than other similar levees? • Can differences be justified?	Industry practices change over time, and it is important to understand what other similar levee owners or regulators are doing.
• Do the benefits of the levee outweigh the risks?	This question relates to whether the risks posed by the levee are tolerable. It is important to ask this question and document the answer, along with the rationale behind the answer.
• Are identified risks manageable into the future? • Could population in the leveed area increase in the future? • Could external drivers such as climate change increase risks?	These are important questions to ask where the situation surrounding a levee is changing rapidly. If the situation is dynamic, more conservative decisions might be appropriate.
• Is there a sense of urgency regarding the timing of risk reduction activities? • Is there justification for the timeframe to reduce the risk that is commensurate with the severity of the risk?	It is important to work on high-risk levees and high-priority activities with an appropriate level of urgency. If the urgency of the actions is not commensurate with the magnitude of the risks, it would inform an assessment of whether the 'as low as reasonably practicable' guideline is being met.

Questions to Consider	Comments
• Have all practicable steps to reduce risk been considered? • Are there operational and management aspects that could be implemented to further reduce risk? • Are there consequence avoidance measures that could be implemented?	It is important to consider nonstructural measures that could reduce the risk.
• If the levee failed and there were life safety consequences, could you confidently answer the above questions?	It is essential to have positively demonstrated due diligence in a way that can withstand post-event judicial scrutiny.

On the other hand, the high levee risk may still be tolerable when exceptional circumstances prevent lowering risks through reasonable means. All the following factors must apply for exceptional circumstances to be considered:

- The levee provides special or unique benefits to society at large that justify taking on more risk.
- State-of-the-practice risk management measures are implemented.
- Further risk reduction would be disproportionately expensive in comparison to the benefits or cannot reasonably be accomplished within the physical constraints of the project.

3.2.3 Equity and Efficiency

Investment in levee safety should be managed considering equity and efficiency principles (ICOLD, 2020):

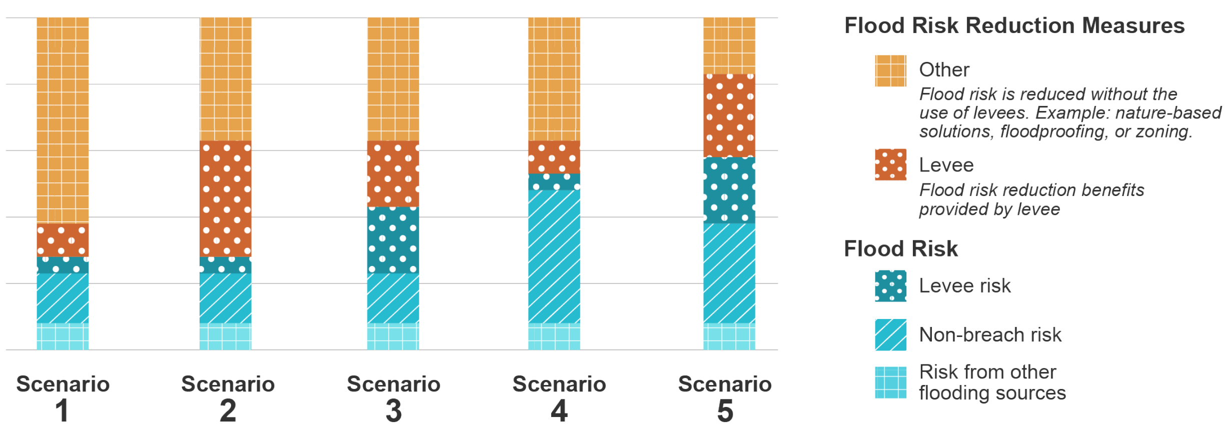
- **Equity**: The right of individuals and society to be protected, and the right that the interests of all are treated with fairness, with the goal of placing all members of society on an essentially equal footing in terms of levels of risk that they face.
- **Efficiency**: The need for society to distribute and use available resources to achieve the greatest benefit.

Risk management always requires trade-offs between equity (providing equal protection to all individuals) and efficiency (equal distribution of societies' resources). Levee risk management practices should strive for equitable life safety risk behind levees, recognizing that individuals and communities have different circumstances. These practices should allocate risk management resources and allow for engagement opportunities to help address unique challenges and barriers related to underserved communities behind levees. For more discussion on community flood resilience and social equity, see **Chapter 12**.

3.2.4 Investment Strategies

Understanding, evaluating, and comparing levee risk reduction benefits, levee risk, and non-breach risk can help in selecting appropriate focus and level of effort for levee risk management activities. It can also help inform decisions on whether to invest in modifications to increase flood risk reduction benefits associated with the levee. Consider the five scenarios illustrated in Figure 5-14.

Figure 5-14: Scenarios Informing Levee Risk Management Activities



Scenario 1: The levee provides limited risk reduction benefits in the leveed area and flood risk reduction is mostly managed through other measures so that the remaining flood risk is low. Since the levee is not heavily relied upon for flood risk reduction, its condition and satisfactory performance are not as critical. Therefore, the benefit of expending resources on reducing levee risk is limited. Scaled-back levee risk management activities may be sufficient for this levee. There is also no strong justification to invest in rehabilitation or modification (raising the levee), since the flood risk is primarily managed through other solutions.

Scenario 2: The levee is a major part of the flood risk reduction strategy and provides significant flood risk reduction benefits. Further, the levee is in good condition and is proactively managed so that the levee risk is low. In this scenario, levee risk management activities are of paramount importance to ensure levee risk remains low. Robust inspection, maintenance, surveillance and monitoring programs, and strong emphasis on building risk awareness in the community—as well as emergency preparedness and planning—are justified. On the other hand, there is no strong justification to invest in modification because the flood risk is low. There is also no need to rehabilitate the levee because it is in good condition and is expected to perform as intended.

Scenario 3: The levee is a major part of the flood risk reduction strategy, but in its current condition, the levee risk is high. In this scenario, there is justification to reduce levee risk by rehabilitating the levee. In addition, robust inspection, maintenance, surveillance and monitoring programs, and strong emphasis on building risk awareness in the community—as well as emergency preparedness and planning—are justified. On the other hand, there is no strong justification to modify the levee since flood risk due to overtopping without breach (non-breach risk) and flooding from other sources is low.

Scenario 4: The levee provides limited flood risk reduction benefits. Flood risk in the leveed area is high and is driven by non-breach risk and/or other sources of flooding. There may be relatively little benefit gained by rehabilitating the levee to reduce levee risk. Scaled back levee risk management activities may be sufficient for this structure. On the other hand, modifying the levee (e.g., raising the crest) may offer a significant overall flood risk reduction benefit. With modifications, changes in levee risk should be evaluated.

Scenario 5: The levee is a major part of the flood risk reduction strategy, but in its current condition, the levee risk is high. Non-breach risk and/or flooding from other sources in the leveed area is also high. This scenario represents the highest overall flood risk of all five scenarios. In this scenario, there is justification to reduce levee risk by rehabilitating the levee. In addition, robust inspection, maintenance, surveillance and monitoring programs, and strong emphasis on building risk awareness in the community—as well as emergency preparedness and planning—are justified. There is also justification for modifying the levee (e.g., raising the crest) or implementing other measures to provide additional flood risk reduction.

Table 5-2 summarizes investment strategy considerations discussed above.

Table 5-2: Investment Strategy Considerations

		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Scenario description and levee characteristics	Levee contribution to risk reduction	Minor	Major	Major	Minor	Major
	Non-breach risk and risk of flooding from other sources	Low	Low	Low	High	High
	Levee risk	Low	Low	High	Low	High
Investment strategy	Rigor of routine activities	Low	High	High	Low	High
	Modify levee?	No	No	No	Yes	Yes
	Rehabilitate levee?	No	No	Yes	No	Yes

The implementation of measures may be phased-in over some time to reduce risks to tolerable levels. The approach is to take actions to incrementally reduce risk as low as reasonably practicable. Activities should be prioritized to reduce risks as soon as reasonably practical. Temporary or interim measures should be implemented until a permanent solution is completed.

3.3 Building Risk Awareness

It is important to share information about the levee and flood risk with those who need the information because of their role or to improve the awareness of the community. An open and transparent exchange of information improves knowledge and understanding of risks and improves the understanding of options available to manage those risks. Refer to **Chapter 3** for guidance on risk awareness, communication, and community engagement. The following questions should be considered about risk awareness:

- Do all parties responsible for levee risk management have a common understanding of levee risk? Best practices for building a common understanding of risk characterization include inviting all interested parties to participate in a risk assessment, and providing clear and complete documentation of risk estimates.
- Do those with the responsibility for emergency response have the best available information with regard to potential vulnerable locations, breach characteristics, and inundation mapping?
- Can those responsible for levee operation and maintenance activities describe levee vulnerabilities and explain how the O&M plan considers site-specific risks?
- Has the community in the leveed area been provided the best available risk information associated with the levee, including potential changes to flood risk over time? Examples include public engagement activities, media stories, or a current community website.

3.4 Fulfilling Day-to-Day Responsibilities

Routine activities such as inspections, proactive maintenance, monitoring, and emergency preparedness are critical elements of levee risk management. When assessing the adequacy of those activities, consider the guidance provided in **Chapters 9 and 10**. The following are considered a baseline or minimum regarding fulfilling daily responsibilities:

- Routine inspections are taking place.
- Risks are routinely evaluated.
- Issues arising that result in increased risk are addressed in a timely manner.
- Levee safety-related O&M activities are performed in a timely manner.
- A monitoring plan is in place and includes the expected performance for each instrument and area to be observed. Additionally, the plan should include procedures to be followed if performance is not as expected.
- An emergency action plan is current.
- The O&M manual is up to date.

4 Risk Management in the Levee Lifecycle

Levee risk management is continuous throughout the levee lifecycle, which typically consists of project formulation, design, construction, O&M, modifications, and levee removal (if needed). Certain levee risk management activities, such as emergency preparedness and response, enhancing community resiliency, and community engagement occur at all stages of the lifecycle.

A first step in developing and implementing levee risk management activities is to understand how the levee fits into the flood risk management strategy (i.e., is the levee relied upon to provide flood risk benefits?). If the levee is not relied upon, other flood risk management strategies will continue (**Chapter 1**). If the levee is relied upon for flood risk reduction, levee risk management activities are implemented as described in this chapter and expanded upon in other chapters in these guidelines.

In the case of a new levee, the normal entry point into the lifecycle is at establishing flood risk reduction objectives and formulating the levee project. In the case of an existing or a 'legacy' levee, parties would typically enter the lifecycle at the O&M stage. However, the lifecycle can be entered in at any point.

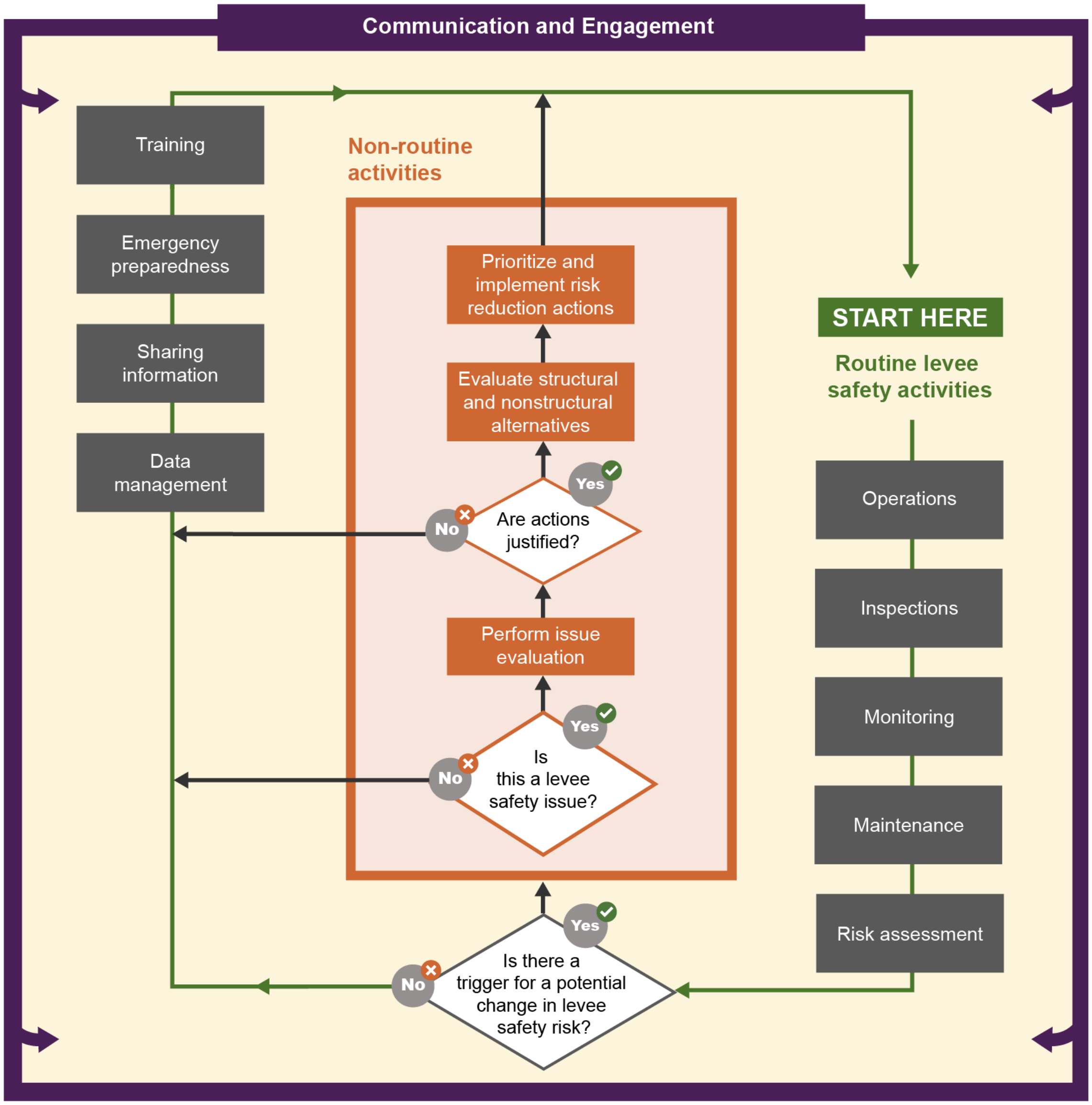
The following sections provide guidance on decisions related to various phases of the levee lifecycle, including use of risk to inform decisions, where applicable.

Levee risk management is an ongoing and iterative process and includes the integration of routine and non-routine activities. Figure 5-15 illustrates this concept. The outer loop (green) depicts continuing and recurring actions, such as normal O&M, inspections, monitoring, periodic re-assessment of risk, emergency preparedness, training, and other routine activities. The order of the routine recurring activities in the outer loop is not intended to be sequential; each of the recurring activities has its own timing. Routine activities are implemented to monitor levee performance and for day-to-day levee risk management.

Non-routine activities (orange) are implemented to address a potential levee safety issue or an identified levee risk. Non-routine activities are triggered by a specific concern, and therefore, not all levees will need to go through this part of the levee risk management cycle. These activities include evaluating the need for immediate temporary risk reduction actions, efforts to assess potential issues, evaluation of remedial alternatives (both structural and nonstructural), and implementation of selected risk reduction measures. While typically infrequent, levees may require emergency response that also triggers non-routine activities.

Both routine and non-routine activities require proactive communication and engagement of stakeholders (purple outer loop), which should be a continuous activity.

Figure 5-15: Routine and Non-Routine Levee Risk Management Activities



4.1 Levee Project Formulation, Design, and Construction

Levees should be formulated, designed, and constructed using a risk-informed approach. A risk-informed approach does not replace the need for traditional planning methods, deterministic analyses and criteria, or standard construction methods, but rather informs where traditional methods should be scaled up (made more conservative) or scaled down (made less conservative). Further, a risk-informed approach does not replace good practices for day-to-day activities, but rather informs them so that the levee owner can focus resources and efforts on O&M actions that help keep levee risk in check.

Formulating, designing, and constructing a levee project directly aligns with the 'taking actions to reduce risk' levee risk management responsibilities described in section 3.

4.1.1 Project Formulation

The goal of a levee project formulation process is to establish a levee footprint, alignment, and height that provides the desired flood risk reduction benefits in an economically, socially, and environmentally sustainable manner. The levee formulation process considers life safety risk as well as other metrics, such as cost-benefit ratio and the net national economic development benefits. In addition, configuring a levee includes setting top of levee profile, establishing the location and dimensions (length and depth) of controlled overtopping, establishing operation and maintenance needs, emergency preparedness requirements, and considering resiliency measures in the overtopping reach. See **Chapter 6** for guidance on formulating a levee project.

The risk assessment during the project formulation phase should concentrate on the uncertainties of input variables having a significant impact on study conclusions and recommendations. It should be completed at the feasibility/conceptual design phase (project formulation) to help evaluate, compare, and select design alternatives.

4.1.2 Design

Levees should be designed using sound engineering principles, processes, and procedures in accordance with the state of the practice. As discussed in **Chapter 7**, the levee design process is flexible and should be scaled to meet project needs. Deterministic analysis and criteria (factors of safety) should provide a basis for initial evaluation of levee designs. The resulting initial deterministic designs should then be evaluated in a risk-informed design process to decide whether they achieve levels of reliability commensurate with consequences of poor performance or a breach, including economics and loss of life. A risk assessment should be performed to refine and confirm the design. Generally, levee designs should ensure that the levee risk is not a significant contributor to the flood risk. This is applicable to new designs, as well as levee rehabilitation and modifications.

As part of the design process, levee reliability should be evaluated in terms of annual probability of breach. The evaluation should consider all credible potential failure modes for all levee features (including ‘human’ systems that require operation such as closure structures) and all loading conditions, including flood levels that overtop the levee. This is necessary for estimating incremental consequences and properly accounting for levee risk and non-breach risk.

In addition to the risk assessment performed during formulation, a risk assessment should be completed during design, typically between 30% and 60% design to achieve the following objectives:

- Provide a reasonable level of assurance that the structure will perform reliably over the full range of loading.
- Confirm the levee risk is tolerable.
- Verify the resulting design meets established flood risk reduction objectives.

All factors driving the levee risk must be clearly understood and considered within the project design. The design should incorporate defensive design features—such as controlled overtopping locations—that effectively manage levee risk, and should consider opportunities for incorporating **resilience**, **redundancy**, **robustness**, and long-term sustainability features. Further, levee designs should consider, refine, and evaluate structural and nonstructural measures to manage overtopping resilience (**Chapter 7**). The goal is to reduce the likelihood of a catastrophic breach during an overtopping event and to reduce potential life safety consequences over a range of overtopping events.

4.1.3 Construction

Construction implements the levee project developed during levee design. The goal of levee construction is to construct the project as intended to achieve the desired flood risk reduction benefits in a cost effective and timely manner, while avoiding impacts to environmental, cultural, and natural resources.

There are two types of risks that should be managed during construction:

1. Construction risk (e.g., cost, schedule, and liability during construction).
2. Flood risk (e.g., flooding of the construction site or leveed area during construction).

Depending on the levee project, identified construction risks either need to be avoided, mitigated, or accepted. New levee and levee modification construction projects with significant financial investment (greater than $5 million) or potential for life loss and significant economic, environmental, infrastructure damages due to poor project performance should utilize a higher degree of construction risk management. New levee and modification construction projects with no life loss or economic damage may utilize a lesser degree of construction risk management. Generally, repairs including breach and emergency repairs also utilize less construction risk management.

Levee construction includes three general phases: pre-construction, construction, and post-construction, that all address levee construction risk. The pre-construction phase includes the work performed after completion of the design and at the beginning of the actual field activities including contract-required workplans and submittals. The construction phase is the period when the physical work occurs and can occur over multiple seasons depending on the complexity of the project. The post-construction phase includes construction closeout activities and preparation of required documentation. The roles of the design team through the phases of construction and specific actions or considerations during these phases are discussed in **Chapter 8**, along with other specifics of levee construction.

To minimize flood risks, if possible, construction should be scheduled during the non-flood season. Construction may require modification of existing flood risk-reduction features such as the temporary decrease of an existing levee’s height or other activities that weaken the levee’s ability to perform during flood events. In these cases, levee risk during construction should be managed by ensuring construction meets the design intent, sequencing construction to reduce flood risk during construction, implementing temporary flood risk reduction measures, and other measures (e.g., specific emergency action plan during construction).

Levee risk is managed by ensuring construction meets the design intent, by sequencing construction to reduce flood risk during construction, and by implementing temporary flood risk reduction measures as warranted. Changes made during construction may require re-evaluation of levee risk. Before construction is complete, the design team should verify that the constructed project meets the design intent and that no new potential failure modes were created by the means/methods of construction and/or unforeseen conditions encountered during construction.

During construction for levee modification and/or rehabilitation, life safety risks should not increase above preconstruction levels. Addressing these risks requires an understanding of the nature of flood hazard at a particular construction site during the construction period, including temporal variability (e.g., likelihood of events of sufficient intensity accounting for seasonality and climatic variability). It also requires an understanding of the timeframes required to prepare for and effectively manage the risk.

Some strategies to manage risk during construction may include:

- Rescheduling construction activities, or limiting critical construction activities, to limit exposure to high risks.
- Forecasting floods with flood event predictors at lead times that correspond to realistic response timeframes.
- Establishing warning and response procedures to address the risks prior to arrival of the flood event.
- Stockpiling of materials and equipment on site to use at short notice if required.

If it is impractical to maintain construction risks at or below preconstruction levels, the levee owner—together with the appropriate regulator and those affected—needs to decide whether the construction risk is tolerable in order to secure future benefits.

4.2 Routine Activities

Collectively, the routine activities described within this section align with all the levee risk management responsibilities described in section 3.

4.2.1 Operation and Maintenance

All levees require regular O&M, including basic repairs to continue providing intended flood risk reduction benefits. Each levee should have an O&M manual with guidance and instructions to project personnel, including procedures and timing of O&M activities during flood events. The level of details can vary depending on the project complexity. The key is to document maintenance processes for consistency and personnel training, and to allow for changes to the processes in response to identified levee safety concerns. The O&M manual should be updated to reflect modifications or changes to levee O&M activities (**Chapter 9**).

LEVEE UPKEEP IS A COST EFFECTIVE INVESTMENT

The cost of levee failure is many times that of initial levee construction including O&M. Therefore, it is prudent and cost-effective to invest in proper levee inspection, upkeep, and maintenance.

4.2.2 Inspections

Levees are subject to changes and deterioration that could lead to development of a potential failure mode. Inspections are intended to observe early signs of distress so that necessary risk reduction measures could be implemented before a potential failure mode develops. In addition to focusing on the levee, inspections should note changes in land use, consequences in the leveed area, and changes within the channel adjacent to the levee.

In general, inspections are categorized as routine, flood-related, or event-driven. Levee inspections inform routine levee risk management activities and serve as the primary basis for evaluating levee condition and performance as part of risk assessments. The scope and scale of inspections can vary depending on the risk and complexity of the levee, the levee feature being inspected, and the inspection type/purpose.

Inspections and observations should focus on potential failure modes and identified levee safety issues specific to the levee. Routine levee inspections should be conducted on a regular frequency to document the physical condition of the levee at a given point in time and the inspection schedule should vary to capture conditions in different seasons and loading regimes. Inspections occurring during a flood event are important and should be carefully documented because they provide valuable performance data that demonstrates how a levee performs under flood loading, which may occur infrequently. In addition, less formal annual inspections by levee owner/operator staff are important to maintain awareness of levee conditions and to inform maintenance and repair activities.

See **Chapter 9** for specific guidance on conducting and documenting various levee inspections.

4.2.3 Monitoring

Instrumentation or other means for observation and monitoring may be used to supplement inspections in evaluating the levee performance. Careful evaluation of instrumentation data on a continual basis may reveal a potential deficiency or developing potential failure mode. Conversely, instrumentation may be a means of confirming that an observed condition is not serious and does not require immediate remedial measures. Not all levees require instrumentation as part of the routine levee risk management. The need for instrumentation should be evaluated using a risk-informed approach considering project specific needs. Each instrument should have a clearly defined purpose, tied to a specific issue and/or potential failure mode.

Instrumentation monitoring frequency should be described in an instrumentation plan in the O&M manual. At a minimum, instrumentation and performance data information should be evaluated as part of routine inspections and risk assessments.

4.2.4 Risk Assessment

The level of detail and frequency of risk assessments should be informed by the levee’s risk characterization. Typically, risk review and reassessment are performed in conjunction with an inspection (but not necessarily with each one), or as needed based on changed conditions that could impact the risk characterization.

Out-of-cycle risk assessments should be completed in response to significant changes in the levee condition or the population and/or infrastructure in the leveed area.

Issue-specific risk assessments may be triggered by a specific concern or observation. In addition, issue-specific risk assessments may be performed when a previous risk assessment has identified that issue as a risk driving failure mode for a levee system. Regardless of the trigger, it is vital that issue-specific risks are evaluated and understood in the system context.

Issue-specific risk assessments focus on a specific potential failure mode, which may require additional site explorations and/or engineering studies. These supporting activities are completed to reduce uncertainty and increase confidence in the risk estimates to inform decisions.

Risk assessments may be performed to re-estimate the risk after levee modifications or nonstructural measures are implemented.

4.2.5 Data Management

Accurate, complete, and current information is necessary to inform and support levee risk management decisions, and good management of that data is essential. Pertinent information should be readily available to gain an understanding of project features, roles and responsibilities, potential failure modes and risk estimates, design and construction records, performance history, and emergency action plans, among others. See companion **Chapters 6, 7, 8, 9, and 10** for a more detailed description on the types of information and documentation that is generated during various stages of the levee lifecycle. Levee owners are responsible for ensuring the levee information is accurate and up to date. The data should be maintained in the National Levee Database.

4.2.6 Emergency Preparedness

An important component of levee risk management is managing potential consequences associated with levee breach or misoperation. Each levee with non-zero population in the leveed area should have an emergency action plan with inundation maps, informed by risk-driving potential failure modes and the corresponding breach scenarios. Emergency action plans and inundation maps may also be required for levees with no population in the leveed area, if critical transportation routes pass through those leveed areas because many flood-related deaths are associated with motorists driving through flood waters.

Emergency planning and preparedness activities are scalable commensurate with the levee risk, size of the population in the leveed area, and the complexity of evacuation procedures. Levees with high levee risk—which is driven by the chance of levee breach prior to overtopping—requires the most robust emergency preparedness and planning efforts. In addition, it should be expected that such levees may require more intense, more extensive, and earlier floodfighting efforts compared to other levees. This is because these levees could develop signs of distress—or even breach—at flood levels well below the top of the levee.

At a minimum, it is a best practice to have a documented process to coordinate all emergency preparedness activities such as emergency action plan exercises, maintaining and updating emergency action plans and inundation maps, preparing for emergency response (e.g., identifying materials and equipment sources for emergency actions), coordinating with local emergency management agencies, and other related activities (such as tabletop exercises). Similarly, potential emergency scenarios and corresponding communication plans (including a communication flow chart with contact names and phone numbers) should be developed and tested (**Chapter 10**).

4.2.7 Sharing Information

Ongoing community engagement creates the foundation for successful levee risk management and provides opportunities to share levee-related information. Being transparent with levee-related knowledge and seeking to educate and inform the community when opportunities become available are best practices. Approaches for sharing levee information are described in **Chapter 3**.

4.2.8 Training

All personnel involved with levee risk management (e.g., operations, inspections, decision making, project management, design oversight, and floodfighting) should be adequately trained. The level of training should be appropriate to the assigned responsibilities of the various personnel and commensurate with the levee risk. Training can be formal (instructor-led training in a classroom, online, or in the field) or informal (on the job) and should be customized based on an assigned role, level of experience, and the required skill set.

4.2.9 Triggers from Routine to Non-Routine Activities

Non-routine activities are triggered when there is an apparent change in the levee risk that requires an initial, scalable evaluation of the risk. Non-routine activities could be triggered by:

- Unusual performance such as the formation of a sand boil, an observed wet area indicating new seepage, sudden change in seepage in comparison to past performance, or change in seepage clarity.
- An incident such as development of a crack in the embankment, movement of a structure, or deterioration at a feature transition.
- Instrumentation monitoring exceeds established monitoring thresholds.
- A significant increase in potential consequences (e.g., development in the leveed area) or a change in the understanding of flood frequency and/or severity.
- Updated risk estimates from a periodic review.

A review and documentation process guideline should be established to guide decision makers on how to initiate the non-routine activity process.

4.3 Non-Routine Activities

Non-routine activities are shown in the middle of Figure 5-15. Details of each step in the process are levee-specific and may depend on regulatory requirements. Procedures for processes to implement non-routine activities should be developed in collaboration with stakeholders. The process should identify the following:

- Specific decision makers and their roles and responsibilities.
- Key inputs into making decisions.
- Documentation and communication of decisions.
- Approvals necessary to support the decision.

The process should also outline considerations related to funding levels, resource allocation, risk queue prioritization, and the schedule for issue evaluation.

The non-routine activities described within this section align with two of the levee risk management responsibilities described in section 3, including understanding risk associated with levees and taking actions to reduce risk.

4.3.1 Is There a Levee Safety Issue?

The initial decision to determine if there is a levee safety issue involves evaluating whether unusual performance, incident, or a revised risk assessment demonstrates that there is a potential issue and whether an issue evaluation is needed. Additionally, if the issue is serious and urgent, temporary risk reduction measures should be implemented and immediate risk communication and appropriate community engagement activities should be developed and implemented, including activation of the Emergency Action Plan, as appropriate (**Chapter 10**).

If the initial review and evaluation conclude there is not a levee safety issue, the process shifts back to routine activities shown in the outer loop of Figure 5-15. Alternatively, the initial review and evaluation may conclude that an issue evaluation is warranted to make appropriate levee risk management decisions and the process will move through the non-routine activity tasks as described herein.

4.3.2 Evaluate Levee Safety Issues

Once there is a decision to further investigate the levee safety issue, a plan should be established to address the key areas of uncertainty and gain additional information (i.e., data investigations, studies, and analyses), reduce uncertainty, and improve confidence in the risk assessment. In a risk-informed levee safety process, it is not unusual for an urgent issue of concern to be initially disruptive, perhaps necessitating some reallocation of resources and re-prioritization of projects. Prioritization of issue evaluation should consider other ongoing activities and be sequenced considering levee risk, confidence, and uncertainty, as well as flexibility of programmatic funding and resource levels.

The evaluation can be phased to initiate relatively easy data collection or study tasks up front, with more complex analyses following in subsequent phases. The scope should be sufficient to address the risks of the potential failure modes of concern and should provide sufficient information for an appropriately scaled risk assessment to support next steps.

4.3.3 Is Action Justified to Reduce Levee Risk?

One of the most important levee risk management decisions is determining whether actions are needed to reduce levee risk. Making this decision requires an understanding of the risk and considering all factors.

The urgency of the risk reduction is also part of the decision. Urgency of risk reduction actions may consider the level of effort to accomplish the actions, particularly for relatively low to moderate cost or low level of effort actions that can be quickly accomplished. Prioritization and urgency should also consider other ongoing non-routine activities to ensure that overall efforts effectively drive levee risk down as efficiently as possible.

4.3.4 Evaluate Structural and Nonstructural Alternatives

After deciding that reducing levee risk is justified, it is appropriate to evaluate both structural and nonstructural alternatives. Structural alternatives typically include construction projects, while nonstructural alternatives typically include enhanced emergency planning and engagement with those living or working in the leveed area. Removing the levee is a structural alternative that can be used to manage risk in concert with nonstructural actions such as property buy-outs or raising structures within the previously leveed area.

Evaluating risk reduction alternatives includes developing conceptual designs sufficient to understand the amount of risk reduction that can be accomplished for each alternative and the associated cost for each. It is also important to understand any impacts to flood risk reduction benefits associated with the levee and the remaining flood risk in the leveed area. The evaluation should follow the general steps for project planning and formulation outlined in **Chapter 6**.

If the urgency of risk reduction is low, and other projects have priority in the risk reduction queue, an interim risk reduction alternative may be kept in place for several years.

4.3.5 Prioritize and Implement Risk Reduction Actions

Upon selecting a preferred alternative that demonstrates adequate risk reduction, the chosen measure should be prioritized (considering other ongoing or planned levee safety work) and implemented. If the alternative involves levee modification/rehabilitation, design and construction activities are initiated. It is important to review the potential failure modes at strategic milestones during the design to:

- Ensure that as the design progresses, risk reduction objectives are still met.
- Prevent design elements that could inadvertently increase the risk.
- Verify that new credible potential failure modes are not introduced by the modifications.

After completion of the construction of levee modification/rehabilitation, a post-construction risk assessment should be performed to verify the design and construction achieved the desired risk reduction.

4.3.6 Return to Routine Activities

After the risk reduction alternative has been implemented and risk assessments are revised to reflect the current as-implemented condition, routine activities for levee risk management resume. The modifications may trigger changes to O&M and/or instrumentation and monitoring.

5 Rigor, Frequency, and Focus of Levee Risk Management Activities

Rigor (level of effort), frequency, and focus of many levee risk management activities can be directly informed by the levee risk as summarized in Table 5-3, with additional details provided in the corresponding chapters. The following factors affect the level of effort, frequency, and focus of activities:

- **Potential for loss of life**. In general, levee risk management activities for levees with no population in the leveed area could be scaled back.
- **Levee risk** (probability of breach or misoperation and associated consequences). In general, the higher the levee risk, the more robust levee risk management activities should be.
- **Levee reliability prior to overtopping**. In general, levees that have known deficiencies and are likely to breach prior to overtopping require a different focus than well-designed, constructed, and maintained levees that are generally in good condition and are expected to perform as intended for floods to the crest of the levee, even if the levee risk is the same in both cases. This consideration can help target risk reduction activities. For example, improving the levee condition could provide significant risk reduction benefits for levees where risk is driven by breach prior to overtopping, but may only be marginally effective for levees where risk is driven by breach due to overtopping. For those levees, activities should instead focus on performance during overtopping and improving evacuation effectiveness. In addition, levees with high risk of breach prior to overtopping require more rigor for observations and monitoring during floods, as well as floodfighting for smaller events and earlier during a larger event. The need for repairs may be more urgent because these levees may exhibit distress even under relatively low flood loading.

Additional considerations that may justify elevating the level of levee risk management activities include:

- Potential impacts to critical infrastructure or historically or culturally significant infrastructure in the leveed area.
- Significance of agricultural resources in the leveed area that could be impacted by levee breach.
- Environmental damages associated with levee breach.
- Social equity and justice considerations (e.g., demographic characteristics and socioeconomic status of population in the leveed area that could elevate vulnerability to damaging flood events).
- Impacts to the regional or national economy that would be caused by levee breach.
- Loss of river navigation due to levee breach.

Table 5-3: Activities Informed by Levee Risk

Chapter	Activities and/or Decisions	Aspects Informed by Risk
Chapter 3: Engaging Communities	Engagement and communication efforts	Focus of the engagement activities, scope, and scale of effort.
Chapter 4: Estimating Levee Risk Chapter 5: Managing Levee Risk	Risk assessment	Type of risk assessment, level of details, frequency of risk assessments, team composition, and required approvals.
	Temporary/interim risk reduction measures	Need for interim risk reduction measures and how they are prioritized.
	Reviews and approvals	Types and hierarchy of reviews and the level of details.
	Project documentation	Minimum requirements and scalability of documentation.
Chapter 6: Formulating a Levee Project	Evaluation of alternatives to modify or rehabilitate a levee	The requirement to consider controlled overtopping and the requirements for target level of risk reduction.
	New levee or modification project	Scope and level of effort.
	Forecasting future conditions for rehabilitation	Horizon for forecasting conditions into the future.
	Selection of levee crest level for modification	Minimum required probability of overtopping.
Chapter 7: Designing a Levee Chapter 8: Constructing a Levee	New levee design	Minimum design requirements for levees with population in the leveed area. Data and information inputs (ranges from relying mainly on existing data to comprehensive site investigation and data collection). Number of reaches to be analyzed (ranges from few to many). Extent of instrumentation to be installed (ranges from limited/none to extensive).
	Design for levee rehabilitation or modification	Risk assessment requirements to support design (ranges from simple to comprehensive/complex).
	Managing construction risk during modification or rehab	Requirements for flood control during construction, minimum construction management requirements.
	Design/construction documentation	Scope and level of details (ranges from simple to comprehensive). Number of submittals to 'levee owner' for review (ranges from none to multiple).
Chapter 9: Operating and Maintaining a Levee	Routine inspection	Frequency of inspections.
	Flood and/or event-driven inspections	Threshold levels for certain activities, scope, and focus of inspections.
	Operations	Minimum requirements for operation proficiency and documentation of operation procedures.
	Maintenance and repair	Timing/urgency of repairs.
	Staff training	Minimum requirements and areas of focus.
	Physical security	Minimum requirements.

Chapter	Activities and/or Decisions	Aspects Informed by Risk
Chapter 10: Managing Levee Emergencies	Emergency action planning	Emergency action plan requirements, including level of details.
	Floodfighting	Expectations for intensity, timing, and required preparations.
	Emergency training	Minimum requirements and focus of training content.
	Emergency exercises	Frequency.

6 Summary

The following is a summary of the key themes related to levee risk management as described in this chapter:

- Risk is dynamic and evolves with time due to changes in any of the components of risk (hazard, consequences, and levee performance). All should be periodically assessed. Responsible levee risk management requires continuous and proactive monitoring of risk and taking actions to reduce it as low as reasonably practicable.
- Floods do not affect all communities and individuals equally. The objective of levee risk management is to deliver the benefits of the levee safely and equitably in consideration of the overall flood risk management strategy. This is achieved by ensuring reliable levee performance in accordance with the established flood risk reduction goals and managing potential consequences of levee breach or misoperation.
- Divided roles, responsibilities, and authorities mean that no single entity has full control over all components of levee risk; all parties have a role. Managing levee risk requires an integrated approach of aligned programs, incentives, and activities that collectively drive risk down and keep it in check.
- Levee safety decisions should be informed by risk. The risk-informed decision-making framework includes risk assessment, risk management, and risk communication/ stakeholder engagement. These three elements overlap and are all critical to managing levee risk.
- Levee risk management decisions should consider how flood risk may be transferred or transformed. Levee risk management activities, including risk assessments, are scalable. The level of effort and the focus of activities can be scaled considering the levee risk.
- Concepts for risk management are applicable to both a single levee and a portfolio of levees.

Related content associated with this chapter is included in detail in other chapters of the National Levee Safety Guidelines as described in Table 5-4.

Table 5-4: Related Content

Chapter	Chapter Title	Related Content
1	**Managing Flood Risk**	• Flood risk management strategies
2	**Understanding Levee Fundamentals**	
3	**Engaging Communities**	• Engagement for risk awareness • Engagement for levee-related activities
4	**Estimating Levee Risk**	• Estimating and characterizing levee risk • Levee risk classification
5	**Managing Levee Risk**	
6	**Formulating a Levee Project**	• Guidance on levee project formulation
7	**Designing a Levee**	• Levee design considerations
8	**Constructing a Levee**	• Construction phases
9	**Operating and Maintaining a Levee**	• Routine O&M activities and inspections
10	**Managing Levee Emergencies**	• Emergency preparedness and planning
11	**Reconnecting the Floodplain**	• Flood risk management strategies
12	**Enhancing Community Resilience**	• Strategies for community flood resilience

6

Formulating a Levee Project

Key Messages

This chapter will enable the reader to:

- **Consider levees in the context of flood risk.** A levee is one of many measures that may be employed as a flood risk reduction strategy. Levee formulation should ensure levees do not contribute significantly to flood risk.
- **Be ecologically and socially aware.** Consider ecological and social risks and opportunities while holding life safety paramount. Pursue solutions that incorporate the natural environment and support the everyday functioning of the local community.
- **Follow and iterate the planning process.** The well-established six-step process should guide formulation. As alternatives are developed, evaluated, and compared, the understanding of risks may change, resulting in the return to a previous step or re-formulation.
- **Evaluate multiple alternatives.** Use a transparent process to compare potential benefits and adverse impacts of multiple project alternatives. Consider life safety, economic and environmental benefits or impacts, and social equity in the evaluation.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Other chapters within the National Levee Safety Guidelines contain more detailed information on certain topics that have an impact on formulating a levee project, as shown in Figure 6-1. Elements of those chapters were considered and referenced in the development of this chapter and should be referred to for additional content.

Figure 6-1: Related Chapter Content

CH 1	CH 2	CH 3	CH 4
Flood risk management strategies	Types of levee projects	Engaging about levee projects	Identifying flood risk Vulnerability
CH 5	**CH 6**	**CH 7**	**CH 8**
Risk-informed decision making Levee risk management	**Formulating a Levee Project**	Levee design considerations	Construction considerations Construction documentation
CH 9	**CH 10**	**CH 11**	**CH 12**
Operating and maintaining a levee		Reconnecting the floodplain	Incorporating community resilience

Contents

1 Introduction 6-1
2 Levees as a Flood Risk Reduction Strategy 6-1
3 Planning Process 6-3
3.1 Planning Team 6-5
3.2 Step 1: Identify Problems, Opportunities, Objectives, and Constraints 6-5
3.3 Step 2: Inventory Current and Forecast Future Conditions 6-9
3.4 Step 3: Formulate Alternative Plans 6-12
3.5 Step 4: Evaluate Alternative Plans 6-15
3.6 Step 5: Compare Alternatives 6-17
3.6.1 Effectiveness 6-17
3.6.2 Efficiency 6-18
3.6.3 Acceptability 6-18
3.6.4 Completeness 6-18
3.7 Step 6: Select Preferred Alternative 6-19
4 Best Practices and Considerations 6-20
4.1 Managing Risk 6-20
4.1.1 Life Safety 6-20
4.1.2 Levee Superiority for Riverine Levees 6-20
4.1.3 Risk Transfer and Transformation 6-21
4.2 Social Considerations 6-23
4.2.1 Collaboration and Engagement 6-23
4.2.2 Social Equity 6-23
4.2.3 Underserved Populations 6-24
4.3 Pursuing Additional Benefits 6-25
4.3.1 Co-Benefit Opportunities 6-25
4.3.2 Natural and Nature-Based Solutions 6-25
4.3.3 Climate Resilience 6-27
4.3.4 Adaptive Management 6-28
4.4 Considerations for All Alternatives 6-29
4.4.1 Laws, Legal Requirements, and Regulations 6-29
4.4.2 Environmental Impacts and Regulatory Compliance 6-30
4.4.3 Work Within Existing Floodplain Management 6-31
4.4.4 Cost and Funding 6-32
4.4.5 Operations and Maintenance 6-33
4.4.6 Documentation 6-34

4.5 Site Specific Considerations 6-36
4.5.1 Land Use 6-36
4.5.2 Right of Way 6-37
4.5.3 Easements and Permits 6-38
4.5.4 Cultural Resources 6-39
4.5.5 Interior Drainage Requirements 6-40
4.5.6 Hazardous Materials 6-40
4.5.7 Borrow Areas/Sources of Construction Material 6-41
5 Interaction Amongst Formulation, Design, and Construction 6-42
5.1 Analysis Considerations 6-46
5.1.1 Addressing Uncertainty 6-46
5.1.2 Scalability 6-46
5.1.3 Planning Area and Levee Reaches 6-46
5.1.4 Available Information 6-47
5.2 Engineering Analyses 6-48
5.3 Risk Assessment 6-50
5.4 Economic Analyses 6-50
5.4.1 Benefit-Cost Analysis and Cost-Effectiveness Analysis 6-50
5.4.2 Incremental Analysis 6-51
5.4.3 Trade-off Analysis 6-52
5.4.4 Distribution Effects 6-52
5.5 Environmental Evaluations 6-52
6 Establishing Levee Characteristics 6-52
6.1 Establishing Design Hydraulic Conditions 6-52
6.1.1 Hydrologic Evaluations for Riverine Levees 6-54
6.1.2 Hydraulic Evaluations for Riverine Levees 6-54
6.1.3 Hydraulic Evaluations for Coastal Levees 6-54
6.2 Setting the Top of Levee Grade 6-55
6.2.1 Base Levee Height 6-55
6.2.2 Additional Height Considerations 6-56
6.2.3 Settlement and Construction Tolerance 6-58
6.3 Levee Alignment 6-58
6.3.1 Temporary Flood Protection 6-59
6.3.2 River Morphology 6-60
6.3.3 Coastal Morphology 6-63
6.3.4 Site Investigations 6-65

6.4 Levee Footprint and Features 6-67
6.4.1 Hydraulic Evaluations 6-68
6.4.2 Site Investigations 6-68
6.4.3 Considerations for Vegetation on or Near Levees 6-68
6.5 Nonstructural Actions 6-69
7 Plan Implementation 6-70
8 Summary 6-70

List of Figures

Figure 6-1: Related Chapter Content 6-i
Figure 6-2: The Formulation Process 6-4
Figure 6-3: Types of Levee Projects 6-4
Figure 6-4: Plan Formulation—Step 1 6-6
Figure 6-5: Plan Formulation—Step 2 6-10
Figure 6-6: Project Timeline 6-11
Figure 6-7: Plan Formulation—Step 3 6-12
Figure 6-8: Ecotone Levee Slope 6-14
Figure 6-9: Plan Formulation—Step 4 6-15
Figure 6-10: Plan Formulation—Step 5 6-17
Figure 6-11: Plan Formulation—Step 6 6-19
Figure 6-12: Transfer of Risk 6-22
Figure 6-13: Continuum of Nature-Based Approaches 6-26
Figure 6-14: GIS Documentation for Spatial Data 6-35
Figure 6-15: Example of a Cultural Resource 6-39
Figure 6-16: Interaction Amongst Formulation, Design, and Construction 6-42
Figure 6-17: Interaction Between Formulation and Design 6-43
Figure 6-18: Outcome of the Planning Process 6-44
Figure 6-19: Analyses Within the Six-Step Planning Process 6-45
Figure 6-20: Engineering Analysis Required for Formulating Levee Characteristics 6-48
Figure 6-21: Interaction Between Levees and Physical World 6-49
Figure 6-22: Determining Top of Levee Grade 6-55
Figure 6-23: Variations in Levee Alignments 6-61
Figure 6-24: Impact of Levees on Coastal Sediment Movement 6-64
Figure 6-25: Example of Wave-Driven Sediment Transport 6-65

List of Tables

Table 6-1: Step 1: Typical Problems, Opportunities, Objectives, and Constraints by Project Type 6-8
Table 6-2: Step 3: Example Considerations for Developing Alternative Plans by Levee Type 6-13

Table 6-3: Step 4: Example Benefits, Co-Benefits, and Costs 6-16
Table 6-4: Social Equity Considerations 6-23
Table 6-5: Land Use Types and Influences on Planning and Design 6-37
Table 6-6: Activities Within Each Phase of Levee Project 6-43
Table 6-7: Available Information 6-47
Table 6-8: Levee Project Type and Risk Estimates 6-50
Table 6-9: Hydrologic and Hydraulic Activities Within Each Phase of a Levee Project 6-53
Table 6-10: Site Investigation at Various Project Phases 6-66
Table 6-11: Geotechnical Considerations 6-66
Table 6-12: Related Content 6-72

1 Introduction

This chapter is focused on how to formulate a levee project. The guidance in this chapter applies when a community has gone through a process to understand their flood risk and has decided to pursue a flood risk management strategy that includes a levee. A generic planning process—as well as the unique consideration associated with formulating a levee project—are covered in this chapter.

Principles of levee formulation described in section 2 should be carried throughout the levee formulation process and into final design and construction. In addition to principles, several best practices and considerations are described for the reader to keep in mind as decisions are being made. Best practices are ways in which to achieve the overarching principles.

The goal of planning is to identify a cost-effective, technically feasible, and socially and environmentally responsible solution that meets project objectives. A step-by-step planning process is presented to provide a structured, scalable approach to develop alternatives and select the most appropriate levee project that aligns with a community's values. Throughout the planning process, analyses and evaluations are required to advance to next steps in the process. Descriptions of these analyses and the results used to establish levee characteristics are provided.

Typical readers of this chapter are those that are involved in the planning and design of a levee project including planners, engineers, levee owners/operators, decision makers, and other stakeholders affected by the project.

2 Levees as a Flood Risk Reduction Strategy

As discussed in **Chapter 1**, a comprehensive flood risk management strategy should reduce the risk of human and socio-economic losses caused by flooding and improve the resilience of communities against flood impacts. Some communities have already specified flood risk reduction strategies in their state or local hazard mitigation plans (**Chapter 11**). **Chapter 12** describes a communities' need to understand its exposure to flood risk, its greatest vulnerabilities, and carries forth the principle of achieving community resilience. Best practices for achieving community resilience may be categorized under four groups of actions:

- **Prepare**: Community education and awareness, individual actions, and community emergency planning.
- **Absorb and resist**: Structural (e.g., levee) and nonstructural measures, stormwater drainage systems, land use planning, property acquisition, and building codes.
- **Restore and recover**: Flood insurance, recovery plans, grants, and emergency funding.
- **Strengthen and adapt**: Continual assessment of resilience and identification of new or improved ways to achieve resilience goals.

To sustain resilience, communities should consider various combinations of structural, nonstructural, and nature-based measures to achieve flood risk reduction goals; levees are just one measure.

The selection of a flood risk reduction measure depends on many factors, including, but not limited to flood risk drivers and the effectiveness of a given measure in addressing risks, achieving environmental goals, understanding physical project constraints, availability of funding, and existing regulations, policies, and practices. A wide array of measures and actions have potential to reduce flood risk to life, health, and property while also restoring natural floodplain resources. Whatever measures are selected, it is essential that the flood risk management strategy—including land use decisions—supports community values and aligns with the long-term vision and goals for community development and priorities regarding what to protect and to what level. The likelihood of successful implementation—from taking a conceptual idea through the formulation, design, permitting, construction, and long-term O&M—should be addressed at the onset of a project.

It is also good practice to use redundant and complementary risk reduction measures. This redundancy increases the likelihood of successful reduction of flood impacts, even if one measure fails or does not perform as expected. An example of a redundant flood risk reduction measure might be a backup power supply for automated closure gates in case the primary power source is lost during a flood event. Communities should seek solutions to reduce flood risk that promote community values and align with its long-term vision related to residential and commercial development and the protection of assets. Examples of actions that communities can take to better understand and/or reduce the consequences of flooding are provided in **Chapter 1**.

The practices presented in this chapter are intended for new levees, if selected as a viable part of the risk reduction strategy, or for existing levees that require rehabilitation or modification to continue to be viable for a community's unique situation. These practices also apply to planning for a levee removal for situations where the levee is no longer a viable flood risk reduction strategy for a community. The overarching principles that should be central throughout levee formulation are:

- Hold life safety paramount
- Do no harm
- Enhance natural resources
- Make risk-informed decisions
- Reflect community values, goals, priorities, and risk tolerance
- Align with management of the floodplain

The goal of levee formulation is to select a preferred levee alternative that provides acceptable solutions to identified flood risk problems while considering the environmental setting. Levee project formulation includes establishing:

- **Top of levee profile**, including the level of flood risk to be provided, required levee height, and design of controlled overtopping section(s), if practical.

- **Levee alignment**, including setting back the levee to promote floodplain function and tie-ins to the natural ground or human-made structures whenever possible.
- **Levee footprint**, including crown width, levee slopes, and required right of way for the maintenance corridors.
- **Levee features** and other project elements to achieve the project objectives, such as designed environmental features that will work in concert with the levee.
- **Nonstructural actions**, including flood warning systems, evacuation planning, and community engagement to manage flood risk and levee risk once the levee is in place.

The levee configuration may be composed of multiple features that together comprise a whole systems approach that acts as a barrier to help prevent floodwater from entering the leveed area. The levee formulation process should demonstrate that the selected project is cost-effective and justified to achieve the desired objectives. The formulation process is successful when the proposed levee project is implementable, supported by the affected communities and is aligned with broader floodplain management goals for the community, county, state, and larger region. Most importantly, the decision to construct or modify a levee should be made with the understanding that levees do not eliminate the flood risk, but if implemented as part of a comprehensive flood risk management strategy, they can reduce risks to desired levels.

3 Planning Process

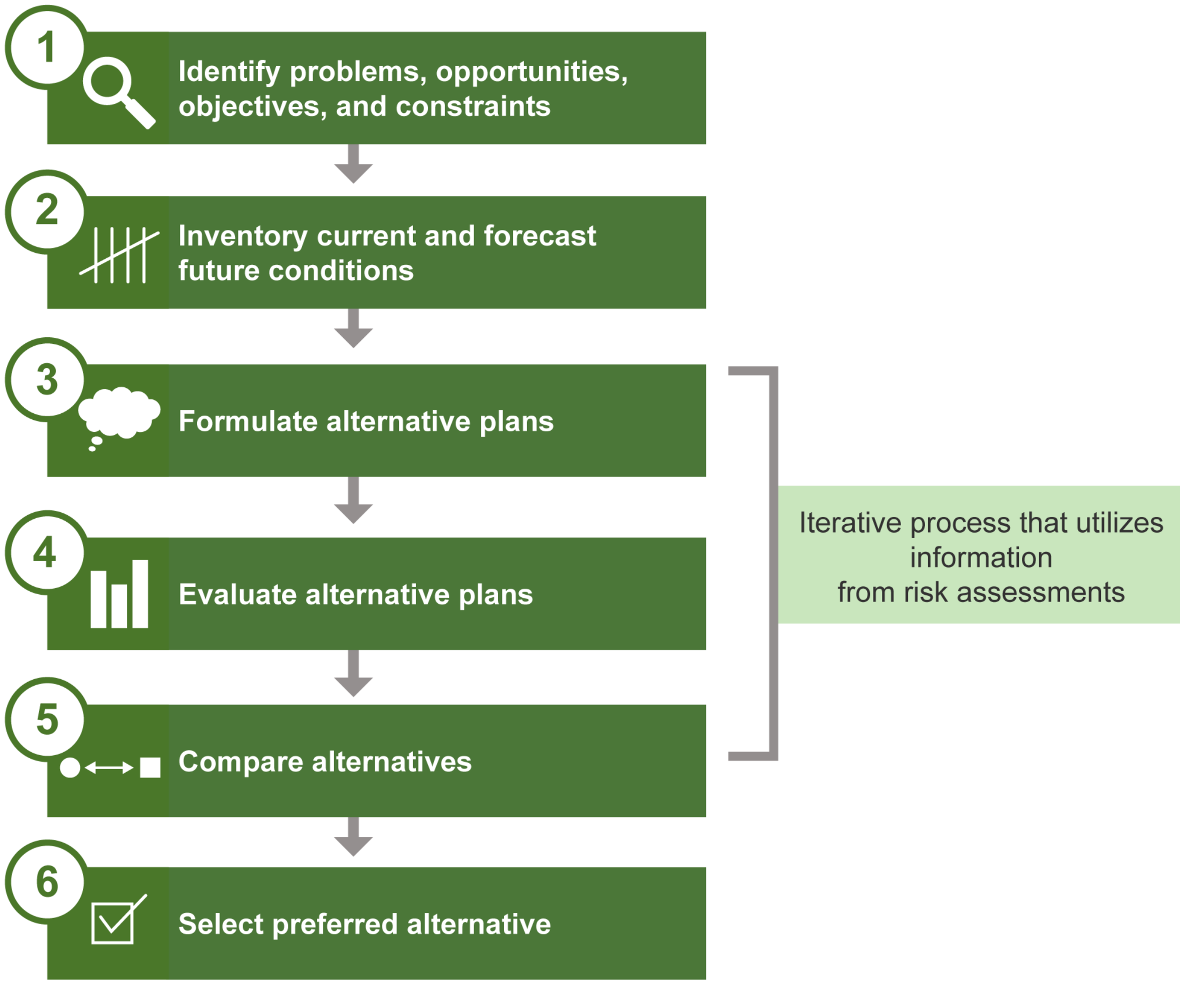
The generalized planning process defined herein and shown in Figure 6-2 is a structured, scalable approach with a framework that can be applied to any levee project.

This planning process is iterative and adaptive. As more information becomes available, it may be necessary to circle back to some of the previous steps. The steps may be done sequentially or concurrently—and could also be combined or abbreviated as appropriate—depending on the complexity of decisions. Regardless of the level of detail selected, risk assessment is an integral part of the planning process and should be performed throughout the six steps identified in Figure 6-2. As the formulation process moves through Steps 3 through 5, alternative plans may be adjusted to consider various constraints and opportunities, which could result in a change to one or more aspects of flood risk (i.e., levee risk, non-breach risk, or flood risk from other sources). As these risks are estimated, it may be necessary to return to an earlier step in order to make adjustments based on the assessment of risk.

The planning process should begin with scoping, which is initiated to lay the ground rules for levee planning. It includes defining the required level of detail of analyses, identifying areas of uncertainty, and engaging with parties involved in the planning process, as well as those affected by implementation of the project.

The purpose of scoping is to obtain the perspectives of others and build consensus on goals and objectives so that the desired outcome is clearly understood and broadly supported.

Figure 6-2: The Formulation Process



Recall the different types of levee projects described in **Chapter 2** and shown in Figure 6-3. Formulation for a levee project is needed for all levee project types except repair. Issues leading to a repair project, such as undesired vegetation or encroachments, likely have an obvious cause and the solution is straightforward, not lending itself to the need for evaluation of multiple alternatives.

Figure 6-3: Types of Levee Projects

Depending on the type of levee project, the plan formulation steps may vary.

3.1 Planning Team

The plan formulation process should be performed by a multidisciplinary team, including:

- Planners/project managers
- Engineers
- Risk assessment experts
- Environmental and cultural resources experts
- Community representatives

Depending on the objectives of the study, there may be experts with specialized expertise who need to be added to the team. Scientific professionals well versed in sediment transport, fluvial geomorphology, fish biology, botany, forestry, ecology, and soil science can assist in planning and design processes for levees.

It is recommended to involve experts to assist with choosing plants that are native and have the most desirable qualities. Specifically, a botanist or forester could have significant expertise in how trees will respond to their environments—including how roots can be expected to grow based on species characteristics and local hydrology. A soil scientist could provide valuable information about how water will move through the soil profile and how to optimize or discourage plant growth using compaction and texture selection. A botanist, biologist, or ecologist can provide information of what types of plants—herbaceous and woody—to plant based on the goals of the project and the expected conditions.

Other disciplines to consider include real estate professionals, economists, archeologists, and tribal liaisons.

3.2 Step 1: Identify Problems, Opportunities, Objectives, and Constraints

The first step of the planning process is identifying the area-specific problems and opportunities for study (Figure 6-4). Problems and opportunities should be framed in terms of the specific planning objective. Project constraints are also identified in this step. The following general definitions are specific to the planning process:

- **Problems:** The issues that the project is intended to address (e.g., flood risk reduction). Once defined, they guide efforts to develop solutions.
- **Opportunities:** Issues other than the problem that could be addressed with the project and/or benefits that could be realized as part of the project.
- **Objectives:** Statements of the desired results of the project to address the problem and realize opportunities. Objectives should describe measurable outcomes of the project.
- **Constraints:** Restrictions on the project from outside sources such as legal, policy, environmental, or other resource considerations.

Figure 6-4: Plan Formulation—Step 1

1

Identify problems, opportunities, objectives, and constraints

What problems are we solving?

What criteria contribute to acceptable solutions?

What peripheral opportunities may be incorporated into the solution?

Examples of potential problems, opportunities, objectives, and constraints by levee type are shown in Table 6-1. The problems and opportunities should be specific to the planning area. When considering construction of a levee, the problem might be a specific flood hazard to be addressed. Refer to **Chapter 1** for a discussion on understanding flood risk. Information in this chapter will inform identification of the problem for new levees. Refer to **Chapter 5** for methods to identify problems for levee rehabilitation and modification projects.

Examples of opportunities include increasing climate change resilience, incorporating nature-based solutions to benefit the environment, considerations for adaptive management measures (section 4.3) to iteratively address changing circumstances or new information received about the project, recreational features, and public spaces. All potential opportunities should be documented and considered in early stages of plan formulation. Priorities and preferences of those impacted should be understood and incorporated, thus community engagement at this early stage is strongly encouraged.

Once problems and opportunities are identified, objectives and constraints should be defined to guide planning efforts. Objectives are clear and concise statements aimed to solve problems and realize opportunities. They should include information about the desired outcome, location of where results will occur, and timing and duration of the effect. The objectives should consider current and future conditions. Constraints are restrictions, obstacles, or limitations on solving identified problems and realizing opportunities. Typical constraints are often related to limited resources, including expertise, data, funding, or time. Legal and policy constraints may also limit the ability to meet project objectives.

Project-specific constraints might include areas where land acquisition will be difficult, avoiding protected environmental habitat or species and sensitive cultural resource areas, laws or regulations, risk transfer and risk transformation considerations, or inadequate resources. Constraints should be identified early on, but may change between planning, design, and construction. Often, funding sources will be dictated by state and/or federal programs, with specific qualifying metrics to obtain that funding. While setting project objectives, it is important to keep potential funding opportunities in mind as the life of the project can be limited by a lack of appropriate funding. Identifying constraints early helps illustrate options that simply are not possible.

STEP 1 EXAMPLE: PORTLAND METRO LEVEE

The project study area lies along the Columbia River in Oregon and includes 27 miles of levees with several cross levees that reduce the risk of flooding for the cities of Portland, Gresham, Fairview, and Troutdale. Built in 1917, this system of levees and pump stations was intended to provide critical flood risk reduction and stormwater management.

- Problems: Flood risk varies along the levee reach and a railroad at the downstream end of the study area was not designed as a levee, but is integral to excluding flood waters from the leveed area. Operation and maintenance (O&M), as well as access for inspection on this portion of the embankment, are prohibited by the railroad. In addition, there are multiple low spots and missing or incomplete sections of floodwall, lack of redundancy for pump stations, and portions of the levee that do not meet current standards.
- Opportunities: Reduce the likelihood of life and economic loss due to flooding, increase the ability to floodfight, increase recreational opportunities, maintain the existing natural and cultural resources, and increase public awareness of flood risk.
- Objectives: Reduce flood risk in a manner that minimizes impacts on resources and is acceptable to the community.
- Constraints: Cross levees will stay in place, the railroad embankment will not be considered part of the levee system, and existing road infrastructure such as bridges will not be modified.

(USACE Portland District and Columbia Corridor Drainage Districts, 2021)

While states and communities regulate and manage floodplains ultimately to reduce flood damages, it is important to also emphasize that flood risk management activities can provide opportunities to align with other community goals and achieve multiple benefits, such as recreational, environmental, social, or cultural benefits. Representatives from state regulatory bodies, scientific professionals, and tribal experts well versed in the local aspects of sediment transport, fish biology, botany, and archaeology are important to include in the planning process. Identifying opportunities that promote multiple benefits across a community can help to obtain additional funding sources and staffing by both municipal and non-governmental organizations. Perhaps more importantly, a solution that embraces a variety of techniques to reduce flood risk and promotes other community goals is more likely to retain long-term community-wide support.

Table 6-1: Step 1: Typical Problems, Opportunities, Objectives, and Constraints by Project Type

Levee Project Type	Problems	Opportunities	Objectives	Constraints
New	• Flood risk hazard has been identified	• Incorporation of nature-based features • Co-benefit opportunities • Adaptive management • Enable other land uses • Recognize environmental justice • Recreational development • Alignment with public values	• Reduce flood risk	• Difficult land acquisition • Disturbance of environmental habitat or species • Disturbance of sensitive cultural resource areas • Laws or regulations • Risk transfer • Funding for planning, design, construction, long-term O&M • Natural environment: topography, soils, population, existing structures or utilities, water surface level • Staffing/expertise for long-term O&M • Governance to manage O&M • Climate change • Inadequate resources • Presence of hazardous, toxic, or radioactive waste
Rehabilitate	• Existing levee no longer provides flood risk reduction as design intended	• Incorporation of nature-based features • Co-benefit opportunities • Alignment with public values	• Provide/restore level of risk reduction as designed • Reduce levee risk	
Modify	• Need for increased level of risk reduction • Identify how levee modification might change level of risk reduction	• Incorporation of nature-based features • Co-benefit opportunities • Adaptive management • Enable other land uses • Recreational development • Alignment with public values	• Reduce flood risk, including levee risk	
Remove	• Existing levee is in a state of failure • Need for ecological restoration • Need for floodplain storage during a flood • Need for groundwater recharge • Existing levee is being rerouted or replaced (e.g., setback levee) • Other flood risk mitigation features have made the levee functionality obsolete • Change in potential consequences (lives and property)	• Create or enhance native habitats within previously leveed area • Groundwater recharge and/or flood-managed aquifer recharge • Co-benefit opportunities • Floodplain storage during a flood • Managed community retreat • Recreational development • Enable other land uses • Alignment with public values	• Maintain or reduce the risk to human life • Maintain or reduce the risk of economic damage to businesses, residences, manufacturing facilities, and critical infrastructure (e.g., agriculture, medical centers, schools, roads, bridges, fuel, and energy production and distribution facilities) • Maximizing ecological benefit • Maximizing multiple opportunities/benefits such as recreation, aquifer recharge, geomorphic processes, agricultural, etc. • Minimizing the need for long-term maintenance • Incorporating climate change and sea-level rise considerations	• Difficult land acquisition • Disturbance of environmental habitat or species • Disturbance of sensitive cultural resource areas • Laws or regulations • Risk transfer • Funding • Topography • Soils • Exposure (who and what are in harm's way) • Climate change • Inadequate resources • Public acceptance • Presence of hazardous, toxic, or radioactive waste

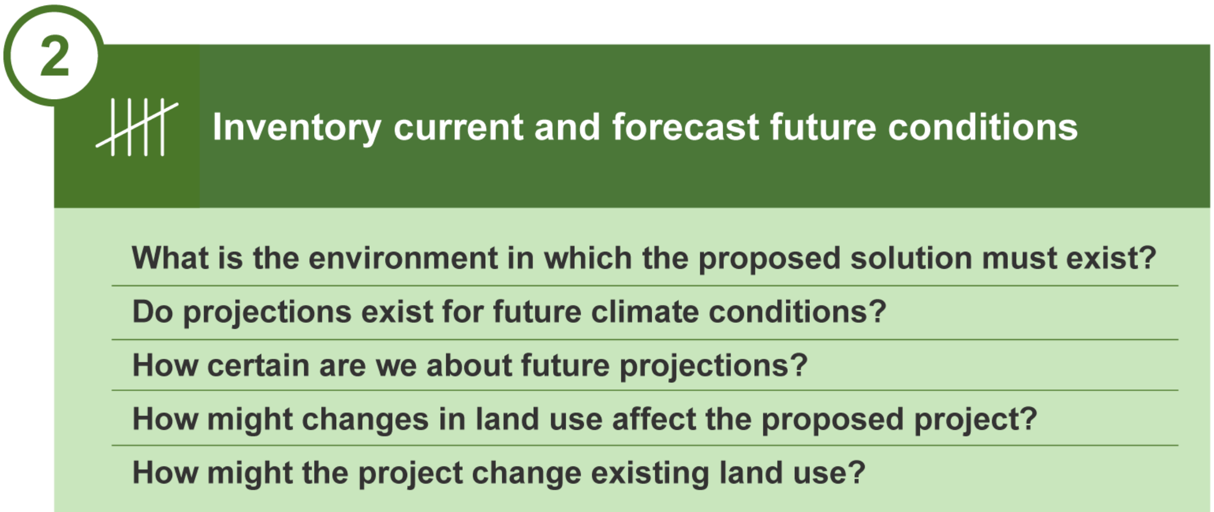
3.3 Step 2: Inventory Current and Forecast Future Conditions

This step includes inventorying current conditions and forecasting future conditions relevant to the problems and opportunities identified in Step 1. Information gathered in this step further refines the problems and opportunities by providing quantitative or qualitative descriptions of the current and future with or without-project conditions (Figure 6-5). Conditions to consider that may change over time include:

- **Topography of the project site**: This should include existing and any future anticipated changes to topography of the project area that would impact flood flow through the watershed or channel.
- **Geotechnical and geological characterization:** Investigation of subsurface conditions that could impact the selection and scale of various project features is required. Soil type and hydraulic properties of subsurface materials will impact construction considerations and longer-term levee sustainability.
- **Existing or planned infrastructure and land use:** The types of infrastructure and other aspects of the current and future areas that may or may not be protected by the flood risk reduction strategy. Conversion from open space or rural areas to more developed urban areas should be investigated and included in the future condition.
- **Ecological, cultural, and tribal resources:** Factors that could potentially impact the selection of the type and location of flood risk reduction measures should be considered.
- **Exposure (property, people, environment, cultural)**: Exposure incorporates a description of where the flooding occurs at a given frequency and what exists within that floodplain (**Chapter 4**). Tools such as flood inundation maps showing extent and depth of flooding, structure inventories, population data, crop data, and habitat acreage illustrate exposure. Consideration should be given to areas of planned or anticipated development, areas of natural ecosystems, and locations of cultural resources. Additionally, consideration should be given to the diversity of the community including but not limited to those who are unhoused, have lack of access to resources, are disabled, or have limited English proficiency. Consideration should also be given to areas that include structures with large populations that include schools, hospitals, nursing homes, or correctional facilities.
- **Flood conditions at levee**: Hydrologic and hydraulic analyses of river and coastal wave and water level conditions are required to estimate flood water surface levels and potential floodplains for various conditions (i.e., without project, with project, and considering levee failure or misoperation). Flood levels and frequency of flooding may change over time.
- **Climate change**: With anticipated increases in temperature and precipitation frequency and intensity, potential for increased runoff and resulting water surface elevation and sea level rise should be included in future forecasts. Future forecasts should include more climate change impacts to levees than have occurred historically, and in many cases, plan for new impacts from weather that previously may not have posed significant threats.

- **Hazardous waste**: An early assessment of potentially hazardous waste contamination should be conducted as early as practical. The assessment should include the existence of, or potential for, contamination on lands—including structures and submerged lands—in the study area. Investigations should also address lands external to the study area that could contribute hazardous waste to the study area that could impact or be impacted by the project.

Figure 6-5: Plan Formulation—Step 2



Forecasting future conditions requires research and technical analyses. Research might include investigating a community's development plans, construction of transportation facilities such as roads, highways, or rail systems, or estimating population growth. Technical analyses may be required to forecast future climate conditions using the latest climate science and models. Since future conditions are unknown, uncertainty should be included with forecasted future conditions.

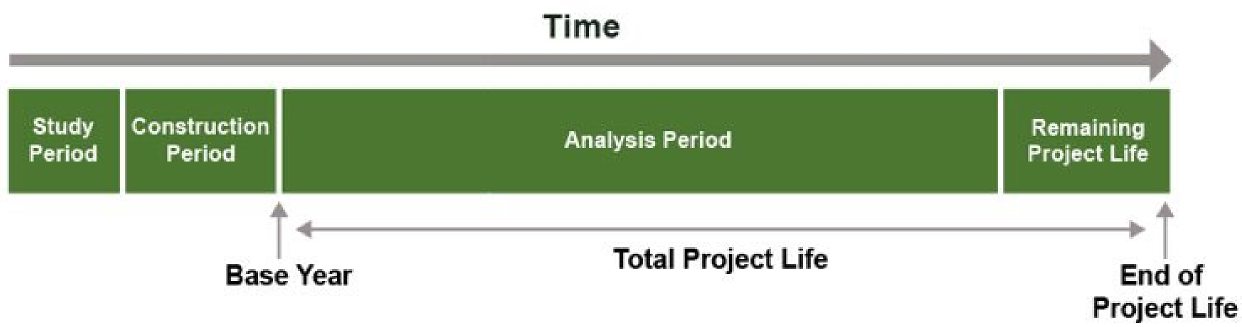
Uncertainty should be characterized—quantitatively and/or qualitatively at the commensurate level of detail—for all levee projects. Assumptions used in forecasting/projecting future conditions should be clearly and explicitly documented. Where uncertainty may meaningfully impact the investment decision, multiple baselines can be used, with a clear explanation of the basis and assumptions underlying each. Climate change (i.e., how the climate changes over time) and climate variability (i.e., swings in climate conditions exacerbated by climate change) are highly uncertain and should therefore be captured in the definition of future conditions.

Analyses and investigations required to inventory and define existing and future conditions can be costly and time intensive. The effort of the analysis should be scaled to fit the study area and align with the resources and data available. For example, staffing resources to investigate current and future conditions might not be readily available and flood risk and/or potential consequences may be few. In this case, the level of effort spent in investigating current and future conditions might be scaled back. However, where potential consequences from flooding are likely high, a larger effort should be expended on establishing current and estimating future conditions.

Forecasting future conditions requires developing and understanding the project life and key milestones for the project. The National Economic Development Procedures Manual (Scodari, 2009) defines the planning horizon for the economic analysis of a project as including the study period, construction period, base year, period of analysis, and project life, as shown in Figure 6-6.

- **Study period:** Initiation of the study to the initiation of project construction.
- **Construction period:** Project installation.
- **Base year:** The point in time when the project is functionally operational. Usually, the base year coincides with the end of the construction period.
- **Analysis period**: Base year to some number of years (generally 50 for levee projects) into the future.
- **Project life:** Period that a normally operated and maintained project will function as it was designed. For most water resources projects, the project life exceeds the analysis period. For example, if a levee is properly designed, constructed, operated, and maintained, the life expectancy of that levee often exceeds the planned 50 years.

Figure 6-6: Project Timeline



To compare a project's benefits and costs that may accrue unevenly over the planning horizon, two points in time must be selected where these values will be compared. Typically, this is the base year, which can be considered as the current condition. The future condition is typically the end of the analysis period, which for a levee project is typically 50 years or more. However, for large scale multi-purpose projects with additional infrastructure, a longer project life may be more appropriate and used. The same project timeline should be used for each alternative evaluated. Other items to allow time for in the overall schedule of a levee project might include:

- Environmental constraints or permitting requirements that could cause delays in site work for certain times of the year.
- Engagement with the public.
- Consultation with tribal nations if tribal lands or cultural resources are expected to be impacted.
- Land acquisition.
- Legal requirements.

Through the process of forecasting future conditions, additional opportunities and constraints may be identified that require revisiting Step 1. For example, if new development within the planning area is anticipated, the opportunity to include recreational trails or ecosystem educational stations along the project alignment may be considered. Conversely, new development may pose problems not present before, such as increased interior drainage or the new community may not support the project if their concerns were not considered as part of the formulation and design of the project.

3.4 Step 3: Formulate Alternative Plans

Alternatives are formulated to achieve the planning objectives by solving the identified problems and realizing opportunities, while taking into account known constraints (Figure 6-7). Alternatives might include structural or nonstructural measures, strategies, or programs (Table 6-2). When formulating alternatives, it is important to understand levee risk and incorporate the management of those risks into the potential solutions. More information can be found in **Chapter 5**.

Figure 6-7: Plan Formulation—Step 3

3

Formulate alternative plans

What are specific ways to achieve project objectives while avoiding constraints and maximizing opportunities?

How can structural, nonstructural, and nature-based solutions be included in alternative plans?

Life safety is the primary consideration in alternative formulation, but are there other measures to include that provide a co-benefit?

Individual measures that address specific project objectives are identified first. These measures will become the building blocks for plan formulation and may include structural, nonstructural, or nature-based solutions. Individual measures may be combined to form a broad spectrum of alternatives, ranging from no action to robust activities. Screening out options from consideration is not part of this step since eliminating measures too early may bias the selection of those measures that remain under consideration. It is an iterative process where all feasible combinations of measures are considered.

Some alternatives might be better at addressing one objective over another. Alternatives should be developed with life safety at the forefront, while also considering economic and environmental benefits or impacts and promoting social equity. For example, enhancements that advance environmental goals might include infrastructure that reduces greenhouse gases, limits sediment deposition, or enhances habitat. This is the first step of the plan formulation process that could be iterative based on new information developed during the planning process. Refer to **Chapter 12** for ideas on incorporating community resilience into alternatives.

Future conditions forecasted in Step 2 of the planning process are uncertain, which may lead to formulating alternatives that either do not meet or possibly exceed the objectives. Adaptive management strategies should be considered at this point in the planning process to adjust to future needs (see section 4.3). For projects where the level of uncertainty of future conditions is high, alternatives that include adaptive management strategies will enable flexibility in investments over the life of the project and provide the appropriate level of benefits for each adaptive change made.

Typically, a ‘no action’ condition is included in the development of alternatives. Taking no action defines the condition of the project area if left alone (i.e., nothing is done to address the identified problems). The ‘no action’ alternative provides a benchmark to compare alternatives. For alternatives to be considered, they should convincingly demonstrate that they would be preferred over the ‘no action’ condition.

Table 6-2: Step 3: Example Considerations for Developing Alternative Plans by Levee Type

Levee Project Type	Considerations
New	• No action • Levee alignment (embankment, floodwall, tie-ins) • Levee overtopping location and elevation • Incorporation of ecosystem restoration features, including seeding, planting, and irrigation (if needed to meet project objectives) • Complementary nonstructural measures (flood warning systems, evacuation/emergency planning, land use planning, community outreach) • Incorporation of features with co-benefits, such as nature-based features • Minimize future maintenance requirements
Rehabilitate	• No action • New technologies to restore original levee functionality • Incorporation of ecosystem restoration features, including seeding, planting, and irrigation (if needed to meet project objectives) • Minimize future maintenance requirements
Modify	• No action • Options to decrease operations and maintenance burden • New levee overtopping elevation • Levee realignment • Features to achieve new elevation or alignment • Increased levee reliability • Complementary nonstructural measures (flood warning systems, evacuation and emergency planning, land use planning, community outreach) • Incorporation of ecosystem restoration features, including seeding, planting, and irrigation (if needed to meet project objectives) • Incorporation of features with co-benefits, such as nature-based features • Minimize future maintenance requirements

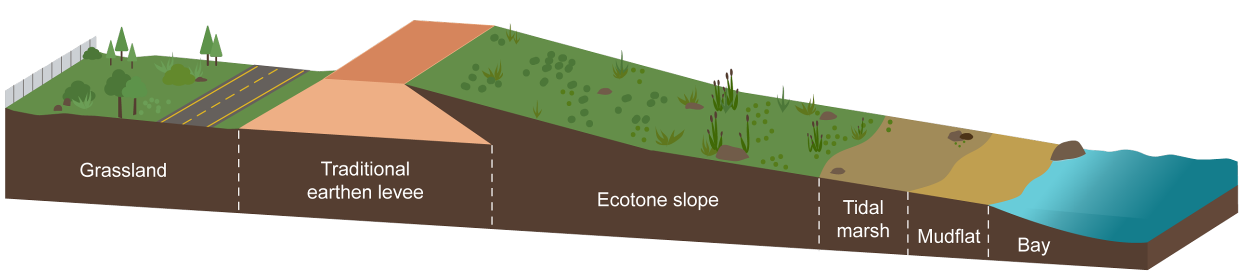
Levee Project Type	Considerations
Remove	• No action • Extent (vertical and horizontal) of levee removal required to meet project objectives • Locations to place excavated levee material • Reevaluation of what was once interior drainage, inclusion of features to safely convey drainage from adjacent areas to a waterbody • Incorporation of ecosystem restoration features, including seeding, planting, and irrigation (if needed to meet project objectives) • Incorporation of features with co-benefits, such as nature-based features • Minimize future maintenance requirements

INNOVATIVE AND EMERGING TRENDS: HORIZONTAL/ECOTONE LEVEES

Many coastal and bayside communities are installing what is known as a horizontal levee, also called an ecotone levee, seaward of a traditional earthen embankment (Figure 6-8). This consists of a vegetated berm at a much gentler slope than the main embankment, naturally vegetated with native plants that transition from upland coastal species to aquatic species. Other elements to an ecotone levee could be installation of oyster/mussel beds and sand berms. Such ecotone levees provide a number of co-benefits. The gradual slope and natural vegetation provide a significant buffer which reduces wave heights, storm surge, and coastal flooding, allowing smaller and less costly traditional levees to be built or maintained. They also provide important habitat restoration, coastal ecology, and potential recreation opportunities.

Maintenance on ecotone levees is generally less costly and intensive than that of traditional earthen embankments as vegetation is left ‘natural’ and significant management is not required. The ecotone slope reduces impacts to the traditional levee behind it, lowering maintenance and repair within the traditional earthen embankment, as well. However, the ecotone habitat must be inspected annually and maintained as necessary to keep it healthy and effective. Generally, inspection should include water quality testing and monitoring of the ecotone geomorphology. Vegetation should be inspected to meet specific design criteria. Maintenance should include debris removal, replacing or restoring vegetation or oyster beds, adding sand or sediment to assist in vegetation establishment, and adjusting any berms as needed (Figure 6-8).

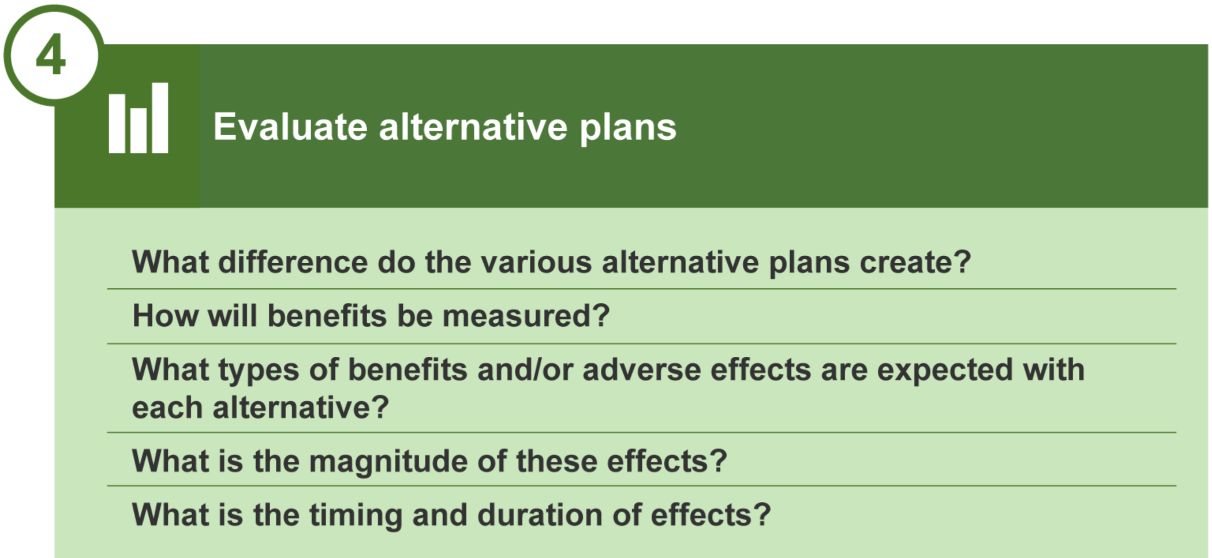
Figure 6-8: Ecotone Levee Slope



3.5 Step 4: Evaluate Alternative Plans

Step 4 includes developing quantitative analyses and qualitative narratives that can be used to compare alternative plans. The evaluation should compare future conditions with and without the project and with each alternative in place (Figure 6-9).

Figure 6-9: Plan Formulation—Step 4



The without-project condition should reflect the most-likely conditions expected in the future in the absence of a project; the future without-project is the standard against which all plans are evaluated. Each alternative plan is evaluated by comparing the with- and without-project conditions to determine the plan’s benefits and impacts. Therefore, a with-project condition must be forecasted for each alternative plan. Consistent criteria to evaluate the alternative plans is developed and might include required resources, meeting the study planning objectives, and compliance with applicable policies. Beneficial and adverse impacts should be characterized for each alternative taking into consideration magnitude, location, timing, and duration.

Multiple planning scenarios and alternatives should be evaluated to identify sustainable and resilient solutions. Analysis of project benefits and potential adverse effects should be evaluated for each alternative using the most likely future condition with project features in place. Differences between with- and without-project conditions for all selected project evaluation metrics should be quantified or described qualitatively. The future condition should include assumptions about climate conditions and potential land use changes.

Alternative evaluation also includes a preliminary screening of alternatives to identify those that will be carried forward and compared. The alternative screening is not based upon comparison with other alternatives, but solely upon the ability of each alternative to solve problems and meet objectives, while taking advantage of opportunities within the identified constraints. Care should be taken to not screen out options too early in the process.

Consistent evaluation criteria and metrics that will be used to estimate the benefits and potential adverse impacts of each alternative plan and the extent to which it meets the project objectives should be specified early in the planning process. **Life safety is paramount** and must be considered in alternative plan evaluation. Life safety benefits are difficult to relate to a dollar value, but risk assessments offer a method for quantifying the remaining life safety risk associated with various plans to allow life safety benefits to be understood and compared. **Chapter 4** provides information on how life safety risks can be evaluated and compared. **Chapter 5** discusses the use of risk information to evaluate an alternative.

A **benefit-cost analysis** is conducted to determine the benefit-cost ratio, which is often used to compare and justify alternatives. However, benefits not typically included in a traditional benefit-cost analyses should also be considered. For example, flood risk reduction alternatives for a small community may not yield economic benefits equivalent to an urban area due to fewer structures and subsequently less structural damage, but may include significant life safety, environmental and cultural benefits. These other project benefits are difficult to quantify and may need to be accounted for qualitatively. Similarly, an effort should be made to include all project costs; often the benefit-cost analysis only includes project construction costs. Other expenses such as operation, maintenance, repair, and rehabilitation costs can be significant and should be considered for inclusion in the overall evaluation of alternatives. Examples of benefits, co-benefits, and costs for a project are shown in Table 6-3.

EXAMPLES OF PLAN EVALUATION FRAMEWORKS

There are several frameworks for evaluating alternatives. Examples:

- SMART Planning (USACE, 2015).
- Broadening Benefits and Anticipating Tradeoffs with a Proposed Ecosystem Service Analysis Framework (Wainger *et al.*, 2023).
- Benefit Accounting for Nature Based Solutions (Brill *et al.*, 2021).
- California Department of Water Resources: Handbook for Assessing Value of State Flood Management Investments (California DWR, 2014).

Project specific evaluation frameworks can also be developed.

Table 6-3: Step 4: Example Benefits, Co-Benefits, and Costs

Benefits	Co-Benefits	Costs
• Life safety • Flood damage reduction • Possible reduction of flood insurance rates	• Recreational • Social • Habitat creation/ restoration • Social equity	• Construction • O&M • Emergency response • Property acquisition • Permitting • Environmental mitigation

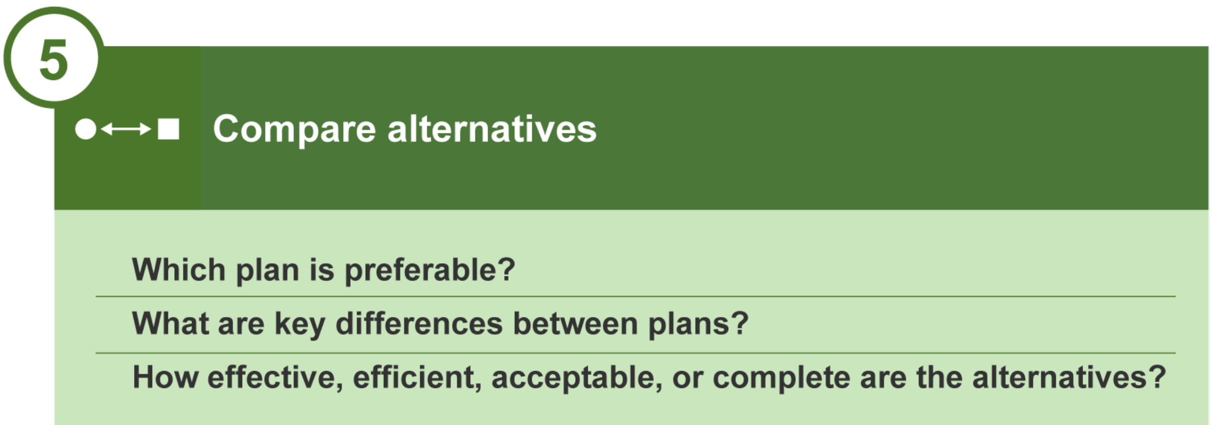
Supporting analyses should be scaled to fit the study area and align with the resources and data available. In general, analyses to be performed include those that help characterize life safety risks, social impacts such as equity, environmental impacts, flood risk reduction benefits (including cost-benefit ratio), and any other project-specific metrics.

be developed that includes project specific criteria that alternatives would be evaluated against. Project specific criteria might include weighing environmental benefits against structural damage reduction or community support. No matter what evaluation framework is selected, it should be established by the project planning team at the beginning of the planning process. How benefits are quantified or qualified, how they will be scored, weighted, or evaluated must be clear and agreed to before evaluation can begin.

3.6 Step 5: Compare Alternatives

Step 5 compares the analyses and narratives of the alternative plans against each other with a focus on their outcomes (Figure 6-10). This comparison should include consideration of a no action plan. The outcome will be a ranking of alternatives.

Figure 6-10: Plan Formulation—Step 5



Comparison of alternative plans is focused on effectiveness, efficiency, acceptability, and completeness, along with other identified project-specific criteria. At this stage of the planning process, certain criterion might be weighted more heavily than others based on the primary intended outcome. In addition to effectiveness, efficiency, acceptability, and completeness, resilience and sustainability should also be considered in plan comparison.

Both resilience and **sustainability** measure a levee's ability to meet its original objectives over time. Resilient alternatives should sustain climate-related changes and maintain its intended level of performance over the life of the levee. Sustainable alternatives need to balance environmental, economic, and social impacts of today, while having the ability to retain and maintain that balance into the future.

3.6.1 Effectiveness

Effectiveness is the extent to which a plan contributes to addressing problems and achieving objectives. An effective plan makes a significant contribution towards the solution. The most effective alternatives make significant contributions to not just a single objective, but to all the planning objectives. If the functionality or success of an alternative is uncertain, or less certain than another alternative, its effectiveness may be compromised and should be further investigated. For levee projects, the focus for effectiveness is likely in terms of the amount of risk reduction achieved with the alternative.

3.6.2 Efficiency

Efficiency is the extent of cost effectiveness of an alternative plan in alleviating problems and realizing opportunities. Some potential metrics to evaluate efficiency include dollars per unit of economic benefit, least cost of attaining a given objective, or reduced opportunity costs relative to accomplishing other alternatives.

3.6.3 Acceptability

Acceptability is the workability and viability of the alternative plan with respect to acceptance by state and local entities and the public, and compliance with existing laws, regulations, and public policies. Specific criteria for acceptability should be developed in coordination with other federal and state agencies, stakeholders and community members, tribes, and the project owner/operator. Criteria typically includes impacts to natural, cultural, and socioeconomic resources, potential to develop adequate mitigation in the vicinity, willingness of private parties to sell affected lands and facilities, and compliance with existing authority. The ability to implement the project also informs a project's acceptability. The alternative should be feasible from technical, environmental, economic, financial, political, legal, institutional, and social perspectives.

STEP 5 EXAMPLE: PORTLAND METRO LEVEE

The Portland Metro Project conducted an investigation about the future of the area without the project. The investigation included detailed engineering and economic evaluations to quantify flood risk and the population at risk (Step 1). Through several iterations of measure identification and screening, alternatives were developed (Step 3) and evaluated (Step 4) based on how well they met the established objectives. When comparing the alternatives (Step 5) using effectiveness, efficiency, acceptability, and completeness as a guide, the study team was able to screen out an alternative because it did not meet flood risk management objectives or the purpose and need of the project. Also, costs for the screened-out alternative far outweighed the benefits. The benefit-cost ratios, impacts to natural resources, reduction in life safety risk, and reduction in uncertainty related to flood risk were considered when comparing the remaining alternatives (USACE Portland District and Columbia Corridor Drainage Districts, 2021).

3.6.4 Completeness

Completeness considers the extent to which an alternative provides and accounts for all necessary investments or other actions to ensure the realization of the planned effects. The completeness of each alternative will consider whether necessary components and actions are identified, including the adequate mitigation of significant adverse impacts, and the degree of uncertainty (or reliability) of achieving the intended objectives. If an alternative is found to be incomplete, either measures must be added, or complete reformulation of the alternative is required to achieve all objectives and benefits. If objectives and benefits cannot be achieved, the alternative—or measures comprising the alternative—should be evaluated to confirm whether it is worthwhile to carry forward. If not, the alternative should be screened from further consideration.

3.7 Step 6: Select Preferred Alternative

Selection of an alternative amongst those considered should demonstrate how and why the plan stands out from the other alternatives considered, including a no-action plan. This will include the results of the evaluation (Step 4) and comparison (Step 5) of the alternative plans and justification for the selection (Figure 6-11).

Figure 6-11: Plan Formulation—Step 6

6

Select preferred alternative

Which plan is most easily implemented?

Does the selected alternative require any modification from the original concept before handing off to design?

What strategic guidance must be followed in the path forward (regulatory, community acceptance, funding, etc.)?

The selection of an alternative should be based on a comparison of the performance of each alternative with the evaluation criteria chosen to measure performance in Step 4 and to compare plans in Step 5. Justification must be presented clearly as to why a specific plan was selected based on its relative performance across the various criteria. In certain situations, even though a project may be technically, economically, socially, financially, and environmentally feasible, other influences, such as political or limited support from the community may limit its ability to be implemented.

STEP 6 EXAMPLE: PORTLAND METRO LEVEE

Once a focused set of alternatives was agreed to by the study team, and study results compared, the benefits were compared to the project costs. Benefit-cost ratios were calculated, where the benefits (in dollars) are divided by the costs to get a “ratio.” All alternatives had a benefit-cost ratio above 1.0. However, the alternative that was ultimately selected had the lowest benefit-cost ratio but the greatest annual net benefits. It was rated highest in terms of the extent to which the objectives were met, and the net benefits provided more uniform flood risk reduction throughout the study area, especially in areas that met definitions for environmental justice considerations, and provided the greatest reduction in life safety risk (USACE Portland District and Columbia Corridor Drainage Districts, 2021).

4 Best Practices and Considerations

Best practices outlined in these guidelines should be followed throughout the entirety of the levee formulation process described in section 3. Additional considerations, which may be general in nature or project-specific, may need to be taken into account during individual steps of the planning process. This section outlines best practices and other considerations associated with formulating a levee project.

4.1 Managing Risk

4.1.1 Life Safety

One of the overarching principles of these guidelines is to hold life safety paramount. Accordingly, a primary best practice is to formulate levee projects with a focus on human life while taking into account all potential failure modes. As discussed in **Chapter 4**, factors that influence life loss include, but are not limited to, the depth and velocity of flooding, levee performance, socio-economic characteristics of the population, warning systems, evacuation plans, emergency response, and other preparedness measures.

Planning for both existing and proposed levee projects requires the evaluation of risks imposed by the levee on the population in the leveed area (levee risk), as well as evaluating the overall flood risk with the levee in place (**Chapter 4**). Quantifying consequences for both existing conditions (no levee) and with a levee in place, will help communities understand any potential adverse or beneficial impacts to life and/or property. Reduction in flood risk should be quantified in terms of project benefits (e.g., reduced consequences, social or environmental benefits) for use in evaluation and comparison of levee alternatives that include varying levee height, alignment, and/or footprint.

Alternatives should be considered in terms of the tolerability of the remaining flood risk and whether or not risks have been managed to be as low as reasonably practicable. The evaluation must consider the specific characteristics of the flood risk and the leveed area, as well as the values of stakeholders (**Chapter 5**).

4.1.2 Levee Superiority for Riverine Levees

Levee superiority is the concept of designing portions of the levee at higher elevations except in a location where initial overtopping is desired and can occur in a more predictable fashion. The best practice is that, where feasible and practical, levees should be designed and constructed with locations where overtopping can be controlled. Levee superiority can be included in the design of a single levee or within a systemwide setting.

Should overtopping or a breach occur as a result of flooding, the breach is more likely to initiate at the intentionally designed location, providing opportunities for more orderly floodplain evacuation and reduced reconstruction requirements (time and cost) after a breach. The surface protection of the levee at the designated location can also be reinforced to reduce the likelihood of breaching.

More complex scenarios for assessing levee superiority might include the following:

- Locations where two separate levees exist across the river from one another—one surrounding highly urbanized areas, the other mostly agricultural area, but both having similar levee elevations. Through risk-informed decision making, the levees could be modified such that overtopping into the agricultural area occurs before the urban area to reduce potential life loss consequences. Note that this option for levee superiority would require extensive collaboration and engagement with all affected landowners and other stakeholders.
- Locations where there are adjoining but independent levees and there is a potential of a 'chain failure,' whereby the breach of one levee may trigger the breach of the next. In this situation, levee superiority may involve the provisions of relief structures at the upstream end of the adjoined systems.
- Locations where flank or tie-back levees exist along tributaries to the river. The hydrology for the tributary may provide higher water surface profiles than a river, or the tributary may be flashy with short warning times and potential dangers from quick overtopping. Superiority of levee crest levels along the tributary reaches over those for the mainstem reaches may be appropriate. For long or complex levee systems, multiple overtopping reaches should be considered.
- Locations where there are embedded structures such as gravity drains, pump stations, and closure structures. Here the superiority approach would be to provide for increased crest elevations for 100 to 150 feet immediately upstream and downstream of the embedded structure to avoid overflow around and into the structure and any resulting damage.

Water surface profiles, distribution of overtopping volumes, and evaluation of the subsequent consequences are needed to understand where overtopping sections should be located so that overtopping initiates at the least vulnerable location where impacts of flooding are the least damaging. Documenting overtopping consequences in the leveed area is an element of the flood risk management strategy, along with emergency action plans and local flood warning systems.

Decisions regarding overtopping locations should consider risk transfer and risk transformation. It is also important that with reasonable confidence, the overtopping location be designated and maintained for the life of the levee.

4.1.3 Risk Transfer and Transformation

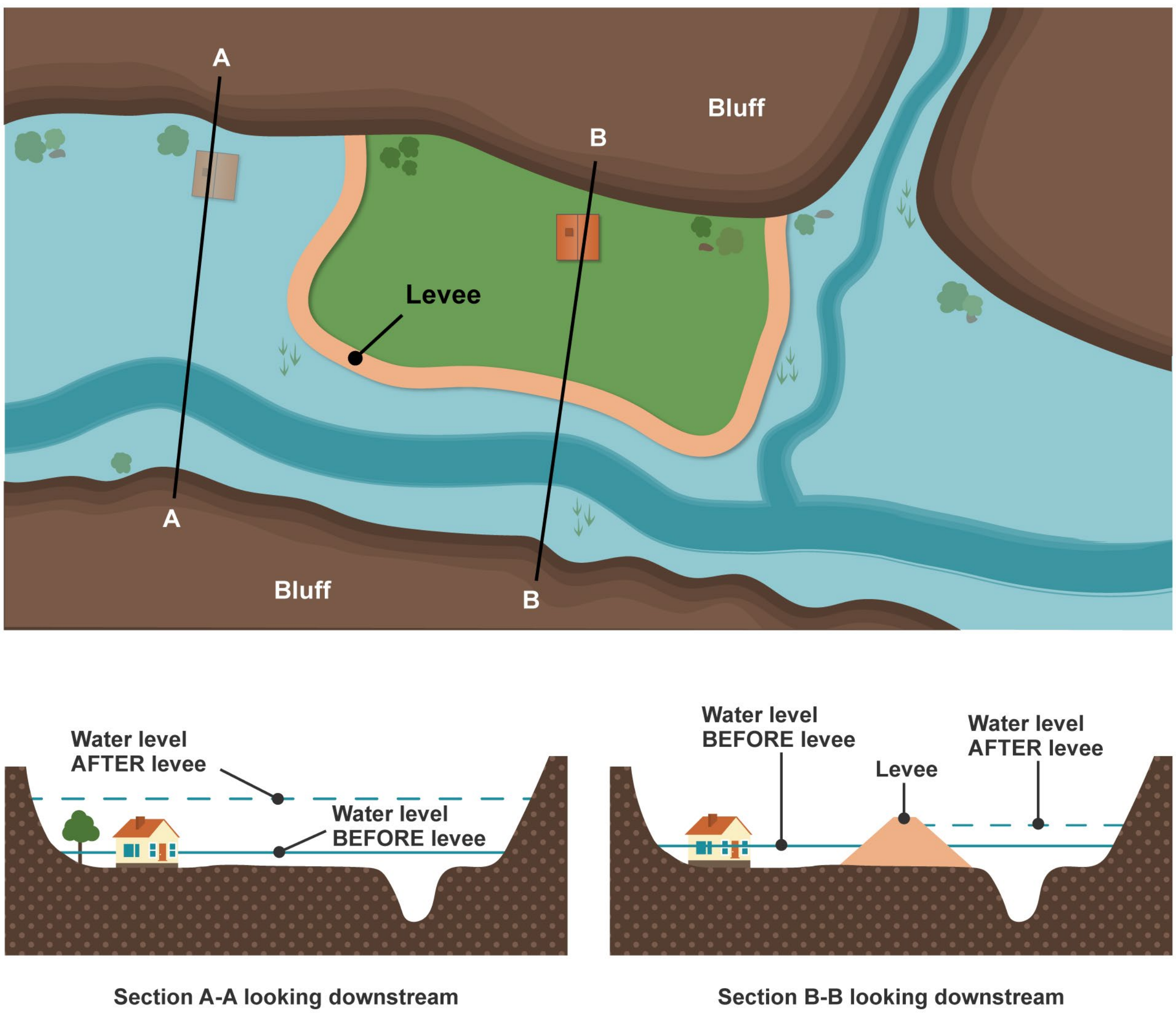
Risk transfer occurs when an action shifts flood risk from one area to another. As shown in Figure 6-12, a new levee narrows the river channel and may cause elevated water levels upstream (represented by Section A-A in the figure) and along the levee (represented by Section B-B in the figure). The levee may also cause higher flow velocity along the opposite bank (bluff) that could induce erosion and impact adjacent properties.

Risk transfer should be avoided or mitigated. For example, setting back a levee from a river channel can minimize impacts to channel flow capacity, potentially preventing or minimizing the transfer of flood risks to areas outside of the leveed area.

Risk transformation occurs when risk is altered as a result of changed conditions, including mitigating another risk. For example, flood risk in the presence of a levee is different than without a levee. Prior to levee construction, flooding happens gradually at the rate of rise of the flood source. With a levee in place, levee breach can occur suddenly, potentially leading to increased life safety risk. In addition, construction of a levee often encourages development within the leveed area. Increased population within the leveed area would transform the risk (i.e., increase the risk). Nonstructural flood risk management measures like evacuation planning and land use planning are needed to address the increased risk associated with an increase in population.

The best practice is to minimize or mitigate for risk transfer and to recognize and address risk transformation in the planning and design process. The impacts of risk transference and/or transformation should be assessed during the formulation and evaluation of alternatives since these impacts could result in an infeasible project.

Figure 6-12: Transfer of Risk



4.2 Social Considerations

4.2.1 Collaboration and Engagement

From scoping a potential project and formulating alternatives to selecting a viable plan, collaboration and engagement is necessary at all levels and stages of the planning process.

During scoping, engaging with community members and leaders can help identify problems and opportunities that may not be readily apparent when formulating a levee project. Problems such as flooding in certain areas and the social/economic/environmental impacts, as well as opportunities such as incorporating recreational features that benefit the community or reducing the potential impact of a project on landowners.

Those that live within the impacted community may view issues from a different lens than those that study and propose mitigation measures. By understanding the problems and opportunities as identified through the experiences of community members, the planning team will be less likely to screen out viable measures or alternatives that might better fit a community's needs during the plan formulation process.

The planning team should incorporate a variety of opportunities to engage with community members at different points during the plan formulation process. When communities are engaged throughout the entire planning process, there is a better chance for support of the project. In addition to scoping the work, numerous opportunities to engage with community members exist during plan formulation. Engagement is especially important during the comparison of alternatives and plan selection. When communities are engaged throughout the entire planning process, there is a better chance for support of the project. Additional information on engagement is included in **Chapter 3**.

4.2.2 Social Equity

When planning a levee project, it is important to identify underserved communities that may be disproportionately impacted by flooding—due to the absence of resources, remnants of historically discriminatory policies or continued marginalization—and work to build social equity so that everyone has an equal opportunity to meaningfully participate in the levee formulation process (Table 6-4).

Table 6-4: Social Equity Considerations

Factor	Questions to Ask
Equitable distribution of social, environmental, and economic costs and benefits of a project.	• What are the costs and benefits? • To whom are these being distributed? • What are the group-based differences in costs and benefits?
Recognition and acknowledgement of historical injustices and/or present-day vulnerabilities related to the project.	• Is there a historical and/or current-day context of disproportionate costs and benefits related to past projects? • Is this context being recognized in the current project? How so? • Are impacts to all potentially affected groups being considered?

Factor	Questions to Ask
Equitable participation in decision-making processes for the design, construction, and O&M of the project.	• Have all potentially affected groups been identified as stakeholders in the project? • How and to what degree are each of these groups involved in the project processes and decision making?

Federal, state, and local agencies have either developed, or are developing, policies to support equity as part of flood risk management strategies and should be referenced when formulating a levee project. These policies could provide for:

- Availability of current mapping tools that help identify and distinguish those communities that traditionally have been disproportionately or adversely impacted by flood risk hazards.
- Requirements for engagement.
- Proportion of benefits allocated to certain communities.
- Regulatory requirements for identifying potential effects and mitigation measures in consultation with affected communities (U.S. EPA, 1969).

4.2.3 Underserved Populations

According to a recent study analyzing data from the National Levee Database (NLD) and the Climate and Economic Justice Screening Tool[1] (Vahedifard *et al.*, 2023), results indicated that a substantially larger number of communities who live behind levees across the nation are considered disadvantaged in terms of race, education, poverty, and disability. In addition, flood risk, whether in a leveed area or not, tends to negatively impact historically underserved and socially vulnerable communities disproportionately, as they often have fewer resources to recover from a major flood event.

When planning for a levee project, whether building a new levee or rehabilitating or modifying an existing levee, it is important to consider anyone who may be negatively impacted by the proposed project, especially underserved populations. For example, will construction of a new levee cause the displacement of low-income, mobility restricted, or unhoused populations? If the potential exists, it is important to work with community leaders, trusted community service groups, and those community members to develop a plan that will lessen the impacts. This could include options to move the levee alignment or establish a relocation plan (rather than resort to forced displacement) that provides resources and financial assistance to help those community members move out of the project area.

Planning for a new levee or rehabilitation or modification of an existing project could present an opportunity to begin developing a public engagement strategy and incorporating it into the planning process. Underserved communities living behind levees often lack (1) awareness about the importance of levees and the role they play in reducing flood risk, as well as the risks associated with living behind a levee, and (2) resources to adequately maintain the levee.

[1] Climate and Economic Justice Screening Tool: https://screeningtool.geoplatform.gov/en#3/33.47/-97.5.

Increasing knowledge and awareness of levee benefits and risks is a critical first step in building more resilient communities. The positive outcomes from increasing community knowledge and awareness of levees are discussed in greater detail in **Chapter 3**.

4.3 Pursuing Additional Benefits

4.3.1 Co-Benefit Opportunities

In addition to the primary purpose of flood risk reduction, levees can provide important social, cultural, historical, ecological, and recreational co-benefits, serving as riverine habitat corridors, regional trails, parks, transportation links, and community infrastructure such as community centers. The best practice is to seek opportunities to introduce or enhance such co-benefits. Examples of potential co-benefits include, but are not limited to:

- Transportation corridors.
- Recreation and tourism.
- Ecosystem and habitat restoration and preservation.
- Water and air quality improvement.
- Replenishing groundwater.
- Climate effects mitigation through carbon storage and sequestration from added vegetation.

Co-benefit opportunities should be considered in Step 3. In Step 4, the evaluation of alternatives with co-benefits should be handled differently than those alternatives with a single purpose. For example, a multi-criteria decision analysis could be utilized to incorporate multiple layers of benefits across varying categories, as opposed to single purpose projects with a primary benefit.

To evaluate co-benefit opportunities, use a multi-disciplinary team and multi-criteria decision-making tools, with the understanding that not everything can or should be quantified or monetized. Some benefits—such as damage reduction to structures—are more straightforward to quantify and monetize. However, other benefits, such as ecosystem services, environmental justice, or improvements to community resilience are not. Experts in these areas can supplement the planning team by helping to identify the associated benefits for consideration. Benefit-cost analysis has limitations and should not be the only metric considered in evaluation and comparison of alternative plans. Decisions should be informed by, but not based on numbers. Further, it is important to link decisions with an understanding of the benefits and impacts.

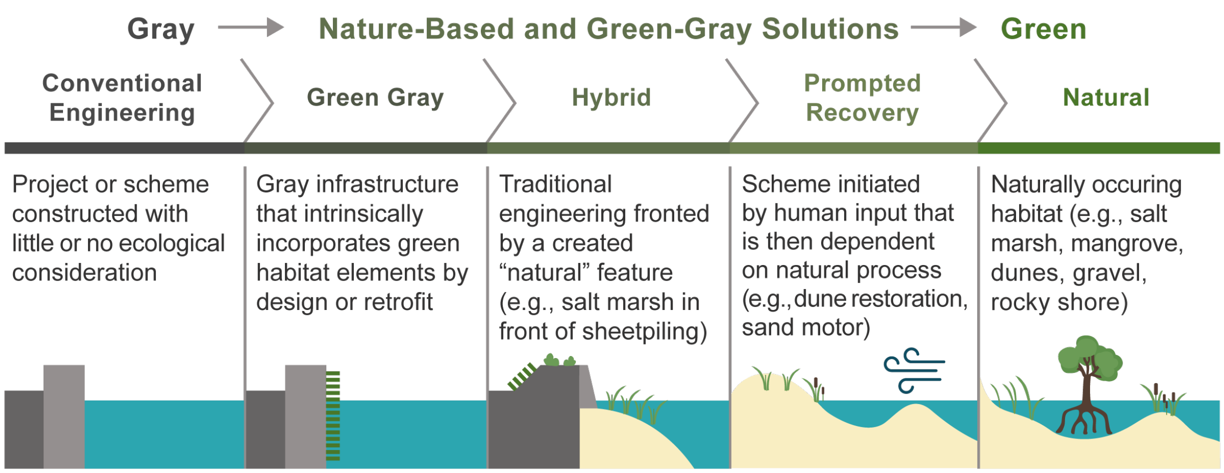
4.3.2 Natural and Nature-Based Solutions

If the levee cannot be set back from the channel to benefit floodplain function, the levee should be designed to incorporate vegetation to recover some amount of floodplain function or maximize environmental benefits. The best practice is to formulate levees with a holistic approach that incorporates and balances structural elements with natural and nature-based designed features to reduce flood risk, while preserving, restoring, and enhancing ecosystems.

The term **natural and nature-based features** in relation to levees refers to the use of landscape features to enhance environmental benefits, while retaining flood risk management benefits. These landscape features may be natural (produced purely by natural processes) such as beaches, dunes, wetlands, reefs, and islands, or nature-based (produced by a combination of natural processes and human engineering) including such features as planting berms or planting benches. The creation or modification of a levee also provides opportunities for ecological enhancement and redundancy in flood risk reduction. In the context of levees, this may range from simple additions to conventional levees (embankments and floodwalls) to major environmental engineering where the levee just exists as a backstop final line of defense after much of the hazard has been dissipated by ecological measures (Figure 6-13)[2] (Brill *et al.*, 2021).

Natural and nature-based features provide opportunities to develop solutions with co-benefits that incorporate both direct benefits, such as reducing erosion, to diverse co-benefits valued by the society. Examples of co-benefit opportunities are listed in section 4.3.1. Incorporation of natural and nature-based features is considered in Step 3 as a measure to include within an alternative.

Figure 6-13: Continuum of Nature-Based Approaches



A balanced combination of measures could include, in addition to levees, the use of floodplains, floodways, and natural ecosystems for rerouting and storing floodwaters and incorporating natural marshes and wetlands to reduce storm surge, waves, and/or flow velocity. Natural and nature-based features can provide many positive benefits to flood risk reduction and environmental enhancements. Common natural and nature-based features vary based on the type of environment where the levee will be constructed and can include:

- Coastal environments:
  - Beaches and dunes (dissipate waves and reduce erosion).
  - Coastal wetlands (flood protection and erosion control).

[2] Figure adapted from the *International Guidelines on Natural and Nature-Based Features for Flood Risk Management.*

  - Reefs (dissipate waves).
- Riverine environments:
  - Reconnecting floodplains (reduces runoff, slow flow, and decrease peak discharges by retaining and restoring water).
  - Removing obstacles or providing secondary channels (increased conveyance capacity).

In river systems, restored floodplains can store and convey water, and upland forests can help slow and retain runoff, reducing flood loading on the levees. In many coastal areas, naturally occurring habitats and geographic features can provide some protection from the coastal processes and storm events. The main habitats involved in nature-based solutions for coastal levees are tidal salt marshes, mangroves, maritime forests, coral and shellfish reefs, beaches, and dunes. Flood risk reduction is achieved through (storm) water absorption through infiltration, flood storage, or wave and surge attenuation. For example, the sloping nearshore bottom of beaches causes waves to break and dissipate wave energy across the surf zone. Similarly, dune fields are physical barriers that reduce inundation and wave attack on the inward side of the dune. Landscape features can help to build and stabilize shorelines and riverbanks, thus reducing erosion.

Ecosystems can be a significant source of resilience for levees. When formulating a levee project, the team should consider ecosystem processes in order to provide enhanced capacity to deal with uncertainties and unexpected events. Natural features are often more resilient than human-made infrastructure because they adapt more readily to changing conditions such as sea-level rise or land subsidence. Because the building blocks of natural and nature-based features are natural (e.g., sediments and plants), the environment itself is a source of natural resupply and repair. For example, existing or restored sediment transport processes could be sufficient to sustain a natural island or wetland that is providing flood risk reduction value. The adaptability of landscape features as flood risk reduction measures provides value with respect to uncertainties. For example, an island that is enhanced or constructed to attenuate storm surge and waves for a community could be expanded if experience and evidence indicate that expansion can increase flood risk reduction benefits.

The International Guidelines on Natural and Nature-Based Features for Flood Risk Management (Bridges *et al.*, 2021) provide practitioners with guidance on the conceptualization, planning, design, engineering, construction, and maintenance of nature-based solutions to support flood risk management projects. It is important to consider using natural and nature-based features as part of the flood risk management strategy. However, alternative features must meet the intended objectives, so striking a balance between operational watershed management and any potential nature-based solution is also important.

4.3.3 Climate Resilience

Climate change impacts on coastal or riverine levees and on internal drainage systems behind levees are significant risk factors that should be addressed in planning and design as a best practice. Impacts of climate change will differ across the country and those impacts that have the potential to affect the project planning area should be identified.

Climate change risks cannot be evaluated based on past events alone, but will require special predictive studies covering the levee lifecycle. The quantification of this risk and incorporating climate change risk reduction and resilience measures in levee design, modification, or rehabilitation are important considerations that should not be overlooked or underestimated. Quantification of climate change impacts should be considered in Step 2 where future conditions are forecasted.

Some federal and state regulatory agencies have completed climate change studies for planning purposes on actual projects. These studies may provide the guidance needed for a new project in the region or examples of how the study should be performed. A funding agency may require existing study results be applied or specify how climate change analysis is to be performed and applied as a condition of funding the project.

CLIMATE CHANGE CASE STUDIES

The U.S. has experienced significant weather shifts over the last decade in ways that place levees at risk. Levee owners, operators, regulators, and design professionals must understand the shifting trends in regional climate threats and manage levees with consideration of these rapidly evolving conditions. While climate models have advanced, they produce different results, as each has its own assumptions and methodologies for representing local, regional, and global climates. This makes planning for levee projects challenging. Case studies where climate science has been used in the levee formulation process are provided below.

- The U.S. Climate Resilience Toolkit (https://toolkit.climate.gov/case-studies) provides a library of case studies to show how people are building resilience in their communities.
- The California Department of Water Resources' Central Valley Flood Protection Plan is California's strategic blueprint for Central Valley flood risk management. The 2022 Update focused on climate change and how to plan a resilient flood system for the future. The study looked at projections of increased warming, extreme precipitation, changes in flood magnitudes and frequencies, and overall changes in timing, duration, and magnitude of flows (California DWR, 2022).
- The city of Richmond, California, examined a broad spectrum of the community's climate change vulnerabilities and looked to prioritize adaptation responses based on the greatest risks and needs. The outcomes were used to inform planning efforts to reduce overall flood risk (City of Richmond, 2016).

4.3.4 Adaptive Management

Levee projects are set within the natural environment and, when working with nature, the best practice is to expect change and manage adaptively. Adaptive management is a multi-step, iterative process for adjusting management measures to changing circumstances or new information about the effectiveness of the project or the system being managed. Adaptive management addresses uncertainty through phased project implementation. It introduces the ability to make adjustments to the project throughout its lifecycle to meet or improve expected outcomes and benefits. It allows phasing of projects—instead of needing to minimize uncertainties up front—and provides flexibility to change direction or adapt the overall strategy.

Adaptive management can aid levee formulation and design by avoiding overbuilding to account for uncertainty. It saves cost by not overdesigning up front, while providing the ability to adapt the design over time, as needed, sustaining project life span and benefits. It can also be applied to handle design uncertainties and actual performance post-construction, to adapt with real-time data as they are being gathered. Overall, the process can reduce lifecycle project costs, reduce the risk of failure, improve outcomes, allow an expansion of knowledge for decision making, and optimize O&M costs over time.

To maximize benefits derived by adaptive management, its applicability to specific levee project conditions and needs should be considered as part of the levee formulation process based on the following three conditions (Rist *et al.*, 2013; Williams, Szaro and Shaprio, 2009):

- There are relevant and measurable uncertainties in the outcomes of management actions, or the system being managed.
- The project is controllable, allowing for future modifications in management actions.
- There is a low risk of irreversible harm to the environment or society (compared to no action).

Adaptive management should be considered in:

- Step 2: Current and future conditions will dictate the magnitude of adaptive management needed for an alternative.
- Step 3: Adaptive management measures should be included in formulation of alternative plans.

An example of adaptive management is the consideration of climate change in levee design. While much definitive work has been performed recently in understanding climate change, large uncertainty remains in forecasting future conditions, as climate science continues to evolve. Levees have a long, often indeterminate, lifecycle and climate change presents a dynamic condition that may not be fully understood. Moreover, it may be infeasible to finance a measure that is formulated around a conservative estimate of climate change projections, or the term required to finance and construct such measures may be so lengthy as to present unacceptable interim risk to the impacted community. Thus, an adaptive management strategy could be purchasing adequate right of way and designing levee features to accommodate modifications to address future conditions.

4.4 Considerations for All Alternatives

4.4.1 Laws, Legal Requirements, and Regulations

Many states, federal agencies, and local governments have water resource setback laws, more commonly known as riparian buffer strip laws. These laws often restrict the types of activities that can be conducted within a designated distance of the watercourse. Representatives from state regulatory bodies often serve as the best resource on state laws and implementing guidance on any other legal requirements. Planning and permitting departments should be engaged early to understand regulations and restrictions on construction of the project, timing to acquire needed permits, typical needed mitigation elements, and fees. Additionally, engaging with and gaining support from state and local governments can help ensure the project will move forward, rather than facing delay due to a denied permit.

4.4.2 Environmental Impacts and Regulatory Compliance

The best practice is to minimize potential impacts from a levee project on environmental, natural, and cultural resources, and develop a mitigation strategy in the event that certain impacts are unavoidable. Adhering to regulatory processes and obtaining required permits is critical to advancing a project to the design and construction phases. Determination of which regulations are in need of compliance is often dictated by the funding used. Federally funded projects are required to follow the National Environmental Policy Act process as described in the callout box.

NATIONAL ENVIRONMENTAL POLICY ACT REQUIREMENTS FOR FEDERALLY FUNDED PROJECTS

The National Environmental Policy Act process requires an assessment of potential environmental impacts caused by the project and several alternative approaches to be evaluated. The key elements of that process include:

- Determining the project's purpose and need and the range of alternatives to be considered, including the no action. Identifying potential environmental impacts.
- Coordinating with relevant agencies including federal, state, local, tribal (if applicable), and others as necessary.
- Involving the public.
- Identifying mitigation for unavoidable impacts.
- Documenting the analysis and decisions (defined further below).

The National Environmental Policy Act also requires either an environmental assessment or environmental impact study before the levee construction project begins. These submittals are often completed during the formulation phase of a project. Typically, one of three different levels of analysis and documentation will be required: (1) categorical exclusion; (2) environmental assessment; or (3) environmental impact statement.

A federal action may be categorically excluded from a detailed environmental analysis if the proposed work does not have a significant effect on the environment. If a categorical exclusion does not apply, an environmental assessment may be required. Environmental assessments are intended to include a brief discussion on the purpose and need of the proposed project, alternatives analyzed, environmental impacts of the proposed alternatives, and a listing of agencies and persons consulted. If significant impacts are anticipated by the proposed project, an environmental impact statement may be required. An environmental impact statement is more detailed and the effort to produce it is more rigorous than an environmental assessment.

Other state and local processes and permits should be investigated and reviewed during formulation of a levee project, as described in the regulatory processes/permits callout box.

These assessments and studies will help inform levee formulation and construction activities to minimize and reduce impacts to environmental and natural resources. The results of these efforts should be thoroughly integrated into the construction documents for the levee project such as the details of easements, access, construction techniques, construction working seasons and hours, and construction materials. Any environmental considerations on the site that need to be protected by the constructor—or that may necessitate special working arrangements—are commonly identified in the environmental assessment and included in the construction document.

Regulatory permit requirements and associated procedures are in place to ensure that if the proposed project impacts existing natural resources (e.g., biological, cultural), those impacts are limited to the extent practical. For unavoidable impacts to critical resources, appropriate mitigation is provided. Activities related to regulatory compliance touch every phase of the formulation, design, and construction process.

EXAMPLE OF REGULATORY PROCESSES/PERMITS

Some federal and state agency permits and reviews that should be anticipated during formulation of levee projects include:

- **National Environmental Policy Act**: Applies to discretionary projects that are funded, authorized, or carried out by federal agencies.
- **Clean Water Act Section 404 and Rivers and Harbors Act Section 10**: Section 404 of the Clean Water Act establishes a program to regulate the discharge of dredged material or placement of fill material into waters of the U.S., including wetlands. Section 10 of the Rivers and Harbors Act requires approval prior to the accomplishment of any work in, over, or under navigable water of the U.S.
- **Endangered Species Act Section 7 Consultation**: The Fish and Wildlife Coordination Act requires federal agencies that permit or license water resource development projects to consult with the U.S. Fish and Wildlife Service, the National Marine Fisheries Service, and the appropriate state wildlife agencies regarding potential impacts on fish and wildlife resources and measures to mitigate those impacts.
- **Magnuson-Stevens Fishery Conservation and Management Act**: If a project has the potential to impact essential fish habitat, the lead federal agency should consult with National Marine Fisheries Service and conduct Section 7 consultation.
- **National Historic Preservation Act Section 106**: Section 106 accounts for the effects of actions on cultural resources listed in, or eligible for listing in, the National Register of Historic Places.
- **State, regional, and local jurisdictional environmental permits**: State departments of fish and wildlife, water quality control, and other local agencies may have regulatory pathways that will need to be completed before construction. In addition, local jurisdictions are likely to have regulatory pathways and requirements that will need to be followed for levee construction projects.

This list is not exhaustive and appropriate permitting specialists should be included on the project team.

Prior to the onset of the planning phase, federal, state, and local permit requirements should be identified in conjunction with an approach that conforms to the regulatory requirements. Consultation with key agencies and tribal nations should also be initiated early in the process to confirm regulatory constraints and specific requirements. Getting multiple agencies and tribal nations in the same initial consultation meeting may be helpful to build consensus around appropriate fish and wildlife requirements and to strive for consistency of project specific regulatory input. Federal and state fish and wildlife agencies have specific requirements that should be incorporated into the planning and design of ecosystem restoration components of a levee project.

4.4.3 Work Within Existing Floodplain Management

The best practice is to align levee project formulation with watershed floodplain management, flood risk management strategies, community development plans, and land use decisions throughout the planning and design process.

Project formulation activities aligned with existing floodplain management efforts are particularly important during the following planning steps:

- Step 1: Existing floodplain management strategies or requirements associated with designated floodplains or floodways may result in the formulation process.
- Step 3: Formulation of alternative plans should be cross-referenced with other plans, laws, and regulations, as applicable, to ensure compatibility.
- Step 6: The ability of an alternative to be compliant with existing floodplain management requirements may hinder or enhance selection of that alternative.

The best practice is to be aware of, recognize, and align levee project formulation with existing floodplain management or flood risk management strategies and requirements. The Federal Emergency Management Agency (FEMA) is the federal agency responsible for administering the National Flood Insurance Program. This program is intended to help property owners recover more quickly and at less cost post-flood. Additional information on the National Flood Insurance Program is provided in the callout box in section 4.4.4.

Most states and many communities also have hazard mitigation plans, which should also be a consideration during project planning. State hazard mitigation officers and local or county floodplain managers are good resources to engage early in the formulation process. In addition, the local FEMA regional office can assist in providing additional information.

4.4.4 Cost and Funding

A best practice critical for project success is preparing a funding strategy for the lifespan of the levee and to consider all potential costs associated with the project. Community leaders and stakeholders must agree to and plan for funding sources and management of funds. Project funding strategies can vary greatly and may include any combination of a local, state, or federal cost share.

Levees typically need to meet some test of economic viability over the period of economic appraisal—typically in the range of 50 to 100 years. Sometimes, identifying multiple potential functions for levees and co-benefits can attract additional funding from other partners and allow an improved multi-functional concept to be developed. Several grant programs exist to support funding of levee projects. Existing state or local hazard mitigation plans should be reviewed to ensure compatibility with the proposed project.

Project formulation activities aligned with cost and funding should be considered during the following planning steps:

- Step 1: Limited funding for initial and long-term costs over the life of the project can be a constraint.
- Step 3: Preliminary costs may help screen out measures in initial plan formulation.
- Step 4: Costs for the levee project and anticipated funding resources for future costs may limit scoring for an alternative.
- Step 6: Costs and funding sources may impact the selection of an alternative.

NATIONAL FLOOD INSURANCE PROGRAM

The National Flood Insurance Program provides flood insurance from potential flood damage for personal property, residential properties, and non-residential properties. Communities can participate in the National Flood Insurance Program if they agree to adopt and enforce floodplain ordinances that reduce flood risk. Each state or community that participates must adopt the minimum National Flood Insurance Program requirements or can enforce more stringent requirements. It is important early in the formulation process to understand if the state and community participate in the National Flood Insurance Program and what specific related requirements have been adopted.

As part of the National Flood Insurance Program, FEMA develops flood insurance rate maps, which are officially adopted by the participating community, for both establishing the flood insurance rates and floodplain management activities. Rate maps should be reviewed to understand already established areas of potential flood risk, limitations on construction within a special flood hazard area or floodway, and how the project may alter this existing information. Note that these rate maps are updated frequently; therefore, the project team should research the latest available flood insurance studies, resulting mapping, or if map revisions are currently underway. The project formulation team should avoid floodways already depicted on flood insurance rate maps when considering levee alignments. If avoiding a floodway is not feasible, the formulation team should work with FEMA to determine necessary actions.

National Flood Insurance Program requirements will include limits on changes to the floodway and flood risk transfer. The floodway is the channel of a river or watercourse and the adjacent land areas that must be reserved in order to discharge the 1% flood event or base flood, a requirement of the National Flood Insurance Program. There also may be land use restrictions for areas that have been subject to reoccurring flooding. In addition, the National Flood Insurance Program has specific processes for the consideration of levees. Different areas, such as the floodway, are depicted on these maps. The existing flood insurance rate maps are a good starting point to understand any impacts the levee project may have on the National Flood Insurance Program regulations.

Once a levee project has been constructed, communities can request a letter of map revision to depict the effects the levee has on flood risk. Letters of map revision are generally based on the implementation of physical measures that affect the hydrologic or hydraulic characteristics of a flooding source and thus alter the flood risk. Through this process, a community's flood risk is reevaluated with the levee in place, floodplains depicted on flood insurance rate map panels are revised, and flood insurance needs are reassessed.

4.4.5 Operations and Maintenance

The risk of levee failure, potential associated consequences, and recovery costs increase without proper O&M of a levee system. Therefore, the best practice is to invest in proper levee inspection, maintenance, and repair. An additional best practice is to define expectations for long-term levee O&M, including required technical capabilities and funding. **Chapter 9** provides guidance on operating and maintaining a levee.

Project formulation activities aligned with O&M should be considered during the following planning steps:

- Step 1: Limited resources for proper O&M (staffing and cost) over the life of the project can be a constraint.
- Step 5: Factors such as effectiveness and efficiency may be influenced by the ability to provide proper operations and maintenance for a project. For an alternative to be effective, it needs to significantly contribute to the solution of the problem. For an alternative to be efficient, it must be cost effective. Lack of a proper O&M strategy makes effectiveness and efficiency challenging, as degradation of the levee without proper O&M would impact both.

- Step 6: Costs for O&M may impact selection of an alternative.

Adequate space should be allowed for maintenance, inspection, patrolling during flood inspection, and floodfighting. O&M requirements, including inspection and emergency operations (floodfighting), should be included in the geometric design. For example, the steepness of a levee slope may need to be limited to allow for safe mowing operations. Also, O&M requirements may require widened turnaround areas on the crest, as well as periodic ramps spaced along the levee alignment, connecting the crest to the levee toe for access and emergency operations.

Since O&M requirements may influence the selection of a preferred alternative—expectations for levee O&M along with costs and funding sources—should be outlined and agreed to as part of the levee project formulation. Questions to consider include:

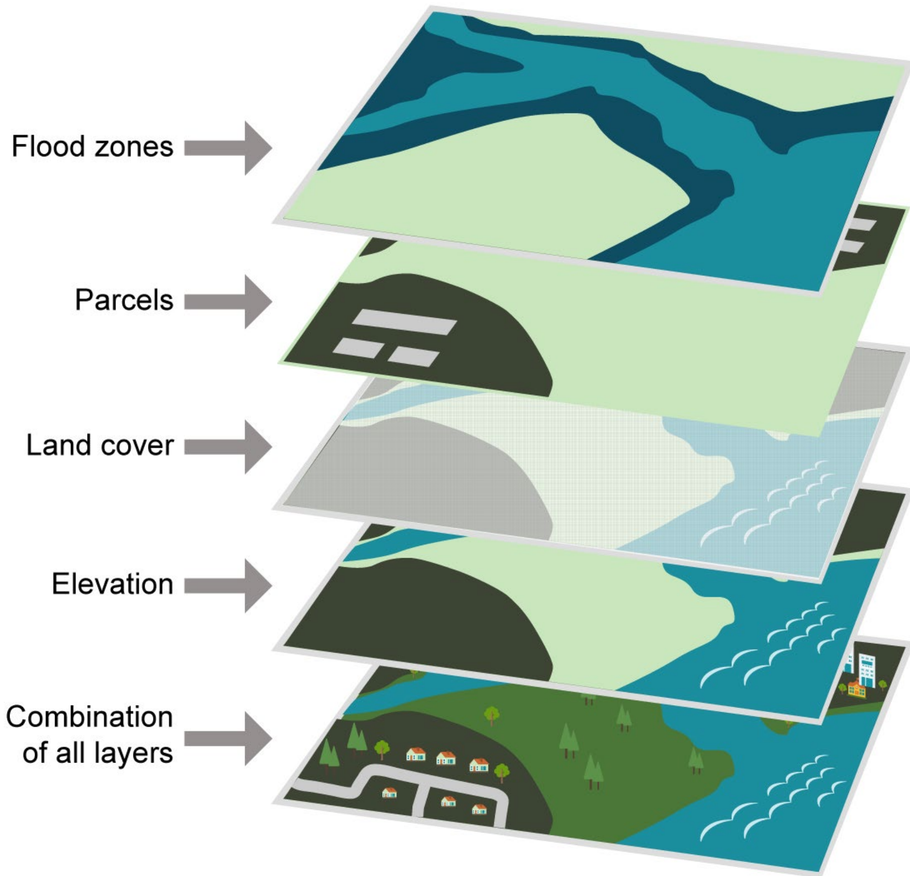
- Who is responsible for conducting the O&M of the levee?
- Does the responsible party have the appropriate funding and resources for a proactive, ongoing long-term O&M program?
- What are the maintenance expectations? For example, does the levee need to be well manicured or can it be left more natural to create wildlife habitat? Does the levee need to be maintained for public safety if used for recreation, or is it in a rural area where this is not a concern?
- Does the levee require active operation (e.g., closing road closure structures or installing demountable floodwalls) and does the responsible party have capacity and capability to operate the levee in a timely manner?

4.4.6 Documentation

Throughout project development (i.e., all steps of the planning process), important data, computations, and engineering and scientific management decisions should be well documented as a best practice. The required level of documentation will depend on the project's size, regulatory requirements, and potential impacts to health, safety, and the environment.

The project documentation system or repository should be established at the onset of the project, with all relevant background information and data organized appropriately. It is a best practice to assemble spatial data into a geographic information system (GIS) database for ease of visualization, usage, and manipulation, as shown in Figure 6-14.

Figure 6-14: GIS Documentation for Spatial Data



The National Levee Database, developed and maintained by the U.S. Army Corps of Engineers (USACE) and FEMA, with collaboration with federal, state, and local governments, captures all known levees in the U.S. The database includes the location of levees, people and assets behind a levee, responsible entity, and other information related to levees. It provides users with the ability to search for specific data about levees and serves as a national resource to support awareness and preparedness around flooding. The NLD houses information that should be reviewed (if available) for any levee project during the formulation process.

Any field reconnaissance during the planning phase and site characterization and investigation during the design phase should be added to the documentation repository, with clear references for the data or information source. This will allow easy access to all relevant data from the planning, design, and regulatory team members to feed into design analyses and regulatory impact assessments. During design, all data, project plans, and specifications should be added to the repository as the project progresses through conceptual, feasibility, and final design. During construction, the project documentation system may be updated and refined to meet the needs of construction documentation, as outlined in **Chapter 8**. Alternatively, it is not uncommon for the construction bid documents to require the contractor to develop their own document management system. If that is the case, certain background or baseline condition documents and data will need to be transmitted to the contractor.

4.5 Site Specific Considerations

4.5.1 Land Use

Past, current, and planned future land use can influence the planning and design of a levee project as summarized in Table 6-5; therefore, the best practice is to research any potential changes in land use and communicate this to the planning and design teams. For example, the proximity of existing development may restrict the possibilities for levee alignment. Conversely, changes in land use in the watershed could influence stormwater runoff characteristics and the resulting loading on the levee or interior drainage requirements.

In undeveloped areas such as forests and grasslands, rainfall and snowmelt collect and are stored on vegetation, in the soil column, or in surface depressions. When rainfall intensity exceeds the ground's infiltration capacity, or the rate at which soil can absorb surface water input, runoff occurs. However, in winter months when the ground is frozen or saturated from rain events or snowmelt, overland flow infiltration is limited, and runoff can occur more quickly.

Similarly in urban areas—where much of the land surface is covered by roads and buildings—there is less capacity to store rainfall and snowmelt. Construction of roads and buildings often involves removing vegetation, soil, and depressions from the land surface. The permeable soil is replaced by impermeable surfaces such as roads, roofs, parking lots, and sidewalks that store little water, reduce infiltration of water into the ground, and accelerate runoff to ditches and streams. Even in suburban areas, where lawns and other permeable landscaping may be common, rainfall and snowmelt can saturate thin soils and produce over land flow, which runs off quickly. Dense networks of ditches and culverts in cities reduce the distance that runoff must travel over land or through subsurface flow paths to reach streams and rivers. Once water enters a drainage network, it flows faster than either over land or subsurface flow.

Existing infrastructure features, such as public roads and railroads, may influence the levee alignment or features. In some cases, the levee alignment may run perpendicular to roads or railroads and will need to be designed to permit vehicles and trains to pass through. This situation will require specific considerations for levee operations, inspections, construction schedules, evacuation planning, and testing of closures.

In other cases, it may appear convenient to tie a levee alignment into an existing embankment or use an existing embankment as part of the levee alignment. This should only be done if it can be confirmed that the existing embankment—which was not originally designed to serve the purpose of a levee embankment—can be analyzed, improved, and operated for the purpose of flood risk management. Otherwise, using existing embankments as part of the levee alignment should be avoided. The transportation agency, railroad company, or owner of an existing embankment should be consulted early in the planning phase to alert them about the project and to help identify barriers that may influence the proposed levee alignment or design.

Most importantly, land use decisions directly impact what will be in harm's way if a levee were to breach. Development in the leveed area could increase potential consequences associated with levee breach or misoperation, thus elevating levee risk. This potential should be considered when planning a levee.

Project formulation activities aligned with land use should be considered during the following planning steps:

- Step 1: Limited land availability can be a constraint.
- Step 2: Current and any anticipated changes in future land use must be understood through research in this step.
- Step 3: Information collected in Step 2 will inform formulation of alternative plans.

Engagement of community members in the levee formulation process—population at-risk in the leveed area, as well as community officials and entities responsible for the land use decisions and success of the proposed project—is critical for building awareness of the benefits and risks associated with the levee and informing land use decisions. To be effective, these discussions require coordination and planning at the watershed level to ensure that flood risks are not unfairly shifted from one community to another.

Table 6-5: Land Use Types and Influences on Planning and Design

Land Use Type	Influences on Levee Planning and Design
Past	• The presence of cultural resources, ordinance, and contamination may affect project acceptance/approval, design, cost, as well as pose issues during construction. • Historic utilities may create preferential seepage pathways or hindrances to construction and may require design changes or removal/mitigation during construction.
Current	• May impose right-of-way constraints on levee alignment, footprint, and construction activities. • Influence runoff characteristics of the water shed, impacting the volume and timing of river flows. • Influence shoreline behavior in coastal areas. • As a secondary function, the levee may be used as a travel route, which may complicate future improvement activities.
Future	• Long-term regional development plans for the area may constrain design/layout. • Future development may affect runoff characteristics and the resulting flood loading on the levee and interior drainage requirements. • Future utilities or penetrations may introduce new failure modes to the levee. • Future development increases the population and structures to be protected, and so may affect selection of flood risk reduction strategy and levee modification.

Note to table: Adapted from The International Levee Handbook (Eau and Fleuves, 2017).

4.5.2 Right of Way

It is important during the planning process to identify the access corridor required by the entire levee alignment. The **access corridor** is the area needed for maintenance, inspection, and floodfighting and to provide additional room in the future for levee improvements. Providing an access corridor allows for a buffer between the levee and any adjacent land activities reducing potential impacts. Acquiring the needed right of way for a levee can be challenging, especially in urban areas. For example, future development or existing infrastructure often narrow the available space for a levee footprint and the available borrow area. The best practice is to consider the current and future right-of-way requirements as part of alternatives formulation, evaluation, comparison, and selection (Steps 3, 5, and 6). It is a good practice to secure sufficient right of way to allow for construction, planned O&M, emergency response, as well as potential future rehabilitation and modifications. Refer to **Chapter 8** for construction considerations in the right of way.

Within the existing or proposed right of way for a levee project, the location of utilities should be considered. Often the presence of utilities may dictate the alignment of a levee. Before proposing a levee alignment, the local utility department should be contacted to locate all existing and planned utilities. Another site-specific condition to consider may be hazardous, toxic, and radioactive waste contamination. Existing public records should be reviewed, or site testing may need to be considered during the formulation process. Right of way may be constrained by existing structures, political boundaries, environmental areas of concern, acquisition costs, or other factors. These constraints should be identified during planning for all alternative conceptual projects being considered. It is common that for some levees, floodwalls are used in areas that have right-of-way constraints.

In addition to procuring the right of way for levee construction, the following elements should be considered when identifying real estate needs:

- Having adequate room for operation, maintenance, inspection, monitoring, and emergency response activities.
- Having extra space for future expansion of the levee to accommodate design flood criteria changes, changes in hydrology/hydraulic criteria, or to make modifications or rehabilitation for risk reduction.
- Procuring city or county zoning of a strip of adjacent land beyond that required to construct, operate, and maintain the levee to provide a buffer to reduce the impacts of adjacent activities that can endanger levee integrity.
- Procuring temporary easements and rights of entry, as needed, for use during construction to access work and borrow areas.

4.5.3 Easements and Permits

Property surveys should be performed to establish owners of potentially affected properties. Real estate impacts will include permanent land acquisition, permanent easements, and temporary easements required to complete the project. These impacts should be assessed in the early planning phase (conceptual, as shown in Figure 6-17), as easement acquisition can be time-consuming. The need for easements and permits should be considered in Step 1 when constraints are identified.

Existing infrastructure crossings potentially affected by the levee or by levee construction should be identified and the applicable permitting agency criteria identified. This could include buildings and bridges, utilities, roads, railroads, culverts, pump stations, and other facilities. These locations can be obtained from existing maps and record plans but should be field verified. In addition, sensitive environmental or cultural areas may be identified, creating design constraints, required permits, or mitigations.

4.5.4 Cultural Resources

Cultural resource assessments should be conducted during the formulation stage of a levee project. These may include historic and prehistoric archaeological sites, historic districts, and built environment resources, including but not necessarily limited to buildings, structures, and objects (Figure 6-15). This may also include traditional cultural properties and sacred sites, including cemeteries, human remains, and features or sites associated with significant events or practices in the traditional culture of an ethnic group. It can be common for levee projects to have cultural constraints; therefore, cultural resources should be investigated in Step 1 when constraints are identified.

Figure 6-15: Example of a Cultural Resource

Archeologists conduct cultural resource surveys to preserve artifacts found at the site of the Rio de La Plata flood damage reduction project in Dorado, Puerto Rico; August 2019.

Levee projects are often located in areas where there were historically early settlements including Native American settlements and burial grounds. Encountering unknown cultural resources during construction can cause significant delays and increase costs. Thus, it is a best practice to properly prepare for incorporating cultural constraints as follows:

- Identify cultural resources that may be present in the levee project area.
- Evaluate the significance of each identified resource.

- Assess the direct and indirect impacts of the proposed levee construction on the resource including visual effects.
- Identify measures to avoid adverse impacts to a significant cultural resource.

Cultural resource assessments are used to help evaluate, assess, and identify measures to avoid adverse impacts and they vary in level of effort based on the historical significance of the area, as well as the size and nature of the levee construction project. These assessments can include conducting literature reviews, record searches, and archaeological and historical surveys of the levee project area. Assessments are often performed by or under the supervision of a qualified archaeologist.

4.5.5 Interior Drainage Requirements

Interior drainage is a source of flood risk. Any flood risk reduction project, including levee construction, should include consideration of all flood risks throughout the process. A best practice is to assess the impact of the proposed levee on internal drainage of the leveed area. This can include review of existing drainage plans or analysis of the existing topography to establish the natural drainage patterns. The presence or need for drainage ditches, culverts, and pump stations should also be noted.

Project formulation activities aligned with interior drainage requirements should be considered during the following planning steps:

- Step 1: Interior drainage flooding induced by the levee could be a constraint.
- Step 2: Investigate existing drainage features that might impact levee alignment or geometry needs. Understand future precipitation trends and how they may impact interior flooding.
- Step 3: Measures may need to include levee features to manage interior drainage.
- Step 4: Evaluation of the levee project should include any changes in existing drainage the project might impose and how well any measures address those impacts.

Where this interpretation cannot be completed, additional investigation may be required. **Chapter 7** presents guidance on design of interior drainage features.

4.5.6 Hazardous Materials

The early identification of hazardous, toxic, and radioactive waste will be critical to project planning, because rehabilitation of these materials can add significant project cost and schedule delays. Further guidance can be found in Engineer Regulation (ER) 1165-2-132 (USACE, 1992).

During the project formulation and design, a preliminary waste classification assessment based on the collected site investigation data should be made. However, this assessment may be limited for a number of reasons including:

- The data was collected for site characterization purposes and not for waste disposal assessments.
- The site investigation may have identified contamination but not fully delineated it.

- The locations of the test pits/boreholes and the depths of any samples may bear no relationship to the physical mass of waste soil that needs to be excavated and disposed.

Project formulation activities aligned with the presence of hazardous materials should be considered during the following planning steps:

- Step 1: If hazardous waste is identified within the project area, this poses a significant constraint. Early identification of hazardous waste is critical to minimize wasted time and effort in the plan formulation process.
- Step 2: Investigate hazardous waste within the study area that might impact levee alignment.

If identified during planning or alternative selection, sites with hazardous, toxic, and radioactive waste can be avoided so mitigation will not be required as part of construction. If these sites cannot be avoided, mitigation of hazardous materials may either be the responsibility of others to address prior to levee construction or the rehabilitation requirements should be included as part of the design.

4.5.7 Borrow Areas/Sources of Construction Material

Construction materials may include earthfill, clays, sands, and aggregates, riprap and other erosion protection materials, concrete, structural steel, sheetpiling, and bentonite. The best practice is to identify sources of construction material early in the project formulation process. During this identification process the team should:

- Confirm borrow material can be obtained in a reasonable time to avoid construction delays.
- Ensure the material will meet the requirements for strength, grading, and permeability.
- Allow time to complete environmental and cultural studies.

Borrow sites potentially affecting flood risk—such as excavation adjacent to an existing levee—should be excluded from the project.

Hauling borrow materials will likely be a large cost and an environmental impact driver. In many cases, borrow sources may require processing and mixing before use for the embankment. If material is not commercially available, the levee owner may have to acquire property, or rights to develop a property, to obtain the material. These should be identified early to confirm the source can be used.

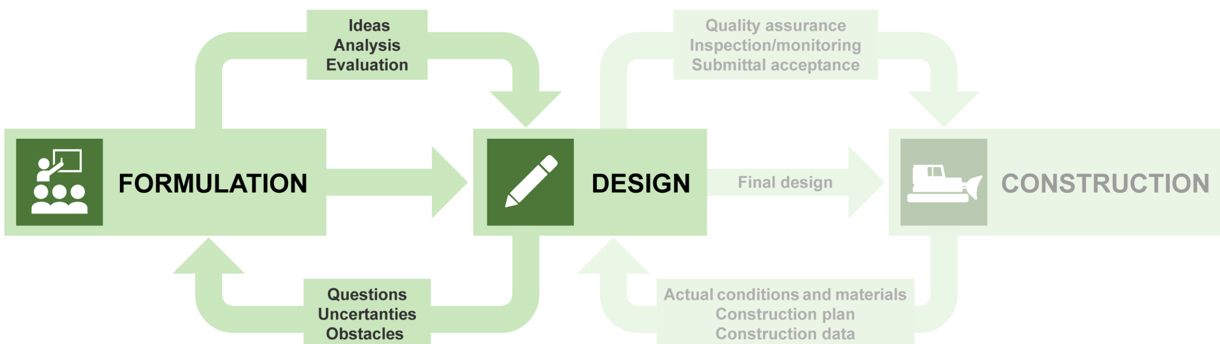
Project formulation activities aligned with the consideration of borrow material should be considered during the following planning steps:

- Step 1: Availability of borrow areas/construction material could be either an opportunity if material is readily available, or a constraint if located far from the project site.
- Step 2: While inventorying current and future conditions, availability of material should be considered if conditions could potentially change. For example, if land use changes from open space (where material is more available) to a developed area (where material is less available).

5 Interaction Amongst Formulation, Design, and Construction

Formulation of a levee project starts with the realization that there is a need for action. From there, an idea or solution is developed. This idea gets expanded and refined throughout the formulation process. As the idea/solution becomes more defined, there is enough information to start the design process. As design nears completion, information is handed to the construction team, such as specifics on final investigations, plans and specifications preparation, site needs, and monitoring plans. This interactive process is shown in Figure 6-16.

Figure 6-16: Interaction Amongst Formulation, Design, and Construction



Formulation and design evolve in parallel, as shown graphically in Figure 6-17, and each informs the other during this evolution. For example, if as the project is formulated, the community rejects a component of the levee, a new idea might be needed and the design changes. Over time, the level of effort for formulation recedes and that of design increases until the final design is reached. Levee formulation activities begin conceptually (conceptual phase); then the feasibility of the conceptual ideas are examined and preliminary design started (feasibility phase); and lastly design is finalized before heading into construction (final phase). Activities within each phase of the levee formulation process are described in Table 6-6.

Figure 6-17: Interaction Between Formulation and Design

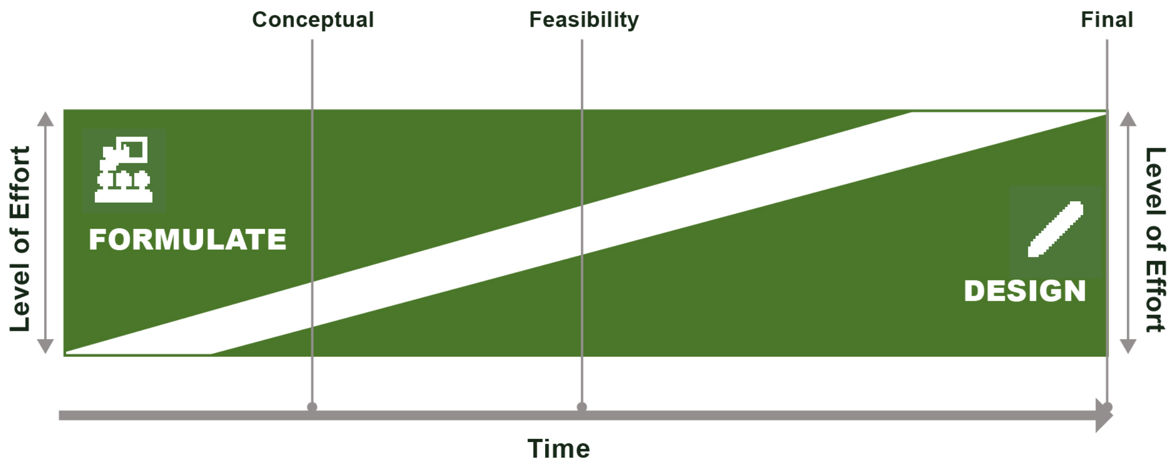


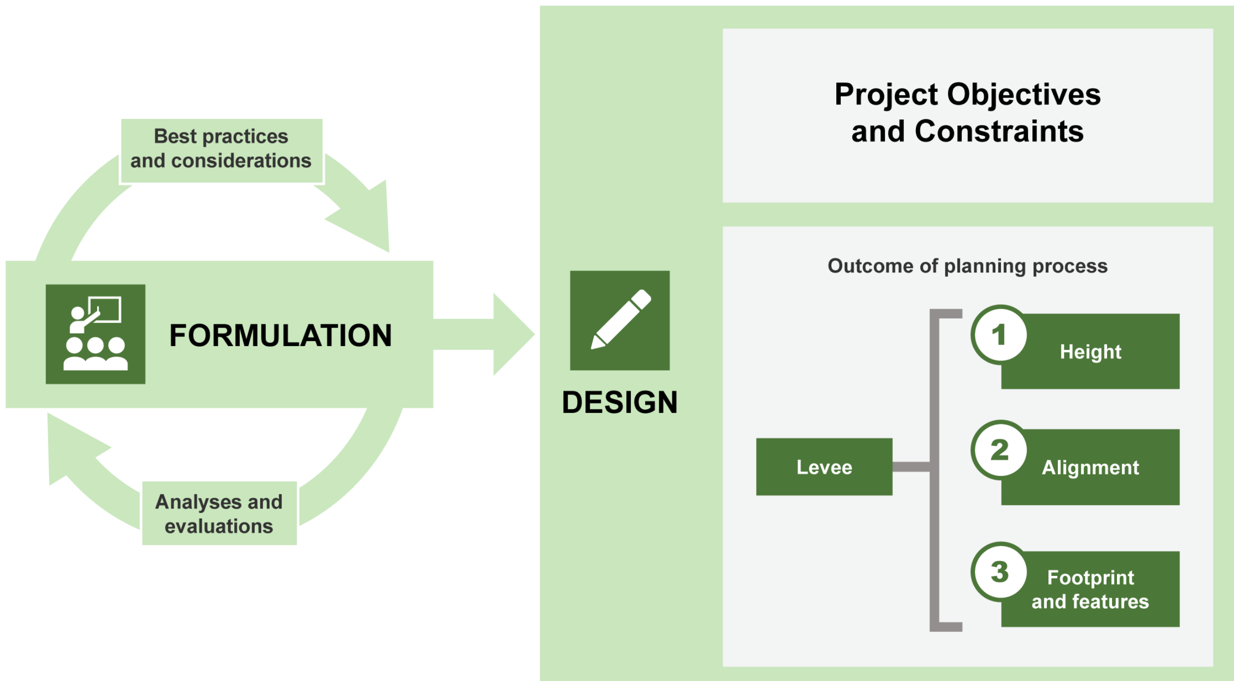
Table 6-6: Activities Within Each Phase of Levee Project

Phase of Project	Activity
Conceptual	Initial assessment based on available information. Some investigation may be required to support the hydraulic characterization of the site. The information is sufficient to allow rudimentary modeling and calculations to be undertaken for a few options, which can be used to assess the viability of proceeding with some form of flood risk management project.
Feasibility	More detailed information gathered, and more extensive modeling and calculations undertaken for a broader array of options. Information is sufficient to allow the options to be worked up to a level of detail that allows them to be costed so that decision makers can determine which option is to be taken forward to design and construction. This may include developing a better understanding of the interaction of the levee, ground, and hydraulics, as well as the issues that will affect the levee performance. Findings allow the scoping of additional data collection (quantity and nature) required for the detailed evaluation. At this stage, the hydraulics are typically well defined but additional field data may be required to support the more sophisticated analytical/numerical models. Where no or very limited quantitative data are available, limited investigations may be required to inform the geotechnical assessment.
Final	The primary objective of this stage is usually the characterization of the ground through a rigorous program of investigation. Some additional hydraulic data may be required but this is usually well defined by this stage. There may be a need to update or refine data, specifically if there is a need for advanced hydraulic modeling. The development of the final project schema and preparation of construction information (plans and specifications at various levels, typically 30%, 60%, 90% and 100% final design) is completed in the final phase prior to going to construction.

Note to table: Adapted from The International Levee Handbook (Eau and Fleuves, 2017).

Engineering analyses and evaluations during levee formulation are needed to identify the levee geometry and features. The goal is to identify these as early as possible and with enough confidence to move into design. To move forward with design, the top of levee profile (levee height), levee alignment, levee footprint, and levee features should be identified, while incorporating the best practices and considerations outlined in section 4. Project objectives and constraints will also be carried through to the design phase as shown in Figure 6-18.

Figure 6-18: Outcome of the Planning Process

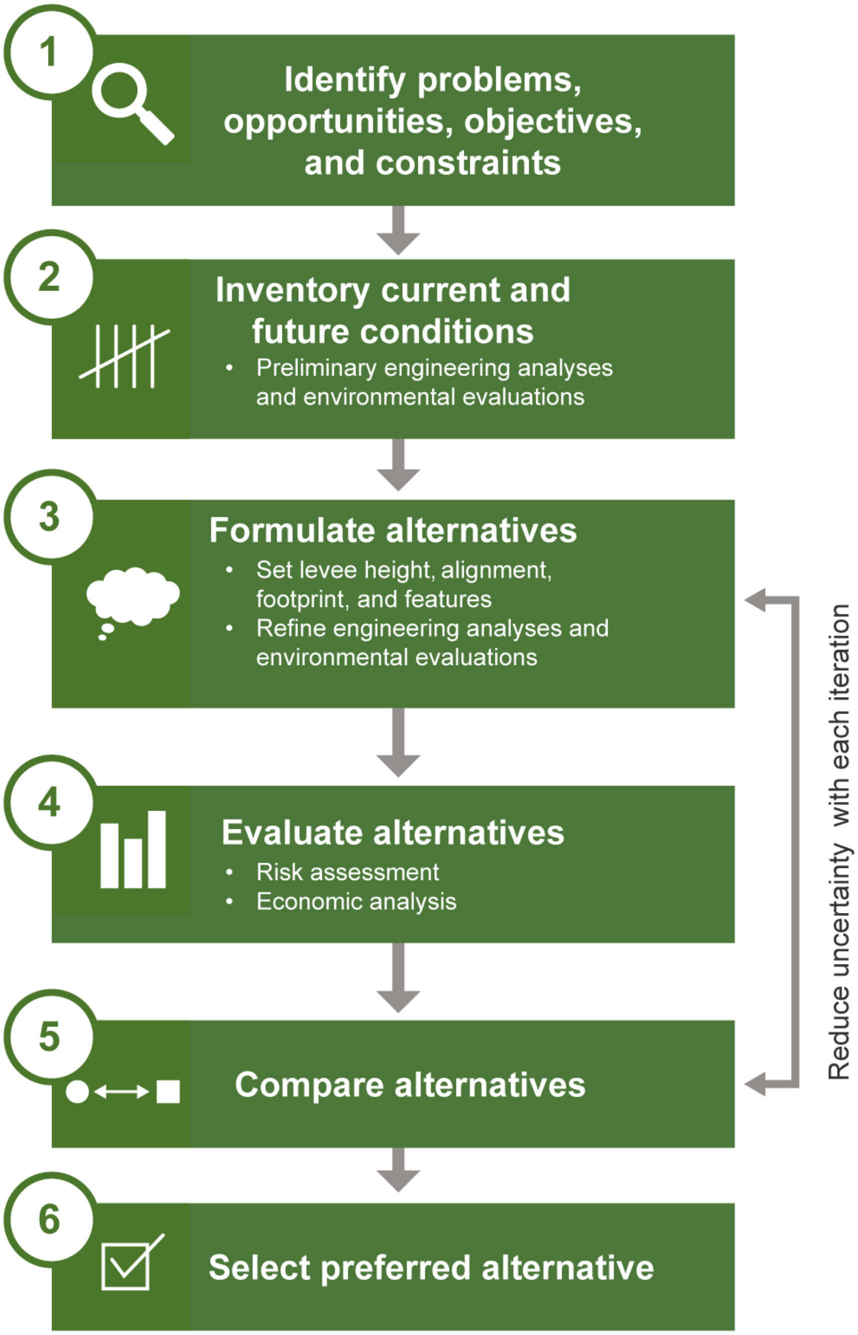


To determine the appropriate levee characteristics for the specified application, supporting analyses, studies, and evaluations are required. Supporting analyses include engineering analyses, risk analyses, economic evaluations, and environmental assessments to set the levee geometry and features. How they are incorporated into each of the planning steps is illustrated in Figure 6-19.

Some preliminary engineering analysis and results from taking inventory of current and forecast future conditions in Step 2 are required in advance to formulating alternative plans in Step 3. This would be done at the conceptual level of planning and design. Once the preliminary levee characteristics have been identified, risk and economic analyses are used to evaluate alterative plans in Step 4. At the conclusion of Step 4, consequences and benefits are better understood for each alternative. At this point, the planning process may become iterative as more data and information is collected.

The iterative process typically is completed within the feasibility phase of planning and design. Within each iteration, the level of uncertainty about each analysis is reduced. This iterative process may continue until the team has decided that the planning objectives have been met and the residual planning risks are acceptable to the community, allowing for the completion of alternative comparison in Step 5 and selecting an alternative in Step 6. Checks for constructability, O&M requirements, and lifecycle costs should be conducted throughout this iterative process. At the conclusion of the feasibility phase, a decision is made to enter into the final phases of planning and design for the selected alternative.

Figure 6-19: Analyses Within the Six-Step Planning Process



5.1 Analysis Considerations

5.1.1 Addressing Uncertainty

Because future conditions are inherently unknown, the best practice is to include a level of uncertainty with current and forecasted future conditions. Levee formulation is a dynamic, iterative process with uncertainties in each step of the process. Assumptions made during evaluations and modeling are used to inform levee formulation, even for current conditions. Uncertainty in these assumptions should also be included. It is important to acknowledge and articulate sources of uncertainty and knowledge limitations.

Further, since levees may exist for a long period of time—some existing levees are close to 100 years old—it is important to consider larger timescales, and hence larger uncertainties when formulating a levee. Key assumptions used in the projections should be explicitly stated. Examples include future population growth, changes in land use, and climate forecast. Where uncertainty may meaningfully affect the investment decision, multiple planning scenarios should be considered, with a clear explanation of the basis and assumptions underlying each.

5.1.2 Scalability

The level of detail and complexity of planning, analyses, and evaluations will depend on the decisions being made, necessary actions to address uncertainty in the results, level of difficulty of the problem, and the cost of addressing the risks. The best practice is to include greater analytic detail in projects with greater uncertainty, complexity, risk, or cost. Whereas for projects with lower uncertainty, complexity, risk, or cost, less analytic rigor may be required. Conversely, in some cases, high risks to life safety may warrant consideration of not waiting for more detailed assessments and proceeding with the study and implementation as quickly as possible.

In addition, the level of detail required to make levee formulation decisions will grow over the course of the study, as the process moves from an array of alternatives to a single recommended alternative.

Factors to consider when determining the appropriate level of analysis:

- Magnitude and significance of specific problems and opportunities the levee project seeks to address, expected impacts, resulting risk exposure, and/or costs.
- Complexity in science, engineering, uncertainties, ecosystems, cultural values, resource management, and best scientific information available.
- Projected service or operational life of the project or facility.
- Stakeholder and community concerns.
- Authority under which the investment decision/recommendation is made and degree of performance or irreversibility of that investment decision.

5.1.3 Planning Area and Levee Reaches

The planning area refers to the specific geographic area where alternative levee plans are formulated and evaluated. The best practice is to specify a planning area that includes the geographic scope necessary for analyzing the nature and extent of problems and opportunities.

Additionally, potential locations of resources and existing projects that would be directly, indirectly, or cumulatively affected by, or that could affect, the alternative plans (often called the affected area) should be considered. In the process of describing problems and opportunities, the planning area may be adjusted to accommodate new understandings of physical, biological, and economic relationships. The planning area is typically larger than the affected area. It is also possible that the geographic boundaries for evaluating hydraulic, economic, and social impacts do not coincide, thus it may be necessary to define multiple (overlapping) planning areas.

For levee evaluations and analyses, sections of the levee may be grouped together as a levee reach. Each reach should be defined by discrete lengths such that each length has similar geotechnical, geometric, past performance, construction and remedial history, and/or hydraulic loading (USACE, 2022). The number of reaches may depend on the stage in project formulation and data availability but should consist of enough reaches to capture proposed project features or changes in cross section.

5.1.4 Available Information

During the formulation process, especially in the early stages, the best practice is to include as much available information as possible (Table 6-7). As the team gets farther along in the process, more refinement and development of project-specific information should be used as analysis results and formulation of alternatives move into design.

Table 6-7: Available Information

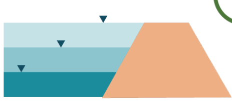
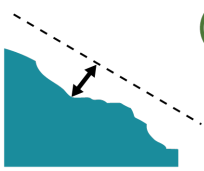
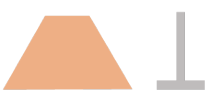
Data	Description
FEMA floodplain mapping	The flood insurance rate maps for an area can help communities view and visualize local flood risk. To access the maps, FEMA has a flood map service center that is searchable by address, place, or longitude/latitude coordinates. In addition to the rate maps, there are supplemental non-regulatory resources available on the FEMA website.
National Levee Database	The NLD is a dynamic database with levee data from federal agencies, states, tribes, territories, and local sources.
Levee Screening Tool	USACE created the Levee Screening Tool to characterize levee risk. Authorized users can enter information related to hazards, conditions, performance, and consequences and apply engineering judgment to describe the performance and potential consequences of the levee system. USACE has applied the Levee Screening Tool to over 1,700 levees in the NLD; these levees are referred to as screened levees.
Water level or tide gage data	National Oceanic and Atmospheric Administration has an online database for tide gage data searchable by location or gage ID. U.S. Geological Survey water data for the nation includes water resource data collected at approximately 1.9 million sites in all 50 states and other areas of the nation.
Geologic and soils data	U.S. Geological Survey geologic maps and Earth Resources Observation and Science data center for imagery, Bureau of Land Management maps and aerial photographs, Natural Resource Conservation Service soils mapping, and state geological surveys.

Data	Description
Previous studies	Research should be conducted to gather available information for the study area that may have been developed previously. This information could include topography, bathymetry data, hydrologic or hydraulic models, utility locations, site investigations, environmental assessments, hazardous materials surveys, or risk analyses. Check with local, state, and federal governments to identify previous studies that may have useful data for the specified project.

5.2 Engineering Analyses

Several types of engineering analyses are required to determine the top of levee profile, levee alignment, levee footprint, and levee features. The types of analyses required, and the results needed to establish these levee characteristics, are shown in Figure 6-20.

Figure 6-20: Engineering Analysis Required for Formulating Levee Characteristics

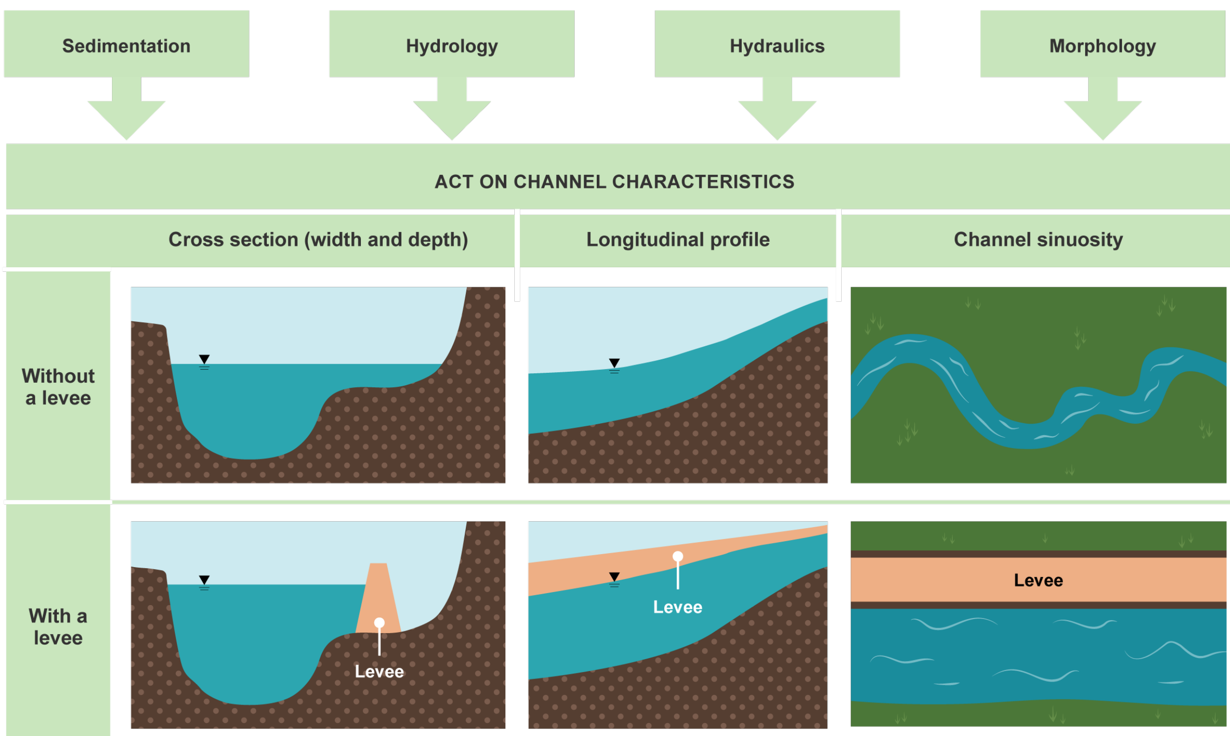
	Levee characteristics	Engineering analyses	Engineering analysis results	Other considerations
	1 Levee height	• River/coastal hydrologic and hydraulic analyses • Wind wave	• Water surface profile • Annual exceedance probability • Wave and storm surge potential	• Superiority
	2 Levee alignment	• River/coastal morphology • Geotechnical	• Geomorphologic process • Subsurface conditions	• Right of way • Interior drainage • Hazardous waste
	3 Footprint and features	• Hydrologic • Geotechnical	• Levee slopes' impact on wave height • Subsurface conditions	• Borrow availability • Right of way

The level of detail in the analyses should be in line with the scale and risk of the project. For levee projects that will reduce flood risk to leveed areas with significant populations and damageable properties, the analysis should be more robust, such as development of detailed modeling, thorough site investigations, and a comprehensive and rigorous evaluation of potential impacts and consequences. For smaller leveed areas with less consequences, a scaled back analysis could be considered, mainly relying on available data and analyses. Regardless of the scale of the project, the flood hazard and potential flood risk reduction provided by the project should be transparent and clearly communicated to the community.

As the plan formulation moves from conceptual to feasibility stages and eventually to final design, the analyses and evaluations required to determine levee characteristics, could become iterative. Once a conceptual plan is conceived and levee characteristics identified, a risk analysis should be performed to understand the reliability of the initial design and residual risks. If the consequences are more significant than a community wants to accept, revision to the conceptual design would be needed. With each iteration, and repeat of risk analyses, the uncertainties about analyses results will be reduced.

Levees are a part of the physical world and must interact within the environment within which they are constructed (Figure 6-21). Hydrology, hydraulics, and sedimentation of riverine and coastal systems are influenced by natural processes. However, the presence of levees will modify and interact with the natural surroundings. In formulating a levee project, it is necessary to understand how natural and human-made systems interact and affect each other. For example, wetland restoration can lead to changes in wave heights through the frictional effects of vegetation blades, stems, and branches on water flow, and reduce the loading on coastal levees, which, in turn, can influence damages and maintenance costs. Setting back levees from the watercourse provides more storage for larger storms and helps reconnect the floodplain and restore ecosystems. At the same time, a wider floodplain allows the river to follow a more natural meander slowing water flow and erosion, and thus reducing the risk of levee scour. Thus, there is a need for engineering analyses with the levee project in place to understand how it could potentially alter existing conditions.

Figure 6-21: Interaction Between Levees and Physical World



Note to figure: Adapted from The International Levee Handbook (Eau and Fleuves, 2017).

5.3 Risk Assessment

During formulation of a levee project, flood risks need to be estimated and understood. The type of levee project will guide the risk assessment and risk estimates required, as illustrated in Table 6-8. Guidance on estimating risks is provided in **Chapter 4**. In addition, **Chapter 5** provides guidance on investment strategies related to balancing flood and levee risks that should be considered in levee project formulation, including the type of levee project. For example, if a rehabilitation project is needed to reduce levee risks and the extent of the work required is significant, there may be an opportunity to increase the risk reduction benefits provided by the levee.

Table 6-8: Levee Project Type and Risk Estimates

Levee Project Type	Risk Estimates
New	• Flood risk without the levee. • Optimizing level of risk reduction provided by levee. • Non-breach risk with levee in place. • Levee risk (prior to and with overtopping). • Flood risk from other sources with levee in place.
Rehabilitate	• Existing/intended risk reduction benefits. • Non-breach risk. • Levee risk (before and after rehabilitation). • Optimizing level of risk reduction provided by the levee. • Impacts of rehabilitation on flood risk from other sources.
Modify	• Existing risk reduction benefits of the levee. • Target risk reduction benefits provided by levee. • Non-breach risk (existing and modified). • Levee risk (existing and modified). • Impacts of modification on flood risk from other sources.
Remove	• Existing risk reduction benefits of the levee. • Non-breach risk (existing). • Levee risk. • Flood risk without the levee.

5.4 Economic Analyses

Economic analyses are often used in the levee plan formulation process to evaluate the effectiveness and efficiency of potential alternative plans. Various types of economic analyses can be performed to evaluate alternatives.

5.4.1 Benefit-Cost Analysis and Cost-Effectiveness Analysis

Benefit-cost analysis is commonly used to identify and measure (usually in monetary terms) the different benefits and costs of proposed alternatives and then compare with each other to determine if the benefits of the alternative exceed its costs. It is a systematic process for identifying, quantifying, and comparing expected benefits and costs of an investment. All benefits and costs that arise during the life of the project are included in the analysis. For alternative comparison purposes, benefits and costs over the project life are brought to a present-day value using a discount rate. Benefit-cost analysis is the primary method used to identify whether an alternative is economically justified. An alternative is justified when:

- Estimated total benefits exceed total estimated economic costs.
- Each separable purpose (for example flood damage reduction or ecosystem restoration) provides benefits at least equal to its costs.
- The scale of development provides maximum net benefits (in other words, there are no smaller or larger alternatives which provide greater net benefits).
- There are no means of accomplishing the same purpose which are more economical.

Various types of benefits and co-benefits in a levee project can be included in a benefit-cost analysis, which could include but are not limited to:

- Flood damage reduction.
- Recreation.
- Ecosystem restoration.

Federal, state, and local agencies have specific methods, assumptions, and benefit categories that may be included in benefit-cost analyses. The most relevant guidance—and that which is most appropriate to the project—should be investigated.

Cost-effectiveness analysis focuses upon comparing the whole life costs of alternatives, which achieve or exceed an objective, that can be expressed in specific, non-monetary terms (i.e., acre-feet, milligrams per liter, habitat units). For example, if the objective of the project is to reduce the floodplain depth to less than 1 foot, then a cost-effectiveness analysis would compare the costs of alternative plans that meet or exceed that objective. The plan that delivers the specified objective at the least cost would be the most cost-effective alternative. Cost-effectiveness analysis is particularly important when the objective cannot be monetized and therefore cannot be included in a traditional benefit-cost analysis. Ecosystem restoration benefits are an example of this. Although there are techniques to place monetary values on the outputs of ecosystem restoration projects, traditionally these types of projects are evaluated by computing the cost-per-restored-habitat-acre or some other physical measure (such as habitat units), and comparing these costs, as well as the incremental changes in costs and outputs among proposed alternatives (California DWR, 2008).

5.4.2 Incremental Analysis

Incremental analysis is a process used in plan formulation to help identify alternatives that deserve further consideration in an efficient manner in USACE's ER 1105-2-100 (USACE, 2000b). The analysis consists of examining increments of alternative plans to determine their incremental costs and incremental benefits. Increments of plans continue to be added and evaluated as long as the incremental benefits exceed the incremental costs. For example, a project might start with a levee of low height, then add height in steps or increments (say 1 foot). For each increment of height, the added (incremental) costs and added (incremental) benefits are estimated. As long as the incremental benefits exceed the incremental costs, it makes sense to add the foot of height because the extra foot adds more to benefits than to costs. When incremental costs exceed incremental benefits, no further increments of height are added (USACE, 2000b).

5.4.3 Trade-off Analysis

Some project benefits are not easily expressed in monetary terms, such as ecosystem restoration or recreational features. Trade-off analyses include defining monetary and non-monetary effects of a project as gains and losses.

5.4.4 Distribution Effects

Traditional benefit-cost analyses produce information monetizing the benefits to justify project costs; however, it does not distinguish which groups within a society benefit more or less. Evaluation of distributional effects might be answered by asking: does the project benefit some groups more than others? Are benefits being equally distributed amongst the community? Economic techniques can be used to weight benefits and/or costs to better reflect the community impacted.

5.5 Environmental Evaluations

Environmental impact studies should be conducted in coordination with federal, state, tribal, and local environmental agencies as part of any planning process for a new levee. Levee alignment and footprint should minimize the impact to the environment. This is especially true where there is critical habitat along the levee. In these regions, it is generally desired that allowances be made for waterside vegetation along the bank as it provides critical habitat and shading (beneficial for water temperatures) for aquatic species. This can sometimes be accomplished by setting the levee back from the watercourse. In some cases, a levee setback is not an option, and consideration of features that allow for the coexistence of habitat or vegetation along or near the levee should be considered.

6 Establishing Levee Characteristics

6.1 Establishing Design Hydraulic Conditions

The hydraulic conditions for project formulation and design should be evaluated based on hydraulic modeling that provides water levels (or water levels and wave conditions in coastal situations) along the levee alignment. Hydraulic models are used to estimate a design water level and ultimately set a design top of levee grade (section 6.2).

Both hydrologic and hydraulic models should be calibrated using observed data wherever this is available. Data may include aspects such as historical high-water events, areas flooded, and/or wave conditions. Older data may require conversion to current horizontal and vertical datums. Where no significant changes have occurred in the watershed and existing levee alignments have not changed, the amount of modeling may be reduced if the period of record is sufficient to derive a reasonable estimate of long-term water levels. Known climate change trends should be used to adjust predictions and historic data.

Following this evaluation, design water level and wave loadings on the levee features should be established together with a range of other conditions above and below these design conditions against which the performance of the levee should be checked. Areas where insufficient topography is available to assess the design loads should be identified for further survey or bathymetry. The outcome of hydrologic and hydraulic evaluations are design water levels, flows and wave conditions used to set levee geometry (Table 6-9).

Table 6-9: Hydrologic and Hydraulic Activities Within Each Phase of a Levee Project

Phase of Project		Typical Information	Use of Information
Conceptual	Office based data collection	• Bathymetry • Topography, light detection, and ranging • Aerial photographs • Rudimentary models • Approximate estimates of stage-discharge relationships • Statistics for available gage data • Information from existing studies	• Provide a general understanding of the river, coastal, or estuarine system. The level of understanding will vary with the extent of information available. • Provide information to inform scoping of subsequent phases of investigation. • Provide information to support preliminary project/design decisions.
	Field based data collection	• Observation of stream channel, sediments, vegetation, floodplain, existing infrastructure, and flood control features • Identify potential impact areas • Morphologic assessment of river or coastal system • Water levels • Waves and currents • Topography	
Feasibility		• Additional bathymetric and topographic surveys • Develop detailed hydrologic and hydraulic models for river, coastal, or estuarine systems • Morphological studies • Perform risk-based analysis	• Support development of higher resolution models. • Assess system performance. • Evaluate alternative solutions. • Set top of levee elevation. • Determine designed overtopping location requirements.
Final		• Develop O&M manual • Design of designed overtopping sections • Detail calculations/modeling for erosion protection	• Provide owner information and instructions to operate and maintain project. • Provide sufficient information to allow the detailed design to be developed.

Note to table: Adapted from The International Levee Handbook (Eau and Fleuves, 2017).

6.1.1 Hydrologic Evaluations for Riverine Levees

As described in **Chapter 4**, hydrology relates to the estimation of precipitation intensity and duration, the resulting quantities of surface water runoff generated from a specific area or watershed and the resulting stream flow in rivers. Watershed hydrology thus governs water surface elevations in streams and rivers and knowing the magnitude and probability of large events is critical in levee formulation and design.

6.1.2 Hydraulic Evaluations for Riverine Levees

Hydraulic evaluations estimate the range of flow and water level characteristics that may occur in rivers, from those in rare, large floods to normal, everyday flows. Such evaluations should be repeated throughout the levee lifecycle, since water levels and flows in rivers continually change due to precipitation, watershed runoff, and changes in channel morphology. Details on recommended approaches to hydraulic evaluations and hydraulic modeling are provided in **Chapter 4**.

The results of these evaluations inform levee geometry (sections 6.2, 6.3, and 6.4), which includes levee height, footprint, features, tie-ins, alignment, and managed overtopping.

A probabilistic hydrologic and hydraulic risk and uncertainty analysis, including climate change considerations, may be performed to assess the confidence in forecasted water levels. Based on the likelihood of water levels exceeding the design top of levee grade, this analysis may suggest additional levee height. Allowance should also be made for the following:

- Increased water levels near bridges and other structures.
- Wave runup (where significant wave action is possible) making use of the recommendations for coastal levee situations in **Chapter 4**.

6.1.3 Hydraulic Evaluations for Coastal Levees

For coastal levees, the design top of levee grade will be set on the basis of hydraulic studies which consider the effect of wind, water level, and climate, together with wind and wave setup, wave runup and overtopping calculations (**Chapter 4**). The outputs of the studies will be estimates of water level and wave conditions for a range of annual exceedance probabilities, or return periods. These should be provided at a series of locations along the levee system identified with levee design cross-sections (transects), and delivering these may require local wave transformation calculations.

At these locations, runup, and overtopping calculations may then be undertaken, often using empirical models to help to determine levee geometry. In addition, the wave conditions at the levee will determine any armoring required. In complex situations, physical models may be required to assess wave overtopping and armoring.

SEA LEVEL CHANGE CONSIDERATIONS

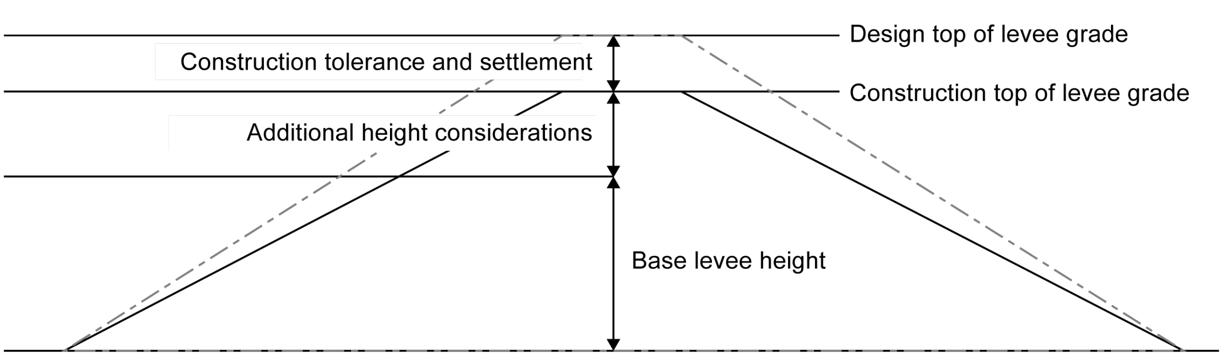
For coastal levees, a range of future relative sea level change scenarios will need to be incorporated in the two-dimensional coastal hydraulic model, providing a comprehensive understanding of how changing long-term water levels can impact storm water levels, as typically this relationship is not linear. If that is not possible, a relative sea level change increase can be applied to water levels from current conditions in planning stages, although understanding the localized effects and impacts on wave conditions will lack accuracy without running the complete storm scenarios in the two-dimensional hydraulic model.

6.2 Setting the Top of Levee Grade

The top of levee grade represents the top of the barrier at a particular location along a levee system. The objective for determining the top of levee grade is to determine a minimum top of levee grade that will accomplish the intended objectives of the levee. The minimum top of levee grade for a levee embankment is denoted as the design top of levee grade shown in Figure 6-22. The same approach can be used for other levee features such as floodwalls, closure structures, etc. There are three typical components for determining the design top of levee grade:

1. Base levee height.
2. Additional height considerations.
3. Construction tolerance and settlement.

Figure 6-22: Determining Top of Levee Grade



Paving, including asphalt, concrete, gravel, or aggregate-type surfacing should be above the design top of levee grade and considered with setting the construction top of levee grade.

6.2.1 Base Levee Height

The base levee height is the height of the levee that represents the highest water surface profile for the range of flood events the levee is intended to exclude from the leveed area. Hydrologic and hydraulic evaluations are used to determine water surface profiles and are typically performed using deterministic methods (i.e., does not explicitly account for uncertainty) with expected hydrologic and hydraulic evaluation values over the analysis period. Adjusting the levee height to account for uncertainty in hydrologic and hydraulic evaluations is discussed more in section 6.2.2 (e.g., hydraulic assurance). The hydrologic and hydraulic evaluations to determine water surface profiles for the base levee height should account for the following expected conditions over the analysis period:

- Discharge rates (i.e., flow) based on expected future rainfall and runoff.
- Localized infrastructure influence on water levels (e.g., bridges).
- Channel/river curvature effects (e.g., super elevation water surface profile).
- Channel/river conveyance roughness and cross-section geometry.

- Effects of waves.

When waves can occur during a flood, the base levee height should be increased above the still water surface profile to include the effect of waves on water levels for the range of water surface elevations the levee is intended to exclude. Waves can occur during coastal flooding or riverine flooding with significant wind and fetch distances. Wave runup occurs when individual waves break on the waterside levee slope and the broken wave bores advance up the slope. Refer to sections **Chapter 4** on how to determine effects of waves.

6.2.2 Additional Height Considerations

Determining the design top of levee grade also requires incorporating other considerations in addition to the base levee height (Figure 6-22). There are many factors that influence these other considerations, but the primary factors for additional height considerations include:

- Hydraulic assurance
- Subsidence
- O&M access
- Superiority
- Uncertainty

Currently in practice, a combination of deterministic methods (i.e., does not explicitly consider uncertainties) and probabilistic methods (i.e., explicitly consider uncertainties) are used to determine the additional levee height related to these factors. The best practice is to use probabilistic methods, which consider the likelihood or probability of water surface profiles occurring to determine additional levee height. Using probabilistic approaches to systematically account for uncertainties is particularly important when evaluating overtopping risk where a levee breach could lead to significant consequences.

SUBSIDENCE

Approximate point of maximum subsidence in the San Joaquin Valley, California. The land surface subsided roughly 9 meters from 1925 to 1977 due to aquifer-system groundwater withdrawals. Signs on the telephone pole indicate the former elevations of the land surface in 1925 and 1955. (Credit: Richard Ireland; U.S. Geological Survey.)

Hydraulic assurance is the probability that a water surface profile will not be exceeded during a flood with a particular frequency of occurrence considering the full range of uncertainties in the hydrologic and hydraulic evaluations. Determining the levee height needed for hydraulic assurance is best performed using probabilistic methods. ER 1105-2-101 (USACE, 2019) is a good source of information on how to determine hydraulic assurance. A 90% hydraulic assurance is a common target used to ensure a levee can exclude any floods from the leveed area with a reasonable level of confidence. A 90% hydraulic assurance means that there is a 90% probability that the top of levee grade will not be exceeded (i.e., overtopped) for these floods. Achieving a 90% hydraulic assurance can require 2 to 3 feet of additional levee height above the base levee height in riverine situations.

Subsidence is a gradual settling or sudden sinking of the Earth's surface due to removal or displacement of subsurface earth materials. Subsidence can be caused by human-made activities (e.g., aquifer-system compaction associated with groundwater withdrawals) and/or natural processes (e.g., natural compaction or collapse such as with sinkholes or thawing permafrost). Subsidence is an important consideration when determining the design top of levee grade especially for levees intended to exclude coastal floods. Regional datums provide practices for estimating subsidence rates. When selecting additional levee height, the project team should consider:

- The amount of the levee height adjustment needed to account for subsidence impacts on both the design levee grade and flood water surface profiles.
- Adjusting the levee height to account for subsidence over the analysis period for the project.
- That the goal of the adjustment is to ensure the levee excludes the floods it is intended to rather than maintain a design levee grade.
- For coastal levees, subsidence will only impact the design levee grade—not the water surface profile. Levee height subsidence adjustments will be to maintain the design levee grade.
- For riverine levees, subsidence may impact the elevation of both the design levee grade and water surface profiles.

FREEBOARD

Freeboard is an outdated method of levee design that adds a factor of safety to levee height to account for uncertainties, usually expressed in feet above a specified flood level. Freeboard has been used to compensate for unknown factors (i.e., hydrology and hydraulic uncertainties) that could result in greater flood heights than calculated. Freeboard is a deterministic method used to account for these uncertainties.

For levees, it is not considered a best practice to solely rely on deterministic methods such as freeboard to determine the final top of levee grade. Deterministic methods do not account for the full range of uncertainties and can result in additional levee heights that are too low or too high.

The top of levee often provides important O&M access for the levee. Roads built on top of the levee are typically made up of materials that are pervious (e.g., gravel) and are not typically considered to be an effective barrier to exclude flood waters. Paving, including asphalt, concrete, gravel, or aggregate-type surfacing should not be considered as part of the levee excluding flood water from the leveed area. Thus, the levee height should be increased to account for the O&M access (e.g., the thickness of the road).

Superiority is an important consideration when determining the final top of levee grade. As discussed in section 4.1.2, superiority helps to manage levee risk and flood risk by managing overtopping within a levee system and flooding within a watershed. Determining the levee height needed for superiority requires careful consideration of flood risk transfer within a watershed, as well as tradeoff between levee overtopping performance, levee overtopping consequences, and levee project construction costs. A risk assessment may be used to establish adjustments to the levee height (higher or lower) at different areas of the levee alignment to preferentially select where the levee will overtop in areas of lower consequence.

Accordingly, levee height adjustments may be greater in some areas of the alignment than others. The amount of added levee height might also depend on the ability of the levee to resist breaching from an overtopping event, termed overtopping resilience. Different methods to increase overtopping resilience may be employed during design. These will include design of erosion-resistant elements on the levee crest and landside slope or the use of designed overtopping sections, typically in conjunction with superiority.

At the coast, further levee height adjustments may be necessary in order to limit the amount of wave run-up and overtopping to acceptable quantities. The extent of height increase can be moderated by adding additional roughness elements to the water side of the levee.

6.2.3 Settlement and Construction Tolerance

The difference between the construction top of levee grade and the design top of levee grade is based on the amount of settlement that is expected to occur after construction and the tolerance (i.e., variation of elevation) allowed during construction. Thus, settlement and construction tolerance are important considerations for determining the top of levee grade to be shown on construction plans to ensure the desired design top of levee grade is achieved.

Settlement can occur due to consolidation of soils both within the levee embankment and its foundation when constructing a new levee or modifying and/or raising an existing levee. It is important to account for this settlement to ensure the constructed top of levee does not settle below the final top of levee grade. The construction top of levee grade shown in Figure 6-22 includes the expected settlement. Refer to **Chapter 7** for approaches to determine settlement and methods for settlement control.

Levee construction work typically has tolerances to allow for inherent variances in construction materials and workmanship skills. The inclusion of tolerances are an integral part of quality designs and determining the construction top of levee grade. Tolerance in construction is a permissible deviation from a dimension, construction limit, or physical characteristic of a material. Permissible construction tolerances should be carefully considered and specified in the construction documents. Construction tolerances above the top of levee grade (plus tolerances) are typically in the range of 0.10 foot, but a higher amount of plus tolerance may be used with careful consideration of the impacts. Construction tolerances below the construction top of levee grade (minus tolerances) should not be allowed.

The top of levee grade should also account for post-construction settlement in establishing construction top of levee grade. As discussed in section 6.1, the levee should be over-built, to account for the expected settlement.

6.3 Levee Alignment

When setting a levee alignment, several factors should be considered, which could include but not be limited to:

- Alignment of existing levees
- Underlying soil conditions
- Geomorphological processes
- Potential hydraulic impacts
- Environmental benefits
- Habitat

- Accommodation of interior drainage
- Proximity of existing high ground
- Existing and future land use
- Location and use of designed overtopping locations and temporary flood storage areas
- Location of existing and/or planned utilities
- Existing vegetation

As discussed in section 4.5.2, right-of-way constraints may limit alternatives for setting the levee alignment. Right of way obtained for the levee should include adequate room for maintenance, inspection, performing flood inspections, and floodfighting.

Geotechnical analyses will be required to understand subsurface ground conditions and how they may impact levee performance with the proposed alignment. In initial stages of plan formulation, all existing geotechnical data should be collected and used to evaluate and compare the conceptual levee alignments for the range of alternatives. As the project moves into the feasibility stage, limited on-site field investigation may be required to collect site-specific information for one or more preferred alternatives. Geotechnical exploration at this stage might include standard penetration testing or cone penetration testing to identify soils and provide a rough estimate of soil strength. During final design, a rigorous program of site investigation will be required to characterize the levee foundation soils. Additional information on subsurface investigations can be found in section 6.3.4 and Engineering Manual (EM) 1110-2-1913 (USACE, 2000a).

When considering new or modified levee projects, opportunities for levee setback should be included. Setting back a levee from the main channel can mitigate impacts to channel flow capacity, potentially preventing or minimizing the transference of flood risks to areas outside of the leveed area. Setting back levees also offers the potential for environmental benefits by preserving existing floodplains or reconnecting the floodplain to areas that have been cut off (**Chapter 11**).

The presence of utilities may dictate the alignment of a levee. Before proposing a levee alignment, be sure to check with the local utility department to locate all existing and planned utilities. In some cases, it will not be possible to avoid all existing utilities and they will have to be relocated. Utility relocation can add significant costs to a levee project.

The alignment of the levee can also be designed to create areas for the storage of interior drainage during times when gravity pipes through the levee are closed. The amount of storage required will depend upon the level of risk reduction desired from interior drainage flooding and whether a pump station will be constructed as part of the levee system.

6.3.1 Temporary Flood Protection

Ideally, levee work should not be scheduled during known flood prone seasons. Furthermore, there may be levee reaches where temporary flood protection is not practical, in which case specifications should limit construction to outside of the flood season. However, if work has to be scheduled during flood prone seasons, flooding should be minimized and limited to the extent possible by temporary flood protection measures.

The alignment of the temporary flood protection should be determined during the formulation process and be arranged such that when operating, the resulting river levels are no higher than they would have been prior to commencement of construction. The selected height and geometry of the temporary flood protection should take into account the likely severe water level/wave events associated with the period of construction. The selected water levels may be lower than those used for the design of the permanent levee system. In this case, a plan for any necessary emergency raising should also be developed. Because, for any given water level, encounter probabilities will be lower for the relatively short construction period. Encounter probability is the likelihood of the design event being exceeded within the design lifetime.

DESIGN EVENT SEVERITY FOR TEMPORARY FLOOD PROTECTION

It is suggested that the encounter probability of the selected design event for the temporary protection should be of the same order as that for the permanent levee system. Thus, if the permanent levee is designed for a 500-year return period event with a design life of 50 years, it will be appropriate to design the temporary flood protection for a construction period of 3 years for a 30-year event. Encounter probabilities or return periods of design events can be calculated using the simple equations:

Encounter Probability (%) = (1-(1-1/Return Period(year))^Period(year))*100.

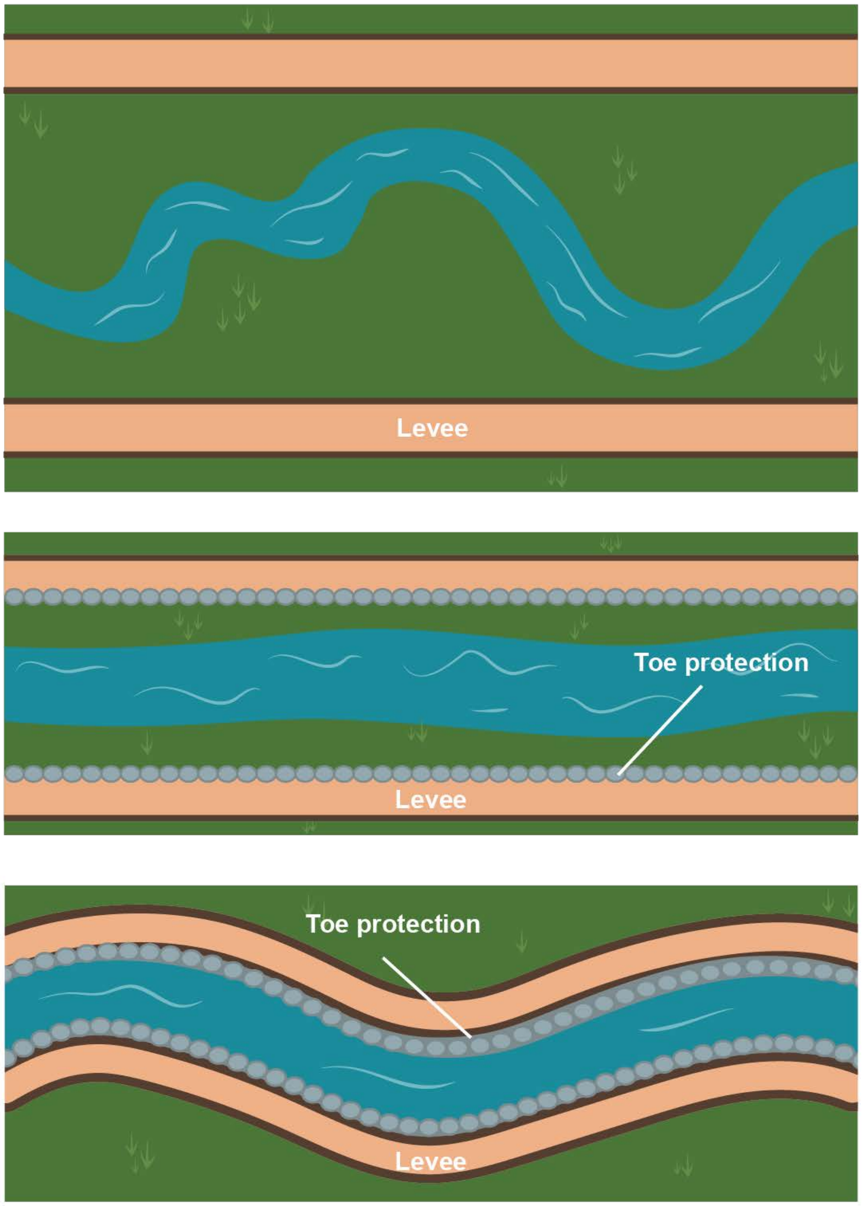
Return Period(year) = 1/(1-(1-Encounter Probability(%)/100))^(1/Period(year)).

The temporary flood protection should also be designed such that levee risk (**Chapter 4**) is not increased during construction.

6.3.2 River Morphology

A river's morphology is the relationship of the stream channel and floodplain to the geology and physiology of the region. Factors that will affect a river's response to its natural environment include sources and supply of sediments, vegetation, previous catastrophic events, earth movements, changes in land use and development, and past human intervention, such as construction of levees, hydraulic structures, or dredging. Methods and data needed to investigate a system's geomorphology include researching aerial photographs, maps, surveys, hydrologic records, soil reports, and consultation with local residents. Understanding historic channel behaviors will inform future morphology. A river's course will likely change over time and will impact levee alignment. Its riverine (fluvial) geomorphologic process—which includes erosion and deposition of sediments—could also influence the need for increasing levee stability and preventative erosion measures. Given a river's geomorphology and anticipated natural progression over the levee lifecycle, variations on levee alignments should be considered as shown in Figure 6-23.

Figure 6-23: Variations in Levee Alignments



a. Wide setback

b. Moderate setback with continuous bank and toe protection

c. Realigned and confined sinuous channel

After project alternatives have been developed, evaluation of potential impacts the project might have on the system should be investigated. Once a system's natural processes have been altered, it is most likely the stream or channel will respond by altering the channel cross section, slope, or planform. A channel's planform describes the channel type as being straight, meandering, or braided. Initial response may only occur mainly within the project reach, but long-term response may affect upstream and downstream reaches.

6.3.2.1 Sedimentation

There is a delicate balance between a basin's runoff, channel velocity and depth, concentration and size of sediment particles moving with flow, the width, depth, slope, hydraulic roughness, planform, and lateral movement of the stream channel. This is a dynamic balance that changes frequently within nature where changes can be exacerbated with human intervention such as a levee project. Sedimentation is not equally likely along the entire project reach. In general, potential for greatest sediment problems is likely at:

- Increased channel width.
- Bridge crossings.
- Abrupt breaks to steeper channel bottom slope.
- Reaches where the channel bottom slope becomes flatter.
- Changes in channel alignment.
- Tributaries entering or water diversions.

Sedimentation studies should be conducted to identify areas of excessive erosion and deposition. Data sources include U.S. Geological Survey, National Weather Service, Natural Resources Conservation Service, Agricultural Stabilization and Conservation Service, and state and local agencies. Levee projects create both sinks and sources for sediment with deposition of sands and gravels or the erosion of sands and silts. Consideration of a movable bed and the sediment exchange rate between the water column and bed surface is complex. Methodologies in sediment transport computations and estimates are provided in EM 1110-2-1416 (USACE, 1993) and EM 1110-2-1418 (USACE, 1994a). Computer programs such as those provided by USACE Hydrologic Engineering Centers include tools that provide one- and two-dimensional sediment transport, as well as mud and debris flow capabilities.

6.3.2.2 Erosion

The potential for erosion must be evaluated and addressed in plan formulation and design, as it is one of the principal causes of levee damage and can lead to both overtopping and prior-to-overtopping failures, as described in EM 1110-2-1913 (USACE, 2000a). Loadings due to stream velocity and/or wind-wave action produce hydraulic shear stresses that can act on an embankment slope and potentially compromise the levee cross section. The degree of erosion will depend on the hydraulic loading, duration of loading, topography and bathymetry, soil characteristics, vegetation, and armoring (if any). Erosion is increased by a number of factors that might include:

- Compromised levee prism geometry.
- Geomorphologic trends as indicated by channel migration and historical damage.
- Streamflow velocity, depth, duration, and shear.
- Wind-wave shear stress.
- Levees, stream banks, or berms constructed of erodible materials.
- Detrimental hydraulic anomalies, such as encroachments.
- Absence of beneficial vegetation or other slope protection (described in Appendix D of the Central Valley Flood Protection Plan: Conservation Strategy) (California DWR, 2017).

Velocity and shear stress computations for assessment of erosion potential can be found in EM 1110-2-1913 (USACE, 2000a) and EM 1110-2-1601(USACE, 1994b). EM 1110-2-1416 (USACE, 1993) and EM 1110-2-1418 (USACE, 1994a) provide guidance on hydraulic considerations for scour and deposition and evaluation of channel and project stability, respectively.

6.3.3 Coastal Morphology

Coastal morphology is the study of the morphological development and evolution of the coast as it is modified by the influence of winds, waves, currents, and sea level changes. The alignment of coastal levees should ideally be set back in such a way as to limit their impact on coastal change. Setting levees back from the immediate coast can also allow space for wave energy to be absorbed by intermediate beach systems, salt marsh and mangrove areas, with the result that levee heights can be reduced.

Levees built too close to the coast may lead to coastal erosion in two particular locations:

- In areas in front of the levee in locations where the mean sea level is rising. Levees in such locations can cause the active coast (including any mangrove or marsh areas) to be subject to 'coastal squeeze' (Figure 6-24) and limit the natural sedimentation that would compensate for rising sea levels.
- In areas downdrift from the leveed area due to wave-driven transport of sediment along the shore. The levee traps sediment updrift and thus causes shore erosion on the downdrift side (Figure 6-25). Continued shoreline erosion may undermine the levee and cause damage to land or property along the shore. Coastal erosion may also arise in the future as the distance between the levee and the shoreline reduces due to sea level rise.

EM 1110-2-1100 (USACE, 2002) provides details of approaches to assessment of coastal sedimentation and erosion.

Figure 6-24: Impact of Levees on Coastal Sediment Movement

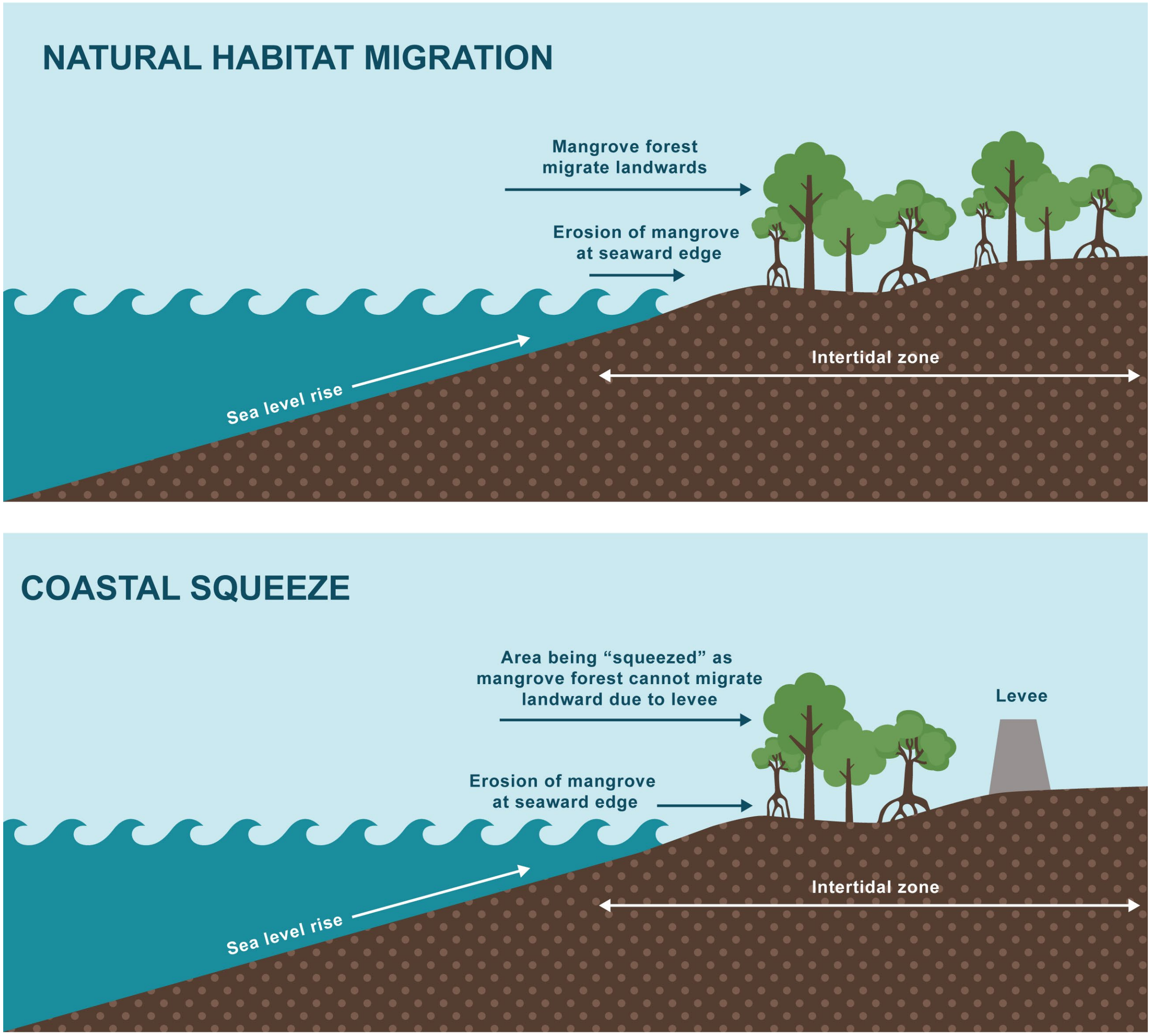
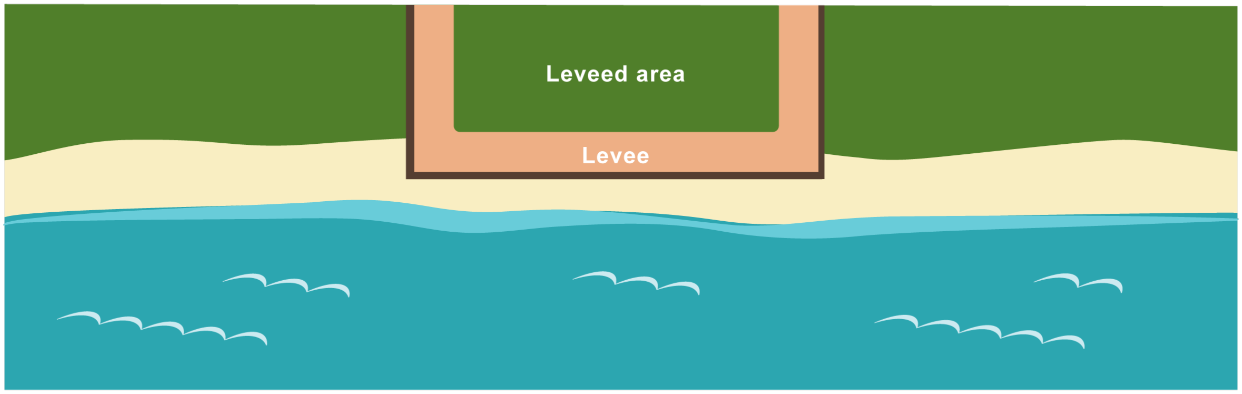
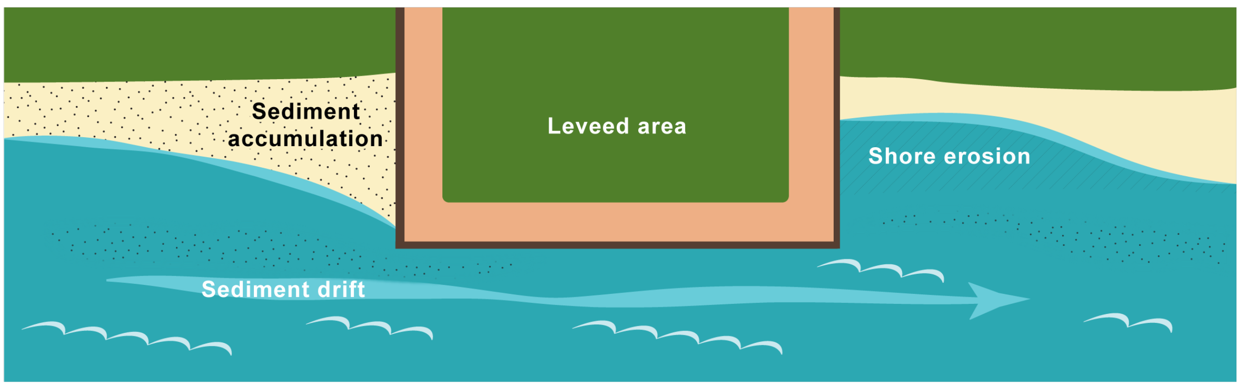


Figure 6-25: Example of Wave-Driven Sediment Transport



Alignment 1



Alignment 2

6.3.4 Site Investigations

Site investigation is discussed in detail in the site characterization part of **Chapter 7**. Results are used to inform the planning, design, and construction of the levee. Investigation can be costly and time-consuming and should therefore be carefully planned to optimize the information obtained. The purposes of the geologic and site investigations for setting the levee alignment and top of levee elevation should include:

- Characterizing existing levee features, including embankments and berms.
- Obtaining geological and geotechnical data to develop design analyses parameters.
- Characterizing foundation conditions to help evaluate alternate levee alignments and to assess settlement (see below) when determining levee height.
- Developing reach and sub-reach boundaries.

The planning of site investigation should be informed by prior risk assessment. Areas of higher risk will likely need a higher intensity of geotechnical exploration, characterization, and analyses. In addition, the focus on analysis of probable failure modes will dictate exploration locations and depths.

Table 6-10 summarizes goals and the extent of site investigations in different phases of planning and design. The data required for each design phase will vary and be progressively more intense. Site investigation should be performed in phases for larger and more complex projects. This phasing will allow review of information obtained to inform further investigations, as well as allow more targeted investigation for specific design features as the design progresses.

Table 6-10: Site Investigation at Various Project Phases

Project Phase	Investigation Goals	Intensity of Investigation
Problem identification	• Existing conditions characterization	• Low: widely spaced explorations, may rely on geomorphologic and geologic mapping or historical reports.
Conceptual	• Inform planning level design; identify constraints	• Low: confirm expected geologic conditions and investigate potentially problematic geologic conditions.
Feasibility	• Inform feasibility analyses; identify fatal flaws	• Moderate: sufficient explorations to identify any fatal flaws and support feasibility of alternatives and establish comparative costs.
Final design	• Inform final design analyses	• High: sufficient characterization for detailed design.
Construction	• Confirm design assumptions	• As required to verify design assumptions.

Geotechnical considerations will vary depending on the type of levee project, as shown in Table 6-11.

Table 6-11: Geotechnical Considerations

Project Type	Consideration
New	• Heterogeneity and/or variability in geotechnical properties over varying distances could complicate soil characterization. • Presence of contaminants could be mobilized during ground disturbance. • Identification of usable borrow material. • Identification of areas where a groundwater cut-off is required to limit seepage during a flood can disrupt the natural groundwater flow. This could elevate the groundwater level and mobilize contaminants.
Modification	• Thorough understanding of internal structure and soil properties of the existing levee is required. • The existing levee may have a complex internal structure due to successive phases of historical raising or repair.

6.4 Levee Footprint and Features

The size of the levee footprint is determined by both physical constraints like available land on which to construct the levee and on levee performance considerations.

Understanding the space available for levee construction is critical in formulation of the project. Information on parcel boundaries, access corridor, and easement information should be collected and thoroughly understood. Limited space may result in designing a levee with steeper side slopes or a narrower crown. Levee performance factors such as slope stability, erosion, and seepage will determine if these adjustments to the levee design are feasible. In general, floodwalls are used when there is insufficient land to construct the required levee footprint.

For levees where performance considerations are not controlling factors, the selection of levee crown width and side slopes is controlled by many aspects such as type and ease of construction and safe access for maintenance. The inclusion of features to obtain co-benefits, such as walking paths or planting berms, may also impact the levee footprint.

Features included in a levee design also depend upon both performance and practical factors, as well as matters concerning the management of interior drainage. Foundation conditions may require stability berms or seepage control systems be included in the levee design. Hydraulic conditions may require erosion protection. Access requirements may require the inclusion of closure structures and space limitations may require the use of floodwalls instead of embankments.

Allowing vegetation, such as trees and shrubs, on levees has been long debated as they lead to uncertainties and can impact levee performance and access. Tree roots can create shortened and preferential seepage paths that may lead to levee failure. In stormy and windy weather, trees may blow over and create a hole in the levee, which could lead to significant erosion. Dense vegetation may also reduce visibility to the underlying levee, making inspections and floodfighting more challenging. Significant advances have been made over the past few decades in understanding how vegetation may not only impede but could also improve levee performance. Vegetation on levees can provide a benefit by enhancing ecosystem habitat and may actually increase levee performance by reducing soil erodibility and can stabilize riverbanks or slopes.

Levee construction can cut off natural flow patterns, preventing rainfall and other interior waters from flowing via natural drainage paths to the flood source. This interior water must be managed during floods, and either stored in dedicated ponding areas within the leveed area or evacuated from the leveed area via pump stations. During times when the levee is not loaded, gravity pipes through the levee may allow rain and other interior water to flow naturally to the flood source. These and other features that may be included in levee design are discussed further in **Chapters 2 and 7** and include:

- Embankment
- Floodwall
- Closure structure
- Seepage control systems
- Erosion protection

- Stability berms
- Pump stations
- Gravity pipes
- Instrumentation
- Natural and nature-based features

6.4.1 Hydraulic Evaluations

As discussed in sections 6.1.2 and 6.1.3, hydraulic modeling estimates the storm surge and wave heights that are used to determine the base levee height. One of the factors that influence wave heights is levee geometry. Flatter, longer slopes and/or the inclusion of berms to attenuate waves can decrease wave height. An iterative process of hydraulic modeling can be used to strike a balance between increasing the levee footprint and/or increasing the levee height to account for wave height.

6.4.2 Site Investigations

Seepage and slope stability performance of a proposed levee must be evaluated and addressed during plan formulation and design since both are common failure modes that can lead to levee breach. Geotechnical factors associated with these failure modes often determine the required size of the levee footprint, the shape of the levee cross section, and/or the necessary levee features. The potential for slope stability failures and detrimental seepage can both be ameliorated through flattening levee slopes or the incorporation of features such as relief wells, seepage/stability berms, or cutoff walls into the levee design. Slope stability and seepage performance must be evaluated and addressed during plan formulation as the slope adjustments and/or features required to address these failure modes can add significant cost and right-of-way requirements to the levee project. Computations to assess seepage and slope stability conditions can be found in EM 1110-2-1913 (USACE, 2000a).

6.4.3 Considerations for Vegetation on or Near Levees

It is important to understand expectations for vegetation management on or near the levee system during planning and into design and construction. Inclusion of vegetation into a levee design may be driven by a number of reasons including, but not limited to:

- Creation of habitat or improvement of habitat for special status species.
- Providing on-site mitigation for project impacts.
- Providing shading to reduce water temperatures.
- Providing shading to enhance recreational trails or areas adjacent to the levee.
- General environmental enhancement for aesthetic purposes.
- Improvement of water quality.
- Tribal cultural reasons.

- Engineering with nature-utilizing plantings to meet engineering objectives such as erosion resistance.

Meeting these needs early in the planning and design phases can greatly reduce issues later in the process. The ideal planting plan uses native species and optimizes access for floodfighting and maintenance for levees. Planning for the maintenance of the levee crown and landside slope should be accomplished to help ensure full access and visibility. Specific analysis would be required if there is a desire to have vegetation other than herbaceous plantings on the waterside of the levee. Consideration should be given to the habitat needs of target species, the hydrology and hydraulic forces that will be present in the floodplain, and any ancillary benefits (such as recreational benefits) that would likely be achieved. Designs should focus on the reestablishment of process (e.g., channel migration or point bar formation). There should be an understanding and acceptance that the area will and should change over time, as natural floodplains are dynamic. However, as proximity to the levee increases, planting plans should give increasingly greater priority to the stability and longevity of the levee structure. Plants which can reduce the overall maintenance burden for the levee, such as by reducing erosion, should be prioritized.

Since there are several hundred species of trees, and several thousand species of shrubs and other plants in the U.S., it is more practical to consider which species' characteristics are ideal for various planting zones around levees or for different levee reaches, rather than identifying specific species. Consideration of species characteristics should always begin with management objectives. Some management objectives to consider and how certain types of vegetation could affect those objectives include the following:

- What type of access is needed? Heavy equipment? Trucks? Pedestrian access?
- How often will the waterside operations and maintenance corridor need to be accessed?
- How will the waterside slope of the levee be inspected? By vehicle? Helicopter? Boat? Remote sensing? Drone?
- What is the maintenance budget and who conducts the maintenance?
- What types of burrowing animals are present in this area? Can the planting plan be optimized to discourage these animals?
- Are there other incidental uses that might drive vegetation selection choices?

6.5 Nonstructural Actions

Even though implementation of a levee project can reduce flood risk to a community, some level of uncertainty and residual risk remains. Nonstructural actions—including flood warning systems, evacuation planning, and community engagement—are necessary to manage levee risk once the levee is in place. The goal of nonstructural actions is to minimize this residual risk. As discussed in **Chapter 12**, increasing a community's awareness through education of the risks and benefits of a levee project, is a step toward preparedness before, during, and after a flood event. With increased awareness, individuals and communities can take action to reduce exposure and vulnerability of property to flood risk.

7 Plan Implementation

A major component of levee project formulation is developing a process for plan implementation. A levee project plan could have all the flood risk reduction potential to meet the identified objectives, but if it is not implementable by the community, it cannot progress to design and construction.

The division of roles and responsibilities with expectations for O&M, cost sharing, funding, permitting, planning, design, and construction schedules must be made clear for all invested parties. While much effort, as described in this chapter, is required to formulate a levee project, additional coordination and cooperation with the project team is needed to move beyond formulation of the plan.

As mentioned in section 5, the interaction between formulation, design, and construction is often iterative. Collaboration amongst the multi-disciplinary team is needed for successful plan implementation to foster smooth transitions between project phases. While a benefit-cost analysis to ensure the project is justified economically is a step toward reaching construction, it is vitally important to validate that the project is financially feasible. Additionally, a funding strategy should be established that includes means for covering construction costs and long-term O&M funding to ensure the project is completed and maintained such that the project reaches its intended design life, and beyond. Without long-term O&M funding, levee risk increases greatly over time. Note that once a levee plan is implemented, it should be revisited as conditions change, such as climate, development, updated floodplain information, floodplain management plans, or environmental regulations.

8 Summary

Once a community has established that their flood risk management strategy will include a levee, the generalized six-step planning process as described in section 3 should be used to arrive at the best alternative solution. Principles of levee formulation should include:

- Hold life safety paramount.
- Do no harm.
- Enhance natural resources.
- Make risk-informed decisions.
- Reflect community values, goals, priorities, and risk tolerance.
- Align with management of the floodplain.

Several best practices and considerations should be used by the plan formulation team not only in planning, but carried through to design and construction. Analyses of the study area is needed to formulate levee characteristics, which include engineering analyses, risk assessments, economic analyses, and environmental evaluations.

The goal of planning is to identify a cost-effective, technically feasible, and socially and environmentally responsible solution that meets project objectives. The levee plan formulation process should produce properly designed levee features intended to provide a certain level of flood risk reduction benefits to a community. The outcome of levee plan formulation passed on to the design team will be:

- Levee height
- Levee alignment
- Levee footprint and features
- Nonstructural measures

As conceptual ideas are refined and more is known about the study area, the level of effort for levee design increases and plan formulation decreases.

Having an implementation plan is critical to a project's success. The implementation plan should include how the plan will transition from formulation to design and construction, funding, real estate requirements, O&M needs, considerations for changes over time, and adaptive management options, at a minimum.

Related content associated with this chapter is included in detail in other chapters of the National Levee Safety Guidelines as described in Table 6-12.

Table 6-12: Related Content

Chapter	Chapter Title	Related Content
1	Managing Flood Risk	• Flood risk management strategies
2	Understanding Levee Fundamentals	• Types of levee projects
3	Engaging Communities	• Engaging about levee projects
4	Estimating Levee Risk	• Identifying flood risk • Vulnerability
5	Managing Levee Risk	• Risk-informed decision making • Levee risk management
6	Formulating a Levee Project	
7	Designing a Levee	• Levee design considerations
8	Constructing a Levee	• Construction considerations • Construction documentation
9	Operating and Maintaining a Levee	• Operating and maintaining a levee
10	Managing Levee Emergencies	
11	Reconnecting the Floodplain	• Planning for levee removal
12	Enhancing Community Resilience	• Incorporating community resilience

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7

Designing a Levee

Key Messages

This chapter will enable the reader to:

- **Understand the best and evolving practices.** Design practices for levees continue to evolve based on a better understanding of levee performance.
- **Scale the design to the problem.** The level of investigation and study should be risk-informed and scaled to the size and nature of the work.
- **Adapt to specific design features.** Each levee feature requires specific design considerations appropriate to its function, form, and failure modes.
- **Incorporate resilience features.** Add features that absorb adverse loadings without breaching, facilitate rapid recovery, and provide the potential for strengthening and adapting to changing hazards and consequences.


LEVEETOWN, USA

Other chapters within the National Levee Safety Guidelines contain more detailed information on certain topics that have an impact on designing a levee, as shown in Figure 7-1. Elements of those chapters were considered and referenced in the development of this chapter and should be referred to for additional content.

Figure 7-1: Related Chapter Content

CH 1	CH 2	CH 3	CH 4
Levee form and function Types of levee projects	Levee features	Engaging for levee projects	Flood and levee risk Risk assessment
CH 5	**CH 6**	**CH 7**	**CH 8**
	Levee alignment Crown elevation and geometry	**Designing a Levee**	Instrumentation Construction and utility considerations
CH 9	**CH 10**	**CH 11**	**CH 12**
Instrumentation and monitoring			Community resilience

Contents

1 Introduction 7-1
2 Design Process, Principles, and Considerations 7-1
2.1 Design Process 7-1
2.1.1 Conceptual Design Phase 7-3
2.1.2 Feasibility Design Phase 7-5
2.1.3 Final Design Phase 7-7
2.1.4 Design Products 7-9
2.1.5 Construction Process Support 7-11
2.2 Principles 7-14
2.2.1 Design Criteria 7-14
2.2.2 Risk-Informed and Scalable 7-15
2.2.3 Resilience 7-16
2.2.4 Quality Control 7-17
2.3 Considerations 7-19
2.3.1 Selecting a Levee Designer 7-19
2.3.2 Cost Estimating 7-20
2.3.3 Easements and Permits 7-23
2.3.4 Project Implementation Scheduling 7-24
2.3.5 Vegetation 7-24
2.3.6 Encroachments and Penetrations 7-26
2.3.7 Challenges 7-26
2.3.8 Levee Feature Modifications or Rehabilitation 7-27
3 Site Characterization 7-29
3.1 Gathering and Reviewing Existing Information 7-29
3.1.1 Information Gathering 7-29
3.1.2 Data Storage 7-30
3.2 Additional Investigations 7-30
3.2.1 Data Gap Analysis 7-32
3.2.2 Topography and Bathymetry 7-33
3.2.3 Geotechnical and Geomorphic 7-33
3.2.4 Hazardous Materials 7-37
3.2.5 Utilities 7-38
3.2.6 Sources of Construction Material 7-39
3.3 Analysis and Interpretation 7-40
3.3.1 Geometry 7-40

3.3.2 Water Level and Wave Conditions 7-40
3.3.3 Interior Drainage Requirements 7-40
3.3.4 Geologic and Geomorphic Environment 7-40
3.3.5 Geotechnical Design Parameters 7-41
3.3.6 Selection of Levee Reaches for Analysis 7-42
4 Levee Features 7-42
5 Embankment 7-44
5.1 Elements 7-44
5.1.1 Geometry 7-44
5.1.2 Inspection Trench 7-45
5.1.3 Materials 7-46
5.1.4 Common Required Analyses for Embankment Levees 7-48
5.2 Stability Control 7-49
5.2.1 Loading Conditions 7-51
5.2.2 Shear Strength Selection 7-52
5.2.3 Stability Analyses 7-53
5.3 Erosion Control Features 7-55
5.3.1 Erosion Analysis 7-57
5.4 Settlement Control 7-57
5.4.1 Settlement Analysis 7-58
5.5 Modification and Rehabilitation 7-58
5.5.1 Seepage and Stability 7-58
5.5.2 Levee Crest Elevation Raise 7-58
5.6 Seismic Considerations 7-60
6 Floodwalls 7-61
6.1 Reinforced Concrete Floodwalls 7-61
6.1.1 Geotechnical Design 7-62
6.1.2 Overtopping Resilience Design 7-64
6.1.3 Structural Design 7-65
6.2 Steel Sheetpile Floodwalls 7-67
6.2.1 Design Procedures 7-68
6.2.2 Potential Failure Modes 7-68
6.2.3 Loads 7-69
6.2.4 Methods of Analysis 7-69
6.2.5 Overtopping Resilience 7-70
6.3 Mass Concrete Gravity Walls 7-70

6.3.1 Design Procedures 7-71
6.3.2 Toe Protection 7-71
6.3.3 Controlling Runoff and Overtopping Resilience 7-71
6.4 Demountable Floodwalls 7-71
6.4.1 Design 7-73
6.4.2 Other Considerations 7-74
7 Closure Structures 7-74
7.1 Selection of Type of Closure Structure 7-75
7.2 Closures Across Transportation Corridors 7-77
7.2.1 Vehicular Closures 7-78
7.2.2 Railroad Closures 7-78
7.2.3 Waterway Closures 7-78
7.2.4 Pedestrian Closures 7-79
8 Transitions 7-79
8.1 Design Principles for Transitions 7-80
8.2 Dealing with Specific Mechanisms 7-81
8.2.1 Embankment Slope Erosion 7-81
8.2.2 Cracking and Hydraulic Separation Leading to Seepage and Internal Erosion 7-82
8.2.3 Differential Settlement 7-82
9 Seepage Control Features 7-83
9.1 Seepage Analysis 7-83
9.1.1 Potential Failure Modes 7-83
9.1.2 Analyses Approach 7-85
9.1.3 Design Criteria 7-85
9.2 Seepage Cutoff Walls 7-86
9.2.1 Alignment and Other Design Considerations 7-86
9.2.2 Depth 7-88
9.2.3 Composition 7-88
9.2.4 Advantages and Disadvantages 7-88
9.3 Seepage Berm 7-89
9.3.1 Drainage Layers 7-90
9.3.2 Width 7-90
9.3.3 Height 7-91
9.3.4 Composition 7-91
9.3.5 Advantages and Disadvantages 7-91
9.4 Landside Pressure Relief Systems 7-92

9.4.1 Alignment 7-93
9.4.2 Spacing 7-94
9.4.3 Depth 7-94
9.4.4 Capacity and Materials 7-94
9.4.5 Advantages and Disadvantages 7-94
10 Controlled Overtopping, Channels, and Floodways 7-95
10.1 Locations of Controlled Overtopping 7-95
10.2 Channels and Floodways 7-96
11 Interior Drainage Systems 7-97
11.1 Pipes 7-98
11.1.1 Pipe Material 7-101
11.1.2 Pipe Design 7-101
11.2 Ancillary Components 7-102
11.2.1 Gatewells 7-103
11.2.2 Valve Vaults 7-105
11.2.3 Headwalls and Gates 7-105
12 Pump Stations 7-106
12.1 Design 7-108
12.1.1 Hydrologic Studies 7-108
12.1.2 Pump Station Type 7-108
12.1.3 Sump Pit and Adjacent Levee Design 7-108
12.1.4 Pump and Motor Selection 7-108
12.1.5 Pump Controls 7-109
12.1.6 Forebay and Sump Sizing 7-109
12.1.7 Pipes 7-109
12.1.8 Trash Racks 7-110
12.1.9 Spare Equipment 7-110
12.2 Power Supply 7-111
12.3 Other Considerations 7-111
13 Instrumentation 7-111
13.1 Instrumentation and Monitoring Plan 7-111
13.2 Instrumentation of Embankments 7-112
13.3 Instrumentation of Floodwalls and Structures 7-113
13.4 Post Construction Monitoring 7-113
13.5 Water Level and Tide Gages 7-113
14 Levee Access 7-113

15 Summary 7-115

List of Figures

Figure 7-1: Related Chapter Content 7-i
Figure 7-2: Interaction Between Formulation, Design, and Construction 7-1
Figure 7-3: Design Process 7-2
Figure 7-4: Process for Conceptual Design 7-3
Figure 7-5: Process for Feasibility Design 7-6
Figure 7-6: Process for Final Design 7-8
Figure 7-7: Support Process for Construction 7-12
Figure 7-8: Examples of Temporary Flood Protection 7-14
Figure 7-9: Example of Quality Control Testing During Construction 7-18
Figure 7-10: Estimate Accuracy Improves with Time 7-23
Figure 7-11: Example Field Investigations 7-32
Figure 7-12: Typical Plan and Profile Sheet with Geomorphology 7-36
Figure 7-13: Example of Utilities in the Project Area 7-38
Figure 7-14: Typical Site Characterization Analysis 7-41
Figure 7-15: Typical Embankment Elements 7-44
Figure 7-16: Example Inspection Trench 7-45
Figure 7-17: Typical Homogenous Embankment Section 7-46
Figure 7-18: Typical Zoned Embankment Section 7-46
Figure 7-19: Typical Coastal Embankment Section 7-48
Figure 7-20: Typical Drained Stability Berm 7-51
Figure 7-21: Typical Combination Berm 7-51
Figure 7-22: Typical Slope Stability Analysis 7-54
Figure 7-23: Typical Erosion Repair 7-56
Figure 7-24: Typical Embankment Raise 7-59
Figure 7-25: Example Floodwall 7-62
Figure 7-26: Floodwall Geotechnical Failure Modes 7-63
Figure 7-27: Example Combined Sheetpile Floodwall System 7-68
Figure 7-28: Sheetpile Wall Failure Modes 7-69
Figure 7-29: Typical Mass Gravity Wall 7-70
Figure 7-30: Example of Demountable Floodwall 7-72
Figure 7-31: Typical Demountable Barrier Cross Section 7-73
Figure 7-32: Example Closure Types 7-75
Figure 7-33: Examples of Transition Locations 7-80
Figure 7-34: Blanket Conditions 7-84
Figure 7-35: Typical Seepage Cutoff Wall—New Embankment 7-87
Figure 7-36: Typical Seepage Cutoff Wall—Existing Levee 7-87

Figure 7-37: Typical Seepage Berm 7-89
Figure 7-38: Throughseepage Pressure Relief Systems 7-93
Figure 7-39: Underseepage Pressure Relief Systems 7-93
Figure 7-40: Typical Drainage Pipe Penetration—Embankment Levee 7-99
Figure 7-41: Interior Pump Station Pipe Penetrations 7-100
Figure 7-42: Detail of Pipe Passing Through Floodwall 7-100
Figure 7-43: Example Gatewell with Sluice Gate and Operating Shaft 7-104
Figure 7-44: Example Headwalls with Flap Gates 7-105
Figure 7-45: Discharge Cone or Bell for a Pump Station 7-110
Figure 7-46: Information to Include in a Monitoring Plan 7-112
Figure 7-47: Example Access Roadway 7-114

List of Tables

Table 7-1: Final Design Products 7-9
Table 7-2: Typical Accuracy Ranges for Construction Cost Estimates 7-22
Table 7-3: Main Challenges of Levee Design 7-26
Table 7-4: Geotechnical Borings Considerations 7-34
Table 7-5: Investigation at Various Project Phases 7-35
Table 7-6: Levee Feature Design Requirements 7-43
Table 7-7: Stability Feature Design Requirements 7-49
Table 7-8: Stability Berm Elements 7-50
Table 7-9: Erosion Control Feature Design Requirements 7-56
Table 7-10: Settlement Design Procedures 7-57
Table 7-11: Floodwall Design Elements 7-62
Table 7-12: Load Condition Categories 7-66
Table 7-13: Advantages and Disadvantages of Demountable Barriers 7-72
Table 7-14: Recommended Closure Types for Different Design Scenarios 7-77
Table 7-15: Seepage Cutoff Wall Design Elements 7-86
Table 7-16: Seepage Berm Feature Design Requirements 7-90
Table 7-17: Landside Pressure Relief System Feature Design Requirements 7-93
Table 7-18: References for Design of Mechanical Components 7-103
Table 7-19: References to Design of Pump Station Components 7-107
Table 7-20: Related Content 7-116

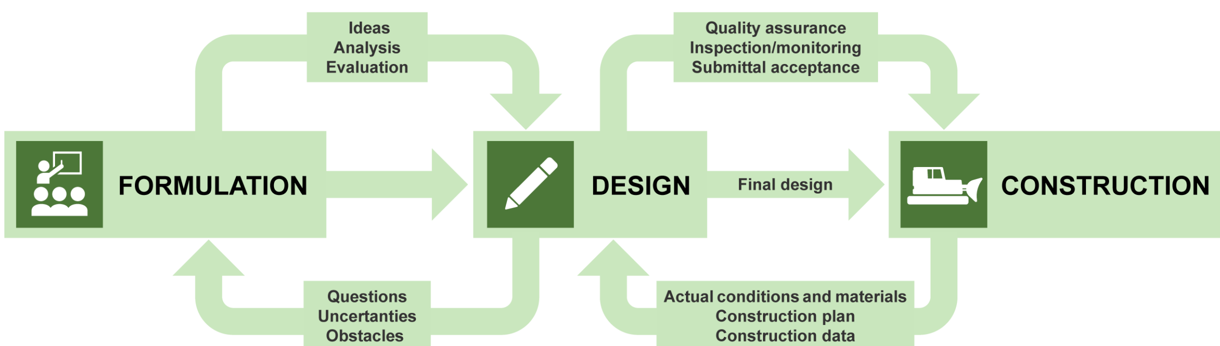
1 Introduction

The purpose of this chapter is to present best practices, criteria, and design principles for levee features that reduce risk posed from coastal, riverine, or rainfall flooding. As described in **Chapter 2**, levee features include earthen embankments, floodwalls, seepage control systems, closure structures, transitions between features, interior drainage systems, and instrumentation for construction and post-construction operation and monitoring of the levee. Coordinating design with levee formulation, risk assessment, and construction activities is also addressed.

The guidance in this chapter is provided for use by qualified professional engineers, planners, and floodplain managers working with federal, state, and local regulators; levee owners; and contractors specializing in levee formulation and design.

The guidelines provided in this chapter should be read in conjunction with the those in **Chapters 6 and 8** because the three processes have close connection, as illustrated in Figure 7-2. In addition, the guidelines in this chapter should be applied to conceptual, feasibility, and final design phases of a levee project, whether the project is a new levee or an existing levee requiring modification or rehabilitation.

Figure 7-2: Interaction Between Formulation, Design, and Construction



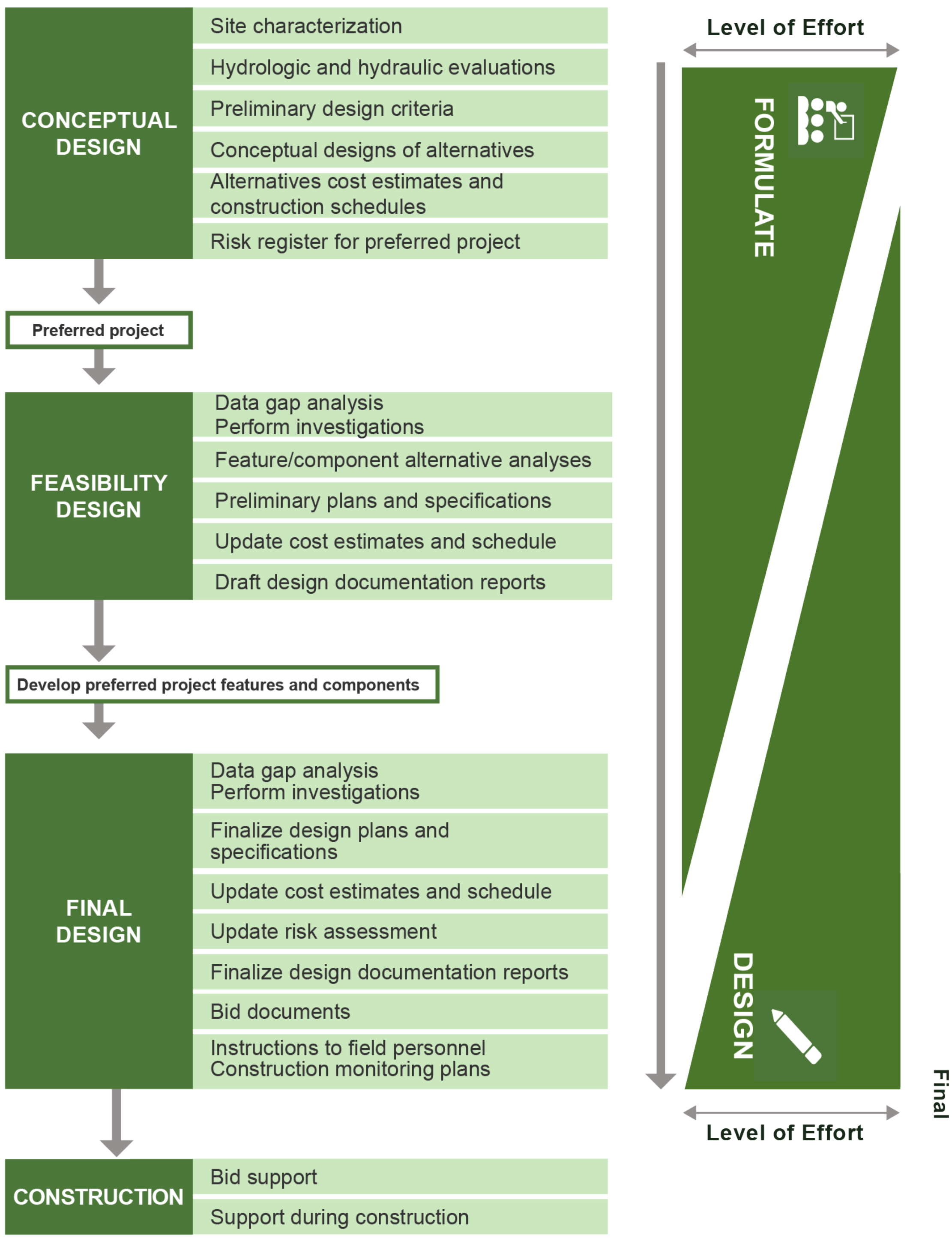
2 Design Process, Principles, and Considerations

2.1 Design Process

Design is an iterative process, involving multiple steps that may be repeated in each phase that progressively increases the level of design detail. Figure 7-3 shows the typical process for general engineering design. Details are provided in subsequent sections of this chapter describing the variations in design practices for levee and floodwall features.

Formulation of a levee project starts with the realization that there is a need for action (**Chapter 6**). From there, an idea or solution is developed. This idea gets expanded and refined throughout the formulation process. As the idea or solution becomes more defined, there is enough information to start the design process. Levee formulation and design evolve in parallel, as shown on the right-hand side of Figure 7-3, and each informs the other during this evolution. Over time, the level of effort for formulation recedes and that of design increases until the final design is reached.

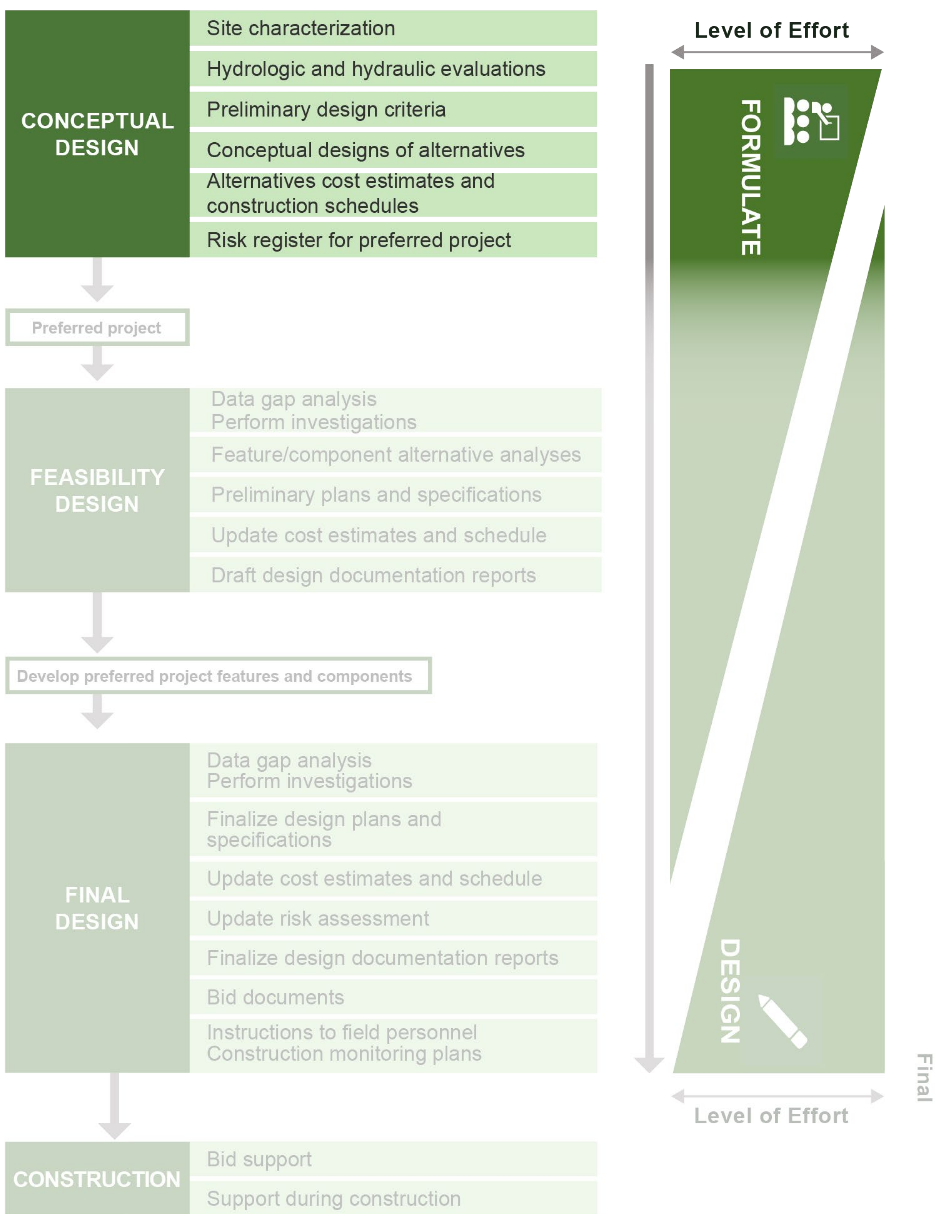
Figure 7-3: Design Process



2.1.1 Conceptual Design Phase

The conceptual design phase supports the project formulation process (**Chapter 6**) in a high-level evaluation of alternatives to identify a preferred project alternative that meets the project objectives (Figure 7-4). Project formulation activities such as potential failure mode analyses, risk assessments (**Chapter 4**), and community engagement (**Chapter 3**) are key sources of information to guide the conceptual design phase especially when evaluating alternatives. The formulation process should inform the design process about important constraints and opportunities for the conceptual designs (e.g., environmental, cultural, and political). Determination of constraints, opportunities and site characterization are particularly important for modification/rehabilitation projects, especially when the projects are in more urban areas where significant development has taken place since the original levees were constructed.

Figure 7-4: Process for Conceptual Design



Conceptual design phase for new levees and levee modification/rehabilitation projects (Figure 7-4) typically include:

- Performing site characterization (data gathering) for topography, geotechnical/geological conditions, existing infrastructure and utilities, and real estate boundaries (section 3). Note the following:
  - After reviewing available data and visiting the alternative levee alignments, the design team may recommend performing some limited site investigations (e.g., topographic mapping, geotechnical investigations, utilities) to better characterize site conditions in critical areas.
  - During the design of a levee modification or rehabilitation, utilities that were installed after construction of the original levee should be characterized and evaluated to establish if they should be remediated or relocated for levee safety or to facilitate construction of the levee. It is not uncommon to include utility modifications or relocations as part of levee modification or rehabilitation projects to reduce or eliminate utility risks to the levee system and to comply with applicable federal, state, and local regulations. Refer to **Chapter 8** for utility considerations for levee construction.
- Completing hydrologic and hydraulic evaluations (including any associated coastal storm surge and/or riverine hydraulic studies), taking into account changing conditions like those associated with climate change. Refer to **Chapter 6** for more information on hydrologic and hydraulic evaluations. When performing these evaluations, the following should be performed:
  - Evaluation results should be combined with other factors (e.g., wave action, potential levee settlement, overbuild, and resilience considerations) to establish the minimum top-of-levee elevations (and cross sections of coastal levees) to meet flood risk management objectives.
  - If managing interior drainage is a significant factor when evaluating alternative design concepts, then interior drainage studies should be considered in this phase.
  - For an existing levee project, current coastal storm surge, riverine flooding, and interior drainage studies may require updating for levee modification and rehabilitation projects, particularly if climate change impacts were not previously considered.
- Developing appropriate design criteria (section 2.2.1) for the conceptual designs.
- Preparing conceptual designs for each alternative project, including levee alignments, top of levee elevations, and associated features to a level of detail sufficient to define the alternative. Guidance on selection of levee alignments, determining design water levels and level crest levels can be found in **Chapter 6**.
- Developing the preliminary cost estimates (section 2.3.2), construction schedules (section 2.3.4), and drafting the risk register for the preferred project. See **Chapter 8** for more information on risk registers.

On completion of the conceptual phase, the preferred project (including features) should be optimized to achieve project goals as part of the project formulation process. A similar process is achieved in the feasibility and final design phases through more in-depth studies, usually after more site characterization data has been collected.

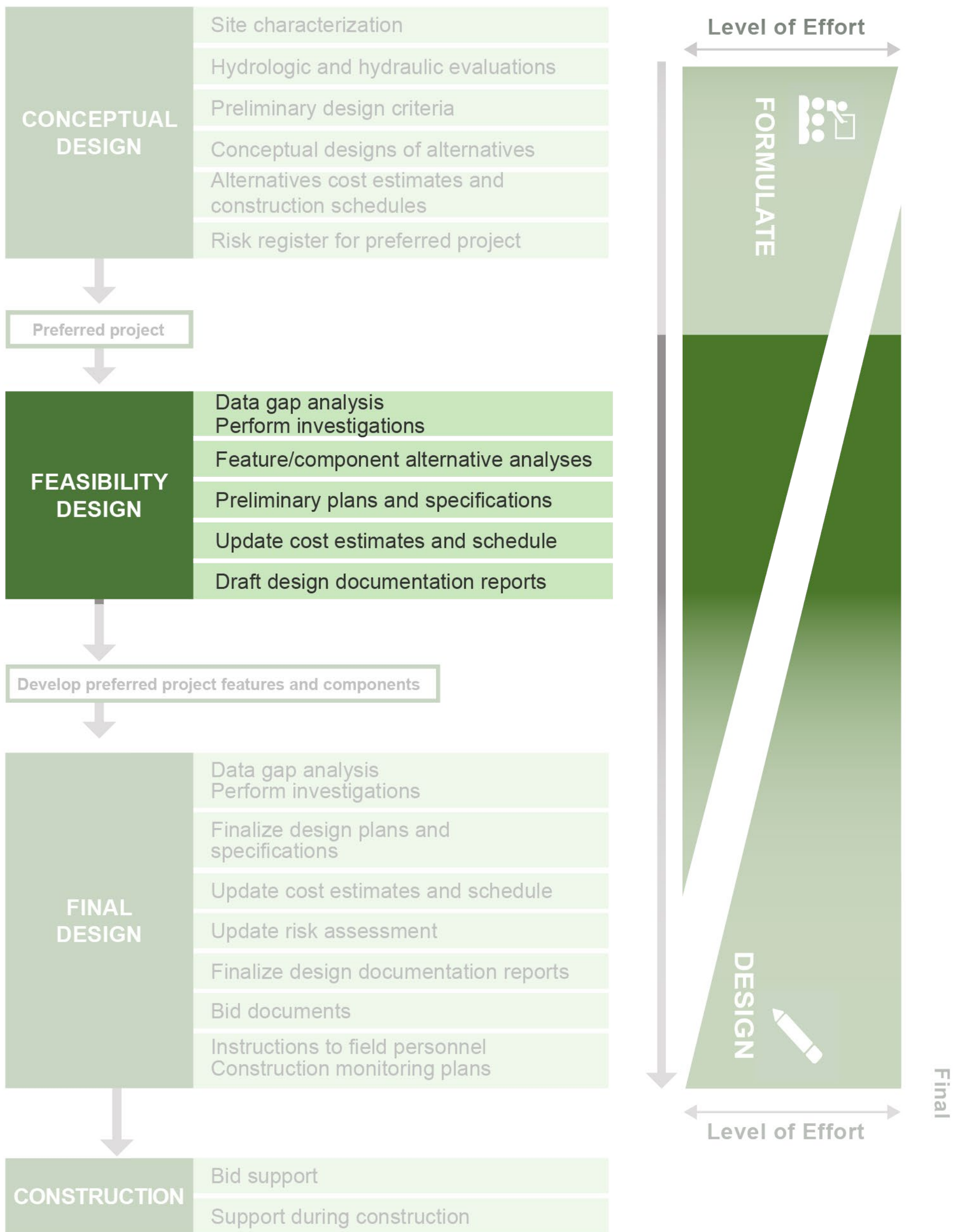
2.1.2 Feasibility Design Phase

The conceptual design of the preferred project is advanced during the feasibility design phase (Figure 7-5).

While the levee crest level and alignment are determined as part of the formulation process, the final crest level and alignment may be adjusted during the feasibility design phase (or even final design phase) to meet the requirements of providing the most viable compromise between economy and minimal environmental and social impacts. In this respect, the iterative process of site characterization (section 3) should identify subsurface conditions that would impede the project such as dense or weak foundation layers.

During the feasibility design phase, alternatives for each feature are compared to determine which best accomplishes the project objectives, considering technical feasibility, cost, risk mitigation, resilience, and other factors. A basis of design report is prepared including a list of any anticipated technical specifications (sometimes even including skeleton specifications for key elements of the levee project).

Figure 7-5: Process for Feasibility Design



Other key activities during this phase are the following:

- **Perform field investigations and site characterizations**. These activities are planned and completed to fill data gaps required to further the analysis and advance the design. These activities may include aerial mapping, site-specific topography and bathymetry, foundation investigation, and utility surveys. A geotechnical data report is prepared.
- **Undergo further refinement of the project's design criteria**. The feasibility design should be risk-informed, scalable, and incorporate resilience where appropriate.

- **Prepare a utility study**. A utility study is prepared to locate all existing utilities in, under, or adjacent to the levee or proposed levee alignment. Utility penetrations may include water mains, sewer mains, agricultural irrigation systems, gas lines, petrochemical lines, and the like. Other utilities may include conduit and duct bank penetrations for electrical and communication lines. The output of the study is a utility and encroachment inventory with planned actions and responsibilities:
  - Utility relocations: It may be necessary to work with utility owners to relocate utilities. It is preferred that utilities run up and over levees and avoid penetrations through levees. Relocation of utilities should start early in the design phase in order to complete relocation work prior to construction, thus avoiding costly delays to the construction of the levee itself. Costs to relocate utilities may have to be included in the project cost estimate. Utilities within or under the levee may require relocation, as well as utilities adjacent to the levee, to provide required clearance for service roads adjacent to the levee toe or for operation and maintenance (O&M).
  - Utility replacements: If relocation is not possible, utilities may require replacement where an analysis and projection of deterioration rates suggest their residual life is less than that of the planned life of the levee, and failure of the utility would present a risk to the levee.
- **Perform ecological assessments**. These assessments of hazardous, toxic, and radioactive waste and draft feasibility design plans may be used to help focus site environmental studies and evaluations in support of federal and state permitting documentation. In turn, the environmental studies may suggest preliminary environmental mitigation measures for incorporation in the design.
- **Update construction cost estimates**. These estimates should be updated at the end of the feasibility design phase, supported by a preliminary construction schedule and a preliminary constructability review.
- **Update the risk register for the preferred project**. The risk register from the formulation study should be reviewed and updated, reflecting any design-related risk reduction measures incorporated into the design, as well as the results of the constructability review.

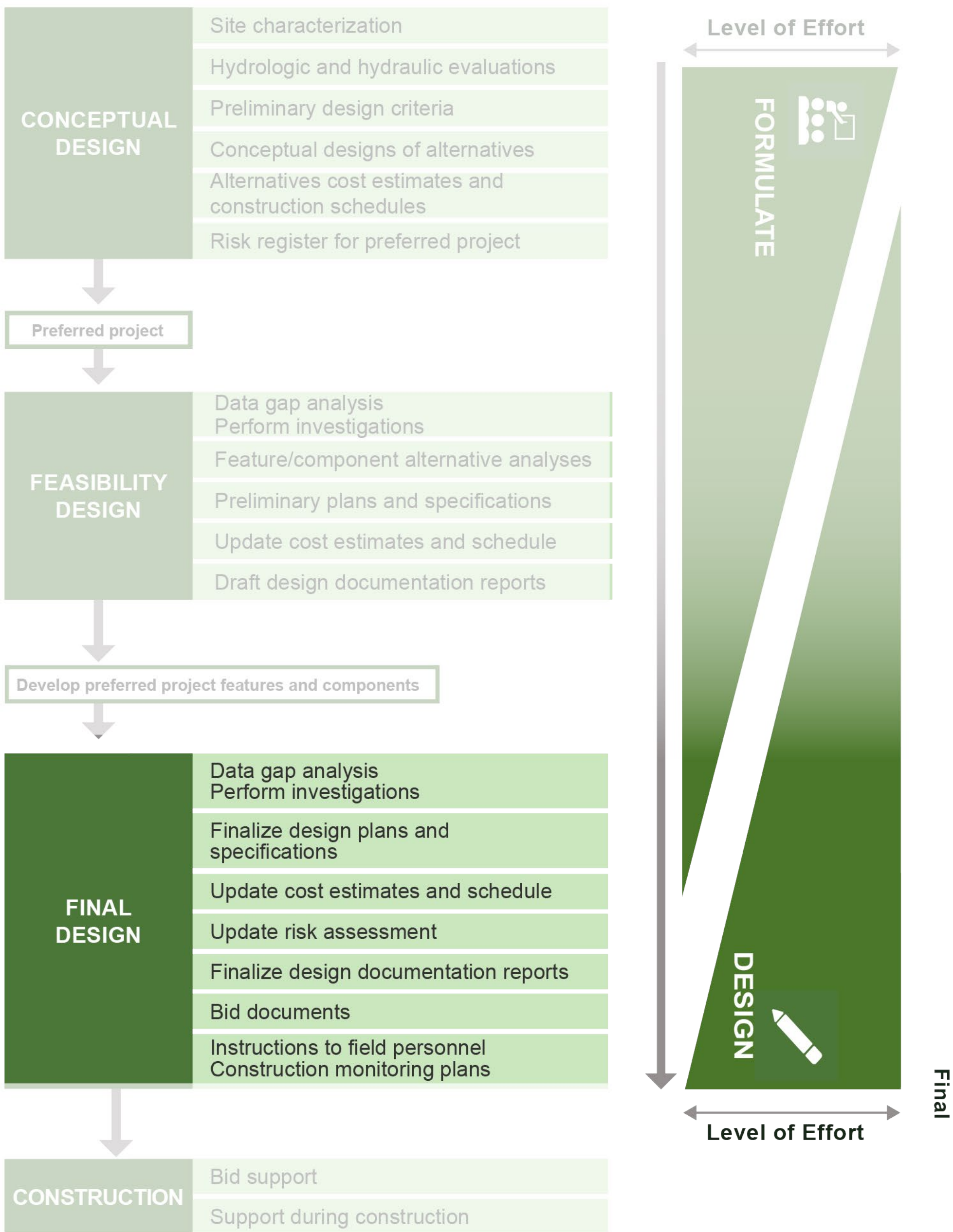
The completion of the feasibility design phase results in a more defined project with project features and components accompanied with draft design documentation reports and updated construction cost estimates and schedules. The cost estimates and schedules are often used for budgeting/funding purposes prior to moving into final design.

2.1.3 Final Design Phase

The final design phase (Figure 7-6) takes the selected project configuration from the feasibility design and develops it further to a bid package, ready-to-advertise for constructor quotes, discussed further in **Chapter 8**.

This phase should include final investigations, analyses, plans and specifications preparation, and preparation of support documents, such as a basis of design report or similar. The phase also should include support of the bid process, such as preparing responses to bidder inquiries, preparing bid addenda documents, and assisting the levee owner with bid evaluations.

Figure 7-6: Process for Final Design



During the final design process, it is best practice to incorporate phased reviews at various levels of design completion. Higher risk levees may need more reviews at different phases for the responsible agencies, levee owners, and stakeholders to review and comment on the progress and quality of the design, as well as verify project goals and objectives are being met. They also provide an opportunity to review project cost and schedule updates and project affordability. Depending on the size of the project and scalability considerations, submittal milestones may include:

- **The 30% design**: Layout plans and details sufficient to define the required features and facilities and their locations, as well as a list of technical specifications and first draft of a geotechnical data report.
- **The 60% design**: More advanced design, including addressing comments on the 30% submittal, draft technical specifications, draft cost estimate, and updated draft geotechnical data report.
- **Draft 100% design**: A substantially complete design with specifications, cost estimate, list of bid items, bid item descriptions, construction schedule for final reviews, and final draft of the geotechnical data report.
- **Ready-to-advertise design package**: Refinement of all project features and assessment of opportunities to optimize design, as well as preparation of construction documents and opinion of probable construction cost.

2.1.4 Design Products

Table 7-1 lists the final design products that generally become part of the contract documents for bidding and those intended to provide an information bridge between designers and the construction personnel administering the contract.

Table 7-1: Final Design Products

Products for Bid Support	Products to Inform Construction Personnel
Final project plans and specifications (sections 2.1.4.1 and 2.1.4.2)	Basis of design report (section 2.1.4.4)
Cost estimate and construction schedule (sections 2.3.2 and 2.3.3)	Designers' instructions for field personnel (section2.1.5.1)
Geotechnical data report (section 2.1.4.3)	Construction instrumentation and monitoring plan (section 13)

2.1.4.1 Project Plans

Project plans, prepared by the designers, are important because they define all of the work to be constructed for a new levee project, or for the modification or rehabilitation of an existing levee. For existing levees, project plans should also include provisions for temporary flood protection measures during construction. The plans should ideally be prepared using computer-aided drafting software. Plan sets are usually submitted to permitting agencies as electronic files or hard copy printed sets. A drafting standard should be established for the project. An example reference for computer-aided drafting standards would be architectural, engineering, and construction computer-aided design standard (USACE, 2019). The plans normally include aspects such as:

- Location information.
  - Project site and feature location plans, and survey control drawings.

    - Real estate information, demolition plans, utility locations, and relocation plans.

- Site characteristics.
    - Geotechnical profiles and cross sections with boring information superimposed.
    - Historic tide gage information and design water surface profiles.
- Details of the levee construction itself.
    - Alignment plans and profiles for the new levee or existing levee to be modified or rehabilitated showing crest and catch profiles, side slope points, berms, working limits, environmental constraints, real estate, and other information.
    - Cross sections, elevations, and detail sheets.
    - Excavation and backfill plans, sections, and details for each levee feature.
    - Borrow areas and haul routes.
    - Features with the levee: mechanical and electrical components, floodwalls, closures, and drainage systems.
- Temporary flood protection measures.
- Other information needed to fully define all requirements for the features and components to be constructed.

Some details may be left to the constructor to design, finalize, or obtain from a supplier, such as details of shoring, staging, and dewatering arrangements, since the constructor is best suited to develop constructability plans. However, initial consideration should be given to such issues during the design process to confirm the basic feasibility of the proposed construction and to facilitate review of constructor submittals (**Chapter 8**). Requirements for submittals should be identified and defined in the documents for construction. Submittals by the constructor should be reviewed and accepted by the designers before the construction work is executed. Selected submittals may also require review by the funding source or permitting agency.

2.1.4.2 Project Specifications

The project specifications should define the technical requirements and include both general and technical specifications:

- General specifications include contractual requirements governing administration of the construction contract and the working relationship between the levee owner, designer, and the constructor.
- Technical specifications for the different project elements should be prepared by the designer. These form the basis for how the constructor will bid and perform the construction work.[1]

The specifications should also set out quality assurance and quality control requirements during construction (**Chapter 8**), as well as required submittals and field approvals.

[1] United Facilities Guide Specifications may provide a helpful starting point for developing these specifications. More information can be found here: https://www.wbdg.org/ffc/dod/unified-facilities-guide-specifications-ufgs.

2.1.4.3 Geotechnical Data Report

The geotechnical data report documents the available subsurface and laboratory data information, including the data obtained under any new investigation. The report normally focuses on information on the index and design properties of subsurface soils. The geotechnical data report describes the following:

- The project and site description based on available site-specific documents and information from prior investigations.
- Additional geotechnical investigation performed, including methods and procedures, location, and depths of borings, in situ tests, the types and frequency of samples obtained, and laboratory test assignments.
- Presentation of compiled data including field boring logs, in situ, and laboratory test results from prior and performed investigations.

The geotechnical data report is sometimes included in the contract documents as a baseline for defining existing conditions.

2.1.4.4 Basis of Design Report

The basis of design report should be compiled to document the design process, analyses, and reasons for key design decisions. It typically includes all design criteria and provides all key design calculations in appendices. This will be an important document during construction, used to verify the design intent and support the evaluation of impacts due to changed conditions. Since risk assessment results (**Chapter 4**) are central to final design, this information and associated decisions about design adjustments, as discussed in section 2.2.1, should also be documented in the basis of design report. This report also will be critical to understanding the project after construction. The report should be provided regardless of the project size.

The basis of design report may include geotechnical aspects, or they can be included in a separate geotechnical basis of design report, which would establish the geotechnical bases of design for the new levee construction or modification/rehabilitation design. The geotechnical aspects included in either report generally include:

- Summary of geotechnical and geologic conditions.
- Characterization of the subsurface materials to establish parameters for design analyses.
- Evaluation of design parameters based on the characterization and analyses results.
- The results of design analyses.
- Remedial design and construction recommendations.

2.1.5 Construction Process Support

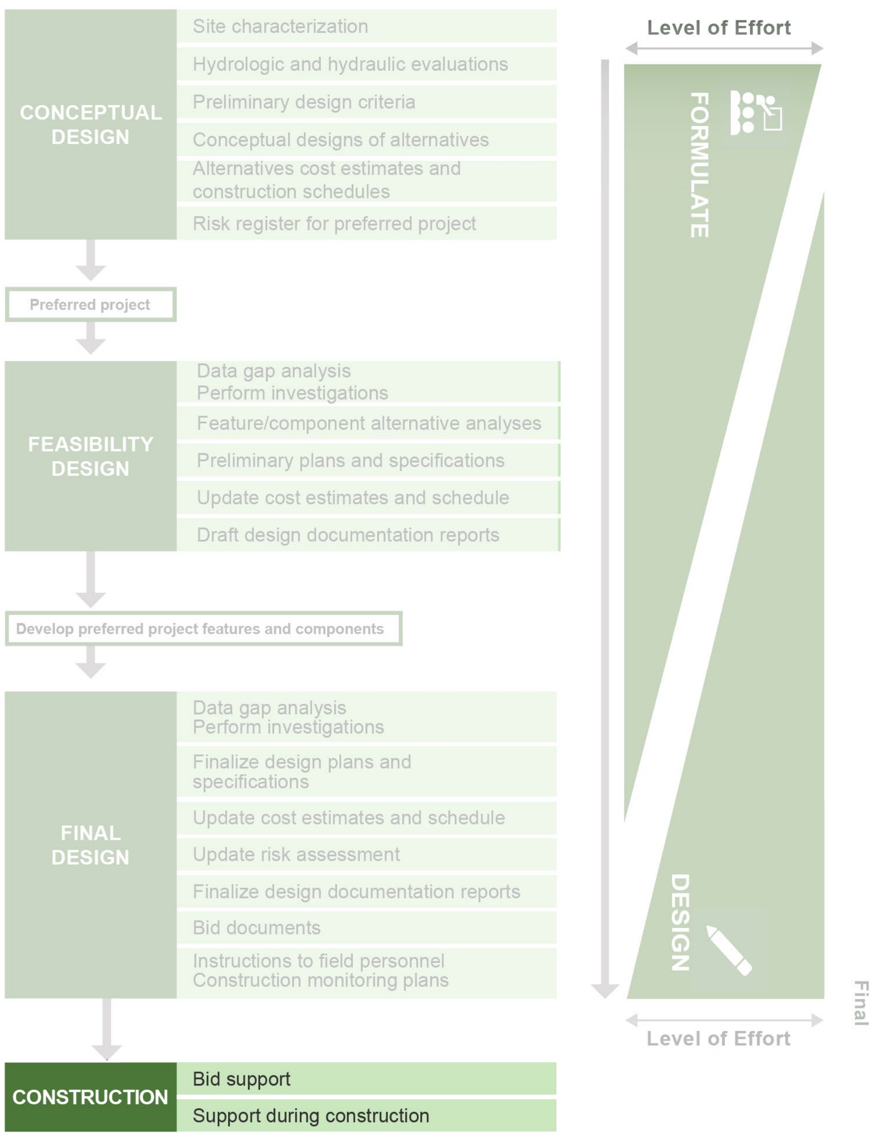
2.1.5.1 General Issues

A successful levee construction project requires a well-defined and clearly understood construction project scope (Figure 7-7).

Defining and conveying the project scope begins during levee design and carries into levee construction, since levee designs should be constructable. Input from levee construction professionals during the levee design process can help ensure the design is constructable (**Chapter 8**). Issues to be considered (including in the cost estimate, described in section 2.3.2) include:

- Assessment of the temporary stability of parts of the levee requiring significant temporary structures or features such as large bracing or dewatering systems.
  - Ultimately, it will be the constructor's responsibility to design any temporary structures or dewatering systems; however, the designer is obliged to consider these issues in order to make sure that the levee is buildable.
- Access for construction machinery or equipment that may require larger dimensions than those necessary for the design of the completed levee.

Figure 7-7: Support Process for Construction



The levee constructor should understand the important aspects of project design that may require special attention or action during construction. The designer should provide such information and instruction—commonly known as ‘engineering instructions [or considerations] for field personnel’—to the levee constructor and the field personnel performing inspections and accepting the work. These instructions should not replace the need for periodic inspections by the designer. Small projects may not require such instructions. The instructions should highlight:

- Design assumptions that should be confirmed during construction.
- Key design elements requiring special attention.
- Required field approvals.
- Other pertinent information for the construction team.

2.1.5.2 Temporary Flood Protection

Ideally, levee work should not be scheduled during known flood prone seasons, although changes in climate mean that such seasons are no longer so well defined. Furthermore, there may be levee **reaches** where temporary flood protection is not practical, in which case specifications should limit construction to outside of the flood season. However, if work has to be scheduled during seasons when flood impacts are a possibility, flooding should be minimized and limited to the extent possible by temporary flood protection measures. The alignment and height of any necessary temporary flood protection should be evaluated as part of the project formulation process (**Chapter 6**).

To mitigate flood risk to leveed areas during construction, temporary flood protection measures should be identified as required, particularly when designing levee modifications or a rehabilitation. Figure 7-8 shows some examples of temporary flood protection for levee construction. These measures should be capable of rapid implementation during construction if the functionality of a section of any existing levee is diminished. The most common potential diminished functionality conditions are:

- A degraded levee crest associated with improvements, or a rehabilitation being made.
- Stripped levee slopes with no erosion or wave action protection.
- Decreased levee section or significant landside excavations.

Figure 7-8: Examples of Temporary Flood Protection

Soil filled bags being used at a levee toe to provide additional flood protection to construction project.

In designing temporary flood measures, the following issues should be taken into account:

- Seasonality of flooding and the potential changes in flood timing and severity due to climate change (**Chapter 1**).
- Constructability of temporary flood measures during a flood when conditions are bad.

It is also important to bear in mind that levees with diminished functionality downstream from a major dam may be affected by fluvial flows if major releases from the dam are required for operational or emergency reasons.

The selected height and geometry of the temporary flood protection should take account of the likely severe water level/wave events associated with the period of construction. For any given water level, the encounter probability will be lower for the relatively short construction period, and the selected water levels may be lower than those used for the design of the permanent levee system; in this case, a plan for any necessary emergency raising should also be developed. Temporary flood protection planning is discussed in **Chapter 8**.

The temporary flood protection should also be designed such that levee risk (**Chapter 4**) is not increased during construction.

2.2 Principles

2.2.1 Design Criteria

Design criteria are the explicit goals that a levee project must achieve during the design process in order to be successful (i.e., for the levee project to achieve its intended flood risk reduction benefits). These criteria play a crucial role in shaping the outcome of the levee design process. A general requirement for any levee design is to ensure the levee provides the intended flood risk reduction, including the features and transitions between them as a complete system. This generally requires the levees to be designed to ensure the levee does not breach before it overtops. Resilience of the levee during an overtopping event is also an important consideration during design. A levee design should also be economically feasible and constructable.

For levees, design criteria are synonymous with deterministic standards (e.g., height, factors of safety, limiting values of seepage gradient, minimum dimensions of levee components, etc.) that should be met in order to achieve a reliable and resilient levee. Recommended design criteria for various levee features and components are provided later in this chapter. It is important to note that deterministic standards have the following limitations:

- Deterministic standards are developed from empirical observations for a limited range of conditions that may not be consistent with the local levee project conditions.
- Deterministic standards do not account for every failure mode that can occur on a levee and can overlook critical failure modes.
- Deterministic standards do not explicitly account for uncertainty in the design parameters and methods leading to uncertain levee performance.
- They do not account for planned flood fighting which can significantly affect the levee performance.

2.2.2 Risk-Informed and Scalable

The design of new levees, modifications, or rehabilitation of existing levees should use a risk-informed approach that uses a risk assessment to evaluate and adjust the design. A risk assessment can help fill gaps in limitations of deterministic standards to supplement the design process. Implementation of a risk-informed approach therefore involves a two-step process—an initial design followed by a risk-informed design adjustment using a risk assessment.

1. **Perform initial deterministic design**. The initial deterministic design follows the usual design criteria and guidance documents (many of which are cited in this chapter). However, the effort/rigor put into the investigations and analyses should be scaled according to the initial estimates of flood and levee risk (**Chapter 4**). Thus, levees with high potential consequences in their leveed areas will be designed with greater confidence and reliability by reducing uncertainty through more comprehensive investigation and analyses.
2. **Evaluate and adjust design as necessary using a risk assessment**. Since the deterministic design does not tell the whole story, the initial deterministic design should be evaluated and adjusted as necessary according to the assessed risk (**Chapter 4**) associated with that initial design. In higher risk situations, such adjustments may include the addition of complementary resilience measures to increase robustness, redundancy, and recoverability. These may include adjustments that:
   - Ensure the levee will perform adequately for a full range of loadings to the extent possible, ensuring that the levee will not breach before it is overtopped.
   - Ensure risk-driving potential failure modes that remain from the initial deterministic design are adequately addressed.
   - Incorporate additional features that make the levee more resilient without signficant increases in cost.

In lower risk situations, by contrast, a value engineering approach may be adopted in order to remove costly features that are not critical to the performance of the levee. Adjustments may not be necessary for some levee designs.

When adjustments are made to the initial deterministic design, the adjusted design should be reevaluated according to the assessed risk associated with the adjusted design. Further adjustments may be necessary after this reevaluation. In some situations, the initial deterministic design may result in costly design features that are not critical to the levee's performance and, where costs are significant, an adjustment to optimize cost may be necessary. All adjustments including those to optimize cost should be reevaluated according to the assessed risk associated with the adjusted design to ensure the levee meets its design goals and its intended flood risk reduction benefits.

Using a risk assessment to evaluate and adjust a levee design is different than managing implementation of the project—also called project risk—during formulation, design, and construction.

2.2.3 Resilience

The concept of community **resilience** is discussed in **Chapter 12**. Designing a resilient levee system involves consideration of robustness, redundancy, and recoverability, taking into account the various areas of uncertainty associated with the levee including:

- The timing and extent of climate-related changes to the hazards over the life of the levee.
- The performance of the levee itself as it changes with time. This includes understanding performance, not just at the selected design condition, but also at lesser and greater conditions, including when the levee is overtopped. This range of performance is typically expressed in the form of fragility curves (**Chapter 4**), which describe the variation in probability of damage/failure as the hazard loading on the levee increases.
- Changes in land use within the leveed area.

With regard to robustness, design criteria should be developed based on the established project flood risk reduction objectives and the increasing uncertainty inherent in the modeling the performance of the levee towards the end of its life. Levees should be designed to accommodate all potential loading conditions, not just the nominal design water level. In particular, consideration should be given to how the levee will perform in cases where the design water level (or wave overtopping rate in the case of coastal levees) is exceeded. In regard to these conditions that are higher than design loading, consideration should be given to measures such as adding levee surface reinforcements at points of first overtopping of fluvial levees. Such reinforcement should be aimed at ensuring that the overtopping which would take place there does not cause erosion and breach the levee. The points of first or preferred overtopping will be determined by considerations of levee superiority (**Chapter 6**).

With regard to redundancy, consideration should be given to adding additional features to enhance the ability of the system to withstand extreme conditions, should one feature fail. Adding natural and nature-based features is one option to increase the redundancy of a levee, as discussed in **Chapter 6** and Bridges *et al.* 2021. Other measures that the community might put in place to limit flood risk are discussed in **Chapter 12**.

With regard to recoverability, consideration should be given to the approaches to be adopted:

- To promptly restore the levee to a serviceable condition in the event of damage.
- To promptly remove excess flood water from the leveed area.

2.2.4 Quality Control

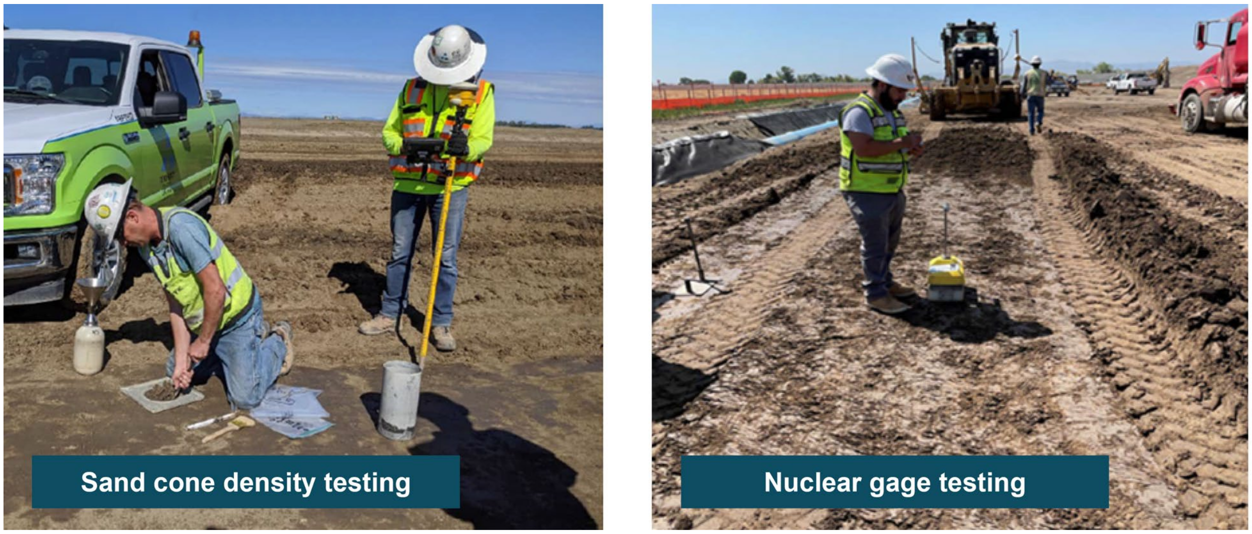
Quality control in all phases of design is an important risk reduction measure and is a companion process to the necessary quality control during construction (see Figure 7-9 and **Chapter 8**).

An appropriately staffed and scaled quality control process can help identify and correct errors during the design process. This process should ensure that studies, reports, criteria, plans, specifications, and other technical work products undergo comprehensive and rigorous checking and quality control reviews. A project should have a quality plan that:

- Includes checking and quality control procedures and documentation.
- Takes account of the selection and use of software for design analyses, including the testing and verification of the software itself (either by the designer or a third party).
- Includes verification of important analyses (as practical) by using more than one method, or more than one computer program, with independent processing of the information and data.

The number and extent of design reviews should be influenced by the results of the risk assessment (**Chapter 4**). When the risk assessment results indicate high risk, independent reviews at interim phases of project design may be implemented as an additional risk reduction measure. Independent design reviews may consist of a consulting board review and/or a constructability review.

Figure 7-9: Example of Quality Control Testing During Construction



Sand cone density and nuclear gage testing was performed on the subgrade of the San Joaquin River. An existing drainage ditch adjacent to the landside levee toe was backfilled and a new drainage pipe was installed; April 2021.

2.2.4.1 Independent Expert Review

An independent expert review provides a credible, objective assessment of the levee design. This is important for levee designs where breach or failure of the designed and constructed levee project could lead to loss of life. These reviews often focus on:

- Is the levee design appropriate?
- Did the levee design overlook any critical items?

Independent expert review often occurs during the final design but may begin during the formulation or feasibility phase.

Independent experts should be senior practitioners from outside the design team. They also should be available to assist the design team with other matters, including guidance on site investigations, performing design studies, resolving design issues, working with agencies, and other concerns that may arise. The makeup of the independent expert reviewers should be commensurate with the design features and may include civil, structural, geotechnical, and hydraulic engineering disciplines. Other disciplines such as botanists, biologists, and ecologists should be included for natural and nature-based features. For smaller projects, one reviewer may be appropriate.

The reviewers typically continue reviews into the construction phase, providing continuity between design and construction. In addition to periodic site visits during construction, the reviewers can also provide the levee owner, design team, and construction management personnel with suggested guidance on managing construction issues, such as changed conditions or problems meeting specification requirements.

2.2.4.2 Constructability Reviews

Constructability reviews are an important part of the risk reduction strategy for a project and should be included in the schedule for the final design. In this review, bid documents are to be reviewed by a qualified construction specialist or team if appropriate, based on the features and components of the project. The goals should be to verify completeness, constructability, coordination of documents, and a clear presentation of requirements for bidding and execution of the work. The review can be applied to new levee projects, as well as to levee modification and rehabilitation projects.

The qualified construction specialist should be a senior practitioner who is familiar with the elements to be constructed, as well as with applicable construction techniques and practices. The specialist may be associated with the engineering firm performing the review who is not involved with the design or associated with a separate firm under contract with the levee owner for providing comprehensive construction management services. Some of the benefits of a comprehensive constructability review include:

- Potential for receipt of more bids.
- Receipt of more confident, lower bid pricing.
- Fostering good working relationships between the levee owner, designer, and constructor.
- Reduced chances for changes, claims, and disputes during construction.
- Better prospects for delivery of a quality finished product, on schedule and within budget.

2.3 Considerations

2.3.1 Selecting a Levee Designer

Selecting the appropriate levee designer is an important decision to ensure successful completion of a levee project. The levee designer should be experienced in design of levees and familiar with local conditions and requirements. For complex levee projects, the designer is often made up of a team with appropriate technical disciplines to characterize the site and design the levee features. Typical levee designer functions include:

- **Project management**: Managing and controlling all aspects of the project, including budget, schedule, and quality.
- **Technical leadership**: Technical analyses and design of the levee features.
- **Technical support**: Generally including hydraulic, geotechnical, structural, and civil engineering, along with cost estimation. Other disciplines may include, but not be limited to, surveying, environmental science, geomorphology/geology, data management, computer-aided-design, cultural resources, landscape architecture, and mechanical, electrical, and hazardous materials engineering.

2.3.2 Cost Estimating

In the early formulation and design phases, cost estimating provides essential input to the decision-making process, particularly when evaluating alternative components. In the later design phases, cost estimating should become more comprehensive, supporting financial planning for the project and providing a baseline to track and control construction costs. Cost estimating should also cover O&M costs.

Cost estimates for levee projects should be:

- Comprehensive, well documented, accurate, and credible.
- Developed to a degree of confidence and accuracy appropriate to the level of completion of the levee design. As a corollary, the quality, reliability, and level of completion of the design that forms the basis of the costing should be commensurate with the expected accuracy of the cost estimate.
- Performed or updated within a reasonable time of their intended use.

2.3.2.1 Estimate Components

A complete project cost estimate typically includes construction contract costs and non-construction contract costs (including O&M costs), both of which need to be considered in financial planning for the project. Thus, allowances for construction contingencies (e.g., changed site conditions, change orders, and claims) should be added to the anticipated bid price at the time of appointing the constructor. Refer to for additional guidance regarding contingencies.

The non-construction contract costs are real costs over and above the constructor's contract cost that need to be part of the overall financial plan for the project. Some of these costs include:

- Licensing and permitting costs.
- Environmental mitigation costs.
- Site characterization costs, including surveying/mapping, geologic and geotechnical investigations, laboratory testing, and data analysis.
- Engineering and design, including plans and specifications, supporting design, and geotechnical reports.
- Construction management services, including the construction manager, inspectors, and testing laboratories.
- Levee owner administrative and staff costs during design and construction.
- Temporary and permanent property acquisition costs and public utility relocation costs.
- Long-term O&M costs.

2.3.2.2 Estimating Methods

In the conceptual and feasibility phases of a project, judgment and parametric modeling may be used because of the lack of design detail. Parametric (or stochastic) modeling uses available cost information from other similar projects or for similar types of work and scales these costs up or down to reflect differences between the similar project and the new project. For example, if a cost per mile is known for an existing embankment levee or floodwall, it can be applied to the planned work after adjusting for regional cost differences and any differences in height and width. This sometimes is referred to as a top-down estimate. The judgment of a qualified cost estimator should be taken into account in using the existing cost data.

In the later phases of design, detailed quantity estimates should be made for each work item (e.g., place and compact fill, form and place concrete). The unit costs then should be developed by considering material, labor, and equipment needed to complete work items. This is referred to as a deterministic or bottom-up estimate.

SOURCES FOR COST ESTIMATE CLASSES

- American Society for Testing and Materials International E2516, Standard Classification for Cost Estimate Classification System (E06 Committee, 2019).
- Association for the Advancement of Cost Engineering International, Recommended Practices, 17R–97 (AACE International, 2020), 18R-97 (AACE International, 2020), and 56R-08 (AACE International, 2020).
- U.S. Army Corps of Engineers, Engineering Regulation 1110-2-1302, Civil Works Cost Estimating (USACE, 2016c).

2.3.2.3 Estimating Software

Cost estimating software packages reduce the time required to prepare cost estimates and can help to increase the accuracy of estimates by enabling the utilization of proven standard formats, processes, and procedures. If possible, the same estimating package should be used through various phases of the project to facilitate efficient transfer of cost estimate information. In some cases, the funding agency often specifies requirements for cost estimating software. In general, cost estimating construction cost software should contain:

- Standard formats, processes, and procedures.
- Ability to easily update labor, material, and equipment costs (unit prices).
- Flexible report writing.
- Area cost factors for specific location of the construction activity.
- Historical construction cost data.
- Cost risk analysis.

2.3.2.4 Cost Estimate Accuracy and Class

Construction cost estimate accuracy depends primarily on the maturity of design detail available when the estimate is prepared. As design details are refined, the cost estimate becomes a more detailed bottom-up estimate, with less reliance on contingencies. Figure 7-10 shows the improvement in accuracy of a cost estimate through the various phases of design (from conceptual to final design) according to a class based on design maturity.

Table 7-2 (adapted from the sources in the callout box) shows a typical, commonly used estimate classification system for process and general building construction industries, based on percent of design completion. The table also shows the intended use for the estimate in each class, methods used to develop the estimate, and the typical contingencies for each class.

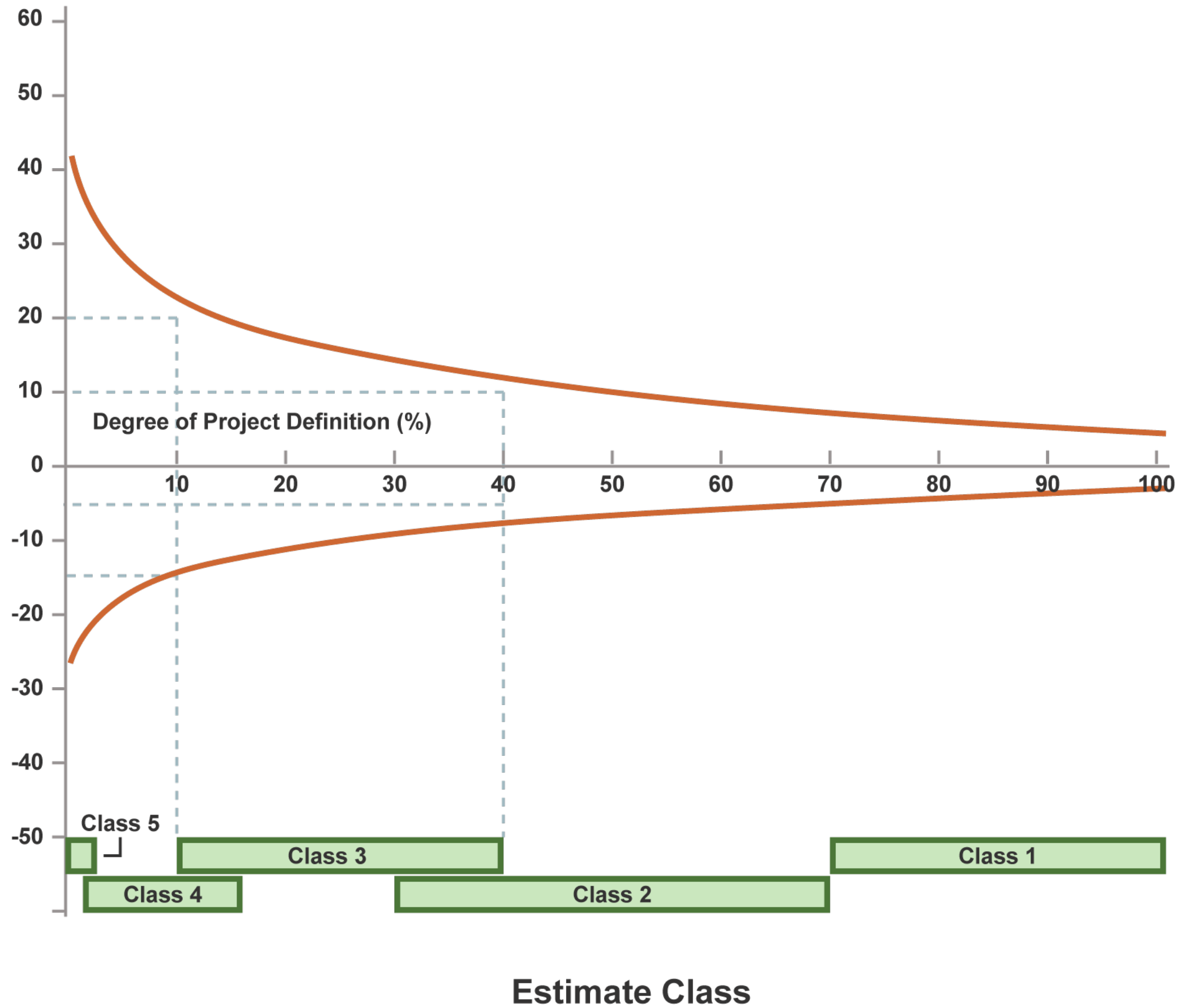
Table 7-2: Typical Accuracy Ranges for Construction Cost Estimates

Estimate Class	Maturity of Design[1] (percent)	End Use	Estimating Method	Typical Contingency[2]
Class 5	0% to 5%	Concept screening	Judgment, parametric model	40% to 200%
Class 4	5% to 10%	Study or feasibility	Factored costs, parametric model	30% to 100%
Class 3	10% to 60%	Budget authorization or control	Semi-detailed unit costs, assembly level take-offs	20% to 50%
Class 2	60% to 80%	Control or bid/tender	Detailed unit costs, detailed take-offs	15% to 30%
Class 1	80% to 100%	Check estimate or bid/tender	Detailed unit costs, detailed take-offs	5% to 15%

Notes to table:

1 Maturity of design as a percentage of a complete 100% final design.
2 Range of contingencies to achieve 80% confidence level in the cost estimate (common industry standard). A schedule cost risk analysis, as outlined in the Cost Guidance and Schedule Risk Analysis Guidance (USACE, 2009), can be used to inform the level of contingency for the project.

Figure 7-10: Estimate Accuracy Improves with Time



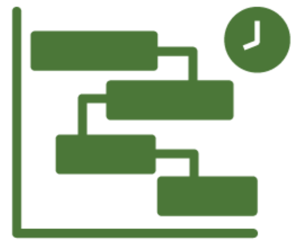
As design maturity increases, the end use of the estimate progresses from strategic evaluation and feasibility studies to funding authorization and budgeting, and then to project budget control.

- Class 5 estimates are based on preliminary technical information and are often referred to as rough order of magnitude estimates.
- Conceptual phase estimates would generally be Class 4 or Class 3, based on design maturity and the requirements of the funding agency.
- Feasibility study estimates are typically Class 4.
- Final design estimates can be Class 1 or Class 2, as required by the funding agency.

2.3.3 Easements and Permits

Easement and permit requirements identified during the project formulation phase (**Chapter 6**) should be confirmed during design.

2.3.4 Project Implementation Scheduling



The purpose of a project implementation schedule is to:

- Define distinct tasks that should be executed in proper sequence to successfully complete the project.
- Prepare an accurate cost estimate (section 2.3.2.2); thus, the schedule becomes a cost risk management tool.

A project implementation schedule typically covers the project from conceptual through final design, permitting activities, construction, and project closeout. The initial schedule usually is at a high level and becomes more refined throughout the project life, as project details are finalized.

Scheduling usually commences by breaking tasks into manageable work elements, referred to as the work breakdown structure. Each task is assigned a duration—usually based on past experience, known duration rate, or other reasonable assumptions. Links between tasks are added that control when tasks can begin or should end to achieve milestone completion dates. Tasks can be resource/cost loaded (e.g., manpower, equipment) to assist in resource allocations, budget planning, and budget control. Some benefits from scheduling include:

- Providing schedule duration input for preparing cost estimates and evaluating escalation.
- Supporting budget development and budget control for tasks and for the entire project.
- Guiding resource management and the allocation of resources to complete tasks.
- Providing a tool to track progress and identify schedule delay issues.
- Allowing stakeholders to follow project progress.

Commercially available software packages are available to prepare schedules. They should be evaluated to determine which are best suited for the project. Some permitting and funding agencies specify the software to be used. Because the schedule will be a living document that will need to be updated periodically throughout the formulation and design process, schedule software should not change.

2.3.5 Vegetation

Having the appropriate vegetation type and approach for long-term management on and near the levee is essential to ensuring the levee performs, operates, and is maintained as intended. For example, the type of vegetation at the levee overtopping location may have a positive or negative impact on levee performance. Herbaceous grasses or forbs that have dense root systems may provide some erosion resistance that reduces the potential for breach during some overtopping events, while the presence of a lone tree or the absence of consistent vegetation may accelerate erosion during an overtopping event.

In general, desirable characteristics of vegetation management on or near levees include:

- Does not inhibit access for visual inspections, especially during flood events.
- Avoids activities that can damage levee features and lead to poor levee performance.

- Ensures appropriate ground cover is used to reduce soil erosion.

Characteristics of desirable species include:

- Requires little or no mowing.
- Able to resprout (i.e., perennials).
- Have fine, deep fibrous roots which will lend strength during an overtopping event and hold the vegetation and soil in place.
- Are unpalatable to local burrowing animals.
- Will withstand the seasonal climate and weather, including drought tolerance if relevant to the local environment.
- Are salt tolerant as appropriate to the expected levels of salinity (for levees in coastal areas).
- Are fire resistant (unless controlled burns are part of the maintenance plan).

For most situations, herbaceous vegetation (e.g., grasses, wildflowers, and forbs) satisfies these desirable characteristics. However, other types of vegetation on or near the levee may be needed to satisfy the levee project objectives such as environmental benefits, laws, and regulations. These types of vegetation should only be used on or near a levee when there are intentional design elements to accommodate this vegetation.

When considering the appropriate vegetation type and spacing of plantings during design, experts—such as scientific professionals and tribal experts (if applicable) well versed in sediment transport, fluvial geomorphology, fish biology, botany, forestry, ecology, and soil science, in addition to the traditional engineering team—should be included in the design process. It is vital to ensure all maintenance tasks, including any vegetation maintenance tasks, are evaluated and deliberate (or designed). As such, vegetation planting and/or management are included in the O&M manual to ensure that all maintenance actions can be effectively carried out without undue regulatory hinderance.

Designed vegetation elements (e.g., other than grasses), which allow vegetation to thrive without compromising the levee or creating a maintenance burden, can be incorporated. Designed vegetation elements to incorporate shrubs, trees, or other woody plants in a deliberate manner can enhance the environment while reducing uncertainty of compromising levee performance. These vegetation elements should be designed considering the following:

- Levee features are not damaged or perform poorly due to the vegetation throughout the life of the levee (this includes considering potential impacts of vegetation growth, maturity, and death).
- Long-term maintenance requirements can be reasonably and satisfactorily performed.
- Necessary access, inspection, and floodfighting are not hindered.
- The required confidence and reliability of the levee is achieved.

Examples of vegetation design elements that accommodate types of vegetation other than grasses on or near levees include levee setback, enlarged levee embankment, planting berm or bench, and/or planting boxes.

2.3.6 Encroachments and Penetrations

Encroachments include any activity on or physical intrusion on, over, through, or under the levee that is not related to the flood risk reduction benefits or other co-benefits the levee is intended to provide. Examples are buildings, fences, pipelines, and other utilities. Where possible such encroachments should be avoided, but where necessary the design should be adjusted to limit the impact on levee performance.

Penetrations are a subset of encroachments which, as they pass through or beneath a levee. are of particular significance for levee performance. Design issues to be addressed in such situations include:

- Leakage from pipe penetrations.
- Differential settlement adjacent to the penetration.
- Seepage and internal erosion along the outside of the penetration.
- External erosion due to water flow around the penetration as it passes into the levee.

Further information on pipes is provided in section 11.1 and detailed guidance on designing for levee penetrations is available in Engineer Manual (EM) 1110-2-2902 (USACE, 2020b).

2.3.7 Challenges

Despite their apparent simplicity, the design of levees can be surprisingly challenging compared to what would appear to be more complex structures. Table 7-3 gives a summary of the main considerations that help to address the challenges that arise during the design process.

Table 7-3: Main Challenges of Levee Design

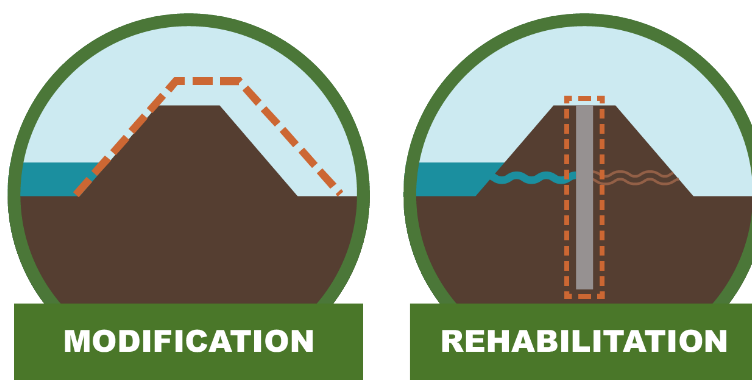
Design Challenge	Chapter or Section	Summary of Associated Design Considerations
Site characterization and its impact on design	Section 3	• Existing information and collecting new information about site conditions is critical. Required information includes topography, bathymetry, geology, geotechnical, hydrologic and hydraulic data, utilities. • Information gathering and interpretation occurs in every phase of formulation and design. • Soft alluvial foundation soils need special attention. • Materials taken onsite are prone to variability, imperfections, and deterioration with time.
Design coordination with construction	Section 2.1.5	• Coordinate on variability in site conditions and construction materials. • Coordinate regarding aspects that require special attention or action during construction, including instrumentation and monitoring.
Levee reach selection	Section 3.3.6	• Established to support analysis and design of the levee. • In highly variable ground conditions, a potentially large number of reaches may be necessary for analysis.

Design Challenge	Chapter or Section	Summary of Associated Design Considerations
Levee crest level	Chapter 6	• Level should be set to provide the planned flood risk reduction throughout the design life. • Superiority, wave runup, potential settlement, and resilience should be considered in establishing the level.
Temporary flood protection	Section 2.1.5.2	• Should be included in all levee designs, particularly where the project construction schedule will cover multiple years. • Applies to coastal, as well as riverine levee systems, and locations where internal drainage could adversely impact levee construction on the landside.
Closure structures	Section 7	• Design of these structures needs to avoid introducing points of vulnerability into the levee system.
Transitions and other points of weakness	Section 8	• Need to avoid loss of integrity at the transition point between different features, which could lead to failure of the levee at these points.

2.3.8 Levee Feature Modifications or Rehabilitation

Levee **modifications** include activities that change the original operation and function of a levee. It includes raising a levee, modifying its alignment, or changing features. Levee **rehabilitation** includes activities that restore a levee to its original operation and function due to two possible causes:

- Extensive deterioration, including damage by high water or other incidents.
- Deficiencies from design/construction.



Rehabilitation is more substantial than normal maintenance and repair and is not routine in nature. Rehabilitation should restore the features to add serviceability and design life.

The equivalent of conceptual and feasibility phases for design of such modifications or rehabilitation for an existing levee is a phased evaluation process of the existing structure to determine the necessity of the modifications or rehabilitation. While the principles and best practices for design of a new levee are still generally applicable, the evaluation process should include the following steps:

- Evaluation of existing and future conditions (including climate change and development in the floodplain), which may have increased the hazards faced by the levee and the consequences of failure.
- Development of acceptance criteria based on back-analysis of historical performance where existing structures do not meet current codes or guidelines.

- Analysis of the existing levee using methods that accurately describe its behavior without introducing excess conservatism.
- Identification of rehabilitation options.
- Repeat analysis of the levee performance for each option.
- Selection of a preferred option—likely making use of a decision matrix—including life safety, cost, environmental and community impacts, and benefits for formulation, evaluation, and selection.

Note that existing levees may have performance information that can be used to identify potential deficient areas and target modification efforts. The amount and quality of performance data is highly variable across different levees. When available, this information can be used as part of a risk-informed approach, to prioritize levee modification projects and select appropriate design criteria.

The level of analysis for performance evaluation should be commensurate with the decision being made. Analyses should reduce uncertainty enough to allow confident decision making. The analysis process for levee evaluation is typically phased, and the need for each phase is dependent on the outcome of the previous phase.

- **Preliminary analysis**. This is performed based on available data and the actual conditions of the levee. Before performing an analysis, the available existing data and information about the levee should be collected and reviewed, including geologic and foundation data, design plans, as-built plans, periodic inspection reports, damage reports, plans of previous modifications to the levee, and other pertinent information. The designer should inspect the existing levee to assess its condition.
- **Comprehensive analysis**. If the preliminary analysis indicates the existing levee does not meet safety and performance objectives, a plan of action for a comprehensive evaluation should be developed. The plan should determine the extent of the exploration and testing program needed to accurately define soil parameters, the analytical program needed to accurately define the loading conditions, the remedial schemes to be studied, and the extent of any additional parametric studies. An exploration, sampling, testing, and instrumentation program should be developed to determine the magnitude and reasonable range of variation for the parameters that have significant effects on the safety and performance of the levee, as determined by parametric studies. Analysis of the levee should be performed using the material properties and strength information obtained from the sampling and testing program.
- **Advanced analysis**. If the stability of the levee is still in question after completing preliminary and comprehensive analyses, advanced analytical studies should be considered to reduce uncertainty where the risk and/or cost of remediation is high. These studies should use two- and three-dimensional finite element methods to capture the interaction between the foundation, backfill, and the structure, and to capture the capacity of the structural system to distribute loads to adjacent monoliths and abutments.

3 Site Characterization

The goals of characterization are to identify hydraulic, geotechnic, and morphologic design requirements and constraints, as well as to establish design parameters. Developing an understanding of the system characteristics to facilitate a design that meets the project objectives will require consideration of the available information and additional data that will improve confidence in the design.

Levee alignments frequently traverse varying conditions and could fail at the weakest location. Accordingly, designs should characterize the full alignment length and identify reaches that may be critical. A balance should be established between investigation expenditures, construction costs, and risk reduction objectives according to the degree of risk associated with the levee (**Chapter 4**). Increased investigation costs will reduce uncertainty, increase confidence, and may reduce construction costs by decreasing design conservatism. However, this reduction will not be linear and full characterization of conditions at every location is not practical.

Existing data should be evaluated to characterize the site. Then, additional investigation to improve design confidence, reduce construction costs, and better understand flood and levee risk can be planned. This should be an iterative process and can be most efficient when performed in phases. Even so, project budget and schedule needs may require eliminating phases.

Characterization activities generally include existing information gathering and review, interpretation, and data gap analysis. These activities are not linear because existing information gathering and review is a one-time process, while interpretation and investigation frequently are performed in phases, sometimes correlated to the design phases (i.e., conceptual, feasibility, final).

3.1 Gathering and Reviewing Existing Information

Information gathering and review should be performed to understand available information and to characterize the alignment to the extent possible. This should allow evaluation of opportunities for investigation to improve design confidence. The data gathering and review process should involve collecting and cataloging existing information pertinent to a flood risk reduction project. The data will be useful throughout the project, including during formulation, risk assessment, and other levee lifecycle activities.

3.1.1 Information Gathering

For project design, the information will be used to characterize site conditions and develop design parameters. Typical documents to review should include:

- Results of risk assessments.
- Documents for existing levee features.
  - Data from the National Levee Database (NLD) for existing levees.
  - As-built drawings and reports of existing features.
  - O&M manuals.

    - Inspection reports.
    - Performance history.
    - Geophysical test results.
- Existing geotechnical data from other projects designed/constructed in the area.
    - Existing publicly available information.
    - Existing hydrologic and hydraulic data, water level gage data, and tide gage data.
    - Topographic and bathymetric maps.
    - Geologic and geomorphic maps.
    - Information on, and classification of, the groundwater regime.
    - Published papers, reports, and available information from local, state, and federal agencies, such as the United States Geological Survey and the U.S. Army Corps of Engineers (USACE).
- Information from the formulation phase.
    - Environmental, cultural, and real estate studies.
    - Levee siting concerns or constraints received from community members or other stakeholders.

The information gathering and review process should be fluid and ongoing throughout design, as data gaps and analysis needs are identified. The purpose of the process should be to collect and assimilate sufficient data at each design phase to inform required decisions, culminating in the successful final design of a levee meeting project objectives.

3.1.2 Data Storage

The framework for data storage should be developed during the formulation phase of the project (**Chapter 6**), for use by the project team in each step of the design process and allow additional information and data to be added as it is collected. This database can be used to evaluate data gaps to be filled during the investigation phase. Geographic information system (GIS) databases, particularly for larger or more complex projects, offer one way of providing systematic storage of collected project information and data. GIS allows for easy access and review, which is essential to facilitate the design processes and for project documentation. Relevant data should also be uploaded to the NLD (**Chapter 4**).

3.2 Additional Investigations

The assembled data should be reviewed to assess whether sufficient data is available for design. The design data requirements will vary based on the design phase, with conceptual design requiring the least data and final design the most. Data requirements should be risk-informed and consider uncertainty and conservatism. The degree of conservatism and acceptable levels of uncertainty should be informed by the results of the risk assessments. The investigation process should be undertaken to fill identified data gaps, to move the project design forward. Factors to consider in developing an additional investigation program include previous experience, proposed levee height and side slopes, likely foundation conditions (geology and geomorphology), likely duration of high-water events, and the nature of available borrow materials. For existing levee projects, additional factors include construction history, levee conditions, past performance, topographic/bathymetric anomalies (e.g., depressions in toe blankets), presence/nature of structures and utilities in embankments, and extent of mitigation measures.

The extent and scope of investigations will vary over a project's lifecycle, as data needs increase and project funding becomes available. Additional investigation may cover many different aspects, but the most common will be:

- Topographic survey and bathymetry
- Inspection and testing of existing levee features
- Geologic and geotechnical investigations
- Hydrologic and hydraulic data collection, water level gage data, and tide gage data
- Utility surveys
- Hazardous materials surveys

Figure 7-11 shows typical field investigation of foundation conditions through the collection of boring samples.

Figure 7-11: Example Field Investigations

Drill rig with hollow stem auger used for extraction of soil cores at Dawson Field within the U.S. Department of Agriculture Research Center, Georgia.

3.2.1 Data Gap Analysis

The data gap analysis should review all available data and determine where additional information is needed to support design and to minimize design and construction risks. As mentioned above, the determination of requirements for additional data should be informed by the analyzed flood and levee risks (**Chapter 4**). The risk assessment results will aid in the identification of acceptable levels of uncertainty for the levee project and the selection of the appropriate degree of conservatism.

The timing of the data gap analysis will be important to allow sufficient time to obtain permissions for property access and necessary permitting activities. Gap analysis should be ongoing, but should be performed specifically on two occasions:

- Near the end of the conceptual phase to support data gathering for the feasibility phase.
- Near the end of the feasibility phase to support data gathering for final design.

3.2.2 Topography and Bathymetry

Topographic survey and bathymetry should establish baseline grades, critical for hydraulic analyses and the design of levee features. Drone surveys may be beneficial in the formulation and design phases and should be considered.

Control and topographic survey accuracy and data collection will be important. EM 1110-1-1005 (USACE, 2007) provides guidance on planning and executing a survey program, survey datums, accuracy requirements, and other topics. EM 1110-2-1003 (USACE, 2013) provides useful guidance on performing hydrographic (bathymetric) surveys, including datums, methods, and accuracy. The project datum should be established and consistently used throughout the design and construction process.

Conceptual design may be performed with less topographic coverage, provided sufficient understanding is available to assess required features. As the design progresses, additional survey and bathymetry may be required to refine design features and meet requirements. During geometric interpretation, locations where insufficient topography is available, or the topography lacks sufficient detail should be identified for additional topographic surveys and/or bathymetry surveys.

Also, visible aspects of buried utilities (e.g., pipe inlet/outlet elevations, pull box, and manhole locations) should be located by ground surveys as part of developing topographic mapping for the project.

3.2.3 Geotechnical and Geomorphic

The purpose of the geologic and geotechnical investigations is to characterize subsurface conditions that impact levee performance and design. Investigations can be costly and time-consuming; therefore, they should be carefully planned to optimize the information obtained. The purposes of the geologic and geotechnical investigations should include:

- Characterizing foundation conditions along the levee alignment and adjacent areas.
- Characterizing existing levee features, including embankments and berms.
- Obtaining geological and geotechnical data to develop design analyses parameters.
- Characterizing groundwater conditions and their seasonal variability for project features and borrow areas.
- Developing reach and sub-reach boundaries (section 3.3.6).

3.2.3.1 Geotechnical Investigation Planning

The planning of geotechnical investigation should be informed by any prior risk assessment. Areas of higher hazard flood risk and/or levee risk (**Chapter 4**) generally should have a higher intensity of geotechnical exploration, characterization, and analyses. In addition, the focus on analysis of probable failure modes should dictate exploration locations and depths.

A comprehensive geologic and geotechnical investigation plan should be developed, considering potential failure modes, site-specific conditions, cost, permitting, and coordination. A written comprehensive plan should be developed for field investigations, to justify the selection of exploration techniques, locations, sampling plan, and depths.

Issues to be taken into account in developing spacings of borings include:

- Need for borings at the crest location and at the landside and waterside of the levee.
- Verification of cone penetration testing with conventional material recovery borings and standard penetration testing.
- Appropriate spacing of borings along the levee alignment (section 3.2.3.4).

Issues to be taken into account in determining the depth of any boring include:

- Identification of the uppermost low permeability layer.
- Definition of aquifer characteristics.

Carrying out sufficient geotechnical borings is a project risk reduction measure that better informs design. Geotechnical boring methods should be selected based on the expected geologic conditions, required exploration depths, sample requirements, and project budget and scale. The boring plan should accommodate the levee feature being considered (embankment, floodwall, closure structure, or transitions). Table 7-4 presents some key considerations when utilizing geotechnical borings.

Table 7-4: Geotechnical Borings Considerations

Item	Investigation Goals	References
Exploration locations, spacing, and depths	The location, spacing, and depth of boring and cone penetration test explorations should be risk-informed and project-specific and/or from previous experience in the area. Typical spacings along the levee alignment will be between 200 to 1,000 feet, being more closely spaced in expected problem areas (such as areas of poor past performance or locations of critical geologic features like oxbows or recent channels) and more widely spaced in expected less-problematic areas (such as older geologic formations without past performance distress).	EM 1110-1-1804 (USACE, 2001a), EM 1110-2-1913 (USACE, 2000)
Sampling and laboratory testing	The purpose of sampling should be to log and characterize levee stratigraphy and obtain samples for laboratory testing, to aid in developing property parameters for analysis and design.	ASTM International standards generally
Groundwater measurements	Groundwater levels, if encountered, should be measured during explorations and monitored to provide information needed for design.	EM 1110-2-1908 (USACE, 2020a)
In situ testing	In situ tests often are the best means for determining the engineering properties of subsurface materials and, in some cases, may be the only way to obtain meaningful results.	EM 1110-1-1804 (USACE, 2001a), TM 5-818-5 (Departments of the Army, the Navy, and the Air Force, 1983)

An engineering geologist or geotechnical engineer with levee drilling experience should be assigned to drill rigs, to oversee the work, to classify soils onsite, and prepare field drill logs. Caution is required when drilling in levees to avoid damage (e.g., hydrofracturing). Engineer Regulation (ER) 1110-1-1807 (USACE, 2023) provides a good outline of the drilling program plan. Permits may be required for drilling in existing levees. Time for this approval process should be incorporated into the schedule for the field work.

Geotechnical analysis should consider uncertainty in parameters and stratigraphy. Sampling and laboratory testing is intended to reduce this uncertainty, lowering project risks and costs. The sampling and testing program should be specifically designed to accomplish this purpose.

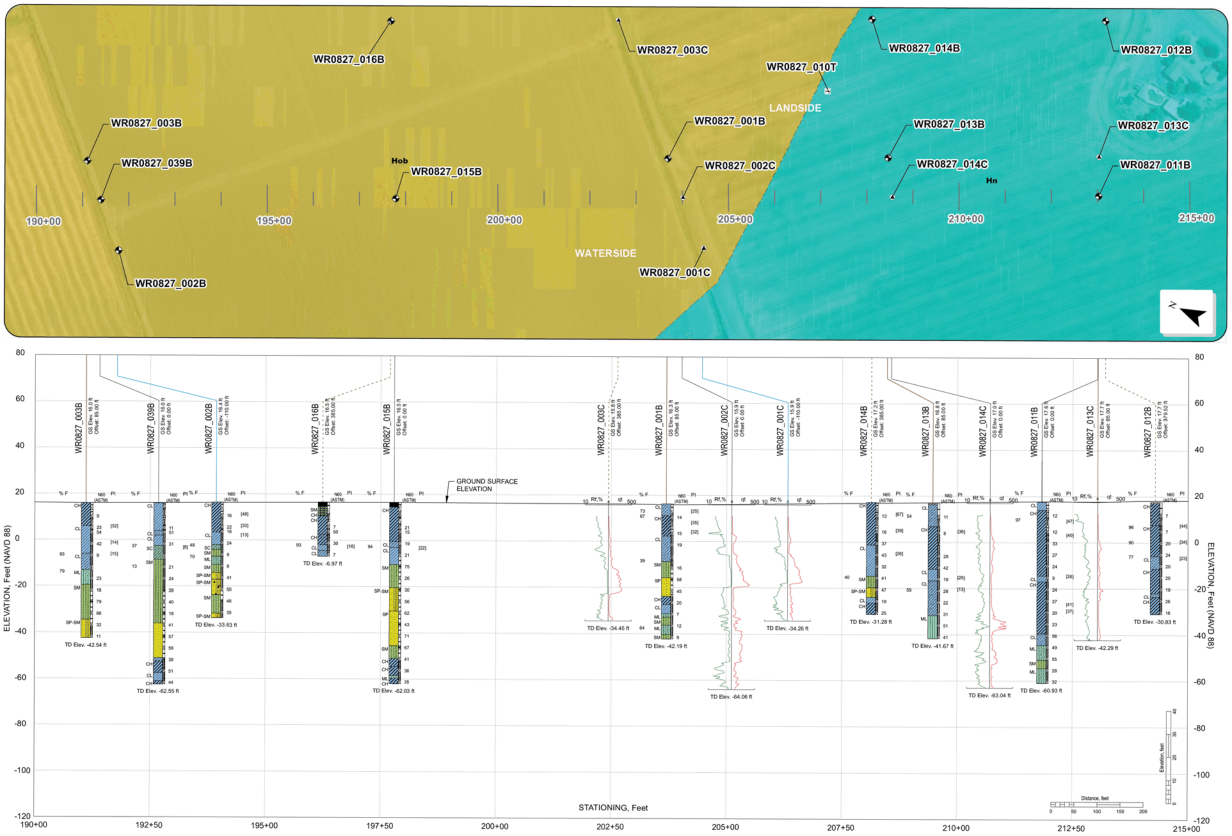
Table 7-5 summarizes goals and the extent of investigations in different phases of formulation and design. The data required for each design phase will vary and be progressively more intense. Geotechnical investigation should be performed in phases for larger and more complex projects. This phasing should allow the review of information that is obtained to inform further investigations, as well as allow more targeted investigation for specific design features as the design progresses.

Table 7-5: Investigation at Various Project Phases

Project Phase	Investigation Goals	Intensity of Investigation
Problem identification	Existing conditions characterization	Low: Widely spaced explorations, may rely on geomorphologic and geologic mapping or historical reports.
Formulation	Inform formulation level design; identify constraints	Low: Confirm expected geologic conditions and investigate potentially problematic geologic conditions.
Alternative analyses	Inform feasibility analyses; identify fatal flaws	Moderate: Sufficient explorations to identify any fatal flaws and support feasibility of alternatives and establish comparative costs.
Final design	Inform final design analyses	High: Sufficient characterization for detailed design.
Construction	Confirm design assumptions	As required to verify design assumptions.

Data obtained from information gathering and review, previous exploration phases, and preliminary analyses should be used to inform field investigation. The amount of available data should increase as the project progresses, and informed planning of targeted field investigations should improve efficiency, reduce uncertainty, and save in design and construction costs. Figure 7-12 shows a sample of a plan and profile sheet that can be used to summarize geotechnical boring data and geomorphologic mapping data collected along the levee alignment.

Figure 7-12: Typical Plan and Profile Sheet with Geomorphology



3.2.3.2 Geomorphologic Mapping

Geomorphologic mapping should be used to understand historical depositional environments that should govern the locations of potentially problematic deposits and the variability of deposits. Figure 7-12 shows a sample geomorphologic plan. It can be used to target specific exploration locations if additional investigation is needed. Mapping can also be particularly useful to identify soft foundation and areas of high potential seepage when it is combined with historical performance information and geophysical surveys.

An understanding of geology and geomorphology in the project area is critical to understanding and reducing uncertainty. By understanding the potential variability of geologic units, the appropriate number of samples and laboratory tests can be selected to characterize these deposits. More variable deposits may require more sampling and testing, where less variable deposits may require less sampling and testing.

Correlation should be made between the different soil types obtained from subsurface explorations with their parental rocks by reviewing available existing geology publications and subsurface investigation information. This should help identify the formation processes that originated the deposits on which the flood risk reduction system was or will be constructed. Geological information also can be used to identify areas where additional subsurface exploration will be required, and to define the limits of the weak areas. Depositional environments should include continental (alluvial, aeolian, fluvial, lacustrine), transitional, marine, and glacial.

3.2.3.3 Geophysical Surveys

Geophysical techniques can be used to obtain information on linear variations in stratigraphy, (e.g., configuration of soli/bedrock contact, foundation sands and gravels, lenses, and bar deposits). This can help assist planning of targeted explorations in areas of variation. Correlation with geomorphologic mapping can help inform uncertainty in geologic characterization of the project alignment.

Geophysical surveys also will be helpful in confirming the location of buried utilities and locating unknown utilities along the levee alignment. Additional guidance on managing utilities is presented in section 3.2.5.

As set out in more detail in EM 1110-2-1913 (USACE, 2000), geophysical investigations may also be useful in developing an understanding of existing earthen embankment levees. Understanding may be gained on issues such as:

- Changes in internal configurations of zoned embankments.
- Locations of lost or concealed metallic pipes.
- Soil gradation changes along levees.
- Embankment fracturing (including desiccation cracking), differential settlement, or subsidence.
- Possible areas of piping and internal erosion, including:
  - Piping or voids around or beneath concrete or metal structures (e.g., conduits).
  - Animal burrows and associated voids.

3.2.3.4 Groundwater Conditions

Determination of the groundwater regime and its classification is important—at least at a regional level—for seepage assessments and design of cutoff walls, for informing interior drainage requirements, and for assessing the feasibility of excavating borrow material.

Classification topics for riverine situations should include:

- Whether the river in question is a gaining/losing stream and whether it acts as a groundwater divide.
- Whether there are artesian conditions present.
- Whether there is a perched water table.
- The nature of any seasonal variations in groundwater levels.

Measurement of groundwater elevations can be facilitated by piezometers, monitoring wells, relief wells, dissipation during cone penetration testing, observations from standard penetration test borings, falling head tests, and other sources.

3.2.4 Hazardous Materials

If the levee project formulation process identifies that mitigation of hazardous materials is required and is not the responsibility of others to address prior to levee construction, rehabilitation requirements should be included as part of the design. Whoever is responsible for the management of the hazardous waste that will be disturbed by the levee construction should work with the designer and constructor in the management, treatment, and disposal of the hazardous waste.

3.2.5 Utilities

The presence of overhead and buried utilities can adversely affect levee construction if not properly addressed in formulation and design. It is common for levee projects to have utility constraints, especially in urban areas. Encountering unknown utilities or required utility relocations during construction can cause significant delays and increased costs.

A survey to identify utilities in the project area should be initiated during any ground topographic survey activities during the initial planning phase (Figure 7-13). If there are known utilities, the following are practices that should be used:

- All utilities should be clearly identified in the construction documents so that the levee constructor is well informed of the utilities in the project area. This includes identifying and conveying any requirements for construction around the utilities.
- Coordination of utility relocation and levee construction activities should occur prior to and during construction between the levee owner/levee designer, levee constructor, and the utility owner in the project area.

Figure 7-13: Example of Utilities in the Project Area

View of utilities (pipes and electrical lines) running along the levee landside toe right of way.

A utility survey should be initiated during the initial formulation phase. Avoidance of existing utilities (e.g., petroleum pipelines, transmission line corridors, or large buried water transmission pipelines) may be a factor in selecting alternative levee alignments. Identification of utilities in the vicinity of the levee alignment should include research of records and field reconnaissance studies. Important information that should be gathered includes:

- Type of utility, owner, existing easement information.
- Location and depth or overhead clearance at the levee location.
- For pipelines, product carried (e.g., water, petroleum products) and risk level.
- Location and depth of water supply or drainage channels and pump stations.
- Inspection and testing reports, repair history.
- Material of construction, size, and age.

Geophysical surveys also may be conducted along the levee alignments to identify unknown utilities and other features not shown in available records or on existing as-built drawings. Identifying abandoned drainage culverts and electrical/communication conduits on projects in developed and undeveloped areas is not uncommon.

Responsibility for relocating, modifying, or removing utilities should be determined. A public utility company typically is responsible for relocating, modifying, or removing its utilities. Coordination with the various utilities should begin as soon as possible, so the work can be completed before levee construction at the utility site is scheduled to begin. The work should be reflected in the planned construction schedule for the project to track progress. Instances may occur where utility relocation may fall within the scope of design. For example, existing discharge pipelines in a levee at a municipal drainage pumping plant may be elevated in the levee, or water mains may be relocated as part of the design and construction for a levee rehabilitation project. This type of work should be coordinated between the levee owner and utility owner during the design phase.

For utilities (new or existing) that penetrate levees, there should be an analysis demonstrating that the penetration does not impact levee performance. This can be accomplished with a risk assessment. For existing utilities that may negatively impact performance, relocation or modification of the utility should be considered. EM 1110-2-2902 (USACE, 2020) provides guidance on factors to consider in evaluating penetrations through levees. The elevation of the penetration relative to the design water surface should be evaluated along with the design life of the penetration and corrosion condition.

3.2.6 Sources of Construction Material

Potential sources of construction material should be revisited as design progresses to confirm they will meet the specification requirements for strength, grading, and permeability. Construction materials may include earthfill, clay, sand, aggregates, riprap and other erosion protection materials, such as concrete, structural steel, sheet piling, and bentonite. This information will also support preparation of the environmental documentation (e.g., truck traffic, air quality impacts), cost estimating, and schedule preparation. See **Chapter 8** for discussion on borrow areas for earthfill for levee construction.

3.3 Analysis and Interpretation

The dimensions, composition, and condition of any existing levee features should be established. Known performance of these features under load should be evaluated.

3.3.1 Geometry

The selection of levee alignment and crest elevation (with their implications for cross-section geometry) is discussed in **Chapter 6**. An understanding of the existing topography is required to establish design geometry, including along the length of the alignment and laterally beyond the alignment at least 150 feet toward both the waterside and landside. (Note that EM 1110-2-1913 (USACE, 2000) recommends expanding this 150-foot corridor on either side of the levee in order to meet the level of accuracy required for best practice in seepage analyses. For example, a 25-foot-high levee would need ground information for at least 500 feet from the levee.)

Existing geometry can be interpreted by plotting of lateral (perpendicular to the alignment) cross sections at regular intervals. The interval that should be selected depends on the available data and the design phase. Closer spaced intervals should be plotted during later phases of design and when more data is available.

Cross sections should also be plotted at areas of interest, such as where existing non-levee features intersect the alignment, or where poor performance of existing levee features have been recorded. Performance of the natural coast or riverbank where new levees are being designed also may warrant additional cross sections. Obtaining additional survey information at these locations also may be appropriate to refine the cross sections.

3.3.2 Water Level and Wave Conditions

The evaluation of water level and wave conditions should be undertaken as part of the project formulation process. This is discussed in **Chapter 6**.

3.3.3 Interior Drainage Requirements

The impact of the proposed levee on internal drainage of the leveed area should be assessed. This can include a review of existing drainage plans or analysis of the existing topography to establish the natural drainage patterns. The presence or need of drainage ditches, culverts, and pump stations also should be noted. Where this interpretation cannot be completed, additional investigation may be required. Section 11 presents guidance on design of interior drainage features.

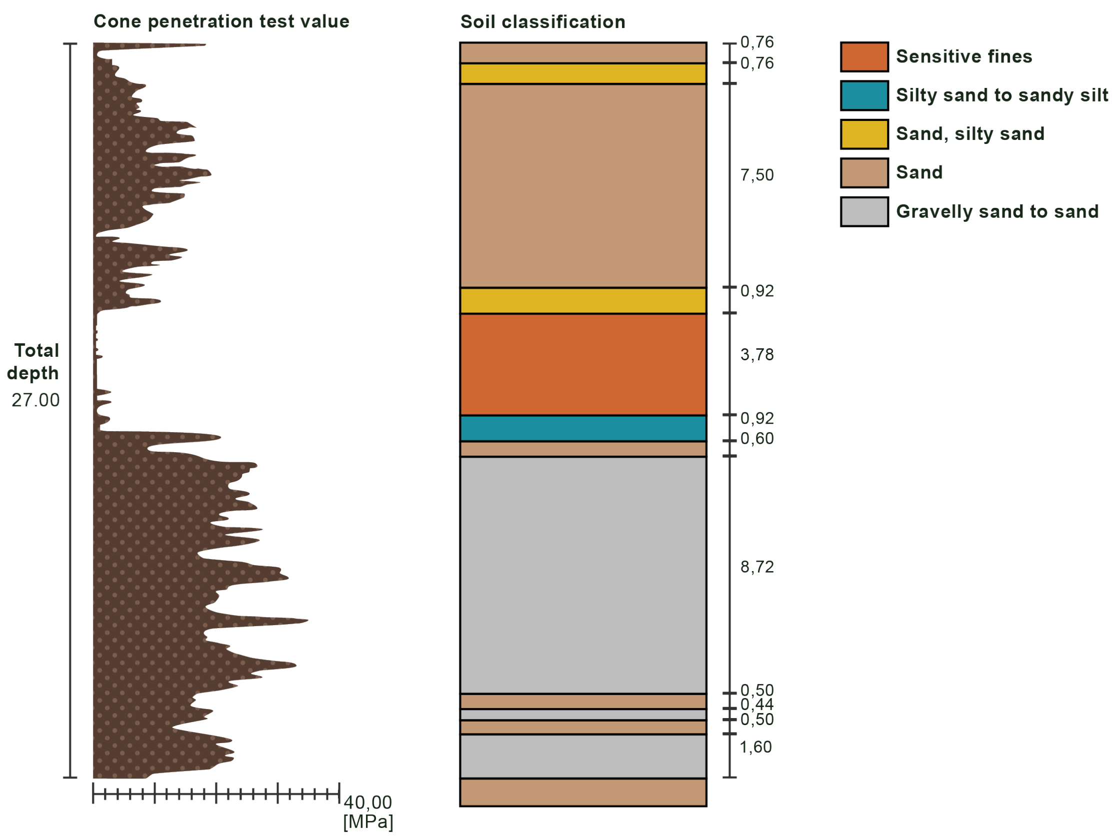
3.3.4 Geologic and Geomorphic Environment

Understanding the geologic and geomorphic conditions along the project alignment is critical to characterization of the existing foundation conditions and the future performance of the levee. Mapping of geologic units facilitates grouping of soils encountered in geotechnical units by similarity of depositional environments, age, structure, and mineral composition. Because testing every soil encountered during exploration is impossible, identifying similar materials for grouping is critical.

Geomorphic processes both influence how existing soils were deposited and how they may behave in the future. Rivers and coastlines are active areas with scouring, sediment transport, and deposition ongoing. The construction of levee features may affect these processes. The design team should understand these processes and the potential impacts on the expected performance of the levee features and incorporate resilience features as needed.

Figure 7-14 gives an example of an analysis of the foundation soil stratigraphy from field collected cone penetration testing.

Figure 7-14: Typical Site Characterization Analysis



3.3.5 Geotechnical Design Parameters

Geotechnical design parameters should be established for the project. These parameters should be based on engineering properties, including gradation, plasticity, compressibility, permeability/conductivity, shear strength, and density. These parameters can be established based on sampling and laboratory testing of the materials, known parameters for the mapped geologic units, and field test results. Additional guidance regarding evaluation of design parameters and performing analyses is provided in the Guidance Document for Geotechnical Analysis (California DWR, 2015).

Because exploration and laboratory test data are always limited, geotechnical parameters should be correlated to geologic and geomorphologic mapping and depositional environments. This allows estimation of the limits of conditions indicated in explorations and identification of soil units with similar engineering properties.

Longitudinal geologic profiles and geologic cross sections should be plotted to assist in interpreting geologic conditions. The geomorphologic maps should be assessed to understand differences in soil properties and stratigraphy. Although these cross sections frequently are plotted perpendicular to the levee alignment, designers should remember levees are three-dimensional, and critical conditions can occur oblique to the levee alignment and during analysis may require adjustments to reflect the three-dimensionality of a particular situation (see in particular the discussion on seepage in section 9.1.2).

3.3.6 Selection of Levee Reaches for Analysis

Reach selection is the process of identifying sections of the levee that possess similar characteristics. A levee reach can be represented by a single cross section and set of design parameters. Reach selection should be undertaken as part of the project formulation process, discussed in **Chapter 6**. It should be informed by the results of the risk assessment (**Chapter 4**)—where the risk is lower it may be feasible to analyze fewer cross sections and embrace the wider envelope of design parameters associated with longer reaches.

Initial reach selection may be modified during the design process based on findings from initial analyses, additional investigations, and further characterization. As set out in EM 1110-2-1913 (USACE, 2000) modifications may arise as a result of changes or clarifications in physical features and hydraulic loadings, improved geological/geotechnical/geophysical data, or further information on past performance and maintenance activities.

4 Levee Features

This section introduces levee system features and key design elements of those features; the design of these features is explored in greater depth in the following sections. The features are common to new levees, levee modifications, and levee rehabilitation. The levee should include features that exclude water, divert water, or control the release of water (**Chapter 2**).

The levee may be made up of multiple features and combinations of features as described in detail in **Chapter 2**. These commonly include:

- Embankment
- Floodwalls
- Closure structures
- Transitions
- Seepage control features
- Channels and floodways
- Interior drainage systems
- Pump stations
- Instrumentation

Table 7-6 shows features, associated elements, and common analyses required for design.

Table 7-6: Levee Feature Design Requirements

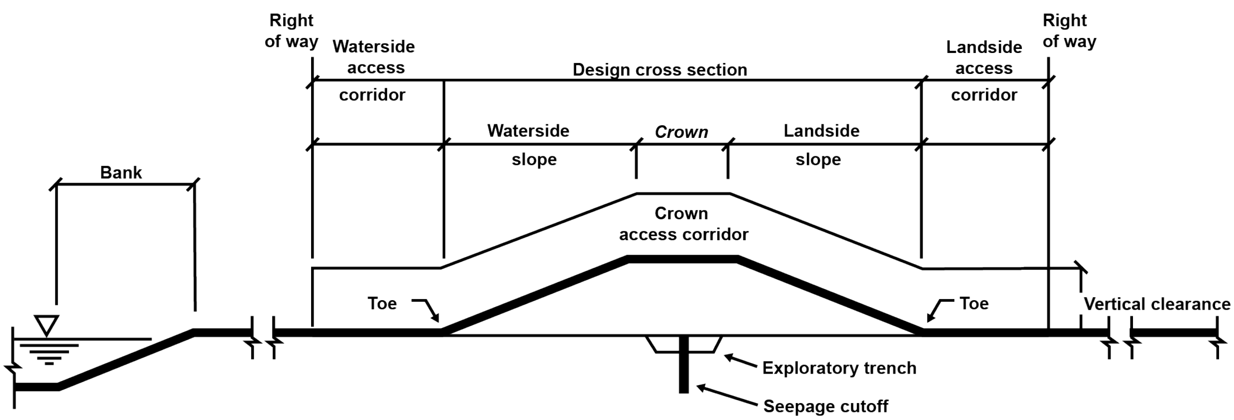
Feature	Design Elements	Common Required Analyses
Embankment	• Crest elevation • Geometry • Exploratory trench • Right of way • Composition • Seepage control (if needed) • Stabilization measures (if needed) • Erosion protection • Overtopping protection (if needed)	• Seepage • Stability • Erosion • Settlement
Floodwalls	• Top of wall elevation • Wall type • Structural materials • Foundation • Interface with embankment • Seepage cutoff • Erosion protection • Penetrations • Scour protection	• Seepage • Overturning and sliding • Wall deflection • Structural failure • Settlement
Closure structures	• Sill elevation • Materials • Foundation • Width (access characteristics) • Operation	• Seepage • Overturning and sliding • Wall deflection • Structural failure • Settlement
Transitions	• Geometry • Material type • Erosion protection	• Erosion • Cracking • Settlement
Seepage control features	• Dimensions • Composition • Capacity • Collection	• Underseepage • Throughseepage
Channels and floodways	• Capacity • Side walls/slopes • Structural elements	• Hydraulics • Structural failure • Global stability • Flow
Interior drainage systems	• Size • Materials • Seepage protection	• Required flow capacity • Internal drainage • Structural failure
Pump stations	• Pump sizes • Electrical • Security • Piping • Sump	• Internal drainage and uplift • Power requirements • Structural failure
Instrumentation	• Type • Location • Data collection	• Displacement • Settlement • Water level/pressure • Hydraulics

5 Embankment

5.1 Elements

Figure 7-15 shows a basic embankment cross section for new levee construction. Required dimensions typically should be established based on design analyses, using applicable design criteria, or based on applicable guidelines for the project. Note the need for landside and waterside access corridors, as discussed in **Chapter 9**.

Figure 7-15: Typical Embankment Elements



5.1.1 Geometry

The embankment geometry includes the height of the embankment, the embankment crown width, and the embankment slopes. The geometric design also may include benches, berms, access corridors, and exclusion zones for utilities.

Side slopes of embankment levees should generally not be steeper than 3 horizontal to 1 vertical, as this facilitates the use of mowers for maintaining the grass cover. Unique situations (e.g., lack of space) may call for landside slopes steeper than 3:1, but the risks to maintenance operations should be fully evaluated before adoption. Levees constructed of sand may well require side slopes of 5:1 or flatter to prevent throughseepage.

Determination of the crown width should consider constructability of the levee, access needs for O&M, width needed for haul trucks, and equipment needed for floodfighting. Crown width should generally be a minimum of 20 feet, although some applicable standards may allow a lower figure.

This geometry may need to be modified, based on site-specific conditions and other factors such as available right of way, existing use (e.g., a public road on the crown), O&M, and risk-informed design analyses.

In the case of coastal levees, analyses of wave runup and overtopping will affect the final decisions about the embankment slope and crown level. The waterside slope should be adapted to limit wave runup and thus is generally flatter than that required for fluvial levees.

5.1.2 Inspection Trench

An inspection trench (sometimes termed exploratory trench) should be excavated under all new levees. The purpose of this trench is to expose or intercept any undesirable near-surface foundation features not identified during design. Inspection of the trench also allows the designer to assess the near-surface foundation conditions directly beneath the levee for comparison with anticipated geotechnical conditions, determined from the project's subsurface explorations to determine any areas of large unacceptable fills or utility problems.

The trench should be at or near the centerline of the levee fill, or at or near the waterside toe of sand levees, so as to connect with waterside impervious facings. The trench typically should be a minimum of 6 feet deep, measured from grade after clearing, grubbing, and stripping the levee foundation. The bottom width of the trench should be 8 to 12 feet, to allow inspection by the designer, and for subsequent backfill compaction using mechanical equipment. The trench may be deepened if local utilities are installed deeper, if the designer requires over-excavation or other treatment, and if pockets of unsuitable material are encountered during inspection of the trench. Figure 7-16 gives examples of inspection trenches.

Trenches should be backfilled with compacted fill, consistent in quality with the material to be used in the overlying embankment. Procedures for backfilling the trench to grade should be provided in the technical specifications. Where the levee design incorporates a seepage cutoff wall into the foundation, inspection of the trench excavated for installation of the cutoff wall might fulfill the purpose of an inspection trench; however, the trench should be excavated and inspected early in the construction process to provide an early warning of problems.

Figure 7-16: Example Inspection Trench

An inspection trench being excavated and a view of the trench revealing the foundation soils. The trench is under a 1,800-foot-setback levee along the right bank of the Sacramento River in California.

5.1.3 Materials

The embankment may be homogeneous (Figure 7-17), constructed using one soil type, or zoned (Figure 7-17), constructed using several different soil types placed in well-defined zones within the embankment.

Figure 7-17: Typical Homogenous Embankment Section

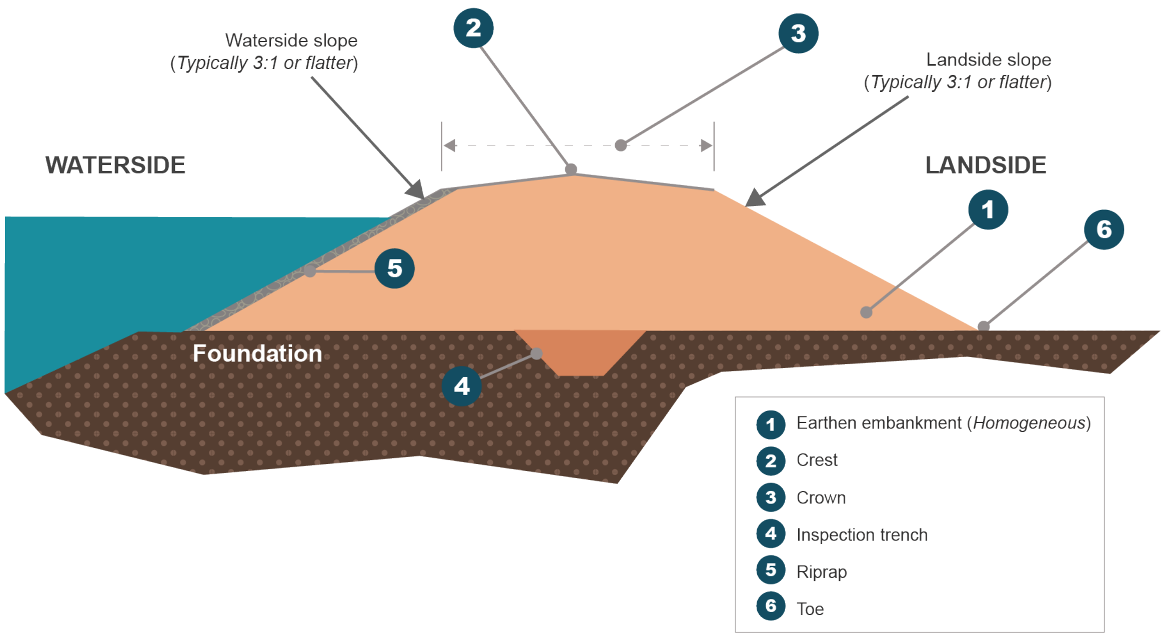
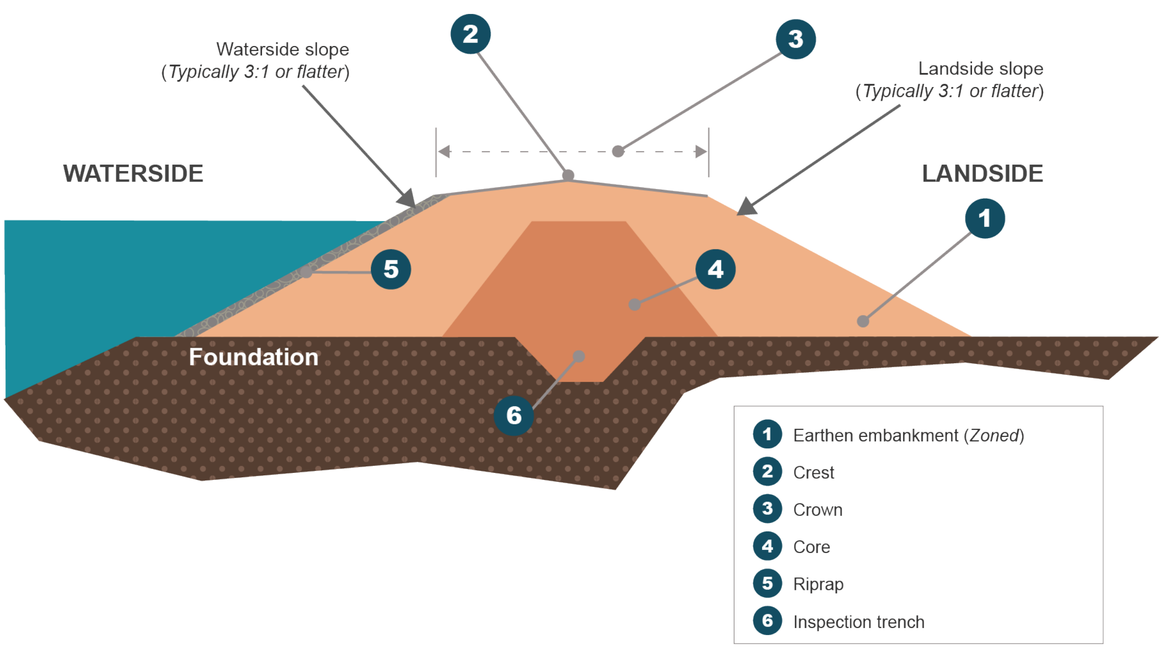


Figure 7-18: Typical Zoned Embankment Section



The homogeneous embankment is constructed using one soil type. The soil may come directly from borrow sources, or may require blending of materials from one or more sources to meet the strength and permeability requirements.

Where low permeability material is in limited supply, or cost-prohibited to obtain, a zoned embankment can be considered. The low permeability material is typically placed in a central core zone that is flanked on both sides with ‘shell’ zones formed of higher permeability soils suitable for embankment construction as described below. Note that the central core zone may be shifted to the waterside, but the required top elevation of the core for seepage control should not be reduced. Moving the core zone in the landside direction is not recommended. A low permeability blanket zone placed at the waterside face of the levee might be considered, but this approach is typically used as a throughseepage remediation for an existing levee, not for a new embankment levee.

Higher permeability material in the shell zones may improve landside embankment and foundation seepage control (section 9) and slope stability (section 5.2) by lowering the hydraulic gradient through the shell. More permeable material on the waterside slope can reduce the potential impacts of rapid drawdown (section 5.2) depending on its gradation.

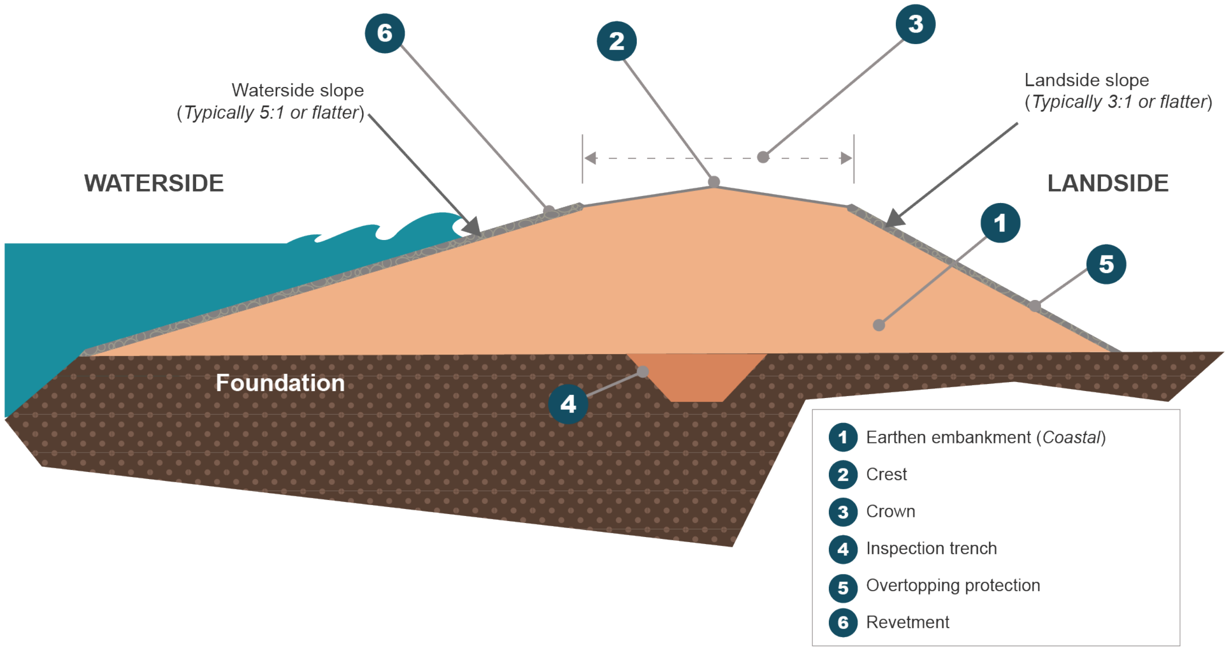
To control internal erosion, the design of a zoned embankment should also evaluate filter compatibility between adjacent zones and where zones contact the foundation. (See EM 1110-2-1913 (USACE, 2000) for further information on filter criteria and procedures for evaluating and designing filters for soil compatibility.) Incompatibility of soils can lead to soil migrating from one zone into another (piping or internal erosion), resulting in the creation of voids and possible levee failure. If filtering between zones is necessary, the following may be considered:

- Provide graded granular filters at zone contacts and on the foundation on the landside of the core zone only. Depending on soil gradations in the adjacent zones, a multi-stage filter may be needed to prevent piping. Use of geotextiles as an alternative to graded granular filters is not recommended because of the increased risk of clogging, the risk of creation of voids to one side of the geotextile, and the risk of creating preferred paths for sediment movement at joints.
- Provide one or more transition soil zones within the shell material both waterward and landward of the core with gradations that meet the filtering criteria.
- Place the shell material on the waterward and landward sides of the core so that finer, compatible material is against the core zone, but the material progressively becomes coarser toward the waterward and landward slopes.

Note that the primary consideration for the shell zone is filter compatibility to prevent internal erosion, not seepage control. The use of graded granular filters as both a filter and drain to meet seepage or stability criteria is described in section 9.

Figure 7-19 shows a coastal levee embankment and some added components that may be incorporated due to coastal hazards. The embankment may be homogeneous or zoned as described above. Surface erosion protection (e.g., rock armor) may be required to resist erosion due to wave action on the waterside slope. Due to potential for wave overtopping, it is possible that erosion protection may also be needed on the crown and landside slope.

Figure 7-19: Typical Coastal Embankment Section



The zoned or homogenous embankment should be composed of compacted soil meeting the seepage control and strength properties established by risk-informed design analyses. The material should not include high-plasticity soils, organics, or other swelling or compressible soil. The soil should also be free from hazardous waste and environmental contaminants. The homogeneous or core zone material should be of low-erosive potential to reduce the risk of throughseepage-induced internal erosion. In terms of the shell zones in zoned embankments, in addition to the gradation requirements discussed above, the design should specify maximum heights of material layers, their moisture content, and compaction requirements; these requirements for the shell zones will likely differ from those specified for the core zone.

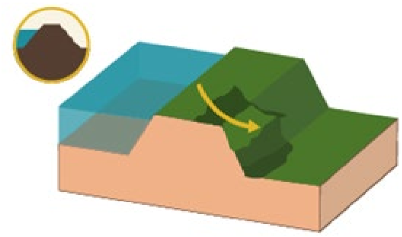
5.1.4 Common Required Analyses for Embankment Levees

The embankment should be designed and constructed to function under the required flood loading without loss of its structural integrity and stability, considering all potential failure mechanisms that could compromise its ability to function as designed.

Analyses generally completed to support earthen embankment feature and element designs include seepage (discussed in section 9.1) and resultant internal erosion, slope stability, external erosion, and settlement (which are discussed in this section). These analyses typically are deterministic but should be risk-informed and include analysis of probable failure modes. The results should be compared against established criteria that may be project-specific or regulatory. Design modifications may be required where analyses results do not indicate expected performance meeting the project objectives. This may include changing the embankment geometry or composition, or the addition of seepage control, stability, or erosion control features. These features are described next.

5.2 Stability Control

Instability of levee slopes is a potential failure mode that should be mitigated because it can lead to inundation of the leveed area. Instability can result from throughseepage, saturation of soft embankment soils, soft foundation soils, or undermining by erosion. The potential for instability will be affected by the following:



Instability

- Shear strengths of the levee embankment and foundation, which may vary over time.
- Pore water pressures in the soil, which likely will vary over time.
- Weight of the levee embankment and foundation.
- Compressibility of the levee foundation.
- Geometry of the levee and adjacent ground surface, which may vary over time, especially in areas vulnerable to erosion.

Waterside slope stability with rapid drawdown may also be a risk factor for the levee that should be evaluated. The starting water surface elevation for waterside rapid drawdown analysis should be the design water surface elevation. A lower elevation can be selected if the stratigraphy of the levee embankment is configured so this lower starting point will result in a more critical analysis. The drop in water surface should be selected based on historical hydrograph records for the study area. Further guidance for analyzing the waterside drawdown case is presented in the Guidance Document for Geotechnical Analysis (California DWR, 2015).

Risk reduction measures for levee slope instability can include flattening levee slopes, embankment or foundation drainage including drained stability berms, removing and replacing soft foundation or levee materials, and ground improvement measures. Design elements for stability control features are shown in Table 7-7.

Table 7-7: Stability Feature Design Requirements

Stability Feature/Action	Associated Potential Failure Modes	Design Elements	Advantages	Disadvantages
Drainage including internal and/or foundation drainage, drained stability berm	• Slope stability • Internal erosion due to throughseepage	• Alignment • Width • Height • Composition	• Cost • Lower construction risk	• Does not reduce underseepage risk. • May still allow boils and require floodfighting.
Removing and replacing weak materials	• Slope stability • Throughseepage • Settlement	• Material to be removed • Composition of replacement material	• Cost • Lower construction risk	• Feasibility of removal. • May require temporary flood risk reduction measures.

Stability Feature/Action	Associated Potential Failure Modes	Design Elements	Advantages	Disadvantages
Ground improvement	• Slope stability • Settlement	• Composition of materials	• Lower construction risk	• Cost • Schedule

Flattening embankment slopes usually will increase the stability of an embankment, especially against shallow failures that take place entirely within the embankment. Flattening slopes also spreads the embankment load more uniformly and increases the length of potential slip surfaces, thereby increasing resistance to sliding, especially for deeper failure surfaces.

Slope flattening typically is considered in design of a new levee and as a possible rehabilitation for an existing levee with poor performance history caused by low strength of the embankment and foundation soils. Where stability risk includes other factors such as throughseepage, slope flattening by itself may not be an option. Drained stability berms may be more appropriate.

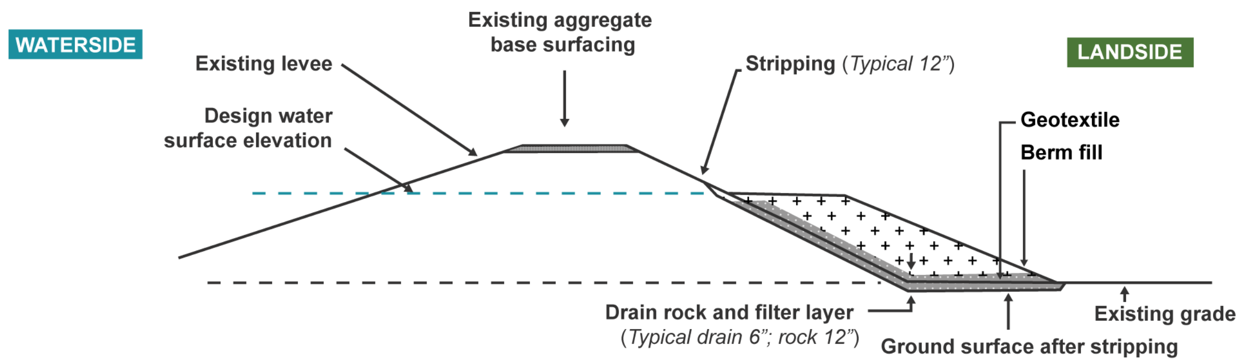
Stability berms increase the resisting mass at the toe, reducing the likelihood of slope instability. Table 7-8 summarizes stability berm elements and advantages and disadvantages. Design elements are discussed in the following paragraphs.

Table 7-8: Stability Berm Elements

Stability Feature	Associated Potential Failure Modes	Design Elements	Advantages	Disadvantages
Stability berm	• Slope stability • Internal erosion piping	• Alignment • Width • Height • Composition	• Cost • Lower construction risk	• May not reduce seepage. • Does not reduce underseepage risk. • May still allow boils and require floodfighting.

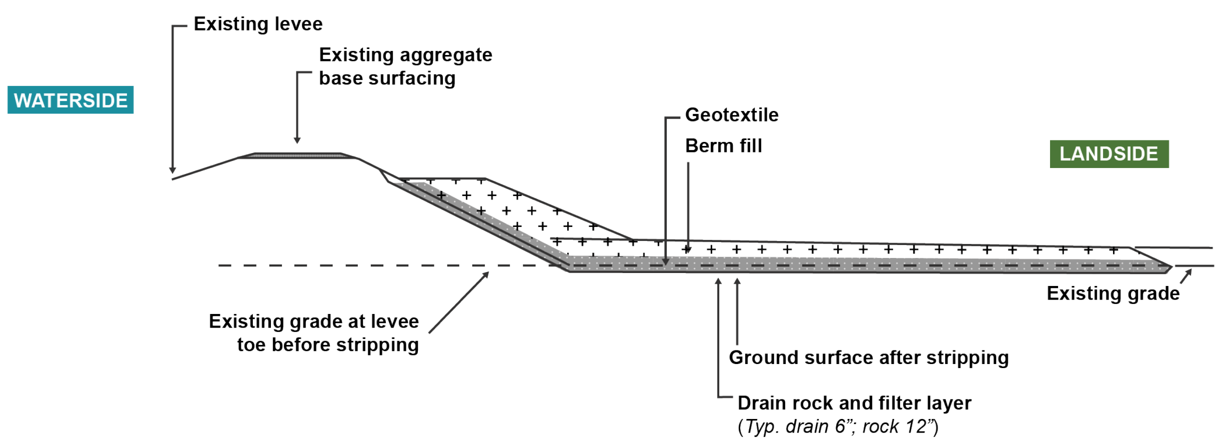
Figure 7-20 shows details for a typical drained stability berm. The berm is constructed along the landside of an existing levee. The stability berm may incorporate a drain layer on the foundation and levee slope to accommodate potential throughseepage. If the concern is only slope stability because of the low strength of the embankment soils—and throughseepage is not a concern—the drain layers may not be needed but a geotextile may still be used to provide additional strength to the berm (rather than to provide a filtration function, which is prohibited by some regulating agency guidelines).

Figure 7-20: Typical Drained Stability Berm



Where both throughseepage and underseepage conditions exists, a combination of drained stability berm and **seepage berm** may be used to remediate slope stability and seepage. Figure 7-21 shows the details of the combination berm.

Figure 7-21: Typical Combination Berm



The top width of the stability berm should be determined from slope stability analyses, considering actual soil properties and seepage conditions. A typical width is 15 feet. Determining the width of the seepage berm is discussed in section 9.3.2. The height of the stability berm on the landside should match the design water surface elevation on the waterside. Berm fill can be levee fill or other suitable random fill, excluding highly plastic clays or organics. The presence of locally available borrow materials should be considered in design.

5.2.1 Loading Conditions

The slope stability of a levee embankment usually is analyzed for the most critical loading conditions that may occur during the life of the project. These loading conditions are as follows:

- **Case 1, steady-state seepage (landside)**: Flood loading applies when water levels on the waterside exceed the landside levee toe elevation. Water exists long enough that the phreatic surface within the levee embankment has been fully established.

- **Case 2, rapid drawdown (waterside)**: The pore pressures within the levee embankment are dissipated slower than the water level is drawn down. Phreatic surfaces before and after drawdown should be defined.
- **Case 3, end of construction (landside and waterside)**: This case represents undrained conditions for low-hydraulic conductivity embankment and/or foundation soils, where excess positive pore water pressure is present because the soil has not had time to drain since being loaded in compression and shear. The phreatic surface usually is at or below the landside toe for this case.
- **Case 4, undrained loading**: It is also reasonable to perform a short-term stability analysis with the design flood loading. For many levees, this case will result in a similar slope factor of safety as the end of construction case. However, there are other situations (e.g., where there is a geotextile on soft soils or there are I-walls on the earthen embankment), the water loading can result in a lower factor of safety.

5.2.2 Shear Strength Selection

A range of methods may be used for selecting and assigning shear strength properties to levee embankment and foundation materials. Detailed shear strength characterization is described in Appendix D of EM 1110-2-1902 (USACE, 2003). The methods range from estimating strengths using empirical relationships (related to simple index testing) to comprehensive in situ (standard penetration testing N-values or cone penetration testing tip resistance) and detailed laboratory shear strength testing, combined with careful evaluations of the full range of soil behavior over the range of potential loadings. Published relationships may be and often are used for preliminary analyses, but advanced design and risk analysis projects may warrant site-specific testing.

In selecting shear strengths, the designer should distinguish between free-draining materials and non-free draining materials. Free-draining materials are defined as coarse-grained materials with little or no fines (typically less than 12%), so when sheared, excess pore pressures are rapidly dissipated and thus are unlikely to cause problems. Free-draining materials are assumed to remain drained, and their shear strength is characterized by their drained strength parameters for all loading conditions. Non-free-draining materials are defined as fine-grained materials or coarse-grained materials with significant fines, so when sheared, they generate (and sustain with respect to loading) excess pore pressures.

Shear strengths for analysis of specific situations should be guided by the following:

- Steady-state (case 1) and rapid drawdown (case 2): To evaluate strength and stability at steady-state and rapid drawdown, consolidated undrained triaxial with pore pressure measurement and consolidated drained triaxial, or direct shear, are performed to measure the shear strength. For long-term stability and stability during rapid drawdown, the soil may be fully or only partially saturated. However, if the soil is below the groundwater table or beneath the phreatic surface, the pore water pressures are positive, and for design purposes, the soil is assumed to be saturated. If the soil is above the water table or in a zone of capillarity and where pore pressures are negative, the beneficial effects of negative pore water pressures are conservatively neglected by assuming the pore water pressures are zero. Conventional effective stress shear strength parameters are used for both the saturated (positive pressure) and partially saturated (zero pressure) zones. The effective stress shear strength parameters are measured on specimens fully saturated before laboratory testing, regardless of the saturation that may exist in the field.

- End of construction (case 3) and undrained response to flood load (case 4): To evaluate strength and stability in these cases, unconsolidated-undrained shear tests are performed to measure the shear strength. In this case, the shear strengths are expressed as a function of total stresses, and the approach is valid for both saturated and unsaturated soils.

5.2.3 Stability Analyses

Stability analysis methods are well defined and can be performed using commercially available, fully documented software. As described in section 3.3.6, critical embankment sections for analysis should be selected based on geometry, loading, and geologic conditions. The accuracy of the analysis depends on the extent and quality of subsurface data and material testing available to make the stability models. Experienced professionals should be in charge of interpreting subsurface data, defining soil stratification, and assigning properties to the soil strata.

Slope stability analysis normally adopts a limit equilibrium approach to evaluate the following:

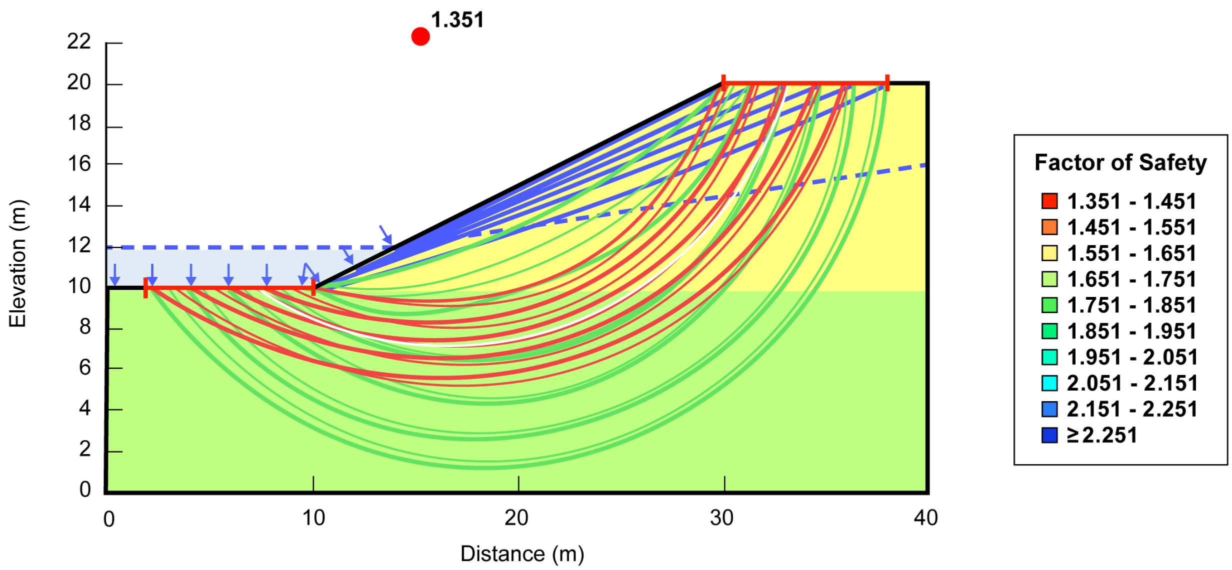
- Landside levee slope stability for static steady-state conditions corresponding to the selected water level conditions.
- Waterside levee slope stability for rapid drawdown conditions.
- Landside levee slope stability for special loading conditions.

The following is the process for a slope stability analysis:

- Select the representative levee cross section in a reach (i.e., the critical section with the least favorable condition) based on the geometric data from LiDAR, bathymetry, and stratigraphic material properties from geotechnical investigations (reach selection and cross section selection described in detail in section 3.3.6).
- Establish water surface elevations and apply appropriate surcharge loads.
- Obtain applicable pore pressures from seepage analyses (section 9.1).
- Select and verify shear strength properties of the applicable soil layers (section 5.2.2).
- Choose appropriate analysis methods.
- Perform the analysis, document the results, and compare with the past performance, if applicable.

Slip surfaces (circular, noncircular, optimization): Modern limit equilibrium method-based computer programs available for analyzing slope stability require assumption of a slip surface for which a **factor of safety** is calculated. Multiple potential surfaces are assumed and the one with the lowest factor of safety is called the most critical slip surface; the associated factor of safety for this surface should meet specified criteria. Most programs have search algorithms used to find the most critical slip surface, but the appropriateness of the resulting information should be verified prior to adoption. Figure 7-22 shows the results of a typical slope stability analysis, indicating the different slip surfaces analyzed and their associated factors of safety.

Figure 7-22: Typical Slope Stability Analysis



When the slope stability analysis is complete, the designer should document whether the reach meets criteria or not for the applicable loading conditions with current configurations, whether a mitigation measure is needed or not.

Generally, the minimum required factor of safety is 1.4 to 1.5 for steady-state seepage (case 1), depending on water level, 1.0 to 1.2 for rapid drawdown (case 2), depending on the duration of waterside levels before drawdown and 1.3 for end of construction (case 3), and for undrained response to flood loading (case 4). Further guidance is available in EM 1110-2-1913 (USACE, 2000).

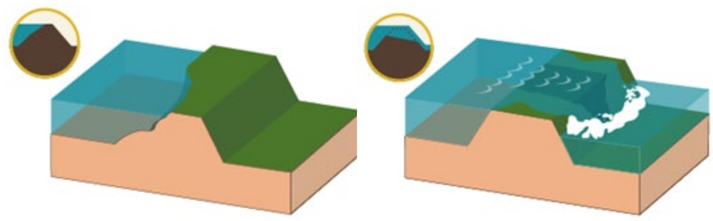
FACTORS OF SAFETY IN MORGANZA TO GULF LEVEE PROJECT

Morganza to the Gulf is a large levee project along the Mississippi River in Louisiana. The project includes 98 miles of levees that will reduce risk to 52,000 structures and 200,000 people from hurricanes. Following Hurricane Katrina, design standards for levees and floodwalls for the levees in New Orleans were changed to increase the global slope stability factor of safety for still water scenarios from 1.3 to 1.5. These higher factor of safety requirements were applied to the feasibility study for the Morganza to the Gulf project and resulted in a significant increase in the estimated project cost.

A risk assessment was performed in 2012 to evaluate the Morganza to the Gulf levee design and also revisited the performance of levees during the Katrina event. The majority of issues during Katrina were associated with floodwalls, not embankment levees. The embankment levees that were designed to a factor of safety of 1.3 performed well. Based on the risk assessment and associated deterministic analyses, lowering the global slope stability factor of safety from 1.5 down to 1.3 did not adversely impact reliability of the levee system. The ability to learn from previously load-tested levees during Hurricane Katrina did influence this decision.

The project was approved using the reduced global factor of safety of 1.3 that resulted in a smaller levee prism and is projected to save taxpayers about $7 billion.

5.3 Erosion Control Features



Erosion protection can be required for different potential erosion sources, including surface runoff during precipitation, riverine or coastal flow, waves, and overtopping.

Where erosion of the landward slope occurs due to overtopping, the failure may be via surface erosion (progressive removal of surface layers) or via head cut, where the erosion causes progressive removal of vertical cuts from the landward face of the levee. The factor that determines which of these two mechanisms occurs depends on the composition of the embankment. Erosion can occur slowly or very rapidly, depending on the site conditions and the erodibility of the levee material. Either way, the process eventually leads to collapse of the levee crown. Erosion can also decrease slope stability and increase the potential for backwards erosion piping.

Erosion on the landside embankment face also can occur because of throughseepage. Erosion can result in progressive loss of embankment that shortens seepage paths and creates slope instability that can result in levee failure.

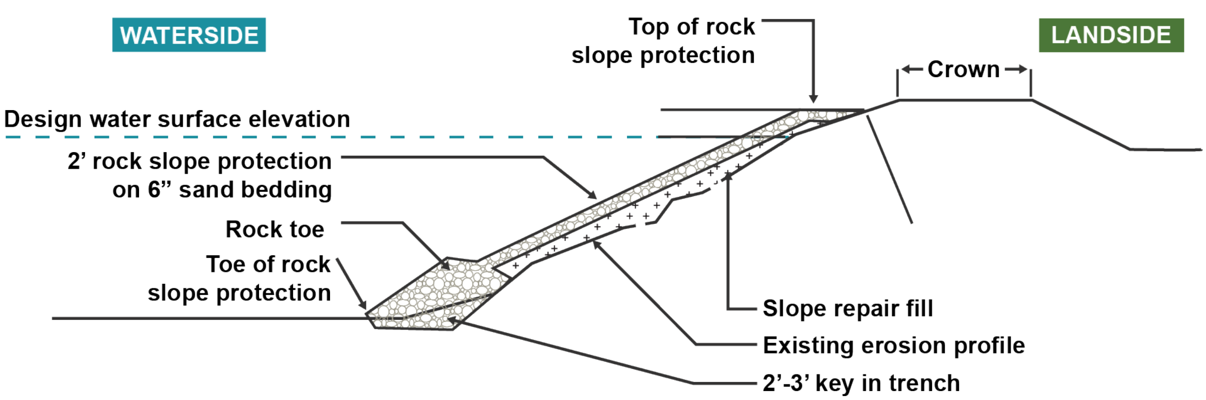
Progressive erosion of the waterside bank and toe because of scour may occur, particularly on the outer side of river bends and on coasts subject to wave action. Such scour can be particularly hazardous as it may not be observable if submerged. Bathymetric surveys should be part of site characterization and may require repeating in areas susceptible to waterside bank and toe erosion, to monitor for erosion undermining the levee. In addition, the geomorphologic process should be studied, understood, and monitored to identify locations potentially susceptible to scour. Table 7-9 summarizes erosion control feature design elements and their design requirements.

Table 7-9: Erosion Control Feature Design Requirements

Erosion Control Feature	Associated Potential Failure Modes	Design Elements	Advantages	Disadvantages
Armoring/ bedding	• Surface erosion • Overtopping erosion • Riverine erosion • Wave erosion	• Areal extents • Height • Composition	• Low maintenance	• Aesthetics • Cost • Constructability
Vegetation	• Surface erosion • Overtopping erosion • Riverine erosion • Wave erosion	• Areal extents • Height • Composition	• Cost • Aesthetics	• Increased maintenance

Erosion likelihood is commonly mitigated through armoring and vegetating the levee. Figure 7-22 shows typical rock armoring details for the waterside face. Design elements for armoring include rock gradation, locations, height, and placement techniques.

Figure 7-23: Typical Erosion Repair



Vegetation is most commonly used as protection against surface runoff erosion of the embankment slopes. Vegetation should be designed based on local conditions and regulations, as described in section 2.3.5.

Resilience to overtopping can be increased by armoring the crown and rear face. This is particularly recommended at locations of controlled overtopping, as discussed in section 10.2.

5.3.1 Erosion Analysis

Erosion analyses can include simple, empirical review of bank or coastline erosion and expert elicitation of likely morphological processes.

At specific locations, evaluation of soil erosion due to currents, waterside wind/waves, and landside overtopping can be used via the widely used linear excess stress erosion models to estimate erosion rate as a function of hydraulic shear stress and soil erosion resistance.

Riprap armoring/bedding can be sized using widely used stability relationships for rock of different sizes, taking account of the fact that well-interlocked permanently placed rock will be more stable than loose launchable rock toes designed to move into and fill areas of scour (see EM 1110-2-1601 (USACE, 1994b)). Safety factors may need to be increased to take account the risk of freeze-thaw and of vandalism. (A minimum individual rock weight of 80 pounds is usually sufficient to prevent theft and vandalism.)

SOURCES FOR DETAILED GUIDANCE FOR PERFORMING EROSION ANALYSIS

- EM 1110-2-1913 Design and Construction of Levees (USACE, 2000).
- EM 1110-2-1100 Coastal Engineering Manual (USACE, 2002).
- Guidance Document for Geotechnical Analysis (California DWR, 2015).
- *Evaluation of Potential for Erosion in Levees and Levee Foundations*, Center for Geotechnical Practice and Research #64 (Duncan *et al.*, 2011).
- *International Levee Handbook* (Eau and Fleuves, 2017).

5.4 Settlement Control

Levees often are constructed over areas with highly variable subsurface conditions. Although it is desirable to construct levees in foundation conditions that require minimum post-construction measures to account for settlement because of alignment constraints, it often becomes necessary to construct levees across highly compressible foundations. Table 7-10 expands on the procedures commonly applied to levee projects to deal with this situation.

Table 7-10: Settlement Design Procedures

Settlement Procedure	Design Considerations
Remove and replace	• May be used to reduce settlement in areas where shallow soft deposits or fill layers exist. • Becomes less feasible where compressible layers are deep, or where high-water tables exist that will require dewatering during construction.
Staged construction	• Requires adequate time for consolidation. • Settlement monitoring instrumentation readings during construction may be used. • Levee lifts can be scheduled to be placed after completion of the original construction.
Prefabricated vertical wick drains	• Allow rapid construction of levees over very soft foundations. • Design is optimized by maximizing the wick drain spacing to achieve an appropriate degree of consolidation needed within the time available for the consolidation.

Settlement Procedure	Design Considerations
	• The long-term performance of wick drains should be considered in seepage evaluations.
Preloading and surcharge fills	• Typically uses material not meeting levee fill requirements; it is placed before levee construction and removed before final levee construction. • Where stability conditions allow, surcharge placed to heights in excess of the final levee height may be placed to accelerate the consolidation time needed during construction.
Soil improvement or amendment	• Soft foundation soils can be excavated, treated (such as drying), and replaced in lifts and compacted. • Additives used in soil improvement should have the effects on hydraulic conductivity and strength evaluated and measures taken to avoid any negative impact. • Deep mixing methods are viable alternatives with considerations: - Deep mixing methods introduce hardened elements in the levee and/or levee foundation that can cause differential settlement. - Projects that are candidates for deep mixing methods are those where levee materials can deform without cracking, rather than those that are stiff or hard.

5.4.1 Settlement Analysis

Settlement analysis methods are well-defined and can be performed using commercially available, fully documented software. The accuracy of the analysis depends on the extent and quality of subsurface data and material testing available to make the stability models. Guidance on performing settlement/stability analyses for levees is presented in EM 1110-1-1904 (USACE, 1990).

5.5 Modification and Rehabilitation

The following sections provide guidance for some typical modifications and/or rehabilitation that may be required for existing embankment levees to implement risk reduction measures. Such measures may be needed to accommodate settlement or water surface elevation design criteria changes for riverine levees because of changed hydrology, or coastal levees because of hurricane tides and storm surges.

5.5.1 Seepage and Stability

Seepage analysis is discussed in section 9.1. Required stability modifications or rehabilitation can be made by constructing one or more of the options discussed in the remainder of section 9: cutoff walls, seepage and stability berms, blanket drains, and relief wells.

5.5.2 Levee Crest Elevation Raise

Levee enlargement by adding embankment fill or constructing a floodwall on the levee crown are the two most economical and practical approaches to provide additional levee height.

5.5.2.1 Enlargement Using Earthwork

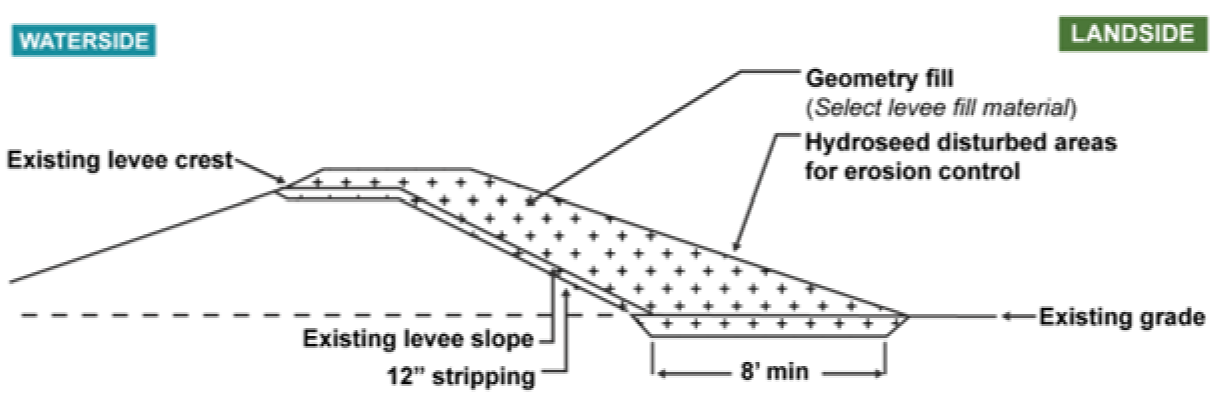
Levee enlargement may be accomplished using one of the following three methods:

- Landside enlargement by elevating the levee crown and thickening the landside slope using suitable compacted fill, as shown in Figure 7-24, with a maximum slope of 2 horizontal to 1 vertical for the bench cut into the existing levee. Analysis of landside material placement should take material compatibility and filter requirements into account.
- Waterside enlargement by elevating the levee crown and thickening the waterside slope using suitable compacted fill.
- Straddle enlargement by elevating the levee crown and thickening the waterside and landside slopes using suitable compacted fill.

The advantages and disadvantages to be considered for each method may include:

- Methods with landside slope enlargement could require additional right of way.
- Methods with waterside slope enlargement could be more costly if rock slope protection is present, or if groundwater or tidal conditions exist.
- Methods with waterside slope enlargement may have more environmental impacts, may change the erosion pattern within the river, and can encroach on the hydraulic capacity of the channel, possibly increasing the design water level for all levees in the system.

Figure 7-24: Typical Embankment Raise



Geotechnical investigation should be completed to confirm the material properties of the existing embankment soil and proposed fill. New fill should be comparable or better than the existing fill; compacted to at least the same density. Enlargement for stability and settlement should be checked, and if applicable, throughseepage or underseepage should be assessed, following the guidelines presented in this chapter. After stripping, the new fill should be bonded with the existing fill by scarifying and compacting existing surfaces and benching existing slope surfaces. Thin fills should be avoided. The horizontal width of new fill should be wide enough to accommodate hauling and compaction equipment.

5.5.2.2 Raising Embankments Using Floodwalls

Floodwalls (section 6) can be constructed on levee earthen embankments to increase crest elevation. This method may be appropriate when the existing right of way is not available or is too expensive to acquire, if the foundation conditions do not permit an increase in the levee section using earthwork, or where short wall height is needed to increase the levee crest elevation.

Floodwall advantages and disadvantages are:

- This may not be economical compared to using earthwork for the enlargement, and economic comparisons should be performed.
- The floodwall would restrict access to the waterside of the levee.
- This may affect O&M activities and access to the waterside slope for emergency response activities.

The floodwall should have adequate stability to resist all forces that may act on it. Geotechnical investigation of the existing embankment should be considered to confirm the material properties used to evaluate floodwall stability. Two common types of a floodwall used for enlargement are the I-wall and the inverted T-wall, as described in section 6.

Note that I-walls are less robust than other wall types, particularly in soft soils and when the wall is taller than a few feet. They can be more susceptible to overtopping erosion in certain conditions.

5.6 Seismic Considerations

Levee seismic performance generally is of moderate concern because of the low probability of a damaging seismic event, especially in combination with a flood event. However, regions of high seismicity may warrant a review of levee performance. In such high seismic areas, a levee may be evaluated for the likelihood of foundation failure because of liquefaction for a design seismic event that may result in slope failures and loss of freeboard. This may require geotechnical evaluations of the levee and foundation to better characterize the materials present. If liquefaction is not determined to be an issue, further evaluation may not be needed. However, if liquefaction may be an issue, further evaluation should be considered, including a risk assessment of failure and impacts on the leveed area. Guidance for seismic evaluations of levees is presented in the Guidance Document for Geotechnical Analysis (California DWR, 2015).

Risk-reduction measures for seismic concerns include the removal and replacement of susceptible foundation soils, ground stabilization measures, and compaction grouting. Another risk mitigation measure is the development of a contingency plan to rebuild or partially rebuild the levee within a short timeframe if liquefaction were to occur.

6 Floodwalls

Different wall types may be required based on the desired height, the available right of way, geologic conditions, operability, and aesthetics. For further guidance, refer to USACE EM 1110-2-2502 (USACE, 1989a). Typical design steps for a floodwall would include:

- Establish the design flood water surface elevation or profile along the length of the barrier.
- Set the required height of the barrier by combining the design water surface elevation with estimated wave heights and freeboard allowance.
- Establish design load combinations, including dead loads, water and wave loads, wind loads on exposed surfaces, and allowance for debris impact.
- Design all of the components based on critical load combinations to meet applicable structural codes for the material used (e.g., American Institute of Steel Construction Manual for steel members).
- Evaluate the barrier-foundation system for overturning and sliding stability under the worst combination of design loads. Safety factors of 1.25 or higher should apply.

Concrete T- or L-walls generally have been found to provide greater resilience and are preferred. These walls have T- or L-shaped foundations that provide overturning and sliding resistance. In addition, the wall stiffness reduces deflections and the potential for formation of gaps between the wall and soil that can lead to wall failure.

Sheetpile walls sometimes are used when insufficient right of way can be obtained to construct concrete walls. One advantage of sheetpile walls is they can be driven or pushed into the surface to form an integrated seepage cutoff. However, sheetpile walls historically have deflected under load, leading to wall rotation and subsequent overtopping and failure. If used, detailed analyses are required to establish expected sheetpile wall deflection under the design loads.

Stabilized earth walls also can be considered. A stabilized earth wall essentially is a steepened waterside slope made stable by reinforcing. This reduces the footprint of an earthen-type structure. Erosion protection will be required to protect such walls from flow and waves.

Demountable floodwalls may be considered in situations where a permanent obstruction is undesirable, although they typically include some permanent foundation features.

Each of these types is discussed in more detail in the following sections.

6.1 Reinforced Concrete Floodwalls

Reinforced concrete floodwalls are an option for coastal and riverine floodplains and may be used aloneor in combination with embankment levees to provide the required level of flood risk reduction. They generally are employed where space is limited and thus an embankment levee may not be a viable option.

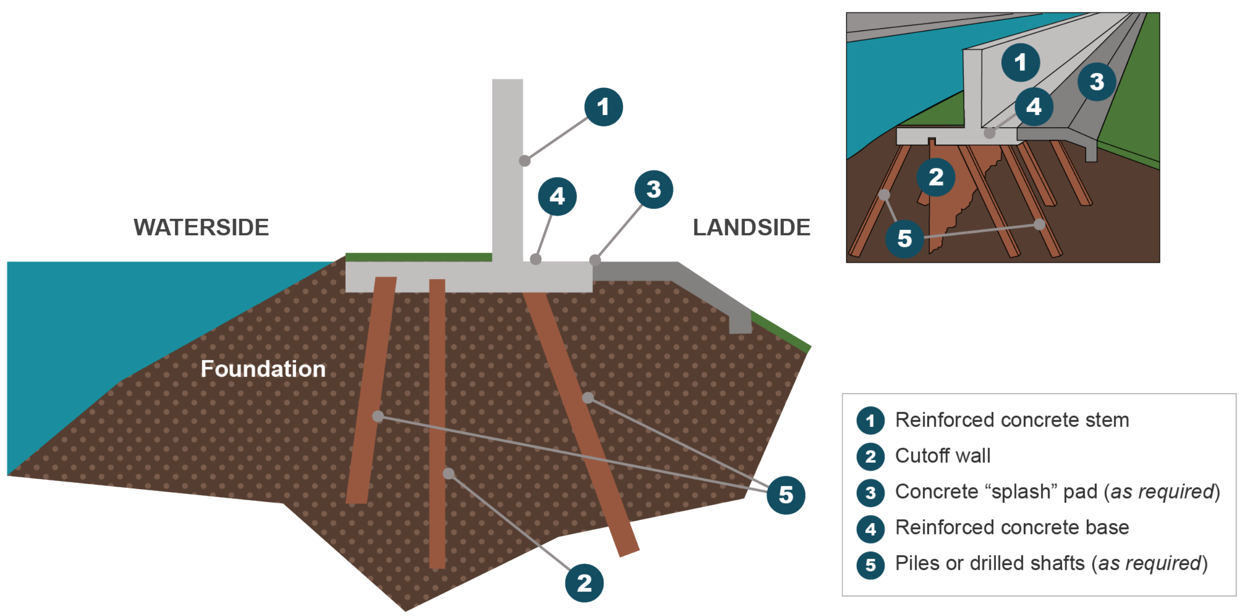
Table 7-11 and Figure 7-25 illustrate the design elements for the floodwall and the analyses normally required for design. Walls should be designed for all applicable static, hydrodynamic (wave), and resilience design loads. Boat or barge impact loads also should be considered if applicable, based on levee location. Seismic loading also may apply, but usually does not control the design of the wall.

Floodwalls may breach through different processes that cause loss of wall height or allow water to pass through the wall alignment. A wall-related failure mode generally is related to some geotechnical instability or an internal structural failure causing an uncontrolled release of water.

Table 7-11: Floodwall Design Elements

Feature	Design Elements		Common Required Analyses
Floodwalls	• Top of wall elevation • Structural materials • Interface with embankment • Erosion protection	• Wall type • Foundation • Seepage cutoff • Penetrations • Scour protection	• Seepage • Overturning and sliding • Wall deflection • Global stability • Settlement

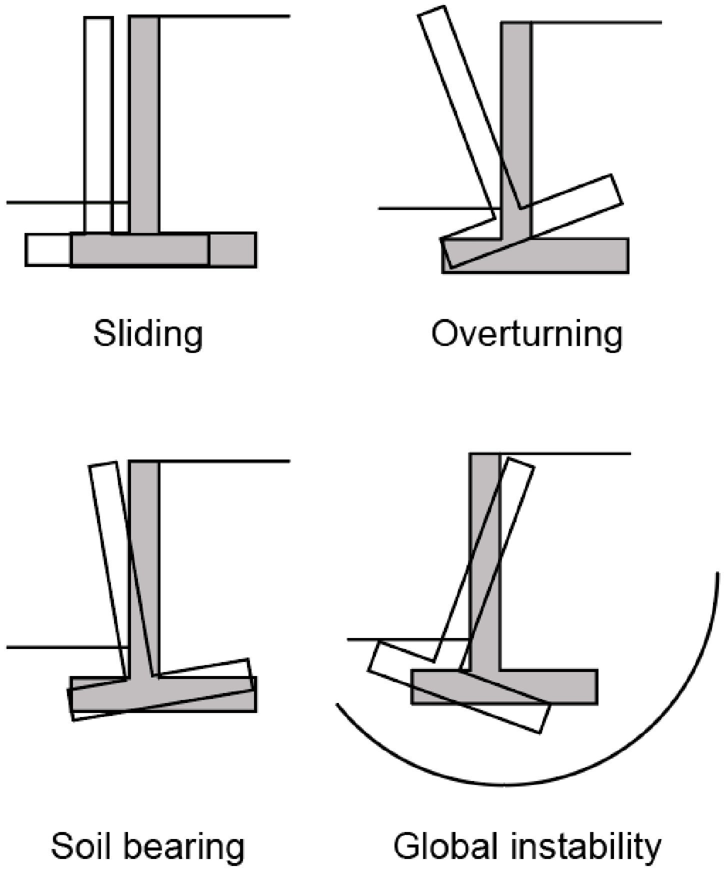
Figure 7-25: Example Floodwall



6.1.1 Geotechnical Design

A geotechnical stability failure typically causes some displacement associated with sliding, overturning, loss of bearing, or undermining of the wall. Displacement of a wall can be initiated by inadequate stability, either translational or rotational, or a combination of both. Figure 7-26 shows the potential failure modes for a floodwall. Contributing factors commonly associated with a wall instability include overtopping erosion, wave over splash erosion, overload, increased uplift, heave, low soil strength, or waterside gap formation.

Figure 7-26: Floodwall Geotechnical Failure Modes



Analyses generally completed to support the geotechnical design of floodwalls include:

- Wall overturning
- Wall sliding
- Wall deflection and gap formation
- Settlement
- Bearing failure
- Flotation
- Underseepage
- Slope instability undermining the wall

Additional design may be required for floodwalls that have openings to allow pipe penetrations and drainage. Seepage and piping issues are discussed separately in section 9.

6.1.1.1 Gravity Foundations

Foundations are normally designed using allowable stress theory. For normal operations and design flood stages—and to avoid overturning—the resulting load on the foundation should normally remain within the middle third of the base.

Gravity foundations where the floodwall is supported on soil are generally only used for riverine or inland levees. Further, protecting the soil foundation from scour that can occur in both flowing riverine floods and the wave action in coastal hurricane floods is critical. A concrete sheetpile toe wall should be on the waterside of the slab. The toe wall should be designed for scour depths and also provide cutoff. Guidance for designing soil founded structures is available in EM 1110-2-2100 (USACE, 2005) and also EM 1110-1-1905 (USACE, 1992a).

6.1.1.2 Pile Foundations

Pile foundations can be required for inland floodwalls with weak soils. Coastal floodwalls often require pile foundations to resist the high lateral forces produced by waves.

Pile foundation designs currently are performed by using either allowable stress design or load and resistance factor design, but normally use allowable stress design with service loads. Further guidance on pile foundations for levees may be found in EM 1110-2-2906 (USACE, 1991).

Pile capacity in firm soils and those that bear on rock can be designed efficiently with the end bearing greatly increasing bearing capacity. Where rock foundations are shallow, there may be insufficient tension capacity provided by pile wall friction to overcome hydrostatic uplift. As a result, anchoring tension rods into the firm foundation may be necessary.

In softer soils, ground instability and settlement can greatly increase the loading on the piles. Ground improvements should be considered to relieve the loads placed on piles.

The most economic design may be soil improvements versus piles. Those improvements include preloading, the addition of stability berms, and the use of deep mixing methods, although deep mixing methods are not always less costly.

Where concrete floodwalls are added to the crest of earthen embankment levees, the additional resistance offered by pile foundations may be required to avoid instability of the embankment (section 5). Piles are used to nail the foundation and provide the added resistance that, when combined with the soil capacity, meets the embankment stability factors of safety. However, impacts of pile driving on the existing features of the earthen embankment need to be taken in to account and any resultant deformations and cracking will need to be remediated.

If used, pile foundations can account for approximately 30% of the structure cost.

6.1.2 Overtopping Resilience Design

Overtopping of floodwalls can result in scour of the landside and subsequent wall failure. Coastal floodwalls and inland floodwalls within designated overtopping reaches are the most vulnerable. In these areas special care should be provided in the design of overtopping protection.

Research has established empirical relationships to permit the design of scour protection measures according to the design overtopping rates and volumes. Measures can include hard surfaces, such as concrete or riprap, grass/sod for lower rates, or other erosion control features.

6.1.3 Structural Design

The structural design includes design of individual wall structural members and additional checks such as:

- Flexural and shear strength of piles, wall stem, and base slab heel and toe.
- Foundation heel and toe flexural and shear.
- Wall deflection.
- Key shear strength (and flexural strength if needed).
- Rebar laps and embedment.
- Steel reinforcing ratios for all structural members (including for crack control).
- Wall connection to existing tie-in structures, such as bridge abutments, wall transitions, and others.
- Anchorage to existing structures.

Additional design may be required for floodwalls that have openings to allow pipe penetrations and drainage.

The initial step to design floodwalls is selection of the structural design criteria, which includes load combinations, factors of safety, or demand-to-capacity ratios.

- **Loading conditions**. Load cases for riverine and coastal hurricanes are similar in that hydraulic loads are the principal loads. Load factors (and allowable stress design) consider the return period of the storm event and load case combination frequency. Load combinations may be identified as usual, unusual, and extreme, as shown in Table 7-12.

DETAILED GUIDANCE FOR STRUCTURAL DESIGN

The following documents may be referenced.

- USACE EM 1110-2-2100 (USACE, 2005) Stability Analysis of Concrete Structures.
- USACE EM 1110-2-2104 (USACE, 2016) Strength Design for Reinforced Concrete Hydraulic Structures.
- USACE EM 1110-2-2502 (USACE, 1989a) Floodwalls and Other Hydraulic Retaining Walls.
- USACE EM1110-2-2107 (USACE, 2022) Design of Hydraulic Steel Structures.
- USACE EM 1110-2-2906 (USACE, 1991) Design of Pile Foundations.
- American Concrete Institute 318-14 Building Code Requirements for Structural Concrete (ACI Committee 318, 2014).
- American Concrete Institute 350-20 Code Requirements for Environmental Concrete Structures (ACI Committee 350, 2021).
- American Association of State Highway and Transportation Officials 2012 Load and Resistance Factor Design Bridge Design Specifications (AASHTO, 2012).
- U.S. Bureau of Reclamation 2019 Best Practices in Dam and Levee Safety Risk Analysis (USACE and U.S. Department of the Interior, Bureau of Reclamation, 2019).

When selecting load combinations, see the following from the above list: EM 1110-2-2104, American Association of State Highway and Transportation Officials, and U.S. Bureau of Reclamation allowing appropriate selection of design criteria. American Society of Civil Engineers Structural Engineering Institute 7-22 (ASCE, 2022) can also be used when including conditions for flood loads.

Table 7-12: Load Condition Categories

Load combination Categories	Annual Probability (p)	Return Period (tr)
Usual	Greater than or equal to 0.10	Less than or equal to 10 years
Unusual	Less than 0.10 but greater than or equal to 0.0013	Greater than 10 years but less than or equal to 750 years
Extreme	Less than 0.0013	Greater than 750 years

  - Usual loads refer to loads and load conditions, which are related to the primary function of a structure and can be expected to occur frequently during the service life of the structure. A usual event is a common occurrence, and the structure is expected to perform in the linearly elastic range.
  - Unusual loads refer to operating loads and load conditions of infrequent occurrence and/or short term. Since risks can be controlled by specifying the sequence or duration of activities and/or by monitoring performance, construction and maintenance loads are classified as unusual loads. Loads on temporary structures used to facilitate project construction are also classified as unusual. For an unusual event, some minor nonlinear behavior is acceptable, but any necessary repairs are expected to be minor.
  - Extreme loads refer to events that are highly improbable and can be regarded as emergency conditions. Such events may be associated with major accidents involving impacts or explosions and natural disasters because of earthquakes or flooding, which have a frequency of occurrence that greatly exceeds the economic service life of the structure. Extreme loads also may result from the combination of unusual loading events. The structure is expected to accommodate extreme loads without experiencing a catastrophic failure, although structural damage that partially impairs the operational functions are expected, and major rehabilitation or replacement of the structure may be necessary.

- **Concrete resistance**. Building Code Requirements for Structural Concrete and Commentary (ACI Committee 318, 2022)specifications dictate minimum concrete strength, maximum water cement ratios, and other durability requirements. The critical concern for mass concrete is the increased thermal stresses brought on by the hydration process. Thicker placements are more susceptible to increases in thermal stresses. Unacceptable cracking can compromise the structural integrity of the reinforced concrete. A set thickness does not exist among the codes that establishes whether the placement is mass concrete. A common threshold is 5 feet; other considerations are the ambient temperature, structure size and restraint, and concrete mix ingredients.
- **Analysis methods** predominantly use load and resistance factor design. Concrete design should consider both serviceability (durability) and strength. Durability criteria limits tension stress and the resulting tension cracks that lead to spalling and corrosion of reinforcement. (Note that the provision in Building Code Requirements for Structural

Concrete and Commentary (ACI Committee 318, 2022) that allows tension in reinforcing steel used in floodwalls to approach yield should be limited to infrequent events.)

6.1.3.1 Design of Submerged Structures

Structures submerged in water and those exposed to water loadings are considered concrete hydraulic structures. The term implies serviceability (durability) is part of the design. The duration and frequency of exposure to water should be considered when selecting the design criteria. Durability is increased when crack width in concrete is minimized, resulting in less penetration of water to corrode rebar. This can be accomplished in design by limiting the tension in the reinforcement and increasing the amount of concrete cover. Alternatively, epoxy-coated rebar or stainless-steel rebar can achieve the same service life.

FURTHER GUIDANCE FOR STRUCTURAL DESIGN OF MASS CONCRETE SEAWALLS

The following documents cover the formulation, design, and construction of seawalls:

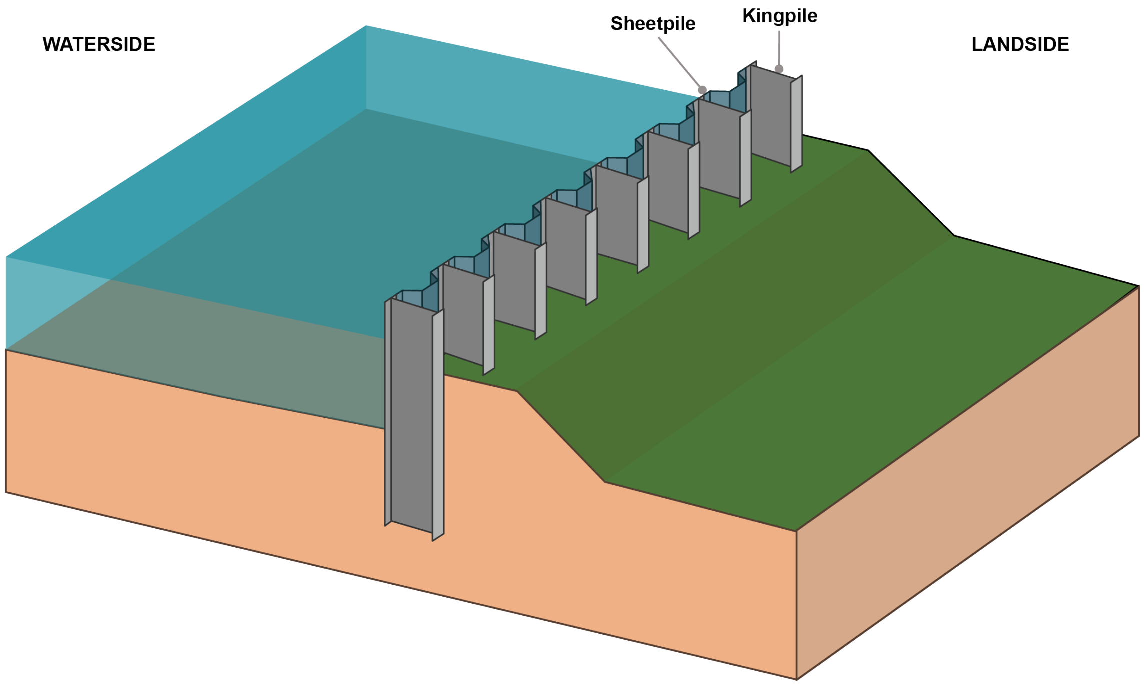
- USACE EM 1110-2-1100, Coastal Engineering Manual-Part V (USACE, 2002b).
- USACE EM 1110-2-1614, Design of Coastal Revetments, Seawalls, and Bulkheads (USACE, 1995a).

6.2 Steel Sheetpile Floodwalls

Steel is the most common material used for sheetpiling walls because of its inherent strength, stiffness, ductility, relative light weight, and long service life when protected from corrosion. Steel sheetpile walls are commonly known as I-walls and consist of a driven, vibrated, or pushed row of interlocking vertical pile segments to form a continuous wall. The wall may extend to the full height with sheetpile or be constructed with sheetpiling in the embedded depth and a monolithic cast-in-place, reinforced concrete wall in the exposed height (sheetpile with concrete cap). A possible disadvantage of I-walls can be excessive deformation, leading to poor performance and potential failure under the maximum design loads.

Combined wall systems are typically used when regular sheetpiles are not strong enough to carry the required loads. Combined wall systems (see Figure 7-27) consist of two primary components, the king pile and the intermediary sheetpiles. The intermediary sheetpiles transfer horizontal loads to the king piles, while the king piles carry the majority of the bending moment and shear, and also may carry vertical loads. The wall components are driven, vibrated, pushed, or drilled into place.

Figure 7-27: Example Combined Sheetpile Floodwall System



6.2.1 Design Procedures

The design of sheetpile floodwalls require the following components:

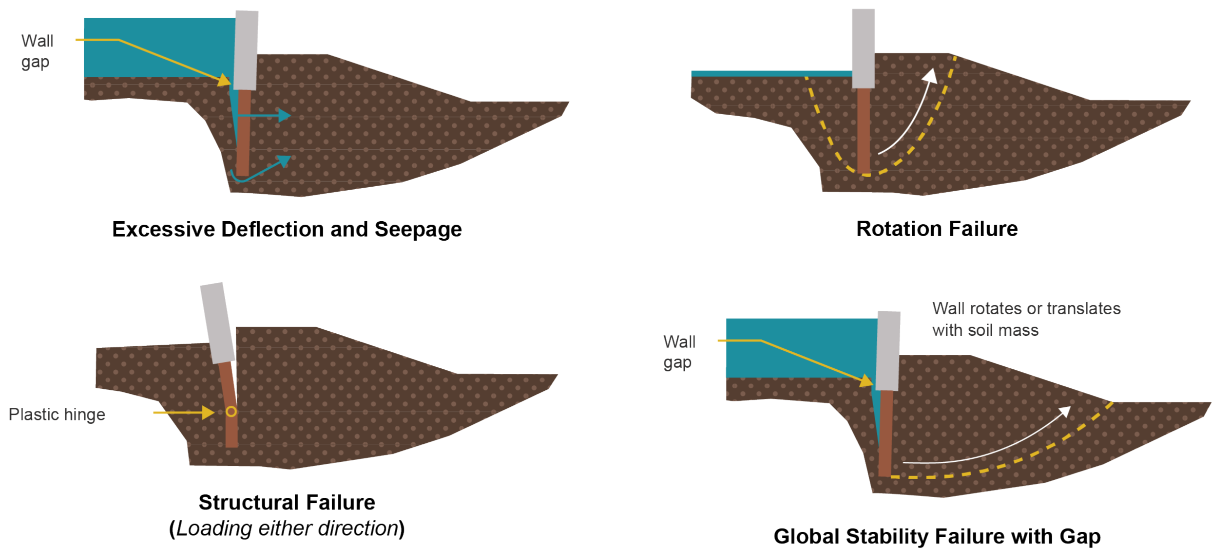
- Evaluation of the forces and lateral pressures that act on the wall.
- Determination of the required depth of piling penetration.
- Computation of the maximum bending moments in the piling.
- Computation of the stresses in the wall and selection of the appropriate piling section.
- Design of any support system.

However, before these operations can be initiated, certain preliminary information should be obtained. In particular, the controlling dimensions should be set. These include the elevation of the top of the wall, the elevation of the ground surface in front of the wall (commonly called the dredge line), the maximum water level, the mean tide level or normal waterside elevation, and the low water level. A topographical survey of the area also is helpful.

6.2.2 Potential Failure Modes

As shown in Figure 7-28, the potential failure modes of a steel sheetpile wall include excessive deflection and seepage, structural failure, rotational failure because of inadequate pile penetration, and global stability failure.

Figure 7-28: Sheetpile Wall Failure Modes



6.2.3 Loads

The loads on a sheetpile wall are primarily from the soil and water surrounding the wall and from other influences, such as surface surcharges and external loads applied directly to the piling, including earth pressures, water loads (i.e., hydrostatic and seepage forces), and surcharge loads and other applied loads. The loading conditions—including usual, unusual, and extreme cases—are the same as for concrete floodwalls (section 6.1). See EM 1110-2-2502 (USACE, 1989a) for further details.

6.2.4 Methods of Analysis

The two basic types of steel sheetpile walls are cantilevered walls and anchored walls.

A cantilever wall is assumed to rotate as a rigid body about some point in its embedded length. This assumption implies the wall is subjected to the net active pressure distribution from the top of the wall down to a point (subsequently called the "transition point") near the point of zero displacement. The design pressure distribution then is assumed to vary linearly from the net active pressure at the transition point to the full net passive pressure at the bottom of the wall. Equilibrium of the wall requires that the sum of horizontal forces and the sum of moments of any point are both equal to zero. The two equilibrium equations may be solved for the location of the transition point and the required depth of penetration. Walls designed as cantilevers usually undergo large lateral deflections and are readily affected by scour and erosion in front of the wall. Because the lateral support for a cantilevered wall comes from passive pressure exerted on the embedded portion, penetration depths can be quite high, resulting in excessive stresses and severe yield.

An anchored sheetpile wall derives its support by two means—passive pressure on the front of the embedded portion of the wall, and anchor tie rods near the top of the piling. For higher walls, the use of high-strength steel piling, reinforced sheetpiling, relieving platforms, or additional tiers of tie rods may be necessary. The overall stability of anchored sheetpile walls and the stress in the members depends on the interaction of a number of factors, such as the relative stiffness of the piling, the depth of piling penetration, the relative compressibility and strength of the soil, and the amount of anchor yield. In general, the greater the depth of penetration, the lower the resultant flexural stresses. Design of an anchored sheetpile wall usually uses the free earth support method or fixed earth support method.

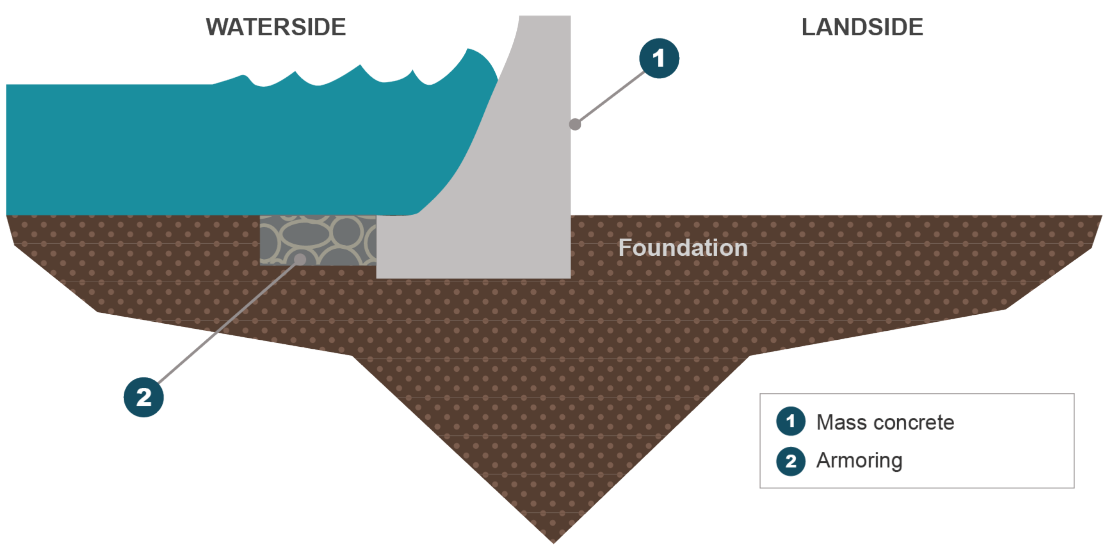
6.2.5 Overtopping Resilience

As discussed for other wall types (section 6.1.2), overtopping of floodwalls can result in scour of the landside and subsequent wall failure; therefore, scour protection should be provided. In the case of sheetpile walls, consideration should also be given to means of limiting penetration of floodwater down the face of the sheetpiling to a location where it may reduce shear strength.

6.3 Mass Concrete Gravity Walls

Mass concrete gravity walls are often used in the coastal environment because of their ability to better manage large wave forces. A gravity wall is typically a massive, concrete structure with its weight providing stability against sliding forces and overturning moments. The key functional element in design is establishing the crest elevation to minimize overtopping, whether from excess river levels or from storm surge and wave runup. Figure 7-29 shows an example of a typical mass gravity wall.

Figure 7-29: Typical Mass Gravity Wall



Where the wall is subject to wave attack, the front face should be curved to deflect wave runup. Under some conditions, wave runup can also be reduced by the inclusion of steps on the front face. The depth of excavation into the foundation will depend on local geotechnical conditions and embedment needed for stability. If the foundation is not suitable to support the wall, or if settlement with time is an issue, a pile foundation or other type of ground improvement may be needed. Depending on height, size, and loading, reinforcing steel may be required for waterside and landside faces, and for the base if piles are used. Proper closure of the wall at the ends either to existing topography or to other flood risk-reduction features is an important consideration.

Waterside toe protection (armoring) is typically required to prevent undermining from wave action.

Finished grading requirements for land development may require some backfilling on the landside of the wall. Maintenance roads may also be present. These loads should be considered in designing the wall. Drainage penetrations through walls may be needed for gravity drainage of landside areas when waterside conditions allow, or for drainage pumping station discharges.

6.3.1 Design Procedures

A gravity wall is a type of floodwall. Refer to section 6.1 for guidance on concrete floodwall design, including potential failure modes, methods of analysis, load conditions, and pile foundations if needed.

6.3.2 Toe Protection

Wave action under normal conditions and during storm events can cause erosion at the waterside toe of the wall. Toe protection commonly includes a sheetpile cutoff wall along the toe to prevent undermining combined with additional rock revetment armoring. Some factors contributing to scour include wave breaking on the wall at low tides, wave runup and backwash, wave reflection, and the nature and grain size of the material at the toe. In addition to the hydraulic forces at work, the changing configuration of the area fronting the wall over time can contribute to scour. More detailed information and procedures for evaluating and addressing scour can be found in EM 1110-2-1614 (USACE, 1995a).

6.3.3 Controlling Runoff and Overtopping Resilience

Wall design should include provisions for erosion protection and drainage of the landside due to potential wave splash and overtopping. Provisions may also be needed for penetrations through the wall as part of managing interior drainage within the leveed area. Penetrations may include gravity drainage pipes with suitable backflow prevention check valves on the waterside, positive close gate valve on the landside, and discharge piping from drainage pump stations.

6.4 Demountable Floodwalls

Demountable floodwalls can be employed in situations where a permanent structure is undesirable. Such situations may include:

- Undesirable loss of ability to see beyond the line of the floodwall.
- The need to avoid restricting access and operation of existing facilities.
- The need to maintain current vertical clearances for existing overhead facilities during non-flooding conditions.

Typical demountable floodwalls are shown in Figure 7-30. Note that the demountable floodwall, as described in this section, is designed as a permanent part of a given project. This should not be confused with temporary measures that can be employed for use during floodfight activities.

Figure 7-30: Example of Demountable Floodwall

Placement of the 17th Street demountable wall in Washington, D.C.

Advantages and disadvantages of demountable floodwalls are summarized in Table 7-13.

Table 7-13: Advantages and Disadvantages of Demountable Barriers

Advantages	Disadvantages
• Generally robust and well-engineered	• Large storage area needed
• Good resistance to loading and debris impact	• Heavy transportation and lifting requirements[1]
• Durable	• Long installation and mobilization period[2]
• Can be increased in height by adding panels up to the height of the frame depending on predicted flood level	• Permanent parts susceptible to damage and vandalism
• Very low seepage through the structure	• May not be appropriate in coastal areas subject to significant storm surge and waves
	• May not be suitable where vessel or barge impact is possible

Notes to table:

1. Commercially available devices may require lighter equipment.
2. Commercially available devices may have shorter installation times.

The selection of the type of demountable barrier will depend on many of the same type of factors that should be considered for closure structures (section 7.2). In particular the following should be considered:

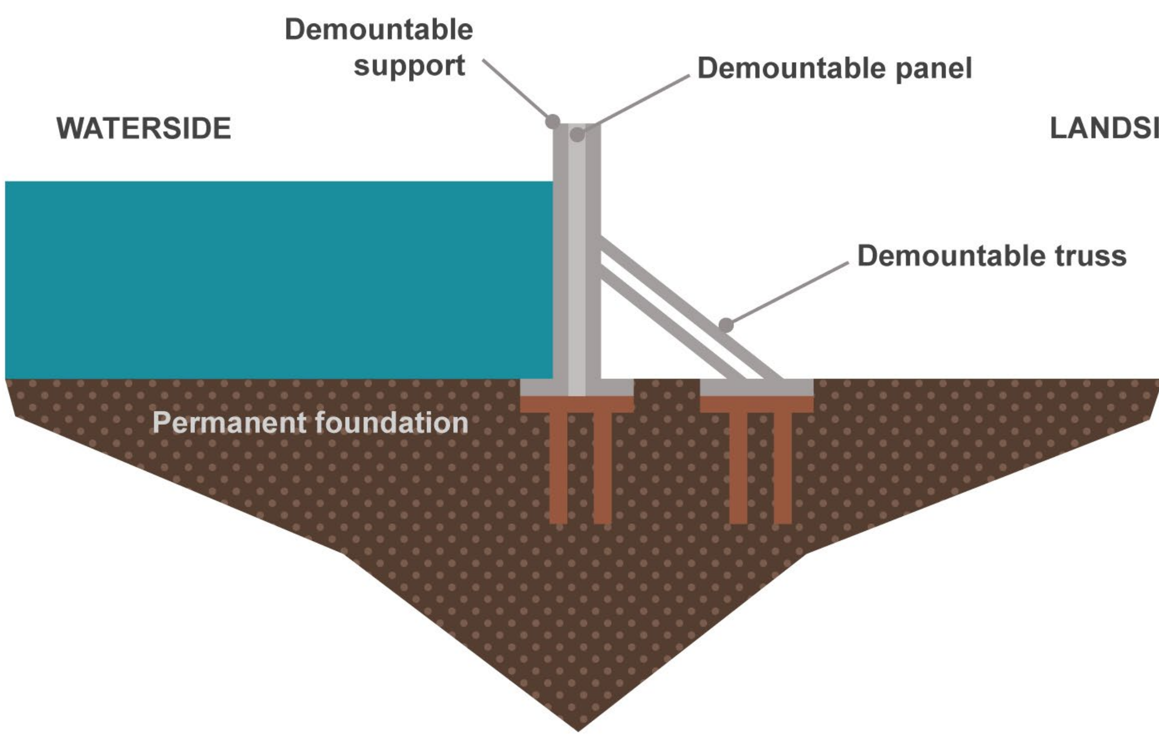
- Time available for installation.
- Storage when not in use.
- Equipment and manpower needs for mobilization and installation.
- Time for which the opening will remain closed prior to, during, and after the flooding.
- Ability to test and conduct emergency exercises.

6.4.1 Design

Figure 7-31 is a typical cross section of a demountable barrier showing the various components that may be needed.

A typical installation may include vertical posts (stanchions) placed at intervals that support a single rigid panel or multiple rigid panels that interlock with the posts. The panels are typically metal (aluminum). Seals are required between the panels and the posts, as well as between the panels and foundation to ensure watertightness. Depending on the height of the barrier and the design loading, it may be necessary to provide bracing struts or a truss to support the posts.

Figure 7-31: Typical Demountable Barrier Cross Section



A foundation block of concrete is typically constructed for support and to resist sliding and overturning loads. For removable barriers, embedded anchorages can be used so that the posts and bracing can be brought to the site and attached to the foundation when needed. Posts and bracing can also be permanently installed in the foundation if desired.

Special attention should be paid to the closure at the ends of the demountable barrier. The barrier should firmly tie into other risk-reduction features (e.g., embankment levees, floodwalls) or into existing topography via a reinforced concrete abutment wall that prevents end-around seepage. Rock slope protection should be placed at closure locations on the waterside to prevent erosion.

The design process should be iterative, considering various combinations of post spacing and panel component heights to find an economical design with reasonable component weight to facilitate installation and removal.

Overtopping resilience should also be considered, as for other types of floodwalls (section 6.1.2). O&M manuals prepared by the designer should include all facets of the demountable floodwall structures, including parts, diagrams, installation procedures, inspection, and maintenance schedules.

6.4.2 Other Considerations

The area selected for storing components should be close to the installation site. It should provide adequate protection of the components from weather damage and vandalism.

The entity responsible for maintaining, installing, and removing the barrier should be clearly identified along with the chain of communication with the agencies responsible for ordering installation of the barrier. The maintaining entity should have proper equipment and personnel qualified in the installation process. A test installation of a short section of barrier should be performed annually. For removable barriers, the foundation attachments and foundation for the barrier should be inspected annually prior to the flood season.

7 Closure Structures

Closure structures (**Chapter 2**) are used to close gaps in the levee alignment, such as where infrastructure (e.g., a road or railroad) or another water body (natural or human-made) crosses or intersects the alignment. This is done to prevent water from entering the leveed area during high water. Closure structures also may be used to provide access through a levee, such as for maintenance or recreation. The preference is to maintain levee continuity, for example, by routing a road over the levee alignment. However, when this is not possible, a closure feature provides an alternative. Figure 7-32 shows examples of closure structures.

Deciding when a closure structure is needed and where to place it along the levee should be carefully considered to ensure the best possible design for the full lifecycle of a project. Design of a steel closure structure should adopt either allowable working stress or load and resistance factor design depending on which approach best suits the project-specific requirements.

O&M manuals should include all facets of the selected closure structures, including parts, diagrams, lubrication points, inspection, and maintenance schedules.

Figure 7-32: Example Closure Types

Examples of two different types of closures. A swing gate closure across a roadway along the Ohio River in Louisville, Kentucky, and a sector gate closure across a waterway in New Orleans, Louisiana.

7.1 Selection of Type of Closure Structure

As described in **Chapter 2**, there are three main categories of closure structures:

- Movable gates (roller, swing, trolley, vertical lift, sector, miter).
- Structural assembled closures (stoplogs of timber, metal, or concrete).
- Earthen assembled closures (using sandbags, soil/gravel baskets, or earthen fill with plastic covering).

The type, location, and number of closures used in a project are important decisions to ensure the levee system will be able to perform as intended during a flood event. Factors to be taken into account in the selection of closure type should include:

- **Time available for installation**.
  - Rapid closure requirements. Levee systems that provide risk reduction against flashy water sources (those that rise and fall within a matter of hours) should only utilize movable gates that can quickly be closed, as there will be insufficient warning time to install other closures. Structural or earthen assembled closures may be used if an extended warning time is available.
    - When a temporary closure is needed across frequently used roads or railroad tracks, movable gates may be the best option, as they can be closed quickly, allowing the greatest amount of time for traffic to evacuate out of an area that could be inundated. This is an important decision factor for active railroad lines.
  - Limitations on manpower and equipment. Where systems have multiple closures as part of a single levee system and there is limited manpower and equipment given the available time to close, the number of closures included in the design may need to be restricted.
- **Time for which the opening will remain closed prior to, during, and after the flooding**. Where closure of an opening is feasible for a longer period of time, structural or assembled closures may be acceptable and cost-effective. Otherwise, use of movable gates are recommended.
- **Size of opening**. Structural and earthen assembled closures may be used across a wide range of opening widths and heights. When selecting movable gates, width and height will affect the selection of the type. For example, mechanical swing gates, though widely used, are more limited in the length of span they can close as compared to rolling gates, which are available in a wide variety of lengths and heights.
- **Storage when not in use**. Movable gates need adequate real estate for storage when not in use.
- **Equipment and manpower needs for mobilization/installation**. Movable gates that require large equipment, such as cranes, for installation should be avoided when possible. These can be designed where real estate is available to store the gate while not in operation.
- **Capital, operation, and maintenance costs**. For some types of movable gates, the O&M costs may be significant and can result in higher expenses over the levee system's service life. Repair of deteriorated concrete and embedded steel components, installation practice and training, availability of future replacement parts, storage, and manpower requirements are all costs that should be considered during the design phase of a project. This is particularly important when considering the use of proprietary closure systems where the availability of replacement parts and supplier support cannot be guaranteed into the future.
- **Ability to test and conduct emergency exercises**. Closures for transportation corridors often have limitations or constraints to being able to test closures. These often require extensive coordination in order to be able to temporarily close the corridor, especially in a non-emergency situation.

These factors have been taken into account in the preparation of Table 7-14, which may be used as an initial guide to assist with selecting closure types. Ideally, the final decision should be supported by project-specific operational equipment, time, and manpower analysis completed to support an evaluation or design risk assessment.

Table 7-14: Recommended Closure Types for Different Design Scenarios

Hydraulic Hazard Condition	Closure Location or Height	Recommended Type of Closure Structure[5]
"Flashy" stream or river	Roadway[1] or railroad[2]	Movable gate (swing, roller, or trolley)
"Slow rising" stream or river	Closure height > 4 feet[3]	Movable gate (swing, roller, or trolley) or structural assembled closure[4]
	Closure height < 4 feet	Movable gate (swing, roller, or trolley), structural assembled closure, or earthen assembled closure (likely soil/gravel baskets, earthen fill with plastic, or sandbags)
Coastal storm risk management systems[6]	Navigation channel with reverse loading	Sector type of movable gate
	Navigation channel only loaded from one side	Sector or vertical lift type of movable gate
	Structures on land	Movable gate (swing, roller, or trolley)

Notes to table:

1. Careful consideration is required when deciding to design a closure versus raising the roadway grade. Raising the grade can eliminate a closure. This may be a critical factor for communities where a roadway is an important evacuation route.
2. Raising railroad grade could theoretically eliminate a closure, but the change of grade would have to be carried over such great distances that railroads generally reject this design suggestion.
3. Applies to both roadways and railroads.
4. Installation of structural assembled closures takes a much larger contingent of manpower to install compared to swing gates or rolling gates. A decision to use this type of closure should be based on an understanding of local manpower resources available during a flood emergency.
5. Selection of the type of closure may be affected by its length since greater local manpower resources may be required to implement some types of longer closures.
6. Rapid intensification of hurricanes points to limiting closure types to those that can be installed very quickly using the least manpower resources.

7.2 Closures Across Transportation Corridors

Operating and emergency planning should include coordination with the applicable transportation agencies to ensure operations do not interfere with the closures. This should also include coordination procedures for periodic testing of closures, including emergency response exercises.

When possible, the levee alignment should be perpendicular to the roadway or railroad where any closure is required. This minimizes the width of the closure opening, which can lower construction costs and shorten installation time of the closure. Benefits of this approach include reducing flood risk and operational interference of the railroad/roadway.

7.2.1 Vehicular Closures

Coordination with representatives from the local community should occur in order to evaluate the community's needs and set the priorities for which streets that cross the levee alignment require closures, may need to be rerouted, or may need to be permanently closed. These decisions also may impact future land use and emergency evacuations.

Generally, gap closures crossing roadways should be perpendicular and at grade. If the roadway is designated as an evacuation route or emergency access, the closure type may well be a swing, roller, or trolley movable gate. Opening widths need to accommodate removable vehicle crash tested barriers, per the governing highway authority requirements. Thus, swing gates may not be ideal, as a large section of removable vehicle crash barriers will be required. Other items to consider are the highway speeds, drainage, and grading.

The opening widths for vehicular gates should comply with the American Association of State Highway and Transportation Officials requirements, as well as with state and local regulations. For overhead roller gates, the minimum vertical clearance between the crown of roadways and fixed overhead components of closures should not be less than 14 feet. Clearances should be coordinated with, and approved by, the relevant transportation organization. Warning signs are required at overhead roller gates.

7.2.2 Railroad Closures

Minimum horizontal and vertical clearances should not be less than that required by the American Railway Engineering and Maintenance-of-Way Association. The normal minimum width of opening provided for railroads is approximately 20 feet for each set of tracks involved in the closure.

The railroad authority should be involved as early as possible in the formulation and design process since the American Railway Engineering and Maintenance-of-Way Association's general guidelines may not be sufficient to satisfy site-specific railroad operations. During design reviews, providing construction phasing plans that highlight sequencing and track down time may be necessary. Other common requirements consist of:

- Crossing perpendicular to the tracks.
- Locating the tops of foundations below the ballast and sub-ballast material.
- Limiting the width of the sill so it fits between the clear distance between railroad ties.
- Taking account of robotic train operations and gas lines used for switch heaters.

7.2.3 Waterway Closures

Waterway closures prevent water from flowing into waterways that intersect the levee alignment. The operability and closure time are key factors when selecting a gate type. Impacts on drainage and navigation will dictate the operation. Common types of movable closures for waterways include:

- **Sector gates**. These gates are the most versatile. They can be designed to operate in adverse conditions and do not impose height restrictions.
- **Vertical lift gates**. These gates can be operated by fixed overhead cranes or by moving gantry cranes. The disadvantages of the vertical lift gates are the machinery requirements and the overhead restriction.
- **Buoyant gates**. These gates also are used but require a steady-state condition to operate, should be closed far in advance of high water, and cannot be opened until the opposing water stages drop.

7.2.4 Pedestrian Closures

Closure structures for pedestrian access ways through floodwalls can be simple gates, typically of steel, with appropriate seals to ensure water tightness. Often these are closeable manually. The form of the gate should be agreed with the local community, including the proposed approach to O&M.

For earthen embankments, closures are rarely provided, although ramps may be required to facilitate people walking up and over the embankment.

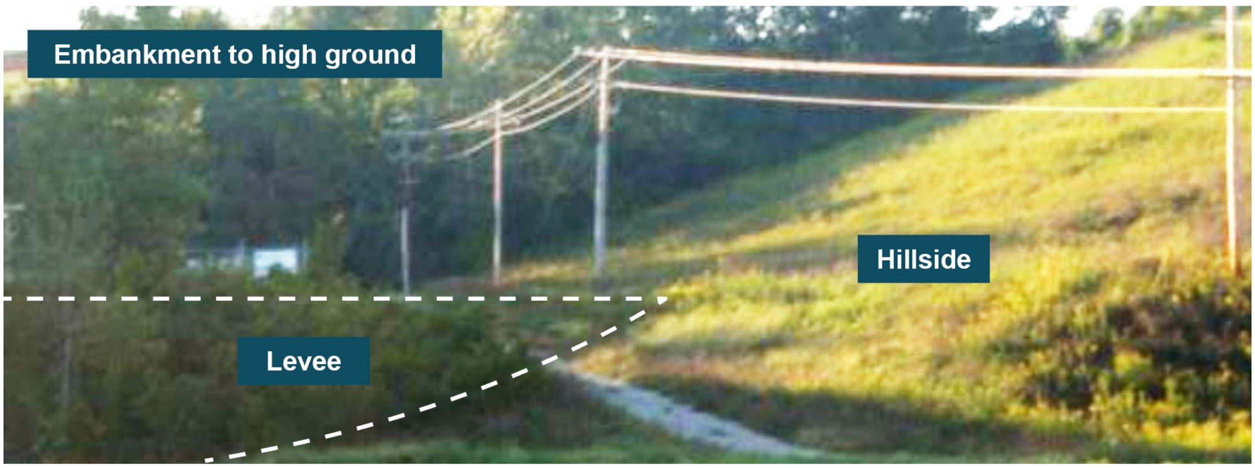
8 Transitions

Loss of integrity at the **transition** locations between different features along the levee alignment can lead to failure of the levee at these points. This risk factor should be addressed in design. Transition locations may include:

- Earthen embankment to floodwall (concrete or steel) transitions.
- Earthen embankment or floodwall transition to concrete closure structures.
- Earthen embankment or floodwall tying into existing natural grade.
- Earthen embankment or floodwall tying to other existing infrastructure, such as bridge abutment walls or road embankment fills.
- Encroachments by pipe and culvert systems into earthen embankments.

Figure 7-33 shows two examples of transition locations.

Figure 7-33: Examples of Transition Locations



Two examples of floodwall transition locations. A floodwall transition to an embankment with riprap providing erosion protection and a floodwall transition to embankment into high ground.

8.1 Design Principles for Transitions

- **Avoid or minimize transitions when possible**. When carrying out levee rehabilitation, it may be possible to remove existing transitions rather than trying to control or address their impacts. Alternatively, a transition may be relocated to reduce loading or improve resilience.
- **Ensure the transition is not the weakest link** in the levee chain, and that this remains the case through the whole life of the levee, taking account of deterioration processes. This may involve being more conservative in the design of the transition than for the adjoining levee segments.
- **Transitions should be gradual**, both in terms of external geometry and also materials and structure types. Abrupt changes in direction increase the turbulence of water flow and lead to increased risk of external erosion. This risk can be minimized by providing sufficient overlap of structures and surface protection systems and avoiding abrupt

changes. In this regard, transitions should be considered in three dimensions (not just in plan or in cross section).

- **Loading conditions**. A range of loading scenarios should be considered including normal operating conditions, design flood events, and extreme events that exceed the design event. The following hydraulic parameters need to be considered:
  - Velocity and direction of flow, including turbulence and possible sediment transport.
  - Water level changes, including any waves and their characteristics.
  - Hydraulic head along and across the transition and the resulting potential for hydraulic separation and uplift.
- **All potential failure mechanisms** should be addressed including:
  - External erosion, which increases at transitions where there is increased turbulence.
  - Internal erosion, especially at cracks at interfaces between earthen structures and hard structures due to increased rates of seepage.
  - Differential settlement.
- **Consider deterioration processes** that could compromise performance over time. For example:
  - Seasonal shrinkage/swelling of clay soils leading to desiccation cracking.
  - Seepage and/or hydraulic separation.
  - Local settlement leading to the possibility of localized overtopping flow.
- **Levee modifications or improvements** may:
  - Cause short-term performance reductions at disturbances to the existing levee system, for example until grass has re-established or the consolidation of the ground has completed.
  - Introduce new transitions (including at existing transitions), with related impacts on levee performance.

8.2 Dealing with Specific Mechanisms

When joining a levee embankment with a concrete or sheetpile structure or floodwall, concerns that should be considered in design of the junction include embankment slope erosion, seepage and internal erosion and differential settlement.

8.2.1 Embankment Slope Erosion

Turbulence may result at the junction between earthen embankments and hard concrete or steel structures (floodwalls, closure structures, etc.) because of changes in the geometry between the levee and the structure. This turbulence causes scouring of the levee embankment if slope protection is not provided. Rock, concrete, or proprietary erosion control systems for slope protection should be considered for the levee embankment at such locations.

8.2.2 Cracking and Hydraulic Separation Leading to Seepage and Internal Erosion

Cracking and/or hydraulic separation at the interface between the embankment fill and the hard structure (e.g., floodwall or drainage control structure) can increase the risk of seepage leading to internal erosion in the form of concentrated leak erosion.

Seepage analyses should be performed to establish the required minimum embedment of a floodwall into an earthen embankment, to reduce seepage pressures and the potential for internal erosion. Seepage analyses also should be performed where earthen embankments or floodwalls terminate into existing topography, to determine whether treatment is required to control or prevent end-around seepage in the hillside.

Concrete floodwalls, wingwalls, and sheetpiles may be extended beyond the concrete structure well into the earthen structure (e.g., along the levee centerline) to increase the length of seepage paths and reduce seepage gradients which might induce internal erosion.

Thorough compaction of the levee embankment at the junction of the concrete structure to ensure firm fill contact with the structure and levee is essential. This helps to decrease the hydraulic conductivity of the embankment material and reduces the risk of cracking or hydraulic separation. In this situation, the exterior of the abutting end walls of the concrete structure should be battered at an angle of 10 vertical to 1 horizontal to assist in ensuring adequate compaction and a firm contact between the structure and the fill. Compaction equipment should be selected based on available working room. Heavy compactors should be used wherever possible, except near concrete structures where light equipment or hand tampers should be used to avoid locking in high residual stresses in the structure. See EM 1110-2-1911 (USACE, 1995) for further details.

8.2.3 Differential Settlement

Differential settlement can result from unequal consolidation of soft foundation soil at the transition between a relatively heavy levee embankment and a relatively light concrete floodwall or closure structure. Such differential settlement can locally increase the rate of overtopping during a flood event and encourage failure by external erosion of the rear face of the embankment.

Thorough compaction of the embankment material is important at locations of potential differential settlement. Furthermore, given that hard structures such as floodwalls with landside scour protection may be more resilient to overtopping than embankments, it may be desirable to add an overbuild settlement allowance to the embankment to ensure that overtopping takes place preferentially over the more robust hard structure. Further guidance on transitioning procedures for a junction between a levee embankment and a floodwall is available in EM 1110-2-2502 (USACE, 1989a).

9 Seepage Control Features

Seepage control features reduce the probability of levee breach arising from internal erosion or foundation erosion from throughseepage or underseepage. A seepage cutoff wall significantly reduces or eliminates the seepage, whereas other options, such as seepage berms, only control the seepage.

- **New embankment levees** to be constructed using low permeable fill meeting the requirements discussed in section 5.1.3 should not be susceptible to internal erosion by throughseepage. The embankment may be homogeneous or zoned. However, a risk of foundation erosion still may exist because of uncontrolled underseepage.
- **Existing levee embankments** may be at risk of potential failure because of internal or foundation erosion potential failure modes, or both, as indicated by historic poor seepage performance or by post-construction geotechnical evaluations. A seepage cutoff wall may be a risk reduction option.
- **Floodwall** seepage control features can be introduced to deal with similar potential failure modes as for embankments. Cutoff walls should be tied into the floodwall to prevent seepage through the interface between the cutoff and the above-grade portion of the wall. Note that the seepage berms discussed in section 9.3 generally are not used with floodwalls because of right-of-way restrictions. For detailed design of seepage control features, reference should be made to the seepage control criteria in EM 1110-2-2502 (USACE, 1989a) and EM 1110-2-2100 (USACE, 2005).

9.1 Seepage Analysis

Two-dimensional, finite element analysis software that analyzes groundwater seepage and excess pore pressure dissipation conditions in porous materials such as soil and rock should be used for analysis of seepage. The accuracy of the analyses depends on the extent and quality of subsurface data and material testing available to make the seepage models. Guidance on performing seepage analyses for levees is provided in EM 1110-2-1901 (USACE, 1986). Experienced professionals should oversee interpreting subsurface data, defining soil stratification, and assigning seepage properties to the soil strata.

9.1.1 Potential Failure Modes

Levee collapse and breach because of seepage results from:

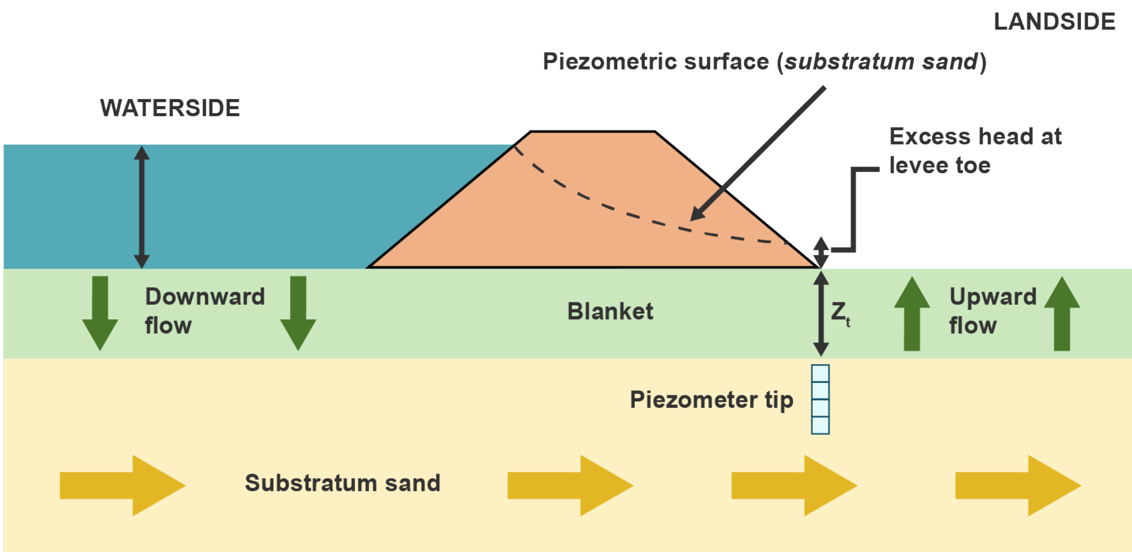
- Backward erosion piping under the levee.
- Throughseepage reducing the soil strength of a levee embankment, causing sloughing and erosion of the landside slope.
- Concentrated leak erosion through pre-existing cracks/flaws in the levee.

Problematic geologic conditions for backward erosion piping include blanket conditions where layers of lower permeability material overlie more permeable deposits, permeable embankment materials, and daylighting permeable layers.

Problematic conditions for concentrated leak erosion relate to the presence of flaws such as animal burrows, tree roots, pipe encroachments, cracking, and/or hydraulic separation at interfaces between earthen embankments and hard structures. Approaches to dealing with concentrated leak erosion are discussed in section 8 on transitions.

Blanket conditions. Figure 7-34 shows a levee section where the water is on the left side and the leveed area is on the right. The green layer is a relatively impermeable clay layer, and the yellow layer is a more permeable sand layer. During high water, flow occurs in the sand layer and water pressure will push upwards on the clay layer, or blanket, on the landside. If the pressure is high enough, the water breaks through the clay layer and carries sand with it, creating a boil and potentially undermining the levee as the piping progresses backwards.

Figure 7-34: Blanket Conditions



Permeable levees—consisting of sand, gravel, non-plastic silt, or continuous layers of these materials—may pose throughseepage hazards. These result from flow through the levee, potentially carrying material and creating backwards internal erosion, causing collapse of the levee. Another potential failure mode for permeable levees is degradation of the landside face caused by throughseepage daylighting on the face, causing erosion. This is a progressive failure mode where the landside slope becomes unstable because of progressive steepening, caused by the degradation.

Daylighting permeable layers, sometimes referred to as leaking layers, are permeable layers directly below the levee that daylight and are exposed at the ground surface on both sides of the levee. These layers allow direct flow under the levee from the waterside to the landside. If sufficient flow and water pressure are present, these conditions can move foundation material toward the landside, creating backwards internal erosion underlining the levee.

9.1.2 Analyses Approach

The seepage analysis objectives are to:

- Estimate steady-state phreatic levels and pore pressures in levee embankment and foundation soils for selected water level conditions; the resulting pore pressure information is also used for slope stability analyses.
- Estimate the phreatic surface breakout location.
- Where a blanket layer is present, calculate the average vertical hydraulic exit gradients.
- Compare the resulting hydraulic exit gradients with design criteria.

Regulating agency guidelines typically require a steady-state seepage analysis, even if flood events are short duration. Analysis sections should be selected taking account of reaches that are significantly three-dimensional (e.g., where there are bends and meanders in the levee).

Material properties selection. Steady-state seepage analyses typically require input of the following material properties:

- Horizontal hydraulic conductivity under fully saturated conditions (kh).
- Ratio between vertical and horizontal conductivities (anisotropic ratio) (kv/kh).

The designers may select material properties to be used for analyses using a variety of methods including:

- In situ hydraulic conductivity tests including a pumping test.
- Laboratory hydraulic conductivity tests.
- For granular soils, empirical methods such as the Kozeny-Carman equation, in combination with the results of gradation tests.
- Empirical charts that relate hydraulic conductivity to void ratio and the effective grain size, d10.

Guidance on selection of material properties is available in the Guidance Document for Geotechnical Analysis (California DWR, 2015).

Three-dimensional effects. Modeled two-dimensional seepage gradients should be increased where appropriate to take account of three-dimensional effects. State of California Department of Water Resources (California DWR, 2015) and (Jafari *et al.*, 2015) provide some rules of thumb for adjustments.

9.1.3 Design Criteria

Levee underseepage evaluation is based on the critical vertical hydraulic gradient/vertical effective stress factor of safety method (Terzaghi, Peck and Mesri, 1996). Originally, levee underseepage criteria were developed for a horizontal ground surface, with a vertical hydraulic gradient assessed from head loss across a blanket at the levee toe. This head loss is divided by the average landside blanket thickness (noted as "Z_t" in Figure 7-34), yielding a hydraulic gradient often referred to as the 'exit gradient.' See EM 1110-2-1913 (USACE, 2000) for guidance on allowable seepage gradients. The exit gradient is then compared with the critical hydraulic gradient for the situation. Critical gradients may need to be adjusted in three-dimensional situations, as discussed for example in (Van Beek *et al.*, 2015).

Throughseepage evaluation is not required for a new levee if it is constructed using low-permeable fill meeting applicable criteria. For an existing levee, if a phreatic surface daylights on the landside slope of a levee under a steady-state seepage condition, it may indicate a potential for throughseepage distress. Low-plasticity, or erodible soils (e.g., silt and sand) are more susceptible to piping and surface erosion than plastic soils (e.g., clays, clayey sands, clayey gravels), and thus the designers should identify this breakout condition for erodible soils as a throughseepage deficiency. Designers should consider the available historical construction data to identify whether zones of potential erodible material are encapsulated by non-erodible soils in the exterior of the levee embankment.

9.2 Seepage Cutoff Walls

Seepage cutoff walls significantly reduce or eliminate embankment throughseepage and foundation underseepage, addressing the risk of failure by backward erosion piping. Design of seepage cutoff walls requires a well-informed understanding of geologic foundation conditions to evaluate the required wall depth and composition. This understanding dictates the appropriate design and construction methods. Table 7-15 summarizes the seepage cutoff wall design elements, advantages, and disadvantages.

Table 7-15: Seepage Cutoff Wall Design Elements

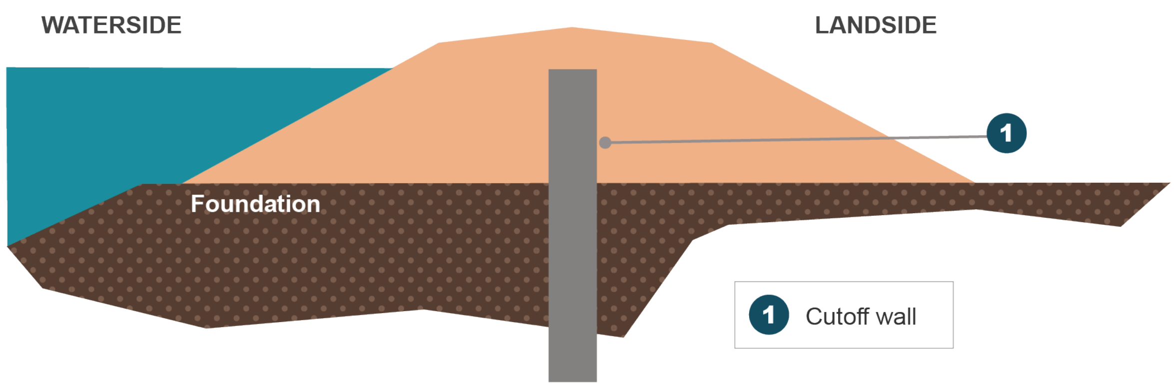
Seepage Control Feature	Associated Potential Failure Mode	Design Elements	Advantages	Disadvantages
Cutoff wall	• Internal erosion piping • Foundation erosion piping • Slope stability	• Alignment • Depth • Composition • Construction method	• Cuts off seepage • No maintenance • No additional right of way	• Cost • Construction risk • Higher groundwater levels during times of low flow

9.2.1 Alignment and Other Design Considerations

For a new levee, Figure 7-35 shows the seepage cutoff wall constructed on the centerline in the inspection trench area. The inspection trench should be backfilled with compacted embankment fill to foundation grade before the slurry cutoff wall is installed. The inspection trench and cutoff wall can be moved laterally from the centerline towards the waterside if necessary. The inspection trench also helps with eventual trench stability and to prevent caving during construction.

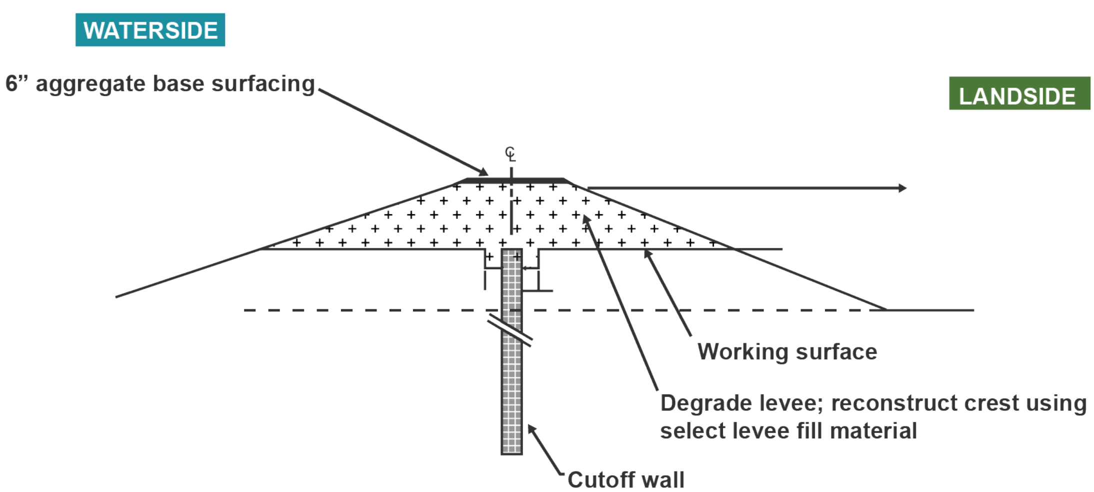
An open trench stability analysis should be completed especially for any cutoff wall constructed at the toe of the levee which has high shear forces from the sloping embankment. For analytical methods for trench stability or seepage/stability modeling, reference should be made to EM 1110-2-1901 (USACE, 1986).

Figure 7-35: Typical Seepage Cutoff Wall—New Embankment



For an existing levee, Figure 7-36 shows an example seepage cutoff wall constructed on the centerline of the levee. In addition to remediating underseepage in the levee foundation, the cutoff wall also remediates throughseepage because it extends upward, through the embankment to the working platform. The top of the cutoff wall should tie into the compacted embankment fill to prevent seepage over the top of cutoff wall.

Figure 7-36: Typical Seepage Cutoff Wall—Existing Levee



During construction of cutoff walls in existing levees, degrading the existing levee crown often is required to establish a working surface wide enough for the cutoff wall construction equipment, with some additional space on at least one side for construction traffic to pass. The typical degrade should be at least one-third of the height of the levee to limit fracture/break-outs—the actual degrade depends on crown width, trenching equipment used, and levee side slopes. The degraded top of the levee should be reconstructed using approved embankment fill. Figure 7-36 shows one method of installing the cutoff wall in a trench excavated below the levee working surface to prevent seepage over the top of the cutoff wall. The trench should be backfilled with embankment fill before wall construction.

Another option for an existing levee requiring underseepage rehabilitation only is to install a waterside toe cutoff wall. This can be an attractive option for existing floodwalls. Toe walls also eliminate the need to degrade the existing embankment levees but require good access to the waterside toe of the levee for construction. This can be a viable option compared to levee centerline walls as long as the waterside slope of any embankment levee is low permeable fill, and the top of the toe wall terminates in that fill.

9.2.2 Depth

The depth of the initial inspection trench should be sufficient to encapsulate the cutoff wall and any expected consolidation/settlement of the wall during initial set.

The bottom of the cutoff wall for a new or existing levee should be set at an elevation that prevents seepage flow under the bottom of the wall. Cutoff wall depths should be determined based on the foundation stratigraphy and thus can vary along the length of the wall. The intent of the wall is to cut off seepage flow in relatively permeable layers (aquifers) underlying the embankment. The bottom of the wall should penetrate into a thick layer (not seam) of low permeable soil (aquiclude) beneath the aquifer layers. A typical minimum penetration into the permeable layer of materials should be 5 to 10 feet. To achieve seepage cut-off, the depth of embedment into the aquiclude may need to vary along the length of the wall as the nature of the aquiclude material varies. Geotechnical drilling and sampling along the wall alignment should be analyzed in design to estimate the required wall tip elevation profile shown in the drawings.

Practical limits exist to the depth of cutoff walls. Construction technology continues to develop, but generally walls deeper than 140 feet are not practical. Walls deeper than 70 feet may require more expensive construction methods.

9.2.3 Composition

Cutoff walls for a new or existing levee may consist of a variety of materials. These include structural elements, such as steel sheetpiles, concrete walls, or mixed in-place walls using slurry trench methods. Mixed-in-place walls can use different mixes, depending on existing in situ soils and the design requirements for wall permeabilities and strengths. Typical mixes for slurry walls include soil-cement, soil-cement-bentonite, and soil-slag cement-cement-bentonite. Further information on slurry walls is available in Slurry Walls: Design, Construction, and Quality Control (Paul, Davidson and Cavalli, 1992).

The type of wall and composition is dictated by the required depth of the wall, constructability, and the required wall permeability and strength properties. For open trench wall configurations, a stability analysis should be conducted as part of the design to evaluate the stability of the open trench. Steel sheetpiles and concrete cutoff walls may be constructable only to limited depth, depending on geologic conditions (e.g., see detailed information in (Bruce, 2013)).

9.2.4 Advantages and Disadvantages

The main advantages of seepage cutoffs are if they are designed and constructed properly, they virtually eliminate seepage through or beneath the levee. After being constructed, the walls require no maintenance. Cutoff walls also require no additional right of way because they are constructed within the planned or existing embankment footprint. Slurry cutoff walls also allow confirmation of geologic layers by observing excavated material as the trench is excavated.

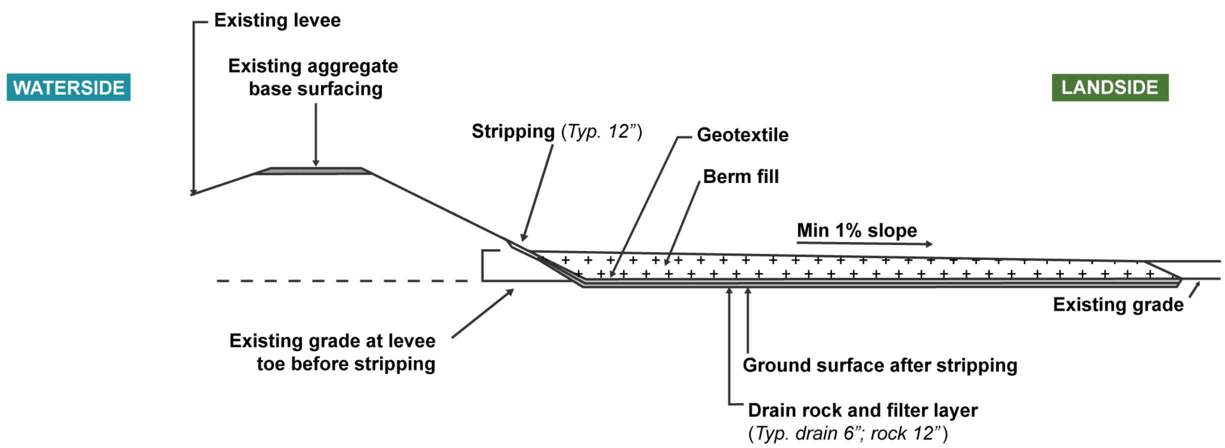
Disadvantages include the following:

- Cutoff walls interrupt regional groundwater flow during periods of low water and thus lead to higher groundwater levels.
- Historically, landside seepage berms have been cheaper than seepage cutoff walls. However, in some areas of the U.S., costs now are comparable because new construction methods have been developed. Also, in some areas, steel sheetpile cutoff walls are competitive with slurry cutoff walls.
- Need for high quality construction including construction quality control.
- Sheetpiles generally are driven or pushed into the ground, and no method is available to confirm the geologic layers penetrated.
- Concrete cutoffs are limited in depth because of trench instability.
- Slurry cutoff walls:
  - Require good control of materials.
  - Some geologic conditions may make slurry cutoff walls infeasible.

9.3 Seepage Berm

A seepage berm is intended to mitigate the risk of embankment breach because of backwards erosion (piping) of the foundation soils from underseepage. Figure 7-37 shows a seepage berm installed on the landside of a levee. Such a berm is required when the seepage gradient at the landside toe of the levee exceeds applicable criteria.

Figure 7-37: Typical Seepage Berm



A seepage berm places weight on top of the landside ground to reduce the potential for heave and thus the migration of underlying soil to the ground surface in the form of sand boils. Depending on the geologic conditions, the required width of the berm may become impractical.

Upward movement of foundation soils to the ground surface still may develop at or outside the landside toe of the berm.

For a new embankment levee, a seepage berm may be an option in cases where a seepage cutoff wall technically is not feasible or is cost prohibitive. Table 7-16 summarizes seepage berm elements and advantages and disadvantages. Design elements are discussed in the following paragraphs.

Table 7-16: Seepage Berm Feature Design Requirements

Seepage Control Feature	Associated Potential Failure Modes	Design Elements	Advantages	Disadvantages
Seepage berm	• Foundation piping breach formation • Embankment piping breach formation	• Drain layer • Width • Height • Composition	• Cost • Lower construction risk	• May not reduce seepage • May still allow boils and require floodfighting • Additional right-of-way required • Potential for maintenance and erosion

9.3.1 Drainage Layers

Seepage berms commonly are drained to facilitate the flow of seepage water away from the levee. If drained, the seepage berm shown in Figure 7-37 may also extend up the landside levee slope (known as a chimney drain extension) to collect any throughseepage. This can be accomplished by extending the drainage layer further up the embankment slope and covering it with a minimum of 2 feet of soil for protection. The chimney section should extend up the levee slope to a minimum of one-third the height of the levee. It can be extended further up the slope, based on performance data or seepage analyses.

The drain usually consists of 6 to 12 inches of highly permeable rock, underlain by a filter layer. Filter compatibility should be verified between the drain rock and filter layer, and between the filter layer and subgrade. Regulating agencies typically do not allow the use of geotextile fabrics on the subgrade as a replacement for the filter layer.

9.3.2 Width

The berm width can be established by seepage analyses. Iterative calculations should be used to establish the point at which the gradients at the toe of the berm reduce sufficiently to discourage development of boils. A wider berm also reduces the likelihood of piping to progress under the levee before water levels drop and provides time for floodfighting. A minimum width of 150 feet is common.

9.3.3 Height

The height of the berm should be sufficient to prevent heave and reduce seepage gradients to meet criteria. A minimum height of 5 feet at the levee toe is common. A minimum height of 2 feet at the berm toe is also common in order to delineate the limit of the berm for maintenance purposes.

9.3.4 Composition

Seepage berms are not structural features and can be constructed of variable materials. However, maintenance requirements should be considered and problematic soils, such as highly plastic clays or organics, should be avoided. The presence of locally available borrow materials should be considered in design; but it is preferable for the seepage berm material to be more pervious than the underlying material or pressures will not be able to dissipate. If impervious soils are used, this will result in higher seepage gradients beneath the berm, requiring significantly longer berms than berms constructed with free-draining soils.

9.3.5 Advantages and Disadvantages

The advantages of berms are that:

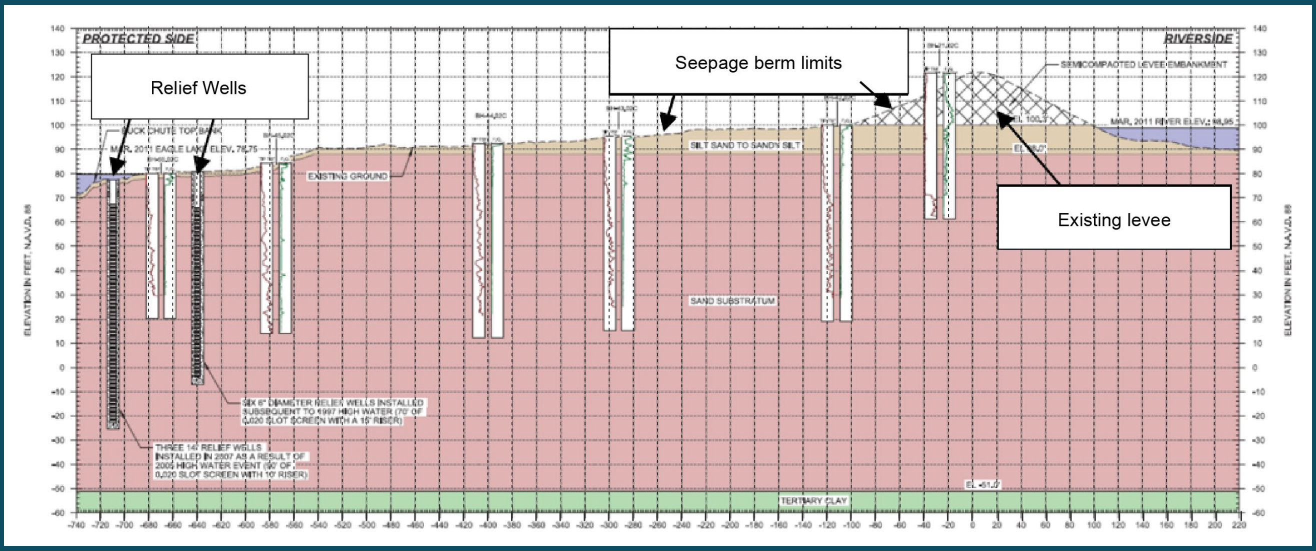
- Any boils which may arise develop further from the levee, reducing the likelihood of backward erosion undermining the levee and allowing time for floodfighting.
- Simplicity of construction being above-grade, results in simpler quality control and higher construction confidence.
- Lower cost. Historically, berms have been cheaper to construct than seepage cutoffs, although the difference in cost has been reduced with recent technological advances for cutoff walls and the challenges of obtaining suitable borrow material for berms.

The disadvantages of berms include:

- Larger footprint, requiring additional right of way. This can be an issue in agricultural and orchard areas because planting can be restricted on the berm.
- Need for maintenance and inspection.
- Difficulties in placing drainage layers for drained berms.
- Water which seeps under the berm to the landside may require control and management.

MISSISSIPPI LEVEE SEEPAGE BERM

An existing levee along the Mississippi River was re-evaluated and redesigned for seepage issues. The initial plan was to install a seepage berm along the landside of the levee. Existing relief wells were located about 400 feet from the toe of the levee and had historical issues with the well screens clogging. The seepage berm was not planned to extend to the relief wells shown in the cross section. The initial design did not require work in the relief well field to meet the required deterministic seepage design factor of safety.



During the design phase, a flood with a 5-year return period occurred. During monitoring of the flood event, sand boils were observed adjacent to existing relief wells.

After the flood, a risk assessment was conducted and identified a zone of continuous fine sand that extended from the river to the relief wells. This fine sand contained low coefficients of uniformity and was highly susceptible to internal erosion. The conclusions of the risk assessment were that the proposed seepage berm did not reduce the probability of failure in this area and that the probability of failure for an internal erosion failure starting in the relief well field was not tolerable. The design was modified to include a filter blanket that would extend laterally beyond the limits of the fine sand in the vicinity of the relief wells. This filter blanket resulted in a $1.5 million cost increase, but also reduced the risk of failure by 3 orders of magnitude. This is an example of an ‘upscaled’ feature added that would not have been considered necessary just to meet deterministic factor of safety criteria.

9.4 Landside Pressure Relief Systems

Landside pressure relief systems can reduce the risk of a breach by reducing seepage pressures at the landside embankment toe while retaining foundation soils. This reduction of seepage pressures at the landside embankment toe reduces the risk of internal erosion. Different pressure relief systems can be considered. The most common types include blanket drains and toe drains to collect throughseepage, and trench drains and relief wells to collect underseepage, which are illustrated in Figure 7-38 and Figure 7-39 respectively.

Table 7-17 summarizes landside pressure relief system elements, and their advantages and disadvantages. Design elements are discussed in the following paragraphs.

Table 7-17: Landside Pressure Relief System Feature Design Requirements

Seepage Control Feature	Associated Potential Failure Modes	Design Elements	Advantages	Disadvantages
Blanket drains and toe drains	• Throughseepage	• Alignment • Spacing • Depth • Capacity	• Cost • Captures critical flows from levee toe	• Maintenance • Allows seepage • Requires drain outlet
Trench drains and relief wells	• Underseepage	• Alignment • Spacing • Depth • Capacity	• Flexible configurations • Small right of way	• Cost • Maintenance flushing • Requires drainage

Figure 7-38: Throughseepage Pressure Relief Systems

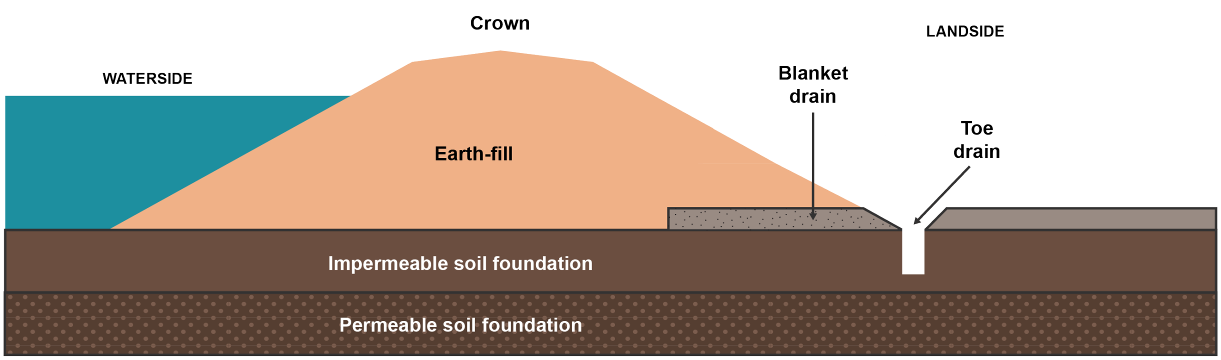
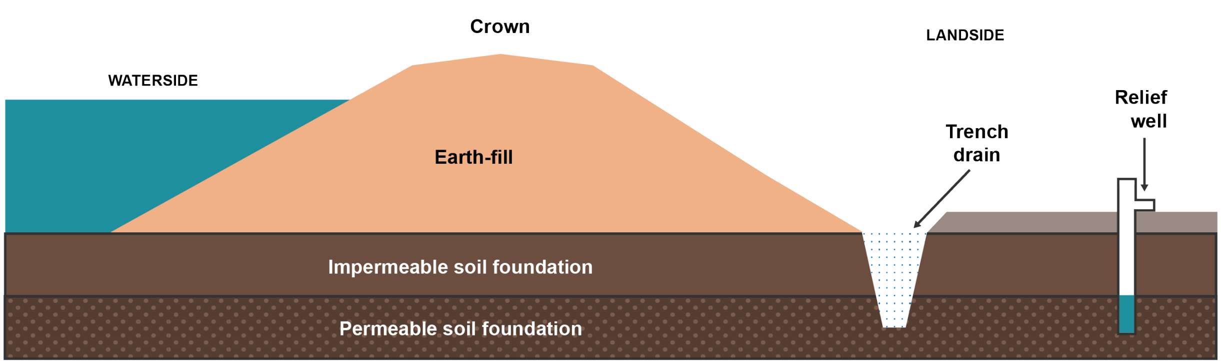


Figure 7-39: Underseepage Pressure Relief Systems



9.4.1 Alignment

The blanket drain and toe drain alignments should be along the landside toe, to capture seepage and relieve throughseepage pressures on the landside. The trench drain can be near the toe or located away from the toe as needed to relieve underseepage pressures on the landside. Relief wells are normally located away from the toe.

9.4.2 Spacing

All three types of drains should be continuous along the segment with seepage concerns. Relief well spacing should be determined by the estimated volume of seepage water to be intercepted to relieve pressure for the design water level (see **Chapter 6**). This should be estimated from the seepage analyses which will account for the head loss at the wells and determine water pressures midway between wells. Established design methods for determining relief well spacing are explained in EM 1110-2-1914 (USACE, 1992b).

9.4.3 Depth

The depth of the toe drains should be sufficient to collect throughseepage at the toe based on seepage modeling.

The depth of trench drains should be sufficient to penetrate into the permeable soil foundation through which underseepage occurs. However, the trench depth may be limited by excavation stability and/or the ability to drain by gravity from the trench and this may limit the use of trench drains in some situations

The depth of relief wells should be established based upon required capacity and the soil profile developed from a review of boring logs drilled at or near each well location. Capacity should be confirmed based upon pump tests performed after installation is completed.

9.4.4 Capacity and Materials

The required capacity of the systems should be estimated from the seepage analyses.

The material in drains should be filter-compatible with the in situ soil to avoid loss of soil into the drain via contact erosion or suffusion. Further details are available for review in EM 1110-2-1913 (USACE, 2000).

9.4.5 Advantages and Disadvantages

Landside pressure relief systems have the advantages of generally being lower cost than some of the alternatives. For modifications and rehabilitation, they are also often easier to install than modifying the levee itself.

The principal disadvantages of landside pressure relief systems are that they require routine maintenance and a drainage design to carry water away from the embankment. This can be challenging in relatively flat environments, where positive gravity drainage is difficult to establish.

Specific challenges for relief wells that should be considered are the following:

- Systems are prone to clogging and need to be cleaned and tested regularly.
- Potential for vandalism of relief wells.
- Need for well permits.
- Relief wells require pump tests every three to five years to verify their capacity. If the capacity reduces below a certain level, the well should be refurbished. If being refurbished does not restore well capacity, well replacement will be necessary.

While these are not insurmountable challenges, whole-life cost estimates should allow for well inspections, pump testing, and replacement of wells from time to time.

10 Controlled Overtopping, Channels, and Floodways

10.1 Locations of Controlled Overtopping

In some settings, the cost may be prohibitive to armor all reaches of a levee to resist overtopping as a resilience measure. As discussed in **Chapter 6**, rather than have overtopping occur at all locations simultaneously, or at locations that cannot be predicted in advance, it may be better for riverine levees to select locations in the formulation phase for initial controlled overtopping. By controlling the locations and preventing breach at those locations but allowing river water levels to be lowered, the magnitude of flood inundation within the leveed area may be reduced, resulting in lower life-safety and economic risk. In coastal settings, locations of controlled overtopping are not advised because the volume of water available for overtopping is unlimited and there is considerable uncertainty where storm surge and wave actions may affect a levee.

The key principles for design of a location of controlled overtopping are as follows:

- Capacity. Sufficient flood water should be released out of the river at such locations to fulfill the primary function of reducing river water levels upstream and/or downstream, elsewhere maintaining river levels below the levee crest.
- Resilience. The structure carrying the design overflow at the location of controlled overtopping for the anticipated duration should perform without significant deterioration or structural failure. Overflow at such locations will be infrequent and therefore the performance of the structure should be robust given the erosive power of overflowing water and that malfunction may lead to serious and unpredicted flooding elsewhere.
- Diversion of water. The likely destination for the water which overtops the levee should be one where the water can be contained and managed safely, normally an alternative channel or a safe area of temporary storage. The frequency of overtopping at such locations should be taken into account in the design and include assessment of the impact of controlled overtopping on the receiving area.

Various types of gates may be fitted at locations of controlled overtopping to risk reduction and regulate the flow discharged. The discharge characteristics of the gates and associated structures and their operation will determine the amount of water passing over the levee. Where gates are used to control rates of overtopping, they may include several gate bays separated by piers. These piers commonly support a bridge or walkway that facilitates the process of gate opening. The piers contain the necessary hardware required to retain the gates and any equipment needed to adjust gate settings. The gates may be engineered to permit overflow in extreme conditions.

Hydraulic design at locations of controlled overtopping consists of two interacting components:

1. Assessment of the impact of the removal of the overtopping water on the remaining flood hydrograph in the channel.
2. Calculation of the flow behavior at the location of the controlled overtopping itself.

The design process is an iterative one and may involve various kinds of computational models and even physical models for final optimization.

The levee surface at the location of controlled overtopping should be designed to carry the range of possible overflows without failure or significant deterioration, given the anticipated durations. Typically, the surface is concrete, riprap, grass, or some variation of these. This requires consideration of:

- Levee surface details.
- Structural integrity of both the levee and the surface protection system.
- Durability of the materials.
- All interfaces (e.g., drainage or bedding layers between the surfacing immediately beneath the overtopping flow and the body of the levee).

Structures at locations of controlled overtopping typically consist of three main parts:

1. A threshold that defines the crest level.
2. A slope that carries the water over the landward side of the levee.
3. A stilling basin that diffuses the energy of the overtopping water at or close to the toe of the levee.

Structures at locations of controlled overtopping need to be designed to carry varying volumes of water:

- During a minor flood, a relatively small volume of water needs to be discharged, and thus the crest structure could be short and only marginally lower than the rest of the levee crest.
- During a major flood, a much greater volume of water needs to be discharged, requiring either a longer crest (which would be expensive) or a lower crest (which would then spill water more frequently than may be ideal).

Lower local crest levels at locations of controlled overtopping often create transitions with the adjoining levee; the recommendations for design of transitions in section 8 should be followed.

10.2 Channels and Floodways

As described in **Chapter 2**, channels and floodways act as a diversion for riverine floodwater flows to be released into less critical areas. Such diversions may include

- Diversion of flood water from the river into the leveed area
- Diversion of water to from the leveed area to another area or basin which is either not prone to flooding and/or where other existing drainage facilities can be used to remove the water.

- Removal of water from a detention basin before the water in a basin rises to a level that can cause damage.

Where the alignment of the channel or floodway is such that it has to pass through the levee, provision should be made for an appropriate design of the crossing location. Regardless of the type of structure used to convey water across/through the levee, adequate channels should be constructed to convey the water to the outlets or control structures to avoid localized flooding. Furthermore, because a levee creates a barrier during flood events, some of the water on the landward side may need to be stored for later gravity discharge or pumping across the levee.

Controlled flow options for the design of the crossing at such locations involve the use of gates and weirs. Design considerations are similar considerations to those already described for closure structures (section 7).

Uncontrolled flow options include various types of fuses designed to be removed under flood conditions. These include:

- Weak fuses which overtop and are washed away (i.e., breach) under high flows. The design of such fuses must ensure that the rest of the permanent levee is able to withstand loss of the fuse material, including provision of any scour protection to the sides and foundation of the fuse.
- Fuses designed to be breached by explosives. A demolition plan should be prepared for such locations, with drill holes installed for the addition of explosive charges.

Additional guidance on best practices for design of channels and floodways is available as follows:

- For design analysis and criteria of design for channels that carry rapid and/or tranquil flows, see EM 1110-2-1601 (USACE, 1994b).
- For determining potential channel instability and sedimentation effects, see EM 1110-2-1418 (USACE, 1994a), or the most recent manual available. The manual aids in identifying the type and severity of channel stability and sedimentation problems, the need for and scope of further hydraulic studies to address those problems, and design features to promote channel stability.
- For the design of reinforced concrete-lined flood control channels which convey rapid and tranquil storm water flows, see EM 1110-2-2007 (USACE, 1995d).

11 Interior Drainage Systems

The levee reduces risk to an interior area from riverine or tidal flooding. Normally, provisions are made in the levee to pass runoff out of the leveed area, preferably by gravity through drainage pipelines and control gate structures if possible. However, during a flood or storm surge event, outlets are closed, and the backup of water to be drained in the leveed area can cause interior flooding from storm runoff. This can be exacerbated by water passing into the leveed area due to throughseepage, underseepage and due to overtopping of levees (including at locations of controlled overtopping, see the previous section). The flooding can be a risk to life, property, and infrastructure, and should be addressed as part of the levee design process.

Interior area drainage formulation studies are therefore an essential aspect of formulation and design of levees. As part of this activity and regardless of the type of structure used to convey water back across or through the levee, adequate ditches, channels (or pipes) should be constructed within the leveed area to avoid localized flooding. During flood events, some of the water on the landward side may need to be stored for later gravity discharge or pumping across the levee.

Although facilities and costs may be minor compared to the levee project, they potentially can affect many stakeholders. Furthermore, interior drainage studies can be complex, depending on the level of development in the leveed area. The extent of the analyses is scalable, based on the size of the interior leveed area and land use. For guidance on conducting interior drainage studies see EM 1110-2-1413 (USACE, 2018).

Penetrations through levees are potential weak points for a failure that could lead to a levee breach. Levee penetrations include various public/private utilities, drainage structures collectively termed pipes, and supporting ancillary structures.

Potential failure modes can develop because of improper choice of penetration materials, deficiencies in the design process and detailing of penetrations, deficiencies in construction, and other causes. Designers should identify and address all potential failure modes. Potential failure modes include:

- Longitudinal seepage along the exterior surface of the penetration or joint seal failures leading to progressive growth of voids in the levee (internal erosion).
- Structural failure of penetrations or ancillary features (e.g., valve vaults, gatewells).
- Settlement of penetrations and ancillary features.
- Shear failure and cracking at connection points to hard features (e.g., at gatewells and headwalls).

Further discussion and guidance on identifying and addressing potential failure modes associated with conduits, pipes, and culverts during the design is provided in EM 1110-2-2902 (USACE, 2020).

11.1 Pipes

Pipes include pump station discharge pipes, gravity drainage pipes, and ducts for utility penetrations to power appurtenances. Where these become penetrations (section 2.3.6) as they pass within or beneath an embankment, careful design is required to address potential failure modes. Detailed guidance on the design of pipes passing through levees is available in EM 1110-2-2902 (USACE, 2020).

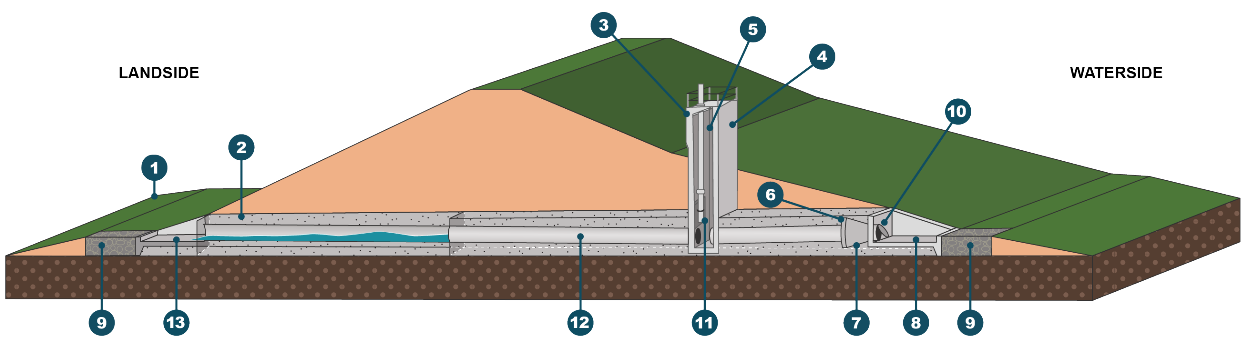
Special care should be given to pressurized pipelines to mitigate the chance of a blowout failure in the levee or foundation. Gravity outlets can be used to drain an interior area during a flood event, as long as the stage on the waterside is lower than the stage in the channel or collection pond on the landside. When the stage on the waterside exceeds the inlet water level, the gravity outlet on the waterside should be closed to prevent backflow. Any manually operated gates should ideally be located on the waterside edge of the levee crest in a vertical gate shaft and be accessible at all times.

Figure 7-40 shows a typical gravity drainage pipe penetration without a pump station. Figure 7-41 shows typical pipe penetrations with a pump station. There may be one or more pressurized pump discharge lines and a gravity drainage pipe used to bypass the pump station and drain water to the receiving body during non-flood periods.

Figure 7-40 shows a couple of features of importance:

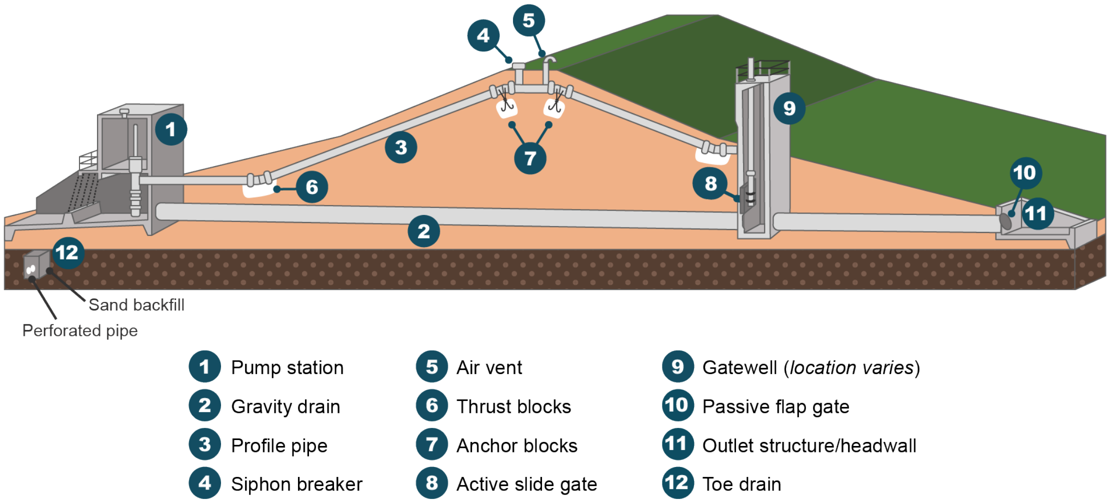
- Pipes should ideally not be bedded directly on compacted earth, but instead should be bedded on a controlled low strength material, which has self-consolidating and cementing characteristics.
- The outer surface of the pipe can act as a focal point for throughseepage during flood conditions leading to concentrated leak erosion. For this reason, a cone of filter material should be provided around the pipe at the landside end in two zones: filter diaphragm and filter transition. This drainage fill minimizes the transportation of fine soil material, provides controlled exit for water seeping along the pipe, and increases the integrity of the levee embankment.

Figure 7-40: Typical Drainage Pipe Penetration—Embankment Levee



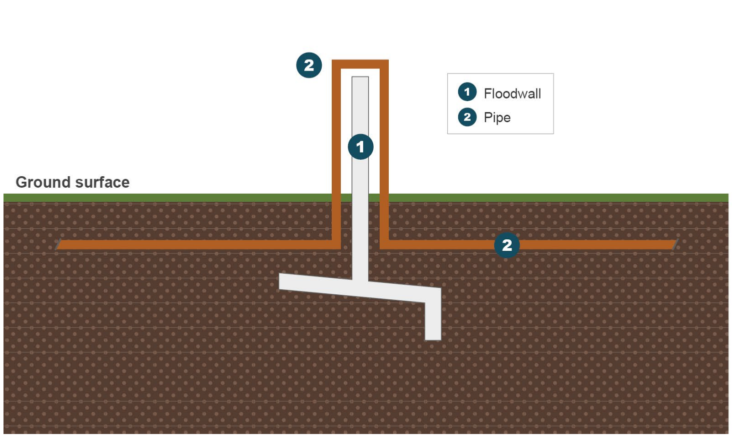
1. Existing ground surface
2. Controlled low strength material
3. Floor stands
4. Gatewell
5. Discharge pipes from pumping plants may terminate in gatewells
6. Filter diaphragm
7. Filter transition
8. Outlet structure
9. Riprap
10. Flap gate required for fast-rising streams
11. Sluice gate
12. Reinforced concrete pipe
13. Inlet structure for concrete pipe

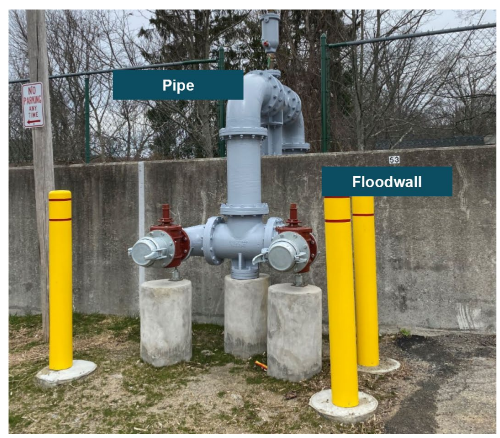
Figure 7-41: Interior Pump Station Pipe Penetrations



Interior drainage pipe and utility penetrations may also be needed for floodwalls (concrete or sheetpile). Figure 7-42 shows typical installation details for the floodwall penetrations. For new interior drainage pipelines and existing utilities to remain, the critical design feature will be sealing the penetration against seepage during a flood while allowing for the possibility of movement (settlement or rotation) of the floodwall over time. The designer should consider avoiding penetration by routing pipes or utilities over the floodwall where practicable. For buried drainage penetrations, the design should include a discharge headwall with rock slope protection to prevent erosion. Extreme care should be used when bedding pipes on earth and consideration given to use of controlled low strength material for bedding.

Figure 7-42: Detail of Pipe Passing Through Floodwall





View of a pipe passing over a floodwall, rather than through the levee under the floodwall.

11.1.1 Pipe Material

11.1.1.1 Concrete Pipe

The following types of concrete pipe are typically used in levee applications:

- Round non-pressure reinforced concrete pipe manufactured according to American Society for Testing and Materials International C76; used with gasketed joints.
- Low-pressure reinforced concrete pipe manufactured according to American Society for Testing and Materials International C361 or American Water Works Association C302; used with gasketed joints. Both standards are interchangeable.

The internal pipe diameter for high-risk levees should be at least 48 inches to facilitate installation, maintenance, and inspection. Other levees may have a minimum diameter of 36 inches.

11.1.1.2 Concrete Box Culverts

Reinforced concrete box culverts can also be used to convey drainage flows through levees. If used, however, box culverts should be cast-in-place with specialized design considerations for the joints. Precast box culverts should not be used because their joints have a history of leakage.

11.1.1.3 Corrugated Steel Pipe Material

Corrugated steel pipe manufactured according to American Society for Testing and Materials International A760 and A796.2.2 with gasketed joints may be a potentially viable option within a levee; however, corrugated steel pipe should only be used for non-pressurized applications with properly designed bedding and backfill.

11.1.1.4 Steel Pipe Material

Steel pipe conforming to American Water Works Association C200 with fittings conforming to American Water Works Association C208 may be used for gravity drainage pipes and pump discharge lines. Pipe is typically mortar lined and cement coated. Joints should be welded. Welded butt strap should only be used for field closures.

11.1.2 Pipe Design

The structural design of pipe penetrations should include all potential loadings, including earth loads (trench/embankment), road and railroad loadings, surface concentrated loadings, construction loads, and internal and external water pressure loadings. All potential loads should be identified and included in the design criteria, along with the proper methods used to analyze and design each feature and component. EM 1110-2-2902 (USACE, 2020), which covers conduits, pipes, and culverts for dams and levees, provides useful design guidelines, including material selection, design methods, loading combinations, safety factors, design details (e.g., trenching, bedding, backfill, use of controlled low strength material), procedures to control seepage along conduits, settlement and pipe connections to hard structures, and design examples.

Cast-in-place reinforced concrete box culverts, if selected, should be designed following the guidance in EM 1110-2-2104 (USACE, 2016b) with particular attention paid to the joint detail, since it is critical to ensure no soil intrusion will be possible (American Water Works Association, 2008).

Steel pipes should have corrosion protection provided either in the form of a resistant surface coating or by using a cathodic protection system. For concrete and steel pipe, specifications should require leak testing of joints as the pipe is assembled. Completed pipe should also be hydrostatic tested following American Society for Testing and Materials International C1103 (C13 Committee, 2022), or other applicable standard/guidelines.

Upon completion of installation, pipe interiors should be inspected and documented to prove a baseline condition for comparison with future inspections.

The specifications should require a detailed construction report be prepared with photographs and record drawings documenting all aspects of construction, including problems encountered, defects encountered, and corrective actions. This documentation is a valuable reference for future inspections, risk assessments, and evaluation of problems that might develop over the life of the project.

INFORMATION SOURCES FOR PIPE MATERIALS AND DESIGN

The following documents provide useful information on pipe materials and design methods with design examples:

- American Water Works Association Manual M9, Concrete Pressure Pipe (American Water Works Association, 2008).
- American Water Works Association Manual M11, Steel Pipe, a Guide to Design and Installation (Dechant, et al., 2017).
- American Concrete Pipe Association, Design Manual, Concrete Pipe. (American Concrete Pipe Association, 1980).
- American Society of Testing and Materials International ATSM C76-22, Standard Specification for Reinforced Concrete Culvert, Storm Drain, and Sewer Pipe (C13 Committee, 2022b).
- American Society of Testing and Materials International ASTM C361-22, Standard Specification for Reinforced Concrete Low-Head Pressure Pipe (C13 Committee, 2022b).

11.2 Ancillary Components

Ancillary components associated with the penetrations may include headwalls, gatewells, and valve vaults. Mechanical components may include slide gates or sluice gates, passive flap gates, air vents, and siphon breakers. A drainage pump station could also be part of the project. This chapter includes guidance for ancillary components while section 12 treats pump stations.

Appurtenant components are important for the proper performance of drainage penetrations. Failure of certain components could lead to uncontrolled releases or levee breach.

For design considerations related to mechanical components, refer to Table 7-18 for references to best practices.

Table 7-18: References for Design of Mechanical Components

Mechanical Component	Best Practice Reference
Sluice gate	• EM 1110-2-2902 Conduits, Pipes and Culverts Associated with Levees and Dams and Other Civil Works Structures (USACE, 2020b). • Engineering Technical Letter (ETL) 1110-2-584 Design of Hydraulic Steel Structures (USACE, 2014). • EM 1110-2-6054 Inspection, Evaluation, and Repair of Hydraulic Steel Structures (USACE, 2001b). • EM 1110-2-3105 Mechanical and Electrical Design of Pump Stations (USACE, 1995).
Flap gate	• EM 1110-2-2902 Conduits, Pipes and Culverts Associated with Levees and Dams and Other Civil Works Structures (USACE, 2020). • ETL 1110-2-584 Design of Hydraulic Steel Structures (USACE, 2014). • EM 1110-2-6054 Inspection, Evaluation, and Repair of Hydraulic Steel Structures (USACE, 2001b). • EM 1110-2-3105 Mechanical and Electrical Design of Pump Stations (USACE, 2020c).
Duckbill check value	• EM 1110-2-2902 Conduits, Pipes and Culverts Associated with Levees and Dams and Other Civil Works Structures (USACE, 2020).
Air vents and siphon breakers	• EM 1110-2-3105 Mechanical and Electrical Design of Pump Stations (USACE, 1995).

11.2.1 Gatewells

Gatewells are typically reinforced concrete structures usually located on the waterside of a levee system. Applicable regulations may require the gatewell be located next to the waterside levee crest. Gatewells typically house active gates (e.g., slide gates or sluice gates) that are closed during flood events to prevent backflow through the pipe. Gatewells may be rectangular or circular. Precast concrete gatewells may be used in lieu of cast-in-place concrete, if designed and detailed to satisfy the loading and functional requirements of the levee system, and if the joints are designed to prevent soil infiltration. Figure 7-43 shows a typical gatewell.

The gate operator is located on top of the gatewell and connected to the gate via a shaft properly attached to the wall. If gates are motor operated, the gate shaft wall anchors should be designed to resist the stall torque specified by the motor manufacturer. Failure to do so may result in a failed closure system that could allow interior flooding.

Figure 7-43: Example Gatewell with Sluice Gate and Operating Shaft

View looking into a gatewell, with sluice gate at bottom.

Waterside gatewells should have an operations platform (i.e., location of actuator or manual controls to lower the gate) a minimum of 1 foot higher than the height of the levee or floodwall to allow access at all times. Gatewells located immediately next to the levee crest provide the advantage of easy access regardless of the river level (**Chapter 9**); otherwise, a platform/bridge or an exterior ladder reachable by boat should be installed to access the top of the gatewell. There should also be access down to the bottom to the pipe and gate. If a bridge is constructed, consider that tall gatewells may require large piers within the embankment, creating the potential for additional seepage paths. For new construction, gatewells should be located at the waterside edge of the levee crest, eliminating the need for boat or platform/bridge access during a flood event.

All gatewell joints, whether cast-in-place construction joints or connections between stacked precast elements, should have a waterstop to prevent the infiltration of embankment material into the gatewell. The design of the waterstop should accommodate the anticipated differential settlement and resulting connection movement without failing. Similar to pump stations, movement of a gatewell due to instability or flotation could affect the performance of the levee by compromising the pipe gatewell. A poorly installed or compromised connection could allow material loss through the defect, leading to internal erosion. In cases where the pipe rests on a concrete cradle, the designer should determine if doweling the cradle and gatewell together is needed and/or appropriate. Typically, gatewells are very deep in order to service the connecting drainage pipe; therefore, the internal erosion process may be active for years, thus removing many yards of embankment material before a surface expression is observed for further guidance see EM 1110-2-2104 (USACE, 2016b) and EM 1110-2-2502 (USACE, 1989a).

11.2.2 Valve Vaults

The valve vault houses isolation valves for pump discharge. The vault is a reinforced concrete structure with grating or hatch covers, located next to the waterside edge of the levee crest. The valve may be a vertical slide gate or other commercially available full-flow valve. Gates or valves should be manually operable; motor operation can be added if desired. Air relief and vacuum relief valves, or a combination of air-vacuum valves, are also needed in combination with the gates or valves. A small access port with a bolted cover is also provided for video inspection of the pipe.

11.2.3 Headwalls and Gates

Headwalls should be installed wherever drain pipes enter or exit the levee toe, and at the landward end of pressurized pipelines. Gates should be provided at each headwall and may be of the various types discussed in **Chapter 2** (sluice or lift gate, flap gate, duckbill). Figure 7-44 shows typical headwalls with flap gates.

Figure 7-44: Example Headwalls with Flap Gates

View of a headwall with a flap gate in Louisville, Kentucky.

Headwalls function to recess the inflow or outflow end of a pipe into the fill slope to improve flow conditions, anchor the pipe, support gates, and control erosion and scour from the pipe outflow area. Headwalls are typically constructed using concrete and should use wingwalls for added stability. All new pipes should have a headwall on both ends. New landside headwalls should have sufficient area on their face to install gated drains associated with an internal seepage filter. To meet coverage requirements related to the internal filter, the height of the landside headwall above the pipe crown may have to be taller than most precast models; therefore, standard U.S. Department of Transportation headwalls may need to be modified.[2]

[2] Reference Chapter 17 of EM 1110-3-136, EM 1110-2-2104 (USACE, 2016b), and EM 1110-2-2002 (USACE, 1995) for additional information and design requirements for headwalls.

12 Pump Stations

Pump stations are included in levees when gravity drainage pipe systems cannot be used to remove water from the leveed area.

If required, the nature and capacity of a pump station will depend on hydraulic calculations linked to the amount of water stored in the interior area under various water levels and the consequences of the associated inundation. Depending on the area of the interior drainage basin, multiple pump stations may be needed at strategically placed locations. The failure of a pump station during a flood could result in considerable damage within the leveed area, causing the loss of some or all of the benefits that justified construction of the project. Consequently, pump station dependability should be the primary consideration during the design and pump selection process.

Pump stations are beneficial to drain interior water when no means exist to add another type of outlet. As shown in Figure 7-41, a typical pump station includes a pump, a gravity drainage pipe, and discharge pressure pipelines that pass through the levee and a gated valve. The pump discharge pipelines should cross through the levee at an elevation above the levee waterside design flood level.

This section provides general guidance for designing the pump station itself. Comprehensive pump station design guidance for civil and structural design—including foundations, loads, safety factors, and design methods—is available in EM 1110-2-3102 (USACE, 1995e) and EM 1110-2-3104 (USACE, 1989b). The major mechanical and electrical equipment selected for use should be rugged, reliable, and well suited for the type of service. For guidance on the design of pump stations, see EM 1110-2-3105 (USACE, 2020c). The pump station structure (frequently reinforced concrete) should be sized to house and support the equipment with adequate room for O&M.

Best practices for design of other components of pump stations can be found in Table 7-19.

Table 7-19: References to Design of Pump Station Components

Pump Station Component	Best Practice Reference
Structural	• Unified Facilities Criteria (UFC) 3-310-04 Seismic Design for Buildings (USACE, NAVFAC, and AFCEC, 2013). • EM 1110-2-3104 Structural and Architectural Design of Pumping Stations (USACE, 1989b). • American Society of Civil Engineers 7, Minimum Design Loads for Buildings and Other Structures (ASCE, 2022). • Federal Emergency Management Agency (FEMA) P-361, Safe Rooms for Tornadoes and Hurricanes: Guidance for Community and Residential Safe Rooms, Fourth Edition (FEMA, 2021). • EM 1110-2-3400 Painting: New Construction and Maintenance (USACE, 1995f).
Mechanical	• UFC 3-410-01 Heating, Ventilating, and Air Conditioning Systems (USACE, Naval Facilities Engineering Command, and Air Force Civil Engineer Support Agency, 2013). • UFC 3-600-01 Fire Protection Engineering for Facilities (USACE et al., 2016). • Unified Facilities Guide Specifications (UFGS) 35 45 01 Vertical Pumps, Axial-Flow, and Mixed-Flow Impeller-Type (USACE et al., 2021). • UFGS 35 45 02.00 10 Submersible Pump, Axial-Flow, and Mixed-Flow Type (USACE, NAVFAC, and AFCEC, 2021b). • UFGS 35 45 03.00 10 Speed Reducers for Storm Water Pumps (USACE et al., 2022). • EM 1110-2-3105 Mechanical and Electrical Design of Pump Stations (USACE, 2020c). • EM 1110-2-1424 Lubricants and Hydraulic Fluids (USACE, 2016a). • EM 1110-2-2704 Cathodic Protection Systems for Civil Works Structures (USACE, 1999). • ETL 1110-2-327 Geometry Limitations for the Formed Suction Intake, (Fletcher, 1990).
Electrical	• UFC 3-520-01 Interior Electrical Systems (USACE et al., 2016). • UFC 3-530-01 Interior and Exterior Lighting Systems and Controls (USACE et al., 2023). • UFC 3-550-01 Exterior Electrical Power Distribution (USACE, NAVFAC, and AFCEC, 2016b). • UFGS Section 26 29 01.00 10 Electric Motors 3-Phase Vertical Induction Type (USACE et al., 2022). • UFGS Section 26 29 02.00 10 Electric Motors 3-Phase Vertical Synchronous Type (USACE, NAVFAC, and AFCEC, 2022b, p. 29). • UFGS Section 26 41 00 Lightning Protection System (USACE, NAVFAC, and AFCEC, 2023b, p. 41).
Connection to interior drainage systems	• EM 1110-2-2902 Conduits, Pipes and Culverts Associated with Levees and Dams and Other Civil Works Structures (USACE, 2020).

12.1 Design

12.1.1 Hydrologic Studies

An interior drainage study and hydrologic studies of the leveed area should be completed as part of the formulation process for the levee project (**Chapter 6**). These studies provide the basis for establishing pumping requirements at various water stages permissible in the leveed area. The studies also provide the basis for designing the pump bypass gravity drainage system if one is provided with the pumping station. Siting the pump station along the levee alignment should be decided in the formulation study as well. The preferred location for a pump station is at the landside levee toe, which reduces the height of the pump column and the depth of the building.

The design should verify that the drainage and hydrologic studies account for all of the flows that may require pumping. In addition to interior storm drainage, other flows may include discharges for seepage collection systems, from wave overflow and from limited levee overtopping, if allowed in the levee design.

12.1.2 Pump Station Type

Pump stations typically have a wet-pit sump and employ vertical mixed-flow or axial-flow pumps. Water is usually pumped directly from storage ponds, ditches, or channels. When practical, provision should be made for exclusion of water from the pump sump and for maintaining the sump in a dry condition during inoperative periods. The operating floor level supporting the pump motors should be set above the maximum water level expected on the inlet side. Pump discharges may be located below or above the operating deck level.

Depending on location, pump stations may be open air or have a building enclosure over the operating deck. Suitable access should be provided to the pump station for construction and for permanent access for O&M.

12.1.3 Sump Pit and Adjacent Levee Design

Sump pits in or adjacent to levees probably cut through the clay blanket and need to be specially considered in seepage design (section 9) and slope stability design (section 5.2). During a flood, the sump pit may well become a weak point along the levee with elevated hydraulic gradients. The best practice is therefore to restrict hydraulic gradients around a pump station sump during a flood to a maximum of 0.3, due to the inability to observe and effectively floodfight anything that does occur.

12.1.4 Pump and Motor Selection

The number and resulting size of stormwater pumps should be determined by an economic study. This study should consider the consequences and related costs due to flooding if one pump malfunctions during a flood event. The greater the number of pumps, the smaller the reduction of the total station capacity if one pump malfunctions. However, this increased protection results in higher equipment, facility, and O&M costs. The need to reduce the impact if one pump malfunctions will most likely be appropriate in urban areas where a pump failure could cause significant property damage and raise ponding more rapidly to life threatening depths. Further discussion and guidance on identifying and addressing potential failure modes during design is provided in EM 1110-2-2902 (USACE, 2020b).

12.1.5 Pump Controls

The decision as to the type of control to specify for a flood control pumping station should be based on providing maximum reliability consistent with economic design. In the majority of cases, controls providing for manual start and automatic stop will be the most economical. From the standpoint of reliability, such controls are preferred. However, some installations may find the use of automatic start and stop controls to be an advantage, such as where limited sump capacity and inflow conditions would make manual starting impracticable due to short operating cycles, or where economy is obtained by using pumps of assorted sizes operating in a predetermined sequence. The control circuits of automatic stations should provide protection against simultaneous starting of all pumping units following a power interruption.

12.1.6 Forebay and Sump Sizing

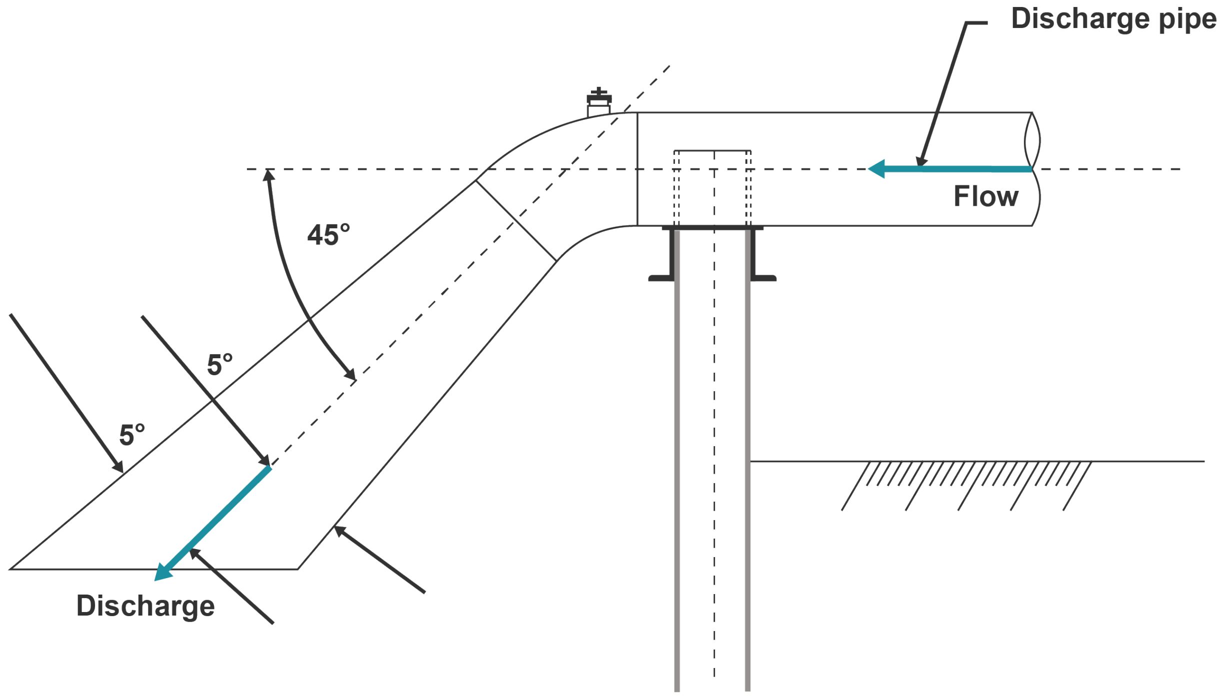
As a minimum, the size of the sump or pond serving the pumps may affect the selection of sizes and number of pumps. Pumps may cycle on and off as the water level in the sump varies up and down with the runoff. Provided sufficient storage so that the time between starts (cycle time) equals or exceeds the minimum operating cycle times to avoid damage to motors. Cycle times are based on motor power (kilowatt and horsepower) and are typically provided by motor manufacturers. EM 1110-2-3102 (USACE, 1995e) provides additional guidance on sizing sumps and forebays.

12.1.7 Pipes

All piping within a pump station structure should be ductile iron or steel with flanged joints or welded joints. In general, a single discharge pipeline should be installed for each pump. On large lines with submerged outlets, the discharge should be terminated in a cone to reduce flow velocity and corresponding exit losses (Figure 7-45). Downturn angle may vary but the flare of the discharge cone should be limited to 10 degrees maximum (five degrees off centerline) to avoid flow separation. Discharge piping should be constructed of steel or ductile iron, although high-density polyethylene piping may provide some advantages for conduit over levee sections where significant settlement is expected. The feasibility of high-density polyethylene should be evaluated during the design phase. All discharge line pipe should be protected on the inside with a smooth coating. Buried pipe should also be provided with an outer protective coal-tar coating and possibly wrapping. Shop coatings should be used to the maximum extent possible due to the enhanced quality control.[3]

[3] Refer to EM 1110-2-3105 (USACE, 2020) for best practices in pipe intake and discharge construction.

Figure 7-45: Discharge Cone or Bell for a Pump Station



12.1.8 Trash Racks

All flows into drainage pumping stations should be screened before reaching the pumps. Conventional bar screens (trash racks) are the preferred method of screening. Suction strainers should be avoided as they clog readily and are difficult to clean. Trash racks should be located to allow incoming flows to pass through the rack before reaching any pump intake, flow to be evenly distributed over the submerged rack surface and raking to be accomplished coincident with pump operation.

Trash racks should have ample net area so that the velocity of the flow through the gross rack area does not exceed 2.5 feet per second. The clear opening between bars should be approximately 1 3/4 inches, but should not exceed 3 inches. Bar spacing should be coordinated with the pump manufacturer.

12.1.9 Spare Equipment

Spare equipment should be considered for equipment whose design is unique or one-of-a-kind in construction, which would make replacement lengthy or very costly. Spare equipment for most pump stations should consist of bearings, impellers, shaft sleeves, temperature probes, relays, switches, lubricators, and any other types of auxiliary equipment being used on the pumping unit. Equipment problems caused by condensation and exposure to sewer gases in pumping stations used to pump sanitary sewage and storm water require additional corrosion resistant materials and sealants. Spare equipment should also include a spare impeller and pump bowl section if there are a large number of pumping units at the project (typically five or more) or there are multiple stations using the same size and type of pump procured under the same contract. Spare parts should also be provided for the prime mover.

12.2 Power Supply

All facilities necessary to supply the electric power required to operate the pumping stations should be provided as part of the flood risk reduction project. Power supply should be coordinated with the utility providing the service to determine the extent of work needed to supply the power and what components would be a cost to the project. The construction required may vary from the simple overhead service drop at the pumping station site at utilization voltage to extensive installations involving transmission lines, switching, and transformer equipment. The substation should be located and constructed so that access is available to the electric utility for maintenance and repair.

In general, flood protection pumping stations should be considered emergency facilities. Equipment and power supply should be selected primarily on the basis of reliability under emergency conditions. The need for additional emergency or standby power supply facilities should be considered.

12.3 Other Considerations

The design should include instrumentation to monitor and record water levels at the entrance to the station and in the receiving water body. This can be incorporated into the monitoring and control system for the station. Flow rate monitoring in the pump discharge piping should also be considered.

For enclosed pumping stations, lighting, heating, and ventilation will be needed. Removable roof hatches should be provided to remove and replace pumps and motors if needed.

The primary cause of equipment deterioration in many pumping stations is simply from lack of operation and long durations of downtime and associated moisture problems caused by this downtime. These conditions should be considered when preparing designs and specifications. The designer should investigate the use of heaters in the housings of motors, motor control centers, and switchgear to help mitigate moisture condensation.

- For example, bearings and seals on pumps can deteriorate if not used or exercised on a regular basis. Excessive moisture in operating buildings can lead to rust and corrosion in electrical cabinets. The designer should give preference to those materials that require the least maintenance and have the longest life.
- Specifications covering the materials and construction considered best suited to meet the usual service conditions should be provided for various pump station equipment.

Pumping stations are critical infrastructure. Security needs should be evaluated and implemented in design.

13 Instrumentation

13.1 Instrumentation and Monitoring Plan

An instrumentation and monitoring plan for the project should be prepared (Figure 7-46), taking into account the recommendations in **Chapter 9**. The extent of instrumentation included in the plan should be informed by the results of the risk assessment (**Chapter 4**). In higher risk situations it may be justifiable to complement other information and analysis by including sufficient instrumentation that will help reduce uncertainty in the understanding of levee behavior both during construction and during flood loading. In lower risk situations, extensive instrumentation is less likely to be justified. However, in either situation, if an observational approach is adopted in order to limit construction costs, instrumentation will be necessary in order to validate the eventual design.

The instrumentation and monitoring plan should be prepared in advance of the commencement of construction so that the construction management team understands how to install and monitor instrumentation, what action limits will apply, and what actions will be necessary to meet the designer's intent. Monitoring during construction ensures adverse conditions do not develop that can jeopardize the work or endanger workers or the public. The plan should indicate the required instrumentation, the timing for placement and baseline readings, threshold action levels, and who is responsible for installation and reading. Common instrumentation for levee projects may include piezometers, inclinometers, and settlement gages or plates. Installation locations and details should be clearly identified on the plans.

This plan generally does not include environmental monitoring, such as noise or air quality. These items should be provided by the constructor as required by the contract documents.

Figure 7-46: Information to Include in a Monitoring Plan

INFORMATION THAT SHOULD BE DEFINED IN THE PLAN WOULD INCLUDE:

- **Specifying the duration and parameters to be monitored.**
- **Identifying the data collection and management techniques.**
- **Setting guidelines for relocating instrumentation in the field, if needed.**
- **Identifying qualifications for the staff installing instruments and taking readings.**
- **Monitoring frequency and threshold action limits, actions required.**
- **Identifying the budget requirements.**
- **Selecting the appropriate instrument.**
- **Identifying reporting requirements.**

13.2 Instrumentation of Embankments

Monitoring instrumentation installed during levee embankment construction and post-construction may include:

- Seepage or groundwater monitoring wells/piezometers for water level or pressure measurements.
- Settlement plates to monitor construction movement of the cutoff wall systems.

- Earth pressure cells to monitor cutoff wall (soil contact stress).
- Inclinometers or tiltmeters to monitor displacement of the embankments.
- Flood water elevation gages.

Piezometers and settlement monitoring measures can be designed in accordance with EM 1110-2-1908 (USACE, 2020a). Access to read monitoring instruments during high water events should be considered in design.

Construction site monitoring may include requirements for visual observation or inspection or automated monitoring via camera or video. Project sites commonly are monitored using artificial intelligence software and ground, mounted, or drone-based cameras.

13.3 Instrumentation of Floodwalls and Structures

The instrumentation for the floodwalls and associated structures should be monitored during construction and post-construction. Instrumentation and monitoring for walls that are part of embankment dams or levees are described in EM 1110-2-1908 (USACE, 2020a). Measurements of movements and pressures furnish valuable information for use in verifying design assumptions. Most importantly, the data may forewarn of a potentially dangerous situation that can affect the post-construction stability of the floodwall or structure.

Settlement reference markers installed to monitor movements should be tied into a permanent baseline, located so it is unaffected by movements of the wall. When establishment of a baseline is not feasible, the relative movements observed between floodwalls and adjacent structures can provide valuable data on behavior of the wall. For floodwalls 15 feet or shorter, the settlement reference markers alone should be adequate. For taller floodwalls, use of inclinometers or tiltmeters should be considered.

13.4 Post Construction Monitoring

The designer may require instrumentation monitoring be continued beyond the end of construction. In this case, the plan should indicate who will assume post-construction monitoring responsibility and how collected data from construction should be transferred.

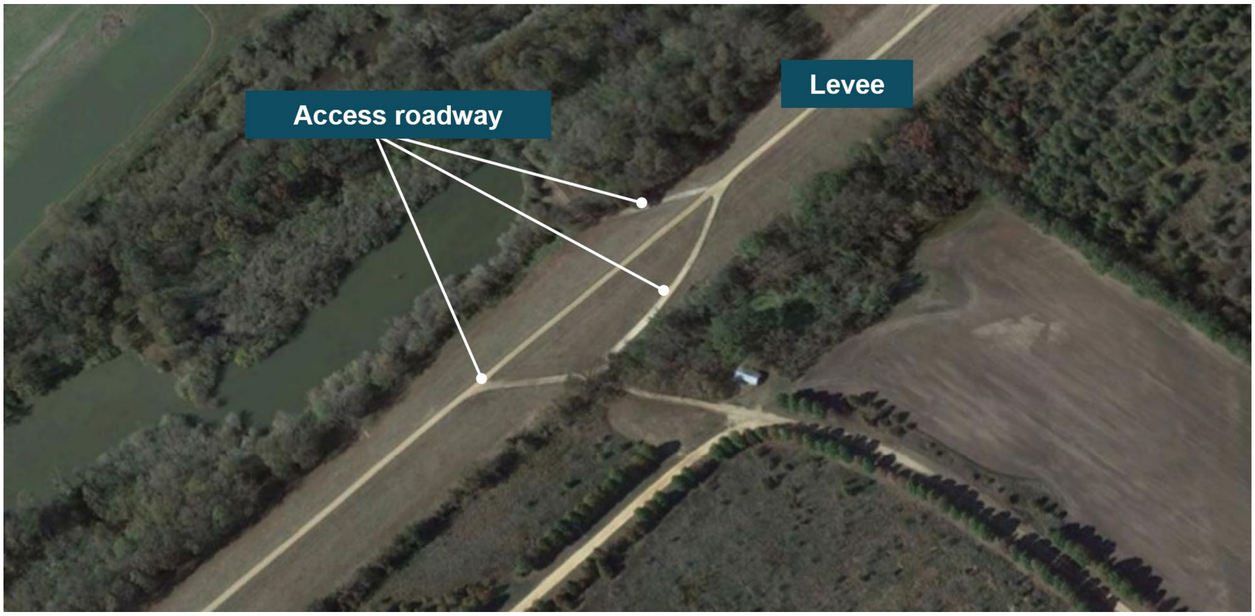
13.5 Water Level and Tide Gages

The design should include locating automatic recording water level gages for creeks and rivers adjacent to the levee system and tide gages for coastal levee systems. These provide needed real-time information to inform operation of the levee. This information will be particularly important in making decisions regarding operating flood protection closure devices.

14 Levee Access

Where possible, access should be provided to the levee at reasonably close intervals from public roads or using private roads with a negotiated easement in place for inspection, maintenance, and floodfighting operations. If possible, these roads should be all-weather roads. Figure 7-47 shows typical access roadways to the levee crest.

Figure 7-47: Example Access Roadway



Access roadway to levee crown of Mississippi River levee north of Vicksburg, Mississippi.

Access roads should be provided on the levee crown for operations, maintenance, and floodfighting operations. Access roads also should be provided for levee structures and appurtenances, including gate or closure structures and pump stations, and be adjacent to relief wells. This type of road should be surfaced with suitable gravel or a crushed-stone base course that permits vehicle access during wet weather without causing detrimental effects to the levee or presenting safety hazards to levee inspection and maintenance personnel. Non-woven geotextiles or geogrids may be used under aggregate surfacing to improve subgrade stability, which may reduce maintenance and improve the ability for vehicles to navigate the road during inspections and flood-fighting operations.

Turnouts should be used to allow for a means for the passing of two motor vehicles on a one-lane access road on the levee. Turnouts should be provided at intervals of approximately one-half mile. They are particularly beneficial where no ramps are within the reach. Turnarounds sometimes are provided to allow heavy equipment to reverse direction on levees.

Ramps should be installed approximately every mile to permit vehicular traffic to access onto and exit the levee crown, and to connect the levee crown with the landside and waterside toes of the levee. Ramps on the waterside of the levee should be oriented to minimize turbulence. Ramps should be angled for side-approach instead of at a right-angle (perpendicular to the levee access road) in order to reduce the requirement for additional embankment material. The ramp width should be determined based on its intended function. The grade of the ramp should be no steeper than 10%. Side slopes on the ramp generally should be the same slope ratio as the adjacent embankment slope and should not be steeper than 1 vertical and 3 horizontal, to allow grass-cutting equipment to operate. The ramp should be surfaced with suitable gravel or crushed stone. The levee section should never be reduced to accommodate a ramp.

15 Summary

As critical infrastructure reducing flood risk, each levee should be designed, modified, or remediated following the current best engineering practices applicable at the time of design. This also includes:

- Appropriately characterizing site conditions, including the reach-by-reach variations.
- Ensuring the design delivers the required level of flood risk reduction, including designing the levee features and the transitions between them as a complete system.
- Delivering an economically feasible approach by optimizing the balance between costs, risks, and benefits.
- Delivering a design which is constructable, while communicating the design intent clearly through the appropriate construction documentation.

The level of investigation and study adopted in the design process should be risk-informed (i.e., scaled to the level of flood risk) and should be scaled to the size and nature of the works. For example:

- For a simple repair, the preliminary design may consist of a few sketches (of a couple of options) and a few notes, put together by an experienced individual following a site visit.
- For a large project involving a new levee through the center of a town, the design process would usually be more extensive, requiring the consideration of a range of options, flood risk assessments, environmental impact assessments and detailed drawings and specifications supported by potentially complex calculations.

Levees should be designed for whole-life resilience, which includes:

- Preparing for both present day and for future hazard loading conditions on the levee systems (such as those associated with climate change).
- Ability of the levee and its components to absorb adverse loading without failing through any of the potential failure modes, including failure during overload conditions exceeding the nominal design conditions. This includes consideration of providing resilience in parts of the levee system to allow the levee to overtop without breaching.
- Ability to readily restore or recover the levee after damage due to adverse loadings.
- Building in the ability to strengthen/adapt the levee to meet future changes in hazards or within the leveed area. (This may include adjusting the land-take to allow for future change.)

Ecological/environmental risks and opportunities should be considered through the design process, incorporating the natural environment into the design wherever possible.

Social risks and opportunities should be considered through the design process, where possible implementing design features that support the everyday functioning of the local community.

Related content associated with this chapter is included in detail in other chapters of the National Levee Safety Guidelines as described in Table 7-20.

Table 7-20: Related Content

Chapter	Chapter Title	Related Content
1	**Managing Flood Risk**	• Levee form and function • Types of levee projects
2	**Understanding Levee Fundamentals**	• Levee features
3	**Engaging Communities**	• Engaging for levee projects
4	**Estimating Levee Risk**	• Flood and levee risk • Risk assessment
5	**Managing Levee Risk**	
6	**Formulating a Levee Project**	• Levee alignment • Crown elevation and geometry
7	**Designing a Levee**	
8	**Constructing a Levee**	• Instrumentation
9	**Operating and Maintaining a Levee**	• Instrumentation and monitoring
10	**Managing Levee Emergencies**	
11	**Reconnecting the Floodplain**	
12	**Enhancing Community Resilience**	• Community resilience

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8

Constructing a Levee

Key Messages

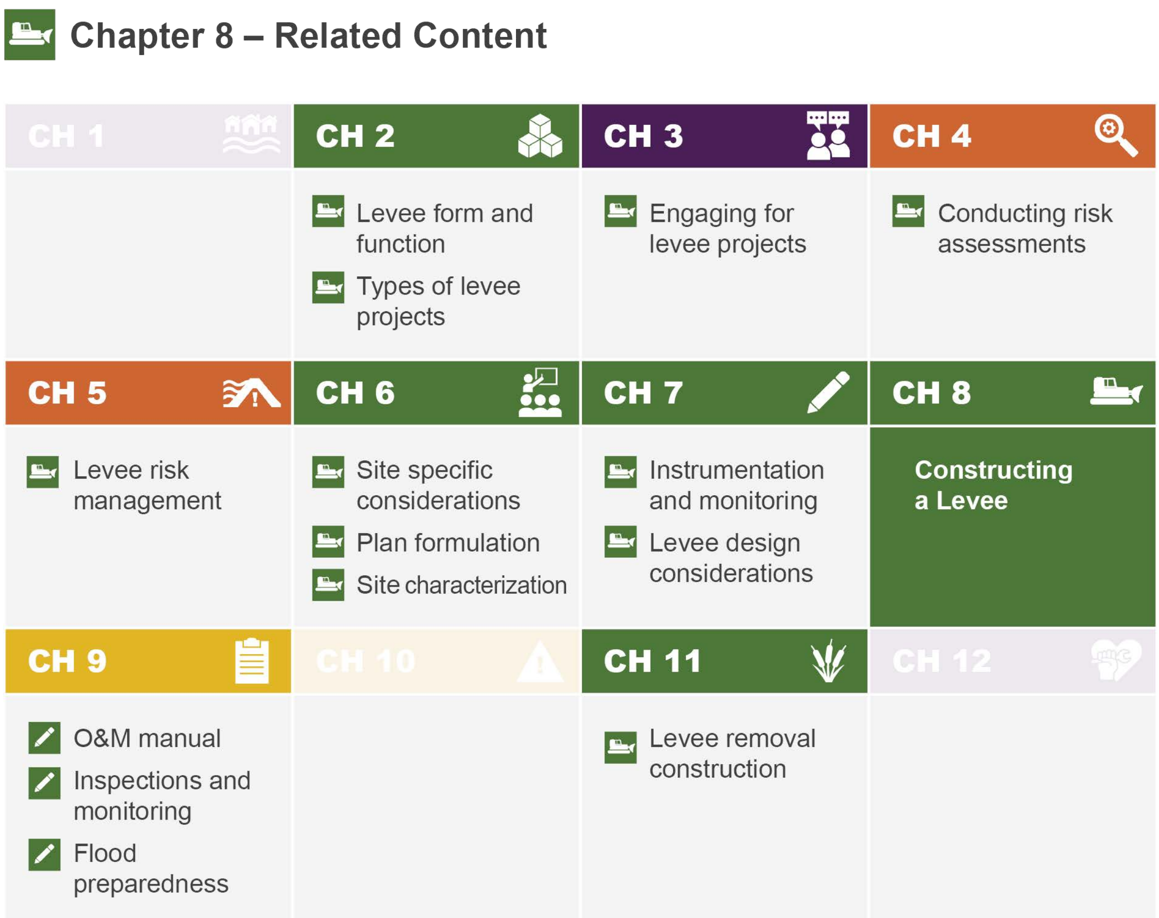
This chapter will enable the reader to:

- **Coordinate.** The coordination of information between levee formulation, design, and construction is vitally important throughout a levee construction project to ensure success.
- **Manage risks.** Flood risk during construction and risks to levee construction (time, quality, cost, safety) should be assessed, communicated, prepared for, and mitigated.
- **Expect variability.** Levee construction projects vary in size and complexity. It is important to understand the procedures and equipment unique to each project feature.
- **Maintain records.** Clear documentation is important to ensure a smooth transition from levee construction to levee operation.


LEVEETOWN, USA

Other chapters within the National Levee Safety Guidelines contain more detailed information on certain topics that have an impact on constructing a levee, as shown in Figure 8-1. Elements of those chapters were considered and referenced in the development of this chapter and should be referred to for additional content.

Figure 8-1: Related Chapter Content



Contents

1 Introduction 8-1

2 Construction Principles and Process 8-1

2.1 Relationship Between Formulating a Levee Project, Levee Design, and Levee Construction . 8-2

2.2 Community Engagement During Construction 8-2

2.3 Types of Levee Construction Projects 8-4

2.4 Levee Construction Process 8-6

3 Preparing for Levee Construction 8-7

3.1 Incorporating Levee Project Constraints 8-7

3.1.1 Access and Right of Way 8-8

3.1.2 Borrow Areas 8-10

3.1.3 Cultural Resources 8-10

3.1.4 Environmental Considerations 8-11

3.1.5 Hazardous Materials 8-12

3.1.6 Noise, Vibration, and Lighting Considerations 8-12

3.1.7 Permits 8-13

3.1.8 Utility Considerations 8-15

3.1.9 Weather and Climate Considerations 8-15

3.2 Evaluating the Constructability of the Project 8-17

3.3 Scoping the Project for Construction 8-19

3.3.1 Third-Party Agreements 8-19

3.4 Selecting a Levee Constructor 8-20

3.4.1 Levee Constructor Procurement Process 8-22

4 Constructing the Levee 8-25

4.1 Construction Plan Development 8-26

4.1.1 Health and Safety Management 8-28

4.1.2 Environmental Management 8-29

4.1.3 Managing Traffic During Construction 8-30

4.1.4 Coastal Construction Considerations 8-31

4.1.5 Temporary Relocations and Diversions 8-32

4.2 Quality Management 8-32

4.2.1 Staffing 8-33

4.2.2 Corrective Actions 8-34

4.2.3 Testing Entity 8-35

4.2.4 Quality Assurance 8-35

4.3 Coordination and Communication During Construction 8-35

4.4 Construction Monitoring and Data Management 8-36

5 Levee Construction Closeout 8-39

5.1 Post-Construction Project Evaluation 8-39

5.1.1 Inspection 8-39

5.1.2 Risk Assessment 8-39

5.2 Project Documentation 8-39

5.2.1 Construction Completion Report and Record Drawings 8-40

5.2.2 Foundation and Embankment Report 8-41

5.2.3 Operations and Maintenance Manual 8-41

6 Levee Features and Construction Considerations 8-42

6.1 Embankment 8-42

6.1.1 Line and Grade 8-42

6.1.2 Subgrade Preparation 8-42

6.1.3 Inspection Trench 8-44

6.1.4 Embankment Composition and Sources 8-45

6.1.5 Blending 8-47

6.1.6 Compaction 8-47

6.1.7 Stability During Construction 8-49

6.1.8 Embankment Slopes 8-49

6.1.9 Erosion Control Features 8-50

6.1.10 Settlement Control 8-53

6.2 Floodwalls 8-55

6.2.1 General Floodwall Considerations 8-55

6.2.2 Concrete T-Walls and L-Walls 8-57

6.2.3 I-Walls 8-59

6.2.4 Mass Gravity Walls 8-61

6.2.5 Structural Backfill 8-62

6.2.6 Levee-Floodwall Combinations 8-62

6.3 Closure Structures 8-62

6.4 Transitions 8-64

6.5 Seepage Control Features 8-66

6.5.1 Seepage Cutoff Walls 8-67

6.5.2 Seepage Berms 8-70

6.5.3 Landside Pressure Relief Systems 8-71

6.6 Channels, Floodways, and Controlled Overtopping 8-75

6.6.1 Channels and Floodways 8-75

6.6.2 Locations of Controlled Overtopping 8-76
6.7 Interior Drainage Systems 8-76
6.7.1 Pipes 8-76
6.7.2 Ancillary Components 8-81
6.8 Pump Stations 8-82
6.9 Instrumentation 8-85
7 Managing Risks During Construction 8-86
7.1 Construction Risk 8-86
7.1.1 Risk Register 8-87
7.1.2 Risk Workshop 8-88
7.1.3 Test Sections 8-88
7.2 Managing Flood Risks During Construction 8-88
8 Summary 8-89

List of Figures

Figure 8-1: Related Chapter Content 8-i
Figure 8-2: Relationship Between Levee Project Phases 8-2
Figure 8-3: Example of Community Engagement 8-3
Figure 8-4: Example of a Levee Construction Project 8-5
Figure 8-5: Levee Construction Process 8-7
Figure 8-6: Example of Construction Access 8-9
Figure 8-7: Sign for an Environmental Protection Area 8-11
Figure 8-8: Inclement Weather Impacting Levee Construction 8-16
Figure 8-9: Levee Construction Performed by a Constructor 8-21
Figure 8-10: Aerial View of Levee Construction 8-25
Figure 8-11: Example Gantt Chart 8-27
Figure 8-12: Example of Public Safety During Levee Construction 8-29
Figure 8-13: Example of Tempoary Erosion Protection 8-30
Figure 8-14: Example of Coastal Levee Construction 8-31
Figure 8-15: Example Survey Control 8-38
Figure 8-16: Example Levee Subgrade Preparation 8-43
Figure 8-17: Example Inspection Trench 8-45
Figure 8-18: Example Borrow Source Excavation 8-46
Figure 8-19: Example of Sheepsfoot and Flat Drum Compactor Equipment 8-48
Figure 8-20: Example Density Testing 8-48
Figure 8-21: Example Embankment Slopes 8-50
Figure 8-22: Example of Riprap Erosion Control Feature Construction 8-51
Figure 8-23: Example of Hydroseeding for Erosion Control 8-53

Figure 8-24: Example Wick Drain Installation 8-55
Figure 8-25: Example of Excavation of an Abandoned Utility....8-56
Figure 8-26: Example Floodwall Foundation Construction 8-57
Figure 8-27: Example Concrete Placement for Floodwalls....8-58
Figure 8-28: Example Pile Driving 8-60
Figure 8-29: Example Closure Structure Construction 8-63
Figure 8-30: Example Embankment/Floodwall Transition Construction 8-65
Figure 8-31: Example Levee Transition Connection (Embankment and Floodwall) 8-66
Figure 8-32: Example Open-Trench Cutoff Wall Construction 8-67
Figure 8-33: Example Mix-in-Place Cutoff Wall Construction....8-68
Figure 8-34: Example Quality Control Testing of Open Trench Cutoff Wall 8-69
Figure 8-35: Example Construction of Landside Berm and Chimney Drain 8-71
Figure 8-36: Throughseepage Pressure Relief Systems....8-71
Figure 8-37: Underseepage Pressure Relief Systems 8-72
Figure 8-38: Example Relief Well Construction 8-75
Figure 8-39: Example of Landside Interior Drainage Construction....8-77
Figure 8-40: Example Interior Drainage Pump Station 8-79
Figure 8-41: Example Construction of a Pump Station....8-83

List of Tables

Table 8-1: Typical Attributes for Levee Construction Projects....8-5
Table 8-2: Construction Considerations for Weather and Climate-Related Issues 8-17
Table 8-3: Common Constructability Issues and Best Practices for Levees 8-18
Table 8-4: Common Documents for Levee Construction....8-19
Table 8-5: Selection Criteria that Can Be Used for Each Primary Selection Factor....8-22
Table 8-6: Advantages and Disadvantages of Alternate Construction Procurement Strategies 8-24
Table 8-7: Material, Equipment, and Labor Availability Issues and Best Practices....8-27
Table 8-8: Basic Quality Management Staffing and Responsibilities 8-33
Table 8-9: Possible Construction Deficiencies for Embankments 8-34
Table 8-10: Common Data in Levee Construction....8-37
Table 8-11: Construction Considerations for Settlement Control 8-54
Table 8-12: Advantages and Disadvantages of Relief Well Drilling Method 8-74
Table 8-13: References to Best Practices for Construction of Ancillary Components 8-82
Table 8-14: Sample Risk Register 8-87
Table 8-15: Related Content....8-90

1 Introduction

The purpose of this chapter is to present the underlying principles, best practices, and situation-specific considerations for constructing levee features. Activities spanning the entire construction lifecycle—preparing for levee construction, constructing the levee, and closing-out construction—are described, emphasizing practices that result in effective levee performance and serviceability. The inherent linkages with project formulation, design, and operation and maintenance (O&M) are addressed early in the chapter to underscore the importance of continuity. Guidance related to managing construction risks, in addition to environmental, cultural, and natural resource impacts, is also covered. The guidance in this chapter is for use by qualified levee designers, constructors, and owners, and these best practices should be applied for the construction of new and existing levee features.

2 Construction Principles and Process

The levee construction phase is vital to ensuring project objectives are met. It involves the physical build of a new levee feature, modification, or rehabilitation of an existing levee feature. Levee construction is often complex, requiring a significant investment of resources (e.g., funds and labor).Levee construction activities, when done improperly, can negatively impact levee performance and **flood risk** to communities, environmental and natural resources, and surrounding critical public infrastructure such as utilities and roadways. It is important for any levee construction project or activity to achieve the following goals:

- Construct the levee project as planned to achieve the intended flood risk reduction benefits, as well as the co-benefits of the levee project.
- Construct the levee project in a cost effective and timely manner.
- Conduct levee construction activities in a manner that minimizes and reduces impacts to environmental, cultural, and natural resources.
- Conduct levee construction activities in a manner to avoid or reduce disruption to local residences, businesses, and industries.

There are many different types of levee construction projects that vary in size and complexity. Each project has a unique set of objectives, constraints, and stakeholders with a vested interest in the project. To achieve the goals of levee construction, it is important to understand the intricate relationship between levee construction activities and the levee project objectives, constraints, and stakeholders involved. The next sections describe key aspects of successful levee construction.

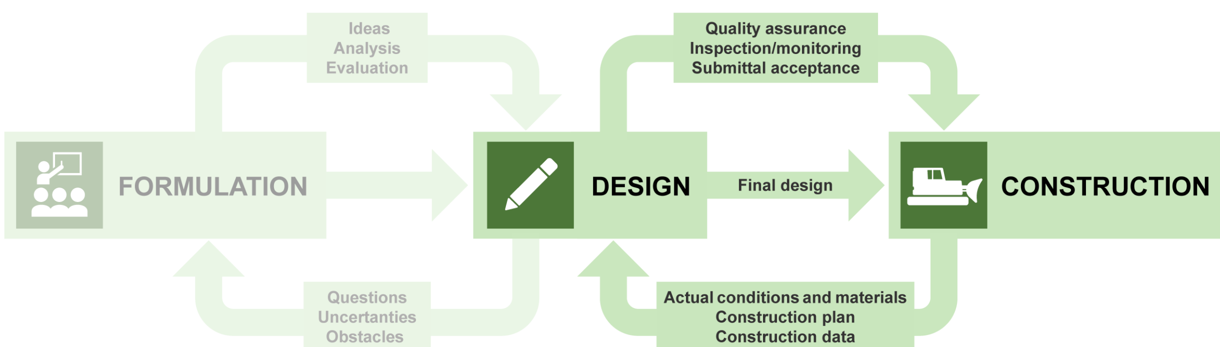
2.1 Relationship Between Formulating a Levee Project, Levee Design, and Levee Construction

The coordination of levee project information between levee formulation, design, and construction ensures a successful project, as follows:

- Formulating the levee project establishes the objectives and constraints of the project using methods described in **Chapter 6**.
- Levee design defines and conveys the levee project scope based on the objectives and constraints using the methods described in this chapter and **Chapter 7**.
- Levee construction involves building the physical structure (e.g., levee, floodwall) based on the project design specifications.

This relationship between levee formulation, design, and construction is shown in Figure 8-2 and emphasizes the relationship between design and construction, including activities and information that is shared between the project phases. Details on these activities are discussed later in this chapter.

Figure 8-2: Relationship Between Levee Project Phases



2.2 Community Engagement During Construction

Engaging community members and impacted stakeholders during construction is beneficial to the project. The engagement increases the likelihood that projects will be widely accepted and helps to create solutions for project constraints that are practical and effective since they draw on local knowledge.

Communication and engagement should be initiated during the levee formulation process and continue throughout levee design and construction (Figure 8-3). Communication during construction should be accurate, timely, and transparent, especially in regard to possible stakeholder disruptions. It is a best practice to understand and take into consideration the unique interests of stakeholders, including but not limited to:

- Adjacent property owners.
- Residents, industries, and business owners of nearby communities.

- Environmental and cultural resources and regulatory agencies.
- Public utility entities (e.g., electrical, water, gas).
- Transportation entities (e.g., road, highway, railroad).

Common questions that stakeholders may ask during construction include:

- Will this project impact or damage my property?
- Will this project disrupt my utilities?
- Will this project disrupt access to my property and/or roads and commute routes?
- Will this project cause damage to the existing levee and increase my flood risk?
- Could this project negatively impact environmental and cultural resources?
- Could this project negatively impact my business or industry?

Refer to **Chapter 3** on best practices for engaging stakeholders and the community for levee projects.

Figure 8-3: Example of Community Engagement

A passing cyclist stops to learn more about improvements to the Sacramento area flood risk reduction system. The displays were part of an April 8, 2016 ceremony where federal, state, and local leaders announced the completion of 22 miles of levee improvements along the American River.

2.3 Types of Levee Construction Projects

Types of levee construction projects can vary in size and complexity; therefore, it is important to understand the different types of projects and the unique considerations for each. The various types of projects include:

- **New levee construction:** Construction of a new levee where no man-made levee features currently exist (Figure 8-4).

- **Levee modification:** An activity that changes the original (e.g., as designed) operation and function of a levee.
  - Example modifications that change the levee function may include raising the levee height or modifying its alignment.
  - Example modifications that change the levee operation may include adding or removing features (e.g., interior drainage, seepage control systems, pipes, gates).

- **Levee rehabilitation:** An activity that restores a levee to its original (e.g., as designed) operation and function. Rehabilitation may be needed due to damage, deterioration, or deficiencies that result in improper levee performance. Rehabilitation is more substantial than normal maintenance and is typically not routine in nature. Examples of levee rehabilitation may include replacement of pipes, pumps, and other significant components; restoration of the levee cross section; and addressing performance issues (e.g., seepage, stability, erosion) that are preventing the levee from functioning as intended.

Figure 8-4: Example of a Levee Construction Project

The Marysville Ring Levee in 2011, with nearly completed portions in the distance, separates the roads and town of Marysville, California, on the left, from the floodplain of the Yuba River on the right.

Table 8-1 shows the typical attributes for the different types of levee construction projects.

Table 8-1: Typical Attributes for Levee Construction Projects

Type of Levee Construction Project	Typical Attributes
New levee construction	• Scope and scale can vary widely depending on the size and types of levee features. • May require multiple constructors with various specialties. • Site condition (access, utilities, foundation conditions) uncertainty may be high.
Levee modification	• Scope and scale can vary widely depending on the degree of modification. • Maintaining the existing levee's flood risk reduction function is typically required during construction. • Site condition (access, utilities, foundation conditions) uncertainty may be lower.
Levee rehabilitation	• Scope and scale can vary widely depending on the degree of rehabilitation. • Less permitting may be required as the work typically occurs within previously permitted areas. • Maintaining the existing levee's flood risk reduction function is typically required during construction.

2.4 Levee Construction Process

For any type of levee construction project, the levee construction process can be divided into three general phases—preparing for levee construction, constructing the levee, and levee construction closeout.

Preparing for levee construction starts during project design and ends when a constructor has been identified. Proper preparation for levee construction will help ensure the success of the project. Some important questions that should be answered during this phase include:

- What is the scope and cost of the levee construction project?
- Are there enough funds available for levee construction?
- How will the levee constructor be selected?
- How will the levee project constraints be addressed during levee construction?

Constructing the levee begins when the levee constructor starts work on the project and ends when construction is near completion. Proper execution of the project scope is vital to ensuring the levee satisfies its intended objectives. Some important questions that should be answered during this phase include:

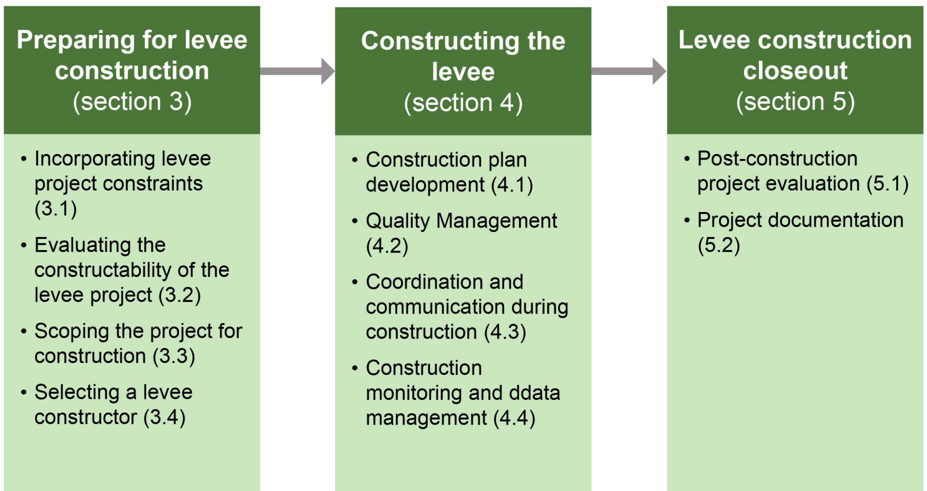
- What type of labor, equipment, and materials is needed for the construction project?
- How will site safety—including public safety—be maintained?
- How will quality be controlled and assured during the construction work?
- How will completed work be maintained during the identified warranty period?

Levee construction closeout is the final phase of the levee construction process. This phase begins when the construction is near completion and ends when the constructed levee is placed into operation. Some important questions that should be answered during this phase include:

- Does the constructed levee meet the intended objectives?
- Has all construction documentation been collected and stored properly for future use?
- Is there sufficient understanding and documentation on how to properly operate and maintain the levee?
- Have all the parties that will be involved in levee management activities been coordinated with and given sufficient information to fulfill their roles?

The levee construction process is summarized in Figure 8-5. The following sections of the chapter will provide best practices on how to successfully implement each phase of the process.

Figure 8-5: Levee Construction Process



3 Preparing for Levee Construction

As stated previously, proper preparation for levee construction will help ensure the success of the project. The main topics that are covered in preparing for construction include:

- Incorporating project constraints into levee construction.
- Ensuring the levee project is constructable.
- Preparing documents for levee construction.
- Selecting a levee constructor.

3.1 Incorporating Levee Project Constraints

There are a variety of levee project constraints that require proper planning to ensure they are addressed and do not negatively impact construction (e.g., costs and schedule). The following is a list of common constraints that should be considered during levee construction:

- Access and right of way
- Borrow areas
- Cultural resources
- Environmental considerations
- Hazardous waste
- Noise, vibration, and lighting

- Permits
- Utilities
- Weather and climate

3.1.1 Access and Right of Way

Access and right-of-way constraints can adversely impact construction due to the inability to access the construction site and/or having insufficient right of way to properly construct the levee. These should be obtained prior to the start of construction.

Recommended access and right-of-way best practices include:

- Proactive traffic management coordination with the local municipality, highway authority, railroads, or regulatory body to minimize delays during construction. See section 4.1.3 for information on managing traffic during construction.
- Development and implementation of a public engagement approach using multiple media approaches (i.e., meetings, websites, call-in numbers) (**Chapter 3**).
- Begin the permitting process as early as possible involving all necessary parties and regulatory agencies, including the acquisition of all necessary access agreements or permits and compliance with any restrictions imposed.
- All areas required for construction activity should be acquired before construction.
- Consider compulsory purchase of access and construction areas as an approach of last resort unless there are long-term maintenance benefits.

Access routes for construction may include over land and by water both to and from the levee construction site, borrow area, and material handling area (Figure 8-6). These typically consist of permanent or temporary routes. Adequate access routes are critical to ensure that construction materials can be delivered on time, and labor and equipment costs are kept within budget. Inadequate access routes can severely affect the overall construction schedule and pose potential safety hazards. Regular maintenance of haul or access roads should be performed during construction to minimize the risk of delivery interruptions during construction.

Figure 8-6: Example of Construction Access

The levee constructor pre-positioned earthern material to fill an old ditch and build seepage berms adjacent to a levee in Greene County, Arkansas. In the background, heavy equipment operators continue to maneuver material for the project; August 2021.

Access routes should:

- Have the ability to withstand construction equipment loads.
- Provide adequate space for the movement and maneuvering of heavy equipment required for construction.
- Provide a safe working environment and ensure the safety of the public.
- Not violate local planning restrictions on noise, vibration, and air quality.
- Not create significant interference to normal traffic flow.
- Have adequate clearance between the roadway and overhead utilities and not endanger buried utilities due to traffic loads.
- Provide access routes to allow for material delivery at points along the length of the entire project.

3.1.2 Borrow Areas

Borrow areas are utilized to provide the earthen material necessary for the levee project. Further discussion on this topic is included in **Chapters 6 and 7**. The levee owner may identify suitable earthen borrow sources to be used during construction or may allow the constructor to identify sources and demonstrate material suitability through the submittal process. Sampling and testing of material in borrow sources is important to avoid delays and increased construction costs. Testing can include test pits that cut down through the soil, to provide representative samples of blended materials, if blending is needed to meet the material requirements. Borrow areas should be capable of providing a minimum of 120% to 150% of the quantity required to construct the project. Selection of suitable borrow areas requires compliance with engineering specifications, as well as environmental, cultural, and water quality laws and regulations.

In general, properly selected and designed borrow areas should satisfy the following:

- Not adversely impact the reliability (i.e., increase the potential for levee underseepage, instability, erosion) of the levee project during and after construction.
- Contain suitable earthen material for the entire levee project.
- Be in compliance with local, state, and federal laws and regulations often related to environmental resources, cultural resources, and water quality.
- Be accessible (i.e., ingress and egress rights are not inundated by flood waters) during the construction of the levee project.
- Have locations and configurations that are optimized to minimize levee project construction costs.

Refer to the United States Army Corps of Engineers (USACE) Engineer Manual (EM) 1110-2-1913 (USACE, 2000a) for best practices regarding the selection and design of borrow areas for levee projects.

3.1.3 Cultural Resources

Cultural resource assessments should be conducted during the formulation stage of a levee project (**Chapter 6**). If significant cultural resources are within the levee project area, the following are common activities that should take place prior to and during construction:

- Secure agreements (may include permits) with federal, state, and cultural or tribal organizations prior to work in the area to ensure any potential damage is mitigated.
- Train construction staff on the cultural resources within the project area and methods that are used to reduce impacts.
- Monitor (part time or full time) and consult with cultural resource experts during construction.

Cultural monitoring may be required, as well as coordination with tribal representatives, throughout the project formulation and construction. Cultural resource issues may affect the levee constructor’s plan and schedule; therefore, proactive communication between all stakeholders should be maintained to minimize work being stopped or significant delays.

3.1.4 Environmental Considerations

Environmental considerations are important for many levee construction projects. Levees are often located in areas with environmentally sensitive area protection and/or with protected and endangered species and associated habitats (Figure 8-7). An environmentally sensitive area often requires restrictions on sound, duration, working days and hours, accessibility of terrains, vibrations, dust, light pollution, and temporary changes of groundwater level. A list of common environmentally sensitive areas include:

- State and national parks
- Wetlands
- Habitat for threatened and endangered species
- Monuments and protected landscapes
- Biodiversity habitats and species
- Polluted areas or areas with hazardous waste
- Forest preservation areas

Permits are often required for levee construction activities in environmentally sensitive areas. Refer to section 3.1.7 for more information on permits for levee construction.

Figure 8-7: Sign for an Environmental Protection Area

Sign indicating a native growth protection area in Snohomish County, Washington.

3.1.5 Hazardous Materials

Unknown hazardous materials are a construction risk. Investigations for hazardous materials (see **Chapters 6 and 7**) should be performed during project formulation and design to characterize and map the materials and develop plans for avoidance or removal and disposal.

All parties should be aware of the nature of hazardous materials and develop appropriate life safety precautions for project personnel working with or near the hazardous materials.

3.1.6 Noise, Vibration, and Lighting Considerations

Levee construction can induce to adverse impacts associated with noise, vibration, and lighting restrictions due to:

- The inherent nature of the construction activity (e.g., excavation, loading, hauling, compaction, rock unloading, and piling installation).
- The fact that water is acoustically 'hard' (i.e., sound waves move over water rather than penetrate).
- The close proximity of the public.
- The close proximity to environmentally sensitive areas.

Conflict may arise due to the need to maximize the use of a floating or marine plant and the need to optimize the time windows available for desirable hydraulic conditions, such as tidal conditions in coastal sites. These time windows can occur outside of acceptable working hours, which can lead to an increased number of public complaints.

On some projects, the working hours for noisy operations are defined within the construction documents, although there may be opportunities for extending working hours through coordination with impacted stakeholders. Extensions to working hours may be critical to achieving an effective and efficient construction schedule (particularly on projects that are impacted by tidal conditions). The effect of working hours on the public should be carefully considered and extensions outside acceptable working hours should be avoided as far as practicable. When extended working hours are necessary, affected members of the public should be advised in advance with information regarding duration and the need for the construction work during those times.

In addition to the adjustment of working hours when construction work is taking place, the following measures should be considered:

- Effective noise suppression for all activities, including ensuring all vehicle noise reduction equipment and silencers are fully operational.
- Schedule intrusive activities at less sensitive times within the allowable working day based on needs of the community (including the tourist industry and business). For example, schedule deliveries outside the morning and evening rush hour.
- Consider the effect of noise on the natural environment, such as on birds in the breeding season.

Vibration due to construction activities may have negative impacts on properties of adjacent landowners, residents, and business owners. Where possible, agreement on reasonable vibration damage arrangements should be sought before the project starts. Depending on the project scope, setting, and local regulatory environment this might include agreement on:

- Use of noise meters, parameters to be monitored, and administrative procedures.
- Pre-construction structural monitoring and assessment.
- A vibration monitoring program, if appropriate.

Lighting is essential for many activities to maximize construction working hours, including the use of machinery and to provide suitable working conditions. Lighting can also be used as a deterrent to vandalism. However, light can be a source of annoyance to residents, so it is important to keep site lighting at the minimum brightness necessary for adequate security and safety. The lighting should be located and directed so that it does not intrude on any properties nearby and the use of infrared lighting for security should be considered. Wildlife can also be disturbed by artificial lighting such as sea turtles near beaches.

3.1.7 Permits

Permits are generally required for levee construction. Permits may be required for the use of land, construction activities in environmentally sensitive areas, and transportation of levee construction equipment and materials. Failure to anticipate permitting requirements for the levee construction project can result in adverse impacts to construction schedules and potential legal actions and resulting fines for the constructor or claims to the levee owner. Prior to initiation of construction, a review should be conducted to identify all permits required to construct the levee project. Upon completion of a preliminary set of plans that show the footprint of all levee features with necessary O&M corridors, permit requirements should be identified and permit pre-application discussions should occur with appropriate regulatory authorities.

Permit requirements and responsibilities should be included in the construction documents. Application for permits and licenses should be initiated well in advance to provide adequate time to complete the permit process. Extensive data collection and analyses may be required to accommodate proposed construction activities or acquisition of additional land necessary for construction. If there are any deviations from the original construction documents, relevant regulatory organizations should be contacted to determine how the changes impact requirements for licenses and permits.

More information is provided in the next sections on the aspects of common permits for levee construction.

3.1.7.1 Permits for Use of Land

Proper land acquisition is critical to the success of the construction project and should be planned accordingly. The constructor may determine that lands proposed for levee construction by the levee owner are inadequate to facilitate the preferred construction activities. Constructor preferred routes and lands may be subject to local restrictions. However, the local community may issue temporary permits under special circumstances that include landowner consent, financial reimbursement guarantees, and security bonds.

Temporary permits may be necessary for:

- Rights of way and permission for borrow and temporary material sorting areas.
- Construction of haul roads across floodplains.
- Expansion of rights of way adjacent to levees for increased equipment access.
- Additional lands required for temporary material unloading and storage capabilities.
- Alternative borrow and/or disposal areas not designated in the construction documents that will provide more material or will shorten haul time.

3.1.7.2 Permits for Transportation of Equipment and Material

Levee construction often requires the transportation of construction equipment and materials on public roads, highways, waterways, and railways. This may require permits for construction from local, state, and federal agencies to utilize these public transportation routes. A list of common levee construction activities that may require a permit to transport equipment and materials is provided below:

- Transport of large equipment on specialized carriers.
- Waivers of restrictions that limit vehicle size, wheel weight, and wheel type to use city and rural roadways.
- Cross railway lines and bridges.
- Temporary construction activities or within or adjacent to an existing road or utility.
- Temporary road closures to transport equipment.

3.1.7.3 Permit for Environmental Impacts and Compliance

Levee construction activities should comply with jurisdictional local, state, and federal regulations for air and water quality, as well as restrictions on construction activities in environmentally sensitive areas. Water and air quality requirements may vary with location along a levee alignment depending on the length of the levee project and various jurisdictions the levee project encounters. Permits for construction activities may be required for:

- Operation of equipment that emits fumes.
- Disposal and/or burning of construction debris and vegetation from clearing and grubbing activities.
- Waste material processing such as bio-remediation composting.
- Abstraction of groundwater when dewatering an excavation.
- Discharge of construction wastewater to a natural watercourse or sewer.
- Placement of fill materials into wetland or waterway.
- Storage of fuels/hazardous material.

3.1.8 Utility Considerations

As discussed in **Chapters 6 and 7**, it is common for levee construction projects to encounter utilities, especially in urban areas. Encountering unknown utilities or unexpected utility relocations during construction can cause significant delays and increased costs. Utility surveys should be conducted to identify utilities in the construction area prior to construction. All utilities should be clearly identified in the construction documents so that the levee constructor is well informed of the utilities in the project area. Any additional information obtained during construction on utility locations, relocations, and/or abandonment procedures should be documented during construction and included in the construction closeout activities (section 5).

3.1.9 Weather and Climate Considerations

Levee construction is particularly susceptible to extreme temperature, precipitation, relative humidity, river flow, and tides. These conditions may significantly impact construction timing and operations. Levee construction can be affected by weather and climate conditions in coastal and riverine environments in two ways:

- Restricting work by affecting construction operations.
- Causing flooding, both to the construction site and the leveed area.

Inclement weather may require a temporary suspension of construction activities that could significantly affect the construction schedule (Figure 8-8). Temporary construction features such as haul roads, construction equipment, material unloading, and storage sites could be adversely impacted if not properly designed.

It is important to plan for weather and climate conditions by considering:

- Variability and severity of the weather and climate conditions that could potentially occur.
- Impacts to the flood risk and levee risk during various stages of levee construction due to these conditions.
- Potential construction delays, costs, and adverse impacts if schedule and cost contingencies are not in place.

Planning for weather and climate considerations during levee construction should include:

- The amount of downtime for land-based or water-based construction activities, due to inability to access the site. High water levels can impact the accessibility of land-based activities and low water levels and wave effects can impact the accessibility of water-based activities.
- Whether temporary flood protection measures should be included for the partly completed works. This can entail phasing the work so that partial completion of more robust parts of the permanent work occurs, or to protect/reinforce the more vulnerable parts during times when storms are anticipated.
- Whether it is appropriate to completely shut down construction activity for the season in which most severe weather or flooding occurs.

Figure 8-8: Inclement Weather Impacting Levee Construction

Rain impacts levee construction in Sacramento, California, as construction activities are delayed until drier, more favorable site conditions occur.

Table 8-2 has a list of construction considerations for common weather and climate-related issues.

Table 8-2: Construction Considerations for Weather and Climate-Related Issues

Weather and Climate-Related Issue	Construction Consideration
Construction activities should be avoided during heavy rain seasons or extreme drought conditions.	• Construction documents should clearly identify any expected weather delays before construction commences. Average rain days can often be obtained from the National Weather Service. • Plan for construction activities to occur during months with historically good weather conditions (flood stages, rainfall, and relative humidity).
Riverine and coastal levee (e.g., earthen embankments, floodwalls, and other levee features) construction activities should be avoided during peak flood seasons, high-water events, coastal storms, and hurricane season without appropriate precautions.	• Secure local tidal, weather, and flood stage historical records from local, regional, and national sources. • Detailed construction sequencing may be needed to ensure the levee provides some seasonal flood risk reduction. • Ensure construction of haul roads and material storage facilities are at elevations that are not likely to be impacted by flooding during construction. • Temporary flood protection measures may be constructed if no other options are available, however, this is a costly alternative, which has varying results. • Emergency action planning, including early warning systems, may be needed to minimize flood risk during construction.
Construction activities should be avoided during extreme cold weather.	• Plan for construction activities to occur outside of the months with historically cold weather, especially if there is a risk of ice jam causing river levels to rise. • Concrete work (floodwalls, pump stations, interior drainage systems, etc.) should be avoided during extreme cold weather. If no other options are available, certain construction techniques such as heating elements, variable concrete mix designs, or enclosed pours may be needed. • Plan on placing borrow materials in warm weather, not while in a frozen state or on frozen ground.

More discussion on how to manage flood risks during construction is captured in section 7.

3.2 Evaluating the Constructability of the Project

Evaluating the constructability of the project is an important part of managing risks during construction and should performed during the final design. The constructability of the levee design should be evaluated based on:

- A review of project objectives.
- Funding.

- The construction schedule.
- The experience, capabilities, materials, and equipment of potential levee constructors.

The review should include a detailed understanding of the purpose of the completed project, its operational function, and the construction risk associated with the project. Refer to **Chapter 7** for more information on best practices for conducting constructability reviews. A list of common constructability issues that impact levee construction is shown in Table 8-3 and should be considered when evaluating the constructability of the project.

Table 8-3: Common Constructability Issues and Best Practices for Levees

Constructability Issue	Best Practice
Working around environmentally sensitive areas (e.g., no work in a particular area during the mating season of a threatened or endangered species)	• Identify all sequencing considerations during the planning phase and highlight them in the contract so the constructor has adequate information to sequence the work activities. • Sequence construction in environmentally sensitive or fragile areas based on information contained in environmental documents.
Availability of land for the project	• Ensure proper title is available for purchased land when planning the work. • Some levee projects cover a very large geographic area with multiple construction contracts. This may require the land acquisition be staged and sequenced.
Rate of embankment construction affected by soft foundation conditions	• Consider methods for phasing construction of earthwork on soft soil: – Increase the height in stages, with a period of consolidation between the stages. – Increase the height in one stage, with controlled consolidation of soft soil layers. – Increase the height in one stage, after soil improvement. • Additional measures to minimize delay during phasing of earthwork such as: – Temporary application of extra weight (e.g., pre-load) to accelerate settlements. – Use of vertical drains to accelerate the consolidation process. – Improve stability by using geotextiles, geogrids, or geotubes. – Use of flatter slopes and lower density fill materials to improve foundation stability. – Undercutting or over-excavation of foundation to remove soft or unsuitable materials and replace with suitable embankment.
Flood events occurring during construction	• If there are certain work items that should be sequenced—such as installation of temporary flood protection measures prior to levee excavation—it should be clearly defined in the construction documents. • Consult hydraulic engineers familiar with the project to ensure that sequencing does not create adverse flood conditions.
High groundwater table at the construction site	• Incorporate dewatering systems (e.g., systems that lower the ground water table) into the design and construction documents.

3.3 Scoping the Project for Construction

Defining the scope of the project for construction is accomplished by preparing documents for construction during design. Common documents and their uses in construction are shown in Table 8-4. These documents are typically developed during levee design and prior to the start of construction. It is important to ensure these documents collectively describe the scope of the levee construction project, while incorporating all necessary project constraints.

Table 8-4: Common Documents for Levee Construction

Document	Use in Construction	Source of Best Practice
Project plans and specifications	Defines all of the work including technical requirements.	Chapter 7
Cost estimate and construction schedule	Supports financial planning for the project and provides a baseline to track and control construction costs and progress.	Chapter 7 (Cost estimate) Section 4.1 (Construction schedule)
Geotechnical data report	Source for subsurface and laboratory data information, and provides a baseline for defining existing conditions.	Chapter 7
Basis of design report	Verifies the design intent and supports the evaluation of impacts due to changed conditions during construction.	Chapter 7
Engineering instructions for field personnel	Information and instructions from designers to levee constructors and field personnel performing construction inspections and accepting construction work.	Chapter 7
Construction instrumentation and monitoring	Instructions on how to install and monitor instrumentation, what action limits will apply, and what actions will be necessary to meet the designer’s intent.	Chapter 7
Permits	Informs levee construction general conditions, methods, construction schedule, and quality management plan.	Section 3.1.7
Third party agreements	Procedures for minimizing impacts to existing infrastructure, cultural resources, or environmental resources affected by the construction activities.	Section 3.3.1

3.3.1 Third-Party Agreements

Third-party agreements are often required for levee construction. A third-party agreement is typically a legally binding, real estate agreement between the levee owner and a major project stakeholder (e.g., tribes, environmental organizations, railroads, highway agencies, utilities, the off-site borrow pit owner), whose existing infrastructure, cultural resources, or environmental resources are affected by the construction activities.

Examples of third-party agreements are as follows:

- Agreement executed with a railroad providing ‘no-train’ windows on a mainline rail corridor to facilitate construction of a closure structure across the live track. The constructor should be made aware of the scope of their responsibilities to complete the work within the ‘no-train’ window.
- Agreement executed with the owner of an active borrow pit, which would include the location of an off-site borrow source. The constructor should be made aware of any limitations placed on them by the borrow area owner to safely excavate, load, and haul borrow from the borrow area.
- Agreement with local public safety agencies that may include instructions related to the timing of partial demobilization and protection of completed work if flood waters threaten the construction site.
- Agreement may contain requirements for on-site monitoring in environmentally or culturally sensitive areas during significant construction activities (e.g., excavations).

3.4 Selecting a Levee Constructor

Selecting the appropriate levee constructor is an important decision to ensure successful completion of a levee project. Many levee construction projects are publicly financed—either through bonds or taxes—which requires use of procurement methods for constructors that meet the levee owner’s established requirements (Figure 8-9). Levee construction is often characterized by a high degree of mechanization. Constructors are usually highly specialized as this type of construction requires specific types of skills and equipment. The types and number of constructors for a levee construction project depends on the size and complexity of the project. For larger levee construction projects, there may be several smaller constructors (referred to as sub-contractors) managed by a larger constructor (referred to as a general contractor).

Figure 8-9: Levee Construction Performed by a Constructor

Construction of a floodwall requires a levee constructor with specialized skills and equipment; 2017.

It is important to select a levee constructor that can complete the construction in an efficient and cost-effective manner. There are two primary factors that are used to select an appropriate levee constructor:

- Technical merits based on qualification and demonstrated competence.
- Cost merits based on fees, price, work hours, or other cost information.

Table 8-5 provides a list of common criteria used for each factor. The importance (i.e., weighting for decision) of each factor varies depending on the type of project and procurement method. The levee owner should decide whether the technical merit is more important than cost merits, or if technical merit is equally important to cost merits.

A summary of pros and cons of each procurement method to inform levee constructor selection is provided in this section.

Table 8-5: Selection Criteria that Can Be Used for Each Primary Selection Factor

Primary Factor	Selection Criteria
Technical	• Demonstrated competence of similar projects • Qualifications of project personnel • Experience and past performance of the organization • Experience and past performance of assigned individuals • Experience and past performance with the desired delivery system • Capacity to perform the work • Financial strength and bonding capability • Management plan, subcontractor relationships, and technical capabilities • Safety plan and safety record • Quality assurance plan
Cost	• Unit price • Total project bid • Labor rates • Labor hours

3.4.1 Levee Constructor Procurement Process

Various procurement/contracting strategies may be considered by the levee owner, considering factors such as time, capital cost, and project-related risk. For public works projects involving levees, the levee owner should first check with the local regulators having jurisdiction and with applicable contracting codes covering the projects to verify which contracting strategies are permitted. For large projects with multiple distinctly different features, more than one strategy may be considered. The most common of these are set out as follows, with advantages and disadvantages summarized in Table 8-6.

3.4.1.1 Design-Bid-Build

Design-bid-build is the most common project delivery method for public works projects. Separate contracts are awarded to the designer and to the constructor who submits the lowest responsive and responsible bid. The levee owner sometimes retains a construction manager (who can also be the designer) to administer the contract. The levee owner (or representative, who can also be the designer) coordinates with the regulatory permitting agencies.

Construction risks associated with design-bid-build can be minimized by performing comprehensive site investigations, developing robust design details, establishing minimum constructor qualifications or prequalifying constructors, and establishing a strong partnering relationship between the levee owner, designer, and selected constructor. Early constructor involvement during the design phase can also help to minimize risks, as long as such involvement does not preclude constructors from bidding on the work.

3.4.1.2 Construction Manager at Risk

The levee owner selects the construction manager at risk through a competitive request for qualifications process. The construction manager at risk commits to delivering the project within a guaranteed maximum price, based on the version of the construction documents and specifications available at the time of the guaranteed maximum price, plus costs for any other reasonably inferred items or tasks. By giving the levee owner the guaranteed maximum price before bids, the entity assumes the risk of bids coming in higher because they are contractually bound to deliver the project per the plans and specifications (along with any additional allowances), as defined in the guaranteed maximum price.

The construction manager at risk will typically provide professional services and act as a consultant to the levee owner in the final design development and construction phases. Typically, the entity can also provide some of the actual project construction, depending on the availability of bidders and the expertise of the company. In addition to acting in the levee owner's interest, the construction manager at risk needs to manage and control construction costs to avoid exceeding the guaranteed maximum price because, contractually, any costs exceeding that price that are not change orders are the entity's financial liability.

The levee owner has the option to terminate the construction manager at risk before establishing the guaranteed maximum price if the pricing or scope of services is not acceptable. In that event, the levee owner would then bid the design documents in the open market, the same way it is done with the design-bid-build delivery method.

3.4.1.3 Progressive Design-Build

Progressive design-build is a hybrid between the design-bid-build and construction manager at risk project delivery methods. The levee owner typically selects the design-bid-build entity based only on qualifications, not on price. Construction pricing is then developed as the design progresses. Like design-bid-build, this method can save time in the overall schedule by overlapping the design and construction phases and allowing some design work to begin while site investigations continue to develop the data needed to complete all designs. Progressive design-build's main features include:

- The design-builder is retained by the levee owner early in the life of the project.
- The design-builder generally is selected primarily on qualifications and their final project cost/price and schedule commitment are not established as part of the selection process.
- The design-builder delivers the project in two distinct phases. Phase 1 includes budget-level design development, pre-construction services, and negotiating a firm contract price (either lump sum or guaranteed maximum price) for phase 2. Phase 2 includes final design, construction, and commissioning.

If for any reason the parties cannot reach agreement on the phase 2 commercial terms, then the levee owner may consider an 'off-ramp' option, which will delay project completion. This is a risk factor to be considered in selecting this method.

Table 8-6: Advantages and Disadvantages of Alternate Construction Procurement Strategies

Procurement Strategy	Basis of Constructor Selection	Advantages	Disadvantages
Design-bid-build	• Competitive sealed bid: Low bid of total construction costs. • Best value bid: Technical score and total construction costs.	• Provides levee owner with most pre-construction input into the design. • Potential for lowest pre-construction price.	• Little opportunity for pre-construction collaboration between designer and constructor. • Levee owner has to set aside budget funds for risk factors such as unforeseen conditions and deficiencies in the design documents.
Construction manager at risk	• Best value proposal: Technical source/sum of fees, general condition. • Qualifications based selection: Demonstrated competence and qualifications.	• Commits to delivering the project within a guaranteed maximum price and assumes the risk of total actual costs coming in higher than that price. • Allows opportunity for pre-construction collaboration between the construction manager at risk and their constructor.	• Levee owner has lower pre-construction input. • Levee owner has to set aside budget funds for risk factors such as unforeseen conditions and deficiencies in the design documents.
Progressive design build	• Best value bid: Technical score and total construction costs. • Best value proposal: Technical source/sum of fees, general condition. • Qualifications based selection: Demonstrated competence and qualifications.	• Allows for collaboration between owners, designers, and constructors which can reduce cost and construction risks. • Saves time by overlapping the design and construction phases. • Promotes transparency in costs as each phase tracks project costs and how design changes impact costs and schedule. • Reduces cost as construction risks are managed early in the project leading to less construction cost contingencies.	• Requires significant owner resources to effectively manage. • May not be allowed for some entities due to procurement regulations. • The design-builder is selected without knowledge of the design and construction project cost.

4 Constructing the Levee

Constructing the levee begins when the levee constructor starts work on the project and ends when construction is near completion (Figure 8-10). Proper execution of the levee project is vital to ensuring the levee satisfies its intended objectives (i.e., flood and levee risk reduction benefits, as well as co-benefits), while working within the identified constraints.

The main topics that are covered for the phase of constructing a levee feature include:

- Developing a construction plan.
- Ensuring desired quality of levee construction is achieved.
- Coordinating and communicating during construction.
- Managing construction data.

Figure 8-10: Aerial View of Levee Construction

Aerial view of the Bear River Setback Levee construction in August 2022 in Wheatland, California.

4.1 Construction Plan Development

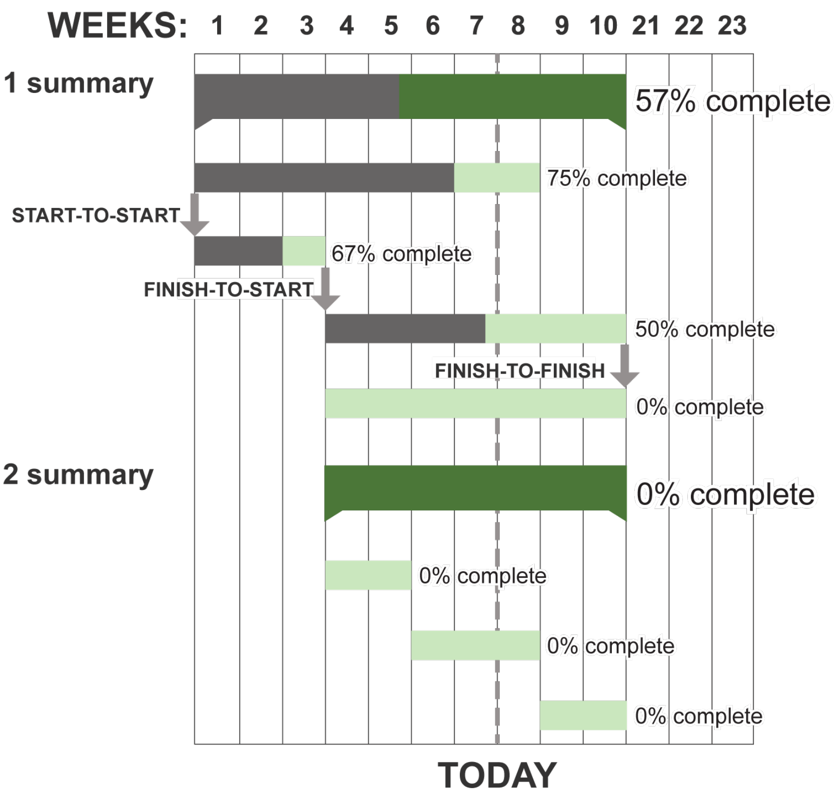
A plan for constructing the levee should be developed to include:

- The selection of appropriate construction labor, equipment, and materials.
- A schedule of construction activities to complete the project on time.
- Procedures for effective management of construction and flood risk.

Labor, material, and equipment should be analyzed and determined based on the levee project requirements defined in the project plans and specifications. The complexity and effort in developing a construction schedule should be commensurate with the size and complexity of the project. Based on the project scope, the following are best practices for developing a construction schedule:

- **Identify the critical path**. This is important in determining the timeline for completion of each project task. The critical path approach identifies the essential construction activities that must be completed in a specific succession on the project.
- **Develop a work breakdown structure**. Breaking down the project into smaller tasks makes it easier to manage and complete on time. Each task should have a defined start and end date.
- **Create a Gantt chart**. A Gantt chart is a graphical representation of the schedule that shows the timeline of the project and the dependencies between tasks. An example Gantt chart is shown in Figure 8-11.
- **Allocate resources**. Assigning resources to each task will help in managing the project efficiently. This will include labor, materials, and equipment.
- **Determine project milestones**. Identifying key milestones in the project will help to track progress and communicate achievements to stakeholders.

Figure 8-11: Example Gantt Chart



If construction activities are not properly sequenced, the levee project may be delayed and costs increased significantly. Material, equipment, and labor availability issues can also delay construction activities. Best practices for resolving common material, equipment, and labor availability issues are provided in Table 8-7.

Table 8-7: Material, Equipment, and Labor Availability Issues and Best Practices

Material, Equipment, and Labor Availability Issues	Best Practice
Availability of necessary materials and resources for the project	• Large projects may be divided into smaller projects to ensure equipment and labor shortages are not encountered. • If possible, projects in the levee should be phased and programmed to avoid extreme peaks in demand for material, equipment, and labor. • Early in the design process, preliminary material quantities should be used to evaluate the local supply chain for delivery and price with a focus on effects of increasing demand with the current supply chain. • Consider pre-ordering particular material prior to the start of construction.
Alternative materials and methods	• The constructor may submit a request for alternatives to a specified method or material to improve project costs, schedule, and/or performance.

To effectively manage risk during construction, it is important to identify potential risks to the project and include procedures to managing these risks in the construction plan. This should include contingency plans in case of delays or unexpected challenges. Best practices for managing risks during construction is discussed in section 7.

Local laws and regulations will often dictate requirements for managing on-site job and public health and safety, environmental impacts, and traffic. This should be included in the construction plan. Failure to manage these effectively can have severe consequences to construction. Best practices for managing health and safety, environment, and traffic during construction is provided in the following sections.

As construction progresses, the construction plan should be regularly reviewed and updated to help identify any issues, and take corrective measures to keep the project on track.

4.1.1 Health and Safety Management

The construction plan should address on-site job and public health and safety management during construction. Levee construction normally involves heavy machinery and exposed working conditions—both have the potential to be hazardous to staff working on site. In addition, levee construction often involves activities near open water that can bring other health and safety risks normally unrelated (or less often related) to machinery or construction work. Waterborne diseases should be considered in health and safety hazard identification, as well as the risk of drowning in adjacent waterways or other water hazards. :

The health and safety management approach should emphasize preventive action to avoid incidents happening in the first place by appropriate staff training (such as in the use of heavy machinery), raising awareness of construction site hazards, and using good construction practices that prevent injury and ill health. A site incident log should be kept, and regular reviews made to monitor the types of incidents that occur. Measures should be instigated to reduce the likelihood of reoccurrence.

Public safety should be maintained at all times. Generally, to provide such protection, the public should be restricted from entering the site by signs, barriers, fences, or other means (Figure 8-12). The warning signs should be placed at prominent locations. For a levee project, this may include restricting access from the water. In urban areas, transient and/or unhoused populations can be particularly difficult to manage during construction. In situations where an unhoused population exists within the construction site, coordination with local governmental authorities should occur and appropriate protocols and procedures followed. Plans to manage underserved populations must be developed during the planning phase (**Chapter 6**), and these plans should be carried through design and construction of the levee project.

All workers and visitors to the site should be trained in the health and safety protocols and be required to adhere to them while on site. Public access to the construction site should be restricted and any visits permitted during construction (e.g., for education or information dissemination purposes) should be carefully controlled.

Figure 8-12: Example of Public Safety During Levee Construction

Safety fencing was installed to protect the general public while levee work was underway along the north bank of the American River, just east of its confluence with the Natomas East Main Drainage Canal in north Sacramento, California; August 2013.

4.1.2 Environmental Management

The equipment, materials, procedures, and schedule-defined construction plan should comply with all environmental permits and cultural restrictions. Common levee construction restrictions include reducing impacts to endangered species, managing unwanted material releases into water bodies, soil erosion control during construction, proper handling of historic artifacts, and reducing impacts of haul routes, noise, and vibrations. See sections 3.1.3 and 3.1.4 for considerations on how to manage environmental and cultural constraints.

For most levees, the construction plan will at least include stormwater pollution prevention approach (sometimes referred to as a stormwater pollution plan), which describes processes to reduce erosion, migration of sediment, and other waste from the site into rivers, lakes, coastal waters, and/or adjacent properties. During and immediately following construction, temporary erosion protection for earthen slopes and sediment control may be required under the project's stormwater pollution prevention approach. The U.S. Environmental Protection Agency provides best practices for developing a stormwater pollution plan with the document *Developing Your Stormwater Pollution Plan, A Guide for Construction Sites* (EPA, 2007). Examples of implementing stormwater pollution measures during construction of a levee project are shown in Figure 8-13.

Figure 8-13: Example of Tempoary Erosion Protection

Workers install straw wattles (left) and silt fences (right) along a new American River levee section in the River Park neighborhood of Sacramento California; November 2014.

4.1.3 Managing Traffic During Construction

It is important to manage traffic because it can cause delays to local residents and create a safety hazard both on and off site. An organized site with well-managed traffic activities—including the storage of construction materials as close as possible to the project site—can provide a positive experience for local residents. Levee construction in urban areas can cause potential traffic tie-ups for residents, trip delays, delayed deliveries to the site, and the loss of access during critical construction times. To minimize these impacts, consider the following:

- Ensure that all drivers are aware of traffic restrictions at and around the site when ordering deliveries.
- Plan the timing of deliveries to avoid vehicles waiting outside the site boundary.
- Load and unload vehicles off the roadway, where possible.
- Designate staging areas where several deliveries are likely to take place over a short period.
- Mitigate construction traffic and their impacts, particularly in the summer.
- Consider allocating a staging area some distance from the site in urban areas, and only calling in deliveries when access to the site is clear.
- Consider the use of in-cab communication systems to maintain control over movements of delivery vehicles.

Construction staff vehicle traffic can negatively impact the public; therefore, the following should be considered:

- Arranging designated parking areas.
- Preventing staff from parking in unsuitable areas and ensuring restrictions are obeyed.
- Implementing a park-and-ride or car-share scheme.

- Avoiding monopolizing public car parking areas, especially those used by high numbers of visitors to the area.

Sometimes construction sites are blamed for disturbance caused by vehicles that are not associated with the site. To avoid this, it may be helpful if site vehicles display some visible identifying marks. While this may not be appropriate for individual deliveries, it can be done for the levee constructor's vehicles.

Some levee projects impacting transportation corridors may require detour and traffic control plans be approved by local transportation agencies. These plans are usually developed in the design phase and included in the plans and specification for implementation by the constructor.

4.1.4 Coastal Construction Considerations

Levees to be constructed along coastal environments or riverine channels affected by tidal changes will require significant constructor planning and timing of all work activities. This especially is true when preparing the foundation and lower portions of a levee that can be inundated daily by tides. This will limit the constructor's effective daily work hours and inspection of the work. Daily flooding of the work may damage completed work; therefore, construction scheduling should be planned based on these tidal effects and rework should be planned in the schedule (Figure 8-14).

Figure 8-14: Example of Coastal Levee Construction

Constructors continue work on a pump station as part of the Hurricane and Storm Damage Risk Reduction System project in New Orleans, Louisiana; April 2016.

4.1.5 Temporary Relocations and Diversions

Establishment and construction of temporary pipe or diversion facilities may be required during levee construction. These often are designed by the constructor, in coordination with local stakeholders and the levee owner, and they should be reviewed by the design engineer to ensure compliance with project requirements.

4.2 Quality Management

Quality management during construction ensures levees are constructed as designed and that they perform reliably over time. The documents for construction should clearly detail the quality management requirements for inspection and acceptance of the construction work as part of a quality management plan. Typical contents of a quality management plan include:

- Purpose and scope of plan:
  - Period pf work covered.
  - Applicability of the plan to proposed construction work.
- Staffing:
  - Responsibilities to implement quality management (Table 8-8).
  - Training and expertise required of the quality management staff.
- Quality surveillance:
  - Frequency and rigor of quality surveillance.
  - Problem solving approaches for deficiencies in construction quality.
  - Deficiency monitoring and tracking (Table 8-9).
- Quality testing:
  - Frequency and rigor of quality testing.
  - Staffing and facilities necessary to implement quality testing.
- Reporting.

The constructor should have arrangements in place to ensure that the specific elements of levee construction are carried out in accordance with the requirements defined in the documents for construction. For example, these elements might include procedures for:

- Drawing plan checking and verification.
- Site/operational activities such as ground clearance and earthwork, as well as compliance with design profiles, site security, and access.
- Selection of equipment and material suppliers.
- Instrument calibration and testing.
- Specialized treatment methods.
- Storage and disposal of waste.

- Corrective actions.

Construction sampling and testing is required to verify contract compliance. Instrument calibration is an important aspect of quality control for which records should be kept. All instruments should be 'in-test' and withdrawn from use if either their calibration has expired, or their measurements become suspect.

The quality management plan should also state a procedure for the resolution of 'rejected' work (or non-compliance) and subsequent corrective actions.

QUALITY CONTROL VERSUS QUALITY ASSURANCE

Quality control is defined as processes used to ensure performance meets agreed-upon customer requirements that are consistent with law, regulations, policies, sound technical criteria, schedules, and budget. Focuses on fulfilling quality requirements of a project, product, service, or process.

Quality assurance is defined as processes employed to assure that quality control activities are being accomplished in line with planned activities and that those quality control activities are effective in producing a product that meets the desired end quality. Focuses on providing confidence that quality requirements of a project, product, service, or process will be fulfilled.

4.2.1 Staffing

The owner, designer, and constructor all play key roles in ensuring that quality management is maintained during levee construction. Table 8-8 identifies the basic quality management staff responsibilities that are critical to the successful completion of a levee meeting good quality practices. Depending on the complexity and size of the project, these responsibilities may be fulfilled by few or multiple personnel. The best practice is to ensure the appropriate level of staffing is provided to fulfill these responsibilities.

Table 8-8: Basic Quality Management Staffing and Responsibilities

Quality Management Staffing	Responsibility
Constructor project manager	• Overall project quality
Construction manager or contract manager (constructor)	• Construction contract quality • Quality compliance submittals • Construction quality manager duties (if/when necessary)
Owner quality manager	• Quality assurance • Quality assurance documentation
Designer	• Quality compliance requirements • Construction quality manager duties (if/when required)
Construction quality manager	• Quality control (including corrective actions) • Quality control documentation • Independent of construction project manager
Testing agency	• Sampling and testing for compliance verification

4.2.2 Corrective Actions

Quality assurance/quality control is necessary to reduce the possibility of construction-related deficiencies that may affect levee performance during and after construction. Failed test results or identified non-conformances should result in corrective actions to resolve the issue. Consequences of failed results may require analysis and a decision based on comparison with the specified requirements, visual examination, and engineering judgment. Corrective actions will depend on acceptability and be very specific to the material location and problem encountered. Corrective action to prevent recurrence is an essential part of quality assurance/quality control. A list of possible construction deficiencies and related consequences to the levee performance for embankments is shown in Table 8-9.

Table 8-9: Possible Construction Deficiencies for Embankments

Deficiency	Potential Consequence
Organic material not stripped from the foundation	• Differential settlements. • Weak embankment/foundation contact layer leading to instability. • Internal erosion caused by throughseepage or underseepage.
Highly organic or excessively wet or dry fill	• Excessive settlements. • Inadequate or weak strength in fill causing instability. • High permeability zones causing instability and/or internal erosion.
Placement of pervious layers extending completely through the levee	• Unimpeded throughseepage, which may lead to internal erosion.
Inadequate compaction of embankment (e.g., lifts too thick, haphazard coverage by compaction equipment, incorrect moisture content)	• Excessive settlements. • Inadequate strength causing instability. • Throughseepage, which may lead to internal erosion.
Inadequate compaction of backfill around structures in the embankment	• Excessive settlements. • Inadequate strength causing instability. • Potential seepage path between the structure and embankment, which may lead to internal erosion.
Inadequate processing of lifts before compaction and/or improper scarification between lifts	• High permeability layers leading to internal erosion. • Weak layers or lift leading to instability.
Seasonal shutdown layers not properly treated or placement in freezing weather	• High permeability layers leading to internal erosion. • Differential settlement of the overlying embankment leading to transverse cracking and subsequent internal erosion.
Cutoff wall gaps and voids	• Concentrated seepage leading to instability and/or internal erosion.

More details can be found in EM 1110-2-1913 (USACE, 2000a).

4.2.3 Testing Entity

To ensure independent verification of the quality of the completed work, using an independent testing laboratory to perform necessary quality control tests is a best practice to implement.[1]

These laboratories should be certified using appropriate laboratory certification standards. Personnel supplied by the independent laboratories should be competent to perform the required tests. The independent laboratory should have their own internal quality management system and supervisory organization, and should maintain a consistent test and report serial numbering format to help facilitate tracking tests and results for each work segment, including certifying test results.

4.2.4 Quality Assurance

A quality assurance approach should be developed to oversee and validate the levee construction quality control plan, including reviewing all quality control test data. The quality assurance program may include a different laboratory to perform independent testing. A reasonable rule of thumb would be to conduct quality assurance testing for approximately 10% to 20% of quality control testing. A higher frequency of quality assurance testing should be anticipated at the beginning of the project to validate the construction quality control testing, and also at times when quality control testing is suspect or problematic.

4.3 Coordination and Communication During Construction

Effective coordination, communication, and sharing of information between the levee owner, designer, and constructor should be maintained throughout levee construction. This is vital to ensuring project requirements are understood and problems that occur during construction are handled properly in a timely manner. The following are best practices to ensure levee project information is effectively coordinated between these phases of a levee project.

- Compliance with local, regional, state, and federal laws and regulations during construction should be maintained. Being out of compliance can cause delays and increases in project costs. The levee owner, designer, and constructor should work together to ensure compliance is met. Construction activities should also be in compliance with mitigation measures defined in project-specific permits (section 3.1.7).
- Documents for construction (section 3.3) should be complete, clearly understood, and free of errors. These documents establish project requirements, a baseline for evaluating conditions during construction, and the roles and responsibilities during construction. Site conditions that differ from the design plans and specifications should be coordinated with levee owners and designers to assess impacts to the levee project.
- All parties involved in levee construction should have access to all relevant construction data and information. This is crucial for efficient construction execution and decision making. Common types of construction data and best practices for managing that data is provided in section 4.4.

[1] American Society for Testing Materials (ASTM) as well as some federal, state, and local agencies establish laboratory certification standards.

- Partnering and conflict resolution should be used to reduce conflict during construction projects. Partnering sessions are often utilized to establish communication channels and methods to advance the project, meeting the ultimate goals of all interested parties. Conflict resolution methods for the levee project are often defined prior to the start of construction in the documents for construction.

ENTITIES INVOLVED IN LEVEE CONSTRUCTION

There are often multiple entities involved in levee construction, dependent on the size and complexity of the levee project. It is important that levee owners, designers, and constructors work together to fulfil their responsibilities.

Levee owners should collaborate to establish project objectives and constraints, levee designers should work together to establish the project scope, and levee constructors should work together to execute the project. All groups should have clear roles and responsibilities established when interfacing with others.

Construction techniques (sometimes referred to as means and methods), sequencing, schedules (including major milestones), personnel qualifications, materials, and equipment should be documented and coordinated to ensure these are appropriate for the levee project. These are commonly documented in submittals, and requirements for submittals are often defined in the design specifications. These submittals provide details on construction implementation plans, including proposed construction techniques, sequencing, schedules, submittal dates, personnel qualifications, and other required information. This documentation, as well as the construction plan, will set the baseline for construction and should be updated as the work progresses.

4.4 Construction Monitoring and Data Management

Construction monitoring and data plays an important role in ensuring the levee design is appropriate for actual site conditions, verifying construction activities are in compliance with plans and specifications, monitoring progress of construction, and informing levee risk management decisions. Construction monitoring and data includes constructor shop drawings and submittals, topographic and/or bathymetric surveys, quality control/assurance test results, and construction inspections. Descriptions of common types of construction data are provided in Table 8-10.

Quality construction data should be maintained throughout the project and the best practices for ensuring quality construction data is discussed in section 4.2. In addition to quality assurance and construction test data, topographic and/or bathymetric surveys are often used in levee construction. These surveys should be timely and accurate (Figure 8-15) to avoid and detect construction problems early. Surveys conducted just prior to commencement of construction activities can provide a clear understanding of the current site conditions, as well as provide a baseline for monitoring progress of construction work. It is a best practice to conduct acceptance (or verification) of topographic surveys to verify the project meets the design intent prior to construction closeout (section 5).

As discussed in **Chapter 7,** a plan for instrumentation and monitoring during construction should be prepared. Site inspections (**Chapter 9**) should be performed to maintain up-to-date knowledge of the construction site and the surrounding area with the objective of discovering any new site conditions that could hinder the project from meeting its objectives. Unforeseen changes during construction could result in complications for the levee project. Site conditions that differ from the design plans and specifications need to be clearly documented and coordinated with levee owners and designers to assess impacts to the levee project.

Table 8-10: Common Data in Levee Construction

Type of Data	Description
Construction administration	Information on administering the construction of the levee including: • Constructor name, contact information, and management staff. • Equipment used for the project. • Types and amount of labor used for the project. • Construction tasks to accomplish the scope of work. • Construction schedule and progress. • Construction budget, costs, and payments. • Change orders, modifications, and variations from the design. • Coordination meetings and correspondence between construction, designer, and owner. • Construction submittal data and information.
Quality assurance and quality control	Data and information related to assuring and controlling quality of the construction work including: • Requirements for inspection and acceptance of construction work. • Quality management staff and testing entity contact information and responsibilities. • Material sampling and testing results. • Calibration record of testing instruments. • Construction topographic and bathymetric surveys.
Accident and safety reporting	Data and information related to monitoring, tracking, and resolving safety issues.
Construction instrumentation data	Data and information related to installing and monitoring instrumentation including thresholds and actions taken when thresholds were exceeded.
Photographs and videos	Photographs and videos taken during construction to document construction conditions and verify compliance with design plans and specifications.
Manual observations	Data and information related to manual observations of construction activities including: • Excavations. • Drilling. • Grouting. • Placement and compaction of fill. • Installation of levee features. • Operation and testing of mechanical and electrical components.
Installation and operation of mechanical and/or electrical components	Data and information related to the installation and operation of mechanical and electrical components. Refer to section 5.2.3 for more information.

For complex levee construction projects, a geographic information system (GIS) may be used to manage construction data. Prior to construction, a baseline GIS is built using design data along with a plan for managing data during construction. This plan often includes procedures for data verification, quality surveillance data collection, backup and disaster recovery, data transfer workflow, and storing the data at construction closeout. During construction, the GIS is updated in real-time to view construction progress and is used to support project decision making.

Refer to section 5.2 for best practices of documenting construction data for future management of the levee.

Figure 8-15: Example Survey Control

A constructor performs a topographic survey at the Wakenda Levee in Carroll County, Missouri. The levee was under repair after it was damaged during the Missouri River flood in 2011; February 2012.

5 Levee Construction Closeout

Levee construction closeout is the final phase of the levee construction process and begins when construction is near completion and ends when the constructed levee is placed into operation. This phase requires ensuring the levee project meets the design intent prior to placing the levee into operation and finalizing the project documentation to support effective levee O&M. The main topics covered for the levee construction closeout include:

- Post-construction project evaluation.
- Construction closeout project documentation.

5.1 Post-Construction Project Evaluation

Evaluation of the finished construction work is a vital step to verify the levee was constructed as intended and provides a baseline for evaluating future levee condition and performance. Post-construction evaluation consists of performing inspections of the finished work, reviewing construction data and instrumentation, and updating the levee risk assessment when necessary.

Refer to **Chapter 5** on best practices for conducting routine and non-routine activities to fulfill levee risk management responsibilities at construction closeout.

5.1.1 Inspection

Detailed observations should be made of all newly constructed or modified levee features to verify the levee was constructed as intended. These observations include vegetation growth, seepage control system performance, embankment stability, settlement, and gate operation. Any deficiencies found during this inspection should be addressed.

In addition to a warranty inspection, a ‘first loading’ inspection should also be conducted for the newly constructed or modified levee features to observe performance during a flood loading. Refer to **Chapter 9** for procedures on conducting levee inspections.

5.1.2 Risk Assessment

Prior to placing the levee in full operation, a risk assessment should be conducted utilizing the data and information from construction (section 4.4) to establish a baseline and to inform the current risk characterization for the levee. Practices and procedures for conducting risk assessments are discussed in **Chapter 4**. This activity should be planned, funded, and coordinated as part of the levee construction project.

5.2 Project Documentation

Project documentation is important to support the management of the levee and inform any potential future rehabilitation or modification. Project documentation provides a fundamental level of information that will be used to operate and maintain the levee. The rigor of project documentation should be commensurate with the complexity of the project.

More complex projects could include a levee data update in the National Levee Database (NLD), as well as a variety of reports, including:

- Environmental and cultural resources
- Foundation and embankment
- Construction completion
- Design document
- Construction GIS data

Documentation for less complex projects may only include the record drawings, a design document report, and an update of NLD data.

HOW TO UPDATE LEVEE DATA IN THE NATIONAL LEVEE DATABASE

The NLD is the national repository for levee data managed by USACE. Updates to the NLD should occur during construction closeout. If data in the NLD is determined to be inaccurate, an update of that data should be initiated through the following methods:

- Email to nld@usace.army.mil.
- Call 1-877-LEVEEUS.
- Submit new or updated data using the data change request button on the NLD homepage (nld.sec.usace.army.mil).

Local USACE Districts may be contacted directly to update data on levees federally authorized and constructed by USACE.

5.2.1 Construction Completion Report and Record Drawings

For complex levee projects, a construction completion report should be prepared as soon as possible after levee construction is completed. The report should contain design decisions made during construction, modifications, and a summary of project construction issues and resolutions. In addition, the construction completion report should contain information about implementation of the observational methods used during construction.

The report should also include record drawings, documentation of exploration trench conditions and observations, compaction reports, concrete cylinder break data, other construction testing results, and measurements taken during construction to verify compliance with construction documents (e.g., plans and specifications) and acceptability of the construction work. The construction completion report should be maintained with other pertinent documentation for the levee, such as the O&M manual, and be readily accessible for future inspections and risk assessments.

For less complex projects, a construction completion report may not be necessary and only record drawings may be used to reflect how the project was built. Record drawings are corrected design drawings (i.e., design plans) showing the as-constructed conditions and reflects on-site changes made during construction.

5.2.2 Foundation and Embankment Report

For levees that pose a significant threat to life safety and/or are fairly complex, a separate foundation and embankment report should be prepared for the levee construction project.[2]

The report should include a summary of foundation and embankment conditions, issues (and corresponding resolutions) encountered during construction, documentation of exploration trench conditions and observations, final foundation approval reports (if necessary), verification of design assumptions (e.g., shear strengths, hydraulic conductivity values), and records of construction testing.

5.2.3 Operations and Maintenance Manual

The designer, in coordination with the constructor, owner/operator, maintainer, and local regulatory agencies (if applicable), should prepare an O&M manual addressing operation procedures needed to support the function of the levee, as well as the required schedule and scope of maintenance requirements. See **Chapter 9** for best practices in developing an O&M manual.

Information that should be gathered during construction to inform O&M requirements for inclusion in the manual may include:

- Cut sheets and operating instructions on electrical and mechanical equipment, as applicable, including screen shots of instrumentation panels.
- Manufacturer’s instructions on electrical components and control panels.
- Training steps and instructions from the manufacturer for more complex machinery, such as pumps and large flood gates.
- Triggers and operating instructions for floodgate closures.
- Recommended inspection and monitoring frequency (see **Chapter 9**).
- Record drawings including all modifications.
- Lubricants and lubrication type, frequency, and methods.
- Warranties.
- Steel coating types and repairs of steel structures.
- Seal adjustments and replacements.
- Manufacturer’s spare parts storage and replacement instructions.

[2] See USACE Engineering Regulation (ER) 1110-1-1901 (USACE, 2017) for best practices to develop a foundation and embankment report.

6 Levee Features and Construction Considerations

6.1 Embankment

Levee embankments and associated berms are composed of compacted soil, as specified in the documents for construction. Best practices for placement and compaction of the soil is required to ensure the required engineering properties (i.e., strength, permeability, and compressibility) are present in the completed embankment, so the feature will function as intended.

6.1.1 Line and Grade

Survey control during embankment construction is essential to correctly locate embankment components and ensure the constructed embankment alignment and grade are as designed. Field staking and surveys should be performed routinely as with any earth-moving project. Interim surveys are recommended to update progress and document earthwork quantities.

6.1.2 Subgrade Preparation

Generally, levees are founded on soil foundations and the discussion on subgrade preparation and treatment provided in this section applies to soil foundations. Minimum subgrade preparation for levees consist of clearing and grubbing, and most levees will also require some degree of stripping (Figure 8-16).

Clearing consists of complete removal of all objectionable and/or obstructional matter above the ground surface. This includes all trees, fallen timber, brush, vegetation, loose stone, abandoned structures, fencing, and similar debris. The entire foundation area under the levee embankment, berms, and other levee project features should be cleared well ahead of grubbing and stripping.

Grubbing consists of the removal—within the levee foundation area—of all stumps, roots, buried logs, pipes, foundation structures, old pilings, old paving, drains, and other known objectionable matter. Roots or other intrusions over 1.5 inches in diameter within the levee foundation area are typically removed to a depth of at least 3 feet below natural ground surface. Shallow tile drains sometimes found in agricultural areas should also be removed from the levee foundation area.

The constructor should anticipate removal of the root ball, large roots (greater than 1.5 inches in diameter), and the underground portion of stumps to a depth of 3 feet (or more depending on the tree type and size as necessary to remove large roots) where trees and stumps are visible above ground and removed as part of clearing operations. The decision to leave tree roots or stumps in place is generally discouraged. However, in some situations, tree roots or stumps may be left in place after consideration of relative root ball or stump size, submergence and the rate of decay depending on wood species, and performance requirements for the levee.

Figure 8-16: Example Levee Subgrade Preparation

Constructors perform the clearing, grubbing, and stripping operation as part of subgrade preparation for the construction of an approximately 1,800-foot-long setback levee along the right bank of the Sacramento River in Yolo County, California; May 2021.

Typically, the constructor is not required to investigate the entire site for buried objectionable materials that are not already identified or apparent; these features should be identified in the construction documents. Also, any buried debris associated with permitted or unpermitted landfill type deposits require special consideration in the construction documents and are not normally covered by a simple grubbing specification. The sides of all holes and depressions caused by grubbing operations should be flattened to a slope no steeper than 1 vertical to 1 horizontal before backfilling.

Backfill—consisting of material of similar nature to adjoining soils—should be placed in layers up to the existing subgrade and compacted to a density at least equal to that of the adjoining undisturbed material. This will avoid ‘soft spots’ under the levee and maintain the continuity of the natural blanket.

After foundation clearing and grubbing operations are complete, stripping is commenced. The purpose of stripping is to remove low growing vegetation and organic topsoil. The depth of stripping is determined by local conditions and normally varies from 6 to 12 inches. Of this depth of stripping, 4 to 6 inches is usually adequate to remove the low-lying vegetation and root systems. Additional stripping excavates and preserves the organic rich topsoil for future use.

Stripping is required for subgrade for the levee embankment and may be needed under berms to avoid leaving a weak plane at the berm/foundation contact. All stripped material suitable for use as topsoil should be stockpiled for later use on the slopes of the embankment.

Before placing fill, the exposed subgrade should be inspected as described in the project plans and specifications to ensure an adequate subgrade exists. Unsuitable materials (i.e., soft or organic spots) in the levee foundation at or near the subgrade surface should be removed and replaced with suitable compacted material. Suitable compacted material should be defined in the project specifications. Unsuitable material for embankment construction should be disposed of using proper methods.

Except in special cases where subgrade surfaces are adversely affected by remolding (e.g., soft foundations for instance), the subgrade surface upon or against which fill is to be placed should be thoroughly scarified to a depth of at least 6 inches prior to the placement of the first lift of fill. This helps to ensure good bond between the foundation and fill, as well as eliminates a plane of weakness at the interface.

Dewatering systems may be required during excavation and backfilling to ensure desirable dry conditions exits. The U.S. Department of Defense provides general guidance for the design and construction of dewatering systems (USACE, NAVFAC, and AFCEC, 2004). Generally, a dewatering system is designed to lower the water table a minimum of 5 feet beneath the work surface or excavation to prevent heaving at the base of the excavation, unstable excavation slopes, and lateral or vertical seepage from entering the excavation. A water table depth less than 5 feet may be used in certain situations.

Approval of the subgrade surface (after preparation and treatment) prior to placement of fill should be required for levee projects and pertinent features. Approval should be conducted by trained and experienced personnel. The designers of the levee project should also be involved in the approval of the final subgrade surface to ensure the levee project requirements are met.

Methods to conduct the approval of the final subgrade surface will vary and should be scalable to the complexity of foundation conditions. Visual observations by field personnel through quality assurance activities may be sufficient for simple levee foundation conditions (i.e., alluvial soil foundations, little to no utilities). For complex foundation conditions (i.e., karst foundations, rock foundations with potential for defects and faults, numerous utilities or other human made features), approval of the final foundation surface may be performed using more formal inspections methods. It may be advisable to proof roll the subgrade with a heavy piece of construction equipment to help identify soft/unstable soil conditions.

6.1.3 Inspection Trench

Preparation and inspection of a trench along the embankment alignment is a best practice. Excavation of the inspection trench is performed before the placement of fill, as described in **Chapter 7**. The purpose of the inspection trench is to verify geologic conditions along the alignment are as expected, and no continuous permeable seams or previously unknown utility penetrations cross the alignment at the foundation depth (Figure 8-17).

Figure 8-17: Example Inspection Trench

An inspection trench was excavated under a 1,800-foot-long new setback levee along the right bank of the Sacramento River in Yolo County, California; June 2021.

6.1.4 Embankment Composition and Sources

The documents for construction (including specifications) will specify requirements for embankment soil fill composition. These specifications are selected to ensure the properties of the constructed embankment satisfy assumptions about material strength, permeability, and compressibility made during levee design. Specification will describe the soil materials that may be included in the levee embankment, as well as acceptable placement and compaction procedures.

Two key concepts should be understood with regard to embankment composition. First, soil materials are naturally variable; therefore, the embankment composition will vary. Design analyses should have considered minimum acceptable properties for the specified soil composition. During construction, the limits will not be absolute, and construction personnel should recognize a small percentage of tests may fall below the minimum required by the specification. In these situations, corrective measures in the construction technique or borrow sources may be required to ensure embankment composition meets the required specifications.

A second key concept is that levees will fail at the weakest point. The composition of the levee embankment should not include zones, vertically or laterally, of anomalous or unwanted material, even if the average test results still meet requirements.

An observational approach is necessary to ensure a homogenous embankment—an embankment without anomalous unwanted zones—meets design requirements. Sampling and laboratory testing should be used to confirm field observations and document material properties, but this cannot be a substitute for observation.

6.1.4.1 Off-Site Borrow Sources

Off-site borrow sources may be required which will necessitate hauling fill material, thereby increasing costs and possible environmental impacts. All haul routes should be identified prior to construction. Borrow sources may be investigated and specified during design or may be left to the constructor to identify. Regardless of how the borrow source is identified, the potential soil needs to meet the specifications. Generally, less construction risk is incurred if the borrow sources are specified and confirmed during design (Figure 8-18).

Figure 8-18: Example Borrow Source Excavation

An excavator strips materials from a portion of the Missouri River Levee, along the left bank, in Rock Port, Missouri, that was damaged by erosion during the 2011 flood. Excavated materials are being reused where possible to construct a setback levee further away from the river; February 2012.

6.1.4.2 On-Site Borrow Sources

For levee rehabilitation or improvements, on-site sources of levee fill may be available from existing embankment material. These sources should be identified for re-use during the design phase. The constructor should develop means and methods for re-use of on-site embankment soil material, including the blending of materials.

Use of on-site material should include an assessment to confirm such use will not increase flood risk. Generally, borrow sources requiring excavation within 300 feet of the embankment are not recommended because of the potential to increase seepage risk. This should be assessed during design.

6.1.5 Blending

Mixing or blending of soils to obtain suitable fill material often is not cost effective and can lead to undesirable and inconsistent material. Obtaining borrow material suitable for the levee project without requiring mixing or blending is recommended, where possible.

Using full-face excavation of borrow soil to minimize any soil stratification during placement of embankment fill is a best practice. If mixing or blending is required to adjust soil moisture content, this should be completed and the blended material should be approved before being hauled to the construction site. Blending on the embankment surface is not recommended; however, moisture conditioning may be required.

6.1.6 Compaction

Compaction of soil fill is essential for short- and long-term strength, permeability, and compressibility performance of the embankment. Compaction densifies the fill by removing air voids, increasing strength, and lowering permeability and compressibility. Failure to compact fill will result in excess seepage, long-term settlement, and potential slope stability issues.

The degree of compaction is established during design and denoted in the project specifications. In addition to assuring an acceptable embankment fill, project specifications for a particular material type may also require a compaction method specifying a loose lift thickness, compaction equipment, and number of passes with that equipment.

Evaluation of degree of compaction for fine-grained cohesive soil is measured in the field against a standard, or by using a modified compactive effort, laboratory-determined maximum dry density, and optimum moisture content, in accordance with applicable standards of the American Society for Testing and Materials. The field-achieved dry density and moisture content is measured using sand cone density tests, supplemented with nuclear density testing gages.

A best practice for placement and compaction of fine-grained cohesive fill is to place loose lifts of moisture conditioned soil, and then apply compactive effort. Lift thicknesses are dependent on the soil being compacted and the compaction equipment being used, but generally should not exceed 8 to 12 inches. Moisture conditioning of the soil should be accomplished before placement of the fill lift, during or before excavation from the borrow source. This will help to achieve a more uniform moisture content.

The compactive effort is dependent on the soil type, and a wide range of equipment types are available (Figure 8-19). Finer grained soil generally is better compacted with non-vibratory sheepsfoot or pad rollers, while sands are compacted with smooth-drummed vibratory rollers. Sand or coarse-grained soils—often used for drains and filters—are controlled by degree of compaction or a method requirement (e.g., number for passes of the compactor). Following lift placement, quality control testing should be performed to determine in situ density and moisture content, and then should be compared to the project specification requirements (Figure 8-20).

Figure 8-19: Example of Sheepsfoot and Flat Drum Compactor Equipment

Constructors continued the compaction of the existing foundation area, as part of the subgrade preparation before the construction of a seepage berm with a chimney drain along the right bank of the San Joaquin River in San Joaquin County, California; June 2021.

Figure 8-20: Example Density Testing

Sand cone density and nuclear gage testing was performed on the subgrade of the San Joaquin River. An existing drainage ditch adjacent to the landside levee toe was backfilled and a new drainage pipe was installed; April 2021.

Field observations and testing to verify proper placement procedures should ensure proper fill compaction. As a best practice, test strips (fills) should be constructed early in the process, to establish optimum loose lift thicknesses and required compaction to meet project requirements. Field observations of moisture should be performed. Following lift placement and compaction, the fill should be tested to verify the observations and document the compaction.

In addition to the construction quality control testing, quality assurance tests should be performed to assure acceptability of the completed embankment. The amount of quality assurance testing should be scalable to the scope and potential risk posed by the levee project. Generally, quality assurance tests should be performed to the extent necessary to verify acceptability of the quality control test procedures and results.

6.1.7 Stability During Construction

Placement of new embankment material on relatively weak soils, such as unconsolidated soft clay or organics, will create pore pressure in the foundation soils as water within these soils is squeezed by the embankment loading. These pore pressures effectively will lower the strength of the soil, creating the potential for instability. These concerns should be addressed in the design phase, and a measure to mitigate instability should be developed for implementation during construction.

The best practice to reduce the likelihood of instability is to phase fill placement to allow the pore pressures to dissipate. This can be accomplished by constructing fills over larger areas to reduce the amount of soil placed within a short period. Slopes, temporary or permanent, should not be constructed steeper than specified in the contract documents, and they should be monitored for development of any instability. Additional monitoring may be recommended.

6.1.8 Embankment Slopes

As noted above, the embankment should be constructed in lifts. To construct the side slopes of the levee embankment to final grade, typically the best practice is to overbuild the slope to full lift width and then cut it back to design grade (Figure 8-21).

Figure 8-21: Example Embankment Slopes

Constructors work to scrape the overbuilt levee toe and prepare the levee landside slope on the right bank of the San Joaquin River in San Joaquin County, California; June 2021.

6.1.9 Erosion Control Features

As discussed in **Chapter** 7, erosion control features can be required for different potential erosion sources, including surface runoff during precipitation, riverine or coastal flow, waves, and overtopping. Prevention of erosion of newly completed construction work is important to avoid damage to the levee project and prevent pollution. Refer to section 4.1.2 on storm pollution prevention approaches during construction. This section will primarily focus on the construction of permanent erosion control features.

Armoring/bedding is a commonly used erosion control feature. Armoring/bedding methods can include riprap, concrete slope paving, engineered revetment, and high-performance turf reinforcement mats. Each method requires different construction materials, techniques, and equipment. Construction best practices for each method is discussed below.

For riprap erosion control features, construction quality control of both stone production and riprap placement is essential to ensure design intent is met. An example of constructing a riprap erosion control feature is shown in Figure 8-22. Design of riprap erosion control features are relatively sensitive to the unit weight of stone and should be determined as accurately as possible.

Riprap coming from the various quarries will not be of the same unit weight, so it is important to confirm unit weights for the riprap used during construction. Commonly, design specifications will provide for two limiting gradation curves for the riprap—and any stone gradation as determined from quarry process, stockpile, and in-place field test samples that lies within these limits—should be acceptable for construction. All stones should be contained within the riprap layer thickness to provide maximum resistance against erosive forces.

Oversize stones, even in isolated spots, may result in riprap failure by precluding mutual support and interlock between individual stones. This could cause large voids that expose filter and bedding materials, and create excessive local turbulence that removes smaller size stones. Small amounts of oversize stone should be removed individually and replaced with proper size stones. Refer to EM 1110-2-1601 (USACE, 1994) for best practices for delivery and placement of riprap for erosion control features.

Figure 8-22: Example of Riprap Erosion Control Feature Construction

Workers install riprap erosion protection along a levee in West Sacramento, California; September 2023.

Concrete slope paving can include cast-in-place concrete or articulating concrete blocks. Care consideration should be used when using cast-in-place when significant settlement of the levee is expected. Cast-in-place concrete should have sufficient joints to handle expected differential settlement, or articulating concrete blocks should be used instead. Joint and crack sealing maintenance is often required when cast-in-place concrete is used.

It is also important to consider site conditions during placement of concrete slope paving. Construction earthwork activities may be needed to provide a flat, unvegetated slope to place the concrete slope paving upon. Cast-in-place concrete should only be constructed in dry conditions and allowed to cure prior to exposure to erosive forces. Articulating concrete blocks should be installed by rather small construction crews with a modest amount of equipment. Construction quality control is used to ensure proper materials and construction practices are used as specified by the designer and manufacturer.

High performance turf reinforcement mats utilize synthetic geotextile materials with natural vegetation, such as grasses, to provide an erosion control feature. Traditional installation of a turf reinforcement mat includes placing or grading the embankment or slope to the required lines and grades, seeding the area, then placing and anchoring the mat with any variety of ground anchors. Vegetation (grasses) is then allowed to grow through the mat whereby the turf is reinforced with the geotextile of the mat. Installation of this erosion control feature can be hindered by the ability to establish vegetation—in some situations the use of sod may be required.

Vegetation is also commonly used as an erosion control feature. Vegetation should be designed based on local conditions and regulations, as described in **Chapter 7**. Hydroseeding is commonly used to establish vegetation where climate conditions are favorable. Establishing vegetation from seeds can be problematic in dry areas where the seeds will not germinate for weeks or even months. Provisions may have to be made to verify germination after rainfall in the area (Figure 8-23). Often, construction closeout requires vegetation established before construction is considered complete.

Figure 8-23: Example of Hydroseeding for Erosion Control

Workers make the first of several passes spraying a protective grass mixture on a new American River Levee section in the River Park neighborhood in Sacramento, California. Once sprouted, the mixture is designed to help shield the slopes from erosion; November 2014.

6.1.10 Settlement Control

As discussed in **Chapter 7**, levees often are constructed over areas with highly variable subsurface conditions and various construction techniques may be required to construct levees upon highly compressible foundations. These techniques should be planned in the design phase and implemented in the initial stages of levee construction (Figure 8-24).Construction considerations for various construction techniques are discussed in Table 8-11.

Table 8-11: Construction Considerations for Settlement Control

Settlement Procedure	Construction Considerations
Remove and replace	• Excavation depths and presence of shallow water tables are limiting factors for construction. • Construction monitoring may be required to ensure all unwanted material is removed.
Staged construction	• Settlement plates and piezometer instrumentation are often required to monitor consolidation conditions and inform fill placement rates. • Construction scheduling and fill placement rates may be uncertain depending on conditions during construction. • Staged construction may be combined with prefabricated vertical wick drains to increase rate of consolidation to prevent delays in construction. • Relocating pipes to higher ground or other areas where consolidation and settlement is not expected may be required.
Prefabricated vertical wick drains	• Wick drains can be installed to depths up to 100 feet. • Sand drainage blanket is often installed to provide working platform and drainage for the wick drains. • Special zone or seepage cutoffs may be required to prevent long-term seepage caused by sand drainage blanket and/or wick drains. • Settlement plates and piezometer instrumentation are often required to monitor consolidation conditions and inform fill placement rates.
Preloading and surcharge fills	• Typically uses material not meeting levee fill requirements; it is placed before levee construction and removed before final levee construction. • Where stability conditions allow, surcharge placed to heights in excess of the final levee height may be placed to accelerate the consolidation time needed during construction. • Preconstruction soil testing and investigation is needed to confirm conditions are appropriate for construction.
Soil improvement or amendment	• Construction techniques should be reviewed and approved prior to construction activities. • Rigorous construction quality control and assurance may be needed to ensure acceptable soil improvement or amendment construction activities.

Figure 8-24: Example Wick Drain Installation

Crews install wick drains along a stretch of the levee to remove excess sub-surface water in New Orleans, Louisiana.

6.2 Floodwalls

Floodwalls must be constructed properly to ensure the levee performs as intended. Construction means and methods for floodwalls will depend on the wall type, foundation type (deep or shallow foundation), construction project type, and project constraints. As discussed in **Chapters 2 and 7**, floodwall types include T-, L-, and I-walls, mass gravity walls, and demountable floodwalls.

T-walls, L-walls, and mass gravity walls are typically cast-in-place concrete walls with either shallow foundations (e.g., on soil or rock) or deep foundations (on piles). Demountable floodwalls have either shallow or deep foundations. I-walls are typically driven-in-place cantilever-type sheetpile, sometimes with a concrete cap, but may also be used with soldier piles at regular spacings to stiffen the taller I-walls.

6.2.1 General Floodwall Considerations

The sequence of construction activities (e.g., sequencing of work) is important to successfully construct floodwalls. Construction sequencing is generally done by the constructor (section 4.1), but requirements for construction sequencing may be determined during design to ensure the floodwall is buildable.

Factors when considering construction sequence includes effects of construction on parties other than the constructor to minimize impacts from degradation of an existing floodwall. Construction of the wall project can be affected by the presence of existing features, such as walls and embankments, channels, buildings, roads, railroads, parking lots, utilities, etc. Considerations for construction sequencing should include construction materials or excavated material that is expected to be stored near the workface. Rights of way and available space to work also should be considered.

For construction of a new project or replacement of a floodwall project, all—or a portion of an existing floodwall—may need to be removed. Removal of existing floodwalls or embankments need to be considered in the construction sequence so that flood risk does not increase. In such cases, a plan to manage flood risks during construction should be developed (section 7.2).

When real estate is available, often the best way to manage flood risks is to build the new floodwall parallel with the existing project. This will allow the levee system to remain intact for a majority of the construction duration. If piles (or sheetpiles) are used as part of a temporary flood protection measure, the piles should generally be left in place. Depending on the soil, it will tend to 'ooze' to fill the pile voids, potentially causing displacement of the new project. Timely coordination with utility owners that have penetrations (Figure 8-25) through proposed floodwalls are imperative in maintaining the construction schedule and avoiding cost increases.

Figure 8-25: Example of Excavation of an Abandoned Utility

Levee work is underway along the north bank of the American River in north Sacramento, California. Complicating the work are land easement rights, an inactive railroad line, and an assortment of buried utilities, such as the sewer line shown here; August 2013.

6.2.2 Concrete T-Walls and L-Walls

To ensure design performance, T-walls and L-walls require sufficient foundation preparation, excavation slope stability review, groundwater management as necessary, and appropriate construction means and methods.

6.2.2.1 Foundations

Shallow foundation excavations deeper than 4 feet requires bracing for vertical cuts. This is a safety requirement mandated by the Occupational Safety and Health Administration or applicable local building codes. Bottom of slab excavations should be below the frost line to protect against foundation heaving. Work platforms are recommended for accurate rebar and concrete placement. When working in soft soils below the water table, it is recommended to place 4- to 6-inch concrete working slabs, referred to as stabilization slabs, over a 6-inch gravel layer (Figure 8-26).

Figure 8-26: Example Floodwall Foundation Construction

Constructors continue work on a new concrete floodwall along Morrison Creek in Sacramento, California. The 3,300-foot-long floodwall will extend an existing floodwall, further reducing flood risk in the area; July 2012.

For deep foundations, a variety of pile types are available for the support of floodwall systems, including concrete and steel pipe and H-piles, micropiles, and drilled shafts. The pile selection in the design phase is influenced by the availability of pile types, strength and capacity requirements, soil conditions, installation impacts on adjacent infrastructure (vibrations), corrosion resistance, and cost.

6.2.2.2 Concrete Placement for Floodwalls

The following practices for concrete placement (Figure 8-27) includes:

- Using the correct vibration methods is crucial to avoid honeycombing in the finished concrete.
- Back up concrete sources are recommended to avoid unplanned construction delays and/or cold joints.
- Unplanned cold joints should be properly prepared before additional concrete is placed to allow proper bonding of joints.
- Thermal concerns attributed to thick placements and higher strength concrete mixes are not common in smaller floodwalls. However, temperature sensors can be used to schedule form removal more efficiently.

Proper curing of the floodwall will also be crucial to achieve full strength development of the concrete; a lack of curing can truncate the hydration process. On flat, base surfaces, curing is accomplished by moist curing (ponding) or curing compounds that meet desired specifications. The curing of floodwalls is predominantly accomplished by moist curing, but other methods can be used. Curing is applied after defects, if any, are repaired.

Figure 8-27: Example Concrete Placement for Floodwalls

Concrete is being placed at the base of the western floodwall tie-in in New Orleans, Louisiana. This floodwall will connect the gap between the Seabrook floodgate structure and the hurricane risk reduction system in Orleans Metro; December 2010.

6.2.3 I-Walls

I-walls can be formed with driven, vibrated, or pressed-in sheetpiles. Construction access for I-walls can be as narrow as 15 feet. Construction access can be reduced further if press-in pile equipment is used. The added benefit of a press-in hammer is the elimination of vibration and noise. Sheetpile installation methods are described in EM 1110-2-2502 (USACE, 2022b).

Polyvinyl chloride sheetpiles are sometimes used for sheetpiling in light duty applications. General use of polyvinyl chloride is for earth retaining walls. It has much less strength (by an order of magnitude) and stiffness (by two orders of magnitude) than steel; however, it is more corrosion resistant and less expensive than steel. It cannot be readily driven in as many types of soil as steel. The pile interlocks are not as strong as in steel sheetpiling, therefore provides less robustness and ability to carry overloads. Prior to deciding to use polyvinyl chloride sheetpiling for a floodwall, a risk assessment should be performed to ensure desired levee performance is achieved.

Where greater height of the floodwalls to resist higher flood loading is needed, combo-walls may be used, consisting of steel sheetpiles with structurally connected steel pipe piles at a designed spacing.

To ensure piles are placed and driven to the correct alignment, a guide structure or templates should be used. At least two templates should be used in driving each pile or pair of piles. Templates should also be used to obtain the proper plumbness of the sheetpile wall. Protective shoes to protect the tip are also available so driving through harder soil strata is possible (Figure 8-28).

Figure 8-28: Example Pile Driving

Sheetpile installation takes place at Tanner Pacific in Foster City, California. The city is constructing a 6.5-mile seawall, upgrading the existing levee structure, and increasing the height of the levee; April 2021.

6.2.3.1 Driving Methods for I-Walls (Vibration, Impact, and Press-In)

There are multiple driving methods for I-walls including:

- **Vibratory hammers**: A vibratory hammer can drive piling up to eight times faster than impact hammers, depending on the type of subgrade. Vibratory hammers are widely used because they usually can drive the piles faster, do not damage the top of the pile, and can easily be extracted when necessary. When a hard driving condition is encountered, a vibratory hammer can cause the interlocks to melt. If the penetration rate is 1 foot or less per minute, the use of a vibratory hammer should be discontinued, and an impact hammer should be employed. The selection of the type or size of the hammer should be based on the soil in which the pile is to be driven. The design engineer should be aware of the soil stiffness and possibility of obstructions, which can cause failure or weakening of the sheetpile during driving. Vibrations from driven sheetpile installation may affect and damage existing structures. Work should be performed in a manner that will limit vibrations at the structure nearest to the work being performed to a maximum of 0.5 inch per second. When driving is adjacent to existing infrastructure, vibrations should be limited to 0.25 inch per second. Vibrations at nearby structures should be monitored during construction, and work practices should be adjusted if recorded vibrations exceed allowable levels.

- **Impact hammers**: Types of driving impact hammers traditionally used for sheetpiles include steam, air, or diesel drop, single-action, double-action, or differential-action. The required driving energy range should be specified in foot-pounds, based on manufacturer recommendations and the type of subsurface soil conditions encountered.
- **Press-in hammers**: The equipment jacks the pile into the ground. The system requires reaction piles be driven to anchor the jack and, after being started, the jack uses the driven piles to resist the jacking force. The jack rides along beams attached to the driven piles. The system is free of vibrations that are a concern when driving next to existing infrastructure. Noise levels are also very low and right-of-way requirements are reduced. The production rate is slower than when using the more common vibratory hammer.

Generally, jetting should not be performed on levees. Jetting should only be used to penetrate strata of dense cohesionless soils. Jetting should be performed on both sides of the piling simultaneously and should be discontinued during the last 5- to 10-feet of pile penetration.

6.2.4 Mass Gravity Walls

A mass concrete gravity wall consists of concrete that is often designed without steel reinforcement. There are generally construction methods for mass gravity walls—conventional placed mass concrete and roller compacted concrete.

Conventionally placed mass concrete gravity walls are characterized by construction using materials and techniques employed in the proportioning, mixing, placing, curing, and temperature control of mass concrete (ACI Committee 207, 2022). The cement hydration process of conventional concrete limits the size and rate of concrete placement and necessitates building in monoliths to meet crack control requirements. Construction procedures include batching and mixing, as well as transportation, placement, vibration, cooling, curing, and preparation of horizontal construction joints between lifts. Refer to EM 1110-2-2200 (USACE, 1995) for best practices in constructing conventionally placed mass gravity walls.

Roller compacted concrete walls are characterized by using construction techniques that are similar to those employed for embankment dams. Roller compacted concrete is a relatively dry, lean, zero slump concrete material containing coarse and fine aggregate that is consolidated by external vibration using vibratory rollers, dozers, and other heavy equipment. In the hardened condition, roller compacted concrete has similar properties to conventional concrete.

For effective consolidation, roller compacted concrete must be dry enough to support the weight of the construction equipment, but have a consistency wet enough to permit adequate distribution of the past binder throughout the mass during the mixing and vibration process, thus, achieving the necessary compaction of the roller compacted concrete and prevention of undesirable segregation and voids. The consistency requirements have a direct effect on the mixture proportioning requirements (ACI Committee 207, 2022). Refer to EM 1110-2-2006 (USACE, 2000b) for best practices in constructing roller compacted concrete.

6.2.5 Structural Backfill

The structural backfill material should be adequately compacted to prevent settlement and development of seepage paths. The amount of compaction required will depend on the material used and the purpose of the structure. Strict control of compaction is required when the fill is a cohesive soil. Precautions should be taken to prevent over-compaction, which will cause excessive lateral forces to be applied on the structure. If heavy compaction rollers are used near the wall, their effect on lateral earth pressures on the wall should be considered in the design. Alternatively, the allowable weight of compactors may be restricted by the specifications to control wall pressures. It is a best practice to start compaction at the wall and work away from the wall to minimize excessive compaction-induced locked-in lateral earth pressures.

If backfill is to be placed on both sides of a floodwall; it should be in simultaneous equal lifts on each side. In some situations, the use of clay backfill is unavoidable, and under these circumstances, very strict controls on compaction is required. During winter construction, frozen backfill material should not be allowed under any circumstances.

In some situations where floodwalls are constructed on soft soils, structural backfill can cause settlement and induce forces (e.g., down drag or settlement induced bending moments) on floodwall structural foundation components (e.g., piles). Refer to settlement control in section 6.1.10 on best practices to control settlement.

6.2.6 Levee-Floodwall Combinations

Floodwalls may be constructed on top of levee embankments, new or existing. This is frequently done when limited right of way is available to construct or raise a levee embankment. It may be necessary to allow embankment settlement before constructing the floodwall. Alternatively, the floodwall may be constructed with an overbuild to account for future settlement of the embankment.

6.3 Closure Structures

As discussed in **Chapter 2**, closure structures are used to close gaps in the levee alignment, such as where infrastructure (e.g., a road or railroad) or another water body (natural or human-made) crosses or intersects the alignment. The construction of closure structures presents unique challenges in coordination, management of water, specialized expertise in fabrication of structural and mechanical components, and quality control/testing (Figure 8-29).

Construction and delivery of closure structures to the site can interfere with normal traffic and local businesses and residents. This might have some effect on selecting the closure structure type or size of opening (**Chapter 7**) and the fabrication method. Traffic interruption issues should be properly managed (section 4.1.3) and coordinated (section 4.3). This is especially important for railroad closures. Transportation restrictions might be another key construction issue for larger closure openings. The ability to deliver the closure structure on conventional trucks should be studied. Special permits or road construction may be required for delivery of larger structures, or they may need to be assembled in place.

Construction of waterway closures presents construction challenges with working on or near water and are often impacted by fluctuations of tide and river conditions. If dry conditions are required for the construction of a waterway closure, this may require draining the waterway (if feasible) or require the use of cofferdams. Establishing dry conditions for waterway closures represent a major construction constraint requiring planning months or even years in advance. Refer to section 3.1.9 and 4.1.4 for more considerations on addressing these construction issues.

Figure 8-29: Example Closure Structure Construction

Workers construct a closure structure on the Wood River Levee system in St. Louis, Missouri; April 2012.

Coordination with state or local transportation departments or railroads is required, both to verify requirements and coordinate construction in their rights of way. Shop drawings or other design verification submittals should be submitted by the constructor with sufficient time for review, fabrication, and delivery.

Large closure structures designed and fabricated specifically for the project (e.g., tainter gates, roller gates, miter gates, vertical lift gates, sector gates) will require additional consideration. Properly qualified constructors can perform the closure structure fabrication. The more common practice is to use a fabrication shop that specializes in the fabrication of gates and mechanical components. Regardless, the fabricator's qualifications should be in accordance with the American Institute of Steel Construction certification programs. Constructability of larger closure structures should be considered including deflection, strength, and stability during stages of construction. Refer to EM 1110-2-2107 (USACE, 2022a) for best practices in fabricating closure structures.

Closure structures, both mechanical and electrical components, should be tested in place prior to construction closeout to verify they can be closed when needed. Shop drawings for closure structure components are common submittals and should be reviewed by the designer prior to acceptance for use. These shop drawings are critical for future operation and maintenance activities and should be properly documented during construction closeout (section 5.2).

6.4 Transitions

A levee consists of an arrangement of features along an established alignment, which creates a need to transition between different levee feature types. Transition locations may include:

- Earthen embankment to floodwall (concrete or steel) transitions.
- Earthen embankment or floodwall transition to concrete closure structures.
- Earthen embankment or floodwall tying into existing natural grade.
- Earthen embankment or floodwall tying to other existing infrastructure, such as bridge abutment walls or road embankment fills.
- Encroachments by pipe and culvert systems into earthen embankments.

General construction procedures for embankments, floodwalls, and closures are discussed in other sections of this chapter, whereas the unique aspects of constructing transitions are discussed in this section.

Sheetpiling is commonly extended into the embankment's levee, as shown Figure 8-30. The sheetpile tie-in maintains the height of the levee if settlement, erosion, or scour occurs, and provides protection against the internal erosion that can occur around the transition. One foot of soil over the top of the piling at the transition allows for grass cover. It also reduces the exposure of piling as the surrounding ground settles, making mowing easier.

Figure 8-30: Example Embankment/Floodwall Transition Construction

T-wall to I-wall to embankment transition under construction in New Orleans, Louisiana.

The sheetpile should extend past the concrete cap into the levee. This distance should either be 10 feet wide, equal to or greater than the height of the levee, or as required by evaluation of internal erosion. Design for internal erosion along the contact between the structure and soil is accomplished by lengthening the seepage path or by providing a filter at the exit to arrest soil particle migration. The sheetpile tie-in lengthens the path that soil particles would need to migrate along this contact for internal erosion failure mode.

Often, a short transition concrete-capped sheetpiling I-wall is installed between the embankment and a T-wall. One of the primary concepts in the development of this transition is to arrange details so there will be a minimum amount of differential movement of joints of monoliths in the transition. Where differential movement is anticipated, the sheetpile interlock should fall within the dove tail slip joint. Where differential movement is not anticipated, the sheetpile interlock can be located outside the wall edge. A dove tail slip joint may also be provided to aid in constructability. First, the levee embankment should be placed and compacted. Then, the sheetpile transition should be driven in order to minimize void spaces along the sheetpile.

The I-wall tie-in can be satisfactorily adopted as a transition section between an embankment and a pile-founded floodwall. That is because this type of construction is done after completion of the embankment. A delay in inserting the I-wall tie-in allows for consolidation of the embankment foundation, thus lessening the differential settlement between the embankment end of the transition and the floodwall. Potential ground improvement measures to mitigate for total and differential settlement are described section 6.1.10. The constructed transition may need to be made higher than required to account for settlement over the life of the project.

Settlement of embankments relative to adjacent floodwall sections may require special considerations to accommodate movement. This can be done with joints. The joint widths and waterstops should be selected to accommodate the expected rotation and movement. This may be done with large center bulbs or, in the case of very large movements, surface mounted neoprene sheets. Surface mounted waterstops should only be used as a last resort. They need to have a durable cover in order to protect them from sun, vandalism, or damage. This cover should also allow for movement.

Erosion control features are often required at the transition between embankments and floodwalls to prevent overtopping erosion (Figure 8-31). Refer to EM 1110-2-2502 (USACE, 2022b) for best practices in constructing embankment/floodwall transitions.

When the transition location is between an embankment and natural ground, the contact between the natural ground and the embankment should be prepared similarly to embankment subgrade preparation discussed in section 6.1.2. The contact should not be steeper than 1 vertical to 1 horizontal to avoid embankment cracking. The embankment inspection trench should be extended into the natural ground to ensure proper levee transition connection.

Figure 8-31: Example Levee Transition Connection (Embankment and Floodwall)

Transition of a floodwall and levee tie-in connection in New Orleans, Louisiana; March 2012.

6.5 Seepage Control Features

Seepage control features can include cutoff walls, seepage berms, and landside pressure relief systems. These features require different construction materials, equipment, and procedures. Best practices for construction of common seepage control features are discussed in the following sections.

6.5.1 Seepage Cutoff Walls

Cutoff walls act as a vertical low permeable barrier through existing embankments, or below the embankment or floodwall. They may include open-trench slurry walls, mix-in-place walls, grout walls, and sheetpile walls.

Open-trench slurry walls can include either a low strength soil-bentonite backfill or a higher strength (100 to 300 pounds per square inch) cement-bentonite backfill. In both cases, a narrow trench (24 to 36 inches) is excavated and initially is stabilized by a bentonite-water slurry for the soil bentonite wall, and a bentonite water-cement slurry for the cement bentonite wall. For the soil bentonite wall, a soil bentonite slurry mixture with a concrete slump of 4 to 7 inches is gravity backfilled into the slurry filled trench. The backfill displaces the slurry and forms a low permeable cutoff wall (Figure 8-32). For the cement-bentonite wall, the slurry used to stabilize the trench excavation self-hardens in 24 to 48 hours and forms the cutoff wall.

Figure 8-32: Example Open-Trench Cutoff Wall Construction

(a) Workers install a seepage cutoff wall in an American River Levee near Del Paso Boulevard in Sacramento, California; September 2014. (b) An excavator cleans out excess material from a seepage cutoff wall trench, as part of the Sacramento River Bank Protection project in West Sacramento, California; June 2012.

For mix-in-place cutoff walls (Figure 8-33), either individual elements (panels) or continuous trench mixing systems can be used. For panel construction, the number of panels constructed per shift is selected by the constructor so every panel can be excavated to the full depth and backfilled or mixed as appropriate in one shift. In either panel construction or continuous mixing, complete depths should be achieved and should not be allowed to be left at partial depth at the end of a shift.

Figure 8-33: Example Mix-in-Place Cutoff Wall Construction

A deep soil mixing rig pumps a cement slurry into the floodwall levee's foundation along the east side of the 17th Street Canal in New Orleans, Louisiana. Blades around the augers mix the slurry with the underlying soil to produce stabilized soil columns that will increase the levee's strength; March 2011.

For panel construction or cold joints in continuous trench mixing systems, a minimum overlap for the full cutoff wall depth is specified to ensure continuity of the cutoff wall. If the panels or cold joints are not successfully joined within the identified time frame, an offset adjacent overlapping segment on the waterside typically will need to be constructed to close the potential gap in the cutoff wall.

Crossing of the completed cutoff wall during construction should be allowed only at designated equipment crossings, where metal plates should be placed over the wall as a temporary measure to prevent cracking/collapse of the trench sidewalls.

Equipment and vehicular traffic not related to cutoff wall construction should not be allowed near the cutoff wall trench to avoid surcharge loading on the trench sidewall.

If adopting an open trench cutoff wall, a stability analysis should be completed on the open trench wall configuration. Open trench cutoff wall construction should be logged continuously and monitored during excavation by a qualified geologist or geotechnical engineer to confirm the bottom of the cutoff wall extends into the designated layer to form an adequate cutoff and continuity has been maintained. This should include logging by both the constructor's quality control trench logger and a quality assurance trench logger.

In open-trench cutoff wall construction—when the bottom of the cutoff wall element is reached—the bottom surface should be probed along the trench centerline, using a weighted tape to confirm the target bottom elevation is obtained. If more than a 6-inch-depth of sediment is found on the trench bottom, the trench bottom should be cleaned by successive light passes of an excavation bucket without teeth over the bottom surface, until the bucket returns free of debris or sediments.

For mix-in-place cutoff walls, multiple systems are available and include vertical auger and horizontal cutter wheel systems. Normal depth capacity of these systems ranges up to 150 feet below grade and can inject and mix a combination of bentonite and cementitious material to form a low permeability cutoff wall.

Before construction of a cutoff wall, the constructor should prepare a bench scale wall mix (soil-bentonite-water or soil-bentonite-cement), including varied mix constituents. Testing should be completed on the various mixes, as applicable, for unconfined compressing strength and hydraulic conductivity, and a recommended production mix should be submitted for review and approved by the design engineer. After being approved, this mix will form the basis for the production quality control and quality assurance testing.

As the cutoff walls are installed, a temporary cap should be placed within 24 hours over the top of the wall. The temporary cap should be a minimum 2 feet thick and constructed using embankment fill material placed without compaction effort. After the wall has been allowed to cure for the full period required by the specifications, the temporary cap and the upper 6 inches of wall should be trimmed to expose a clean surface and prepare a foundation for levee embankment or floodwall.

Wall material may be prone to desiccation and cracking when exposed at the surface, even after the wall has cured. The constructor will need to maintain the top of the cutoff wall at a consistent moisture content until covered by a permanent embankment or concrete floodwall. Protection of the cutoff wall will include minimizing the duration hardened cutoff wall materials are exposed, keeping all exposed cutoff wall materials continuously wetted, and applying protective measures, such as wetted burlap coverings or membrane-forming concrete-curing compounds.

During construction, bulk sampling of the cutoff wall slurry/mix should be performed in the excavation trench a minimum of twice per rig shift (i.e., twice per panel). Samples are taken by the constructor quality control personnel and levee owner's quality assurance personnel for applicable testing (Figure 8-34).

Figure 8-34: Example Quality Control Testing of Open Trench Cutoff Wall

Contract workers check the quality of a recently completed seepage cutoff wall near the River Park neighborhood in Sacramento, California; August 2014.

Acceptance criteria should have been developed during preparation of the project specifications and may include consideration of quality control and quality assurance testing, as well as the results of verification coring and downhole data.

To verify in situ competency of the cutoff wall, depending on the type of cutoff wall and as identified in the specifications, verification coring of the completed cutoff walls may be required at a typical spacing of 500 feet along the production wall alignment.

The verification coring, if used, typically will include collecting core samples, downhole televiewers, and falling head/rising head permeability testing. Detailed requirements should be identified in the specifications. Testing frequency and criteria should be established in the specifications.

A detailed description of cutoff wall system construction methods and issues is presented in Specialty Construction Techniques for Dam and Levee Remediation (Bruce, 2013).

6.5.1.1 Grouting and Sheetpiles

Although not as common, both grouting and sheetpiles have been used as seepage control methods. Grouting techniques include jet grouting and conventional pressure grouting. Both systems use combinations of bentonite and cementitious materials to create an in situ low permeability cutoff wall. Steel sheetpiles also can be used to create a cutoff barrier beneath levee embankments and floodwalls.

6.5.2 Seepage Berms

Landside seepage berms generally are constructed using standard earthwork techniques and can be used to control seepage through or under the levee, and at the same time can increase the stability of the levee.

Berms generally include random or general fill that provide only mass stability and move seepage away from the levee. Undesirable materials, such as high plasticity clays and organics, should be excluded from berm materials.

If the berm is drained, drainage layers typically will include filter sand and drain rock. These materials are designed to be filter compatible, and the constructor’s material submittals should be reviewed carefully for compliance with the specifications. Substitutions should be analyzed for filter compatibility before acceptance.

Placement of drainage layers on levee slopes as part of seepage berms (chimney drains) can be especially challenging, as care needs to be taken to avoid intermixing of the materials and maintain continuity of the drainage layer, as the filter, drain rock, and cover soils are placed on the slope of the embankment (Figure 8-35).

Figure 8-35: Example Construction of Landside Berm and Chimney Drain

Constructors continue work on a chimney drain installation as part of the 150-foot-wide drained seepage berm construction along the right bank of the San Joaquin River in San Joaquin County, California; June 2021.

6.5.3 Landside Pressure Relief Systems

As discussed in **Chapter 7**, common types of landside pressure relief systems include blanket drains and toe drains to collect throughseepage (Figure 8-36), and trench drains and relief wells to collect underseepage (Figure 8-37).

Figure 8-36: Throughseepage Pressure Relief Systems

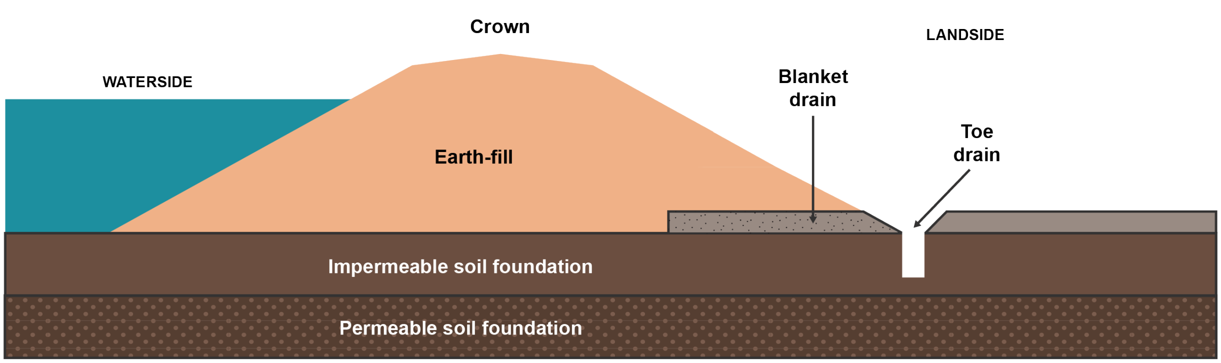
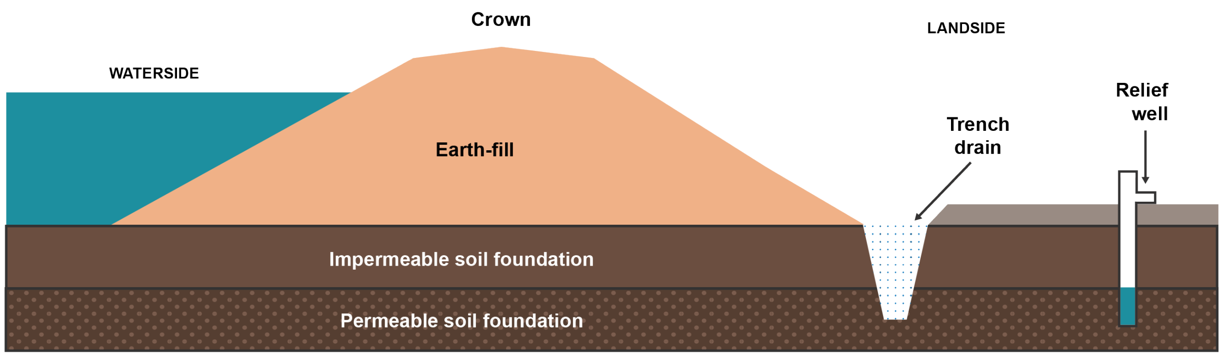


Figure 8-37: Underseepage Pressure Relief Systems



6.5.3.1 Drains

Construction of blanket drains, toe drains, and trench drains requires careful construction procedures to ensure proper materials are placed in the correct location. These drains contain pervious material with a specific particle gradation to ensure proper filtering and drainage. Basic construction procedures include storage (stock piling) of materials, loading of hauling equipment, hauling and dumping, spreading to specified loss lift thickness, wetting, compaction, and horizontal and vertical control. Materials for drains are typically purchased off site and stockpiled on site.

Dust abatement procedures should be used to prevent contamination of fines into the stockpiled material. Drain materials should be wetted prior to handling to facilitate that action, as well as to help minimize segregation. Compaction of drain materials should occur by means of vibratory rollers with the minimum required effort specified that will attain the desired density. For best practices in drain construction, refer to the Federal Emergency Management Agency's (FEMA) Filters for Embankment Dams manual (FEMA, 2011).

6.5.3.2 Relief Wells

Relief wells on the landside of the levee will act to control and relieve seepage pressures under the levee. Construction of relief wells should follow best practices, as outlined in EM 1110-2-1914 (USACE, 1992), and usually are implemented by experienced constructors. The most effective drilling method for any project involving installation of relief wells should be utilized. The method should be selected based on previous experience and consultation with the constructor.

Geology and site conditions, along with well diameter and depth, are major factors that will determine the appropriate drilling method. Relief wells typically vary from 6 to 18 inches in diameter. Boreholes are normally drilled 8 to 12 inches larger than the well diameter to accommodate filter packs. Table 8-12 provides a list of advantages and disadvantages of common drilling methods. Particular care by the constructor should be taken in drilling and the placement of filter pack around the well screen to ensure the well functions as designed (Figure 8-38).

Before installation of relief wells, pilot holes are typically drilled within 5 feet of each well location. These holes are usually sampled continuously or at frequent intervals (less than 3 feet). The purpose of the pilot holes is to verify foundation conditions used for seepage analysis and relief well design. The holes also serve as a check on the design of the relief well filter pack, screen/slot sizes, and screened/blank intervals. Pilot holes can be drilled during the pre-construction engineering and design phase. In this case, information from the pilot holes is included in the subsequent construction documents. Alternatively, pilot holes can be drilled during the construction phase with the final well design performed during well construction. Construction risks (e.g., impacts to schedule and costs) can be greater if pilot holes are drilled during construction due to the uncertainty in conditions.

Once the relief well boring is completed and the tools withdrawn, the boring should be sounded to assure an open hole to the proper depth. All screen and riser to be installed should be laid out. These materials are obtained in standard lengths (e.g., 10 feet) or fabricated in varying lengths. When non-standard lengths are required, it is advantageous to have screen and blank sections pre-fabricated to length by the manufacturer. This is especially important when using stainless screens, due to the difficulty of cutting and welding stainless steel in the field. In either case, all screen and riser must be measured prior to installation to determine its total made-up length. This information should be part of the well construction record. The bottom joint of the well screen should be fitted with a sump or bottom cap.

After installation, all wells should be pump tested to demonstrate the filter pack and screens are allowing flow of water from the wells without loss of foundation fines.

During construction, detailed and accurate observations of all aspects of relief well installation should be documented on site in a timely manner. These records should be included in the project documentation during construction closeout. These records should include information on well material, method of drilling, type, length and size of well screen, and slot size. The filter should be defined as to grain-size characteristics, depth, and thickness. Elevation of the top of the well and the ground surface should be recorded. The depth to granular material, the thickness of that material, and the percent penetration of the well should also be clearly identified. Development data should include the method, the amount of effort, and sand infiltration. The records should show the final sounded depth of the well.

Table 8-12: Advantages and Disadvantages of Relief Well Drilling Method

Common Drilling Method	Advantages	Disadvantages
Cable tool	• Drilling fluid not required. • Borehole remains stable. • Formations with voids can be drilled. • Rigs are simple and economical. • Less well development required compared to standard rotary method.	• Low penetration rates. • Efficiency declines with depth. • Fine-grained formations can be problematic.
Standard (direct) rotary	• High penetration rates. • Ability to maintain open borehole without casing facilitates well and filter pack installation.	• Drilling mud required, can cause plugging, “balling” of bit, etc. • Rigs are large, expensive, and complex with high transportation and daily operating costs. • Requires significant water supply. • Management of drilling fluid requires specialized experience and expertise. • Mud pits in blanket require careful backfilling, compaction, and reseeding.
Reverse rotary	• High penetration rates. • Few or no drilling additives required. • Ability to maintain open borehole without casing facilitates well and filter pack installation. • Less well development required compared to standard rotary.	• Large rig size limits site accessibility. • Requires significant water supply. • Not suited for drilling prolific aquifers and/or materials where loss of circulation is a concern. • Difficult in drilling cobbles or boulders. • Mud pits in blanket require careful backfilling, compaction, and reseeding.
Hollow-stem auguring	• Rigs are simple and economical. • Drilling mud is not required. • Borehole remains stable. • Penetration rates are fast when using bottom plug. • Less well development required compared to standard rotary.	• Augers can smear formation with clays from overlying layers. • Augers must be pulled back while filter material is placed; progress can be slow. • Large augers can get “locked” in saturated sand layers. • Large augers generate a high volume of cuttings.

Figure 8-38: Example Relief Well Construction

Constructors work to install a 95-foot deep relief well for seepage control along the Mississippi River Levee near Vicksburg, Mississippi; September 2011.

6.6 Channels, Floodways, and Controlled Overtopping

6.6.1 Channels and Floodways

As discussed in **Chapter 7**, channels and floodways act as a diversion for riverine floodwater flows to be released into less critical areas. Such diversions may include:

- Diversion of flood water from the river into the leveed area.

- Diversion of water to/from the leveed area to another area or basin, which is either not prone to flooding and/or where other existing drainage facilities can be used to remove the water.
- Removal of water from a detention basin before the water in a basin rises to a level that can cause damage.

Thus, proper sequencing of construction channels and floodways is important in management of risks during construction. When constructing channels and floodways, flows should be managed by diversion, pumping, or sequencing of the construction. One side of the channel is often constructed while providing for diversion of the water on the other side of the channel. After completion of the first side of the channel, flows are diverted to the completed side while completing the opposite side.

Survey control during channel and floodway construction is essential to correctly locate channel and floodway components, as well as to ensure the constructed channel and floodway alignment and grade are as designed. Field staking and surveys should be performed routinely as with any earth-moving project. Interim surveys are recommended to update progress and document earthwork quantities.

Construction of channel erosion control features are similar to that of embankments. Refer to 6.1.9 for best practices in construction of channel erosion control features.

6.6.2 Locations of Controlled Overtopping

Locations of controlled overtopping may include embankments, floodwalls, closure structures, transitions, and erosion protection features. Construction associated with locations of controlled overtopping are similar to the levee features previously discussed in section 6. However, the sequencing of construction for controlled overtopping in relation to the construction of other levee features is a key consideration and should be determined based on effective management of risks during construction (section 7).

6.7 Interior Drainage Systems

Interior drainage system facilities include drainage structures (Figure 8-39) and pump stations (Figure 8-40). Construction practices for these structures are similar to floodwalls, except that large open cuts or braced excavations may be needed, both of which typically require dewatering systems. Testing dewatering systems should be considered in advance of construction to better estimate the dewatering needs to maintain excavations. Braced excavations can be used as temporary flood protection measures when building within the levee alignment. Temporary pumps may be required when the braced excavation blocks the drainage flows. Structures—such as waterway gates constructed in navigation channels—may also require a temporary bypass.

6.7.1 Pipes

It is essential that the construction of pipes associated with interior drainage systems, such as gravity drains or pressurized pipes from pump stations, is performed in a proper manner, as improper construction practices can lead to failure modes that can significantly affect the performance of a levee. Generally, EM 1110-2-2902 (USACE, 2020b) provides the best practices for both the design and construction of pipes for levees. There are several construction considerations involved when work includes the installation of a pipe, including:

- Managing ground water, surface runoff, and/or flooding.
- Pipe installation method.
- Testing and acceptance.
- Construction documentation.

Figure 8-39: Example of Landside Interior Drainage Construction

Excavation and preparation of a trench, followed by installation of a new drainage pipe outside the seepage berm toe, occurs along the right bank of the San Joaquin River in Sacramento, California. An existing drainage ditch adjacent to the landside levee toe is backfilled and a new drainage pipe is being installed; July 2021.

Water management during pipe installations is necessary to prevent schedule delays, increased costs, and lower quality installations. For example, water ponding in the pipe trench can prevent adequate backfill compaction, which may lead to vertical and/or differential settlement between pipe segments.

Excavations which extend below the groundwater table can cause a ‘quick’ condition in the bottom of the trench, which occurs when the upward water pressure reduces the soil’s effective stress, and it begins to behave more like a fluid. This loss of strength creates an inadequate supporting surface for the pipe. The depth of the bottom of the excavation in relationship to the groundwater table, foundation conditions, expected quantity of flow, and size of excavation will dictate the groundwater management method.[3]

[3] The information required for selecting and designing a groundwater control system can be found in Unified Facilities Criteria 3-220-05 (USACE, NAVFAC, and AFCEC, 2004).

Commonly, for the installation of pipes, controlling surface water is typically required for the installation of pipes and may include earthwork/regrading to divert water around the construction site. The installation or replacement of a pipe through a full cross-sectional embankment excavation will typically require temporary flood protection measures (section 7.2).

Pipes may be installed in the foundation beneath a levee by trenching or trenchless methods. Trenched placement involved excavating soil along a path, preparing the excavation to receive a pipe, installing the pipe, and backfilling around the pipe. Although relatively straight forward, the precautions using this method are discussed later in this section. Trenchless methods consist of steerable and non-steerable procedures that produce an overcut, creating an annular space between the excavated soil and the outside of the pipe. These methods often require introduction of water-based lubricants within an annular 'overcut' space between the pipe and the soil to facilitate pipe installation and remove drill cuttings. Trenchless methods are more technically challenging, as it requires specialized equipment and skilled workers to monitor drilling pressures and grouting, and to maintain line and grade by controlling the rate of advancement.

For the trenching installation method, the designer should determine if controlled low strength material or soil backfill is desired, since it will impact the trench dimensions. If soil is used, the excavated trench must be wide enough to accommodate the hand-operated equipment used at an angle to compact the soil within the pipe haunches. During new levee embankment construction, it is generally preferred to partially construct the new embankment so that a trench may be cut through uniformly compacted fill. The partially completed embankment should be constructed high enough that the backfill over the pipe is sufficient to protect it from equipment loads once embankment construction resumes. The bottom of the excavated trench should be tested to verify soil and groundwater design assumptions.

There are generally accepted trenching installation restrictions. Excavations for trenching installations must be designed, excavated, and maintained in a stable condition. Seepage into excavations must be controlled to prevent erosion of soils, which may require dewatering. With the exception of trench boxes, deep temporary shoring of pipe trenches through an embankment should be avoided. The soil disturbance associated with vibratory or impact hammers for deep shoring, such as sheetpiling or piles, could damage otherwise acceptable embankments. Also, the removal of sheetpiling can leave gaps in the embankment or foundation. While trench boxes are less likely to disturb embankment soil, they can create lines of disturbance that must be addressed to prevent creating a preferential seepage path.

Figure 8-40: Example Interior Drainage Pump Station

Workers install a new city sump station with 10 lines near the River Park neighborhood in Sacramento, California.; October 2014.

For trenchless methods, there are also several construction installation restrictions to consider. Excavations at entry and exit areas for trenchless installations must also be designed, excavated, and maintained in a stable condition. Trenchless installations are not recommended through earthen embankments or seepage control features. If any seepage control feature is above or beside the proposed trenchless pipe alignment, a review of whether trenchless method is appropriate for the project to ensure the advancement trenchless technique will not impact the seepage control feature. Entry and exit areas must be backfilled with a low permeability cohesive soil placed around the pipe to prevent a preferred seepage path.

Pipe installations, whether trenched or trenchless, have the potential to create preferential seepage paths from the waterside to the landside. Seepage filters are commonly used to address this issue through relieving local pore pressures by allowing the passage of water while preventing the migration of soil particles (internal erosion) when the levee is loaded. FEMA's Filters for Embankment Dams manual (FEMA, 2011) provides best practices to use when constructing filters.

In cases where significant settlement along the pipe alignment is anticipated, the preferred method of mitigation is preloading the foundation to reduce post-construction settlement. Reducing the post-construction settlement reduces stress on the pipe connections and the chance of producing a sag in the pipe alignment that perpetually holds water.

Pipe segments must be joined according to the manufacturer's instructions to better ensure their success and longevity. In general, pipe segments are placed only after pipe supports or cradles have been properly prepared. Pipe placement should begin at the lower elevation and continue uphill, which uses gravity to help home the joints and maintain a seating force.

The effect of the construction loads on the pipe are a function of the depth of soil cover over the top of the pipe. Heavy construction equipment passing over the top of the pipe should be evaluated when necessary. If the soil cover height is at least 3 feet above the top of the pipe, construction equipment can usually pass over the pipe without issue; however, additional analysis may be required. Methods to estimate loads are provided in Chapter 5 of the American Water Works Association M11 manual (Dechant, Bambei and American Water Works Association, 2017), if required.

Acceptance testing formalizes the approval of newly installed or rehabilitated pipes using inspections and field testing so that the pipe owner does not rely solely on the manufacturer's quality assurance/quality control factory testing. The best practice is to perform an inspection of each installed pipe section after the trench has been backfilled but before the embankment is placed. Post installation inspections provide a baseline for subsequent in-service inspections.

The following provides a list of items that should be considered when evaluating installation compliance with documents for construction.

- All pipes and fittings should have a manufacturer's certification stamp stating that the material conforms to the specification and/or guidance governing the manufacture of the particular pipe material.
- Visually inspect all pipe segments and appurtenances upon arrival at the job site to ensure that they were not damaged during transit before accepting the delivery.
- Lift pipes according to the manufacturer's directions (from delivery vehicles and into trenches) to prevent excessive bending stresses or damage to protective coatings.
- Protect pipes from impact damage, such as scratching and cracks, and store on level ground in the manufacturer's packaging. Follow the manufacturer's recommendations for allowable stack heights, supports, and exposure (temperature and ultraviolet).
- Follow manufacturer's guidance for field repair of damaged pipes, if the repair is not expected to affect performance; otherwise, replace the pipe. Defects vary by pipe material, but common defects include fractures and cracks, coating holidays or damage, and surface defects indicating mixing, molding, or other manufacturing deficiencies. Pipe sections with joint damage should be replaced.
- Each joint should be tested hydrostatically to determine whether it exceeds the maximum joint leakage specified by the pipe's applicable American Society for Testing and Materials International standard or other guidance specified in the documents for construction.
- Ensure that pipe segments that are match-marked (i.e., pipe markings indicating the order of installation) are installed in the correct order.
- Backfill should be tested to ensure it meets the requirements specified in the documents for construction.

- Inspect each segment of pipe for: alignment; settlement or sags; excessive joint offsets or separations; buckling, bulging, and deformation; protective coating damage; seal or weld separations; and other damage. Ring deflection that may occur during installation should not exceed the limits in documents for construction. Reinstall segments with installation deficiencies. Repair or replace damaged segments.
- Identified defects on an installed pipe must be assessed by an engineer for potential impacts to levee performance.

Construction reporting and documentation is a valuable reference for future inspections, assessments, and modifications or repairs. As the pipe installation progresses, field documentation must be assembled as part of a post-construction report. Conditions including joint gaps, tears, misalignment, cracks, and deformations must be noted and reviewed by the condition assessor. The post-construction report should include the following items:

- **Manufacturer documentation**: This documentation should include design drawings for pipe joints; design calculations, proof of design testing, and inspection records for pipes and fittings; and, drawings, design calculations, and specifications for appurtenances (such as slide gates, flap gates, valves, pumps, and pre-formed or precast associated structures, such as gatewells, manholes, headwalls).
- **Acceptance testing documentation and inspection reports**: These reports should be developed and include any additional quality assurance/quality control information.
- **Testing and inspection personnel and equipment information**: This should include a statement of the field accuracy achieved for all measurements, including tolerances. The report typically includes a narrative about required field/measurement calibration and provides proof that all calibration procedures were followed when collecting data within the report.
- **Record drawings and field data**: This data should be provided in a digital format, including the pipe's alignment profile and elevations. Tracking equipment, including method or confirmatory procedure, used to capture the data should also be included.
- **Evaluation of installed condition**: This evaluation should be documented, typically including certification that the pipe and backfill were installed consistent with the final approved plans and specifications.

6.7.2 Ancillary Components

As discussed in **Chapter 7**, ancillary components associated with the penetrations may include headwalls and gatewells. Mechanical components may include slide gates or sluice gates, passive flap gates, air vents, and siphon breakers. For construction considerations related to ancillary components, refer to Table 8-13 for references to best practices.

Table 8-13: References to Best Practices for Construction of Ancillary Components

Mechanical Component	Best Practice Reference
Sluice gate	• EM 1110-2-2902 Conduits, Pipes and Culverts Associated with Levees and Dams and Other Civil Works Structures (USACE, 2020b). • EM 1110-2-2107 Design of Hydraulic Steel Structures (USACE, 2022a). • EM 1110-2-6054 Inspection, Evaluation, and Repair of Hydraulic Steel Structures (USACE, 2001). • EM 1110-2-3105 Mechanical and Electrical Design of Pump Stations (USACE, 2020c).
Flap gate	• EM 1110-2-2902 Conduits, Pipes and Culverts Associated with Levees and Dams and Other Civil Works Structures (USACE, 2020b). • EM 1110-2-2107 Design of Hydraulic Steel Structures (USACE, 2022a). • EM 1110-2-6054 Inspection, Evaluation, and Repair of Hydraulic Steel Structures (USACE, 2001). • EM 1110-2-3105 Mechanical and Electrical Design of Pump Stations (USACE, 2020c).
Duckbill check value	• EM 1110-2-2902 Conduits, Pipes and Culverts Associated with Levees and Dams and Other Civil Works Structures (USACE, 2020b).
Air vents and siphon breakers	• EM 1110-2-3105 Mechanical and Electrical Design of Pump Stations (USACE, 2020c).

6.8 Pump Stations

Construction of pump stations can be complex as it requires close coordination with adjacent levee work as well as construction expertise in earthen, drainage systems, electrical, mechanical, and structural components (Figure 8-41). Where pump stations are adjacent to levee embankments or where right-of-way restrictions exist, the stations are typically located at the landside toe of the levee. Vehicle access to pump stations at all flood elevations should be carefully considered when selecting station location, and adequate provisions should be made to permit safe operation of service vehicles bringing in equipment during construction and O&M.

Figure 8-41: Example Construction of a Pump Station

Construction takes place on the pump station along the Chain of Rocks Levee near Granite City, Illinois. The pump station is one feature of the levee system; April 2012.

During construction, the designer should be involved in the review of shop drawings and record drawings, preparation of the O&M manual, and field and shop inspections. The designer should also be consulted when a field change is recommended or required. Considerations for mechanical components of pump stations, as well as commissioning a pump station during construction, can be found in **Chapter 7**.

Commissioning of a pump station involves bringing a recently constructed pump station into proper working order. Commissioning involves the integration of all component mechanisms into a single system (i.e., pump station) through adjustment of settings and other operating parameters. It also involves operational testing to ensure the station is free of defects, either inherent to the design or inadvertently incorporated during facility construction or manufacture of equipment. It is not always possible to foresee all issues during the design phase, and alterations during construction may produce unintended consequences. Commissioning should not be viewed as strictly taking place at the end of construction, but as a process integral to both the design and construction phase of a pump station project.

During construction, the best practices for the commissioning of a pump station involves the following:

- The levee designer should review construction submittals, respond to constructor requests for information, conduct site visits, witness factory testing, and perform preliminary steps for preparation of the O&M manual.
- The designer should review pump equipment shop drawings to ensure construction requirements are met. It also is the best and least costly time to implement any changes to the plans or specifications required due to design deficiencies, equipment changes, or to implement design improvements.
- In addition to procurement and fabrication submittals, informational submittals covering manufacturers' O&M instructions will provide additional operating requirements on equipment which must be vetted for consistency with project operation.
- Shop drawings should be reviewed by the designer to ensure contract specification requirements for fabrication, equipment, materials, and finishes are met. They should be detailed and include all information as described in the specifications. In addition, they should include requirements for manufacturing and assembly drawings that ensure the pump is being built in accordance with contract requirements, industry standards, and best practices.
- The constructor and pump manufacturers should have approved shop drawings on site. It should also be verified that installation instructions including weights of pump components (e.g., shaft, pump impeller, impeller and diffuser bowls, columns, shaft enclosing tubes, bearings), required rigging equipment (e.g., crane, straps, chains, wire cables), and required drawings are on site.
- Submittals from the pump manufacturer should include requirements to have a two-plane dynamic balancing of impeller at rated operating speeds and at 110% of that speed.
- The pump manufacturer should provide shipping information on how to remove and install the pump. They should also provide information on supporting or bracing of the pump enclosing tube, especially at bearing locations if being shipped completely assembled and ready for installation at the construction site. This is to ensure that the construction shaft does not bend, and the bearings are not damaged.
- After reviewing and approving the shop drawings, the next phase is to do a model and/or prototype test for the pumps and factory testing and inspections for other station equipment.
- Submittals for factory testing plans and test reports are key to the process of commissioning a pump station. On large projects, stipulating the constructor maintain an updated schedule for anticipated testing dates may assist in avoiding conflicts and concerns.
- As construction progresses and the constructor begins integrating systems, questions about design intent, functionality, possible issues, or optional ways of implementing items will likely result in constructor requests for information. The response process is

often the early stage of working out issues that will arise in the commissioning process. Maintaining organized records of requests for information resolutions will likely have an impact on O&M documentation or record drawings.

6.9 Instrumentation

As discussed in **Chapter 7**, instrumentation and monitoring is necessary for understanding the levee behavior during construction and validating design assumptions during construction. The installation of an instrument is not a routine task and requires attention to detail. Poor installation of instruments can lead to erroneous data or even adversely affect the levee. Methods of installation depend on the parameter to be monitored, site conditions, and the type of instrument. Successful installation of an instrument requires the labor of qualified personnel. Geotechnical Instrumentation for Monitoring Field Performance (Dunnicliff, 1993, chap. 17) provides a good overview of installation procedures for geotechnical instruments, most of which have applications for embankments. The Bureau of Reclamation Water Measurement Manual discusses requirements for various water flow measurement devices.

If instrumentation installation is required as part of the levee construction, the design documents should include the following items:

- Purpose of each individual instrument.
- Instrumentation system performance criteria.
- Qualifications of the instrumentation installation personnel.
- Quality control and assurance requirements.
- Submittals required.
- Materials (provide a detailed description of all types of instruments included in the contract, including spare parts commonly stocked).
- Factory calibration requirements.
- Pre-installation acceptance tests.
- Verification of instrument function (including raw and reduced data collection retrieval and sample output submittal).
- Installation instructions (providing a detailed step-by-step procedure to install each type of instrument).

Installed instrumentation casings, tubes, and cables should not significantly alter the mechanical properties of the levee features or provide seepage pathways. If significant embankment or foundation deformation is expected, installation of an instrument should prevent damage to elements such as pipes, tubes, and cables. Detailed information on best practices for installing instrumentation is provided in EM 1110-2-1908 (USACE, 2020a). In general, the following are construction considerations for instrumentation:

- Ensure compatibility between the diameter of the borehole and any minimum and maximum diameter requirements of the instrument.
- Establish conventions for instrument naming, field labeling, and borehole logging.

- Ensure instrument components are handled properly prior to installation to avoid damage.
- Perform pre-installation acceptance tests at the project site before an instrument is installed.
- Test the instrumentation after installation to ensure they are functioning correctly.

After completion of the instrument installation, a report should be prepared documenting the pertinent information regarding the instrument's installation. This information should be included in the project documentation at levee construction closeout.

7 Managing Risks During Construction

There are two types of risks that should be managed during construction:

- Construction risk: Cost, schedule, and worker safety and construction quality.
- Flood risk: Flooding of the construction site or leveed area.

Rigor of managing risks during construction should be commensurate with the levee risk. For higher risk levees, managing risk during construction may consist of preparing a risk register, adhering to a construction emergency action plan, tracking risks throughout the construction period, and providing temporary flood protection during construction to maintain the current level of flood risk reduction. For lower risk levees, a less detailed risk register and emergency action plan may be sufficient.

7.1 Construction Risk

Levee construction requires interpreting and complying with governing laws and regulations; gathering considerable resources (e.g., labor, equipment, and materials); and communicating and coordinating with multiple parties (e.g., owner, designer, prime and sub-contractors, suppliers). These factors—in addition to other unknown conditions such as poor site conditions and weather—exposes the constructor, designer, owner, and public to possible loss (i.e., construction risk). All levee construction projects have some degree of construction risk. Identification and management of construction risk is prudent for successful levee construction and occurs when preparing for levee construction.

Levee construction risks may include:

- Unforeseen/unknown environmental (encountering rare or endangered species), cultural (tribal artifacts), or geotechnical conditions (poor foundation soils) affecting the project schedule or requiring costly design changes. Unforeseen conditions may even make a project unbuildable.
- Changes in costs or availability of construction materials.
- Life safety (e.g., excavation and trenching, near or over water work, working around heavy equipment).
- Releases of hazardous or toxic materials to the environment.

- Positive connection of levee embankment to hardened structures (e.g., floodwalls, bridge abutments, natural ground).

Depending on the levee project, construction risks identified either need to be avoided, mitigated, or managed. New levee and modification construction projects with significant financial investment (greater than $5 million) or potential for life loss and significant economic, environmental, infrastructure damages due to poor project performance, should utilize a higher degree of construction risk management. New levee and modification construction projects with no life loss or economic damage may utilize a lesser degree of construction risk management. Generally, repairs including breach and emergency repairs also utilize a lesser degree of construction risk management.

7.1.1 Risk Register

The degree to which construction risks are managed are measured by how much effort is put into the identification of construction risks and the mitigation or avoidance of those risks. For higher degrees of construction risk management, a **risk register** is often used to document all identified construction risks for the project, along with mitigation actions, costs, and responsibilities. The register is a living document created by the full project team and updated as the project progresses. A sample risk register is shown in Table 8-14.

Table 8-14: Sample Risk Register

No.	Risk Description	L	C	R	Risk Mitigation	Residual Risk		
						L	C	R
1	Lack of suitable soil borrow	Med	High	High	Ensure availability of 200% of suitable barrier.	Low	Low	Acceptable
2	Lack of site access	Low	High	Med	Clear property access routes before the contract is awarded.	Low	Low	Acceptable
3	Availability of needed mechanical/ electrical components: gates, valves, and supervisory control and data acquisition	High	High	High	Levee owner preorders necessary items with a long delivery lead time.	Low	Low	Acceptable
4	Changed foundation conditions	Med	High	High	Perform additional geotechnical investigations to reduce data gaps.	Med	Med	Med

No.	Risk Description	L	C	R	Risk Mitigation	Residual Risk		
						L	C	R
5	Worker safety on water construction	Med	High	High	Develop an enhanced project Health and Safety Plan.	Med	Med	Acceptable

Notes to table:
L = Likelihood, C = Consequence, R = Magnitude of Risk

For levee projects that can utilize a lesser degree of construction risk management, a risk register is typically not used and most construction risk are avoided or accepted.

Levee construction may involve work close to or over water. Flooding of the construction site or borrow areas can occur due to high river levels, coastal storm, or tidal events occur during construction. This could damage ongoing work, make the site unpassable, delay work, or change design conditions requiring a construction modification. These risks should be identified and mitigated.

7.1.2 Risk Workshop

Larger, more complex or risky projects may include risk workshops to understand risks and develop mitigation strategies, and to document conclusions in a risk register. These workshops should be attended by the project team members, including the levee owner, design engineer, construction manager, constructor, and sometimes regulators or other entities. Identifying risks, developing and updating the risk register, and assigning actions to mitigate risks are the main functions of the risk workshop.

7.1.3 Test Sections

A test section in construction is an area where specific construction materials, equipment, and/or procedures are evaluated or tested against construction requirements. To minimize construction risk and improve the quality of the levee design, test sections may be used to provide important information on what materials, means, and methods will best deliver the construction project. Test sections are often performed prior to the commencement of the full project so that the information can be utilized appropriately. Test sections are helpful on large projects, where there is a high degree of uncertainty in the levee design, or where unconventional construction materials, means, or methods are being considered.

7.2 Managing Flood Risks During Construction

To mitigate flood risk to leveed areas during construction, temporary flood protection measures should be identified as required, particularly when constructing a levee modification or rehabilitation. Temporary flood protection measures are generally not required for new levee construction.

A plan for temporary flood protection measures should be prepared during project formulation and design, as discussed in **Chapters 6 and 7**. Temporary flood protection measures provided during construction can include physical, temporary flood protection features, and emergency action preparedness and planning. The temporary flood protection measures should be identified in the risk register and highlight risks within the construction site, including life safety, potential economic losses, and environmental risks.

The simplest temporary flood protection measure is to perform the work during a period when high water events are extremely unlikely or will have reduced potential water levels. In many parts of the U.S., high water occurs seasonally, and construction windows can be specified with low likelihood of high water during that time frame. However, coastal and riverine construction affected by tidal changes should be considered in planning the project. Contract documents should clearly state the required construction periods and what work is allowable outside that time frame.

In some situations, physical temporary flood protection measures are necessary. Examples of these measures include earthen berms, water fillable tubes, and/or manufactured waterproof bulkheads. In areas of potentially high consequences, updating or preparing a construction-specific emergency action plan may be appropriate to be prepared in the event a flood occurs during construction. The plan should include known weaknesses, triggering criteria, communication protocols, required actions, and responsible individuals.

8 Summary

Levee construction is a vital step in ensuring objectives of a levee are met. Levee construction occurs when there is physical building of a new levee feature or existing levee feature that is being modified or rehabilitated.

Success of levee construction relies on proper preparation, execution, and closeout of construction activities. All levee construction projects have some degree of construction risk. Identification and management of construction risk is also prudent for successful levee construction.

Key elements of proper preparation for levee construction includes:

- Incorporating levee project constraints into levee construction.
- Ensuring the levee project is constructable.
- Preparing documents for levee construction.
- Selecting a levee constructor.

Key elements of proper execution of levee construction includes:

- Developing a construction plan.
- Ensuring desired quality of levee construction is achieved.
- Coordinating and communicating during construction.
- Managing construction data.

At levee construction closeout, the levee construction project is evaluated to ensure the levee project meets the design intent prior to placing the levee into operation. Any deficiencies noted during this evaluation should be documented and addressed. Finalizing the project documentation at construction closeout is also completed to support effective levee operation and maintenance.

Related content associated with this chapter is included in detail in other chapters of the National Levee Safety Guidelines as described in Table 8-15.

Table 8-15: Related Content

Chapter 8 – Related Content

Chapter	Chapter Title	Related Content
1	Managing Flood Risk	
2	Understanding Levee Fundamentals	• Levee form and function • Types of levee projects
3	Engaging Communities	• Engaging for levee projects
4	Estimating Levee Risk	• Conducting risk assessments
5	Managing Levee Risk	• Levee risk management
6	Formulating a Levee Project	• Site specific considerations • Plan formulation • Site characterization
7	Designing a Levee	• Instrumentation and monitoring • Levee design considerations
8	Constructing a Levee	
9	Operating and Maintaining a Levee	• O&M manual • Inspections and monitoring • Flood preparedness
10	Managing Levee Emergencies	
11	Reconnecting the Floodplain	• Levee removal construction
12	Enhancing Community Resilience	

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9

Operating and Maintaining a Levee

Key Messages

This chapter will enable the reader to:

- **Tailor actions.** Each levee is unique; therefore, operations and maintenance (O&M) activities should be scaled and scoped appropriately.
- **Practice regular O&M.** Regular O&M prevents normal deterioration from turning into a breach scenario.
- **Manage levee data.** Data management is critical to understanding and making informed decisions about a levee.
- **Promote staff expertise.** An understanding of the goals and activities related to O&M is required for optimal operation.


LEVEETOWN, USA

Other chapters within the National Levee Safety Guidelines contain more detailed information on certain topics that have an impact on operating and maintaining a levee, as shown in Figure 9-1. Elements of those chapters were considered and referenced in the development of this chapter and should be referred to for additional content.

Figure 9-1: Related Chapter Content

CH 1	CH 2	CH 3	CH 4
	Levee functions, features, forms, and lifecycle	Engaging communities about levees Engagement for levee-related activities	Guidance for estimating and portraying levee risk
CH 5	**CH 6**	**CH 7**	**CH 8**
Levee risk management Risk-informed decision making	Understanding levee projects at various phases of the lifecycle Developing a vegetation management strategy	Levee design considerations Modification/ rehabilitation of existing levees	
CH 9	**CH 10**	**CH 11**	**CH 12**
Operating and Maintaining a Levee	Levee emergency preparedness Emergency management and response		

Contents

1 Introduction 9-1
2 Accomplishing Operations and Maintenance 9-1
2.1 Setting O&M Objectives 9-3
2.2 Developing and Updating the Levee O&M Manual 9-4
2.3 Establishing the Access Corridor 9-6
2.4 Implementing a Vegetation Management Strategy 9-7
2.5 Applying Risk to O&M Strategies 9-8
2.5.1 Risk-Informed O&M Strategy 9-8
2.5.2 Prioritization of Levee Risk Management Actions 9-9
2.6 Ensuring Staffing and Resources 9-10
2.6.1 O&M Staff Training 9-10
2.6.2 Outside Expertise 9-10
2.6.3 Establishing an O&M Budget 9-11
2.7 Conducting Inspections 9-11
2.7.1 Conducting Inspections 9-12
2.7.2 Managing Routine Inspections 9-14
2.7.3 Managing Flood-Related Inspections 9-16
2.7.4 Managing Event-Driven Inspections 9-18
2.7.5 Managing Inspections to Inform Maintenance and Repairs 9-20
2.8 Implementing Monitoring 9-21
2.8.1 Levee Instrumentation Monitoring 9-21
2.8.2 Hydrologic and Hydraulic Conditions 9-22
2.8.3 Weather and Storm Forecasts 9-22
2.9 Managing Maintenance 9-23
2.10 Executing Operations 9-25
2.11 Utilizing Levee Knowledge and Managing Data 9-26
2.12 Sharing Levee Information 9-29
2.13 Providing Security 9-30
3 Implementing Operations and Maintenance 9-30
3.1 Embankment 9-33
3.1.1 Inspection and Maintenance 9-33
3.1.2 Operations 9-51
3.2 Floodwalls 9-51
3.2.1 Inspection and Maintenance 9-51
3.2.2 Operations 9-56

3.3 Closure Structures 9-57
3.3.1 Inspection and Maintenance 9-57
3.3.2 Operations 9-61
3.4 Transitions 9-62
3.4.1 Inspection and Maintenance 9-62
3.4.2 Operation 9-63
3.5 Seepage Control Features 9-63
3.5.1 Inspection and Maintenance 9-64
3.5.2 Operations 9-67
3.6 Channels and Floodways 9-67
3.6.1 Inspection and Maintenance 9-67
3.6.2 Operations 9-68
3.7 Interior Drainage Systems 9-68
3.7.1 Inspection and Maintenance 9-68
3.7.2 Operations 9-85
3.7.3 Abandoning Penetrations 9-86
3.8 Pump Stations 9-86
3.8.1 Inspections, Test Operations, and Maintenance 9-87
3.8.2 Pump Operations 9-92
3.9 Instrumentation 9-92
3.9.1 Inspection and Maintenance 9-93
3.9.2 Data Collection for Levee Monitoring 9-95
4 Managing Other Impacts to the Levee 9-96
4.1 Right of Way 9-96
4.2 Encroachments and Permitted Activities 9-97
4.3 Utility Penetrations—Pipes, Conduits, and Culverts 9-101
4.4 Channel Changes 9-103
5 Preparing for Floods 9-104
5.1 Advanced Preparations 9-104
5.2 Flood Response Activities 9-105
6 Summary 9-105

List of Figures

Figure 9-1: Related Chapter Content 9-i
Figure 9-2: Typical O&M Activities 9-3
Figure 9-3: Typical Access Corridors for Earthen Embankments 9-7

Figure 9-4: Trained Staff Inspecting Levees 9-13
Figure 9-5: Examples of Levee Maintenance Conditions 9-25
Figure 9-6: Earthen Embankment Cross Section 9-33
Figure 9-7: Typical Levee Embankment Deficiencies 9-34
Figure 9-8: Examples of Embankment Slope Sloughs 9-35
Figure 9-9: Examples of Embankment Slope Slides 9-36
Figure 9-10: Example of Tension Cracks 9-36
Figure 9-11: Example of Desiccation Crack 9-37
Figure 9-12: Examples of Levee Erosion 9-38
Figure 9-13: Examples of Seepage and Internal Erosion 9-40
Figure 9-14: Example of Localized Crown Settlement 9-41
Figure 9-15: Examples of Damaged Sod 9-44
Figure 9-16: Examples of Damaged Slope and Bank Erosion Protection 9-45
Figure 9-17: Examples of Levee Roads Needing Repair 9-47
Figure 9-18: Burrowing Animal Tunnels Impacting a Levee 9-48
Figure 9-19: Example of Animal Burrows Leading to Levee Breach 9-49
Figure 9-20: Typical Floodwall Damages 9-52
Figure 9-21: Examples of Floodwall Damage 9-52
Figure 9-22: Vegetation Impacting Floodwalls 9-55
Figure 9-23: Examples of Movable Gate Inspection Observations 9-58
Figure 9-24: Examples of Structural Assembled Closure Inspection Observations 9-59
Figure 9-25: Examples of Closure Component Storage 9-60
Figure 9-26: Examples of Transition Zone Damage 9-63
Figure 9-27: Examples of Vegetation and Debris Blocking Drainage 9-70
Figure 9-28: Gravity Pipe-Associated Concerns 9-71
Figure 9-29: Examples of Pipe Problems 9-73
Figure 9-30: Concrete Headwall Conditions 9-77
Figure 9-31: Examples of Sluice Gate Scale and Conditions 9-79
Figure 9-32: Examples of Flap Gate Condition 9-80
Figure 9-33: Examples of Duckbill Valve Scale and Condition 9-81
Figure 9-34: Manhole Inspection 9-82
Figure 9-35: Examples of Drainage Ditch Conditions 9-84
Figure 9-36: Examples of Pump Station Scale and Conditions 9-87
Figure 9-37: Examples of Pump Station Trash Racks 9-90
Figure 9-38: Example of Displacement Measuring Device 9-95
Figure 9-39: Example of Encroachments 9-98

List of Tables

Table 9-1: Non-Flood Event-Driven Inspection Examples 9-19

Table 9-2: Examples of Levee Instrumentation 9-21
Table 9-3: O&M-Related Data 9-27
Table 9-4: List of Items and Issues to be Checked During an Inspection 9-31
Table 9-5: Inspection and Maintenance of Slope and Bank Erosion Protection 9-45
Table 9-6: Examples of Adverse Effects of Encroachments 9-98
Table 9-7: Related Content 9-107

1 Introduction

Operations and maintenance (O&M) includes all activities required for the levee to function as intended. Effective O&M of a levee is key to achieving the flood risk reduction benefits the community receives from the levee. O&M is an integral part of levee management. Seemingly minor maintenance concerns can escalate if left unchecked, raising the cost of the necessary repairs and rehabilitation, or placing property or life at risk. For instance, small areas of erosion can quickly worsen to compromise the levee's integrity if left unrepaired, potentially leading to a breach during a flood. Animal burrows left unaddressed may accelerate seepage, compromising levee integrity. Without regular operation, lubrication, and corrosion prevention, metal gates may fail to close during a flood.

In this chapter, levee O&M best practices are discussed first, followed by best practices for O&M activities. Inspection, maintenance, and operation of levee features by properly trained individuals helps assure a levee can reduce flood risks as designed. Best practices for O&M activities are presented by levee feature, with reference to the potential failure modes relevant to each. The chapter also covers other considerations such as encroachments and flood preparedness.

These guidelines are intended for levee owner/operators, and others with responsibility for operating and maintaining levees. They may also be helpful for local officials, communities, private sector professionals, as well as federal, state, territory, regional, tribal, and local agencies to better understand the issues for ongoing maintenance of levees in their communities.

Experienced levee owner/operators who have detailed knowledge of their own levees and requirements may find new practices or considerations in these guidelines, which could help increase resilience and adjust to climate-driven changes to improve current practices.

For community members and decision makers, this chapter provides an overview of the critical importance of levee O&M within their community, and the intricacies required to maintain levee integrity. Without a clear understanding of the requirements of a levee, community members and decision makers may be unable to fully appreciate the flood risk reduction benefits provided by the levee.

2 Accomplishing Operations and Maintenance

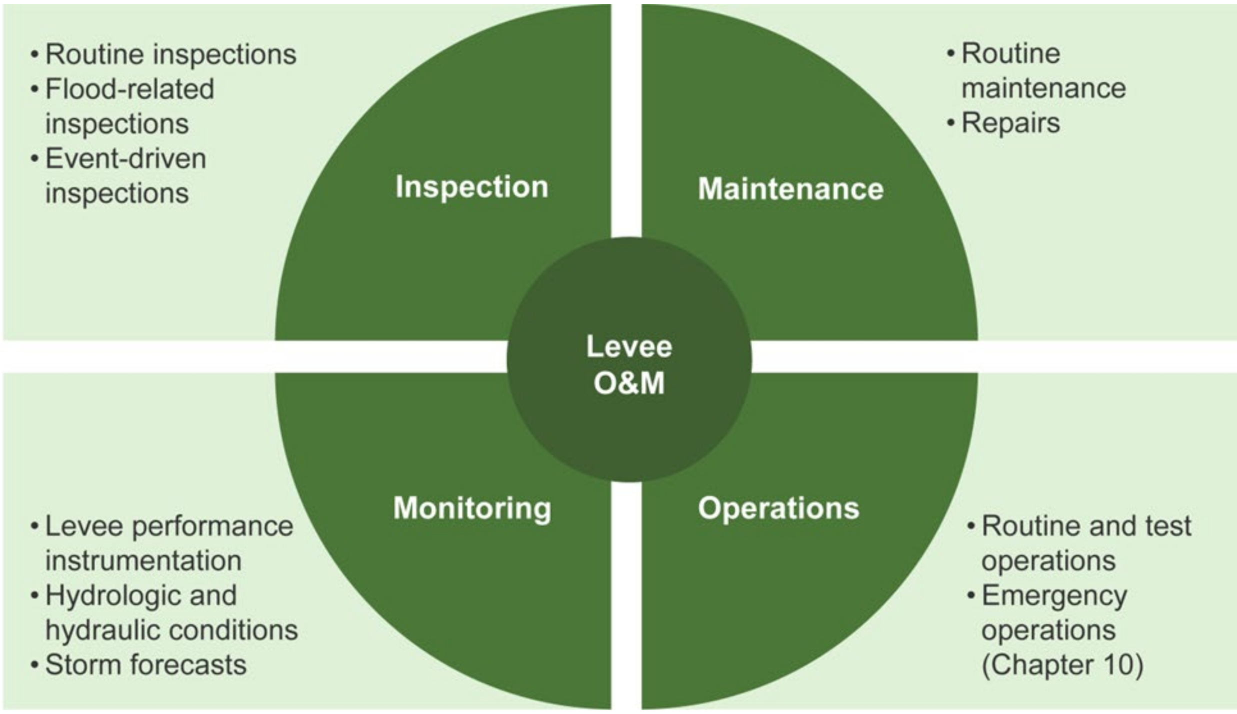
Having a strategy to guide O&M activities provides consistency in activities over time. It can also identify strengths and weaknesses of approaches to O&M that may be beneficial to sustain or adjust. A well-documented strategy can support development and defense of budgets and funding requests. It can be an effective way to educate others on O&M responsibilities and transfer knowledge.

An O&M strategy defines, schedules, and staffs all the necessary activities to maintain long-term integrity of the levee. Effective levee management ensures the following activities occur:

- Monitoring and inspection:
  - Regular inspections of levee features.
  - Regular monitoring of instruments, hydrologic/hydraulic conditions (such as river stage or coastal wave heights), and weather forecasts for large events (from droughts to hurricanes).
- Scheduling:
  - Schedule maintenance and repairs, as needed.
  - Schedule operations or tests of levee features, as needed.
- Preparedness:
  - Flood and emergency preparedness.
  - O&M staff training.
  - Share information regarding levee conditions and potential issues with local officials or others with flood risk management responsibilities (**Chapter 3**).
- Data management and risk evaluation:
  - Perform reporting, data management, and record keeping. Have records from O&M activities available for regular risk assessment updates, risk management, rehabilitation and repair, emergency preparedness, emergency response, and monitoring.
  - Use engineering evaluations and risk assessments (**Chapters 4 and 5**) to inform actions beyond the scope of O&M, such as levee rehabilitation or feature replacement.

The day-to-day management of a levee includes providing for, overseeing, and following up on inspections, maintenance, monitoring, and operations (Figure 9-2). These O&M activities are reoccurring independent tasks that inform each other. When these routine activities identify significant issues, community engagement, risk assessment, and risk management may be required to communicate the issue and identify appropriate solutions that may be outside the scope of O&M.

Figure 9-2: Typical O&M Activities



This section provides an overview of the necessary administrative tasks, including:

- Setting O&M goals and objectives.
- Developing and updating the levee O&M manual.
- Establishing an access corridor.
- Implementing a vegetation management plan.
- Determining the appropriate scope, frequency, and rigor of activities and prioritizing actions based on risk.
- Ensuring tasks are appropriately staffed and resourced.
- Managing inspections, monitoring, maintenance, and operations.
- Using levee knowledge and managing levee data.
- Providing security.

2.1 Setting O&M Objectives

Objectives can help provide structure and focus to the many activities that are required for O&M. Useful objectives are based on unique considerations of the levee and the community to which it provides flood risk reduction benefits. Objectives should prioritize achieving flood risk management benefits first, and secondarily address additional community goals, such as recreation or transportation benefits.

Typical objectives of levee management include:

- Operate and maintain the levee to ensure long-term integrity.
- Train staff to competently handle inspections, maintenance, monitoring, operations, and emergency response.
- Manage and prioritize O&M, rehabilitation, and replacement costs within risk-informed budgets and schedules.
- Ensure partnering and/or community obligations are met.
- Allow for additional community and environmental considerations without compromising the primary flood risk reduction purpose, including:
  - Support transportation, utilities, and recreation.
  - Maintain the levees to protect, restore, and enhance environmental resources.

2.2 Developing and Updating the Levee O&M Manual

The levee **O&M manual** is a customized document which describes specific tasks to ensure the reliability and durability of a levee, and the methods and resources to be used. It is a best practice to define a levee's O&M procedures and document them in an O&M manual during the levee design phase and to create an O&M manual for any existing levee that does not have one. The levee O&M manual is considered a 'living' document to be updated as necessary when changes, improvements, or any modifications are made to the levee.

The O&M manual provides context regarding the purpose of the levee and the various activities and tasks that will be detailed, as well as administrative information pertinent to levee management. This includes the following information:

- Responsibilities and contact information for the levee owner/operator, O&M staff, and others with a role in the levee.
- Levee description and location including:
  - The location of the levee and all levee features, preferably with coordinates and corresponding digital geographic information systems (GIS) records.
  - A written description of the levee with a map.
  - Specific concerns or areas for heightened scrutiny.
- Levee design information, including:
  - Record drawings updated with modifications or observations noted in the field during construction.
  - References to applicable engineering standards. It is best not to duplicate standards in the manual in order to reduce the need to revise the manual with every update to the standard(s).
  - Manufacturer's specifications for equipment and structures, and a list of authorized products (e.g., seeding mixtures, concrete, riprap types).

  - Legal requirements concerning maintenance.
- Processes for addressing issues beyond the scope of O&M including:
  - Appropriate interventions (interim risk reduction measures).
  - Process for tracking and prioritizing longer term actions.
- Environmental considerations that affect O&M practices and timing, such as restrictions to accommodate nesting habitat for migratory birds or habitat for other threatened or endangered species.
- Flood response processes, including water level triggers and staff responsibilities (sections 2.7.3 and 2.10).

The O&M manual defines the tasks associated with inspections, monitoring, maintenance, repairs, and operations for each levee feature. The manual and the tasks within can be scaled to the size, complexity, and risk considerations of the levee. The levee design, construction documentation, and risk assessment for the levee will contribute to the identification of O&M tasks and their scale. A complete O&M manual provides:

- Task frequency and timing, including triggering conditions if activity is condition-based.
- Identification of appropriate type of staff for each task including specific qualifications and applicable training requirements.
- A step-by-step description of the task, including practices to avoid and equipment requirements.
- Where the task is located—the portion of levee or the features involved in the task—with their location and method of access, if needed.
- Task-related concerns, including relevant history of problem areas, known environmental concerns (such as the presence of a listed species), social concerns (such as levee use by the public), or safety concerns (such as mowing steep slopes), and measures to be taken to address these concerns.
- Task documentation methods and data tracking methods.

The level of detail included in the O&M manual for some of these items may vary by the complexity of the task and the levee risk.

The accuracy and usefulness of the levee's O&M manual can be improved by updating it after the first maintenance cycle is completed for a new levee, in response to levee modifications, or if the results of risk assessment or other levee evaluation indicates new concerns or provides recommendations for new methods for maintenance, operation, monitoring, or inspection. The manual may also be improved by updates when there are changes in regulations, policies, technology, or funding. There may be local, state, tribal, or national laws and regulations to consider when creating or updating an O&M manual.

A wide range of factors can shift flood risk and levee risk, in ways that are both regionally specific and rapidly increasing. Many existing levees were designed and built under the expectation that both regional weather and flood patterns, and regional development intensity, would be relatively stable. As those expectations are challenged, levees need more careful monitoring in anticipation of, during, and following rare events driven by climate change. Changes in human-driven development within the watershed—especially in the leveed area—may likewise impact regional water patterns. In addition, updating the monitoring, inspection, and emergency response strategies are necessary reactions to significant changes.

EXAMPLES OF FACTORS THAT CAN SHIFT FLOOD AND LEVEE RISK THAT MAY REQUIRE CHANGES TO O&M

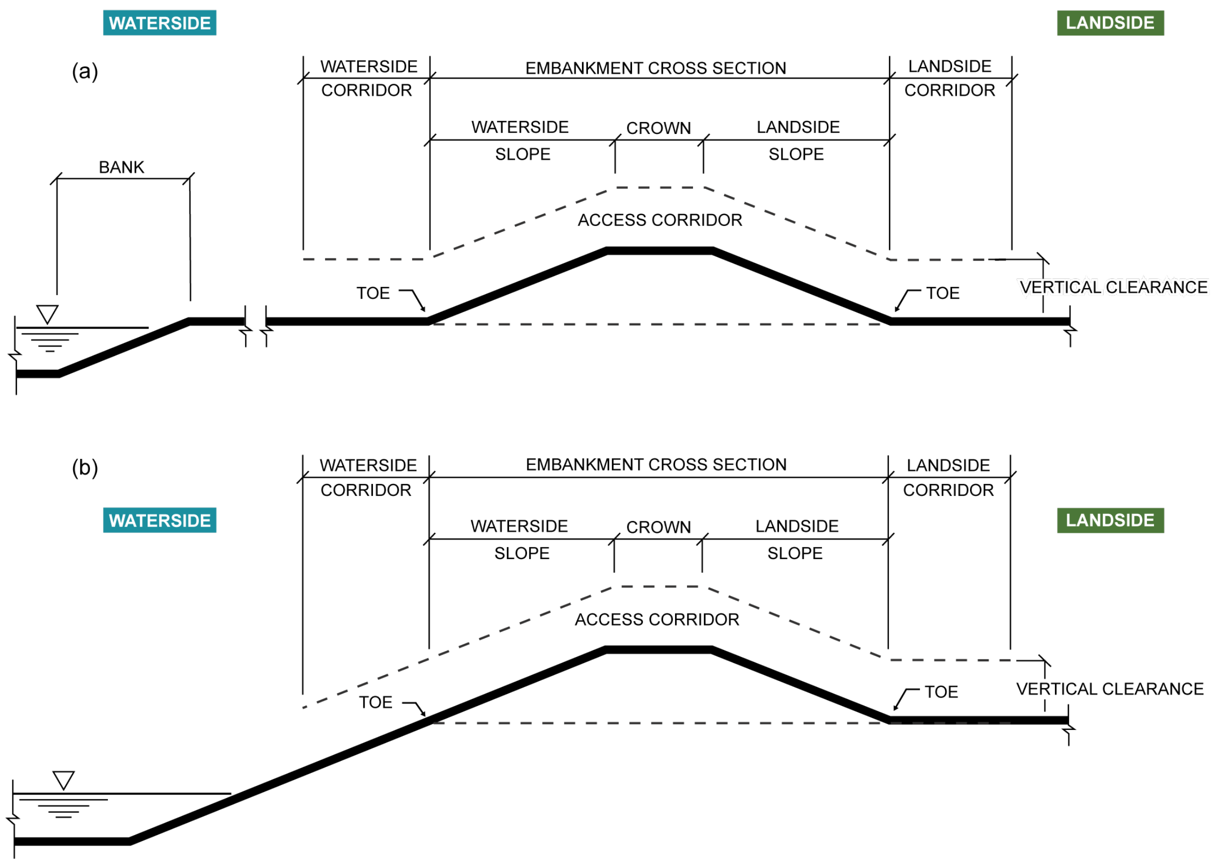
- **Larger or more frequent floods**: Flood size and/or frequency is increasing in most regions of the United States, due to some or a combination of annual increased precipitation, wetter, slower-moving storms with record-breaking rainfall, a shift towards rain rather than snow, and/or more rapid snow melt events. In addition to larger floods, there may be more frequent loading of coastal and riverine levees and levee features—including earthen embankments and floodwalls—which may cause them to experience cumulative damage or deterioration.
- **Shifting flood seasonality**: Inspections scheduled to capture certain expected drainage flow volumes may be misaligned with changing regional conditions. Inspection and monitoring plans with defined seasonal components (such as inspecting interior drainage systems during a wet season) should be reviewed and adjusted periodically.
- **Shifting coastal and riverine morphology:** Larger storms and changing wave and flow patterns may drive sudden, large-scale erosive events, or longer-term shifts in riverbanks and coastlines. Waterside erosive impacts to headwalls, gates, pipes, and embankment integrity may be experienced under higher erosion conditions. An increased frequency of inspection and monitoring may be needed.
- **Increasing riverine or coastal water elevations, either periodic or permanent**: As sea level and some river levels rise, levees will experience increased waterside loading, and backflow of water through gravity drainage structures into low-lying leveed areas. Additional inspections and maintenance may be needed in regions where impacts are suspected. Temporary maintenance solutions may include installing backflow prevention (sandbags, flap or duckbill valves, or similar structures appropriate to specific levee conditions). Coastal levee monitoring should include annual checks of the highest high tide forecasts (including El Niño events and other current-related tide elevating processes).
- **Increased groundwater salinity in coastal regions**: As seas rise, coastal regions are experiencing increased surface and groundwater salinity. Increased corrosion of buried or exposed metal and concrete in estuaries and coastal rivers may drive a need for more frequent maintenance to prevent salinity damage.
- **Extreme non-flood weather events such as high winds and wildfires**: Many regions are experiencing an increase in the intensity and frequency of weather events including wildfires, wind, heat, and draught. Where draught is increasing, a decrease in soil strength due to desiccation should be considered in levee embankments, particularly embankments composed of clay, peat, and silt. Where heat is increasing, adjustments to planting palettes of levee vegetation may be necessary to maintain appropriate vegetation cover. Where strong winds, wildfires, or power outages are possible, inspection plans should be adjusted to ensure rapid inspection of electrical components, gates and pumps, and other weather-vulnerable components immediately following such events. Alternative sources of power for electrically powered levee features should be planned in the event a power outage happens concurrently with a flood.

2.3 Establishing the Access Corridor

To allow and guide O&M activities, it is important to establish an access corridor that defines the space within which levee activities are typically contained. **Access corridors** are needed (1) for maintenance, inspection, and floodfighting; (2) to provide additional room to improve the levee in the future; and (3) to prevent excavations and encroachments that might negatively impact the levee.

The best practice is to establish the corridor dimensions specific to the levee considering the levee risk reduction and co-benefits objectives. For example, flexibility in the dimension of the waterside corridor may be necessary to allow for ecological co-benefits. Figure 9-3 depicts the zones of an access corridor for an earthen embankment. Example (a) in represents a levee which is set back from the bank of the flood source. Example (b) represents a levee which is not set back from the bank. The access corridor for the levee would ideally be established during levee design and construction; however, if there are gaps in the access corridor for an existing levee, addressing these gaps is important to ensure that the entire levee can be properly operated and maintained. These corridors can be used to support the vegetation management strategy for a given levee, further discussed in section 2.4.

Figure 9-3: Typical Access Corridors for Earthen Embankments



(a) A levee which is set back from the bank of the flood source. (b) A levee which is not set back from the bank.

2.4 Implementing a Vegetation Management Strategy

A vegetation management strategy is a plan for managing vegetation on levees developed to prevent vegetation from having a negative impact on the levee. Vegetation management strategies are typically developed during levee design. However, in cases where woody vegetation exists on or near a levee without a plan in place, a vegetation management strategy should be developed and integrated into the O&M manual. A vegetation management strategy could be as simple as mowing all vegetation within the access corridor periodically or it may consist of many specific practices to meet maintenance goals.

Traditionally, sod has been used to vegetate levees and the use of other vegetation types has been discouraged; however, a better understanding of how vegetation impacts levees has resulted in a broader range of acceptable options for levee owners. It is now understood that while trees can contribute to the progression of already existing potential failure modes such as waterside erosion, overtopping, and internal erosion, they are not generally the primary factor that drives levee breach. Provided vegetation is included in a robust levee design effort and the impacts of vegetation on the levee are fully considered in a supporting risk assessment; trees, shrubs, and herbaceous plants may be considered as a part of a levee's vegetation management strategy. Vegetation management strategies can be developed to reflect the experience and preferences of the levee owner and the ecological characteristics and needs of the levee's environment. For example, native vegetation waterside of the levee can provide ecological benefits and induce minimal risk. Additional information on the development of a vegetation strategy is included in **Chapter 6**.

Regardless of the types of vegetation included in a levee vegetation management strategy, the best practice for vegetation management on or around levees is to be intentional, deliberate, and adaptive. Unmanaged and unmonitored vegetation growth can have negative impacts on levee integrity.

Successful implementation of a vegetation management strategy requires ongoing monitoring and adaptation. Inspection and maintenance frequencies should reflect the risk and uncertainty associated with the levee and its vegetation. Inspection observation and levee performance data can be used to make minor adjustments to the vegetation management strategy that improves efficiency or addresses minor issues. When inspection or performance data identifies significant concerns, the levee risk assessment should be updated and the results used to adjust the vegetation management strategy, as needed, to reflect the improved understanding of levee risk.

2.5 Applying Risk to O&M Strategies

2.5.1 Risk-Informed O&M Strategy

Many O&M activities and the degree to which they are managed should be commensurate with the levee risk. It is a best practice to determine the appropriate frequency and rigor of scalable O&M activities based on levee risk with higher risk levees receiving a high standard of care that ensures contributors to levee risk are being adequately identified, monitored, understood, and managed.

Risk can inform the focus, rigor, and frequency of many levee safety activities. Some of the O&M activities that can be scaled based on risk include staff training (section 2.6.1), inspections (section 2.7), levee monitoring (section 2.8), maintenance and repair actions (section 2.9), test operations (section 2.10), and levee security measures (section 2.12). Regardless of levee risk or complexity, management of the infrastructure is critical to maintaining levee condition.

2.5.2 Prioritization of Levee Risk Management Actions

It is a best practice for the O&M strategy to include a process for tracking necessary actions and setting priorities. In some cases, it may be necessary to defer maintenance and repair activities due to a lack of resources. In other cases, rehabilitation projects may require investments beyond the typical, annual O&M budget. In both cases, it is important that actions required to manage levee risk are tracked and prioritized based upon risk as described in **Chapter 5**.

The tracking and prioritization strategies that are most effective for managing risk address all identified levee risk management actions, both on and away from the levee. Actions on the levee are those that directly impact levee condition like maintenance, repair, and rehabilitation. Actions away from the levee are those that help to improve levee management or reduce possible consequences like developing and exercising emergency action plans and sharing levee information with stakeholders. Risk assessment and risk management are the best practice for evaluating levee risk and identifying and prioritizing the full range of risk management actions. See section 2.6.3 on establishing an O&M budget.

Flexibility in prioritizing work is important to address the dynamic nature of levee risk. Revisiting priorities after each inspection and risk assessment can help ensure all required actions are being tracked and that the prioritization reflects current levee condition and risk. Levee risks can change due to newly identified levee issues, such as flood or other damages, or when existing issues deteriorate making action to address them more urgent. In situations such as these, reassessing and possibly changing the prioritization of levee risk management actions can help ensure limited resources are targeted to effectively manage levee risk.

CONDITIONS THAT MAY REQUIRE REHABILITATION TO REMEDY

The following examples describe conditions that may need rehabilitation to remedy.

- **Unstable embankment slopes**: Unstable slopes indicate the earthen embankment loads are greater than the strengths of the underlying foundation soils. Unstable embankment slopes may result in a lower crown elevation or narrower crown width, which increases the likelihood of overtopping and throughseepage during floods.
- **Seepage and sand boils**: During a flood, excessive seepage leads to soft/saturated soils and the erosion of soil from within the levee or its foundation. Seepage, in conjunction with material transportation, can rapidly deteriorate the interior of a levee or levee foundation, resulting in a levee breach.
- **Rock and bedding material displacement**: Reoccurring rock or bedding material displacement during a flood may mean the rock erosion protection and bedding material are undersized for the flow velocity or wave attack.
- **Erosion along floodwalls and rock revetments**: Because of flow turbulence, erosion reoccurs along a floodwall or along the edges of rock revetments.
- **Damaged conduit within levee**: During a flood, subsidence is noted in the vicinity of a gravity pipe. Inspections post-flood reveal that the pipe has severely deteriorated and levee soils are being lost into the pipe.
- **Closure gates fail to open/close**: Closure gates that are not properly inspected, maintained, and operated may result in freezing/locking of the closure gate’s bearings or closure mechanism jamming.
- **Damaged floodwalls**: Floodwalls can be damaged from a single event such as a boat ramming into a floodwall or large/heavy debris in the river flowing into and impacting the floodwall.

2.6 Ensuring Staffing and Resources

Most levees are managed by organizations capable of hiring staff or managing volunteers to carry out operations and management activities. It is essential that O&M is adequately staffed to meet objectives, carry out routine tasks, and respond to emergencies. The number of staff and their qualification and training requirements should be determined based on levee complexity, features, and risk. Managing levee emergencies and further staffing concerns for emergency response is covered in **Chapter 10**.

It is a best practice for O&M staff to have qualifications commensurate with their assigned levels of responsibility and receive training to develop competency in O&M procedures. In many instances, levee O&M tasks can be performed satisfactorily by staff without formal expertise in engineering, geology, or related sciences. For some tasks, including some inspection and maintenance tasks, more formal expertise may be required.

2.6.1 O&M Staff Training

O&M staff should have sufficient training and experience to allow them to conduct inspections, recognize abnormal conditions, perform maintenance functions, implement flood preparedness and operation procedures, and appreciate the importance of their responsibilities. As a rule, training for levee staff should be commensurate with levee risk. Levee staff should understand the risk associated with the levee, including the consequences of a levee breach. Staff for levees that are likely to breach prior to overtopping should be trained to recognize and respond to risk driving potential failure modes, including pre-planned floodfighting actions and notification procedures.

Well prepared staff have both adequate training and written instructions for the O&M tasks under their responsibility, including procedures for monitoring performance, inspecting levee features, identifying encroachments, and reporting abnormal conditions. Periodic staff evaluations help ensure they understand all requirements and can perform their assigned tasks satisfactorily. Safety training commensurate with task risks and all local, state, tribal, and federal laws is important to the welfare of levee staff.

2.6.2 Outside Expertise

Occasionally, there will be a need for activities that are beyond the expertise of available staff or that require specialized equipment. This may occur when there is a need for interior inspections of pipes, relief wells, or toe drains or for pump testing relief wells. This situation can also occur when there is a need for actions that are outside the scope of O&M, such as geotechnical or hydraulic engineering assessments or design; rehabilitation or replacement of levee features; or installation of instrumentation. In these cases, it may be necessary to:

- Train existing staff.
- Procure specialized inspection or testing equipment.
- Reach out to specialized staff elsewhere within the organization (often not applicable for smaller organizations).
- Reach out to specialized staff among the community or stakeholders.

- Contract a specialized firm for the necessary tasks.

When outside personnel are required, it is important that they be technically qualified and experienced in the operation, maintenance, and inspection of the levee or particular feature with which they are working. They will need access to, and to become familiar with, all pertinent documentation, especially the O&M history and procedures of the levee or relevant feature. Having regular O&M staff present for activities on the levee which involve outside personnel can make sure outside staff have adequate support and keep O&M staff aware of outcomes and findings.

2.6.3 Establishing an O&M Budget

Proper levee O&M requires financial means to facilitate the day-to-day management of the levee and the associated activities for inspections, maintenance, monitoring, and operations. Budgets also need to account for periodic increased expenses, such as the replacement of more expensive components like pumps, motors, gates, and pipes as they age and come to the end of their design life. Understanding the funding requirements for both short- and long-term needs—and proper budgeting to account for those requirements—is a best practice for sustaining levee integrity.

Each levee is unique and therefore the O&M budget will be unique for each system. O&M budgets will be informed by:

- The tasks and frequencies identified in the levee O&M manual including required personnel, materials, and equipment.
- The type and age of the levee features and components.
- Increased costs of fuel and other resources due to inflation.
- Increased operational needs due to shifts in leveed area development or climate patterns.

O&M budgets should also account for activities that are outside the scope of O&M, such as rehabilitation or replacement. When the need for these actions arise, long-term budgeting and prioritization can be helpful, as described in section 2.5.2.

2.7 Conducting Inspections

Inspections are the visual observation and documentation of physical condition and operability of the levee. Inspections often include operation of mechanical features such as pumps or gates to fully assess operability. Inspections are key to understanding levee conditions, including the type, location, and severity of deterioration or distress. Thorough levee inspections provide sufficient details to answer the following questions:

- What is the current condition of the levee and how is it changing over time?
- Are current maintenance processes and frequencies adequate?
- How has the levee responded to current or previous loadings?
- Are repairs needed?

- Are there issues or damages that could impact the levee's ability to perform as intended during the next flood?

Inspections can be categorized into three types; each with different goals related to different conditions on the levee:

- Routine inspections: Inspections that are pre-scheduled to occur on a repeating, regular basis to verify O&M and monitor levee health.
- Flood-related inspections: Inspections that occur prior to, during, or immediately after flood loading to document performance, identify the need for emergency response activities, and/or inform maintenance, repair, and rehabilitation needs.
- Event-driven inspections: Inspections that occur in response to an unexpected occurrence or disturbance that is not flood-related to identify the need for emergency response activities, and/or inform maintenance, repair, and rehabilitation needs.

In addition to the above inspections, performing informal visual observations of conditions on the entire levee on at least an annual basis is vital to inform maintenance and repair activities. In addition to planned inspections, visual observations of levee conditions occur during O&M activities, such as mowing the levee grasses or testing/operating equipment on or near the levee. Informal observations of levee conditions may also be reported by members of the community when the levee has people living, working, recreating, or otherwise near the levee. These observations can inform routine inspection and maintenance.

The visual observation of levee conditions through inspection activities is distinguished from monitoring**. Monitoring** is the observation and assessment of levee conditions through collecting and evaluating levee instrumentation and external data and is covered in section 2.8.

Conditions that can damage a levee may be grouped into two categories: (1) those that are ongoing, long term, and repetitive, and (2) those that are short term, singular events. The long term, repetitive, or ongoing issues—such as wave action or burrowing animals—make routine inspections and inspections to inform maintenance and repairs necessary. The most frequent short term singular event that impacts a levee is a flood, which triggers specific flood-related inspections. However, a wide variety of non-flood short-term events, from earthquakes to train derailments, may also cause significant damage. Inspections to respond to these events are termed event-driven inspections.

Additional regulatory levee inspections may be required by the local, state, federal regulators, or authorities, depending on the levee. In general, regulatory inspection considerations are not covered within these guidelines, although the formal documented inspection performed by a regulating agency may fulfill the needs addressed by the routine inspection described above. In that case, a separate routine inspection initiated and led by the levee owner/operator may not be needed.

2.7.1 Conducting Inspections

Inspections are more consistent, efficient, and thorough when properly managed and systematically performed, as shown in . The typical steps to conducting a good inspection are planning and preparing, considering relevant existing data, conducting the inspection, and completing appropriate documentation. Poorly planned and managed inspections cost more, take longer, fail to provide quality information, and do not deliver consistency over time.

Figure 9-4: Trained Staff Inspecting Levees

(a) Inspectors making notes during a floodwall inspection. (b) Inspector making notes during a levee inspection at the Souris River Levee in Ward County, North Dakota.

It is a best practice for inspectors to review all relevant levee data before performing an inspection. Important information to consider includes the levee risk assessment, levee O&M manual, historical levee performance, the levee owner/operator's experience, and best practices provided in these guidelines. What to look for during an inspection is discussed by levee features in section 3.

It is a best practice to use forms or checklists that include criteria for each levee feature to improve the quality and consistency of inspections. For example, the maximum tolerable tilt of a floodwall should be established and understood, providing inspectors clear guidance on what to look for and when to highlight inspection observations. Standardized checklists and consistent training can help inspectors understand inspection criteria.

During any inspection, it is a best practice to be aware of conditions beyond the access corridor and coordinate with adjacent landowners to cooperatively address issues with the potential to impact levee integrity. Possible issues that might be observed outside the access corridor include excavation that could impact performance, river migration, or coastal erosion that could impact embankment integrity. During floods, sand boils with the potential to lead to a levee breach may occur outside of the access corridor.

For any inspection type, the U.S. Army Corps of Engineers (USACE) offers free Levee Inspection System software which can be used to assist with inspections, and when used, the recorded information is automatically imported into the National Levee Database (NLD). The Levee Inspection System includes a checklist with general criteria, which can be used as a starting point to develop criteria for a specific levee. The system can be used to inspect all levee features, but it should be noted that the organization of features within the checklist varies slightly from the organization of features within this chapter. The Levee Inspection System checklist can be obtained through the NLD website.

The information collected during the inspection and presented in the inspection report should guide the next steps. If inspection results indicate an emergency or potential emergency, an emergency response may be triggered as discussed in **Chapter 10**. If inspection results indicate issues outside the scope of maintenance and repair, next steps may include conducting further investigations, installing instrumentation, initiating more frequent monitoring, and/or initiating levee rehabilitation. Evaluation of next steps may involve risk assessment and risk management considerations.

Archived copies of inspection documentation should be maintained for future reference. Results of inspections inform updates to the risk assessment. Risk assessments should be updated on a regular basis or in response to changed conditions observed during inspections that may alter the risk.

2.7.2 Managing Routine Inspections

A routine inspection is a formal and comprehensive inspection consisting of a visual observation of all the levee features by a qualified team of appropriately trained individuals. The purposes of the routine inspections are to evaluate levee conditions and identify potential levee safety issues that could impact levee performance, verify the adequacy of O&M, and inform risk assessments and risk management activities.

2.7.2.1 Frequency and Timing

It is a best practice to determine routine inspection frequency based on the levee risk with consideration given to the physical characteristics of the levee (section 2.5). The following rules of thumb should be considered when determining routine inspection frequencies:

- Routine inspections should be performed at a frequency between one and 10 years, as follows:
  - Levees with a high potential for life loss due to breach should be inspected every one to three years.
  - Levees with any potential for life loss due to breach should be inspected every one to five years.
  - Levees with no potential for life loss may be inspected at a frequency of up to once every five to 10 years.
  - Levees with one or more potential failure modes likely to cause breach prior to overtopping should be inspected on the more frequent end of these ranges.
- Levee conditions that change frequently due to deterioration, animal or human activity, or other forces may indicate the need for more frequent inspections.

The appropriate timing of routine inspections will vary with geography and with levee complexity and risk. Seasonal limitations like intense heat or deep snowfall may impact the timing of inspections. Inspections are more effective when they occur at a time of the year when the levee will be mowed, and all portions of the levee are safely accessible. If the levee is maintained by others, coordination with maintenance crews may be helpful. The timing of inspections for coastal levees should consider whether annual extreme low tides will provide access to areas normally covered by tidal waters.

Alternatively, inspection performed at different times of year—and under varying seasonal rainfall conditions—could provide the ability to observe the levee under a variety of stressors such as periods of frequent heavy rain or periods of drought. One way to do this is to schedule the inspection to inform maintenance and repairs, on an eight-month cycle which over the course of a three-year period would result in inspections occurring in each season: spring, summer, winter, and fall.

Because damage to infrastructure is cumulative, the frequency of inspections may need to be increased in regions experiencing significant climate change and the impacts of the climate trends tracked and documented.

> **EXAMPLES**
>
> California has a defined wet season, with more than 75% of precipitation falling between November and March. Here, routine inspections may be most appropriate in the dry season from June through September. Along the Eastern Seaboard levee inspections may need to be scheduled preceding the Atlantic hurricane season, which typically runs from June 1 through November 30. Here, routine inspections may be more appropriate early in the year during spring.

2.7.2.2 Implementation

For routine inspections, it is important the levee is inspected in its entirety—including all embankment slopes and all waterside and landside features of the levee. It is a best practice for routine inspections to include observing the entire levee by walking, and where appropriate, operating mechanical components (e.g., gates). Inspections by foot allow the inspector to observe conditions which could progress to a breach that may not be observable in a moving vehicle. The composition of the team for routine inspections should be commensurate with the features of the levee. Drone-based levee inspections may be appropriate in some areas but should always be followed by an in-person inspection of potential issue areas. Management of routine inspections requires:

- A qualified team with appropriate training.
- A detailed list of features to be inspected.
- A list of recent or past conditions that need to be checked for changes.
- Inspection templates that facilitate clear and comprehensive data collection. If inspections are staggered throughout the year to document conditions over a range of seasons, the inspection templates should provide season-specific conditions or circumstances the inspection should focus on and document.
- A work plan to promptly review inspection findings and rectify identified deficiencies.

2.7.2.3 Reporting

It is a best practice to document each routine inspection in a formal inspection report. A good levee O&M manual will provide guidance for the content and format of the inspection report. At a minimum, a good report documents all observations made during the inspection with detailed descriptions, dimensions, and photographs. An effective report will place emphasis on those observations that may have the potential to impact levee performance. The best inspection reports document the condition of all levee features, not just those with deficiencies. In general, a complete inspection report includes the following:

- Name/location of the levee inspected.
- Date(s) of the inspection.
- Name of the inspector(s).
- List of levee features that were inspected.
- Overall condition of each levee feature, including any changes since the last inspection.
- Accurate location information for any concerning conditions, distress, or deterioration.
- Photographs showing localized levee conditions, any damages, noted deficiencies, and overall levee condition.
- Sketches with dimensions, as needed, of deficiencies or performance indicators.

Maintaining a report of the inspection findings in the levee's data management system (section 2.11) can organize inspection data to create a history of levee condition over time. Best practice is to upload the report and inspection records for routine inspections to the NLD. Additional sharing of the levee inspection results may be valuable. For example, it may be beneficial to share results with partners who share the goal to sustain the levee's integrity and/or have the ability to support O&M of the levee.

2.7.3 Managing Flood-Related Inspections

2.7.3.1 Frequency and Timing

Flood-related inspections are performed immediately prior to a predicted flood, during a flood, and shortly after a flood. Flood-related levee inspections allow for early detection and response to address levee issues. These inspections also provide critical levee performance data to inform risk assessments and future risk management actions.

It is a best practice to establish predetermined triggers tied to flood-related inspection frequencies in the levee O&M manual or emergency action plan. These triggers will be unique for each levee and should be based upon the level of risk and what is driving it. Higher risk levees with a population at risk and one or more potential failure modes that could result in breach prior to overtopping should have early inspection triggers that allow timely detection of and response to incidents on the levee. Flood inspections for levees without a population at risk may be scaled commensurate with levee risk. Trigger development should also consider the reliability and availability of flood source forecasts and past performance of the levee, including water levels that have initiated performance concerns during past floods.

A levee should have at least three sequential flood-related inspection triggers.

- A trigger to transition from routine operations to flood preparedness operations, including the pre-flood inspection. This initial trigger may be a water level threshold, or it may be a storm or rainfall prediction.
- A water elevation at which flood-related inspections during a flood should begin, typically an elevation at which the levee requires additional inspection or operations to ensure water is excluded or evacuated from the leveed area.
- A water elevation when activities should progress further to emergency operations (**Chapter 10**), which is typically at some defined water height relative to the levee overtopping elevation or at a flood loading that has initiated performance concerns in the past.

Additional triggers may be identified that create steps in the transition from flood operations to emergency operations, which steer the increase in frequency and scope of flood-related inspections and monitoring.

EXAMPLE OF FLOOD-RELATED INSPECTION WATER LEVEL THRESHOLDS (TRIGGERS)

The O&M manual for Earth City Levee, a levee on the Missouri River, identifies appropriate monitoring best practices and outlines gage elevations that trigger both specific actions and increases in inspection and monitoring frequencies (A.M.C.I. Flood Plain Management LLC, 2020).

Once there is a forecast of high water for the levee, pre-flood inspections are triggered to “Check all existing levee and interior drainage system flood countermeasures such as relief wells, culverts, and pump stations to ensure proper function; if assessed as faulty, repair to provide adequate flood protection.”

The O&M manual includes the following table which outlines the water level thresholds and the changes to inspection and monitoring frequencies they trigger:

Gage Level/River Elevation (at identified river gage)	Freeboard*	Inspection/Monitoring Frequency
37.2 feet/450.8 feet	9.1 feet	Once every 8 hours/daylight
38.2 feet/451.8 feet	8.1 feet	Once every 8 hours around the clock
41.4 feet/455.0 feet	4.0 feet	Once every 3 hours around the clock
>38.2 and water level rise of 1 foot per hour		Once every 2 hours around the clock

During these high-water levels, the O&M manual/emergency action plan includes bringing in experienced and trained representatives to supplement O&M staff to support the increased inspection and monitoring frequency.

* Freeboard is the height of the levee above the water level at each gage reading.

2.7.3.2 Implementation

Managing flood-related inspections considers the same practices discussed in routine inspections; however, flood-related inspections should remain adaptive to real-time events by evaluating and updating the frequency of inspections and the required expertise of inspectors based on incoming data. Walking the entire length of the levee may not be practical during floods, but 'boots-on-the-ground' should occur as much as possible to identify potential performance concerns and is necessary in locations of active incidents or where incidents have occurred in the past.

When inspection observations indicate a potential emergent issue, increased frequencies and involvement of other flood response personnel with expertise to evaluate the conditions may be necessary. Specific items to inspect and what to look for are similar to those inspection items presented in section 3. More information on incident detection and response is provided in **Chapter 10**.

Post-flood inspections are crucial for documenting damage. After a flood, an inspection should be performed to observe and document any damage that may have occurred and evaluate the ability of the levee to withstand a future flood. Information collected should be used in evaluating and managing future risks.

2.7.3.3 Reporting

It is a best practice for flood-related inspections to be documented and maintained in the levee's data management system. Documentation is scalable to the severity of the event and the level of inspection conducted but should capture all of the inspections that occurred for a single flood event. 'During flood' records provide critical data on levee performance under hydraulic loading. Any observations of poor performance like slope slides, seepage, or erosion should be recorded with photos, detailed descriptions, and accurate location information. Post-flood inspection records are particularly important, especially any observations of damages that need repair or rehabilitation. The best flood inspection reports document areas of good performance, not just those with concerns. The documentation for flood-related inspection may range from compiled photos and field forms completed during inspection to a full report, but should include:

- Date(s) of the inspection.
- Name of the inspector(s).
- River or tidal gage readings during inspection.
- Project features that were inspected and their condition.
- Accurate location information for any concerning conditions or damage.
- Photographs showing conditions, including any damages identified.
- Sketches with dimensions, as needed, of damages or other problems identified.

2.7.4 Managing Event-Driven Inspections

Managing event-driven inspections requires identifying the potential range of non-flood events that could cause levee damage, developing staffing, and guiding appropriate inspections should an event occur. Non-flood events which may cause levee damage include seismic events; extreme weather events; auto, train, or boat accidents; or even terrorist actions. The purpose of event-driven inspections is to evaluate if the levee has been damaged.

While it is not feasible to anticipate every possible event that may cause levee damage, it is helpful to maintain an informed list of possible levee impacts for those events that are most likely to occur. Table 9-1 provides example inspection guidance for a variety of potential levee-impacting events. Identifying and engaging with groups focused on existing and changing climate risks, and staying aware of community and social developments can help when identifying and proactively planning for possible events. Local USACE, Federal Emergency Management Agency, and state emergency management agencies are good sources of up-to-date, regional climate change information, and may be able to recommend regional climate professionals to help identify new or growing risks specific to a levee and its operations.

Table 9-1: Non-Flood Event-Driven Inspection Examples

Event	Potential Impacts	What to Inspect for
Windstorm (including tornadoes, hurricanes, other high wind events)	May cause significant physical damage to natural and built infrastructure, including erosion, structural damage, and debris impacts.	Check for wind-driven erosion of levee embankment or riverbank, downed power lines, debris, downed trees, and potential structural damage to levee features.
Extreme or prolonged heat	Extreme heat events may damage levee features made of concrete, asphalt, metal, or plastic, or which include electrical components.	Inspect heat-vulnerable levee features, test instruments, and electrically operated structures.
Wildfire	Intense heat during wildfire can melt metal, plastics, buried culverts and crack concrete. Post-fire debris, ash, and sediment may clog channels, pipes, and inlet/outlet structures.	Inspect fire-impacted levee features after wildfire safety risks have passed. Inspections should include the integrity of buried components (such as pipes or instruments), vegetation damage, and erosion potential. Additional inspections for post-fire debris impacts may be advisable based on regional conditions.
Power outages	Power outages may be associated with storms, wind, heat, power, or grid-management policies. Outages may cause surges which damage electrical components and instrumentation.	Inspect power lines, outlets, power-driven instruments, and electrical components such as power cables.
Seismic hazards	Earthquakes may impact levee feature stability.	Inspect all levee features after any seismic event above a magnitude 5.0, or in accordance with the levee O&M manual, including levee embankment, slope or bank protection, vertical structures or buildings, and pipes. Test instruments for appropriate function.

2.7.4.1 Frequency and Timing

Inspections for non-flood events are generally timed as soon as possible after an event has occurred and once it is safe for the inspection to be completed. The safety considerations for performing responsive inspections following a tornado, social unrest, an earthquake, or a railroad incident are each quite different. Therefore, providing staff safety training specific to and appropriate for responding after non-flood events is an important component of levee O&M management.

2.7.4.2 Implementation

Event-driven inspections are similar to routine inspections; however, in event-driven inspections, only a portion of the levee or some of the levee features may be potentially impacted and require visual observation, making these inspections scalable to the circumstance. Expertise involved in these inspections should be determined by the damages expected from specific events. If inspection results indicate damage or other issues, the repairs should be made before the next flood season, if possible.

2.7.4.3 Reporting

It is a best practice to maintain documentation of event-driven inspections in the levee's data management system. The documentation is scalable to the level of inspection conducted. Records may be compiled photos and field forms or a short write-up, but typically includes the following information:

- Date(s) of the inspection.
- Name of the inspector(s).
- Project features that were inspected and their condition.
- Accurate location information for any concerning conditions or damage.
- Photographs showing conditions, including any damages identified.
- Sketches with dimensions, as needed, of damages or other problems identified.

2.7.5 Managing Inspections to Inform Maintenance and Repairs

Inspections to inform maintenance and repairs are inspections performed by levee owner/operator staff to identify areas or features that require attention. Inspections to inform maintenance and repairs can be targeted to specific areas of the levee, with some areas or features being inspected more frequently than others. It is a best practice to inspect all areas of the levee at least once a year to allow issues to be identified and addressed before they can become large problems that require rehabilitation. It may be sufficient to drive most areas of the levee, but some areas may require walking, dependent upon the levee risk and the type of damages typically observed. Inspections to inform maintenance and repairs are most useful when they are scheduled such that identified issues can be addressed prior to typical flood season.

Inspection documentation sufficient to communicate the location, type, and scope of needed maintenance or repair actions will allow the inspection report to inform maintenance and repair plans, as well as the development of annual budgets. A formal inspection report documenting inspections to inform maintenance and repairs may be helpful but is not necessary.

Should an inspection to inform maintenance and repairs identify issues that are beyond the scope of O&M, performing a routine inspection may be warranted to fully document levee condition and inform plans for larger actions, like levee rehabilitation. A risk assessment can be performed to help identify risk management actions based on the result of the routine inspection.

2.8 Implementing Monitoring

Monitoring is the observation and assessment of levee conditions through collecting and evaluating levee performance and external data. The performance data comes from levee instrumentation and external data and includes hydrologic and hydraulic conditions, as well as weather and storm forecasts. Monitoring and tracking data over time is critical for an understanding of risk-related trends.

2.8.1 Levee Instrumentation Monitoring

Levee instrumentation can provide critical early warning signs of levee distress. Additionally, levee performance instrumentation can inform risk assessment, levee risk management, flood response activities, and levee rehabilitation.

The types, locations, and number of instruments are unique to each levee based on its features and conditions. Table 9-2 identifies conditions which may be monitored and the instrumentation or method that is typically used.

Table 9-2: Examples of Levee Instrumentation

Condition	Instrument or Method
Seepage and groundwater conditions	• Piezometers • Discharge flow monitors
Slope movement	• Inclinometers
Floodwall movement	• Tilt meters • Crack meters
Settlement	• Settlement monuments • Surveys of levee crest, slopes, top of floodwall

Not all levees require instrumentation. The best practice is to design levee instrumentation and develop the monitoring plan using a risk-informed approach considering levee-specific needs. Each instrument should have a clearly defined purpose, tied to a specific issue and/or potential failure mode. The frequency and timing for collection and evaluation of instrumentation data should be based upon levee risk information, including the likelihood the monitored potential failure mode could cause a breach over the range of possible loading conditions. Rigorous monitoring procedures should be employed when there is a population at risk and a likelihood that the monitored potential failure mode could result in breach prior to overtopping. Engineer

Manual (EM) 1110-2-1908 provides details on measurement methods, data processing, data evaluation, and determining appropriate measurement frequencies (USACE, 2020a).

Selecting instrumentation and developing an instrumentation plan is typically accomplished during levee design or levee rehabilitation and is discussed in **Chapter 7**. The designer understands the intricacies of the design, the underlying site conditions, the material properties of the constructed features, the assumptions that form the basis of the design for the levee, and the goals of instrumentation. The instrumentation monitoring strategy is typically established to validate assumptions made during the design and to understand the long-term performance under various loading conditions. Instrumentation may also be installed to gain more information about a potential failure mode identified based on levee performance data or a risk assessment.

An instrumentation plan includes collecting baseline readings and setting evaluation criteria and threshold action levels. Baseline readings and evaluation criteria are critical for comparison to subsequent readings to identify developing potential failure modes. Monitoring frequency should be adapted to real-time events and changes in the understanding of the levee risk. Long-term trends are also important, and spreadsheets, charts, and plots of the data can be utilized to better understand the levee performance over time under varying site conditions.

Monitoring frequency should be increased during floods. Piezometers in particular can provide early indication of levee instability through their measurement of pore water pressure in or below the levee. A sudden increase in pore water pressure indicated by piezometer data may require swift actions to prevent an emergency. Based on the levee risk, consideration may be given to automating instrumentation of piezometers, which allows for remote, real-time measurement of pore water pressure, and may allow more rapid evaluation of field conditions and response to potential problems. Automated instruments may also overcome problems accessing piezometers during floods. **Chapter 10** discusses instrumentation monitoring during emergencies.

Record keeping of instrumentation data is important to inform risk assessment and levee risk management. It is a best practice to maintain levee instrumentation data within the levee's data management system to ensure it is organized and easily accessible (section 2.11).

Inspection, maintenance, and data collection for levee instrumentation are discussed further in section 3.9.

2.8.2 Hydrologic and Hydraulic Conditions

Potential flood conditions can be anticipated by monitoring actual and forecasted river levels for riverine levees and tidal and wave heights for coastal levees. Anticipating flood conditions allows implementation of proper operation activities outlined in the O&M manual, such as closing sluice gates, operating closure structures, and performing flood-related inspections. As described in section 2.7.3 and 2.10, the water level thresholds that trigger specific action will be unique for each levee. Where available, it is beneficial to monitor river and coastal hydrologic forecast information as well.

2.8.3 Weather and Storm Forecasts

Monitoring weather and storm forecasts is important for levee safety and flood preparedness. Pertinent forecast information could include heavy rainfall, tornadoes, hurricanes, or flooding.

Impacts to levees can also occur from non-extreme weather events, where monitoring rainfall or precipitation, temperature, wind, and storm forecast information can inform response actions. Such weather information should be monitored to maintain situational awareness for water level and wave height trends. It is also important to consider weather as a safety factor for those who might be outdoors operating or inspecting the levee. For example, if thunderstorms that would bring the risk for lightning are forecast, staff should be advised not to work outdoors.

> **NATIONAL WEATHER SERVICE RESOURCES**
>
> The National Weather Service provides all kinds of weather, water, and climate outlook and forecast information on the website: https://www.weather.gov/.
>
> The National Weather Service's "Weather Ready Nation" initiative website is available to help communities/individuals with information to be ready and prepared for the impacts of weather, water, and climate events: https://www.weather.gov/wrn/.

Other conditions may also impact the physical levee. For example, wildfires upstream of a levee reduce the vegetation within burned areas, causing erosion and soil migration into the waterways. This increases sediment loads within the river system, which can result in a river level higher than anticipated for a given storm event. This in turn can impact the ability of the levee to contain a storm event that was not previously considered problematic with respect to overtopping.

2.9 Managing Maintenance

Maintenance includes all activities required to maintain or restore a levee to the desired safety or working condition to ensure it functions as intended. It includes preventative maintenance, repairs, and replacement of components. It is a best practice to develop a long-term strategy for managing levee maintenance that includes the appropriate frequency, scale, and scope of activities based upon levee risk and the physical characteristics of the levee, as well as a plan for budgeting and staffing activities.

Routine maintenance over the life of the levee ensures that all features of the levee are in working order and includes:

- Addressing issues identified during inspections and monitoring (e.g., repair of animal burrows, repair of slope covering, and repair of fencing).
- Intentional routine maintenance of the levee features (e.g., mowing of embankment slopes, checking operational readiness of levee components, such as pumps, drainage systems, closure systems, gates, and valves).
- Ensuring unobstructed access to all levee features so that maintenance and emergency vehicles have appropriate access. Potential obstructions include fences, gates, trees, and other structures.

It is helpful to document completed maintenance of levee features using checklists or forms. It is a best practice to keep a comprehensive record of completed maintenance activities, including the date the activity occurred, who performed the activity, the location, the resources used, and the work procedures employed. Detailed maintenance records provide information to evaluate the condition of the levee and inform future maintenance and repair needs. The maintenance records should be incorporated into the levee's data management system to ensure they are available to inform future actions (section 2.11).

All levees should have repairs and maintenance performed frequently enough to avoid long-term deterioration of any component. General maintenance schedules should be based on the expected design life and the current age of levee components, known rates of change and deterioration, and inspections. It is usually best for identified repair needs to be addressed prior to the next flood season. If no flood season exists, then performing maintenance and repairs at least annually will prevent minor issues from deteriorating further. Maintenance activities may occur more frequently (e.g., several times per year), based on the type of maintenance (such as mowing) and the risk of the levee.

MAINTENANCE TO REHABILITATION

An example of maintenance evolving into the need for rehabilitation is the progression of earthen embankment erosion. If the results of an inspection indicate the toe of an earthen embankment has experienced minor erosion, the placement of a small zone of riprap as revetment may resolve future erosion. In this scenario, the repair may be considered maintenance. Conversely, if the erosion resulted in the loss of waterside toe support, causing cracks along the waterside slope and along the embankment crown (i.e., an unstable slope), the failed/sloughing embankment slope may require rehabilitation, including evaluation by an engineer to determine the cause of the erosion.

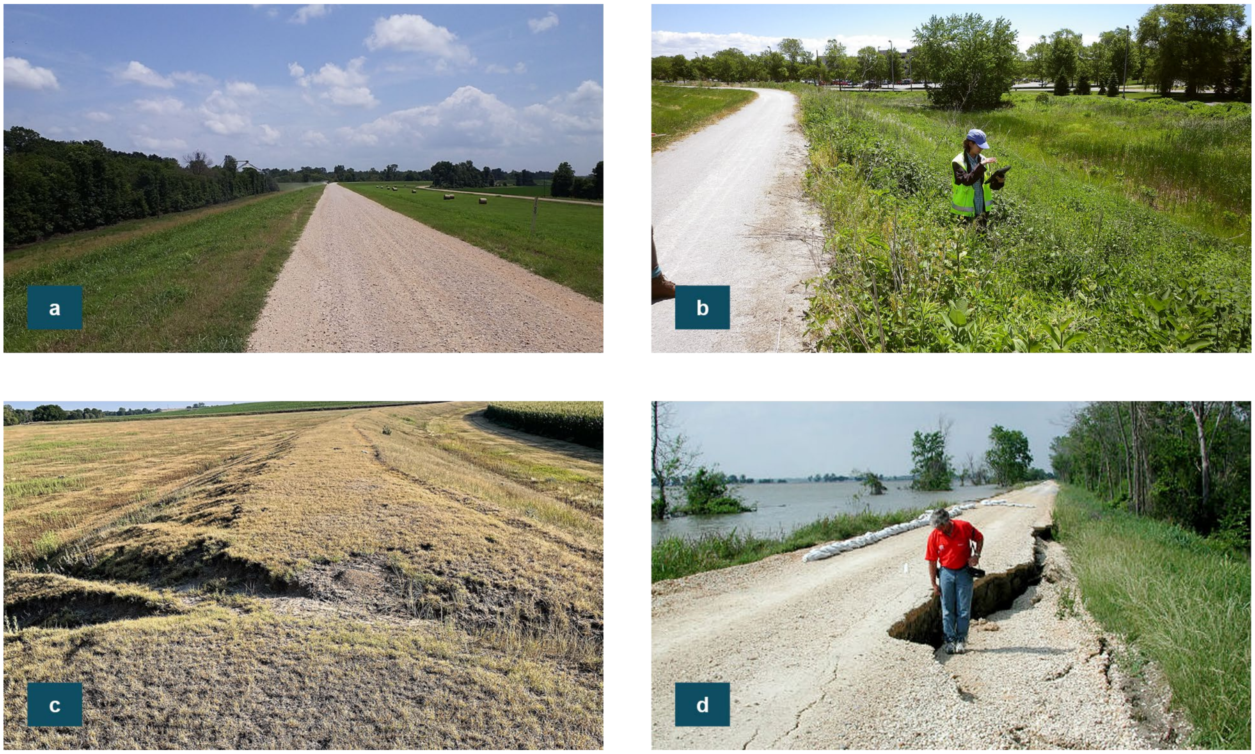
Levees with higher risk should have the highest standard of care with maintenance and repair of high-risk levees receiving high priority. Repairs should be given the highest priority when there is a population at risk and the issue in need of repair could cause breach prior to overtopping. If complete repairs are not immediately possible, interim risk reduction measures may be needed to manage risk temporarily while complete repairs are designed and resourced.

When maintenance cannot sufficiently address a problem for a levee feature—or a more significant underlying issue is identified—the feature may require rehabilitation or replacement. Figure 9-5 provides examples of a range of maintenance conditions, from a well-maintained levee to a slope slide that needs further investigation outside the scope of O&M.

In some cases, a lack of resources may make it necessary to defer maintenance activities. In these situations, decisions must be made concerning the priority of needed maintenance and repairs. These prioritizations should be made based upon levee risk, with those actions that manage or reduce levee risk most effectively having higher priority. In other cases, large rehabilitation or replacement projects may require investments beyond that of the typical annual O&M budget. In both cases, it is important that any needed interim risk reduction measures be employed, and all required long-term actions be tracked and prioritized based upon risk as described in section 2.5.2.

Floodfighting or other emergency response to a levee incident may trigger urgent action. **Chapter 10** covers planning and implementing these immediate response activities that would need to occur ahead of full rehabilitation.

Figure 9-5: Examples of Levee Maintenance Conditions



(a) Well-maintained, recently mowed levee slope with grasses baled and ready for removal. (b) Levee slope covered by tall vegetation that is inhibiting inspection. (c) Levee with erosion rills in need of repair. (d) Large crack developing into a slide through levee crown that requires further investigation and interim risk reduction measures.

2.10 Executing Operations

Operations includes those activities or services required for system components to function as intended. Operation of levee features includes routine operations and test operations. Each type of operable feature or component has its own set of unique operational activities that support it before and during its operation. Operation considerations by features are discussed in section 3. In some cases, such as pump stations for interior drainage, routine operation may be outside the management of the levee owner/operator.

During floods, operation activities outlined in the O&M manual will need to be performed, such as closing sluice gates and operating closure structures. It is a best practice to develop feature-specific triggers for operation based on flood source conditions—such as certain water levels for riverine levees or storm predictions for coastal levees. The feature-specific triggers can be established by considering the amount of advance notice provided by flood forecasts, the time required to secure necessary staffing and materials, and the time required to complete the operation of each feature. If a levee has multiple features that require operation, the cumulative time to operate all features should be considered. For more discussion on developing triggers, see section 2.7.3.1, which describes the process for developing triggers for flood inspections that apply to the levee as a whole.

Test operations—such as test placement of closure structure or test operation of pump stations—are performed to ensure all operable components of the levee are in working order and that responsible individuals are properly trained. Checklists are helpful to document completed test operation. Good documentation includes recording that an activity occurred and documenting details regarding resources used and work procedures followed, as well as any malfunctions, issues, or damages and action taken in response. This will help ensure that levee features can be properly operated during floods and will help determine maintenance and repair needs. Incorporating the test operation records into the levee's data management system will allow the operational conditions to be tracked over time and will provide a source of data for operational and budgetary planning (section 2.11).

It is a best practice to determine the frequency of test operations based upon a consideration of levee risk, as well as the specific characteristics of each feature. In general:

- Test operations of all levee features should occur during routine inspections.
- Features with potential for life loss associated with misoperation should have test operations at least annually.
- Other factors to consider:
  - Inspections to inform O&M are much more effective when they include test operations of mechanical features such as pumps, culvert gates, and mechanical gates for closures.
  - Features with complex operation or coordination procedures may need more frequent test operations.
  - The experience level of staff may influence the frequency, with less experienced staff benefiting from more frequent test operations.

2.11 Utilizing Levee Knowledge and Managing Data

Managing data and keeping organized, accurate, up-to-date records are vital to inform O&M. The data and records from O&M also provides input for risk assessment, risk management, rehabilitation, repair, flood emergency response, and monitoring.

For these reasons, it is a best practice to maintain appropriate levee records in a well-organized and lasting way.

Table 9-3 outlines the types of data produced during O&M and how it may be used in O&M activities.

Table 9-3: O&M-Related Data

Type of Data	Description of Data	O&M Application
Operation records	Records may include, but are not limited to: • Dates and notes for the test and flood operation of pump stations, gates and closure structures. • Documentation of flood and other emergency preparedness activities. • Information on stockpiling materials and implementing emergency drills.	• Ensure operation of the levee features occurs at appropriate intervals. • Identify information to reference when conducting maintenance, and to flag for necessary repairs.
Maintenance records	Records may include, but are not limited to: • Date and notes for periodic maintenance of earthen embankment, including mowing and other vegetation management and repair of roadway/trail damage, animal burrows, and minor erosion. • Date and notes for periodic maintenance of floodwalls, including vegetation management and repair of concrete surfaces and monolith joints. • Cleaning and lubrication of mechanical features and components. • Maintaining pump station buildings and security fencing. • Periodic cleaning and coating (painting) of metallic components. • Periodic maintenance of interior drainage systems (e.g., flap gates, drainage ditches).	• Ensure required maintenance specified in the O&M manual is occurring. • Record changes such as major rehabilitations to inform engineering evaluations. • Provide a written record of maintenance completed for reference in future inspections. • Evaluate effectiveness and efficiency of maintenance processes. • Identify components and features that may need larger rehabilitation, replacement, or modification due to high maintenance and repair costs.
Visual inspection records (levee owner/operator-generated)	Record of levee inspections may include: • Condition of levee features. • Observations of any deficiencies. • Any changes that are noted to historically identified deficiencies.	• Increase understanding of the condition of the levee and how it is changing over time. • Help identify significant issues regarding the condition and operation of the levee. • Determine needed maintenance and repair activities. • Identify encroachments of concern from an engineering or access standpoint.
Records of permitted activities within levee prism and right of way	A detailed record of all activities for which permission has been requested/granted/denied including: • The location of the activities and whether the request was granted/denied. • The conditions under which the activities were permitted.	• Help the levee owner/operator verify that the conditions in the permit are being upheld (as appropriate). • Help the levee owner/operator keep the levee inspection checklist updated.

Type of Data	Description of Data	O&M Application
As-built drawings	Drawings indicating the design that was constructed for all features of the levee, such as earthen embankments, berms, relief wells, seepage ditches, floodwalls, interior gravity pipes, and channels.	• Help the levee owner/operator understand the original design and site conditions, and the O&M required to retain levee integrity. • Help identify and pinpoint issues and their causes.
Levee site condition	A comprehensive record of all items an inspector may expect to find on the levee. This may include, but is not limited to the location of: • Levee feature components. • All known encroachments and permitted activities. • All penetrations (levee-related pipes and utility penetrations).	Assist levee owner/operators to: • Identify new, unpermitted encroachments and evaluate permitted encroachments. • Know features requiring maintenance. • Anticipate encroachment challenges when performing maintenance. • Inform flood-related inspection procedures.
Past performance data and performance evaluation data	Past performance data, type of distress, the loading at the time the distress was noted, and any effect on the levee, including but not limited to details on floodfighting such as where measures were required to address sand boils or to prevent overtopping. This may also include studies that predict future levee performance.	• Assist in evaluating future performance and other activities within the levee prism. • Inform flood-related inspection procedures and emergency preparedness actions. • Inform evaluation of requests to permit activities/encroachments on the levee. • Informs risk assessments and rehabilitation considerations.
Instrumentation data	Record of instrumentation data and data evaluations.	• Understand changes from previous monitoring periods. • Understand how levee features are impacted by changing site conditions. • Informs risk assessments and rehabilitation.

A data management system can help record and store the large amounts of information related to operating and maintaining a levee. A classic paper-based system, a digital computer file system, a smart data system in the form of geospatial information housed on a GIS digital platform, or a combination of these systems could be used.

Data loss can be prevented by making data redundant. Data backups are critical to ensure lost data can be replaced. Electronic data should be backed-up regularly, and paper records should have scanned electronic back-ups. If possible, electronic data should be stored on multiple hard drives and have an offsite backup. Data stored solely on paper or on devices that do not have an active backup process in place is particularly vulnerable to loss and corruption.

Many levees are long linear structures with a significant amount of available data. Because of this, it can be helpful for the levee-related descriptive data to be accessible through a GIS digital platform. A GIS is a geo-referenced/spatial data platform that provides a more powerful method to handle spatially referenced data compared to conventional information systems, computer aided design systems, or digital mapping systems. One of its main advantages is the ability to manage, combine, and analyze a great variety of spatial data, using topological and spatial analysis functionalities.

As detailed in **Chapter 5**, the NLD is a national GIS database developed and managed by USACE to maintain critical data about the nation's levees. Data management best practices include providing the appropriate levee data for storage in the NLD, including inspection results and reports. The NLD may also contain information that will be useful in accomplishing O&M activities, such as spatially accurate information about the location of features and original construction data.

HOW TO UPDATE LEVEE DATA IN THE NATIONAL LEVEE DATABASE

The NLD is the national repository for levee data managed by USACE. If data in the NLD is determined to be inaccurate, an update of that data should be initiated through the following methods:

- Email to nld@usace.army.mil.
- Call 1-877-LEVEEUS.
- Submit new or updated data using the data change request button on the NLD homepage (nld.sec.usace.army.mil).

Local USACE Districts may be contacted directly to update data on levees federally authorized and constructed by USACE.

2.12 Sharing Levee Information

Sharing levee information with those impacted by the levee is a best practice that provides benefits to both the community and the levee owner. Routine sharing about levee O&M builds trust in the people and organizations that manage the levee and creates a sense of ownership for the levee within the community. Knowledgeable community members can help alert levee owner/operators about any problems they may notice or advocate for necessary levee funding.

Helping community members become aware of the existence of a levee, along with the benefits and limitations associated with that levee, can empower them to take actions that reduce their risk such as following evacuation orders during a flood event and purchasing flood insurance. When engaging about the levee, it can be helpful to partner with organizations and individuals who are trusted within the community, such as homeless shelters, food banks, faith-based organizations, and community leaders. Successful engagement is an ongoing process, not a one-time event. **Chapter 3** provides best practices for sharing levee information before, during and after flood events.

CASE STUDY: SHARING LEVEE INSPECTION INFORMATION

The California Department of Water Resources works with local levee owners to annually inspect levees within California's Central Valley. Results from these inspections are used by levee owners, USACE, and others to better understand levee conditions and the level of care the levee is receiving. Inspection reports are also available to the public through the California Department of Water Resources website: https://water.ca.gov/Programs/Flood-Management/Maintenance/Levee-Inspections.

Making inspection reports available to the public can increase understanding of the condition of the levee, as well as the diversity and scope of required O&M actions. This can increase support for levee projects, as well as increase trust in levee owner/operators.

2.13 Providing Security

It is a best practice to provide appropriate security for levee infrastructure based on the features, the multi-benefit use of the system (e.g., if the embankment crown also serves as a community bike trail or road), and an assessment of risks for the specific levee. It is important to protect levee infrastructure from damage or threat from human activity (e.g., accidental damage, theft, or even criminal and terrorist acts targeting the levee), and to protect the public from hazardous conditions. Security measures may include physical measures such as access controls, including fencing and gates, and deterrence measures such as signs.

Non-vehicular public access along levees is generally not considered to be a security problem, except typically at specific locations such as pump stations. Aspects of inspecting the viability of security measures, especially pre-flood inspections, include checking to ensure key infrastructure components are still in place and have not been damaged or stolen. For example, it is not uncommon for flap gates to be stolen and sold as scrap metal.

Security measures related to levee penetrations and closure structures can protect these features from vandalism or other harm. Pump houses, pipes, culverts, and flood gates may benefit from signage, fencing, locks, and alarms. Sensor systems may also be considered for detecting problems remotely. Such systems may include pressure sensors, motion sensors, or disturbance detection cables.

For levees with a population at risk, at a minimum, public access to pumps, gates, or other operable features should be restricted. Additional security measures may be appropriate if there are potential failure modes that could be negatively impacted due to human activity, either malicious or inadvertent. Increased security measures may also be warranted if portions of the levee are located in remote areas, areas where vandalism is known to occur, or if levee features are made of materials that can be recycled for profit.

Awareness and appropriate vigilance are key to the security of levees and supporting facilities. As such, suspicious activities should be immediately reported to the appropriate authority.

3 Implementing Operations and Maintenance

This section covers best practices in levee inspections, maintenance, and operations of specific levee features with examples and case histories.

Inspections and maintenance are a first line of defense against many of the common levee potential failure modes, allowing levee owner/operators to identify and repair conditions which are impairing levee integrity. Section 2 discusses the management for inspection and maintenance efforts.

In this section, within the discussion for each levee feature, the following topics will be presented:

- What to look for at the levee site.
- Which potential failure modes the observed conditions may indicate.
- The maintenance and repairs appropriate when issues are identified.

- Operational requirements, if appropriate.

Chapters 2 and 4 describe the various levee potential failure modes referenced in this section.

Table 9-4 provides a general overview of typical levee features included in inspections, and general issues of concern relevant to each feature. Details of the inspections for the levee features noted are further presented in subsequent sections.

Table 9-4: List of Items and Issues to be Checked During an Inspection

Inspection Item	Issues to Look for:
Earthen Embankment	
• Levee surfaces (crown and slopes) • Slope coverings (sod and other herbaceous vegetation, riprap, and other erosion protection) • Access corridor	• Sloughs or slides • Tension cracks • Desiccation cracks • Erosion or bank caving • Seepage • Settlement • Depressions/rutting • Overtopping (evidence of/historical record of) • Animal burrows • Gaps in adequate sod or other herbaceous vegetative cover • Erosion protection damage • Debris to be removed • Vegetation in need of maintenance • Human activity (digging, etc.) – either permitted activities or encroachments
Floodwalls	
• Concrete structures • Joints between monoliths • Floodwall foundation • Access corridor	• Excessive cracks, spalling, or flaking • Exposed rebar • Tilt or movement of wall • Torn or deteriorated waterstops • Overtopping (evidence of/historical record of) • Foundation seepage, settlement, or erosion • Animal burrows near floodwalls • Debris to be removed • Vegetation in need of maintenance • Human activity (digging, etc.) – either permitted activities or encroachments
Closure Structures	
• Condition of movable gates • Stored materials (condition and organization) • Condition of seals and structural elements at installation location	• Loss of structural integrity • Obstructed movement of movable components • Seals that are not watertight • Stored material damage or deterioration • Impacts or changes to stored materials accessibility and security • Debris to be removed

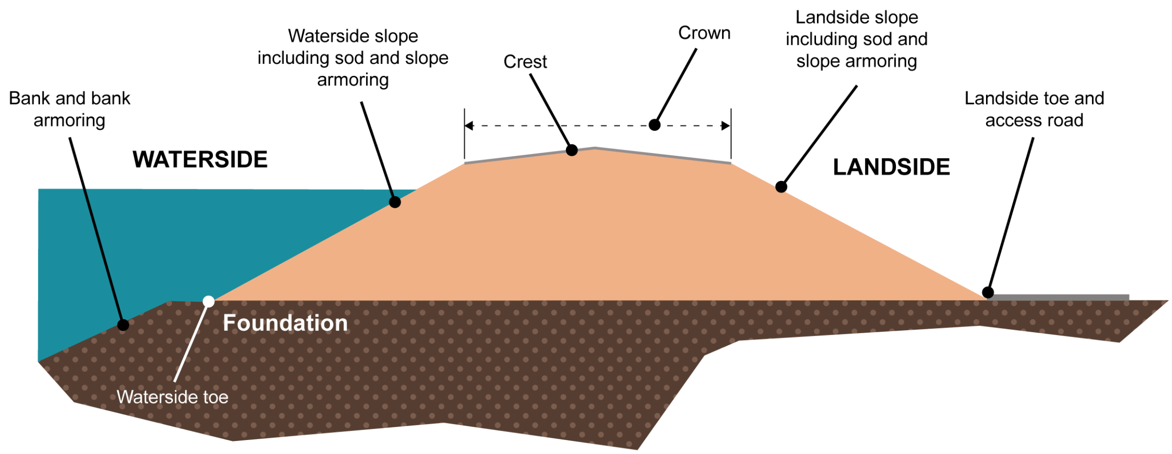
Inspection Item	Issues to Look for:
Seepage Control Features	
• Seepage berms and stability berms – Earthen fill – Covering (sod/grass) – Drainage and discharge components • Relief well systems – Drainage and discharge components – Filter pack and other downhole components – Valves, gaskets, well guards, cover plates, flap gates on outlets, and other components • Cutoff walls	• Changes in berm geometry (settlement, depressions, or rutting) • Clogged drainage features • Gaps in adequate sod and other herbaceous vegetative cover on berms • Obstructed flow of water through all drainage components or structures • Biofouling or clogging of relief wells • Damage to exterior relief well components • Settlement above cutoff walls • Debris to be removed • Vegetation in need of maintenance • Human activity (digging)—either permitted activities or encroachments
Interior Drainage Systems	
• Gravity pipes • Pipe outlets • Gates • Gatewells • Concrete surfaces (e.g., gatewells, outfalls, or intakes) • Drainage ditches, ponds, and swales	• Blockage of any portion of the drainage system by silt, sediment, vegetation, or debris • Signs of pipe-associated internal or surface erosion • Corrosion of concrete or metal components • Loss of structural integrity (pipes, gates, headwalls, gatewells, and associated structures) • Obstructed movement of gates • Seals that are not watertight • Obstructed flow of water through all drainage structures • Reductions in sluice gate operability • Access issues with gatewells
Pump Stations	
• Pump station building and contents • Pump and pump motor • Electrical supply	• Damage, disrepair, or settling of pump station building • Loss of, or damage to, building ventilation, gas detection, and electrical systems • Deterioration of spare parts, tools, and other stored building contents • Dangerous conditions from poorly stored electrical, chemical, or mechanical items • Blockage of pump inlet and outlets • Sand boils near pump intake • Mechanical issues with pump motor, instrumentation, and alarms • Deterioration of pump back-up power
Levee Transitions	
• Feature geometry changes • Feature or material type changes • Changes in loading	• Erosion, depressions, or sinkholes • Missing or degrading erosion protection • Gaps in adequate sod and other herbaceous vegetative cover • Debris to be removed

Inspection Item	Issues to Look for:
Instrumentation	
• Observation wells • Piezometers • Water level monitors in discharge features • Inclinometers • Tiltmeters • Crack meters • Settlement monuments • Staff and stream gages	• Damage • Deterioration • Loss of calibration • Debris to be removed

3.1 Embankment

Earthen embankments are the most common levee feature. Figure 9-6 depicts the components of an earthen levee embankment which are described in detail in **Chapter 2**.

Figure 9-6: Earthen Embankment Cross Section

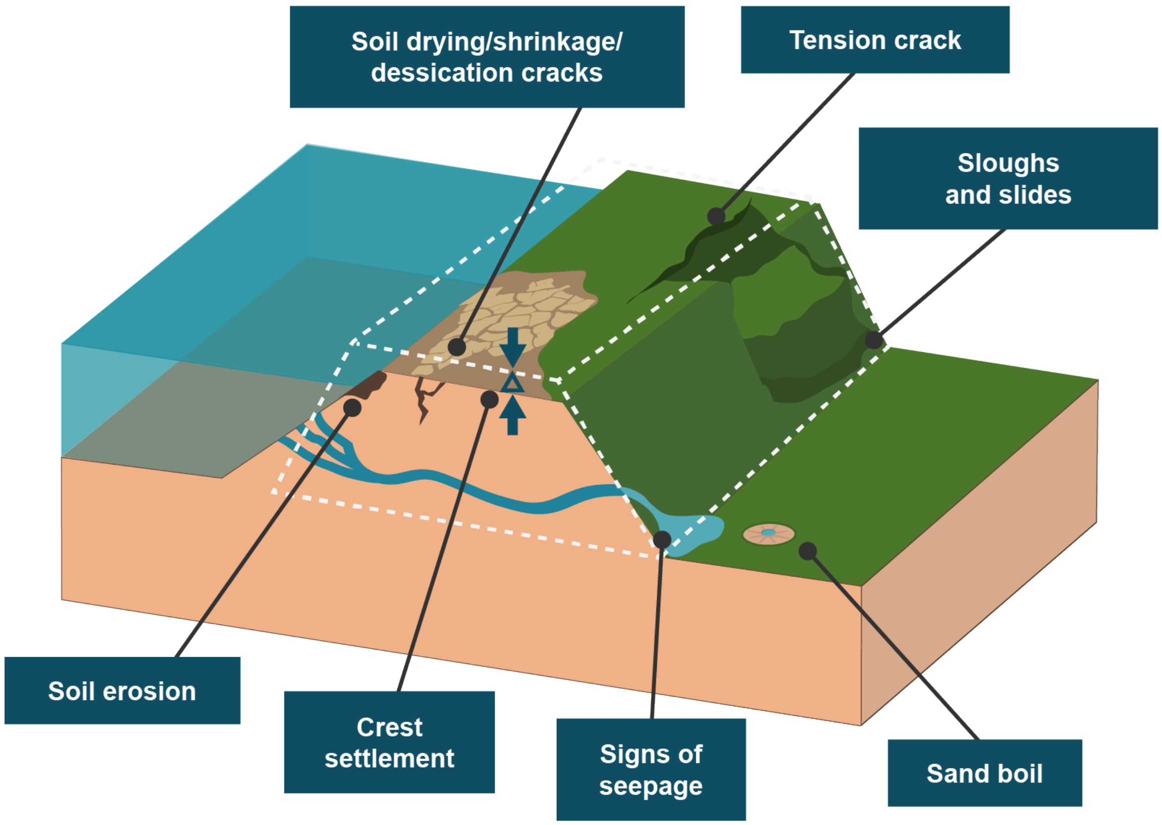


3.1.1 Inspection and Maintenance

Earthen embankments have many aspects to inspect and maintain including levee slope stability, seepage through or beneath the embankment, erosion of the embankment or its foundation, levee crest elevation, sod and other herbaceous vegetative coverings, erosion protection, and the condition of associated roadways. Most of these aspects can be inspected during any inspection, however some performance related aspects like seepage and erosion are best observed during and immediately after floods.

Maintenance that occurs under O&M includes scheduled routine activities, such as mowing grass, rodent control, debris clean-up, and repairs to address minor issues identified during inspection and monitoring. It is a best practice to schedule embankment inspections to immediately follow mowing or other appropriate levee vegetation maintenance activities to improve visibility of levee slopes. When significant rehabilitation outside the scope of O&M is needed, risk assessment and risk management processes can be used to identify and prioritize risk reduction actions. Section 2.5.2 discusses prioritization of risk reduction actions.

Figure 9-7: Typical Levee Embankment Deficiencies



3.1.1.1 Embankment Slope Stability

Unstable levee slopes can reduce the ability of the earthen embankment to hold back flood waters by reducing the width and height of the earthen embankment. Inspections of embankment slopes are conducted to identify existing failures and to evaluate the potential for future slope failures.

Unstable embankment slopes, as shown in Figure 9-7, present themselves as sloughs and slides. Tension and desiccation cracks indicate the possible development of slope stability issues. Inspecting embankment slopes for these conditions and potential maintenance and repairs for these items are discussed individually below.

3.1.1.1.1 Sloughs and Slides

Sloughs and slides are areas where earthen material has moved downhill on the embankment slope. This may be caused by:

- Saturated slopes due to throughseepage or prolonged periods of rain.
- Flood levels decreasing faster than pore water pressure within the levee can dissipate.
- Natural decreases in the strength of clay embankments as they age.
- Erosion of the lower portion of the levee or of an adjacent channel slope.

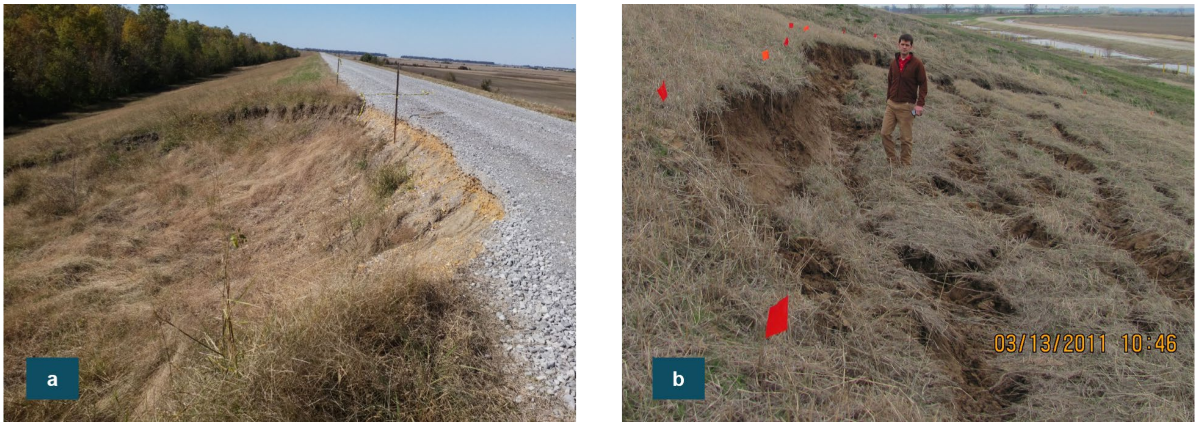
Inspectors should note any areas of slough or slides and record extents and scale. Sloughs are the movement of a shallow mass of soil down a slope. Sloughs expose underlying soils and are often considered a maintenance issue. Slides are the movement of a large mass of soil down a slope. They are deeper embankment failures and are often a levee performance or levee integrity concern. Slides on a levee appear as a mass of the embankment that has dropped down-slope, exposing a near-vertical soil face (scarp) and resulting in a bulging of soil at the embankment toe. Figure 9-8 provides some example photos of sloughs and Figure 9-9 provides some example photos of slides.

The damaged slope should be repaired by excavating the failed soil and reconstructing the slope. Just pushing the displaced soil back into place will not repair the underlying failure. Prior to mitigating the unstable slopes, a geotechnical and/or hydraulic investigation and analyses may be needed to understand the underlying reason(s) for the damaged slopes.

Figure 9-8: Examples of Embankment Slope Sloughs

(a) Isolated area of near-surface soil mid-slope on a levee in Mississippi has dropped down-slope and exposed underlying soils. (b) Isolated area of near-surface soil on the upper slope of a levee in North Carolina has dropped and exposed underlying soils.

Figure 9-9: Examples of Embankment Slope Slides



(a) A large portion of the embankment at the crown of a Mississippi River levee has dropped down-slope, exposing a near vertical scarp of exposed soil. (b) A large portion of the embankment has dropped down-slope on the landside of a levee in Missouri, exposing a near-vertical scarp of exposed soil about 3 feet in height; March 2011.

3.1.1.1.2 Tension Cracks on Slopes or Crown

Tension cracks are cracks that occur when the stress in the embankment exceeds the strength of the soil. Tension cracks may indicate a serious slope stability issue and therefore it is important to fully document them during inspections. Tension cracks can be a precursor to slides. Typically, tension cracks appear as single or multiple, relatively deep, straight, or curved cracks that parallel the riverbank or embankment crown (Figure 9-10). These cracks may be several inches to over several feet in depth. Temporary measures to slow the development of an unstable slope include covering the tension cracks with plastic or backfilling the cracks with soil to reduce infiltration of rainwater/surface water into the cracks. Water-filled tension cracks increase the potential for slope failure. A more aggressive temporary action would be to place a soil or rock berm to add weight to the levee toe to decrease the likelihood of a slope failure.

Figure 9-10: Example of Tension Cracks

(a) Tension crack about 3 inches wide and 12 inches deep at the crown of the Chehalis-Centralia Airport Levee. (b) Tension crack with 1 to 4 inches of separation behind wooden soil-retaining structure in California.

3.1.1.1.3 Desiccation Cracks

Desiccation cracks, also known as shrinkage cracks, are cracks due to soil shrinkage that occur when high plasticity/expansive soils experience a decrease in water content. Soils that have shrink and swell potential are generally high plasticity (i.e., expansive) clays and elastic silts that are prone to volume changes directly related to water content variations. Desiccation cracks can run longitudinally or transverse to the levee or may appear as blocks. They are generally narrow and shallow, not extending more than a few inches in depth, but during long periods without rainfall, desiccation cracks may extend as much as 2 feet deep. The first indication of drought-caused instabilities may be desiccation cracks.

If left unmitigated through several cycles of wetting and drying, excessive desiccation cracks can reduce the internal strength of the levee. Thus, it is important to document them when they are observed (Figure 9-11). Increasing the monitoring frequency can help rule out a misidentification of a tension crack as a desiccation crack.

Figure 9-11: Example of Desiccation Crack

Measuring a desiccation crack in the Hoosick River Levee, near Hoosick Fall, New York.

Desiccation cracks usually do not require maintenance action, but deep or extensive cracking may warrant repair by scarifying, moisture conditioning, and recompacting the desiccated areas.

In extreme situations, replacing expansive clays/elastic silts with non-expansive engineered fill may be considered.

3.1.1.2 Erosion (External) and Bank Caving

Erosion is the removal of soil material from the earthen embankment, channel, foreshore, or beach by wind, flowing water, or waves. Erosion has been accelerating in many areas of the U.S. due to larger or more frequent floods and waves, wildfires, and even extreme heat and drought events, which can kill protective vegetation. Human and animal activity can also damage vegetation and disturb surface soils, making erosion more likely.

Erosion can remove portions of the levee and its foundation making seepage and slope stability issues more likely; or change the foreshore or water channel in ways for which the levee was not designed. Landside slope erosion can also occur during a flood, as a direct result of overtopping, leading to a levee breach. When this type of erosion is observed, levee breach may be imminent. Examples of embankment erosion are shown in Figure 9-12.

Figure 9-12: Examples of Levee Erosion

(a) Personnel measure erosion following a high-flow event along a levee in West Virginia. (b) Erosion furrows on upper slope of a levee embankment in Mississippi.

During inspections, erosion from rainfall may be observed in the form of rills—usually running down the embankment slope—or erosion due to the flood source may be observed in the form of loss of channel banks and erosion of the embankment slopes. A thorough inspection for erosion issues includes documentation of the following:

- Soil removal from embankment or bank surfaces above the water line by floods, waves, wind, or any other natural processes.
- Soil removal (or scour) of channel slope below the water line.
- Bank caving or areas of localized waterside slough or slide that occurs when the slope of an embankment becomes unstable.

Minor erosion can typically be easily repaired, but if erosion is not addressed quickly, it can progress to compromise the levee integrity and become unrepairable by maintenance techniques alone. Minor erosion can be repaired through replacement of displaced material with similar material. Consider adding slope armoring if the issue is recurring or has the potential to become severe. If the issue is more advanced, elevating it to the potential for rehabilitating the entire section of the embankment may be necessary.

> **CASE STUDY: IMPORTANCE OF EXTERNAL EROSION REPAIR**
>
> Levee name – Southern Enterprise
>
> USACE District – Little Rock
>
> Year of breach – 1990
>
> Cause of breach – Embankment erosion
>
> Short synopsis – The Southern Enterprise Levee was breached prior to overtopping due to erosion during the May 1990 flood. The levee had been previously damaged by erosion at the breach location during the 1986 flood and repairs had not been accomplished at the time of 1990 flood.
>
> The levee was removed at the breach location and reconstructed along a different alignment, farther away from the river channel.

3.1.1.3 Seepage (Internal Erosion)

Seepage is the internal movement of water through a levee embankment (throughseepage) or its foundation (underseepage). **Internal erosion** is the movement of soil particles caused by water passing through a body of soil. Internal erosion occurs on a levee when seepage exits on the landside levee face or foundation at or beyond the levee toe with sufficient force to erode and carry soil particles from within the levee foundation or embankment. Internal erosion can cause collapse of the overlying embankment and subsequent breaching.

Seepage typically only occurs during floods. Routine inspections and inspections to inform maintenance and repair can identify signs of seepage including areas of unusual wetness or water-loving vegetation on the landside slope or at the landside toe area (Figure 9-13). During floods, seepage can be observed as flowing water emerging from landside slopes and from the ground surface landward of the levee. Internal erosion can be observed as sand boils on landside slopes and landward of the landside toe, or significant depressions or holes in the embankment, especially near pipes. In some settings, sand boils can appear a significant distance out from the landside toe. During floods, inspections for seepage should include areas outside of the access corridor, especially if there are ditches or depressions in the area.

Because internal erosion typically causes damage within or underneath the embankment, there are not typical maintenance techniques to appropriately address the issue. Pervasive and problematic seepage locations should undergo geotechnical evaluation to determine if seepage remediation is needed and if so, the preferred seepage remediation method. If evidence of internal erosion is observed during a flood, floodfight procedures such as ringing sand boils with sandbags should be used to decrease the likelihood of levee breach. Planning and implementation floodfight actions are discussed in **Chapter 10**.

Figure 9-13: Examples of Seepage and Internal Erosion

(a) Isolated vegetation is denser and taller than the nearby vicinity as an indication of potential seepage. (b) Throughseepage emerging at the landside toe of a levee on the Mississippi River during a flood. (c) Very small sand boils (pin boils) moving negligible amounts of soil near the toe of a Mississippi River levee. (d) Medium sand boil transporting material along the Mississippi River levee. (e) Two large sand boils in a pump station ponding area in Illinois. Note the 'milkshake foam' in the foreground is often an indicator that sand boils are forming underwater. (f) Material emerging from around a deteriorated piezometer during a flood near the conflux of the Ohio and Mississippi Rivers. This can be a particularly concerning situation since the damaged piezometer can provide a direct pathway for seepage.

3.1.1.4 Embankment Elevation

Levees may experience settlement and/or subsidence. **Settlement** is a downward movement of soil in the levee or its foundation. **Subsidence** is sinking of the ground surface because of underground material movement. It is often caused by loss of soil under or within the levee due to animal burrowing, internal erosion, or other factors. Subsidence can also be a regional decrease in surface elevations due to natural consolidation or the removal of water, oil, natural gas, or mineral resources. Settlement and subsidence can both result in a lowering of the embankment's crest, thereby increasing overtopping risk. Differential settlement can move the location of initial overtopping, changing who and what is impacted first during levee overtopping. Severe differential settlement may induce transverse cracks which could allow water to flow through the levee causing a breach. Settlement and subsidence can also cause increased risk of damage to pipe penetrations through or under the levee.

Figure 9-14: Example of Localized Crown Settlement

Settlement in levee crown with elevation difference of about 1.5 feet on levee in Arkansas.

Inspectors can identify embankment elevation issues by looking for visible localized elevation changes or cracks that may indicate settlement or subsidence; however, gradual reductions in embankment height may not be detectable without a survey. Therefore, the best practice is to conduct topographic surveys at a frequency informed by the physical and risk characteristics of the levee including:

- Regional subsurface conditions.
- The number, type, and location of utility and other penetrations through or below the levee.
- Past settlement performance.
- Who and what would be impacted by levee overtopping.

If sufficient past data exists that indicates very low likelihood that future settlement will occur, a longer survey interval may be appropriate. When a levee is constructed over soft compressible soils, frequent surveys may be needed immediately after construction to track settlement and verify the design. Less frequent surveys may be adequate as time passes and consolidation slows. To support evaluation of levee elevation changes, settlement monuments may be installed as part of levee monitoring, and scheduled surveys may be a part of the levee's instrumentation plan (section 2.8).

Prompt correction of embankment elevation changes is important to avoid further deterioration of the embankment and an increased likelihood for overtopping. Small areas of elevation loss may be repaired by removing the vegetative cover or levee crown road cover, scarifying (i.e., roughening) the exposed levee materials, placing and compacting the same type of material as the original levee composition to restore the design elevations, and restoring the vegetative cover or levee crown road cover.

Adding material to the top of a levee may also be appropriate for longer stretches of embankment elevation change; however, foundation considerations are necessary. If the levee is built on a soft soil foundation, there is risk of further settlement and/or subsidence or a resulting slide because the strength of the underlying soft clays and silts may not be able to support new fill loads. Designed levee rehabilitation may be needed in these cases. In areas with ongoing settlement and subsidence, it is important to have a long-term plan to address ongoing settlement with periodic levee raises. If regional subsidence is the issue, a regional plan to address overtopping risk across levees on a regional scale is a best practice.

Embankment elevation repair may be beyond the scope of day-to-day maintenance if the elevation change observed exceeds the anticipated design settlement. Excess change in embankment elevation could be an indication of several serious issues including:

- Ongoing primary or secondary consolidation settlement beyond the design engineer's assumptions.
- Internal erosion in the levee prism or foundation soils.
- Desiccation shrinkage of the levee.
- Animal burrows causing voids that collapse within the earthen embankment.

CASE STUDY: MANAGING LEVEE RISKS ASSOCIATED WITH SETTLEMENT AND SUBSIDENCE

The Southern Louisiana region is known for its soft and compressive soils. The soil conditions are so severe that levees need to be constructed in multiple lifts with several years in between to allow the foundation soils to settle and strengthen before the next lift is constructed. To make matters worse, the entire gulf coast region is subsiding at an approximate rate of about 0.2 inches per year, due to numerous causes, including water and oil extraction. The result is an extremely dynamic condition where top of levee elevations are continuously changing. This is problematic during hurricane and floods when emergency management agencies and the public need to know as early as possible if overtopping of the levees is likely.

O&M strategies were adapted to maintain current levee elevation data in the NLD to meet the need for accurate levee information during hurricane events. A process was created by the USACE New Orleans District that facilitates high quality survey data collection by levee owners and timely upload of this data to the NLD. In addition, intensive quality management of the NLD has been instituted by the New Orleans District and levee owners to identify and update out-of-date levee elevation data. The diligence of levee owners and the New Orleans District has made the NLD an indispensable source of data that helps state emergency managers and the public understand the overtopping risk associated with hurricanes as they approach the Louisiana coast.

- Consolidation of foundation soils caused by a lowering of the groundwater table.
- External erosion from overtopping flows.

Refer to **Chapter 7** for further discussions on long-term rehabilitation solutions for maintaining embankment height.

3.1.1.5 Sod and Other Herbaceous Vegetative Coverings

Exposed soil on the levee embankment surface is vulnerable to external erosion by wind, precipitation, traffic, scour, wave erosion, and overflow/overtopping. Sod is often used as a levee covering to limit erosion. Other herbaceous plants may also be used as slope covering when included as part of an overall vegetation management strategy (section 2.4). Herbaceous plants native to the area may be more successful in hot regions with insufficient precipitation to support healthy sod coverage.

Nonetheless, bare embankments without vegetative covering may exist in some arid environments. Bare embankments can require increased maintenance due to increased cracking and erosion. In areas where vegetation cannot be maintained, gravel rock slopes and asphalt/concrete covering are typically used for erosion protection. Erosion protection is covered separately in section 3.1.1.6.

Vegetation on and near the levees should be inspected by thoroughly viewing the entire levee to ensure that all areas designed to be protected by sod or other vegetation are covered by a healthy stand of vegetation and documenting all areas of missing or damaged vegetation. Examples of typical sod damage are shown in Figure 9-15. Linear streaks of dying vegetation along roadways, fences, or water edges may indicate the misuse of herbicides.

If the levee is covered with sod or other herbaceous vegetation and it is more than about 12 inches in height during an inspection, it can prevent proper viewing of the levee. If the levee's vegetation management strategy includes woody vegetation, inspections should be performed as described in the vegetation management strategy.

Maintenance activities for sod and other types of slope covering include mowing, grazing, or burning to control vegetation height, watering, fertilizing, aerating, and controlling weeds/invasive species. Repair activities include seeding, placing sod, or replanting over bare areas and then maintaining, as needed.

Figure 9-15: Examples of Damaged Sod

(a) Gaps in sod growth on a levee slope along the Mississippi River. (b) Patchy area of sod cover on a levee slope in Iowa.

3.1.1.6 Erosion Protection

Erosion protection is typically designed, and then inspected and maintained as part of the levee in areas where vegetation is inappropriate or inadequate for erosion control. These conditions may be present on the levee embankment, the channel bank, or foundation soils adjacent to any levee feature. Examples of areas that may require slope protection include:

- Fast flowing river stretches and river bends.
- Along lakeshores with a high wave potential.
- Regions with insufficient precipitation to grow sod and other herbaceous vegetative cover.
- Coastal areas where salt spray is incompatible with dense, healthy grass growth.

In these areas, levees can be protected by a facing of stone, concrete, or another hardscape. Levee slope and channel bank armoring methods can be categorized into the following: stone, concrete, and asphalt methods; cage and block methods; and softer engineering methods.

Inspection of erosion control features should be performed by identifying and documenting all locations where the erosion protection has deteriorated (e.g., cracked, rusted), where erosion is occurring in the vicinity of the feature, and where vegetation is present in the feature. Examples of erosion protection in need of maintenance are shown in Figure 9-16.

Figure 9-16: Examples of Damaged Slope and Bank Erosion Protection

(a) An approximately 3-foot-wide hole in the waterside slope armoring of a California levee. (b) Riprap revetment on waterside slope of an Oklahoma levee partially silted in with vegetation growing within the riprap.

Possible maintenance actions include spraying for or removing vegetation and addressing minor deterioration through actions like filing cracks in pavements or repining geotextiles.

Repair actions may include replacing riprap that has deteriorated or been washed way, replacing sections of damaged or missing pavement, replacing deteriorated gabion baskets, and replacing damaged geotextiles. If the damage is significant, some portion of the levee embankment or bank slope may need to be rebuilt with soil before the erosion protection feature is repaired—these larger levee rehabilitation actions may require engineering design. More detailed inspection and maintenance actions are provided in Table 9-5.

Table 9-5: Inspection and Maintenance of Slope and Bank Erosion Protection

Method	Inspection and Maintenance Needs
Stone and Concrete Methods	
Riprap/riprap grouted with asphalt or colloidal concrete	• Inspect for movement, loss of rocks, a change in rock size (especially after cold events), or toe erosion. Note that one of the benefits of riprap is that some displacement may be allowable. • Inspect for loss of stones or infill. • Saplings or vegetation growing between the riprap stone should be regularly removed to avoid unduly displacing the riprap. • Replace loss or damaged riprap. • Repair grout as needed.
Asphalt revetment	• Inspect for erosion and cracking; increase inspection frequency as asphalt ages. • Cracks should be monitored and checked for signs of sand washout. Sand washout could be indicative of uplift pressure underneath the asphalt. • Repair cracks regularly. • Remove sapling or shrub growth. • Remove, replace, or overlay damaged asphalt.

Method	Inspection and Maintenance Needs
Concrete/pointed masonry-covered levee slopes	• Inspect the slabs for excessive cracking, inspect for signs of underslab erosion. • Replace cracked masonry. • For underslab erosion, mitigate the cause of erosion, remove masonry slab, fill-in eroded area with engineered fill prior to replacing slope covering.
Cage and Block Methods	
Gabions	• Inspect wire cages for corrosion. • Inspect for vegetation growth. • Inspect for damage caused by vandalism or floating debris during high flows. • Replace damaged wire cages made of stainless steel for greater design life. • Remove woody vegetation growth to prevent displacement of cages.
Cellular blockwork	• Inspect regularly for loss of infill. • Replace loss of infill with similar fill. • Inspect for and remove vegetation growth.
Softer Engineering Options	
Geotextiles	• Inspect for exposed geotextile. (If not covered, geotextile is susceptible to being torn by floating debris during high flows, and breakdown and deterioration from exposure to sunlight.) • Re-pin geotextile sections that have lifted from the face of the levee. • Replace damaged geotextile. • Cover exposed geotextile, as appropriate.

3.1.1.7 Crown, Toe, and Access Roads

Proper maintenance of roads along the levee crown and toes and related access roads allows access for inspection, maintenance, and floodfighting (Figure 9-17).

Inspections should note locations, and spatial extent, and severity of the items listed below. The appropriate repair(s) of each item are also provided:

- **Road depressions and rutting**: If depression/rutting is within soil, scarify, moisture condition, place fill, and compact to design elevation. If depression/rutting is within the asphalt covering, overlay to design elevation, recycling existing asphalt to greatest extent possible in the overlay mix.
- **Asphalt or gravel loss**: Repair scheme similar to “road depressions and rutting” above.
- **Road cracks/distress**: Fill in cracks within asphalt roadway with asphalt tack solution; if cracks are extensive, overlay with a layer of asphalt. For cracks within gravel/soil roadway, scarify/moisture condition/recompact to seal the cracks.
- **Impediments**: Fallen trees, exposed tree roots, and debris items across roadways are examples of impediments that prevent traffic flow and should be removed.

- **Turnarounds**: Keep turnarounds (area of the road that is wider) in good working order to allow multi-directional traffic flow.
- **Drainage**: Keep roads properly graded so ponding of water along the road does not occur.

Figure 9-17: Examples of Levee Roads Needing Repair

(a) Gravel loss on an Arkansas levee crown roadway. (b) Rutting on a Columbia River levee slope access road.

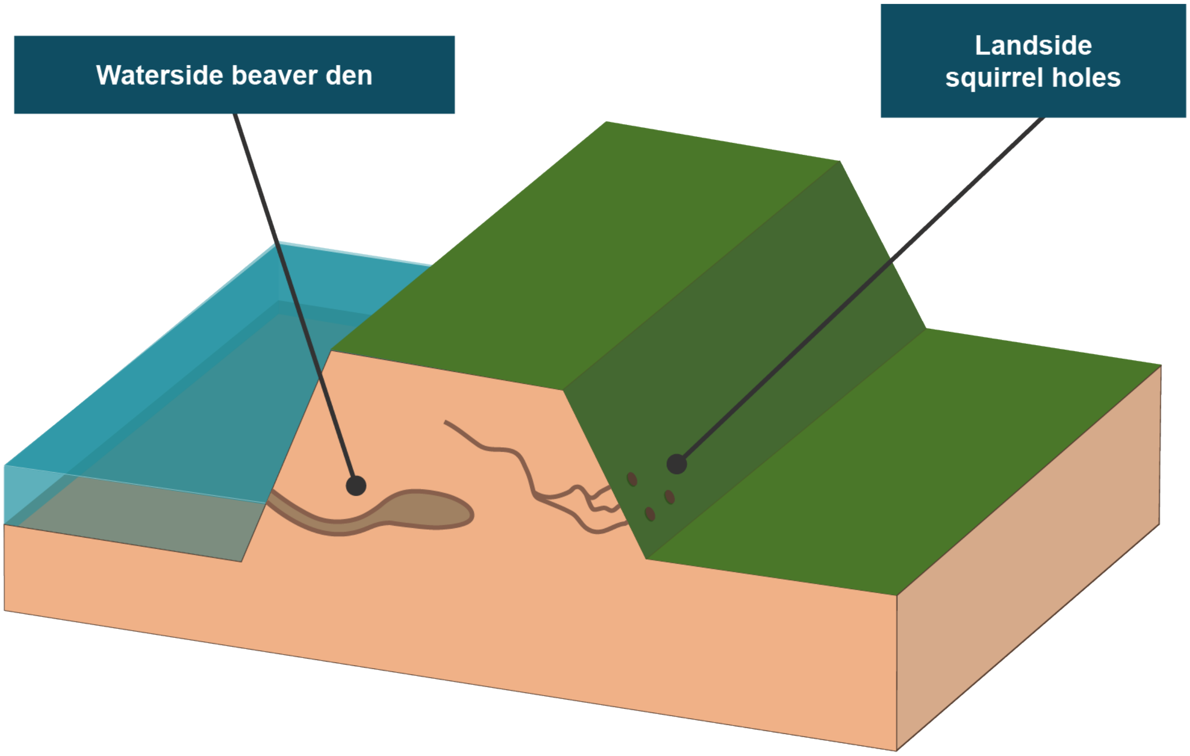
3.1.1.8 Managed Overtopping Sections

Some levees may include managed overtopping sections, locations with a lower crest for intentional overtopping to control and direct flood waters, typically away from populations. For these sections to function properly, inspections and maintenance activities should ensure that no modifications to elevation have occurred, and that the erosion protection (including armoring on both the landside and waterside, as well as protection to the levee crest and toe) is in good shape. Vegetation management and debris clearing is also important, as impeding overtopping flow in these sections will prevent their proper function. Clear signage that identifies the location as a managed overtopping location can prevent sandbagging or other floodfighting techniques that could render the managed overtopping location ineffective. Any development in the leveed area adjacent to the managed overtopping sections should be monitored.

3.1.1.9 Burrowing Animals

Burrowing animals dig holes or tunnels into levees for habitation and to find food. These burrows may be short, single tunnels to lengthy, complex tunnels that can traverse a levee cross section. The burrows can destabilize levee slopes and allow the passage of water through the levee, which can lead to internal erosion and levee breach. Figure 9-18 provides an example of how different animal burrows can collectively increase levee risk.

Figure 9-18: Burrowing Animal Tunnels Impacting a Levee



Close attention should be given to the presence of burrowing animals since they may not be readily detected without a thorough inspection. Animal burrows can be identified by looking for piles of soil, burrow holes, and the animals themselves. Figure 9-19 shows an example of how untreated animal burrows can lead to a levee breach.

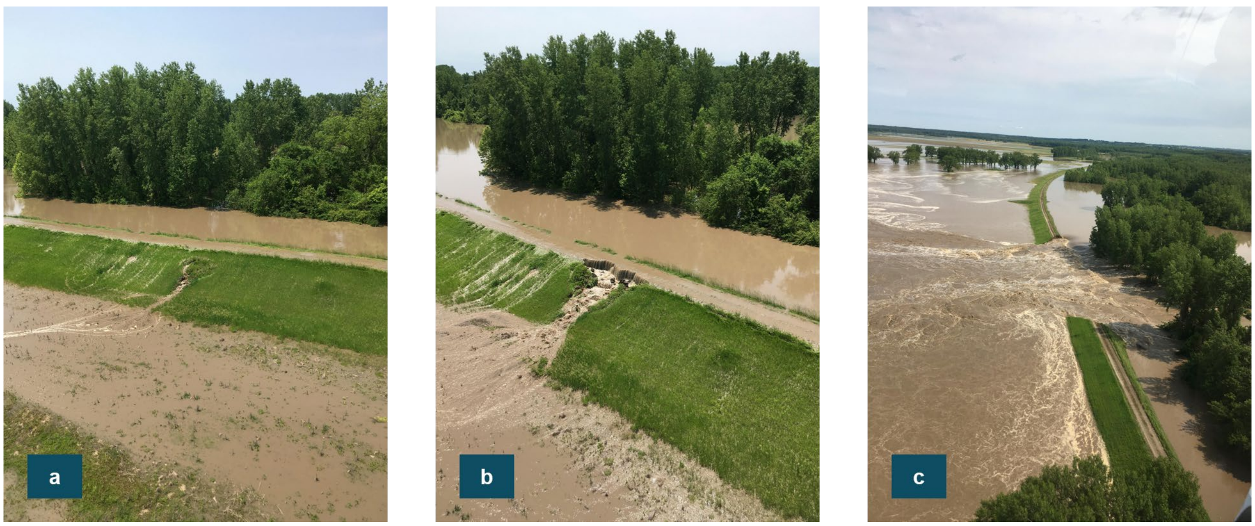
An important maintenance measure is to control the presence of burrowing animals on the levee to prevent burrow holes. An animal control program should include the following activities:

- Identify animal species relevant to their area and the characteristics of the species' activity.
- Assess the risk to levee integrity that may be posed by the animal's burrowing characteristics.
- Identify existing or pending protective or environmental legislation that would shape prevention and repair techniques.
- Formulate plans for preventing future occurrences.
- Formulate plans for repairing existing issues and future issues, as they arise.

Animal burrows can be controlled by maintaining levee vegetation in accordance with a vegetation management strategy that has been designed to discourage the presence of burrowing animals. Planting strategies, such as providing predator perching habitat or utilizing plants unpalatable to burrowing animals, may assist in controlling populations. See section 2.4 for more information on managing vegetation in accordance with vegetation management strategies. See **Chapter 6** for more information on developing vegetation management strategies.

A related strategy may include creating alternative habitats to encourage animals—especially endangered species—to inhabit areas other than the levee. Trapping and relocating burrowing animals through the use of cage traps can provide selectiveness to target particular animals and be highly efficient for animal control. Permits may be required for the use of live traps or to relocate protected species. Installing impenetrable metal mesh just below the surface of the embankment soil can prevent burrowing animals from penetrating the levee prism. Barriers to burrowing may be most beneficial adjacent to agricultural lands or other areas with significant food resources.

Figure 9-19: Example of Animal Burrows Leading to Levee Breach



The progression of a levee breach on the Missouri River due to animal burrows is shown from (a) water seeping through a burrow, to (b) erosion of the landside slope, and to (c) breach.

Once a levee section has become infested by burrowing animals, the holes they created should be mitigated as soon as possible. Methods for repair include:

- Excavate the area around the hole, backfill the excavated area in lifts, and re-compact the material to the same compaction as the adjacent levee. One concern with this method is that either the main tunnel or the tunnels branching off the main tunnel may be missed and not mitigated.
- Backfill the holes with a low pressure, flowable grout, at a viscosity that will adequately fill the holes, and is compatible with the local groundwater chemistry (commonly, a ratio of three cement to one bentonite solution is used). When holes created by the rodents are properly backfilled, their habitat is disturbed, which discourages them from returning to the site.

If burrowing animals cause irreparable damage to the levee, more significant actions may be needed to address the problem, which may fall under rehabilitation. This may happen if the burrow penetrates an impermeable layer of a zoned embankment; if the hole is beneath the levee and provides a path for internal erosion to occur; or the burrows are so large or numerous that they compromise the stability of the levee embankment.

3.1.1.10 Vegetation

Inspection of the earthen embankment and other levee features consists of review of vegetation conditions compared to the established vegetation management strategy for the levee (section 2.4). The impact vegetation can have on both performance and access is considered when a vegetation management strategy is developed. Inspection observations or access issues can be used to inform updates to the vegetation management strategy.

Regular maintenance can keep vegetation in line with the vegetation management strategy. While all levees will vary, the actions below are the most common tasks conducted to maintain vegetation on levees. The actual tasks for a specific levee will depend upon the types of vegetation included in the vegetation management strategy and the access needs of the levee owner.

- **Mowing or other reduction of grasses and herbaceous vegetation to allow for inspection**. In some places, burning or grazing may be used in lieu of mowing. Where possible, mowing (or burning or grazing) should occur after desirable vegetation has set seed. This will ensure that the desirable vegetation comes back year after year.
- **Thinning or limbing of trees to allow for inspection and for equipment access prior to the flood season**. Trees within the access corridor should be limbed to achieve a necessary overhead clearance for equipment. This is usually 8 feet but could be as high as 15 feet depending on equipment used for needed maintenance.
- **Tree inspections to ensure health and stability**. Trees within the access corridor should periodically be inspected for stability and health by a trained professional. Trees with known health or stability warning signs should be assessed more frequently or removed when deemed necessary to prevent damage to the levee.
- **Tree removal to manage levee risk**. Sick or unstable trees—or trees that are negatively impacting levee performance—should be removed, including the removal of their root systems. The extent of root removal should be based on an assessment of levee risk. Where the roots are removed, the area may be rebuilt by backfilling in lifts with material and compaction similar to the adjacent embankment.
- **Trimming or removal of branches or limbs of shrubs to retain flexibility**. Regular and routine trimming of woody shrubs will help them retain flexibility, prevent the accumulation of dead wood, and maintain the vigor of the plant. While appropriate frequency varies by species, a common interval is usually every three to five years.
- **Invasive plant removal to prevent exotic species from rapidly becoming problematic on any levee**. Once established, they can be costly and time consuming to remove. Invasive species can increase fire risk, choke out desirable vegetation, contribute to erosion, and damage nearby ecosystems. Invasive plant inspection and removal should be conducted annually.
- **Supplemental seeding to cover bare spots**. Prior to the growing season, large bare spots should be seeded with the desired native seed mix. Seeding bare spots will help to

prevent invasion by non-native species and will help to protect the embankment and the remaining access corridor from erosion. Ensure native seeds have been properly stratified before planting.

3.1.2 Operations

Earthen embankments are a passive part of the levee and do not require operation. Levee owner/operators' focus should be on inspecting the integrity of the levee embankment and performing necessary maintenance and repairs.

3.2 Floodwalls

As presented in **Chapter 2**, floodwalls consist of various shapes and styles of wall constructed of concrete, steel, vinyl, or plastic. Traditionally, floodwalls are fixed, non-operable structures. They may include contraction and expansion joints designed to mitigate cracking, construction joints where two wall units attach, various drains or weepholes, and/or waterstops of rubber or polyvinyl chloride where a watertight seal is needed at a joint. Each of these areas requires routine inspection and maintenance.

IMPACTS OF CLIMATE CHANGE ON FLOODWALLS

Floodwalls can be one of the levee features most at-risk from extreme weather events and long-term climate change impacts, not only due to their shape and exposure, but also because of their location in highly developed areas. Higher water levels—whether from long-term increased riverine flows in regions where precipitation is increasing, sea level rise in coastal regions, or rising groundwater from a variety of sources—may undermine wall foundations or increase the frequency or intensity of wall loading. The stronger winds, higher waves, and increased flow volumes increasing in frequency across the nation may compromise floodwalls designed for historic weather conditions with breach resulting in a higher consequence from impacting heavily populated areas. Any combination of these loads may decrease the wall's functional design life. Because of this, floodwalls may show first signs of climate change impacts, visible as rising water lines on floodwalls, increased erosion or wall deterioration, or wall tilt. In estuarine areas or coastal rivers, rust and accelerated corrosion of floodwall components may be among the first indicators of local saline intrusion from rising seas.

3.2.1 Inspection and Maintenance

Floodwall inspections include looking for damages by physical impacts, land movement, or material deterioration. Thorough inspections include observing and documenting the integrity of the wall structure and the condition of wall materials, any moving or operable parts, the foundation, and the ground and vegetation within the floodwall right of way. Figure 9-20 shows typical damages including differential settlement, spalling or cracking, and torn or deteriorated waterstops, as well as tilting or movement of the wall. Figure 9-21 shows floodwalls in need of repair.

Figure 9-20: Typical Floodwall Damages

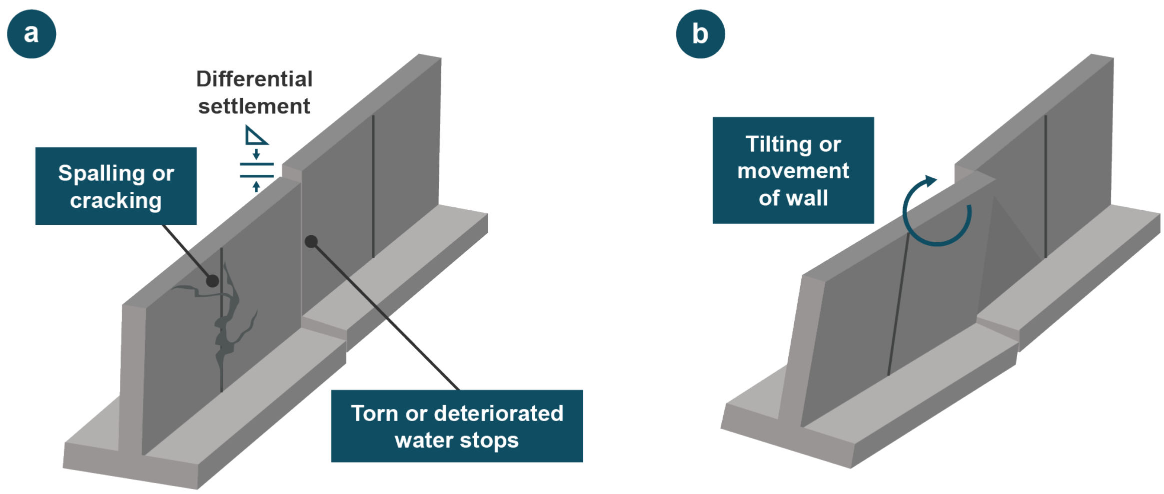
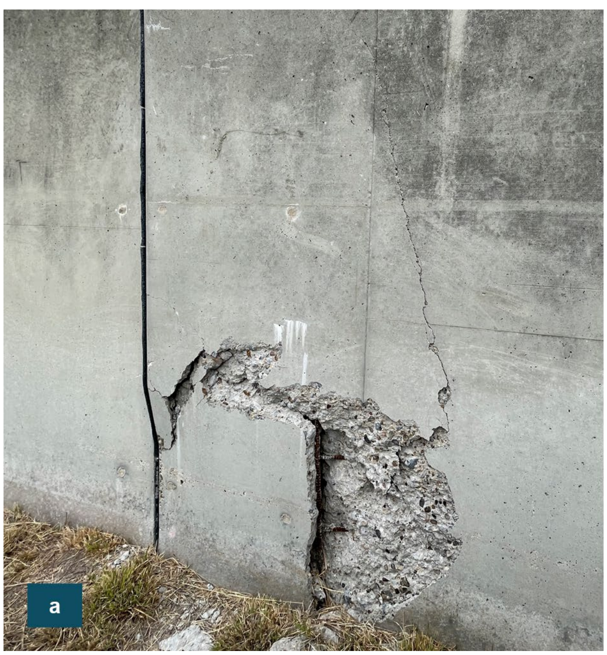


Figure 9-21: Examples of Floodwall Damage



(a) Floodwall in Massachusetts with differential settlement, spalling, and cracking. (b) Floodwall on the Texas coast with monolith failure due to erosion of foundation soils. (c) Large concrete spall on the top edge of a floodwall in Pennsylvania.

3.2.1.1 Wall Structure

Floodwalls should be closely inspected to determine if they are settling or tilting. Floodwalls that have settled or have tilted significantly enough to cause a decrease in top of wall elevation have a greater probability of overtopping. Floodwalls which are out of plumb (or tilted) also have decreased resistance to horizontal loads (either water or soil loads) and may result in cracking and discontinuity between monoliths, which would allow seepage to occur.

Inspectors should be familiar with the configuration of the floodwall and inspect the top of wall and the relationship between adjacent monoliths to identify discontinuities that may indicate tilting, settlement, or both. In cases where movement is continuous along the wall, uniform settlement or tilting may not be easily observed and regular surveys can be used to evaluate wall movement. See section 3.1.1.4 for a discussion of factors when determining the frequency of surveys. The O&M manual should provide criteria for maximum allowable tilting and settlement, but in general, walls with new or increasing movement should be evaluated.

Floodwall inspections also include looking for cracks, spalling, or flaking of concrete floodwalls. Floodwalls composed of steel should be inspected for corrosion. Floodwalls composed of vinyl/plastic should be inspected for cracks or erosion of wall thickness.

For reinforced concrete walls, repairs and maintenance may involve patching, sealing cracks larger than 1/16-inch, and sealing monolith joints. Floodwalls with cracks greater than 1/8-inch may require evaluation for rehabilitation/replacement. Internal elements such as rebar or steel should not be exposed and patching over exposed elements should be done promptly to avoid oxidation or further damage. Cracks should be inspected for efflorescence, or white powdery build-up, as this may indicate water is seeping through the structure. EM 1110-2-2002 provides further guidance for evaluating and maintaining levee features constructed using concrete (USACE, 1995).

In estuaries, coastal rivers, and other areas where rising seas may bring increased salinity, metal floodwalls and metal floodwall components (e.g., bolts, braces) should be checked for signs of increasing corrosion, and if found, replaced with less corrosive materials. Because many concrete mixtures are also susceptible to saltwater corrosion, concrete floodwall components should be inspected for discoloration, cracking, or pitting wherever local salinity may be increasing.

Walls that are acting as soil retaining walls may have drains or weepholes to reduce the potential for hydrostatic pressures on the backside of the floodwall. Inspections should confirm that drains and weepholes are open and able to transmit water from the back of the wall to the front.

3.2.1.2 Foundation

The floodwall and adjacent ground surface should be inspected for signs of settlement or subsidence. During floods, the ground surface should be inspected for unusual wetness on the landward side of the wall, which could indicate underseepage. The observance of sand boils confirms possible detrimental seepage and should trigger further evaluations and possible floodfight actions.

Toe drains at the base of the floodwall should be inspected, as described in section 3.5.1.4.

On the waterside of the floodwall, a gap at the ground interface can indicate that the floodwall is tilting or deflecting. This condition is particularly concerning for I-walls and can indicate the initiation of a failure mode that should be investigated immediately. Bank caving or erosion can indicate the need for erosion protection, and in some cases, potentially problematic changes in river channel alignment or bay/marine currents.

For minor issues, the damage can be repaired or decelerated by replacing lost foundation materials with material similar to or less susceptible to erosion than surrounding soils. Erosion protection, such as riprap or other armoring, should be considered to prevent erosion from reoccurring. Conditions that may be compromising the foundation stability should be evaluated to determine if rehabilitation is needed.

3.2.1.3 Joints

Inspections of floodwall joints include looking for debris and foreign materials, differential settlement or spreading between panels, deterioration of joint material, and deterioration or tearing of the waterstop. Joints should also be inspected at corner monoliths where the joints become critical upon application of load. The presence of hard debris in expansion joints, differential settlement, and damage to the joint filler material can all cause or speed up damage to the waterstop. Once the waterstop is damaged, water can flow freely through the floodwall joints.

Thorough inspection includes viewing all joint material to ensure it is in place and in good condition. If the joint material is missing or the waterstop is otherwise exposed, the waterstop may have been damaged. An inspection of the waterstop may reveal holes, tears, or other defects that will allow water to pass through during a flood. If landside seepage is observed, joints below ground may be damaged. Inspection of these joints may require excavation to determine the condition of the joint material and waterstop.

Maintenance actions for joints include replacing joint material and removing debris. Any joints with visibly torn or parted waterstops should be considered critical for repair. If the differential settlement between monoliths is greater than the allowable threshold, the waterstop is likely torn and should be repaired. Small joint leaks should be plugged with expansive material.

3.2.1.4 Vegetation

Vegetation around floodwalls is inspected and maintained in accordance with the vegetation management strategy for the levee (section 2.4). The strategy should take into consideration how vegetation may impact the inspection and performance of floodwalls. For example, climbing vegetation on the floodwall can damage concrete surfaces and inhibit inspection. Roots from trees and other woody vegetation can damage and clog toe drains, negatively impact shallow floodwall foundations, and increase the chance of seepage and sand boils.

Figure 9-22 shows vegetation within the access corridor that is negatively impacting the ability to inspect the floodwall and may be causing damage.

The best practice is for the floodwall vegetation management strategy to prohibit trees and other woody vegetation within 15 feet of the floodwall or within 8 feet of the edge of the floodwall foundation, whichever is greater. The floodwall may have been constructed in the shape of an

"L" or an inverted "T" such that the underground foundation extends several feet away from the visible wall.

Maintenance actions for vegetation around floodwalls are the same as discussed for levee embankments in section 3.1.1.10.

Figure 9-22: Vegetation Impacting Floodwalls

(a) Vegetation preventing inspection and inhibiting access to closure components. (b) Climbing vegetation preventing inspection of concrete surfaces on a floodwall in Connecticut.

NATURAL AND NATURE-BASED FEATURES IN FLOODWALL DESIGNS

While the best practice has long been to maintain floodwalls free of vegetation, there is growing recognition that incorporating natural and nature-based features into the design of floodwalls and other flood risk reduction features can provide important ecological co-benefits.

For example, rock placed for erosion protection can be designed with textured surfaces. Seawalls can be designed with rough surfaces and pocket rock pools. These added features replace smooth, artificial surfaces with rough surfaces and small pools designed to mimic the natural environment and create habitats for numerous sea organisms. “Greening” seawalls increases the biodiversity of the coastline, improving the health of the local environment and providing opportunities for locals and tourists to interact with a more diverse and natural coastline. These benefits can be achieved relatively cheaply with, very often, negligible impact on asset function, and, in some cases, reduced deterioration rates of the floodwall (Naylor et al., 2017).

Additional information on adding natural surfaces to floodwalls and other opportunities to add environmental features to flood risk reduction infrastructure is provided in the sources below. These publications provide information and best practices to assist in planning, implementing, and monitoring green infrastructure.

References:

- Greening the Grey: A Framework for Integrated Green Gray Infrastructure (IGGI) (Naylor et al., 2017).
- International Guidelines on Natural and Nature-Based Features for Flood Rick Management (Bridges et al., 2021).

A pocket rock pool and ecotile designs on a floodwall in Edenborough, Scotland, showing the difference in biological growth between plain cast and textured surfaces.

3.2.2 Operations

Floodwalls are passive features and do not require operation. Levee owner/operators’ focus should be on inspecting the integrity of the floodwall and performing the necessary maintenance and repairs.

3.3 Closure Structures

Levees frequently require openings in their alignment to allow access across or through the levee where roadways, railways, walkways, waterways (including both navigable and non-navigable types), and airfield taxiway transect the alignment of a levee. Such areas require water-tight closures to be moved into place prior to a flood. Closures addressed in this section do not include gates and valves, or other controls for pipes and other penetrations through a levee that are meant to convey water flow. Closure structures can be classified into three main categories as discussed in **Chapter 2**, movable gates, structural assembled closures, and earthen assembled closures.

3.3.1 Inspection and Maintenance

Prior to performing an inspection of a closure, the inspector should have a good understanding of the closure and how it is operated. One of the most influential factors affecting the ability to successfully operate closures is the operating plan and staff experience. Therefore, each inspection should include a review of the closure plan to ensure all required resources are readily available, staff understands the operation and notification processes, and that processes reflect current conditions. Routine inspections should include test operation of all closures as described in section 3.3.2.

Specific inspection and maintenance considerations for the three main categories of closures are described in the subsection below.

3.3.1.1 Movable Gates

Movable gate closures are typically the simplest most reliable type of closure. These closures are easy to set, require no inventory of parts, and can quickly be moved into place by maintenance personnel.

Prior to performing an inspection of a movable gate closure, the inspector should have a good understanding of the closure and how it is operated including required equipment, which may require reviewing design drawings, operation plans or emergency action plans, previous inspection reports, and O&M records. Movable gates should be inspected to ensure structural integrity, water-tight seals, and operability, including unobstructed movement and appropriate function of automatic components, alarms, or remote controls.

To confirm structural integrity, the gate and its components should be inspected for corrosion, deformation, cracking, and loose bolts or rivets. Seals should be inspected for debris, tearing, or deformation. All visible components (such as gaskets, gasket flange bolts, and hinges) should be inspected for corrosion or damage.

Road surface, rail track, or other sealing surface should be inspected to verify integrity and ensure the closure system will sit properly on the sealing surface. Grades or the cross-sectional shape should be verified not to have changed because of road repaving, reprofiling of railroad tracks, etc., which could prevent proper gate closure.

Operation of movable gate closures during an inspection verifies that gate movement is not obstructed and that the gate seats cleanly with all seals. Gates should open and close smoothly. Manual gates, such as swing gates should operate without the need for excessive force.

Automatic gates should operate when an appropriate trigger (i.e., water) is applied and without manual input. If a gate is operated using equipment, the availability of working equipment and qualified operators should be demonstrated or verified.

Figure 9-23: Examples of Movable Gate Inspection Observations

(a) Paint damage on the surface of a swing gate. (b) Damage to concrete floodwall and rust on a sliding gate stored in an opening in the floodwall. (c) Swing gate hinges in good condition. (d) Wheel on a sliding gate with missing paint and significant corrosion.

Maintenance for movable gates typically includes removing debris that could prevent movement or proper sealing; replacing torn or deformed seals to prevent leakage; lubricating hinges, pulleys, and wheels per manufacturer's instructions; and cleaning or painting the gate surface to prevent corrosion. Examples of movable gate inspection considerations are provided in Figure 9-23.

3.3.1.2 Structural Assembled Closures

Structural assembled closures consist of metal or wooden beams (known as stoplogs) that are placed in guide slots in an opening of a floodwall or in an opening of a levee embankment where a transition has been constructed specifically for the closure structure.

Prior to performing an inspection of a structural assembled closure, the inspector should have a working knowledge of the closure and its operation including the full list of closure components, where and how components are stored and organized, what equipment is required for installation, and the assembly process. This may require reviewing design drawings, operation plans or emergency action plans, previous inspection reports, and O&M records. Structural assembled closures should be inspected to ensure structural integrity and operability including an inventory and inspection of parts and verification that parts are stored in a safe, assessable, and organized manner.

Figure 9-24: Examples of Structural Assembled Closure Inspection Observations

(a) Separation of stoplog structure from concrete cap sheetpile. (b) Guide slots in good condition with some cracking in adjacent concrete gravity wall. (c) Close-up of reprofiled railroad tracks within a stoplog closure that will prevent stoplogs from contacting the seal plate. (d) Damage to concrete seal on a railroad stoplog closure.

To confirm structural integrity, the structure opening, guide slots, and all closure components should be inspected for corrosion, deformation, or other damage. The inspection and maintenance considerations for the floodwall or levee to closure transition structure are described in section 3.2. The guide slot inspection includes checking for and documenting the presence of debris, corrosion, or deformation. Stoplogs should be inspected for corrosion, damage, or deformation. Any deformation of the stoplogs or guide slots that may impact the ability of the stoplogs to be installed or to fit snugly into place should be emphasized in the inspection report.

Road surface, rail track, or other sealing surface should be inspected to verify integrity and ensure the closure system will fit properly against the sealing surface. The cross-sectional shape should be verified not to have significantly changed because of road repaving, reprofiling of railroad tracks, etc., which could inhibit stoplog placement. Any seals should be inspected for debris, tearing, or deformation. Examples of damage to structural assembled closures are provided in Figure 9-24.

Storing removable components in a nearby location landward of the levee will ensure they are readily accessible when floods are forecasted. The storage location should protect components from environmental elements, theft, and vandalism. The inspection should extend to the storage facility with the inspector noting any damages or deterioration to the storage facility and verifying that storage conditions are appropriate for the component material. For example, aluminum stoplogs need to be stored so they are supported along their entire length to avoid deformation during extended periods of storage. Some closure systems may benefit from parts being labeled to ensure parts are installed in the same order each time. The inspector should verify that all components are present and clearly marked and installation instructions are readily available. Examples of component storage methods are shown in Figure 9-25.

Operation of structural assembled closures during an inspection verifies that stoplogs can be installed smoothly within the guide slots and that all logs sit cleanly against their neighbors without visible gaps. It also helps ensure levee staff have the knowledge, equipment, and tools needed to properly operate the closure.

Figure 9-25: Examples of Closure Component Storage

(a) Closure components organized, labeled, and stored on a trailer in a warehouse. (b) Closure component storage shed located on the landside of the levee with some minor damage and vegetation maintenance needed. (c) Closure component storage immediately landside of the levee that provides convenient access but does not protect components. (d) Stoplogs stored in place with graffiti and damage due to a lack of security and protection from the elements.

3.3.1.3 Earthen Assembled Closures

Nonstructural closures—such as traditional sandbag, soil/gravel baskets, and earthen fill—also need routine inspection and maintenance of stored components, storage methods, and the location at which it will be installed. Surfaces where nonstructural closures will be placed should be firm, free of obstructions, and at the appropriate elevation. A thorough inspection will check for and document any new structures, changes in elevation, or other changes that could impact the installation of the closure.

Inspectors should also verify closure materials are in good condition and in appropriate quantity to complete the closure. Components (such as empty sandbags or soil/gravel baskets) should be replaced promptly when materials show any sign of deterioration. Storage conditions for nonstructural closure materials also need to be appropriate to the material of the closure. For example, it is best to store sand in a dry condition and to store sandbags where they will not mold or deteriorate. Clearly marking components and having installation instructions readily available will help ensure the closure can be efficiently installed during floods.

In some cases, it may be appropriate to coordinate with suppliers to ensure adequate quantities of soil or sand can be acquired on short notice rather than acquiring and storing stockpiles of soil material. If this method is chosen, regular coordination with local suppliers will keep contact information updated, develop relationships, and ensure the continued availability of the material.

3.3.2 Operations

It is a best practice to have a plan for the operation of all closures in place which includes operation triggers, staffing, parts and equipment, installation procedures, and requirements for coordination with other entities. Coordination with other entities, such as highway departments or railroads, is typically necessary before installing a closure to communicate impacts to transportation routes and allow for rerouting of traffic. Closure installation may also impact **evacuation** routes, so close coordination with emergency management agencies regarding planned operations is also essential. Adequate advanced warning should be provided to impacted communities when closures are anticipated to ensure disruptions are understood and accounted for.

There is always the risk that an error or malfunction will prevent proper and

CASE STUDY: EAST HARTFORD TEST OPERATIONS

The town of East Hartford, Connecticut, receives flood risk reduction from a ring levee with two stoplog closures. The stoplog test operations are such a critical part of town safety that they are advertised annually on the town website, and the community is invited to view the operation. The fire, police, and public works department work together each year to erect one of the stoplog structures to its full height. This process ensures each structure is practiced once every two years. Each test operation takes five to 10 hours and uses over 1,000 sandbags and 2,800 square feet of polyethylene plastic sheeting, in addition to timber or aluminum stoplogs.

The town also maintains a general information website for the levee that includes a link to the NLD and that helps to keep the public informed of levee operation, maintenance, and rehabilitation actions.

Annual exercise to practice stoplog closure installation in East Hartford, Connecticut.

timely closure during a flood. Conducting a trial increases the likelihood that the closure can be successfully installed in response to a flood by identifying deficient components, systems, or procedures. Regular practice can increase efficiency during an emergency, especially on closures that require manual assembly. For large or complex manual systems, test operations provide critical training and practice for operating staff.

Test operations should include all staff who will be involved during a flood including, as necessary, rail or traffic operators, first responder teams, and the operator or the contractor who installs the closure. It is also useful to check any alarm systems as part of the test operation. For heavy or complex closures in particular it can be helpful to train staff both individually and as a team. Training and familiarity with the specifics of a closure prior to a flood will help staff react confidently and correctly when waters are rising.

Performing test operations of closures during inspections greatly improves the quality of the inspection. Each routine inspection should include operation of all closures, including review and verification of all associated plans and notification procedures. Some closures should be operated more frequently between routine inspections. Operation frequency is discussed further in section 2.10.

3.4 Transitions

Transitions between two types of levee features create vulnerable locations. As discussed in **Chapter 2**, levee transitions are vulnerable to external erosion and internal erosion at the interface of the distinct features and material types. Therefore, inspections of transition zones are an important part of a levee's regular O&M.

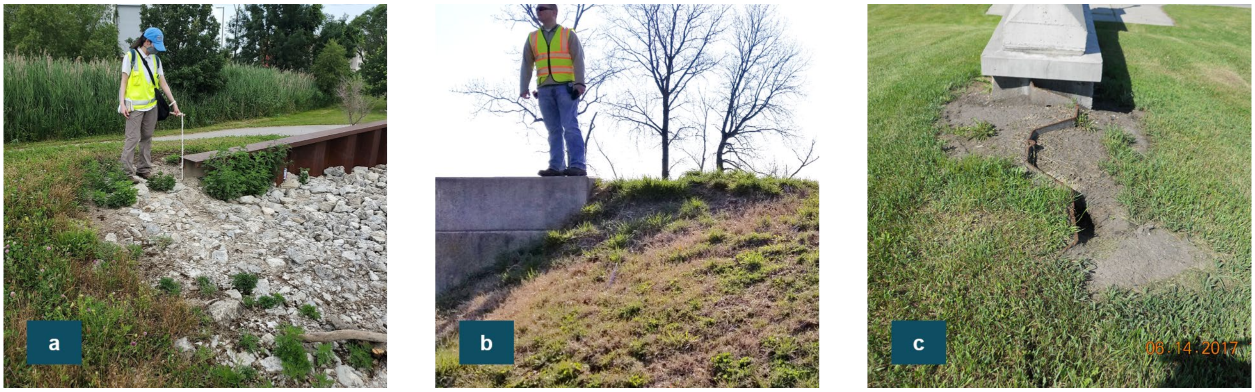
3.4.1 Inspection and Maintenance

Inspection at transition zones includes inspection of the individual features as described earlier in this chapter, as well as the additional scrutiny for signs of erosion or other issues at these potential weak zones.

Routine maintenance within levee transition zones can help to reduce the potential for discontinuities across the transition or weakening of the levee near the transition. For example:

- Embedded structures on the slope of levees have foundations that may be constructed with non-cohesive (sandy/gravelly) materials to promote drainage. If such materials are close to the levee surface, these non-cohesive soils may increase the vulnerability to erosion. Examples of erosion at transition zones are shown in. Being aware of changes in soil types and confirming adequate slope maintenance occurs with appropriate fill material can limit problems in these conditions.
- The application of herbicides on non-earthen features or components, such as riprap, to keep them free of weeds weakens the adjacent vegetation. This increases the vulnerability of the levees to erosion. Staying cognizant of the impact of human activities on vegetation can help inspectors recognize these issues and recommend the maintenance needed to prevent levee erosion.

Figure 9-26: Examples of Transition Zone Damage



(a) Shallow erosion at embankment to floodwall transition. (b) Shallow erosion at embankment to floodwall transition on Missouri levee. (c) Minnesota levee eroded at embankment to floodwall transition exposing sheetpile.

The following are maintenance matters to minimize erosion risk at transition zones:

- Implement erosion protection measures at transition locations where water movement, either by wave/tidal action, river flows, or overtopping flows may cause erosion.
- Observe and evaluate changes in soil type (e.g., sand adjacent to clay).
- Be cautious with the use of herbicides on non-earthen structures adjacent to the earthen structure and evaluate if the use of them can be reduced.
- Check for wet locations that may indicate seepage.
- Promptly repair any areas of material degradation or soil loss due to erosion.

Maintenance and repair of erosion at the transition and other issues for individual features at or near a transition zone should be addressed as described in earlier sections of this chapter. Repairs in these areas will consider the proximity to the transition zone and keep discontinuities at transition zones from worsening. When minor maintenance does not adequately repair a transitional area, a more thorough evaluation and rehabilitation may be required.

3.4.2 Operation

Levee transitions are a passive part of the levee and do not require operation. Levee owner/operators' focus should be on inspecting the integrity of the levee transition zone and performing the necessary maintenance.

3.5 Seepage Control Features

As discussed in **Chapter 2**, seepage control features are designed to improve levee stability and to help control the movement of water through the levee embankment and foundation. Seepage control structures most commonly include seepage and stability berms, relief wells, and cutoff walls.

3.5.1 Inspection and Maintenance

Seepage control features which are no longer functioning can allow erosion of internal embankment and foundation soils which can lead to a levee breach, making early identification and remediation critical. Closely inspecting seepage control systems can help ensure they are functioning properly to protect the levee during a flood. Data collected during floods from piezometers surrounding seepage control features can also provide indications of the need for maintenance or repair. Instrumentation is discussed further in section 3.9.

3.5.1.1 Cutoff Walls

As described in **Chapter 2**, **cutoff walls** provide a vertical low-permeability barrier to seepage flow under and/or through the levee. Although not a common potential failure mode, piping of the cutoff wall's low permeability material into surrounding soil could result in the ground surface above the cutoff wall settling. Viewing the ground surface over the cutoff wall for a linear depression is the primary focus of cutoff wall inspections.

Additionally, providing special provisions for construction activity in the vicinity of a seepage cutoff wall can help avoid damage to the cutoff wall. Appropriate processes for work that requires penetrating the cutoff wall can help assure the cutoff wall and levee embankment form a continuous seepage barrier as originally constructed. For both of these considerations, it is important to know the location of the cutoff wall, as they may be located anywhere within or beneath the embankment. Cutoff walls are not an exposed levee feature and therefore inspection and maintenance are limited.

3.5.1.2 Seepage and Stability Berms

Seepage and stability berms are embankments located at the levee toe to improve levee stability, as described in **Chapter 2**. Inspection and maintenance of seepage and stability berms include viewing the entire berm to identify and document cracks, depressions, settlement, damage to sod or other herbaceous vegetative cover, or other problems and making repairs as outlined in the earthen embankment section 3.1.

In some cases, berms may be designed to work in conjunction with a drainage system, which typically consists of filtered drainage layers and/or pipe networks, as described in section 3.5.1.4.

3.5.1.3 Relief Wells

Relief wells are used to relieve hydrostatic pressure in the foundation of a levee, as described in **Chapter 2**. Once seepage emerges from the relief well, it can either be discharged at the ground surface, often to be managed within ditches and ponding areas, or into a subgrade pipe. Both the relief well and the system for managing seepage water requires inspection and maintenance. See **Chapter 2** for an illustration of typical relief well positioning.

Over time, relief wells can become less efficient at relieving hydrostatic pressure because of clogging of the filter pack, sedimentation build up in the well screen, and biofouling. Clogging of the filter pack and sedimentation within the relief well occurs when the foundation material migrates into the filter pack, making it less permeable and reducing the well's effectiveness.

Biofouling is the buildup of bacteria on the well screen, reducing the area in the screen through which water can flow.

Relief well inspections include visual observation of external conditions, as well as evaluation of internal conditions, which requires special equipment such as depth-to-water indicators and downhole cameras.

External inspections of relief wells can identify damage or deterioration of visible components that could prevent the well from performing adequately during the next flood event. External inspections typically include:

- Inspecting external components, such as valves, gaskets, well guards, cover plates, flap gates on tee outlets, and other components.
- Ensuring vegetation is properly managed in the vicinity of the wells.
- Checking for erosion and sinkholes in the vicinity of the wells.

Internal inspections should be performed to identify issues that will prevent the well from properly relieving hydrostatic pressure before they threaten the integrity of the levee. The risk associated with the levee, the age of the relief well, and typical rates of deterioration can help determine the appropriate frequency of internal inspections.

Internal inspections typically include:

- Inspecting filter pack for migration of soil from surrounding areas.
- Inspecting for clogging/biofouling.
- Sounding wells for evidence of a collapsed screen or deposition of sand or other material in the wells.
- Inspecting any subgrade pipes required to manage seepage water for blockages and for damage or deterioration.

Flood-related inspections typically include checking for and documenting relief well flow. Keeping a record of relief well flow associated with various flood levels can help determine if the relief well performance is degrading over time.

Routine maintenance to keep relief wells operating efficiently includes:

- Keeping the area around relief wells free from vegetation, trash, and debris.
  - Maintaining vegetation in accordance with the vegetation management strategy. It is recommended to keep a 5-foot area around the well free of woody vegetation or vegetation that could block access or observation.
  - Removing trash or obstruction in the well or well guard.
  - Removing accumulated sand or other materials in/around flap gates that could obstruct the flow or prevent proper functioning of the gates.
- Maintaining outfall ditches, bank slopes, or berms in the vicinity of relief wells and horizontal outlet pipes.
- Keeping the ground around the well properly graded/shaped for ease of inspections.

- Keeping the interior of the piping system clear of debris and vegetation.
- Repairing or replacing external components, such as valves, gaskets, well guards, cover plates, flap gates on outlets, and other components, as necessary.
- Relief well pump testing and rehabilitation, as described below.

GUIDANCE

EM 1110-2-1914 provides further guidance on pump testing and well rehabilitation. (USACE, 1992).

3.5.1.3.1 Pump Testing

Pump testing each relief well and comparing the results to tests performed when the well was installed can identify performance losses. Loss of performance may be indicated by changes in well efficiency, specific capacity, or by measured increases in well entrance losses. It is important that pump testing be accomplished by qualified well drillers to ensure proper procedures and data collection. The frequency for pump testing may be defined in the levee O&M manual. Best practice is for pump testing to initially occur every three to five years, which can be adjusted to more or less frequent periods depending on the results.

3.5.1.3.2 Well Rehabilitation and Replacement

The comparison of pump test results to initial installation performance can identify the need for well rehabilitation. Reduced efficiency with time results in higher landside hydrostatic pressures and is typically due to either mechanical, chemical, or biological conditions. Mechanical conditions (well clogging or failure) can be caused by poorly designed filter packs, improper screen and filter pack placement, insufficient well development, and back flooding. Chemical conditions that may occur include carbonate incrustation and iron/manganese incrustation. Iron bacteria can be a biological source of efficiency loss.

Well rehabilitation within the context of routine maintenance includes repairs to damaged external components and mechanical, chemical, and biological rehabilitation of well screens. Mechanical jetting with chemical additives can be used to break down and remove the biological fouling or chemical encrustations. If the well has too much damage or encrustation/biofouling, replacement may be required.

In-kind well replacement may be needed if a relief well experiences any of the following:

- Breakage of well casing.
- Excessive deformation of the well screens due to ground movement.
- Corrosion or erosion through the well screen.

When there is a need for significant rehabilitation—such as multiple well or system-wide rehabilitation, replacement, or design changes to ensure the seepage control system provides the intended level of flood risk reduction—then the work is beyond maintenance and will need rehabilitation of the relief well system.

3.5.1.4 Drains

Drains can be employed alone or in conjunction with other seepage control features to collect seepage through or immediately beneath levee features. Inspections of drain systems should evaluate whether they are in good working condition and that components are not clogged or obstructed. This can be accomplished during floods by looking for and documenting the amount of drainage emanating from the filter system and looking for changes in performance. Low or no flow (in areas where flow is expected) could indicate the feature is clogged. Increased flow may indicate the filter system has failed and/or internal erosion of soils has occurred.

If the drainage system includes a pipe network, periodic internal video inspection should confirm the integrity of the system and help ensure it will function appropriately during a flood. The frequency for internal inspections can be determined similar to internal gravity pipe inspection frequency discussed in section 3.7.1.1.

Seepage and stability berm maintenance typically includes the following:

- Maintaining the design shape of the structure to ensure proper drainage and seepage/stability control.
- Monitoring for and repairing animal burrows.
- Checking drainage system functionality during floods.
- Maintaining surface drainage to ensure proper drainage of the berm.
- Maintaining vegetation growth in accordance with the vegetation management strategy.
- Preventing excavations on or near the berm.
- Keeping drainage layers intact during repairs.

3.5.2 Operations

Seepage control features are generally a passive part of the levee and do not require operation. Relief well collector systems may discharge seepage water to a pump station for evacuation of the discharged seepage water. In this case, it is important to ensure the pump station is operated correctly to provide necessary relief of hydrostatic pressure. Inspection, maintenance, and operation of pump stations are covered in section 3.8.

3.6 Channels and Floodways

Some levees have been designed to function in conjunction with a channel or floodway. This channel is integral to the levee and should be maintained and inspected as part of the system's O&M activities.

3.6.1 Inspection and Maintenance

Designed channels and floodways will be unique depending on the types of features they include and how they are designed to interact with the levee. A separate O&M manual should be developed for designed channels and floodways.

Generally, designed channels and floodways are inspected and maintained by:

- Removing overgrown vegetation and sediment accumulation.
- Repairing channel erosion, especially erosion with the potential to impact levee stability.

- Repairing damaged concrete surfaces or damaged revetments.

3.6.2 Operations

Channels and floodways are a passive part of the flood risk reduction system and do not require operation. The levee owner/operators' focus should be on inspecting the integrity of the channels and floodways and performing necessary maintenance.

3.7 Interior Drainage Systems

Interior drainage systems collect and manage water within the leveed area due to rainfall and other sources. These systems typically include three primary components: pipes, gates, and ditches, each of which requires unique O&M activities. An array of other components may also support management of interior drainage, such as headwalls to minimize erosion, trash racks to minimize debris, and gatewells to access gates and pipes within the levee interior. Whether the system is a simple gravity pipe, or a complex set of drains and gates, regular inspection and maintenance is vital to both maintaining levee integrity and preventing landside flooding. Considerations for each of these are discussed below.

Significant and even life-threatening flooding may occur when interior drainage is poorly maintained or undersized. This is particularly true given current shifting climate trends, many of which have the potential to increase surface and groundwater levels inland of levees. These trends, which vary by region, include those which may increase the frequency and/or the magnitude of interior drainage needs. Regional trends may include increases in annual precipitation, changing rain to snow ratios, faster or earlier snowmelt, increased frequency or severity of large storms, compound weather events, and increased average elevations of river or coastal waters.

3.7.1 Inspection and Maintenance

Blockage by debris, sediment, roots, or ice is one of the most common issues with gravity drainage structures, and is common to pipes, gates, and ditches (Figure 9-27). Both natural and human forces can deposit trash, vegetation, mud, and even large debris like mattresses, shopping carts, and boulders at pipe inlets and outlets. Neighboring landowners may pile yard or agricultural waste against the levee, in streams, or on land that drains towards the interior drainage system. The debris can then wash into and block interior drainage systems during a large rain event.

Channel erosion—combined with silt and sediment build-up—is common after a storm, flood, or wildfire events. Erosion at or upstream of a drainage structure can clog or block drainages. Removing built-up sediment and debris in gravity pipes and ditches will restore the capacity of the interior drainage system. Repairing erosion and regrading the inlet or outlet channels will help prevent further degradation.

Inspecting all drainage system components during each inspection will help to ensure that damages are identified and addressed in a timely manner. Inspection and maintenance activities specific to individual feature types are discussed below. Rehabilitation of more significant issues, such as significant pipe deformation or deterioration, requires efforts outside the scope of O&M.

CASE STUDY: CHANGING CONDITIONS ARE RAPIDLY OVERWHELMING INTERIOR DRAINAGE SYSTEMS IN SOME AREAS

To prevent future flood damage such as that done to New York by 2012's Superstorm Sandy, Manhattan has commenced construction on a $1.45 billion flood barrier project, the East Side Coastal Resiliency Project, to protect residents from coastal flooding via floodwalls and levees.

The project was tested in unforeseen ways when the remnants of Hurricane Ida crossed the U.S. from Louisiana to New York in 2021. The coastal storm surge in New York remained low, but pluvial flooding, inland of coastal barriers, was extreme. Precipitation rates over New York City varied from a 0.5 to 0.2 annual percent chance (or rain that would be expected once every 200-500 years). Twelve people were killed by flooding in low-lying areas. Interior drainage for the in-progress East Side Coastal Resiliency Project barrier has been designed to drain only a 20% annual chance (or 1-in-5-year average) rainstorm co-occurring with a 1% annual chance (or average 1-in-100-year) storm surge. It was not designed to be able to handle the peak intensity rainfall from Ida, which occurred after construction began. This type of extreme inland flooding is increasing in frequency and intensity in most regions of the nation and puts existing interior drainage structures under stress for which it was not designed. Increased inspection and maintenance will be required.

Aerial rendering of the East Side Coastal Resiliency project design (https://www.nycgovparks.org/planning-and-building/planning/neighborhood-development/east-side-coastal-resiliency).

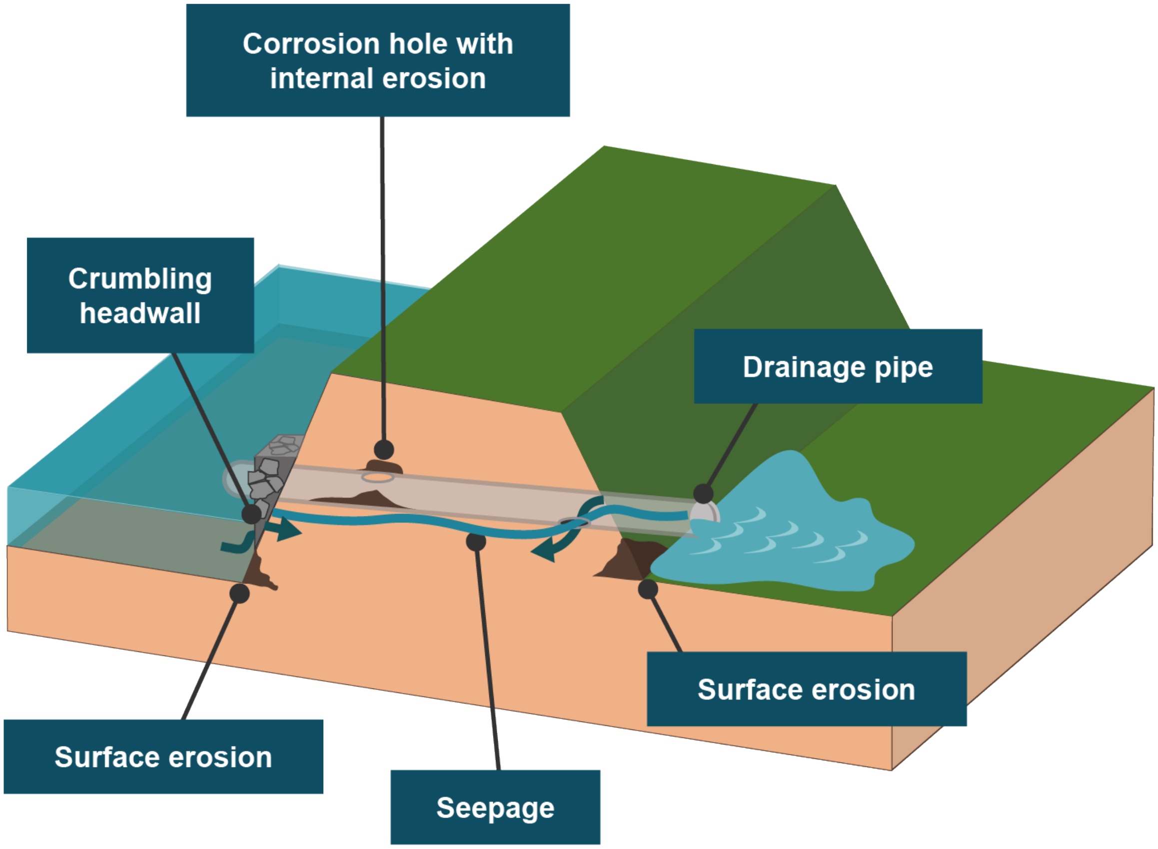
Figure 9-27: Examples of Vegetation and Debris Blocking Drainage

(a) A river in Houston, Texas, choked with trees after Hurricane Harvey. (b) Pipe blocked with ice in northern Wisconsin. (c) Partially blocked trash rack. (d) Community events on levees can generate large quantities of pipe-blocking debris. (e) Wildfire-generated siltation of the Ventura River, California, in 2019.

3.7.1.1 Gravity Drainage Pipes

Gravity drainage pipes are non-pressure drainage pipes designed with the intent to pass flow by using a shallow slope during normal conditions. During flood conditions, gravity drainage pipes are normally closed off with a gate. Several potential failure modes (**Chapters 2 and 4**) are related to issues with these pipes. Pipe damage can lead to internal erosion, in which soil migrates into the pipe through cracks and holes. Internal erosion may also be caused by water flowing along the exterior of the pipe at its interface with the embankment soils (Figure 9-28). Obstruction of flow into or through pipes can prevent appropriate drainage, leading to inland flooding with potentially severe consequences.

Figure 9-28: Gravity Pipe-Associated Concerns



Interior pipe inspections are necessary to ascertain the structural integrity of the pipe and to understand how pipe condition could impact the levee. Interior pipe inspections should include viewing the entire length of the pipe beneath or within the levee. Interior inspections of pipe can be performed manually by walking through the pipe or remotely using instruments. When safe, walk-through pipe inspections are preferred for pipes over 48 inches in diameter to provide the inspector the best ability to observe and measure areas of interest. When hydrologic or pipe conditions compromise safety, remote inspections should be conducted.

Performing exterior inspections allows early identification of issues that could impact performance or progress to major damage. External inspections check the condition of the visible pipe including: the condition of material and joints, the presence of blockages, and the condition of external components like erosion protection, trash racks, and headwalls. Cracking or depressions in embankment soils above and around pipes can be indications of a damaged pipe.

The following is a detailed list of exterior inspection activities:

- Confirm inlet and outlet are open and unobstructed.
- Check for and document pipe flow.
- Check that associated riprap and headwalls are in good condition.

- Check for evidence of erosion or other soil movement adjacent to the structure which might impact water tightness or stability.
- Check for any settlement of the earthen embankment immediately above the pipe.
- Check the condition of gaskets, pipe guards, and trash racks.
- Check pipe diameter at inlet and outlet and note ovaling or visible pipe breakage/stress.
- Monitor for deterioration of pipe interior as visible from outside the pipe. Signs include visual corrosion (e.g., rust, cracks, or holes), evidence of seepage (e.g., staining, evidence of soil migrating into the pipe), and roots penetrating the pipe interior.
- Check connection of pipe to associated features such as headwalls or flap gates. This is a particularly vulnerable location where issues often begin. Check for differential movement, soil infiltration, cracking, or weakness at junctions.

SAFETY PRECAUTIONS FOR VISUAL INSPECTION OF PIPES AND CONFINED SPACES

- Ensure inspection complies with confined space entry regulations.
- Properly train inspection staff for working in confined spaces.
- Ensure pipe dimensions are large enough for safe entry.
- Use appropriate personal protective gear at all times.
- Use gas monitoring equipment wherever a possibility exists for toxic gases (such as carbon monoxide or hydrogen sulfide), flammable gases (such as methane), or oxygen-deficient environments.
- Inspectors should never work alone.

Interior pipe inspections provide more detailed and precise information regarding pipe integrity and involve viewing the entire length of the pipe interior beneath or within the levee, either by walking the interior or by using instruments. Walk-through pipe inspections are preferred for pipes over 48 inches in diameter, when safe, to provide the inspector the best ability to observe and measure areas of interest. When hydrologic or pipe conditions compromise safety, remote inspections through closed circuit television or video recording should be conducted.

Remote pipe interior inspection options include sonar, remote operating vehicles, closed-circuit television, and drones. USACE's EM 1110-2-2902 provides guidance on how to choose both the appropriate inspection methodology and determine the adequate inspection length (when a full inlet-to-outlet inspection is not practicable). It also provides detailed instructions for pipe condition inspections for a variety of levee drainage conditions, including submerged pipes, and should be consulted for detailed recommendations (USACE, 2020).

Interior inspections of pipes include the following activities, with full documentation:

- Examination of joints for separation, root intrusion, and leaks (section 3.7.1.1.1).
- Check for deterioration, such as rust, cracks, holes, or missing bricks.
- Check for deformation or ovaling.
- Check for evidence of seepage, such as staining or evidence of soil deposition.
- Check for debris or sediment accumulation.

- Note flow characteristics (speed and direction).

Examples of pipe problems that may be detected through inspection are shown in Figure 9-29.

Figure 9-29: Examples of Pipe Problems

(a) Loss of protective bituminous coating and minor corrosion on the corrugated metal pipe along the Hutchinson Levee. (b) Pipe inlet filled with sediment and slightly ovaled in Hampshire County, Massachusetts.

Maintenance can extend the service life of a pipe, and includes activities such as cleaning, unclogging, coating, sealing, and repairing small areas of corrosion, concrete spalling, exposed concrete rebar, open joints, and minor cracking. In addition to extending the service life of a pipe, repairs may be necessary when a longer-term correction is not immediately practical.

Removing debris, sediment, and ice from the pipe inlet and outlet will restore drainage capacity. Blockages inside the pipe may require more intensive efforts to remove the debris.

An effort should be made to identify the source of interior pipe sediment, and if necessary, the pipe should be cleaned or flushed using methods appropriate to the pipe size, material, condition, and degree of blockage. Ice formation at a pipe mouth may form a complete block, leading to interior flooding. Ice may be removed by steaming it away or using hand tools.

Pipes should be maintained carefully to avoid damaging the pipe, the levee, or creating long-term operational issues. Overly aggressive maintenance, which can occur with high-pressure or rototill cleaning, may damage protective coatings or the pipes themselves. Adjustments to pipe interiors, such as slip lining, are known to increase the outlet flow velocity, which can lead to erosional conditions at the outlet increasing the potential for backward erosion into the levee and ultimately breach. Use of material-specific maintenance methods is critical, as is following relevant engineering standards and manufacturer's instructions.

For pipes that leak or pipes that are losing structural stability, the rehabilitation method selected should pose the least risk to the levee. It is preferable to slip line the damaged pipes to restore integrity to the pipe and conveyance system. Slip lining involves installing a smaller diameter pipe within the damaged larger pipe. For slip lined pipes, the annular space between the larger damaged pipe and the smaller pipe used as a slip line, would need to be grouted and the ends sealed. USACE's EM 1110-2-2902 and levee-specific operation manuals provide additional detail for both the appropriate cleaning methods and repair techniques for a wide variety of pipe materials (USACE, 2020).

If slip lining is not possible, open cut methods may be required. In general, open cut methods are the least desirable for rehabilitation but may be necessary if there is reason to believe significant soil loss has occurred around the pipe. A professional designer should ensure the abandonment, rehabilitation, or replacement of a levee penetration is accomplished appropriately without harming the levee structure.

NATIONAL ASSOCIATION OF SEWER SERVICE COMPANIES (NASSCO) CERTIFICATION PROGRAM

NASSCO was formed in 1976 as a not-for-profit trade association. Today, NASSCO leads the charge in providing quality education for pipeline condition assessment and inspection. Using the NASSCO Pipeline Assessment Certification Program and their certified inspectors is considered a best practice for assessing and recording pipeline condition. This program is designed to help pipe owners create comprehensive databases to properly identify, prioritize, manage, and renovate their assets based on proper condition evaluations.

CASE STUDY: IMPORTANCE OF PIPE MAINTENANCE AND REPAIR

Failure to adequately maintain, or quickly repair gravity pipes can lead to dangerous situations, as the following sequence of events illustrates. During high water in 2013, a 54-inch diameter corrugated metal pipe failed on a levee that runs along a tributary of the Mississippi River. The first sign of a potential breach was the appearance of a sinkhole formed mid-slope on the levee embankment, paired with a whirlpool/vortex.

Early attempts to stabilize the situation involved several dangerous situations. A truck attempted to approach the sinkhole with repair materials but sunk into the damaged levee and was pulled back out. Rock trucks then arrived on site and began placing rock at the crown, while a bulldozer pushed material into the vortex area. While this was successful in choking off the flow, by the next morning a sinkhole had formed in the crown, just where the numerous dump trucks and bulldozers had been working the previous day. The new sinkhole was rock-filled to the top elevation of the crown. During these efforts, a third sinkhole formed near the crown.

Due to limited funding and weather restrictions, replacement of the failed pipe did not begin until the fall of 2015. The excavation for this replacement was open when a flood began that winter, creating a second emergency management situation. Material was quickly placed in the excavation to restore the levee, but the material quickly began to slough and erode. Plastic sheeting was used to protect the riverside slope and regular surveys of crown height were completed to assess the likelihood of overtopping. The levee was maintained throughout the flood and the 54-inch corrugated metal pipe was successfully replaced in the fall of 2016.

Appropriate and timely pipe inspections and maintenance could have prevented the emergency situation in 2013. Prioritization of the pipe replacement could have prevented the second emergency which occurred in 2015.

(a) Sinkhole caused by a buried pipe failure. (b and c) In 2013, emergency levee repairs occurred at a pipe failure along the Mississippi River. (d) A second pipe failure occurred a few years later at the same Mississippi River site.

3.7.1.1.1 Joint Integrity

Joints along gravity pipes resist infiltration and exfiltration, accommodate lateral and longitudinal movements, and provide hydraulic continuity. Pipe joints include concrete joints, neoprene sleeves, rubber O-rings, gaskets, and steel end rings.

Joint inspections look for damage to joint filler material, signs of pipe separation, and root intrusion through the joint.

Joint maintenance and repair will vary by joint type, accessibility, and pipe material. In general, exposed joints that fail may need to be disassembled and replaced. Refer to levee O&M manuals and manufacturer's instructions for specific maintenance and replacement items , but a few good practices include:

- In addition to routine inspections, in regions that experience freezing ground, schedule pipe joint inspections to look for signs of pipe separation during cold periods.
- Root intrusion through joints should be repaired by removing all roots that have penetrated the joints, addressing associated vegetation on the levee embankment above the impacted joint areas, in addition and repairing defects in the pipe.
- In concrete pipes, joint separation may require complete pipe replacement. When the degree of separation is minimal, slip lining using trenchless technology or pressure grouting may be adequate to limit further deterioration. Open cut methods may be needed if the degree of separation is large, or erosion of pipe backfill materials is occurring.

CORRUGATED METAL PIPE LIFE SPAN

It is important to understand that corrugated metal pipes, frequently used in rural areas or where potential risks to life are low, have a typical life span of 50 years. Replacement of the pipe is therefore expected during the levee's service life, and inspections are as critical to identify the timing of that replacement as maintenance is to delaying it. Certain environmental conditions may expedite pipe corrosion: in regions with salinity intrusions, acidic soils (such as those high in peat moss), or high use of pesticides or fertilizers, inspection and rehabilitation may be needed more frequently than in less corrosive environments. Signs of deterioration in metal pipes include rust, corrosion holes, tearing, and cracks. Conduct maintenance at the first sign of issues to extend the pipe's usable life and avoid more intensive repairs. In order of priority:

- Restore protective coatings (either bituminous or polymer) when corrosion is noted on the inside of a pipe.
- Establish a pipe inspection strategy to regularly evaluate coatings.
- Weld new metal sections in place as patches.
- Cover holes with a cement grout or concrete.
- Open cut and replace or slip line the pipe using trenchless technology.

Examples of corrosion on a pipe's surface and corrosion leading to pipe damage.

USACE's EM 1110-2-2902 provides specific repair information for joint end damage, joint separation, joint infiltration, loose or damaged bolts, and leaking bells/spigots for a wide variety of pipe materials (USACE, 2020).

3.7.1.1.2 Headwalls

Headwalls are concrete structures which protect the end of a pipe (Figure 9-30). They improve flow conditions, anchor the pipe, support any gates, and protect against erosion. Failure of the headwall—or of the connection to a pipe or gate—could allow flood waters to enter the leveed area, or promote levee erosion to the point of breach.

Headwall concrete inspection and maintenance is similar to that for floodwalls, as discussed in section 3.2.1. Headwall inspections also include viewing the full perimeter of the headwall and wing walls looking for erosion or undermining. Inspecting and maintaining erosion control features around headwalls will allow these features to continue protecting the headwall. Surface erosion at pipe outlets may be an early indicator of internal erosion along the pipe length and may warrant further investigation. Early-stage erosion that is verified to be surface only can be repaired by backfilling with properly moisture-conditioned, benched and compacted backfill materials. Compacted backfill may be covered with filter stone and riprap designed to resist the exiting velocities from the discharge pipe.

Figure 9-30: Concrete Headwall Conditions

(a) Concrete headwall in disrepair in Illinois. (b) Concrete headwall in good condition in New Hampshire.

3.7.1.2 Gates and Gatewells

To prevent flow from waterside to landside, pipes through the levee typically have a gate at the waterside outlet. It is best practice for a secondary means of closure, such as a sluice gate located in a gatewell to allow manual pipe closure, be installed. The sluice gate and gatewell are usually at the waterside edge of the levee crown to be accessible during high water stages. Details of the inspection and operation of gates and gatewells and their components with common preventative and/or maintenance solutions are presented below.

3.7.1.2.1 Gates

Gates are structures that allow water to drain from the landside to the waterside of a levee, while preventing the reverse flow. Three types of gates represent the vast majority of culvert gate closures: sluice gates, flap gates, and duckbill valves. Sluice gates are active, or manually operated, while flap gates and duckbills are passive, defaulting to a closed position and opening when interior waters are higher than the flood source. Inspecting gates and removing debris regularly, prior to floods, and after any debris-causing or soil moving events will help ensure proper opening and closure.

Vertical sluice gates, also called slide gates, are generally composed of vertical steel gates that are lowered into place by either a screw stem or a pulley system, both of which may be manually or electrically driven. Along the sealing edge, seating wedges or slides may be present to allow for adjustments to better seal the gate in the closed position.

Sluice gates may be installed either at the outlet of the pipe or within a gatewell somewhere along the length of the pipe. Gatewells are concrete or metal structures which allow access to gates within the interior of an earthen embankment. Sluice gates constructed within a gatewell are typically placed on the riverside slope of the levee near the crown to allow easy access to the gatewell but may be further out on the levee slope or toe, requiring a bridge or even a boat for access during floods. Access challenges posed by such locations complicate the scheduling and performance of gate closures as well as inspections and maintenance. The need for boats and ladders also introduces safety concerns that should be addressed through planning and adequate precautions.

Inspection and maintenance of screw stems and pulley systems address issues such as damage, corrosion, binding, or small debris that can prevent the gate from being operated. Inspections should also include viewing the sealing edge, seating wedge, and slides to identify any damages that could prevent operation or proper sealing. Operation of the sluice gates during each inspection will verify operability and proper sealing. Examples of sluice gate conditions to look for are presented in Figure 9-31.

Figure 9-31: Examples of Sluice Gate Scale and Conditions

(a and b) Sluice gates at different scales in good repair. (c) Gears in need of cleaning and lubrication. (d) Leaking gate. (e) Bent and corroded in-water gate seals. (f) Vegetation encroaching on gate which may block closure.

Flap gates are common outlet closures because they are relative low cost and function automatically. They are designed to be closed except when draining water from the interior, at which time they are pushed open by the water pressure inside the pipe. Their most common issue is blockage (Figure 9-32). Lack of maintenance at the pipe outlet can result in the closure being blocked by silt or debris, preventing or limiting interior drainage capacity. Debris can also wedge flap gates open, allowing floodwaters to penetrate landward of the levee. Inspecting flap gates immediately prior to floods allows possible closure issues to be identified and addressed before the flap gate is submerged. Inspecting and lubricating the hinge and inspecting and cleaning the seal will allow the flap gate to move and seal as intended. Flap gate replacement may be considered if the gate is excessively damaged or corroded or if a water-tight seal cannot be achieved after normal maintenance.

Figure 9-32: Examples of Flap Gate Condition

(a) Flap gate on a gravity pipe through an Oklahoma levee in good repair. (b) Debris preventing flap gate to close. (c) Flap gate rusted and wedged open.

Because flap gates are comprised of recyclable metal and relatively easy to remove, they can be common targets for theft. Increasing the frequency of inspections or adding fencing or other security in areas with high theft potential can deter theft. Pre-flood inspections can ensure the gate is still in existence and functional.

Duckbill gates can be a solution to theft problems associated with flap gates. Duckbills are passive gates made of an elastomer and may be inline or protruding into the drainage ditch/channel. Sunlight, intense heat, and fire are all short- or long-term threats to the elastomer, which can harden or crack over time. Duckbill valves also have a history of attracting nuisance species who consume or pull-apart the material, creating holes. Inspecting duckbills for defects can allow damaged valves to be repaired or replaced before they are needed during a flood. Holes should be repaired according to manufacturer’s recommendations.

Duckbills can also be impacted by debris which can be caught within the duckbill, preventing proper closure during a flood. Example of duckbill valves and possible inspection concerns are provided in Figure 9-33.

Figure 9-33: Examples of Duckbill Valve Scale and Condition

(a) Duckbill valve and headwall in good condition in Indiana. (b) Large duckbill valve on a levee in Oregon with debris preventing proper closure.

Inspections of all gates and associated components include checking and documenting:

- The presence of debris, soil, or sediment blocking the gate or associated ditches or pipes.
- The condition of gates and associated components, including any corrosion, deformation, or deterioration.
- The condition of valves, gaskets, pipe guards, cover plates, flap gates on outlets, and other gate components.
- The presence of erosion adjacent to the structure which might endanger its water tightness or stability.

Maintenance of these components includes the following activities:

- Remove debris from trash racks/screens and gates.
- Sandblast and paint steel components as needed to treat or prevent rust.
- Replace components if structural integrity is judged to be compromised.
- Clean and lubricate bearings, bushings, hinge pins, wheels, and screws.

3.7.1.2.2 Gatewells

Gatewells are concrete or metal structures which allow access to gates located within the interior of an earthen embankment. Gatewells typically house gates that are closed during floods to prevent backflow through the pipe. They may be situated next to the levee crown to provide access regardless of the river level, or may be accessed via a platform, bridge, or boat.

Gatewell inspections include viewing all gatewell joints, particularly the waterstop which prevents movement of levee materials into the gatewell. Close inspection of these components is particularly important given the significant depth of gatewells within a levee. If inspections do not occur, internal levee erosion may be missed for long periods of time allowing many yards of embankment material to be lost before signs of erosion are visible at the levee.

Gatewell inspections also verify that the gatewell is unobstructed and free from hazardous pests. When access to the gatewell involves a bridge or boat, it is important for the safety, condition, and operability of access equipment to be included in inspections and maintenance performed to assure access is safe and functional under all conditions. USACE EM 1110-2-2902 provides additional information on the inspection, and maintenance of gatewells (USACE, 2020b).

3.7.1.2.3 Manholes

Manholes are primarily used to access pipes and gates beneath the ground surface. Common issues associated with manholes are the pipe connections, which, if damaged, may allow infiltration of water and soil into the manhole. Manhole covers are also subject to corrosion and can cause safety hazards when damaged. Manhole inspection includes checking connections and seals within the manholes for signs of damage or infiltration. Inspections also view the condition of concrete surfaces, the manhole cover, and the access ladder. Manholes can present safety issues to inspectors or others if ladders or gates break or deteriorate (Figure 9-34).

Manhole maintenance includes cleaning and painting metal components, repairing pipe joints, and repairing spalled or damaged concrete.

Figure 9-34: Manhole Inspection

(a) Personnel performing manhole inspection. (b) Manhole cover with broken grating. (c) Manhole with severe spalling and exposed rebar.

3.7.1.3 Drainage Ditches, Swales, Ponding Areas, and Catch Basins

Inspection of drainage ditches, swales, ponding areas, and catch basins includes walking and visually examining each component within the leveed area to determine the condition of drainage features. Some or all of these features may be within the responsibility of the levee owner/operator, but they generally connect hydrologically to streams, creeks, drainages, or culverts that are outside of the levee owner/operators' responsibility. It is imperative all areas are inspected and maintained by responsible parties as these areas can significantly impact the functionality of the levee and of interior drainage systems. A good working relationship between the responsible parties and the levee owner/operator is critical in order to assure all areas critical to flood risk management are properly inspected and maintained.

3.7.1.3.1 Drainage Ditches, Swales, and Ponding Areas

Drainage ditches and swales allow interior drainage to flow to ponding areas, gravity drainage pipes, or pump stations. Ditches and swales can be located anywhere within the leveed area but are of special concern to levee integrity when they are located along the landside levee toe. Ponding areas are low points within interior drainage areas located landward of the levee. Ponding areas can be the discharge terminus point of drainage ditches and other conveyance features and may be associated with pump stations. Drainage ditches, swales, and ponding areas often support wetland habitat which may be protected at state or federal levels. Personnel working within them should be informed of, and comply with, any environmental requirements for maintenance tasks.

Inspections of drainage ditches, swales, and ponding areas include the following, with full documentation:

- Check that ditches, swales, and entry points for ponding areas are unobstructed, either by dense vegetation, soil, or debris.
- Check for and document flow within the ditches and swales. Check for and document the flow into ponding areas and volumes retained.
- Compare ditch, swale, or ponding area capacity and cross section to design drawings and note variations.
- Check for erosion and drainage feature bank failures that may endanger the levee or block the drainage feature.
- During floods, inspect for sand boils within ditches, swales, and ponding areas located near the landside levee toe. Sand boils are an indicator that the invert of the drainage feature may be too low, causing seepage issues that could impact levee integrity.

Routine maintenance of drainage ditches, swales, and ponding areas include the following, with full documentation:

- Clear vegetation, debris, and litter as needed for proper conveyance of flow in ditches and swales and appropriate capacity in ponding areas.
- Remove accumulated sediment to maintain the original design grade and cross section. Over excavating these features when they are near the landside levee toe can cause seepage and internal erosion.
- Ensure all cleared debris and sediment is fully relocated well away from the levee toe area to prevent it being washed back into the ditch, swale, or pond.

Appropriate vegetation management within and along ditches, swales, or ponding areas should be covered in the levee vegetation management strategy, as it will vary by region and the unique characteristics of the levee's geography and biology. Where possible, vegetation should be cleared when the ditch, swale, or ponding area is dry, and should always be done in compliance with environmental requirements and regulations. Drainage ditches, swales, and ponding areas tend to support wetland habitat, which has higher environmental sensitivity, and more regulatory protections, than other features. Figure 9-35 shows several examples of drainage ditch conditions.

The configuration and moisture levels in a drainage ditch, swale, or ponding area may complicate the control of vegetation to facilitate adequate conveyance (ditches and swales) or storage capacity (ponding area). Small wetland plants, reeds, and rushes generally allow appropriate water drainage and improve water quality, if sedimentation rates are not high. However, bushes, trees, invasive plant species, and dense vegetation can block water drainage. Removal of detrimental vegetation is best done by hand, or in areas where no or very low-growing vegetation is desired, flame weeders may be an option to remove emergent weeds, if appropriate safety measures are taken. Herbicides should only be used as a last resort, and only in accordance with all laws and regulations. Where removal of large volume of vegetation and roots leaves voids, backfilling, and firmly compacting the area can stabilize the surface and help reduce erosion.

Figure 9-35: Examples of Drainage Ditch Conditions

Various drainage ditch conditions can include: (a) Clear and mowed, (b) Vegetated with reeds, (c) Choked with vegetation, and (d) Choked with debris.

Because blockage of ditches, swales, and ponding areas with debris is the most significant issue with these drainage features, additional inspections are helpful before, during, and after significant weather events (such as floods, windstorms, fires, or heavy precipitation events), and any after debris-generating human events adjacent to the levee (e.g., Independence Day, train derailments).

3.7.1.3.2 Catch Basins

Catch basins are precast concrete structures located at a low point of a ponding area which drain the nearby surface water into a gravity pipe. Catch basins are designed to prevent soil infiltration, but damage or poor design can result in soil loss into the basin. Inspections of catch basins includes viewing the area around catch basins for erosion, settlement, and sink holes. Inspection also includes checking the catch basin for damage such as concrete surface cracks or spalling, missing or damaged joint material, and deterioration of metal grates. Maintenance actions include repairing surface erosion, repairing joints and concrete surfaces, and removing any debris and blockages.

3.7.2 Operations

Gates are typically the only interior drainage system component which require operation. The best practice is to perform test operations of gravity pipe gates during all inspections to ensure gates can be operated to exclude water during a flood. Testing includes opening and closing each gate, confirming appropriate opening under required conditions, inspecting seals as they close to confirm a tight seal, and noting and addressing any issues such as leakage or signs of external erosion.

Operation of vertical sluice gates generally involves lowering a vertical steel gate into place by either turning a screw stem or via a pulley system, which may be manually or electrically driven. Along the sealing edge, seating wedges or slides may be present to allow for adjustments to better seal the gate in the closed position.

For sluice gates:

- Manually open and close operating mechanisms. Verify that both screw and pulley systems operate smoothly without need for excessive force. Clean and lubricate, as necessary.
- If the gate is opened automatically, conduct a full test of that system.
- Remove any gate obstructions if present.
- Clean and lubricate bearings, bushings, hinge pins, wheels, and screws.

For flap gates and duckbill valves:

- Test flap gates by manually opening and closing.
- Verify that flap gates and duckbill valves are fully closed under dry conditions, and seals are fully activated to block water inflow to the gravity pipe.
- Confirm flap gates and duckbill valves open automatically, usually once 1 to 2 inches of water is present and reseal once drainage slows. (This may require inspection during interior rain events.)
- Remove any gate obstructions if present.
- Clean and lubricate bearings, bushings, hinge pins, wheels, and screws.

3.7.3 Abandoning Penetrations

Old or unused levee gravity pipes (and other levee penetrations) present an ongoing risk and involve recurring expenses to periodically inspect and maintain. Abandoning or decommissioning pipes can be accomplished by removing that pipe (or conduit, or other penetration) from service by filling it with appropriate materials. This prevents many levee potential failure modes which could occur with an open pipe. This method of abandoning or decommissioning pipes is usually the most appropriate decommissioning method.

When the pipe's interior condition is significantly corroded, has large holes or open joints, or is structurally unsound, an open cut excavation and pipe removal may be necessary. This tends to be significantly more disruptive. Making abandonment decisions as early as possible can avoid pipe deterioration to the point of needing excavation.

The following general steps apply when planning to abandon or remove a pipe:

- Conduct a full condition inspection of the pipe.
- Understand the soil and groundwater conditions surrounding the pipe.
- Prepare an abandonment or removal plan that includes:
  - How the pipe will be abandoned or removed.
  - Actions required to provide a safe construction site, especially if trench excavation is needed.
  - Appropriate quality control methods to monitor filling or removal of the pipe.

USACE EM 1110-2-2902 provides details for each of these steps under a variety of conditions, and an explanation of when open cut excavation is the preferred choice (USACE, 2020). When pipes are removed or abandoned, it is important the location of the pipe be recorded in the levee records, including in the NLD. This may be important information if there are future problems or work in that area of the levee.

3.8 Pump Stations

Pump stations are structures used to evacuate water from a leveed area through or over a levee by mechanical and/or electrical components. They are typically composed of a structure housing, one or several pumps, and associated piping. Pump stations vary from small sheds to large industrial complexes and move varying volumes of water. Levees with large, leveed areas may include several pump stations.

Inspection, operation, maintenance, and repair of pump stations and pumps by individuals with specialized structural, electrical, hydraulic, and mechanical knowledge helps make sure pump stations can function as designed when needed. Appropriate operator training is critical. Maintaining pump stations so that they are accessible and functional during flood conditions and operating and maintaining pumps on a regular basis can avoid pump failures that lead to damage of the levee or flooding of the leveed area. Figure 9-36 presents several pump stations in varying conditions.

Original pump station designs may be incapable of meeting current interior drainage demands. It is important to monitor trends in ponding and pumping needs associated with the more frequent or intense rainfall that can accompany climate change. In some cases, existing pumps may need to be upsized to meet current and future drainage requirements.

Figure 9-36: Examples of Pump Station Scale and Conditions

(a) Small pump station in good repair. (b) Crisafulli pumps deployed at a small pump station in Illinois to provide supplemental pumping capacity during a large rain event. (c) Test operation of the West Closure Complex in New Orleans, Louisiana.

3.8.1 Inspections, Test Operations, and Maintenance

Because of the wide variation in pump types, sizes, designs, and frequency of use, this description of pump station O&M is limited to a broad overview. Pump station specific O&M manuals provide the necessary detailed guidance for O&M activities. If O&M manuals are limited or missing guidance, equipment manufacturer’s recommendations, and levee-specific operation needs can be used to improve or develop pump station O&M manuals.

Because pump inspections include operating the pump to test its function, this section groups inspections with test operations (see the West Closure Complex case study).

3.8.1.1 Frequency of Inspections, Operations, and Maintenance

The frequency of inspection, maintenance, and test operations for pump stations and their components is based on two factors. The first is the equipment manufacturer's recommendations for pump maintenance and parts replacement, and the second is the specific requirements of the individual pump station, as documented in the levee owner's O&M manual. If the O&M manual does not exist, the specific requirement can be based on an understanding of the frequency of pumping and other considerations discussed in section 2.10.

In general, pump station maintenance includes:

- Semi-annual maintenance to lubricate and correct alignment on all pumps.
- Performance testing each pump annually with follow-up testing after any required repairs.
- Pre-flood and hurricane season inspections to confirm the pump meets all performance metrics.
- Pre-flood and hurricane inspections to confirm operability of both pumps and backup generators in the days to hours prior to an impending flood.
- Post-operation maintenance including thoroughly cleaning the entire pump station, flushing pump house sumps, and inspecting, oiling, and greasing equipment.

Events that may impact pump stations, and trigger inspection and maintenance, include floods, seismic events, extreme heat, wildfire, and extreme wind. Where pre-warning is given for any large weather event that could potentially cause structural damage, pre-event inspections should be performed if safe, and appropriate protections for pumps and pump stations are put into place.

CASE STUDY: WEST CLOSURE COMPLEX IN NEW ORLEANS

The West Closure Complex in New Orleans, Louisiana, the largest pump station in the world, is designed to prevent residential flooding during hurricanes by two mechanisms. In the event of a hurricane, massive gates close to block storm surge from moving upstream towards the city. To keep the gates from trapping high-intensity rainfall, 11 pumps send up to 19,000 cubic feet of water per second past the gates, allowing precipitation to drain downstream and away from the city.

"One of the things we learned from Hurricane Katrina is that you have to operate this equipment to make sure it works when you need it. We run all the pumps and exercise all the sluice gates to make sure everything is running, prior to hurricane season. It is very important that the public trust the system that we have, and [therefore] it is very important that we exercise this equipment at full bore, as if we were having a hurricane, once a year, every year." (https://www.youtube.com/watch?v=3Wg2VqO-5Gs.)

– John Monzon, Regional Director, Southeast Louisiana Flood Protection Authority

Test operation of the West Closure Complex in New Orleans, Louisiana.

Inspections and maintenance of pump stations cover three interconnected systems: the pump station building and components, the pumps themselves, and the power system. Inspection and maintenance for each is discussed below.

3.8.1.2 Building Structure and Components

Routine inspections of the building structure and components include the following, with full documentation:

- Check the building structure, including building settlement and all structural components.
- During floods, monitor the interior pump intake areas and pump station ponding areas for sand boils as the evacuation of interior water creates higher hydraulic gradients and can increase seepage rates.
- Check both inner and outer walls for indications of water damage or siltation.
- Check and calibrate the station ventilation system and gas detection equipment if present.
- Check that electrical outlets and any accessory electrical equipment such as tools and lights are waterproofed and/or elevated above potential flood levels. Check that all shock hazards are clearly labeled, and all moving mechanical parts are enclosed.
- Check for appropriate storage and position of electrical systems, spare parts, tools, fluids, and other necessary pump station components.
- Check that all liquid chemicals, including preservatives, oils, lubricants, and fuel are stored safely above potential flood levels, and in secondary containment.
- Check all equipment and materials are stored free from direct ground contact and away from areas subject to collecting water.
- Check that carbon and low alloy steel surfaces are protected from any contact with corrosive environments to prevent rust formation. All items with machined surfaces should be stored to facilitate periodic examination for damage or rust.

Routine maintenance of building structure and components includes painting; sealing walls, joints, or cracks; and maintaining clean storage areas.

SAFETY PRECAUTION

Many pump stations are considered confined spaces and should be entered by only trained authorized personnel using the required safety equipment.

The station's ventilation system and gas detection equipment should be checked and calibrated.

CASE STUDY: CALYPSO STREET PUMP STATION

The Calypso Street pump station in Monroe, Louisiana is situated on the river side of the levee in downtown Monroe. The station drains 150 acres that includes Monroe's government centers and central business district. Before rehabilitation began in 2020, the station's floor elevation sat lower than the levee's control elevation and was thus susceptible to flooding. Settlement monitoring can reveal such issues before they become critical.

The condition of the Calypso Street pump station prior to repairs beginning.

3.8.1.3 Pump Integrity and Mechanical Operation

Inspections of pump performance and maintenance of pumps should only be done while intermittently running, and adjusting the pump. Pump inspections, maintenance, and test operations are grouped here as 'pump maintenance' to recognize this interplay.

Pumping capacity should be checked to confirm and maintain appropriate water flow. This includes instrumentation of pump flow rates; periodic inspection of water intake lines with down-hole cameras; and verifying the intake and outflow pipes, as well as the intake trash rack, are free of debris and silt. Examples of pump station trash racks are shown in Figure 9-37.

Figure 9-37: Examples of Pump Station Trash Racks

(a) Trash racks for the West Closure Structures in New Orleans, Louisiana, during construction. (b) Trash rack for a smaller pump station in Illinois.

To confirm appropriate motor performance for pumps where operators are on constant duty, the sound of running pumps should be continuously monitored, and any changes in typical pump noise should be investigated. When pumps are operating continuously or several times each day, inspections should include bearing temperatures, seal chamber leakage, pressure gages, flowmeters, and vibration to monitor pump performance and identify issues early. If recording instruments are provided, a daily check can help determine whether the current capacity, pressure, power consumption, or vibration level indicates that further inspection is required.

For less frequently used pumps, motor performance should be evaluated per the frequency described in the O&M manual, but no less than semi-annually.

Best practice is to create a detailed list of applicable inspection and maintenance items to perform during pump inspection and maintenance. Overarching tasks to be detailed in a list for a specific levee would include the following:

- Check the pump motor's temperature, amperage and voltage, coupling and alignment, and noise.
- Perform vibration testing, as per pump-specific manufacturer's guidelines, or refer to EM 1110-2-3015 for specific recommendations (USACE, 1994).
- Check for appropriate pump line pressures, temperatures, and deterioration.

- Inspect and maintain oil levels and lubrication.
- Check and calibrate or replace bearings, packing, seals, suction, and discharge gage pressures.
- Check and correct the alignment of gears, gear drives, pump, and driver.
- Check motor insulation.
- Inspect and adjust “check” and “pressure” relief valves.
- Check belt wear and tightness.
- Check mechanical seals.
- Check and confirm functionality of auxiliary motor components.
- Check and calibrate all instruments and flow-metering devices.
- Check the pump controls and monitors.
- Test the pump alarm system.
- For pumps equipped with shaft packing, check the free movement of stuffing box glands, and clean and lubricate gland bolts. Packing should be removed and the shaft sleeves or shaft (if no sleeves are used) should be examined for wear. Replace packing if necessary.

GUIDANCE

- USACE EM 1110-2-3105 provides specific recommendations for vibratory testing of pumps (USACE, 2020c).
- Institute of Electrical and Electronic Engineers Std 43-2000 describes procedures for measuring insulation resistance of armature and field windings in rotating machines (IEEE, 2000).
- American National Standards Hydraulic Institute 9.6.4 provides maximum allowable vibration values measured on bearing housings of rotodynamic pumps (Hydraulic Institute, 2022).

3.8.1.4 Pump Station Power System

Operation of a pump station requires power. It is important to confirm the availability of primary power sources and back-up sources during inspections. The functionality of the building electrical system should be verified by inspecting and updating aging components as needed. The operability of the back-up generator motor and/or auxiliary fuel systems should be confirmed, including checking that it is lubricated and has the necessary volume of fuel. If applicable, the automatic transfer switches should be verified to be in working order and able to transfer power back and forth between the primary and secondary power sources. Power-related alarms or warning systems should be tested to confirm they will operate during a flood or rain event.

If pumps are operated automatically by the triggering of instrumentation readings, test verification should be performed to confirm pumps will activate at the set threshold level.

For diesel drives, check that the engine will correctly start, and all instruments are working correctly. Verify no overheating is present and that cooling, and exhaust systems are functioning correctly.

Perform electrical inspections after floods, large windstorms, extreme heat events and any power disruption.

3.8.2 Pump Operations

Pump stations operate when interior lands require drainage, and as such, some pump stations are in operation continually, while others may operate annually or less frequent. There are many different pump types and methods to operate pumps. Best practice is to maintain and follow the pump station O&M manual, which typically has detailed operating instructions and considerations. Alternatively, if an O&M manual does not exist, use the manufacturer's instructions. Pump station operations should be performed by appropriately trained staff.

Frequently, pump station operation is managed and conducted by an entity other than the levee owner/operator. When this is the case, clear lines of communication and procedures for pump operations between the operator of the pumps and the levee owner/operator can help assure the pump station and the levee are operated synergistically.

As floods become both more common and more widespread, the probability is increasing that flood response capacity may be reduced or delayed, either because a climate event prevents response personnel from accessing the levee, or because geographically widespread or concurrent events prevent outside assistance from first responders/partners/mutual aid agencies. Retrofitting pumps and gates with remote operational capacity can provide an additional layer of assurance. The same factors increase the likelihood of widespread power outages, which can be mitigated with automatic back-up generators or batteries.

ELECTRICAL INSPECTIONS

Due to climate change, some areas of the country are experiencing record-breaking high temperatures for longer periods of time. Uninsulated electrical equipment can be fully disabled when exposed to prolonged heat for which it was not designed, leaving pumps inoperable or leading to electrical fires.

Record-breaking temperatures above 100°F in Portland, Oregon, in 2021 melted power cables and shut down the city-wide streetcar system. This level of extreme heat is rapidly increasing in all regions of the U.S. and is expected to continue to increase substantially. While flood season and extreme heat events rarely co-occur in mountainous and western regions, they may occur much closer together in hurricane-prone regions. A best practice is to inspect electrical systems following periods of regionally extreme heat and repair any electrical issues expeditiously.

Heat damage to a power cable.

3.9 Instrumentation

Monitoring of levee performance can be accomplished through instrumentation that is installed in or on the levee features and allows for consistent technical measurements to be recorded. Effective O&M includes collecting and evaluating this data, as discussed in section 2.8, to understand changes over time.

A wide variety of instruments are used to monitor levees, and if used and maintained properly, they can provide critical early warning signs of levee distress. Instrumentation can inform risk assessment, levee risk management, flood response activities, and levee rehabilitation and repair needs. It is important to note, however, that instrumentation data cannot replace the need for physical inspection of levee features but provides supplementary information. "Monitoring Levees" published by the U.S. Society on Dams provides an overview of the current state-of-the-practice in monitoring levees (Stateler et al., 2016).

Obtaining the early warnings that instrument monitoring can provide requires:

- Routine inspection, maintenance, and recalibration of instruments, as needed.
- Reliable implementation of the levee-specific instrumentation plan.
- Review of the data against established criteria and threshold action levels related to levee risk, and regular and appropriate data evaluation.
- Reliable long-term storage of instrumentation data.

3.9.1 Inspection and Maintenance

Every instrument has the potential to deteriorate, lose calibration, or suffer damage during exposure to field conditions, including harsh weather, land movement, animal activity, and vandalism. The goal of instrumentation inspection and maintenance is to confirm and prolong the reliability of all levee instruments. This involves detecting faulty data and identifying repair needs in a timely manner.

Poorly constructed or maintained instrumentation can introduce a weak point into a levee. In particular, piezometers can provide an unimpeded flow path for seepage if they are not properly grouted or if they break or deteriorate over time.

The frequency of instrument maintenance depends on the type of instrumentation, manufacturer's guidelines, how critical specific data is to levee risk management, and the exposure of each instrument to damaging field conditions. While instrumentation maintenance is typically covered in the levee O&M manual, a minimum of annual instrument checks and as-needed maintenance is a best practice. In addition to regularly scheduled inspections, inspections immediately following flood or weather events with the potential to damage instrumentation can verify that the instrumentation is intact, and the levee is being properly monitored.

Instrumentation inspection and maintenance includes viewing the visible portions of the instrument to identify damage and missing parts, comparing readings from duplicate instruments to verify they are working properly, and performing additional tasks as specified by manufacturer's warranties and calibration and maintenance guidelines.

Irregular data readings may indicate that an instrument is not working properly. Instrument data may indicate the need for recalibration or repair when:

- There is a sudden significant or unusual change in the data with no obvious environmental cause.
- Data values are within a reasonable range of values, but progressive deviations over time do not track with field observations.
- Instruments are nested, linked, or duplicated and data from one instrument shows trends not followed by remaining instruments.
- Automated or alarmed systems indicate potential data errors.

The existence of a faulty instrument can be verified by checking that unusual readings were read and recorded properly, and if necessary, a visual field inspection and a re-reading of the instrument. Faulty instruments may need to be recalibrated, repaired, replaced, or abandoned.

Having instrumentation recalibrated by appropriately trained O&M staff or outside professionals is important to ensure it functions correctly. Some instruments, such as an embedded transducer or direct-burial devices sealed or grouted in place, cannot be recalibrated, and may need to be replaced when they are no longer performing correctly.

Standard methods used to recalibrate and test instruments are set forth by the National Institute of Standards and Technology. Replacing significantly damaged or non-functioning instruments should be based on a current assessment of levee risk (**Chapter 4**).

3.9.1.1 Hydraulic Head Instrumentation—Piezometers

Open standpipe piezometers, similar but larger observation wells, and automated piezometers are maintained to achieve proper assessment of water levels or hydraulic pore pressure.

Inspection of piezometers includes verifying that all surface components are intact and free from damage or corrosion. During floods, the immediate area around piezometers should be inspected for signs of seepage and sand boils.

Maintenance of manual piezometers includes periodic activities such as flushing, cleaning, bacterial treatment, and ensuring freeze protection. Well cleaning and silt removal via jetting, lifting, or flushing can maintain or restore proper function, but can result in damage if not performed by a trained individual. Staff should also be trained on the potential data impacts of low permeability silt or clay layers, which can delay correct piezometer readings, in some cases, by days to months.

Automated piezometers generally involve buried transducers on which maintenance cannot occur. Functionality can be restored by replacing these components if they fail. Maintaining and calibrating components of automated piezometers according to manufacturer’s specifications by trained personnel will improve their performance and prolong their life. Protecting all piezometer cables from extreme temperature will allow piezometers to function during all weather conditions. Security can be improved by storing cables in a protected and locked steel well casing at the surface.

3.9.1.2 Seepage Flow Instrumentation—Water Level Monitors in Discharge Features

Maintenance of flow and velocity meters includes both mechanical and electrical maintenance and periodic calibration. Maintenance ensures that all moving parts of the meters can function by keeping them clean, lubricated, and free of corrosion and grit. Keeping electrodes of electromagnetic instruments clear of film buildup and calibrated is important for this proper function.

Weirs and flumes depend on accurate elevation control and exact section geometry to measure flow accurately; therefore, maintenance of weirs and flumes includes:

- Checking that the structure is level and that the weir or flume crest is at the same elevation as the zero reading on the staff gage.
- Checking section dimensions.
- Checking weir notch or crest for nicks or dents that may affect accuracy; dressing or repairing nicks or dents to maintain the shape of the section.

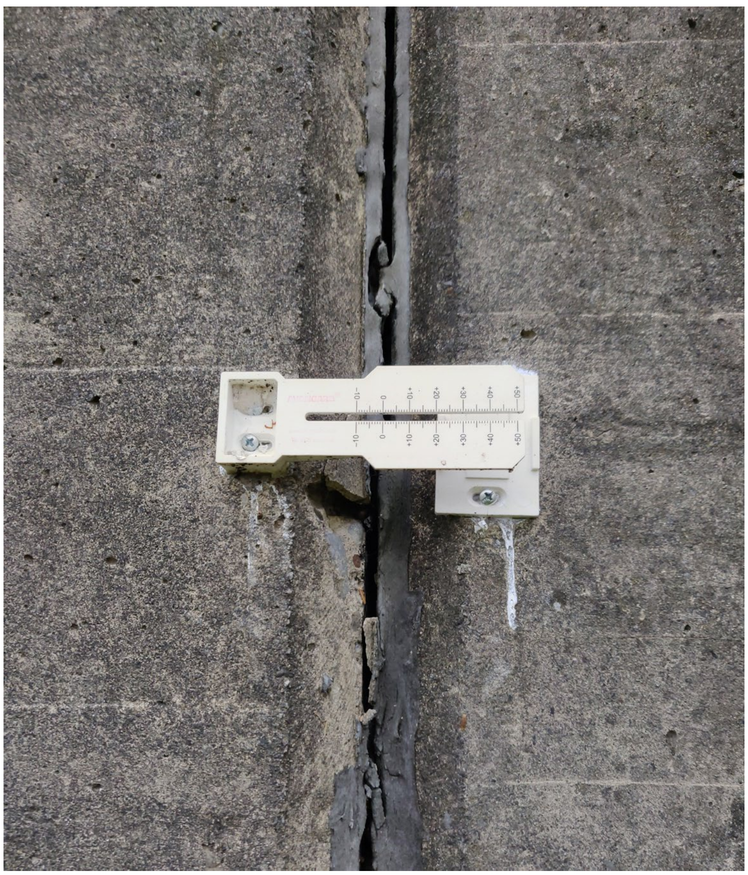
- Replacing components that cannot be repaired.

3.9.1.3 Displacement Measuring Devices

A number of devices measure displacement, either of earthen embankments or of structures such as gates and floodwalls (Figure 9-38). These include inclinometers and tiltmeters to measure slopes of embankments, walls, or structures; crack meters for monitoring the size of cracks and joints; and settlement monuments for soil compression or movement.

Inspection and maintenance include verifying visibility/readability for any embedded device, and cleaning and calibrating (as per manufacturer's instructions) for inclinometers, tiltmeters, and crack meters. Regular servicing of instrumentation by the manufacturer is a best practice**.** Instruments such as inclinometers can be housed in a locked well casing to prevent vandalism or for protection against adverse environmental conditions.

Figure 9-38: Example of Displacement Measuring Device



Concrete floodwall joint monitored with displacement measuring device.

3.9.2 Data Collection for Levee Monitoring

A key part of monitoring a levee using instrumentation is data collection. Data collection includes the field collection, data entry, and data management for the instrumentation data. A good field collection strategy collects data at the frequency that is appropriate for the risks and vulnerabilities of the individual levee, the levee feature, and potential failure mode being monitored. Reading instruments routinely will maintain a history of levee reactions over the range of conditions to which it is exposed. This cumulative record should be reviewed regularly to look for changing trends. Managing the levee instrumentation data within the levee's data management system (section 2.11) will ensure it is properly stored and available for future consideration. The plan for data collection is typically outlined in the O&M manual. Refer to section 2.8 for content related to a levee instrumentation data collection strategy.

For example, if piezometers have been installed to monitor the cutoff wall performance, monitoring piezometers on the landside of the levee during high water periods can be used to determine ongoing effectiveness of cutoff wall through comparison of piezometric elevations to flood levels on the opposite side of the levee. Data can be used to develop estimates of seepage resistance effectiveness.

It is important that appropriate staff and training are in place for instrumentation data collection. Methods for data collection will vary by instrument type, but for manually measured instruments, checklists or standard forms can streamline the data collection process and ensure appropriate information is recorded.

For guidelines associated with developing a monitoring plan for a levee, see **Chapter 7**.

4 Managing Other Impacts to the Levee

There are aspects of levee management that extend beyond the features that make up the levee system. These include right of way, encroachments, and utility penetrations in and around the levee, as well as channel changes.

4.1 Right of Way

Levee **right of way** is the land that has been acquired through fee title or an easement to allow construction, operation, and maintenance of the levee. Right of way is critical to prohibit excavations and land modifications that would endanger the integrity of the levee. Additionally, right of way is needed to allow adequate room for maintenance, inspection, and flood response. Rights should be acquired for the entire levee footprint, including other levee features, such as seepage control measures and interior drainage structures.

To the extent practical, sufficient right of way should also be acquired to provide vehicular access along the landside levee toe, provide control of activities that could impact levee performance, and provide for future levee improvements should it be needed. Right of way should be maintained and inspected for debris, trash, or unpermitted encroachments on a regular basis, as discussed in section 3.

Right of way would ideally be established prior to levee construction; however, due to changing levee management practices, additional right of way may need to be obtained during the O&M phase. To address gaps, the levee owner/operator should have a clear record and understanding of existing right-of-way agreements, fee titles, or easements. With any gaps in existing right of way identified, the levee owner/operator should coordinate with the current landowner to establish the needed right of way. Existing owners may be private, city or county, or commercial including a highway or railroad entity.

Right-of-way acquisition might involve coordination with or be aided by federal, state/territory, regional, tribal, and local agencies, especially if there is shared jurisdiction of the levee. Engaging communities and stakeholders can help in the right-of-way acquisition process by conveying the importance of the levee, the flood risk benefits to the community, and the intricacies of the role that right of way plays in the maintenance, operation, and inspection of the levee (**Chapter 3**).

For levees where there are obstacles to acquiring the necessary right of way—such as where there is existing development near the levee—a long-term plan to obtain rights as development changes should be pursued with the landowners. In the interim, levee owner/operators should work with landowners to try to establish a visibility sightline to allow visual inspection. This coordination might include determining the type of fencing and limiting walls, structures, and other physical obstructions that could restrict the ability to view the levee and its foundation.

4.2 Encroachments and Permitted Activities

An **encroachment** is any activity on or physical intrusion over, on, through, or under the levee, that is not related to the flood risk reduction benefits or other co-benefits the levee is intended to provide (Figure 9-39). Encroachments may have a negative effect on the levee's structural integrity or ability to reduce flood risks. This includes obstructions or physical intrusions that may increase the hydraulic load on the levee and any obstructions or physical intrusions that impact levee performance or accessibility for operations, maintenance, and flood response activities.

Examples of typical levee encroachments include utility lines, pipes, boat docks, stairs, structures such as homes, fences, swimming pools, power poles, roads, irrigation ditches and railways. Encroachments also include activities performed on or near a levee that are not related to its design function, such as farming and excavating.

Table 9-6 presents some of the adverse effects encroachments may have on levees.

Figure 9-39: Example of Encroachments

(a) An approved pipeline crossing with a bridge in Louisiana. The levee was overbuilt to accommodate the installation of the pipe above the design crest. (b) An approved walking trail along the riverside toe in Indiana. (c) Example of unapproved farming encroaching into the access corridor along the Whitewater River in Butler County, Kansas.

Table 9-6: Examples of Adverse Effects of Encroachments

Type of Encroachment	Possible Adverse Effect on the Levee
Embankment-Related	
Improper excavation or other removal of material from the levee, its foundation, or anywhere within the zone of influence of the levee	Could allow uncontrolled seepage resulting in internal erosion that could breach the levee. Could create unstable slopes that cause the levee embankment or floodwall to collapse fail.
Directional drilling	Could cause severe seepage issues.

Type of Encroachment	Possible Adverse Effect on the Levee
Pipes passing through the levee	Could cause seepage with internal erosion along or into the pipe or external erosion at the pipe inlet and outlet.
Degrading the levee crown for road, railroad, and highway crossings	Increased risk of overtopping.
Encroachments that May Cause Hydraulic or Hydrostatic Problems	
Railroad, highway crossings, utility crossings, boat ramps, docks buildings, and bridge piers	Affects a stream's flow distribution during high flood flows. Undesirable flow distributions and patterns may cause erosion of the levee or its foundation which may result in levee breach. Undesirable flow distributions may also increase interior ponding areas or otherwise inhibit interior drainage.
Bridges	If not built high enough, may block flow and accumulate debris, which will raise water elevation during flood and increase overtopping risk.
Any work done in the floodway during the flood season	May impair channel capacity, threaten the ability of the levee to function as intended, and put the construction workers and equipment working in the floodway at risk.
Boat docks	Could interfere with the design channel capacity. Could also threaten levee integrity if the dock's piers/piles penetrate the levee.
Swimming pools, boring holes, power poles, wells, and irrigation ditches located close to the landside levee toe	Could provide a flow path for seepage and induce internal erosion, leading to levee breach.

A permitting strategy is a good way to ensure no activity occurs on the levee that could impact levee integrity or inhibit access for operations, maintenance, or flood response. Certain encroachments may be allowed, provided a thorough assessment of the proposed activity is completed to evaluate impacts to the levee. Also, it should be determined that the activity does not threaten levee integrity or inhibit access. A permitting strategy should include:

1. **A clear understanding of the levee owner's jurisdiction.** The location of levee right of way, levee features, and the zone within which activities could impact levee reliability should be documented. There should also be concise guidance as to what constitutes an encroachment. The levee owner should understand the legal means available for removing unpermitted encroachments.

   There may be situations where activities that have the potential to impact the levee occur or are proposed outside of the levee right of way. In these cases, it will be necessary to communicate potential consequences of proposed or existing encroachments with the encroachment owner and cooperatively discuss options which are less likely to impact the levee.

2. **Community engagement.** Conveying the importance of the levee, its benefits, and the role managing encroachments has on the levee integrity can improve compliance with the permitting and encroachment control strategy. Community members should

understand how the levee owner manages encroachments and how they can help by identifying and reporting concerning activities.

3. **An application process.** Developing and documenting a process for permit application can help ensure the levee owner receives adequate information to evaluate encroachments and can simplify the process for applicants. The process should include a list of required information, the required format of the information, and how it should be submitted. An application form or checklist can be helpful to ensure adequate data is provided to fully evaluate and document proposed encroachments.
4. **Permit review process.** It is helpful to have a process in place for evaluating if and how a proposed encroachment could impact operation, maintenance, or structural integrity of the levee system. The process should include general timelines and a standard for providing feedback and status updates to permit applicants in a timely manner.
5. **Communication of findings to the applicant.** The results of the evaluation should be formally communicated to the applicant in writing. If the encroachment is approved, the levee owner should consider including conditions describing the encroachment owners' responsibilities regarding inspection, maintenance, and repair of the encroachment as it relates to the levee.
6. **Construction monitoring.** It is a best practice for the levee owner, or their representative, to observe and document construction of encroachments to verify they are installed in accordance with permit requirements.
7. **Management of permitting information.** An inventory of encroachments should be maintained in a geospatial database. It is a best practice to include encroachment data in the NLD. Stored data should include the following:
   - A list of existing encroachments, permitted activities, and their location.
   - Encroachment owner with current contact information.
   - As-built records or drawings showing cross sections.
   - Confirmation that permitted activities meet the permit's conditions.
   - Current inspection records, including video inspections of any pipes.
   - Record of all historical encroachments or permitted activities that were abandoned.
8. **Management of existing encroachments.** The inventory of encroachments and permitted activities should be used during inspections to note changes to existing encroachments or permitted activity, and to identify any unpermitted encroachments. Encroachments that were installed without permits and permitted activities that have not been maintained in accordance with the conditions of their permits may adversely impact the levee. Any issues should be repaired as quickly as possible in accordance with the permit.

Refer to **Chapter 7** for design considerations if the presence or removal of an encroachment causes such serious damage that the levee section needs to be rebuilt or rehabilitated beyond the scope of maintenance.

4.3 Utility Penetrations—Pipes, Conduits, and Culverts

Utility penetrations can run alongside or cross through, under, or over levees. These penetrations can be pipes used to convey drinking or irrigation water, natural gas, hazardous chemicals, petroleum products, or sanitary sewage. Conduits may be used for transmitting electricity, cable television, high-speed internet, or phone service.

Failure of these elements can significantly impact the integrity of a levee. Penetrations through a levee are particularly vulnerable locations for seepage since compaction of materials against the penetrating structure may not have achieved densities comparable to other areas. There is also risk for potential erosion into a pipe or along any interfaces of the pipe. These erosion issues can lead to levee breach. Inspecting penetrations regularly can help ensure they do not threaten the integrity of the levee. For all penetrations, it is an important risk management measure to observe the levee embankment and the ground surface in the immediate area to look for depressions, sinkholes, and seepage that may indicate active erosion of internal materials, especially during floods.

Issues related to utility pipes can require significant rehabilitation or even replacement of the pipe to prevent or repair negative impacts to the levee. Examples of potential threats posed by utility penetrations include:

- Water released from a pressurized or non-pressurized water pipe inside the levee causes internal erosion into or along the pipe.
- A leaky pressurized gas line inside the levee creates a gas pocket that either deforms the levee or causes an explosion.
- A leaky hazardous chemical or sanitary sewage pipes at the waterside of the pipe or in the levee creates environmental issues.

Review of all proposed utility penetrations—as well as any changes or repairs to existing penetrations as part of the encroachment permitting process—can help ensure the changes to the levee do not adversely affect its performance.

A good record of encroachment and permitted activities will include a database record of utility penetrations. Levee owner/operators need contact information and established lines of communication with utility penetrations owners or their staff. This includes identified contacts and plans for flood preparedness operations that require operation of utility penetration shut off values.

Utility pipe repairs should be pressure-tested according to specific pipe manufacturer's criteria (e.g., the American Water Works Association standard) before backfilling and compaction around the repair area of the pipe to verify the repair was successful. Best practices for third party pipes include establishing lines of communications with penetration owners, requiring a shut off valve on either side of the levee, and requiring the penetration be inspected, maintained, and repaired, as described in section 3.7.1.1.

If a pipe has been abandoned in-place and filled with grout, the volume of the pipe to be grouted should be precisely computed to determine whether the pipe has been completely filled. If the pipe takes a different volume of grout than that computed, the pipe may be partially clogged, or a void may exist. If this occurs, an open cut removal may be needed.

Common issues with utility penetrations and potential approaches to address the issues are summarized below.

- **No shut-off valves**: All pipes should be fitted with shut-off valves accessible by a responsible owner, in case of emergency. Where these do not exist, pipes should be retrofitted with shut-off values on either side of the levee embankment to ensure these lines can be isolated if needed.
- **Difficulties acquiring inspection reports**: Good relationships and communication between the penetration owner and the levee owner/operator is critical for ensuring proper O&M of utility penetrations. The best O&M approach is to have the penetration owners provide records of the inspections and repairs to the levee owner/operator. Any unresolved issues from pipe inspection or repair should result in keeping the pipe closed or inactive until the issue is resolved. Issues can arise with inspection reports being inadequate, inaccurate, untimely, or missing. To address this, the levee owner/operator should consider withdrawing the permit for the penetration, if one exists, and/or coordinating with the owner to relocate the penetration away from the levee. In some cases, it may be best for the levee owner/operator to undertake the required O&M activities, given proper agreements are in place with the utility owner, to ensure the activities are completed responsibly. Resolution may require obtaining local, state, or federal governmental assistance.
- **Difficulty locating existing penetrations within the levee**: Knowing the locations of existing penetrations is important, as they are a potential pathway for internal erosion and need to be accounted for in levee risk assessment, geotechnical evaluation, and rehabilitation or repair design. Where historical penetrations are suspected, or existing penetrations are known but exact alignment within the levee is not, efforts to identify the penetration locations should be made. These efforts may involve review of historical documents, field review and verification, and in some cases use of ground penetrating radar or sonar techniques.
- **Joint separation**: Concrete pipes, such as for sanitary sewer lines, in particular are prone to joint separation. To avoid joint separation, heavy loads that can cause irregular settlement of surrounding soils (e.g., additional fill material or building loads) should not be allowed near areas of the levee with pipes. If minor separation is observed, slip-line trenchless technology or pressure grouting of the joints should be considered. If the damage is extensive, use of conventional open cut methods may be needed. If the separation has progressed to the point that external erosion of the pipe backfill material has occurred, rehabilitation of the levee may be required.
- **Deterioration of pipes and leaky pressurized pipes**: Deterioration of pipes or leaky pressure pipes may be indicated by fluid coming out of a levee embankment or ponding at the levee toe in an area of a known pipeline crossing. For pressurized pipes, the owner of the pipe should have a documented process to detect pressure loss and quickly notify the levee owner/operator of the potential leak or any other issue. When leaky pipes are detected during inspections, the penetration owner should be contacted to coordinate next steps. A deteriorated or leaky pressure pipe within the levee embankment should not be replaced in-kind. Instead, the existing pipe should be

properly abandoned, and the replacement should be constructed up and over the levee profile.

4.4 Channel Changes

River networks and alluvial channels continually adjust their geometry, conveyance, and extent. River aggradation and incision are both well documented historical responses of river channels to climate change on a geologic scale. As flow volumes and flood frequency shift from recent historical norms, so will patterns of erosion and sedimentation. An increase in large storms could also impact river channels, through multiple modes, including localized erosion and deposition, extreme temporary flows, and the deposition of large-scale debris. Structures that constrain natural channels may be subject to higher stress. Natural floodplains may widen, incise, or shift completely.

Changes in channel characteristics can affect both the load on and the performance of the levee. For example:

- Blockages in the stream such as a fallen tree or debris can increase water levels and therefore the risk of overtopping.
- Changes in sediment transport regimes can increase local erosion and therefore the likelihood of destabilizing a levee slope.

Changes in the channel affect each levee differently depending on the conditions and design of the levee, including its materials, encroachments, and revetments. For these reasons, it is helpful to understand all contributing factors when developing a strategy for a levee impacted by channel change. A good approach is for the levee owner/operators to work with partners to develop solutions that reflect how the levee functions within the floodplain. Potential solutions include repair of erosion damage and adding armoring to the levee and/or channel banks. In some cases, setting the levee back from the flood source can provide more room for the channel which lowers flood levels, decreases flow velocities, and provides environmental benefits associated with reconnecting the floodplain. O&M staff may benefit from the help of a levee design engineer or other professionals, especially when the problem or its solution may have environmental consequences.

EXAMPLE OF AN EXTREME EVENT WITH THE POTENTIAL TO CHANGE CHANNEL ALIGNMENTS

Between 2005 and 2020, portions of the Mississippi River storm surges pushed water upstream five times, including during Hurricanes Katrina (2005), Isaac (2012), Laura (2020), and Ida (2021). Prior to Ida's landfall, the Mississippi was discharging roughly 350,000 cubic feet per second. Under Ida's influence, flow reversed at a rate of 40,000 cubic feet per second. Storm surges such as these have the potential to alter river channels.

Hurricane Ida from the International Space Station. Originally shared on European Space Agency astronaut and Expedition 65 crew member Thomas Pesquet's X account.

5 Preparing for Floods

Flood preparedness for levees focuses on actions before and during floods to ensure the levee functions reliably and issues are detected and responded to appropriately to prevent development of emergency conditions. Good O&M includes following appropriate levee operation procedures during all floods that load the levee, but not all floods will entail emergency response activities. During a flood, levee activities can vary from normal operations (operating levee features to exclude or remove water from the leveed area), responding to incidents on the levee, and responding to emergencies on the levee. Emergency response includes elevated communications and response activities beyond normal O&M. Further discussion of emergency planning and response is provided in **Chapter 10**.

Because emergency conditions can develop unexpectedly during floods, planning and preparing before a flood is essential for reducing the risks to life, property, and the environment. When an emergency occurs, a clearly understood strategy already in place will allow for seamless management of and response to the emergency. This section provides a brief summary of flood preparedness activities that align with emergency preparedness activities covered in **Chapter 10** and overlap with O&M responsibilities.

LEVEE INCIDENTS AND EMERGENCIES

An **incident** is an unexpected occurrence that requires some level of response. Incidents include both non-emergency and emergency conditions. Many incidents do not require action above and beyond typical O&M activities to protect life or property. An **emergency** is an incident during which life and property are at risk and urgent or non-routine response is required.

5.1 Advanced Preparations

Flood preparedness includes regular review and thorough understanding of the O&M manual and emergency action plan, including communication strategies, identification of and training of flood response teams, emergency response actions, as well as identification and management of critical floodfighting materials, equipment, and stakeholder contacts and responsibilities.

Key actions of pre-flood preparedness include:

- **Stockpiling materials and equipment for floodfighting**: It is best practice to document and maintain an adequate stockpile of floodfighting materials and equipment in a location that is easily and quickly accessible during flood response activities. Quantity and type of materials and equipment depend on the size of the levee, complexity of features, and the historical amounts used during previous floods. Good resource management includes regularly inventorying, inspecting, and maintaining floodfight materials and equipment to prevent degradation and replenishing resources found to be degraded. Resource documentation typically includes the location, quantity, and type of material and equipment on hand. Including these actions as part of routine and flood related inspections ensures they are accomplished on a timely and reoccurring basis.
- **Training and emergency action plan exercises**: Training and regular emergency action plan exercises maintain proper readiness for emergencies. This includes understanding responsibilities of all flood response partners, such as levee

owner/operator, local emergency management agencies, public works departments, or transportation departments. Exercises also help clarify and improve general understanding of roles of key individuals within the organizations. Training and exercises can better inform future actions when they are documented, and the records maintained in a location that is easily accessible to personnel. Documentation typically includes the names and roles of the participants involved, activities performed, and lessons learned.

Flood preparedness includes continual awareness of levee conditions, weather conditions, and climate conditions. Climate change is increasing both the frequency and intensity of floods in many, if not most parts of the country. Not only are individual storms growing more extreme, but compound events, such as warm rain quickly melting heavy snowpack, are increasingly frequent. A critical component of flood preparedness includes expecting and preparing for the unexpected.

5.2 Flood Response Activities

When a flood is forecasted, performing activities outlined in the O&M manual—such as reviewing the emergency action plan, closing gates, performing inspections, and other tasks—will help make sure the levee and those responsible for its operation are ready for the flood.

Flood-related and event-driven levee inspections allow for early detection and response to potential levee concerns. Inspecting levees at frequent intervals throughout a flood, with the frequency of inspections increasing as the threat to the levee increases, will enable earlier detection of possible emergency situations. It is a best practice to establish predetermined triggers tied to inspection frequencies in the levee operations and maintenance manual or emergency action plan.

Once flood-related inspections are triggered, heightened monitoring of existing levee instrumentation will improve understanding of how the levee is responding to the flood and may provide early indication of developing potential failure modes.

When issues are encountered that require response activities above normal operations, such as development of a sand boil that requires floodfighting, emergency response activities should be initiated.

6 Summary

By performing the O&M inspection, maintenance, monitoring, and operational activities presented in this chapter, levee owner/operators can reduce the chances of routine and minor issues becoming an emergency or leading to a larger issue requiring significant rehabilitation. Performing these day-to-day functions with trained levee staff can ultimately save lives and protect property. The day-to-day management of a levee includes providing for, overseeing, and following up on inspections, maintenance, monitoring, and operations. These O&M activities reoccur on regular intervals, and although these activities are independent tasks, they can also inform each other.

It is critical for O&M staff to have the appropriate capabilities and understanding of the purpose and goals of the levee and the O&M activities required. O&M staff should inspect the levee, perform routine maintenance, routinely test or operate features and components, and monitor conditions. When routine activities indicate an issue or potential issue, additional inspections, monitoring, and/or repairs should be undertaken or the issue may become more significant and require investigation, risk evaluation, rehabilitation, or emergency response.

Each levee is unique in its features, setting, and risks and as such the O&M activities presented in this chapter should be scaled and scoped appropriately and documented in the levee's O&M manual. The O&M activities, frequencies, and methods should be revisited regularly to incorporate changes in the understanding of levee risks, technology, and regional trends including climate.

Data management is critical in operating and maintaining a healthy levee because keeping track and evaluating the past data will further the success of both present and future operations of the levee. The levee owner/operator should have a data management system to record and store the information that is documented throughout the lifecycle of a levee, including O&M activities. The levee records from O&M can also be utilized to inform risk assessment, risk management, rehabilitation and repair, and flood emergency response and monitoring.

Related content associated with this chapter is included in detail in other chapters of the National Levee Safety Guidelines as described in Table 9-7.

Table 9-7: Related Content

Chapter	Chapter Title	Related Content
1	Managing Flood Risk	
2	Understanding Levee Fundamentals	• Levee functions, features, forms, and lifecycle
3	Engaging Communities	• Engaging communities about levees • Engagement for levee-related activities
4	Estimating Levee Risk	• Guidance for estimating and portraying levee risk
5	Managing Levee Risk	• Levee risk management • Risk-informed decision making
6	Formulating a Levee Project	• Understanding levee projects at various phases of the lifecycle • Developing a vegetation management strategy
7	Designing a Levee	• Levee design considerations • Modification/rehabilitation of existing levees
8	Constructing a Levee	
9	**Operating and Maintaining a Levee**	
10	Managing Levee Emergencies	• Levee emergency preparedness • Emergency management and response
11	Reconnecting the Floodplain	
12	Enhancing Community Resilience	

10

Managing Levee Emergencies

Key Messages

This chapter will enable the reader to:

- **Collaborate and plan ahead.** Successful levee emergency response requires proper planning including partner collaboration and adequate resource management.
- **Share information.** Effective and timely communication with stakeholders and community members is essential during an emergency.
- **Respond rapidly.** Early detection and prompt responses can prevent or reduce the impact of a levee emergency.


LEVEETOWN, USA

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Other chapters within the National Levee Safety Guidelines contain more detailed information on certain topics that have an impact on levee emergency management, as shown in Figure 10-1. Elements of those chapters were considered and referenced in the development of this chapter and should be referred to for additional content.

Figure 10-1: Related Chapter Content

CH 1	CH 2	CH 3	CH 4
Sources of flood hazard	Potential failure modes	Flood-related communication Emergency communication	Risk assessment Potential failure modes Inundation maps
CH 5	**CH 6**	**CH 7**	**CH 8**
Levee risk management Risk-informed decision making		Levee rehabilitation	Construction of long-term repairs
CH 9	**CH 10**	**CH 11**	**CH 12**
Flood-related inspections and monitoring Emergency preparedness	**Managing Levee Emergencies**		Community flood preparedness Evacuation planning

Contents

1 Introduction 10-5
2 Preparing for a Levee Emergency 10-6
2.1 Collaborating with Stakeholders 10-7
2.2 Understanding Levee Risks 10-9
2.2.1 Hazards 10-10
2.2.2 Performance 10-10
2.2.3 Consequences 10-11
2.3 Developing an Emergency Action Plan 10-12
2.3.1 Level of Detail 10-12
2.3.2 Key Elements 10-14
2.3.3 Partner Involvement 10-16
2.3.4 Maintenance and Updates 10-17
2.3.5 Distribution 10-17
2.4 Developing Notification Procedures 10-18
2.5 Understanding Roles 10-19
2.5.1 Common Levee Owner/Operator Activities 10-19
2.5.2 Jurisdictional Oversight 10-20
2.5.3 External Agency Assistance 10-21
2.6 Classifying Incidents 10-21
2.6.1 Determining Incident Classifications 10-22
2.7 Planning Response Actions 10-24
2.7.1 Notification Procedures 10-24
2.7.2 Evacuation Procedures 10-25
2.7.3 Pre-Planned Floodfight Actions 10-26
2.7.4 Transference of Risk 10-27
2.8 Using Inundation Maps 10-28
2.8.1 Hypothetical Scenarios 10-29
2.8.2 Inundation Map Key Characteristics 10-30
2.8.3 Partner Coordination 10-32
2.8.4 Updating Inundation Maps 10-32
2.8.5 Digital Inundation Mapping 10-32
2.9 Managing Critical Resources 10-34
2.9.1 Stockpiling Floodfighting Materials and Equipment 10-34
2.9.2 Alternative Sources for Communication and Power 10-35
2.10 Training and Exercises 10-35

2.10.1 Training ... 10-37
2.10.2 Emergency Action Plan Exercises ... 10-37
2.10.3 Exercise Development ... 10-38
2.10.4 Exercise Evaluation ... 10-38
2.10.5 Exercise Participants ... 10-38
2.10.6 Exercise Frequency ... 10-39
3 Managing a Levee Emergency ... 10-39
3.1 Incident Management System ... 10-40
3.2 Unified Command ... 10-41
3.3 Emergency Operations Centers ... 10-43
4 Operating a Levee During an Emergency ... 10-45
4.1 Incident Detection ... 10-45
4.1.1 Preliminary Response Activities ... 10-45
4.1.2 Flood Source Monitoring ... 10-46
4.1.3 Flood-Related and Event-Driven Inspections ... 10-47
4.1.4 Instrumentation Monitoring ... 10-51
4.2 Data Management ... 10-52
4.2.1 Criteria for Data Collection ... 10-52
4.2.2 Tools for Data Collection ... 10-54
4.3 Floodfight Actions ... 10-55
4.4 Emergency Communication ... 10-56
4.5 Evacuation ... 10-56
4.6 Termination ... 10-57
4.6.1 Communication ... 10-57
4.6.2 Demobilization ... 10-57
4.6.3 Transfer of Command ... 10-58
4.6.4 Closeout/Debriefing ... 10-58
4.6.5 After-Action Report ... 10-58
4.6.6 Transition to Recovery ... 10-59
5 Recovering from a Levee Emergency ... 10-59
5.1 Post-Flood Inspection ... 10-60
5.2 Immediate Repairs ... 10-60
5.3 Long-Term Repairs and Rehabilitation ... 10-62
5.4 Removing Temporary Floodfighting Measures ... 10-62
5.5 Recovery Assistance ... 10-62
6 Summary ... 10-63

List of Figures

Figure 10-1: Related Chapter Content 10-i
Figure 10-2: Collaboration Before, During, and After a Flood 10-8
Figure 10-3: Potential Failure Modes 10-11
Figure 10-4: Emergency Action Plan Scalability 10-12
Figure 10-5: Leveed Area from the National Levee Database 10-29
Figure 10-6: Hypothetical Sacramento River Inundation Maps 10-31
Figure 10-7: Emergency Responder Floodfight Training Session 10-36
Figure 10-8: Incident Commander During an Exercise 10-41
Figure 10-9: Unified Command—Multiagency/Multijurisdictional Incident 10-42
Figure 10-10: Unified Command—Multiagency/Single Jurisdiction Incident 10-43
Figure 10-11: Unified Command—Multijurisdictional Incident 10-43
Figure 10-12: Sandboil Marker 10-51
Figure 10-13: Workers Repair a Levee 10-61

List of Tables

Table 10-1: Emergency Action Plan Key Elements 10-14
Table 10-2: Incident Classifications 10-22
Table 10-3: Example Guidance for Determining Incident Classification and Pre-Planned Actions for Seepage Issues 10-23
Table 10-4: Flood-Related Inspection Tasks 10-49
Table 10-5: Conditions and Attributes to Record During a Flood 10-53
Table 10-6: Typical Floodfight Actions 10-55
Table 10-7: Related Content 10-64

1 Introduction

There are over 7,000 levees that provide flood risk reduction in the United States, with more than 17 million people working and living behind them. Levees are not failsafe and cannot completely eliminate flood risk. Therefore, proper operation, maintenance, and emergency management are necessary to reduce the likelihood of levee breach and the associated potential for loss of life and property.

As climates change, weather patterns fluctuate, levee infrastructure ages, and populations behind levees increase, the potential for floods necessitates a thorough understanding of how to effectively manage a levee emergency.

Levee owner/operators, regulating agencies, and emergency management agencies must be prepared to handle the aspects of potential levee emergencies that fall within their jurisdiction to reduce risks to life and property, while simultaneously taking actions to prevent or stabilize emergency conditions on the levee or reduce the consequences if a levee is breached.

This chapter describes best practices for developing and implementing effective levee emergency management measures to reduce the likelihood and impacts of levee emergencies and improve public safety.

Levee emergency management is divided into four sections as described below.

- **Preparing for a levee emergency**: Section 2 describes emergency planning and preparedness activities to avoid or reduce the risk to human life, property, and critical infrastructure.
- **Managing a levee emergency**: Section 3 describes methods for maintaining situational awareness, coordination, and communication with partners and the public before and during a levee emergency.
- **Operating a levee during an emergency**: Section 4 provides an overview of incident detection and response actions to be implemented to identify and respond to a levee emergency.
- **Recovering from a levee emergency**: Section 5 includes the initial steps of recovery to be taken concurrently with emergency response efforts or immediately following the emergency.

2 Preparing for a Levee Emergency

Levee emergencies should be considered inevitable, which is why planning and preparing before an emergency is essential. When a levee emergency occurs, a clearly understood and effective strategy allows for seamless response. Emergency preparedness for levees focuses on actions to take before and during a flood in response to conditions on the levee to prevent emergency conditions from developing, to reduce the likelihood of levee breach should an emergency occur, and to reduce consequences should a levee breach or overtopping occur.

Preparedness activities allow emergency response to occur more rapidly and efficiently. Emergency preparedness is a continual cycle of planning, training, exercising, and improving that includes:

- Collaborating with stakeholders.
- Understanding levee risks.
- Developing an emergency action plan.
- Developing notification procedures.
- Understanding roles.
- Classifying incidents.
- Planning response actions.
- Using inundation maps.
- Additional preparedness activities.
- Managing critical resources.
- Training and exercises.

The following definitions are used throughout this chapter.

- Incident: An incident is an unexpected occurrence that requires some level of a response to ensure or restore levee integrity or functionality. Incidents include both non-emergency and emergency conditions. Many incidents do not require action above and beyond typical operation and maintenance (O&M) activities to protect life or property.
- Emergency: An **emergency** is an incident which endangers the structural integrity of the levee and places life and/or property at risk. Emergencies typically warrant urgent or non-routine response.
- Emergency management: This is the interdisciplinary function of developing the framework and measures necessary to avoid or reduce the impacts from emergencies.

The primary goals of emergency management are to save lives, prevent injuries, and reduce damage to property and the environment.

- Emergency action plan: An emergency action plan is a formal document that identifies potential emergency conditions at a levee. It specifies pre-planned actions to reduce the likelihood of breach and to reduce consequences should breach or levee overtopping occur.

2.1 Collaborating with Stakeholders

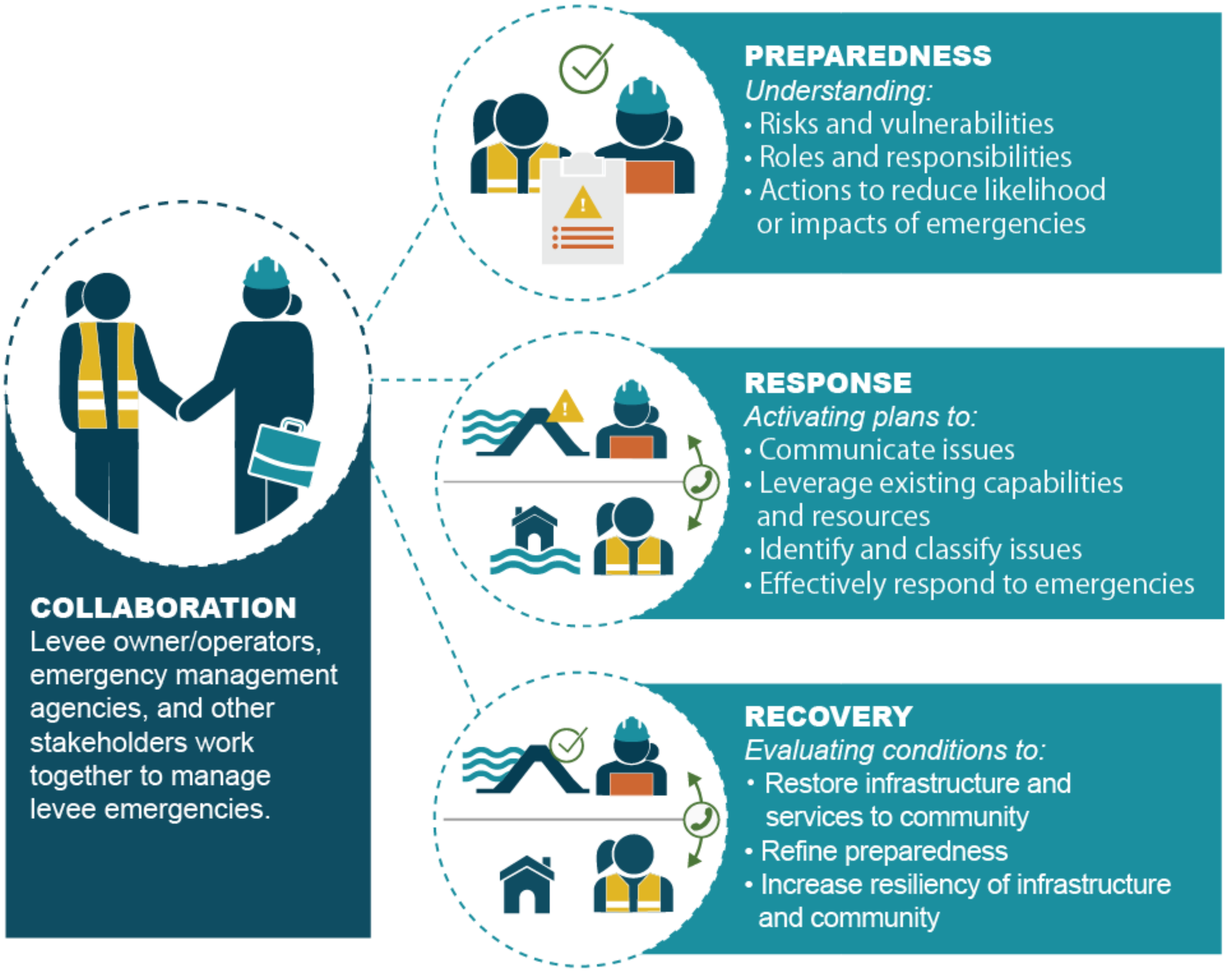
Levee **stakeholders** include individuals, groups, organizations, or businesses that have an interest in, can affect, or be impacted by the levee and decisions about the levee. Key stakeholders who share responsibility for managing the levee or managing some aspect of levee risk are partners in levee risk management. Identifying and developing relationships with partners in emergency response is foundational to effective emergency preparation. During an emergency, valuable time can be lost when there is not a clear understanding of who will execute critical tasks, such as recommending and executing evacuation notifications to the public. Partners with a shared understanding of their roles and responsibilities, available resources, and potential consequences of levee breach can respond more effectively.

It is a best practice to develop a levee emergency action plan (section 2.3) in coordination with partners and to include partners in routine training and exercises. Frequent engagement with partners, including annual meetings between levee owner/operators, emergency management agencies, and other key partners can facilitate a better understanding of roles and responsibilities and enhance emergency readiness.

Sharing the emergency action plan and other critical levee information with communities within the leveed area before a flood occurs can build knowledge and awareness early on about levee risk and incident response processes (**Chapter 3**). This kind of engagement builds trust between levee owners, local officials, community members and other stakeholders, increasing the likelihood that emergency warnings and evacuation notices will be heeded. Establishing relationships and trust early can also help community leaders and emergency management professionals identify areas where vulnerabilities may prohibit community members from being able to take action during an emergency. These vulnerabilities should be addressed in the levee and flood emergency planning process. The most prepared and resilient communities are those in which all stakeholders—including local businesses and citizens—understand the importance of the levee, its risks, and all phases of emergency management activities.

Figure 10-2 depicts multiple ways stakeholders collaborate with levee owner/operators and emergency management agencies to manage levee emergencies.

Figure 10-2: Collaboration Before, During, and After a Flood



It is vital that all entities, jurisdictions, agencies, and authorities that would be involved in an incident at a levee or have responsibilities for warning, evacuation, and post-incident actions be involved in levee emergency preparedness. A wide range of entities are partners in emergency preparation and response. Key entities involved in emergency preparedness include, but are not limited to:

- The owner/operators of the levee for which planning is occurring.
- State and local emergency management agencies.
- Local fire, police, and emergency management services.
- Agencies with flood warning responsibilities (e.g., National Weather Service).
- Land management agencies.
- Other levee owner/operators within the watershed.
- Community leaders and other trusted messengers who can help reach out to members of underserved communities.

- Community members who could be impacted by a levee emergency.
- Transportation and communication entities.
- Federal Emergency Management Agency (FEMA) and other federal agencies.
- Utility companies.

Partner responsibilities during a levee emergency are discussed in more detail in section 2.5 of this chapter.

2.2 Understanding Levee Risks

Understanding the levee risk is an important step in planning for an emergency.

Risk assessments identify and estimate levee risks. These risks can be driven by the hazards to the levee, performance of the levee, or consequences behind a levee. It is a best practice for emergency preparedness planning to address identified levee risk drivers. Best practices for estimating levee risk are detailed in **Chapter 4**.

An understanding of levee risk should inform the scale of emergency planning and preparation efforts. Levees with higher risk should have more extensive and detailed planning and preparation. In particular, levees that have both a potential for life loss due to breach and performance concerns that could cause breach prior to overtopping should have comprehensive emergency preparation and planning that includes all of the best practices identified in this chapter. Emergency planning and preparation for levees

TRAIN BLOCKING CLOSURE STRUCTURE

During Hurricane Ida, a levee intended to reduce flood risks to the Borough of Bound Brook, New Jersey was operationally compromised due to a commuter train blocking a levee closure structure.

The levee includes two vehicle closure structures and two railroad closure structures. The two vehicle structures and one of the railroad structures were closed successfully prior to the storm. However, a New Jersey transit commuter train became immobilized with the tail end of the train across one of the railroad closure structures, preventing its closure. Efforts to move the train were unsuccessful. One gate was closed, while the other was placed against the train with sandbags filling the gaps. However, the arrangement did not hold, and when floodwater from the adjacent creek rose up to the train tracks, water entered the leveed area resulting in significant property damages.

Lessons learned: Pre-coordination and emergency planning between levee owner/operators and the owners of transportation corridors that pass through the levee is essential. Coordination should include plans for typical closures, as well as emergency actions to address unexpected issues. In this case, a plan to move disabled trains and other blockages from the closure opening could have resulted in a more effective response.

Aerial view of a train blocking operation of a closure structure during a flood in Bound Brook, New Jersey.

without a population at risk may be scaled such that the effort and investment is commensurate with levee risk. More discussion on determining the appropriate level of detail for emergency planning is in section 2.3.1.

2.2.1 Hazards

In order to develop hazard-specific emergency action plans, it is important to understand the hazards a levee could encounter. Knowing the specific characteristics of the flood hazard is essential to planning emergency response activities that are appropriately scaled and timed. These characteristics include the:

- Flood source or combination of flood sources that could load the levee.
- Rate at which the flood source typically rises.
- Typical durations of floods.
- Estimated frequency of various flood loadings.

Different sources of flood hazards are discussed in detail in **Chapters 1 and 4**.

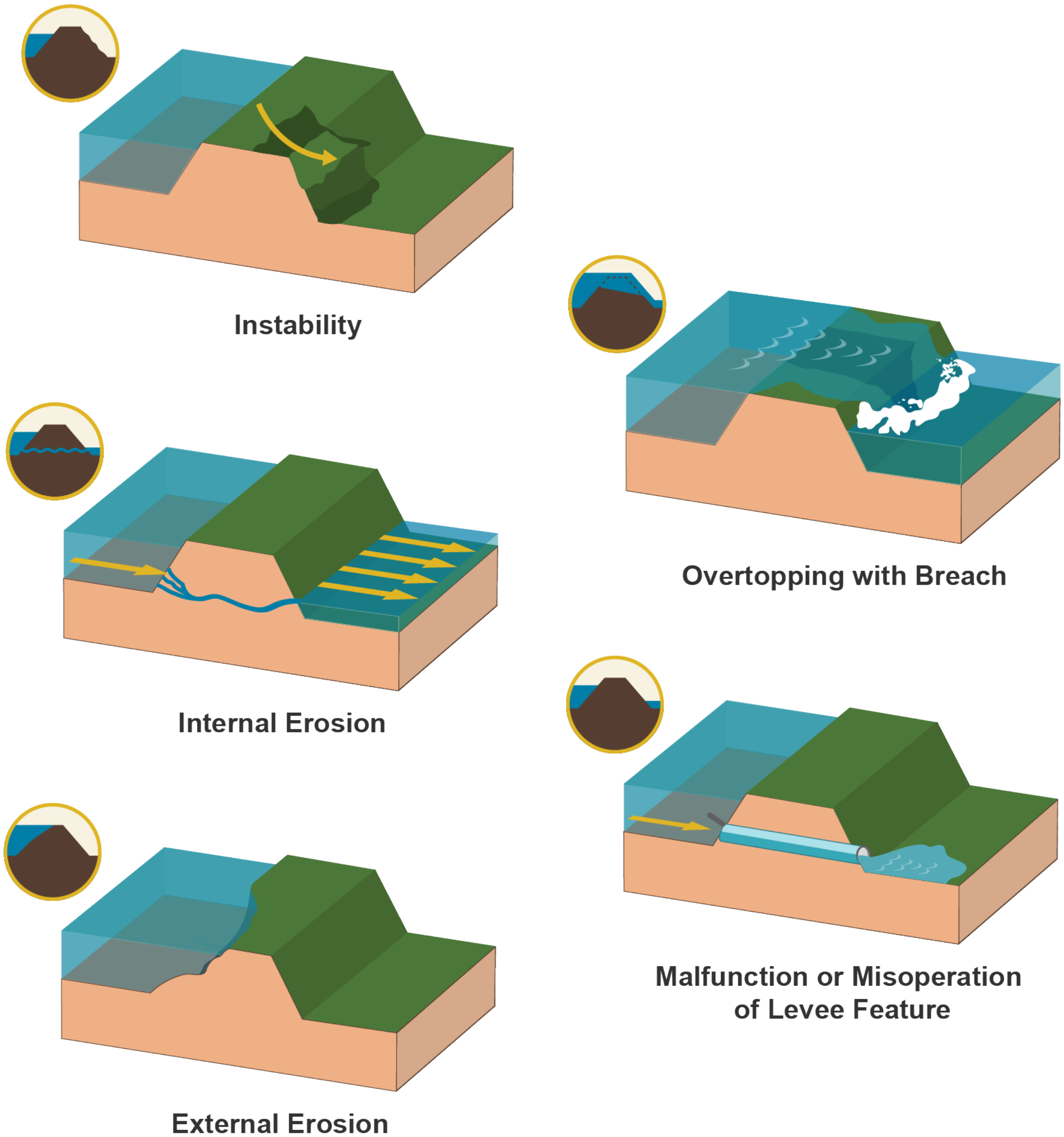
Hazards to a levee can be dynamic and diverse. Earthquakes and weather-related hazards—such as extreme winds, drought, extreme heat, and wildfires—can threaten the integrity of the levee. Climate change is increasing the frequency and intensity of extreme weather events. Emergency preparedness requires careful consideration to ensure the frequency and scale of all current and potential future hazards are accounted for.

2.2.2 Performance

Risk assessments identify **potential failure modes**, which are mechanisms that once initiated could progress to breach of a levee. The five most common potential failure modes for a levee are shown in Figure 10-3. These potential failure modes are introduced in **Chapter 2** and are discussed in more detail in **Chapter 4**.

Understanding the potential failure modes which are likely to occur can inform emergency planning and response, including the focus of flood inspections, the development of pre-planned floodfight actions, and the management of materials and resources.

Figure 10-3: Potential Failure Modes



2.2.3 Consequences

Levee emergencies that result in a levee breach can cause loss of life and significant property and/or environmental damage. Risk assessments can provide information regarding the potential consequences of a levee breach, including infrastructure that could be impacted and communities which may have higher exposure to flooding. Community exposure could be influenced by a population's location within the leveed area, ability to access flood risk and emergency information, or ability to get out of harm's way during a flood.

Risk assessments also estimate the depth of flooding in certain breach scenarios and how quickly floodwaters can move through a leveed area. Inundation mapping can be utilized to portray these impacts visually, as discussed in section 2.8. Consequence assessments are discussed in more detail in **Chapter 4**.

It is a best practice to tailor emergency response actions to the specific characteristics of the leveed area, including community characteristics and the depth and rate of inundation.

The consequences of levee breach may include impacts to other flood risk management infrastructure. For example, a levee breach may impact how water moves through the floodway, increasing the rate or depth of loading on other levees, which could result in cascading flooding or damage. Effective preparedness planning requires identifying and documenting these interdependencies and ensuring proper coordination when a levee is part of a broader flood risk management system.

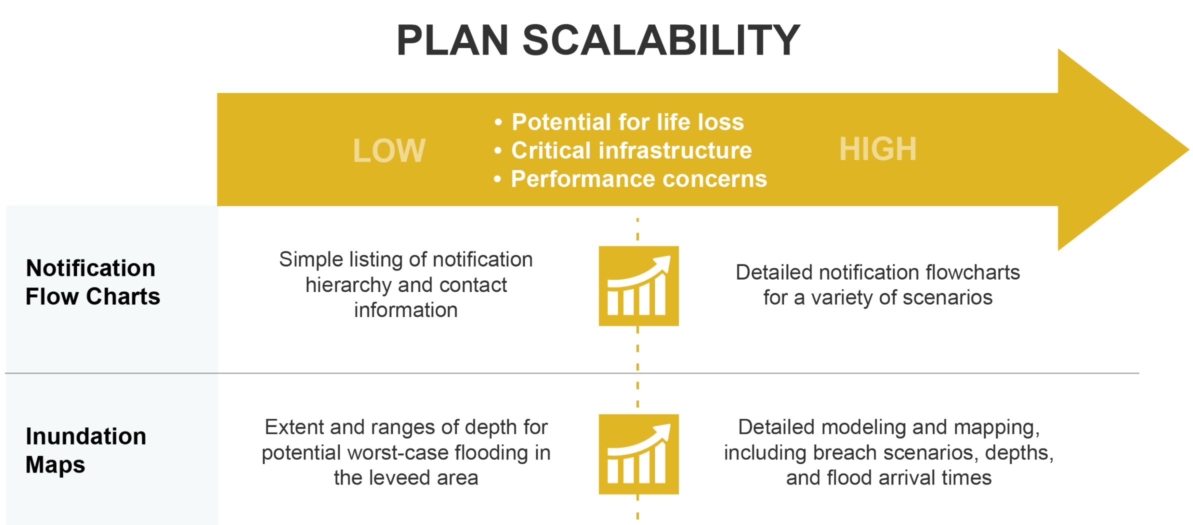
2.3 Developing an Emergency Action Plan

Well-developed and practiced emergency action plans facilitate an effective response to and recovery from a levee emergency based on pre-established and coordinated activities, as opposed to purely reacting to an emergency as it occurs. It is a best practice for each levee to have an emergency action plan that is properly scaled, flexible, frequently updated, and exercised often.

2.3.1 Level of Detail

The appropriate amount of detail to include in an emergency action plan will vary based on the physical characteristics of the levee, the complexity of levee operations, and the levee risk. Figure 10-4 provides examples of how some of the key contents of an emergency action plan should be scaled, depending on the characteristics of the levee.

Figure 10-4: Emergency Action Plan Scalability



Levee owner/operators for levees without a population-at-risk may decide to limit their emergency action planning to:

- Developing an organizational chart or roster with contact information.
- Developing a list and map of important levee features to share with partners.
- Sharing a map of potential flood extents from the National Leve Database (NLD).

Levee owner/operators may also choose to include floodfight procedures in their planning to help ensure the levee will provide its intended benefits.

Emergency planning for a levee with any population at risk should include the items listed in the paragraph above, as well as levee and flood source monitoring procedures, detailed emergency notification procedures, and a description of the levee owner/operator’s role in evacuation decisions and execution.

Higher risk levees—those with a population at risk and a likelihood of inundation either due to breach or overtopping—should have detailed emergency plans that include all of the best practices discussed in this chapter. The focus of emergency planning should be targeted to address the appropriate risk driver. For example, emergency planning for a levee with identified performance risk drivers likely to cause breach prior to overtopping will include detailed inspection, monitoring, and floodfight actions to address the identified performance concern, as well as detailed emergency notification procedures and a description of the levee owner/operator’s role in the evacuation process. Emergency planning for higher risk levees that are not expected to breach prior to overtopping will likely focus on flood source monitoring, detailed emergency notification procedures, and a description of the levee owner/operator’s role in the evacuation process, as well as general floodfight methods to address unanticipated performance concerns.

When determining the appropriate level of detail to include in each section of a levee emergency action plan, levee owner/operators should consider the following questions:

- **Is there risk to life if the levee is breached?** Good emergency action plans for levees where there is a potential for loss of life contain a high level of detail to address and mitigate the risk of life loss. If there is no potential for life loss, the emergency action plan may contain less detail.
- **What is located in the leveed area that could be inundated in the event of a levee breach?** Determine what is located in the inundation area and how leveed area infrastructure should be addressed in the planning process. Infrastructure that may require special consideration include hospitals, schools, nationally or regionally significant industries, hazardous materials, transportation corridors, evacuation routes, and other critical infrastructure.
- **Who is located in the leveed area that could be impacted by a levee breach?** Determine what communities are present within the leveed area and the unique needs they may have during an emergency. It is a best practice for all communities within the leveed area to be engaged and considered in the planning process. Targeted efforts focused on long-term relationship building may be required to develop relationships and build trust with traditionally underserved communities.

- **Who has decision-making authority for taking emergency action on the levee and within the leveed area?** Determine if the decision-making authority for taking emergency action resides at the levee owner/operator level or if local officials need to be involved in the process. Provide clear roles and responsibilities within the plan.
- **What floodfight actions and materials will be required to respond to an emergency at the levee?** Identify actions and materials that will be necessary to protect the levee during an emergency. An emergency action plan is more effective when it clearly identifies anticipated floodfight actions, the materials needed to support them, and where the materials are located and how to use them.

Regardless of the factors that could affect the level of detail in an emergency action plan, the key elements provided below are found in comprehensive emergency action plans. Additional emergency action plan details, sections, appendices, and references can be incorporated as necessary based on the attributes of that particular levee.

2.3.2 Key Elements

Emergency action plans typically contain a consistent set of key elements. The most common elements are discussed in Table 10-1. Ensuring all key elements are included in a levee emergency action plan provides uniform, comprehensive, and consistent levee emergency planning. Other common elements of an emergency action plan include title page, table of contents, signatures page, statement of purpose, and project description. Supplementary information can also be included as appendices to the plan.

Table 10-1: Emergency Action Plan Key Elements

Key Element	Description of Content	Additional Information for:	
		Developing Plan Content	Implementing Plan Content
Notification flowchart and contact information	A notification flowchart identifies who is to be notified of a levee emergency, by whom, and in what order. Notification flowcharts and emergency contact lists ensure prompt and effective notifications during a potential levee emergency.	Section 2.4 Section 2.7.1	Section 4.4
Responsibilities	Clearly defined responsibilities of all partners before, during, and after an emergency improves efficiency and continuity of response efforts. This may include identifying: • Notification and communication responsibilities. • Evacuation responsibilities, if applicable. • Monitoring, security, termination, and follow-up responsibilities. • Emergency action plan coordinator responsibilities.	Section 2.1 Section 2.3.3 Section 2.7.1 Section 2.7.2 Section 2.10	Section 3 Section 4 Section 5

Key Element	Description of Content	Additional Information for: Developing Plan Content	Additional Information for: Implementing Plan Content
Incident detection, evaluation, and classification	An incident classification system allows for quick and clear communication regarding the severity of an incident. It is helpful for each pre-established classification to be associated with typical levee conditions that are likely to be experienced and the associated response actions.	Section 2.6	Section 4.1
Response actions	• Monitoring procedures. • Notification and evacuation procedures. • Pre-planned floodfight actions and materials. • Procedures for responding during periods of darkness, weekends, holidays, and adverse weather.	Section 2.7	Section 4
Additional preparedness activities	Additional information found in a comprehensive emergency action plan: • Implementation time: The total time from detection, required to determine the severity of incident, notify appropriate partners, and take necessary actions. • Site access: Primary routes for reaching the levee during an emergency and alternate access options if the main access route is impacted by flooding of the leveed area. This may include the various levee access methods (e.g., foot, boat, helicopter). • Stockpiling floodfight materials and equipment: Location and quantity of resources for response actions. Contact information for local contractors, suppliers or organizations who may support response activities. • Alternative systems of communication: Available communication systems such as emergency sirens, cellular phones, direct connect, email, intranet, radios, social media, satellite phones and couriers, along with operating procedures for each system. • Alternative sources of power: Location, mode of operation, means of transportation for alternative power sources for operations. • Training and exercises: Types and frequencies of training to ensure those involved in the implementation of the	Section 2.1 Section 2.7.3 Section 2.9 Section 2.10	Section 4.4

Key Element	Description of Content	Additional Information for: Developing Plan Content	Additional Information for: Implementing Plan Content
	emergency action plan are thoroughly familiar with the plan and their responsibilities. • Public awareness and communication: Description of necessary activities to raise awareness before an emergency and ensure effective communication during an emergency.		
Inundation maps	Inundation maps delineate the specific geographical area(s) that would be flooded due to a hypothetical levee breach, overtopping, or malfunction/misoperation of a levee feature. These maps are developed in coordination with the appropriate emergency management agencies. These maps can improve the effectiveness of response actions and evacuation plans by identifying when access routes may be inundated and the depths of flooding.	Section 2.8	
Post-event actions	Documentation and recovery procedures.	Section 4.6	Section 5

2.3.3 Partner Involvement

The first step of emergency planning is identifying all levee emergency management partners. Effective levee emergency planning includes close coordination with all entities, jurisdictions, emergency management agencies, and regulating agencies that typically would be involved with an incident at a levee or that have statutory responsibilities for warning, evacuation, and post-emergency actions.

The process of emergency planning is often as important as the actual plan due to the connections made among the various partners. A list of partners that are typically involved in levee emergency management is provided in section 2.1.

Emergency planning will not be helpful if those responsible for executing the plan are not trained on how to execute it together. Training and exercising a levee's emergency action plan with partners provides opportunities to evaluate the effectiveness of the plan and determine whether the goals, objectives, decisions, actions, and timing outlined in

EMERGENCY ACTION PLAN COORDINATION

It is a best practice for levee emergency action plans to be written and updated in close coordination with partners to ensure consistency and common understanding. Good coordination efforts address the following questions:

- What incidents necessitate heightened awareness?
- At what point during an incident should the levee owner/operator notify emergency management agencies?
- Who in each organization will be responsible for sending and receiving notifications?
- Who will be responsible for decisions about and coordination of protective actions such as evacuation and re-entry?

The goal of coordination is to develop a joint understanding of evolving dependencies and interdependencies.

the plan are appropriate and comprehensive. Gaps or deficiencies in the plan identified during training, exercises, or real-world events should inform updates to improve the plan. Additional discussion of training and exercises is provided in section 2.10.

2.3.4 Maintenance and Updates

Annual reviews of the emergency action plan ensures the plan remains relevant and useable. It is important to immediately update the plan to incorporate changes in personnel and contact information, as well as significant changes to levee or emergency procedures.

It is also beneficial to review the plan after floods and events triggering its activation to determine if there are opportunities for improvement. These reviews may prompt plan updates following emergencies. Feedback provided by stakeholders may also trigger an update. Coordination with partners and redistribution of the plan during significant revisions will help ensure continued understanding of roles and processes by all.

2.3.5 Distribution

All partners should have access to the emergency action plan; however, managing distribution of a levee emergency action plan can be an important part of levee security. It can be helpful to develop a distribution list that is included as an appendix to the plan. The distribution list should include all stakeholders that would be involved in implementing the plan. The list should be reviewed and refined during emergency action plan updates.

In some cases, there may be a need to maintain document control and protect critical information. A good way to do this is by assigning a copy number to each copy of the plan that is distributed and requesting that other copies of the emergency action plan not be made.

When outdated emergency action plans have been replaced in their entirety with new versions, it is good policy for the outdated controlled copies to be returned to the developer or destroyed to prevent misuse. Document control can be maintained for emergency action plans that are made available electronically, through the use of a secure web portal accessible only to the entities on the established distribution list. In addition to electronic copies of the plans, it is best practice to have a limited number of hard copies available in the event of a power outage, cyberattack, or lack of access to the electronic versions of the plan.

To protect critical information, it may be important to limit distribution of technical data and personal contact information contained in the plan. This type of information control can be accomplished by placing technical information—such as engineering details, potential failure modes, and facility details—into an appendix to the emergency action plan and limiting dissemination of the appendix to those who have a specific need for the information. It is also important to ensure that plans containing critical information are labeled appropriately.

Additionally, uploading completed or revised emergency action plans to the NLD linked to the respective levee is encouraged for ease of access by local emergency management agencies and other state and federal partners (USACE, 2016).

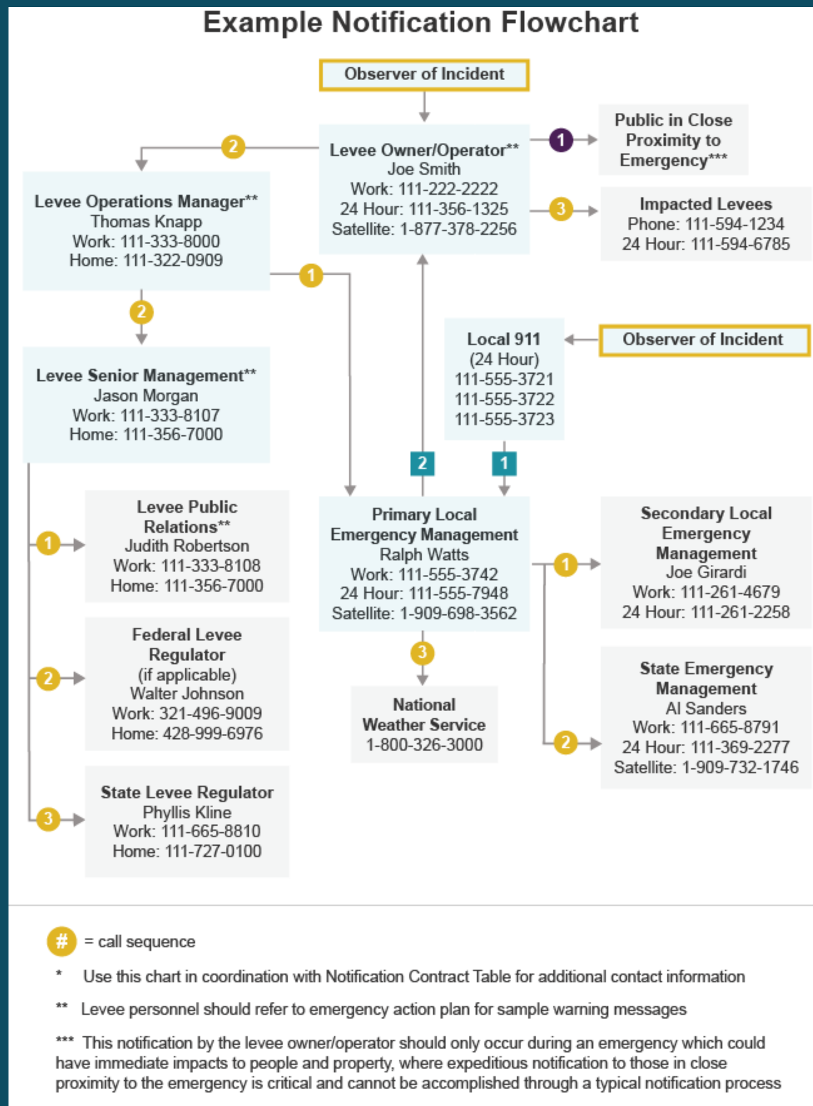
2.4 Developing Notification Procedures

It is a best practice for levee owner/operators to develop and maintain accurate notification flowcharts and emergency contact lists for their levees to ensure prompt and effective notifications during a levee emergency.

A notification flowchart is a communication guide that identifies who is to be notified of levee conditions during a flood, including a levee emergency, by whom, and in what order. It can be beneficial for levee owner/operators to develop internal and external notification flowcharts. Internal flowcharts are used to keep levee owner/operator staff aware of ongoing flood operations. Internal charts are usually implemented when a flood is forecasted and then used throughout the flood for internal coordination. External notification flowcharts are used to keep external partners aware of conditions on the levee once it is loaded and to initiate emergency warnings and inform evacuation decisions should an emergency occur.

It is best to limit notification responsibilities for a single individual to no more than three or four parties and to take into account the magnitude of other responsibilities the person has been assigned.

SAMPLE NOTIFICATION FLOWCHART



Notification flowcharts should be developed in collaboration with appropriate partners to identify who to include and how complex the notification process needs to be. One flowchart or a set of flowcharts may be needed depending on the number of entities involved. At a minimum, useful notification flowcharts will identify communication processes for the levee owner/operator, the local emergency management agency, and the entity responsible for making evacuation decisions. The National Weather Service should also be included in notification flowcharts since they issue flood warnings, particularly in the event of a levee breach or overtopping, which need to be informed by levee conditions. In some cases, particularly when working with underserved communities, trust can be an issue. It is a best practice to identify trusted community leaders that can be included in the notification process to increase the likelihood messages will be received and heeded.

Instructions on how to use the notification flowcharts can be developed to support efficient implementation of the notification process. Thoroughly and regularly exercising notification flowcharts with all involved personnel and partners helps ensure the accuracy of the flowcharts and that all responsible individuals understand their role in the process.

Notification flowcharts that clearly present the information listed below and are included in the emergency action plan are easier to use during an incident.

- Description of the notification flowchart purpose, especially if there is more than one flowchart.
- Prioritization of notifications.
- Specific agencies and individuals who will be notified with names, positions, and telephone numbers.

Supplemental contact information, such as radio call numbers, fax numbers, e-mail addresses, direct connect numbers, and alternate contacts, may be included in a list or table of emergency contacts.

2.5 Understanding Roles

Understanding the roles of all partners responsible for responding to an incident during a flood is important for emergency preparedness. When organizations work to understand their role for incident response within the broader community, as well as work to assign and clarify roles within their organization, both organizations and individuals gain a better understanding of their responsibilities during an emergency.

2.5.1 Common Levee Owner/Operator Activities

The primary objective during a levee emergency is to protect life and property by maintaining integrity of the levee and to facilitate actions to get people out of harm's way if levee overtopping or breach is unavoidable.

These objectives can be accomplished by assigning specific individuals the responsibility to perform, oversee, and make critical decisions concerning the following activities:

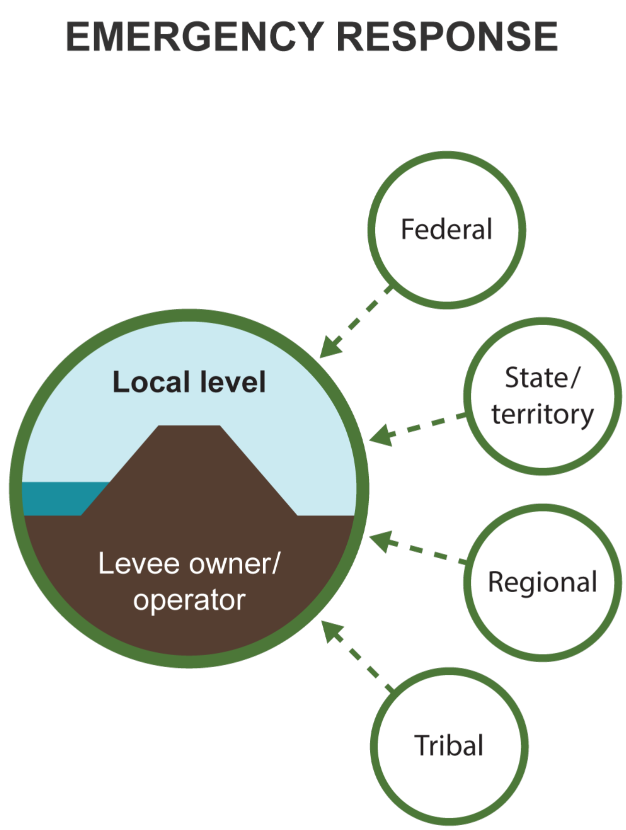
- Maintain situational awareness (flood source monitoring).
  - Monitor meteorological forecasts that may predict the probability of high rainfall or a storm.
  - Monitor flood stages.
- Constantly verify and assess conditions at the levee.
  - Inspect the levee and features.
  - Implement necessary preliminary response actions.

   - Actively monitor events as they unfold and prepare to implement full response activities.
- Notify participating emergency management agencies of levee conditions.
- After the peak of the emergency, initiate post-response and recovery activities to allow a return to normal conditions.
- Communicate termination of the emergency at the levee when emergency conditions have subsided.

2.5.2 Jurisdictional Oversight

Responsibilities for managing flood risks and responding to levee emergencies is commonly shared across several federal, state/territory, regional, tribal, and local agencies. Most activities to reduce the risk communities face from floods are handled at the local level.

Every levee emergency begins at the local level. If the levee owner/operator is unable to handle the emergency, there are many ways the government can assist. For example, the county or state may provide additional assets (e.g., trucks, tractors, radios, helicopters) for flood-related inspections and financial assistance for response and recovery activities.



If a levee owner/operator runs out of supplies, they can request assistance from local and state governments, and if necessary, local and state governments can coordinate additional assistance from the federal government. Depending on the lead time available before an incident occurs, decisions and requests for resources may be made several days in advance so that resources can be mobilized and in position before the arrival of the hazard. Incidents that occur without warning present significant complications and resource challenges. During emergencies, actions to stabilize the levee, evacuate, or shelter-in-place may occur simultaneously with limited resources.

It is important to remember that in order for the government to provide assistance, an emergency declaration must be made. Each level of government has criteria in place that determines whether a situation can be declared an emergency. In instances where an incident at a levee does not meet these criteria, assistance from that level of government will not be provided. Plans should be in place to supplement resources by other means in these situations.

2.5.3 External Agency Assistance

It is vital that levee owner/operators are aware of the type of support that external agencies within their community can provide, and whom to contact to receive the necessary support. A list of common groups that often assist in responding to levee emergencies include:

- Emergency management departments
- Law enforcement agencies
- Fire departments
- Public works departments
- Communication specialists
- Utility/power companies
- Transportation agencies
- Mass care/shelter facilities
- Agriculture/natural resources
- Public health and medical facilities
- Search and rescue agencies
- Hazardous material cleanup companies

Identifying all potential resources and coordinating with the identified resources before an emergency will allow for more efficient communication during an actual emergency. Building relationships with local power and communication suppliers prior to an emergency can allow for early warning of power outages when possible and the potential for priority repairs, when appropriate.

TRUCK STRANDED ON LEVEE DURING FLOOD

In 2019, several roads around the Missouri River levee in Chariton County, Missouri, were closed as a result of construction and flooding. Due to all of the main roads being closed, a truck driver used his global positioning system (GPS) to find an alternate route.

The GPS led the truck driver to the top of a levee that overtopped both in front and behind his truck. The truck driver contacted 911 who alerted the local Chariton County Sheriff's office. The Sheriff's office contacted USACE who was able to use their helicopter to rescue the truck driver. The truck remained on the levee for months.

Ensuring proper road closures are in place to protect the safety of the public and avoid this type of situation is an integral part of managing a levee emergency.

View of the Fruit Stripe Gum semi-truck blocking a levee crown road during a flood.

2.6 Classifying Incidents

Using clear, concise language to describe a flood event is important when communicating with the public and other supporting organizations. An incident classification system provides common terms and consistent definitions that can help quickly and clearly communicate the severity of an incident, general levee conditions, and associated incident management activities. Development and use of an incident classification system helps expedite activities such as evacuation of the leveed area.

To promote nationwide consistency, four levee-related incident classifications, described in Table 10-2, are suggested to aid communication during an emergency. Regardless of the incident classification system chosen for a community or levee, it is important for all entities involved in flood emergency response to understand the incident classification system and the expected responses.

Table 10-2: Incident Classifications

Classification	Description
High flow	Indicates water is flowing through or over the levee as intended by design. This classification may be used to convey to the impacted public that leveed areas may be affected by the flows, but there is no apparent threat to the integrity of the levee. Examples of high-water flow releases that could come through or over a levee include pipe, outlet, or a designed overtopping section.
Non-breach	Indicates a levee-related event that will not, by itself, lead to a breach, but requires investigation, increased monitoring/floodfight action, and notification of internal and/or external personnel. A certain water elevation or storm surge may be defined that requires increased monitoring and surveillance above normal O&M procedures as non-breach. Additionally, this emergency classification may be applied to limited overtopping for a levee with no risk of breaching due to a designed overtopping section or other features designed to withstand wave energy during hurricanes.
Potential breach	Indicates that levee conditions are developing that could lead to breach. Potential breach conveys that time is available for analyses and decisions, and actions should be taken to prevent escalation of the incident to a full breach.
Imminent breach	Indicates the levee has breached, is actively breaching, or is about to breach. Imminent breach typically involves a continuing and progressive loss of material from the levee.

2.6.1 Determining Incident Classifications

It is a best practice for pre-flood preparations to include the development of an incident classification system and guidelines that describe how incident classifications will be applied to the levee. For consistency in decision making, it is best to assign a single individual the responsibility of assessing performance concerns and assigning an incident classification. Table 10-3 provides sample guidance for determining incident classifications for different types of incidents. This table should be modified to guide incident classifications at a specific levee. Levee specific information that can be considered when developing guidance for incident classification includes:

- The level of risk associated with the levee.
- Flood source levels or predictions that indicate response actions are required.
- Instrumentation readings that indicate possible performance concerns.
- Past levee performance.
- Confidence in the success of future floodfight actions.

Table 10-3: Example Guidance for Determining Incident Classification and Pre-Planned Actions for Seepage Issues

ISSUE: SEEPAGE		
Incident Classification	**Action**	**Actions to Be Taken**
Non-breach: Seepage without soil movement, or sand boils that are easily managed with routine floodfight measures.	Notify	Notify the floodfight team of the seepage issue. Consider issuing non-breach notice to partners and the public describing seepage, floodfight actions, and the status of the levee.
	Monitor and inspect	Inspect at least daily. A rising flood source may warrant more frequent inspection. Monitor flood source forecasts. As flood water rises, seepage issues are likely to worsen.
	Floodfight	Raise the water level over each sand boil by placing a ring of sandbags, pipe, or barrel around the boil, blocking culverts in ditches, or using any other means of detaining water that is most practical for the site. The sandbag ring or barrel must have a water discharge elevation that allows water to flow while slowing the water flow enough to prevent soil movement.
Potential breach: Localized seepage or boil(s) observed along the levee with muddy discharge and increasing flow. Emergency floodfight measures are required, but are expected to be successful.	Notify	Notify floodfight team and partners of the seepage issue. Issue potential breach notification to the public in accordance with the emergency action plan. Consider starting voluntary evacuations of areas that would be impacted quickly by a breach and populations requiring more time to evacuate.
	Monitor and inspect	Inspect at least once every six hours and monitor flood source forecasts if conditions are stable. Inspect levee continuously if the flow rate or the material movement from the boils is increasing or if the flood source is rising.
	Floodfight	Raise the water level over the sand boil as described for the non-breach classification. Continue to raise the height of the water as necessary to prevent soil movement. If the size or number of boils makes sandbag rings ineffective, place an emergency seepage berm over the entire seepage area using material that is less permeable than the underlying soils, or build an impermeable soil ring around the entire seepage area to impound water over the seepage area and create a water berm.
Imminent breach: Sand boils becoming increasingly active, moving large amounts of material and floodfighting actions have not been successful. Cracks, sinkholes, or subsidence of nearby levee has been observed. Floodfight actions are not possible or not effective.	Notify	Follow the notification and evacuation processes in the emergency action plan. Notify floodfight team of the seepage issue.
	Monitor and inspect	Continuously inspect the levee performance from a safe location. Drones or other remote observation tools may be considered.
	Floodfight	Floodfight actions are likely not safe. If safe and possible, continue to reinforce the area impacted by the sand boil(s) by placing additional gravel or sand over the area or raising the water level over the sand boil(s). Should the ground surface become very soft, 'quick,' or start to move, evacuate the area immediately.

2.7 Planning Response Actions

Developing pre-planned actions allows for seamless response to incidents and emergencies. Correlating pre-planned actions to incident classifications allows for quick, clear communication of levee conditions to initiate those actions. It is a best practice to develop specific pre-planned actions correlated with the pre-established incident level classification for all plausible levee issues. Pre-planned actions should include incident/emergency notifications and floodfight actions. Table 10-3 provides example response actions that can be used as a starting point to develop levee specific actions that reflect unique levee conditions, available resources, and level of risk.

Understanding how the levee is likely to perform as water levels rise is critical to developing proactive pre-planned actions. Triggers based on current or projected flood source conditions can be developed to inform flood operations. The most useful triggers take into account the rate of rise of the flood source, past performance of the levee, available resources, and the complexity of the levee and the leveed area.

Due to trends in climate change, triggers and pre-planned actions may need to account for increasingly heavy precipitation with rapid flooding potential, higher flow releases from reservoirs, rain-on-snow compound events, increased wave heights, and increasing wind strength. For example, more frequent events may require adjustments in how resources are managed. More extreme events may require the identification of additional labor resources, adjustments to flood operation plans, or updates to emergency notification procedures. An increase in how quickly the flood source rises may require that operation and response thresholds be adjusted.

2.7.1 Notification Procedures

During an emergency there is limited time for determining who should communicate and what should be communicated. When there is a likelihood of life loss associated with levee breach or overtopping, effective notification procedures are essential. Pre-planned and coordinated processes can help ensure notifications are timely and informative.

It is a best practice to develop checklists and/or pre-scripted messages for each incident classification level to help adequately describe the situation to emergency management agencies and other stakeholders.

Examples of a notification checklist and pre-scripted messages are included in Appendix 6-I of Chapter 6 of the Federal Energy Regulatory Commission Engineering Guidelines (FERC, 2015).

An emergency message toolkit that contains information on the appropriate properties of an emergency message, example messages and templates, and other helpful information relating to communicating during a levee emergency can be found in The Guide to Public Alerts and Warnings for Dam and Levee Emergencies (Milleti and Sorensen, 2015).

During a flood event, it is a best practice for those responsible for operating the levee to relay periodic and emergency status reports to the emergency management agencies and other partners, in accordance with notification flowcharts described in section 2.4. Pre-scripted messages can help ensure the timeliness and clarity of all flood- and emergency-related information.

Local emergency management agencies and others responsible for emergency communication will issue warnings and notices to the public. Levee owners can work with their local emergency management agency to provide information about levee conditions to the National Weather Service during floods. The National Weather Service will consider levee information when developing emergency messages and can help to quickly disseminate warnings concerning flash flooding, levee breach, or levee overtopping to the public through the National Emergency Alert System and wireless emergency alerts.

It is beneficial to identify an individual who will have the primary responsibility for disseminating information to the public and handling media inquiries. These individuals are often trained public information officers, but at a minimum, this should be someone knowledgeable of the levee and incident response activities. It is also useful to identify a designated location to handle these communications, such as a joint information center.

SAMPLE PRE-SCRIPTED MESSAGE TEMPLATE FOR IMMINENT BREACH

[Insert title and organization of a local, familiar, authoritative message source.]

The levee in [describe the levee's location in terms that everyone can understand here] started to breach at [insert time here]. Flooding has begun and will quickly worsen. There is rapidly moving water that will reach depths of [insert depth here] feet, which can [describe impacts on people, houses, and cars].

The flooded areas will include: [describe the boundaries of the area that will flood in a way that everyone can understand].

[Evacuation information – typically provided by local sheriff's office or office of emergency services.]

This message will be updated in [insert number of minutes here] minutes or sooner if new information is available.

(Milleti and Sorensen, 2015)

Communications are more successful when the individual with primary communication responsibility works with media outlets and community leaders to craft pre-planned messages. It is important to give thought to the appropriate language, format, message, and messenger, particularly when seeking effective ways to provide emergency information to traditionally underserved communities and vulnerable communities. **Chapter 3** provides additional information on engaging with underserved populations.

It can be helpful for pre-flood notification planning to include identification of conditions under which deviation from the approved notification process may be warranted. In some situations, time may be allowed for on-site personnel to consult with others within their organization prior to initiating notifications to emergency management agencies. However, under an imminent breach incident, steps in the notification process may need to be skipped in order to provide timely notification that facilitates the necessary actions.

2.7.2 Evacuation Procedures

Local and county government agencies are typically responsible for issuing evacuation orders and for evacuation planning. Close coordination with the appropriate governmental agencies and community leaders to clarify the roles of all partners in the evacuation process and facilitate the timely sharing of levee information that informs evacuation decisions is a best practice.

Pre-emergency collaboration with key partners includes:

- Establishing preferred lines of communication.
- Defining roles and responsibilities during an evacuation.
- Ensuring an understanding of the levee's specific incident classification systems (section 2.6).
- Utilizing the levee's risk assessment to establish the most effective evacuation routes and identify potential issues with existing evacuation routes.
- Communicating intended evacuation actions with the community.
- Collaborating with communities to develop solutions for those that may require additional assistance due to lack of mobility/transportation, lack of access to technology/information, or limited English proficiency.

Evacuation planning should recognize there may be communities or locations within the leveed area that require non-typical means of notification. Populations that do not speak English, lack mobility or means of transportation, have limited access to technology, live in extreme poverty, or other characteristics that increase their vulnerability may have difficulty receiving and responding to evacuation notifications. Residences, recreation areas, and campgrounds that are immediately adjacent to the levee pose unique notification challenges, as typical means of notification may not provide adequate time for individuals in these areas to act.

> **EVACUATION PLANNING RESOURCES**
>
> **Evacuation Planning and Re-entry Course** is a course offered in FEMA's Advance Professional Series. This series may be accessed through FEMA's website and offers "how to" training focused on practical information and emphasizes applied skills in disaster operations, management, and coordination.
>
> **Greater Impact: How Disasters Effect People in Low Socioeconomic Status** is a Supplemental Research Bulletin developed by the Substance Abuse and Mental Health Services Administration that is focused on how people in poverty, with low incomes, and of low socioeconomic status experience disasters. Among other topics, it addresses people who may have a lower likelihood of receiving warnings, of having the ability to evacuate, and of accessing post-disaster aid (SAMHSA, 2017).

It is necessary to identify and plan for all evacuation challenges. Tools that may be helpful include issuing emergency notification in multiple languages, providing transportation and shelters, and door-to-door direct notifications. For additional information regarding evacuation planning, see **Chapter 12**.

2.7.3 Pre-Planned Floodfight Actions

Floodfight is the implementation of measures before and during a flood to maintain functionality of a levee or reduce flood damage. Floodfight actions range from routine, pre-planned actions to non-typical, emergency actions that are required to prevent progression of an issue that could lead to levee breach.

Understanding what actions may be required to maintain the levee during a flood event is integral to effective preparedness. This requires a clear understanding of what performance concerns are likely to arise and the techniques that will be used to address them. It is a best practice to develop pre-planned floodfight actions for all likely potential failure modes that are incremental in nature, providing for escalating levels of response based on the severity of the performance concern. Incident classifications are useful for communicating the severity of performance concerns and determining appropriate floodfight actions. An example of pre-planned floodfight actions targeted at dams is provided in Chapter 6 of the Federal Energy Regulatory Commission's Engineering Guidelines, Table 6-K-1 (FERC, 1987).

Examples of floodfight actions for various incident classifications were developed for levees based on the Federal Energy Regulatory Commission's table and are provided in Table 10-3 for demonstrative purposes. This table contains general examples that likely do not address all of the unique physical and risk characteristics of a specific levee.

The highest level of floodfight planning should be implemented when there is a population at risk and one or more failure modes have been identified that are likely to cause breach prior to overtopping. The scale of pre-planned floodfight actions will inform pre-flood preparations including stockpiling floodfight materials and equipment (section 2.9.1) and floodfight staffing and training (section 2.10). Preparing to execute floodfight actions also includes:

- Ensuring adequate access to the levee considering:
  - Locked gates.
  - Issues associated with inclement weather and road flooding due to rainfall.
  - Businesses that operate adjacent to the levee.
  - Areas where the levee is used for grazing animals.
- Identifying sources for adequate lighting to ensure the ability to respond after hours.
- Identifying alternate systems of communication (section 2.9.2).
- Identifying alternate power sources (section 2.9.2).

> **REFERENCE MATERIALS**
>
> The following publications include floodfight techniques to inform incident/emergency planning and response.
>
> - Evaluation Design and Construction of Levees, Engineer Manual (EM) 1110-2-1913, Appendix I, (USACE, 2000).
> - International Levee Handbook, Section 6.5 (Eau and Fleuves, 2017).
>
> Emergency Flood Fighting Methods, State of California Department of Water Resources, Flood Management Flood Operations Branch (CaDWR, 2012).

2.7.4 Transference of Risk

Floodfighting activities are intended to mitigate the consequences of floods; however, some floodfight techniques, such as raising a levee to prevent overtopping, may transfer flood risk to others. This type of risk transfer can impact those behind levees and those within the floodplain that do not have levees.

Levee owner/operators should understand how actions on their levee impact the wider floodplain and ensure proper coordination when a levee is part of a broader flood risk management system involving other levee districts and communities. A best practice is to have a regional plan concerning how floodfight measures—such as emergency levee raises—are implemented throughout a basin.

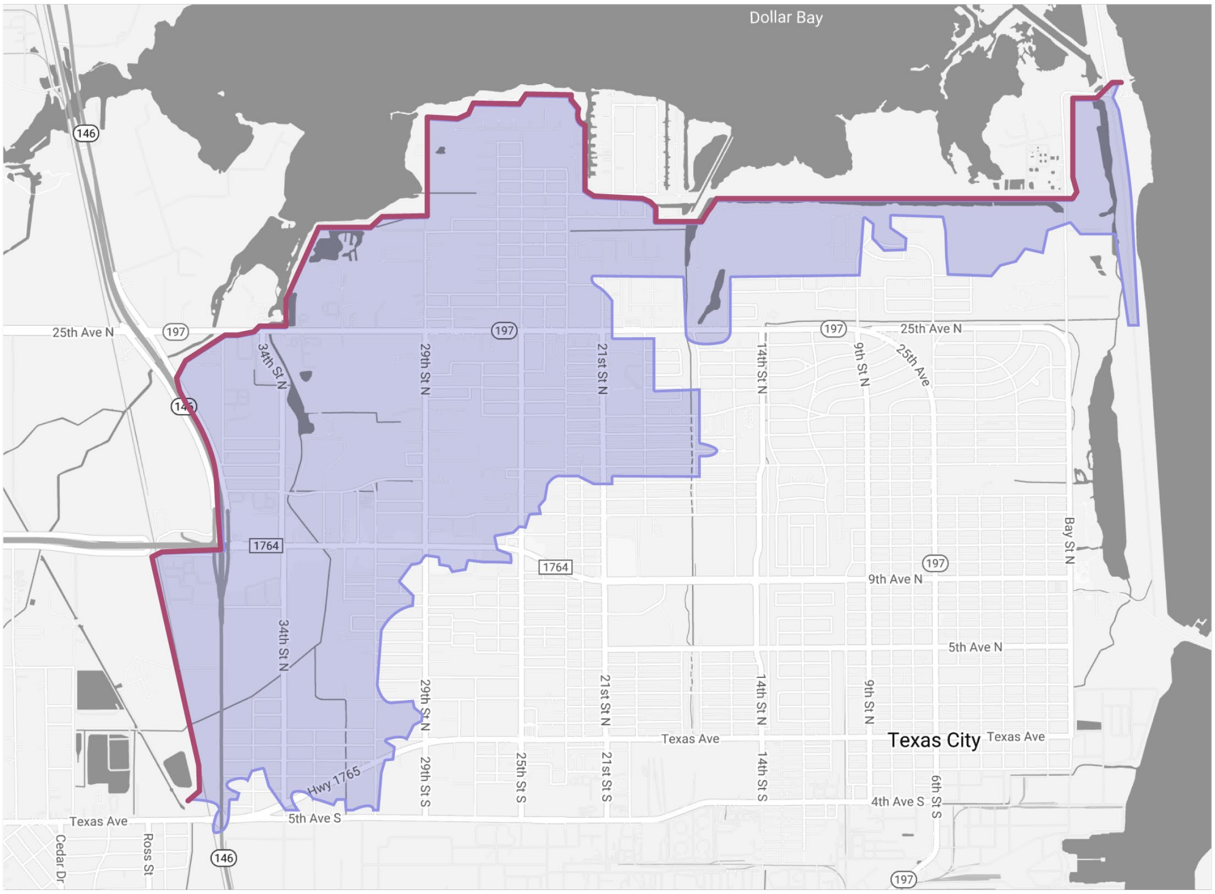
2.8 Using Inundation Maps

Inundation maps are maps that show potential flooding that could result from a hypothetical breach of a levee. It is a best practice to incorporate inundation maps into the emergency action plan. This section provides a high-level overview of the significant concepts to consider when developing levee inundation maps for levee emergency management and identifies resources that contain more information on preparing inundation maps. The rigor required for inundation mapping is scalable based upon the flood and levee risks associated with the levee.

The NLD is a starting point for an inundation map. The NLD displays a shaded area behind all levees called the leveed area. The leveed area is the most conservative estimation of the area that could potentially be flooded due to a levee breach. Generally, the leveed area is developed by projecting the top of the levee back to high ground, with some exceptions based on topography. Viewing leveed area delineations (Figure 10-5) within the NLD can help determine where flooding is possible to inform evacuation planning. This level of rigor in inundation mapping is only appropriate for levees where there is no population at risk within the leveed area.

More detailed inundation mapping showing potential breach or overtopping locations is required for levees with life safety risk. Inundation maps showing worst case flood depths based on worst case inundation scenarios may be adequate for moderate risk levees. Inundation maps that include inundation scenarios tied to risk-driving potential failure modes with flood depths and arrival times are recommended for higher risk levees. It is a best practice, for emergency planning for levees with a potential for life loss to be guided by detailed inundation mapping that identifies flood depths and arrival times for likely breach or overtopping scenarios. Resources for developing and updating inundation maps are described in **Chapter 4**.

Figure 10-5: Leveed Area from the National Levee Database



Galveston County Water Reservoir inundation map delineates the specific geographical area(s) that would be flooded due to a hypothetical levee breach, overtopping, or malfunction/misoperation of a levee feature.

Developing or updating inundation maps prior to an actual emergency is an essential step in levee emergency management as the data, models, and maps can be used for:

- Understanding if there is potential for loss of life, including location and severity.
- Developing emergency action plans and evacuation planning to reduce risks to life and property.
- Communicating flood and levee risks.
- Identifying inundation impact zones to support flood warning systems.

Inundation mapping can also be developed during a flood to show the extent of flooding that could occur based on real-time observed conditions to depict the potential flood hazard more accurately.

2.8.1 Hypothetical Scenarios

Developing inundation maps for a range of hypothetical scenarios could help prepare for a future emergency. Typical scenarios include an overtopping with breach event, in which flood waters exceed the levee height and breach the levee, as well as scenarios in which the levee has failed before it overtops, or the levee overtops but does not breach. Scenarios with prior to overtopping breaches may consider a range of hydrologic loadings, including the design flood level, a historic flood level, or a level which was analyzed in recent risk assessments. In addition to considering various hydrologic loadings on the levee, breach scenarios may also consider the effects of various breach locations. Breach locations may be selected based on known levee vulnerabilities or locations where a breach could have particularly harmful or worst-case consequences. If available, risk assessment results can also be referenced to reveal where overtopping would likely occur or areas most likely to experience a breach prior to overtopping.

Breach parameters specific to the levee are needed to estimate the discharge into the leveed area. Breach parameters include width, depth, and shape of the breach; rate of breach formation; hydraulic head; and anticipated flood flow.

2.8.2 Inundation Map Key Characteristics

The most effective inundation maps include the extent and depth of flooding and the expected travel times to critical locations. Additional information that may be useful includes flow velocities and duration of inundation. Highlighting key locations, such as population areas, recreation areas, and any other significant features within the inundation zone can aid evacuation and rescue actions (Figure 10-6).

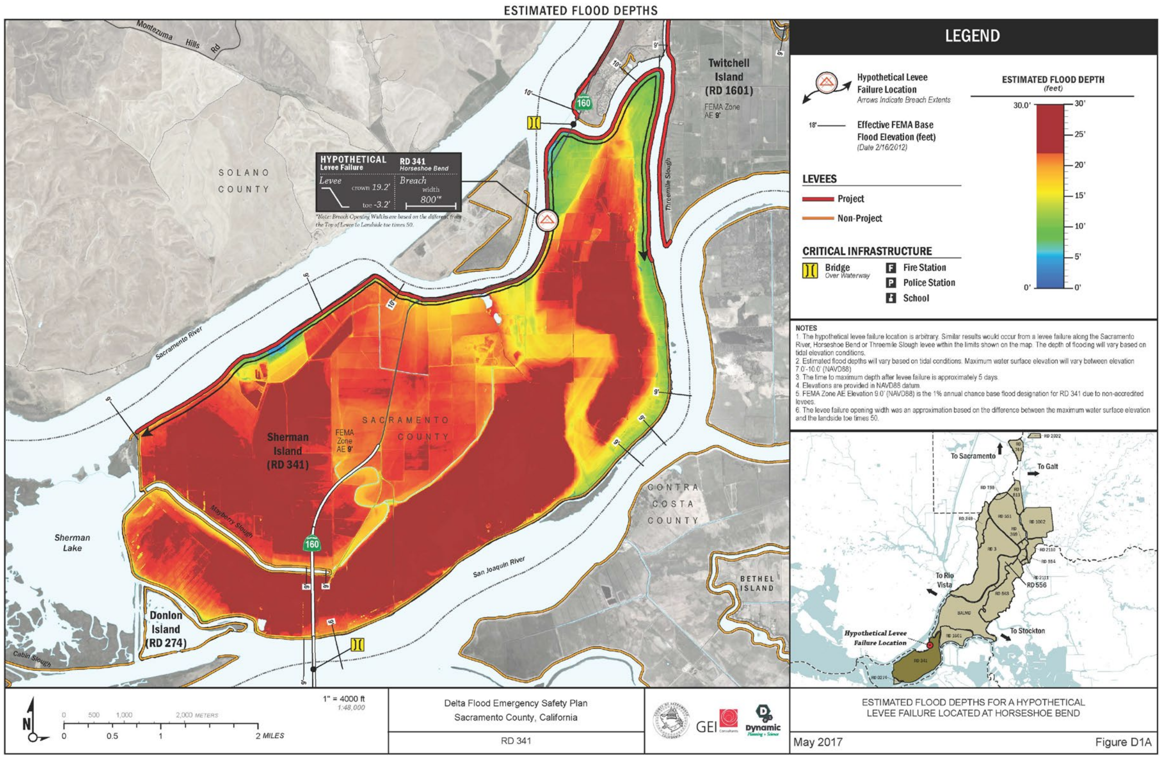
Key characteristics of an inundation map typically include:

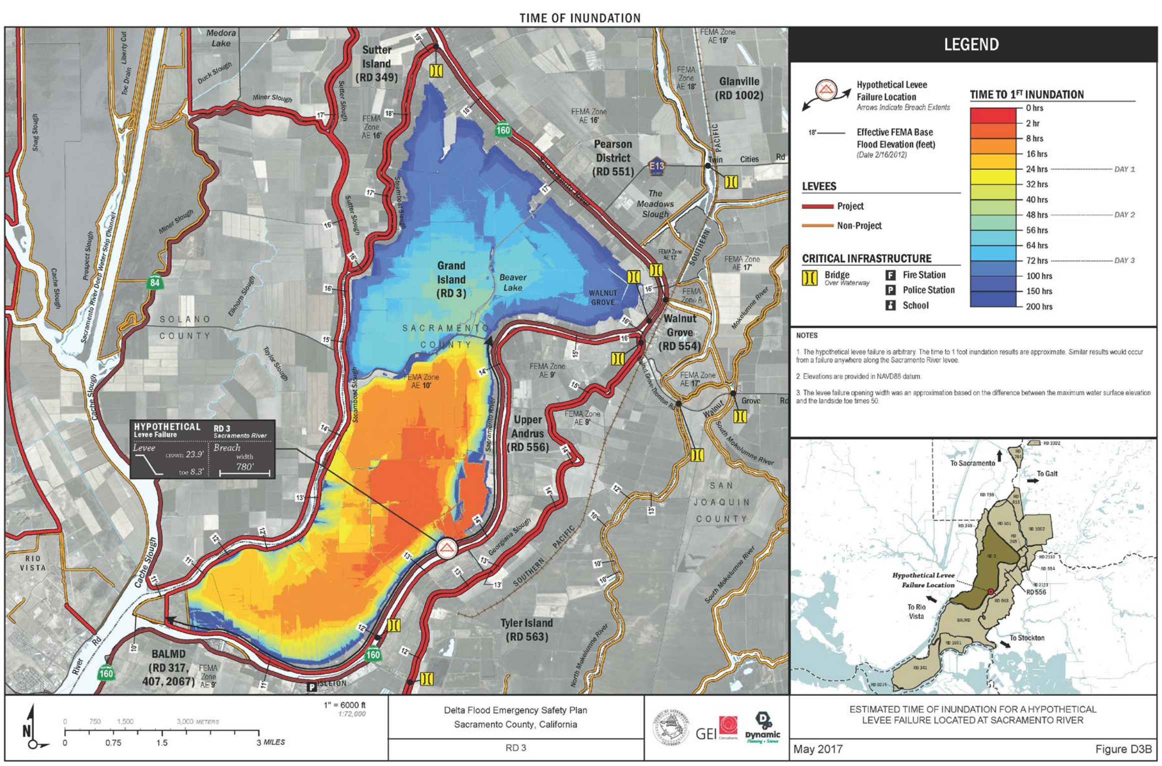
- Inundation zones/polygons (extent and depths of flooding).
- Detailed information at key locations:
  - Flood wave travel times (in hours and minutes).
  - Expected peak water surface elevations or depths.
  - Expected peak velocities.
- Map collar information (map legend, notes to users/disclaimers, map scale box, panel locator diagram, tables, and title block).

Additional information which may be displayed on inundation maps include:

- Incremental rises in water levels.
- Estimated duration of inundation.
- Direction of flow.
- Critical infrastructure, residential and commercial developments, recreation areas, roads, railroads, bridges, and other significant features within the inundation zone.
- Base map data with a scale of at least 1:36,000.

Figure 10-6: Hypothetical Sacramento River Inundation Maps





2.8.3 Partner Coordination

Local emergency management agencies and community officials will rely heavily on inundation maps to effectively warn and evacuate people in the event of a potential levee emergency. Including those who will use the maps in map development and coordination can improve understanding and help to ensure proper implementation.

Emergency communication and actions can be expedited when applicable emergency management agencies retain current copies of the maps, ensure all team members understand how to interpret the maps, and verify the maps contain sufficient and current information.

Having partners review inundation maps to validate terrain data, such as identifying where bridges may block flow, where channels are blocked, where culverts exist under roads, and other items that may impact how the area would inundate can improve map quality.

2.8.4 Updating Inundation Maps

Levee owner/operators and emergency management agencies can keep inundation maps current through reviews to determine if any new developments, buildings, or recreation areas are constructed within inundation zones or if a known change in the levee (e.g., increased/decreased elevation, removal of structures or change in vulnerabilities) occurs. It is a best practice to review and update inundation maps every 10 years in conjunction with updating the levee risk assessment.

It is important to update inundation maps immediately if there are significant changes to development behind a levee that are not displayed on the existing inundation maps and more current base map information is available. Changes in the levee may trigger an update to the levee risk assessment, which may include updates to inundation mapping.

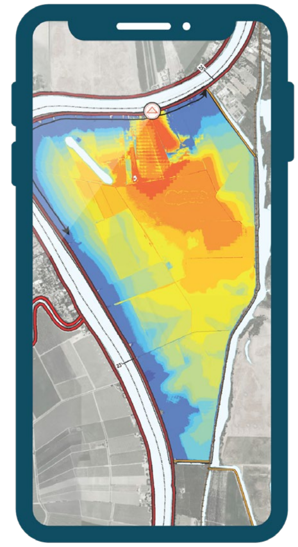
2.8.5 Digital Inundation Mapping

2.8.5.1 Interactive Use of Maps and Geospatial Data within a Digital Environment

Displaying inundation extents and other datasets within a digital geospatial environment provides many potential benefits to emergency responders. Inundation data, including arrival times, duration, and depth of flooding, are not easily annotated on a hard copy map. Multiple datasets can be displayed, and users may query the database for points of interest within the leveed area. Additionally, base map features not shown on an emergency action plan map, such as road centerlines, building footprints, and tax parcels, may provide additional critical information during an emergency.

There are currently numerous geospatial applications available that are fully compatible with mobile devices and allow users to access geospatial data through either locally stored data or web-based mapping systems including online map sites or cloud computing. These applications cater to a wide variety of user abilities—ranging from basic easy-to-use applications with limited functionality to highly complex and flexible applications suited to expert users.

Although mobile geospatial is not a solution suitable for all users and situations, the use of an inundation database—in combination with local and regional geospatial information in the digital environment—can potentially enhance a user's ability to respond when an emergency occurs



and unanticipated circumstances are encountered. Mobile geospatial will likely never completely replace hard copy inundation maps since the geospatial abilities of emergency responders likely vary considerably and there is always the potential for technical complications including power failure, overloaded communication systems, equipment damage, and software failure.

2.8.5.2 Animation

Animation can be another valuable tool for communicating the magnitude of flooding and response time needed in the event of a levee breach. Many software applications used for levee breach modeling provide varying degrees of functionality for plan view animation. Numerous online map applications also support the creation of animations, including flyovers. Although animations may rarely be used during an emergency, unless given a large lead time, they can be valuable tools for training staff identified within an emergency action plan as responders. They can also be an important visualization tool for use in training and in public outreach efforts.

2.8.5.3 Innovative Solutions

Three-dimensional visualization does not always require geospatial data and graphic software applications. A simple, yet very effective, means of communicating the magnitude of inundation in three dimensions can involve the simple annotation of known landmarks with modeled high-water marks associated with a levee breach. Such annotations can help bring the severity of a potential event into context for those not familiar with the potential consequences of a levee breach. This type of visualization can be executed with a minimum of resources; all that is needed is an inundation elevation or depth, an image of a landmark, and a means of referencing the elevation or depth onto the image.

REFERENCE MATERIALS

There are several publications detailing the process of developing inundation maps that contain information applicable to levee owner/operators:

- Federal Guidelines for Inundation Mapping of Flood Risks Associated with Dam Incidents and Failures, FEMA P-946 (FEMA, 2013):
  - Provides guidance on how to prepare dam breach inundation modeling studies and generate maps that can be used for multiple purposes, including dam safety, hazard mitigation, consequence evaluation, and emergency management including developing emergency action plans.
- International Levee Handbook (Eau and Fleuves, 2017):
  - **Chapter 8** covers topics pertaining to inundation and mapping including: input parameters and data requirements, types of inundation models, modeling approaches, model outputs, and treatment of uncertainties.
- Federal Energy Regulatory Commission Engineering Guidelines, Chapter 6 - Emergency Action Plans (FERC, 2015):
  - Provides the Federal Energy Regulatory Commission's requirements for inundation mapping including information surrounding the topics of determining downstream impacts, preparing inundation maps, contents of inundation maps, cross-sectional information, additional information, sample inundation maps, coordination, and updating maps.
- Inundation Maps and Emergency Action Plans and Incident Management for Dams and Levees, Engineer Circular (EC) 1110-2-6075 USACE (USACE, 2002):
  - Provides requirements for inundation mapping for USACE operated and maintained dams and levees.

2.9 Managing Critical Resources

Preparedness activities, including the management of critical resources, should be scaled to be commensurate with levee risk and focused to address identified risk drivers. Levee with a population at risk and potential failure modes that are likely to cause breach prior to overtopping will have the most rigorous incident response planning, including floodfight actions to address risk driving failure mode. Preparedness activities should be tailored to support the scope and rigor of planned floodfight actions.

2.9.1 Stockpiling Floodfighting Materials and Equipment

It is best practice to document and maintain an adequate stockpile of floodfighting materials and equipment in a location that is easily and quickly accessible during flood operations. The quantity and type of materials to be stockpiled depends on the size of the levee, those used in previous floodfights, and anticipated flood operations based on previous risk assessments or evaluations of levee vulnerabilities. Good resource management includes regularly inventorying, inspecting, and maintaining floodfight materials and equipment to prevent degradation and replenishing resources found to be degraded. Resource inventory documentation typically includes the location, quantity, and type of material and equipment on hand.

A readily available and regularly updated directory of local vendors and suppliers for floodfighting materials and equipment including contact information and location is extremely helpful during floods. Contacting local vendors during the initial development of the emergency action plan and annually thereafter helps ensure they are available to provide the necessary materials and labor in the event of an emergency.

When selecting which type of floodfighting material to use, environmentally friendly choices that can be reused for future floods instead of one-time use products, such as reusable sandbags, or water-filled tubes instead of single use sandbags can help reduce waste.

2.9.2 Alternative Sources for Communication and Power

Preparing and training for communication outages concurrent with power outages, as well as identifying and practicing emergency response roles to be performed if communication and power are down during an emergency, improves readiness and resiliency.

Flood preparation activities that include identifying alternative sources of power for automated levee features help to ensure the levee can be operated under a wider range of circumstances. For example, generators can be obtained to provide backup power for electric powered features or multiple sources of fuel can be identified for diesel power pump stations.

Having alternative sources to supplement standard communication processes helps ensure communication can occur during emergency conditions. Many levees are located in remote locations with unreliable cell phone service. To complicate matters, it is common for cell towers to become overloaded during emergency situations. To ensure issues on the levee can be quickly and reliably reported to decision makers, secondary means of communication, such as radios, are imperative.

2.10 Training and Exercises

A plan for emergency response will provide limited value if it has not been practiced and communicated to those who will execute the plan’s procedures. Training and exercises help ensure readiness by providing responders an opportunity to practice specific actions that typically occur during a levee emergency, such as removing debris, responding to sand boils, and performing flood inspections. Training and exercises also inform personnel about the time and resources necessary to complete certain tasks (Figure 10-7). Important practical considerations and physical limitations that could be easily overlooked in a plan are often identified during an exercise.

Figure 10-7: Emergency Responder Floodfight Training Session

Responders training to perform an emergency levee raise in California.

Generally, basic training and exercise activities include:

- Physical operation of project features (e.g., sluice gates, pumping stations, closure structures).
- Notification of emergency response personnel and verification of contact information.
- Testing of communication/backup communication systems.
- Mobilization of inspection teams and inspecting levee features.
- Floodfighting techniques.
- Data collection.
- Activation of rostered emergency teams and operation centers.
- Methods of coordination (e.g., between volunteers, patrols, nearby levee owner/operators, highway departments, state emergency operations center).
- Dissemination of information to the community.

Training and exercises can better inform future actions when they are documented, and the records maintained in a location that is easily accessible to personnel. Documentation typically includes the names and roles of the participants involved, activities performed, and lessons learned.

2.10.1 Training

It is a best practice to create a dedicated incident response team that is continually trained and available for activation, described in section 2.5. An effective incident response team includes a sufficient number of trained people to ensure adequate coverage of the levee at all times. Team members who receive annual training in incident management, including detection, evaluation, classification, notification, and appropriate response actions are better prepared to act during emergencies. Cross-training of personnel in more than one role provides redundancy and flexibility in staffing response efforts.

Staff training for levees with a population at risk within the leveed area should be done on an annual basis. Staff for levees with a potential to breach prior to overtopping should be trained to recognize and respond to risk driving failure modes. The frequency and scope of training for levees with no life safety risk should be based upon the complexity of the levee, the scale of anticipated response actions, and the consequences of levee breach.

2.10.2 Emergency Action Plan Exercises

An emergency action plan exercise is an activity designed to promote emergency preparedness; test emergency action plans, procedures, or facilities; train personnel in emergency response; and demonstrate operational capability. Exercises consist of the performance of duties and operations similar to the way they would be performed in a real emergency. However, the exercise performance is in response to a simulated event.

Exercises play a vital role in emergency preparedness. A well-designed exercise provides a low-risk environment to familiarize personnel with roles and responsibilities; fosters meaningful interaction and communication across organizations; and assesses, validates, and identifies strengths and areas for improvement. Exercises can bring together partners and strengthen the community to reduce impacts of levee emergencies.

The Department of Homeland Security’s Exercise and Evaluation Program provides in-depth information for planning, conducting, and evaluating individual exercises. A high-level overview of the program’s guidelines is provided below (FEMA, 2020).

These can range from simple and informal discussion-based exercises for low complexity, lower risk levees to more formal operations-based exercises for higher risk levees.

Selecting which type of exercise is most appropriate for a particular levee will depend on the specific circumstances of a levee, such as the type and complexity of features which make up the system, the level of levee risk, and identified levee risk drivers. There may also be specific exercise requirements that will be defined by applicable regulating agencies.

2.10.2.1 Discussion-Based Exercises

Discussion-based exercises include seminars, workshops, and tabletop exercises. These types of exercises familiarize participants with existing plans and may result in development of new plans.

2.10.2.2 Operations-Based Exercises

Operations-based exercises include drills, functional exercises, and full-scale exercises. These exercises validate plans, policies, procedures, and agreements; clarify roles and responsibilities; and identify resource gaps. Operations-based exercises include a real-time response, such as initiating communications or mobilizing personnel and resources.

> **TYPES OF EXERCISES**
>
> Discussion-Based Exercises
>
> - **Seminar:** An informal discussion of roles and responsibilities that may include plan training or review.
> - **Workshop:** Seminar to develop plans or procedures.
> - **Tabletop Exercise:** Exercise that employs discussion to simulate a response to a simulated emergency to test plans and procedures.
>
> Operations-Based Exercises
>
> - **Drill:** An activity to test a single operation within a single organization, such as testing warning systems or conducting a call-down drill of a notification flowchart.
> - **Functional Exercise**: Exercise to evaluate coordination, command, and control between various multi-agency coordination centers. Does not involve first responders or emergency officials responding in real time.
> - **Full-Scale Exercise:** A multi-agency, multi-jurisdictional, multi-discipline exercise involving all participants role-playing a 'boots on the ground' response to a simulated emergency.

2.10.3 Exercise Development

Effective design of an exercise starts with the development of a realistic scenario that can lead exercise participants through the various elements of an emergency action plan. Exercises are more effective and efficient when they are designed to match the size and complexity of the levee and the level of risk the levee poses to the community.

Scenarios for a levee emergency exercise based on risk drivers identified in the risk assessment make the exercise as realistic as possible. Scenario development requires collaborative and deliberate sequencing of events that is best completed through an exercise planning process prescribed in detail in the Department of Homeland Security Exercise and Evaluation Program (FEMA, 2020).

Exercise scenarios based on compound events and discussing the different types of likely compound events with stakeholders can help address climate change trends.

2.10.4 Exercise Evaluation

Thorough exercise evaluation requires planning, documentation, observation, data collection, and data analysis. Proper exercise evaluation recognizes the strengths of the emergency management program and identifies areas for improvement.

Evaluation documentation includes handbooks for evaluators, an evaluation plan, exercise evaluation guide, and participant feedback from wherein all participants can provide feedback regarding their observed strengths and areas for improvement.

After analyzing the data collected from the exercise, an after-action report/improvement plan can be developed which documents exercise results and tracks any action items resulting from the exercise. Additional information on after action reports is provided in section 4.6.5.

2.10.5 Exercise Participants

The effectiveness of an exercise in preparing for an event depends on having the right people at the table. Involvement of relevant levee owner/operator personnel, emergency management agencies, subject matter experts, and other partners will assure plans or procedures being discussed or tested are adequately and thoroughly vetted. It can be particularly valuable to engage leaders or other trusted messengers of traditionally underserved communities and socially vulnerable populations to increase trust and identify possible barriers to effective emergency notifications. These individuals can also help develop solutions to overcome these barriers. Participants may vary depending on the type of exercise conducted.

2.10.6 Exercise Frequency

For levees with a population at risk, it is a best practice to perform seminars and drills with partners at least once a year to maintain optimum preparedness, replaced by a tabletop exercise, functional exercise, or full-scale exercise every fifth year. Exercises are not necessary during years in which an actual emergency occurs.

For levees that do not pose a risk to life, annual call-down drills of notification flowcharts and/or seminars may be sufficient.

3 Managing a Levee Emergency

Levee emergencies can cause rapidly changing conditions that impact people and property in multiple counties and geographical areas. Emergency response often involves a range of personnel and organizations that must coordinate efforts to save lives, stabilize the incident, and protect property and the environment. Incident management is more effective when all partners work together to share resources, communicate information, and act collaboratively. Poor incident management can result in the loss of life, increased damage and costs, and permanent harm to a levee owner/operator's reputation.

Response actions are more effective when the partners involved in managing a levee emergency have a shared understanding of the situation, their roles and responsibilities, available resources, current and potential impacts, and the incident timeline. Timely, consistent, and clear communication by levee owner/operators throughout the duration of the emergency can help ensure a high-level of situational awareness for both those internal to their organization and external partners.

3.1 Incident Management System

Federal Emergency Management Agency's (FEMA) National Incident Management System provides a standard and consistent, systematic, proactive approach to guide all levels of governmental and non-governmental entities with a role in emergency management to work seamlessly in responding to emergencies (FEMA, 2015). This approach is effective for any situation that involves coordination among multiple agencies or partners.

The Incident Command System is a fundamental element of FEMA's National Incident Management System. Incident Command System is a standardized, on-scene, scalable, all-hazards incident management approach that provides methods for team organization and in-the-moment response planning, including:

- A standardized approach to the command, control, and coordination of on-scene response (Figure 10-8).
- A common structure within which personnel from different organizations can work together.
- A structure for incident management that integrates and coordinates procedures, personnel, equipment, facilities, and communications.

It is a best practice for levee owner/operators to coordinate with appropriate emergency management agencies to incorporate, implement, and regularly train and exercise the Incident Command System and National Incident Management System principles.

It can be helpful to realize that each entity involved in emergency response is managing an incident from their own perspective. For example, a levee owner may be managing an incident related to a performance concern on the levee structure that includes floodfight actions and notifying and coordinating with others. The local emergency management agency may be managing an incident related to the larger flood event, that includes understanding levee conditions and making flood warning and evacuation decisions. Each entity responsible for some aspect of incident response can implement National Incident Management System, and Incident Command System in particular, to organize and guide their efforts. National Incident Management System training courses, Incident Command System forms, and Incident Command System resources can be found on FEMA's website (FEMA, 2015).

Figure 10-8: Incident Commander During an Exercise

Incident commander communicates from the levee using a radio during the Twitchell Island Exercise in Isleton, California. The annual exercise, led by the California Department of Water Resources in conjunction with the Sacramento County Office of Emergency Services and Reclamation District 1601, is designed to improve communication and cooperation among partner agencies during flood emergencies in the Delta.

3.2 Unified Command

Levee emergencies often involve a response from multiple organizations, each managing an incident from their own perspective. Bringing these organizations together to form a unified command may be appropriate when no one agency or organization has the primary authority or the resources to manage the emergency. Unified command is an authority structure in which the role of incident commander is shared by two or more individuals, each already having authority in a different responding agency. When all organizations agree, establishing a unified command can be an effective approach to establish unity of effort to respond to what would then be managed as a single incident. A benefit of unified command is that it allows resources to be applied regardless of ownership or location.

In unified command, there is no single incident commander. Instead, the unified command manages the incident using jointly approved objectives established during the incident. A unified command allows the participating organizations to retain their own authorities and control their own resources while jointly addressing incidents. Figure 10-9, Figure 10-10, and Figure 10-11 demonstrate the different ways a unified command can be organized, depending on the organizations involved in the response.

INCIDENT ACTION PLANNING

National Incident Management System incident action plans are central to managing incidents and help synchronize operations and ensure that they support incident objectives.

Incident action plans document what needs to be done, who is responsible for doing it, what resources are needed, and how communications should occur. Incident action plans also:

- Record and communicate incident objectives, tactics, and assignments for operations and support.
- Are recommended for all incidents.
- Are not always written but are increasingly important to be in writing when an incident is likely to extend beyond one operational period, becomes more complex, or involves multiple jurisdictions or agencies.

Hamilton County Emergency Management in Indiana requires the creation of an incident action plan for each operational period (generally 12 to 24 hours) during flood operations and includes a sample incident action plan within their floodfight plan (HC-EMA, 2018).

INCIDENT OBJECTIVES	1. Incident Name **Tropical Storm Gordon Flood Fight**	2. Date 09/06/2018	3. Time 0700-1900
4. Operational Period: First Operational Period			
5. General Control Objectives 1. Provide for the safety of all personnel working at the sand barn 2. Ensure all personnel follow safety standards 3. Manufacture sandbags in an efficient manner to meet throughput demands 4. Ensure supply chain management by ordering supplies before they are needed 5. Assist public by answering questions and providing sandbag information 6. Maintain open traffic to allow for continued recycling operations			

By requiring incident action plans for each operational period during a flood, Hamilton County, Indiana, promotes effective and efficient incident operations, as well as accountability.

Figure 10-9: Unified Command—Multiagency/Multijurisdictional Incident

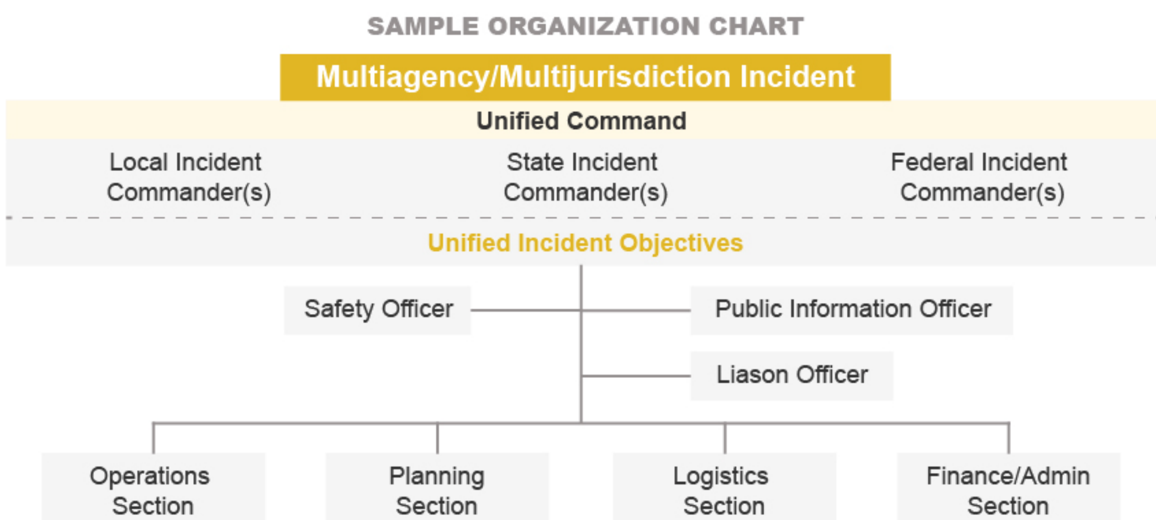


Figure 10-10: Unified Command—Multiagency/Single Jurisdiction Incident

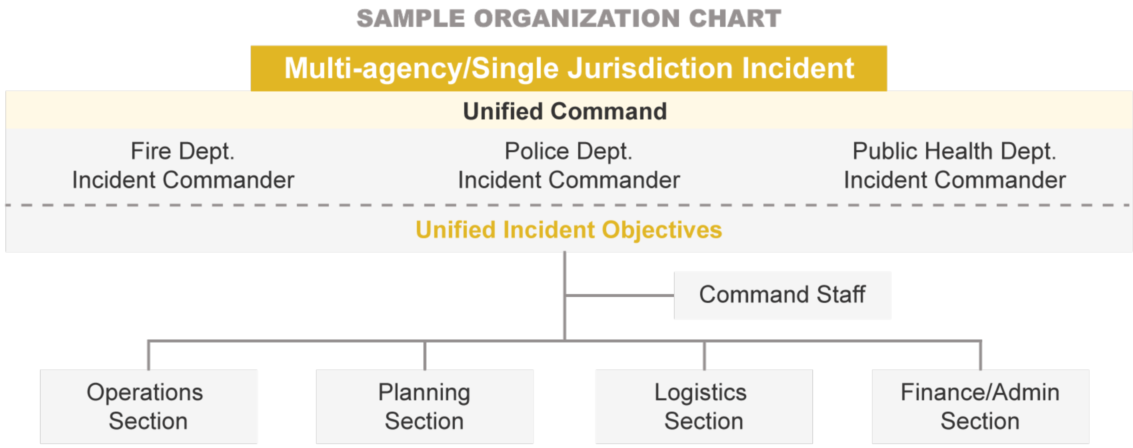
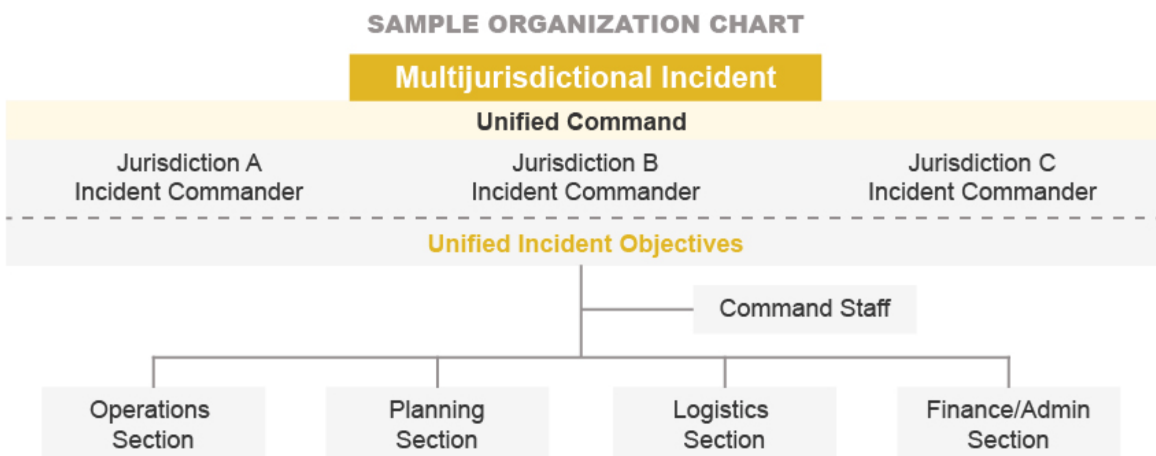


Figure 10-11: Unified Command—Multijurisdictional Incident



3.3 Emergency Operations Centers

An emergency operations center is a physical or virtual location from which coordination and support of incident management activities is directed. Typically, those staffing the emergency operations center during an emergency collect, gather, and analyze data; make critical decisions about the management of an emergency; disseminate those decisions to all partners; and maintain continuity of the response efforts. A key function of the emergency operations center is to ensure those who are performing notification and floodfight actions have the information and resources they need.

It is a best practice for levee owner/operators to establish an emergency operations center from which levee operations and emergency response can be managed. The size and technical sophistication of levee owner emergency operation centers will vary dependent upon the size and complexity of the levee and the level of associated risk.

Once notified of an incident on the levee or a forecasted flood that is expected to impact the levee, local emergency management agencies may also activate an emergency operations center to serve as a central coordination center for emergency response, warning, and evacuation activities. By participating in the emergency operations center, they can help agency personnel better understand the project-specific information and inundation maps and increase efficiency and effectiveness of response efforts.

DISASTER DECLARATIONS

A disaster declaration is a formal statement by the jurisdiction's chief public official (i.e., mayor, county judge, governor, or president) that a disaster or emergency situation exceeds their response capabilities and allows public officials to exercise emergency powers to preserve life, property, and public health.

Emergency declarations can confuse organizations and individuals. All agencies need to understand the implications of operating under an emergency declaration.

<table>
<tr><th colspan="2">Local</th></tr>
<tr><td colspan="2">Local governments may have the authority to declare an emergency and activate emergency agencies within their jurisdiction. Local emergency declarations can also potentially allow agencies to receive state or federal emergency funding, if such funding becomes available.</td></tr>
<tr><th colspan="2">State</th></tr>
<tr><td colspan="2">While unique to each state, generally the governor may declare an emergency by issuing an executive order or other declaration to that effect. The declaration addresses the effective dates and duration of the declaration, geographic areas of the state covered, conditions giving rise to the emergency, and the agency or agencies leading the response activities. The declaration may also identify state rules and regulations that are waived or suspended during the emergency. The declaration of a state emergency triggers an array of authorities and actions by state and/or local governments.</td></tr>
<tr><th colspan="2">Federal</th></tr>
<tr><td>Emergency Declaration</td><td>Upon the request of the state, tribe, or territory, the President of the U.S. can declare an emergency for any occasion or instance when the president determines federal assistance is needed. Federal emergency declarations supplement state and local or Indian tribal government efforts in providing emergency services, such as the protection of lives, property, public health, and safety, or to lessen or avert the threat of a catastrophe in any part of the U.S. The total amount of assistance provided for a single emergency may not exceed $5 million.</td></tr>
<tr><td>Major Disaster Declaration</td><td>Upon the request from the state, tribe, or territory, the President of the U.S. can declare a major disaster for any natural event, including any hurricane, tornado, storm, high water, wind-driven water, tidal wave, tsunami, earthquake, volcanic eruption, mudslide, snowstorm, drought, fire, flood, or explosion that the president determines has caused damage of such severity that it is beyond the combined capabilities of state and local governments to respond. A major disaster declaration provides a wide range of federal assistance programs for individuals and public infrastructure, including funds for both emergency and permanent work.</td></tr>
</table>

Dually as important as the issuance of an emergency declaration, levee owner/operators should also familiarize themselves with the process for how different jurisdictions decide when to declare an emergency is over, which ultimately will affect the availability of additional resources.

4 Operating a Levee During an Emergency

Time is of the essence during a levee emergency. A levee emergency can occur within minutes or over a long period of time and may last days, weeks, or longer, which creates a variable window of opportunity to reduce the impacts of the emergency on the levee and the affected community. Levee owner/operators who have planned and prepared for an emergency and implement appropriate emergency response actions have a better chance of fulfilling their role in avoiding a levee breach and preventing loss of life when a breach is unavoidable.

Constant observation of levee conditions, early detection, communication, proactive floodfighting measures, and an effective emergency notification process can help reduce the likelihood and impact of a levee emergency. The following sections detail common activities to identify and respond to a flood-related levee emergency. Though levee emergencies typically happen during floods, they can occur prior to a flood and the principles and best practices of this section apply to any levee emergency situation.

4.1 Incident Detection

An incident at a levee may be detected by:

- Monitoring the status of the flood source or flood source predictions.
- Monitoring the weather forecast.
- Inspecting and observing the levee.
- Evaluating levee instrumentation data.
- Identifying suspicious activity or security threats.

When a levee-related issue is detected, the incident can be classified to streamline communication and aid in implementing the appropriate response actions, as discussed in section 2.6. Once the incident is classified, the appropriate notifications can be made, and all necessary actions can be taken in accordance with the pre-planned actions that are discussed in section 2.7.

4.1.1 Preliminary Response Activities

When a flood is forecasted, performing activities outlined in the O&M manual such as closing gates, performing inspections, and other tasks will help make sure the levee and those responsible for its operation are ready for the flood. Other important pre-flood actions include partner coordination, especially between the levee owner/operators and local emergency management agencies and activation of emergency operations centers, if warranted. Ongoing communication between emergency management agencies and emergency operation centers through regular situational updates ensures awareness of the response activities and levee condition.

Other important activities to perform when preparing for emergency response include:

- Reviewing the emergency action plan and lessons from previous incidents and exercises and identifying problem areas.
- Verifying that response personnel have access to gate keys, current rosters, contact numbers, staging areas, listing of project features, feature operation plans, and other critical items.
- Coordinating efforts with communities and levee owner/operators in the floodplain.
- Alerting communities within the leveed area to the potential for flooding in coordination with the appropriate emergency management agencies.
- Beginning documenting the situation and sending situation reports to the emergency operations center, appropriate emergency management agencies, or others, as appropriate.

4.1.2 Flood Source Monitoring

Knowing flood source conditions and predictions is invaluable to effective flood operations. It is a best practice to assign an individual the responsibility of monitoring flood source and weather data both before and during a flood event. Before a flood event, monitoring frequencies that provide the levee owner/operator sufficient warning time to execute pre-flood preparation activities can be developed by considering the characteristics of the flood source, the levee, and available resources. During flood events, monitoring frequencies that allow adequate time to respond to changing flood source conditions can be developed by considering the characteristics of the flood source and the actions that will need to be taken if an emergency occurs, such as evacuating the leveed area or performing floodfight actions. There are a number of sources with flood information, a few are discussed below.

4.1.2.1 River Gages

Many of our nation's rivers and streams are monitored by gages. Knowing if a gage is available to inform response actions at a levee and being able to relate gage readings and forecasts to levee loadings is a powerful tool to aid proactive floodfight actions and emergency notifications. The U.S. Geological Survey and the National Weather Service maintain gages in many locations across the nation. There are various other sources of gage information including the U.S. Army Corps of Engineers (USACE) and the Bureau of Reclamation.

The National Oceanic and Atmospheric Administration's National Weather Service provides river gage observations and forecasts for major rivers and streams across the nation. For some locations, the National Weather Service issues daily forecasts that extend out for seven to 14 days. For other locations, forecasts are only issued during floods.

4.1.2.2 National Weather Service Flood Warnings and Weather Forecasts

The National Weather Service has the primary responsibility for issuing flood warnings and providing weather forecasts. It is of utmost importance that those responding to a flood stay apprised of flood warnings and current weather conditions and forecasts. Understanding how various flood stages and/or flows and weather events impact levee operations and performance and what activities are triggered by current or predicted conditions can help prepare for and execute flood operations.

Just as National Weather Service warnings and notifications can inform levee operations, information concerning levee conditions can help inform National Weather Service communications. Including the National Weather Service in planned notification procedures (section 2.7.1) can help ensure proper information exchange between the levee owner, the local emergency management agency, and the National Weather Service during floods. This in turn helps to ensure the public receives timely and accurate notifications and warnings.

FLOOD STAGES VS. INCIDENT CLASSIFICATIONS

The National Weather Service uses various flood stages to describe the level of a watercourse at a given location. These levels do not necessarily correlate to an incident at a levee nor classify the severity of a levee incident.

Flood stages are often used to describe river flooding conditions where gages exist. The levee incident classifications discussed in this chapter are different from flood stages. The incident classifications describe the condition of a specific levee. The incident classifications also provide a basis for the development of pre-planned floodfight actions and notification procedures that correspond with each incident classification so that response can happen quickly when an incident occurs.

4.1.2.3 Flood Warning Systems

Automated flood warning systems can be installed along waterways or bodies of water. These supplemental systems can provide advanced warning of potential flood conditions, particularly in locations where ungaged waterways present a primary hazard. Early warnings can provide valuable time for responding to possible overtopping events or flood loadings that are known to induce seepage or other failure modes. Knowing when these loadings are predicted can expedite emergency notifications and floodfight actions.

4.1.3 Flood-Related and Event-Driven Inspections

Flood-related and event-driven levee inspections allow for early detection and response to potential levee concerns. Inspecting levees at frequent intervals throughout an emergency, with the frequency of inspections increasing as the threat to the levee increases will enable earlier detection of possible emergency situations. It is a best practice to establish pre-determined triggers tied to inspection frequencies in the levee O&M manual or emergency action plan. **Chapter 9** discusses considerations for establishing these types of thresholds.

Effective flood inspections include observation of the entire levee throughout the flood, as any part of the levee can suffer distress that requires immediate attention. However, some locations may warrant closer observation based on the design of the levee, previous performance, and/or areas of known deficiencies. It may be beneficial to assign personnel to specific levee reaches, to ensure adequate coverage.

Important safety considerations include having personnel travel in two-person teams equipped with dependable communication devices and adequate safety and floodfighting equipment. Traveling in and around saturated, cracked, or sloughed/sloughing areas can worsen the levee condition or lead to injury. Using objects, including arms or legs to investigate holes in or around a levee may also pose a threat to the inspector(s).

It is a best practice to perform flood-related inspections prior to an expected flood, during a flood, and shortly after a flood.

4.1.3.1 Initial Flood-Related Inspections

Initial inspections occur after a flood has been predicted and before the levee is loaded. Monitoring of flood source data as described in section 4.1.2 can provide the warning required to accomplish these inspections. Thorough initial inspections can avoid many common issues that consume valuable response resource, such as faulty culvert gates and access issues. In addition to the items that are typically observed during routine inspections, it is also important to consider the following items during the initial inspection prior to a flood or emergency:

- **Levee conditions**:
  - Condition of any recent levee repairs.
  - Flood conditions and any accumulation of trash, debris, ice, etc.
- **Condition of transportation routes**: Levee access roads, rail and roadway crossings, and access to the levee through the leveed area.
- **Closures**: Ensure closure seals are in good condition and prepared for closure installation; verify material, equipment, and manpower is available to install the closures at the pre-established closure thresholds.
- **Instrumentation**: Ensure instrumentation is in good condition and producing reasonable readings.
- **Floodfighting materials**:
  - Confirm availability of all necessary tools and materials (e.g., sacks, sandbags, lumber, and lights).
  - Identify location, quantity, and condition.
  - If necessary, distribute or store the materials at locations that will facilitate movement to where they will likely be needed.
- **Communication**: Locate and check all two-way radios and telephones.
- **Interior drainage systems**: Inspect outlet structures, gates, and other components that might not be accessible later. These structures are typically subject to inundation at lower stages than other levee features.

4.1.3.2 Inspections During a Flood

The criteria for determining when inspections are necessary, and the appropriate frequency of inspections during a flood, are detailed in **Chapter 9.** Thoroughly viewing and assessing all levee features during these levee inspections helps ensure issues will be identified before emergency conditions develop.

Additional methods that can be used to conduct inspections when foot and/or vehicle patrols are not possible include boat patrols to detect riverward scour or sand boils in inundated landside areas, aerial surveillance using rotary and winged aircraft, and aerial unmanned drone surveillance. These additional methods of inspection, while often costly, can provide early detection and identification of levee distress. Early detection may allow the distress to be addressed before levee breach is imminent. The tasks typically accomplished during flood related inspections are provided in Table 10-4.

Table 10-4: Flood-Related Inspection Tasks

Feature	Typical Tasks	Operating and Maintaining a Levee Chapter Reference
Embankment	• Look for sand boils or unusual wet areas on the landside levee slope and landward of the levee toe, denoting size, location and characteristics of the flow and mark accordingly (see Figure 10-12). • Look for slides or sloughs on levee side slopes. • Look for wave wash or scouring on the waterside and landside. • Look for low areas in levee crest. • Inspect managed overtopping sections for obstructions to flow, erosion, and missing erosion protection.	Chapter 9, section 3.1
Floodwalls	• Look for saturated areas, wet areas, soft areas, seepage, sink holes, or sand boils landward of the toe of the floodwall and mark accordingly. • Look for settlement of the floodwall or movement between monoliths. • Look for bank caving that may affect the structural stability of the floodwall. • Inspect toe drain risers/manholes (discharging/non-discharging). • Inspect for any leakage, especially around the monolith joints.	Chapter 9, section 3.2
Closures structures	• Check gap closures for damages or leaks (i.e., stoplog/sandbag). • Ensure alarms are functional. • Look for debris blockage. • Check for missing or damaged parts (pins, bolts, nuts, washers).	Chapter 9, section 3.3
Transitions	• Look for surface erosion at transition locations caused by water movement. • Look for leaks at interfaces between hard surfaces and earthen materials.	Chapter 9, section 3.7
Seepage control features	• Monitor relief wells (flowing/non-flowing) and document when flows begin/rate of flow. • Check for vegetation that may prevent the system from functioning as intended. • Check for debris. • Inspect collector systems and manholes.	Chapter 9, section 3.4
Channels and floodways	• Look for scours resulting from high velocities at waterside and landside toe. • Check crest for signs of instability. • Ensure any flood gates are operational.	Chapter 9, section 3.9

Feature	Typical Tasks	Operating and Maintaining a Levee Chapter Reference
Interior drainage systems	• Check flap/sluice gates for proper closure. • Look for depressions, sinkholes, soft spots or cracking immediately over pipes. • Check for sand boils in landside ditches and ponding areas. • Check for seepage emerging around pipes or from behind headwalls.	Chapter 9, section 3.5
Pump stations	• Verify that assigned personnel are on duty as required. • Run and monitor pumps. • Look for sink holes or wet areas around the perimeter of the pumping plant, and/or settlement of the pump house. These conditions could be the result of separation in the conduits. If separation is suspected, shut down pumps and motors until an engineering review can be conducted to analyze the condition. • Inspect trash racks to ensure they are clear of debris. Clogged trash racks can prevent water from reaching the pump station and cause erosion. • Verify proper ventilation (e.g., fans, vents) of the pumping plant to prevent overheating of pump motors. • Assess conditions and operability of communication and control systems.	Chapter 9, section 3.6
Instrumentation	• Record gage readings (frequency based on rate of flood source change). • Inspect fences on the waterside of the levee frequently to make sure they are free from debris. Clear debris, if possible. The fence may need to be cut to free the debris and decrease the possibility of damage to the levee. • Verify all necessary access roads and ramps along the levee are accessible and usable. • Take photographs of all significant issues (use date/time stamp feature on the camera, when possible).	Chapter 9, section 2.3

Flood-related inspections should include viewing and documenting the entire levee without precluding areas based on adequate performance during past floods. However, special attention including more frequent and thorough inspections may be warranted for areas identified as vulnerable during previous inspections or risk assessments.

4.1.3.3 Inspection Documentation

Inspection findings are only useful if they are documented and shared with the appropriate personnel. Inspection documentation procedures are typically included in the O&M manual. More information on these strategies and the O&M manual is provided in **Chapter 9**.

Clearly and consistently marking distress points in the field helps ensure they can be easily located for future inspection and floodfight action if necessary. Wooden stakes and pin flags are typical tools used to mark distress points. It can be helpful to place a marker at the distress point and on the levee crown. An effective marker indicates the type of distress and the location of the distress point relative to the levee as shown in Figure 10-12.

Figure 10-12: Sandboil Marker

Wooden stake on levee crown indicating the presence of a sand boil near the landside levee toe.

4.1.4 Instrumentation Monitoring

Data collected from instrumentation during a flood gives indications of how the levee is responding to a flood loading. Professionals trained in analyzing the data can identify potential concerns that need further evaluation, remediation, or immediate floodfight action. Separate personnel from those performing flood-related inspections who are qualified to perform data collection and analysis may be needed. It is helpful to develop and document threshold instrumentation readings that trigger additional data collection or emergency response actions. Triggers established prior to a flood event will ensure that emergency conditions are quickly identified, allowing for a more effective response. Various types of levee instrumentation and considerations for installation on a particular levee are described in **Chapters 7 and 9**.

Frequencies for monitoring levee instrumentation during a flood are typically established by the designers of the instrumentation. These frequencies may be adjusted based on recent performance or information from a risk assessment. Documenting the frequencies and procedures for reading and analyzing data in the O&M manual helps ensure these activities are performed correctly so that the data is available to inform response actions.

Abnormal or sudden changes in readings may indicate a potential issue at the levee. Good flood preparedness includes pre-planned processes to quickly evaluate these conditions and then communicate and address them.

Climate change can affect rainfall patterns, flood frequency, water levels, freeze/thaw cycles, and wetting/drying cycles, which can impact understanding of long-term levee performance data. Awareness of potential changes to the environmental factors affecting the levee can help levee owner/operators better evaluate and utilize levee performance data during emergencies.

4.2 Data Management

Data collected during flood events informs immediate flood operations, and identifies necessary long-term levee remediation measures. Good documentation of performance observations during the flood, formalizing the data in a report once the flood is over, and storing the report in the levee's data management system (**Chapter 9**) helps ensure this information is available to inform future actions.

Formal documentation may include incorporating performance observations and response methods into the emergency action plan, revising the O&M manual to address operational or maintenance concerns, or developing an after-action report, as discussed in section 4.6.5. Proper documentation will greatly assist future floodfighting efforts by providing awareness of potentially poor performing areas of the levee and how they have been successfully addressed in the past.

4.2.1 Criteria for Data Collection

Data is more useful when it is collected using consistent criteria and terminology that is universally understood. It is a best practice to develop a standard list of attributes to be documented for each failure mode along with standard language to describe levee conditions. Standardization will help ensure consistent data collection and improve understanding of levee conditions. For example, standard terms can be adopted to describe the size of a sand boil or seepage quantity. Table 10-5 provides a summary of some of the data that should be collected using standardized methods and language during a flood. Detailed best practices for collecting and documenting levee performance data, including an example of standardized terms and definitions, are provided as an appendix on floodfighting in EM 1110-2-1913 (USACE, 2000). It is a best practice to designate an experienced lead to coordinate and oversee performance data collection and ensure consistency.

Table 10-5: Conditions and Attributes to Record During a Flood

Condition Type	Attribute	Description
All conditions	Coordinate (points or lines)	Preferably automated during collection
	Date and time	
	Name of person reporting	
	Photograph or video	Includes date stamp
	Description	Standard language and detailed descriptions of performance
Sand boils	Size	Measured diameter of sand boil throat or use standard descriptions (pin boil, small, medium, large)
	Activity description	Description of the amount of soil material flowing from the sand boil (clear boil, low, moderate, high, or very high activity)
	Location	Distance from levee toe
	Contributing factors	Topography, features, environmental or human conditions which contribute to the condition, such as ditches, pipes, animal burrows, thickness of clay top stratum, pumping of landside water, etc.
Underseepage	Quantity of seepage	Standard descriptions (no seepage, very light, light, medium, heavy)
	Contributing factors	Topography, thickness of clay top stratum
Throughseepage	Quantity of seepage	Standard definitions (no seepage, light, medium, heavy)
	Contributing factors	Levee embankment material, levee slopes, encroachments, transition zones
Erosion	Size	Length, depth, width of erosion Rate of progression
	Location	Location on embankment or relative to features
	Contributing factors	Poor sod cover, high winds, concentrated flows, high velocity, existing erosion protection, etc.
Overtopping	Time of overtopping	Time and date that water started flowing over the top of the levee
	Depth of overtopping	Maximum depth of water flowing over the levee (above pre-existing levee grade without erosion)
	Time of breach	Time the overtopping resulted in a rupture, break, or gap
	Breach width	Approximate width of breach 15 min, 30 min, 1, 2, 4, 8, and 24 hours after breach
Slides	Size	Width at widest extent parallel to levee Vertical displacement (scarp height)
	Location	Approximate location on slope (distance from crown, landside, or waterside)
	Contributing factors	Soil saturation, changes in slope, vegetation, encroachments, etc.
Floodwall issues	Movement	Measurement of movement due to tilting, sliding, or settlement during loading
	Waterstops	Description of flow and height of waterstop failure
Record of closure operation and issues	Type	Stoplog, swing gate, sliding gate, sandbag
	Date and time closure started and completed	Start/stop time for closure installation

Condition Type	Attribute	Description
	Operational issues	Missing parts during installation, broken components during operation, temporary fixes
	Performance issues	Leaking stoplogs, leaking seals, misalignment
Gate closure issues	Effectiveness of closure	Issues experienced during gate operation Quantity of water leaking through gate
Pipe issues	Condition of surrounding soils	Location and size of sinkholes, depressions, or erosion over or near the pipe
	Leakage	Estimate flow through pipe due to leakage or around pipe due to seepage. Distinguish between gate leakage and leakage into the pipe due to pipe defects

It is important that levee inspectors that are collecting the data be able to recognize conditions that may lead to levee breach and know the terminology used to describe them. Ensuring that inspectors are aware of pre-planned actions (section 2.7) can speed response, should immediate action be required to address performance concerns.

4.2.2 Tools for Data Collection

Geographic information system-based data collection systems allow for efficient and consistent collection of performance data. The USACE Levee Inspection System is a mobile application designed by USACE to assist with the process of conducting inspections, documenting conditions, and generating reports. The Levee Inspection System can be obtained through the NLD website. Other commercial mobile collection tools can also be used to collect data.

The most effective tools used for data collection have the following capabilities:

- Collects recommended distress point attributes using standard terminology.
- Collects both line and point data.
- Provides GPS/camera/video capabilities.
- Is easy to carry (tablet or phone size).
- Provides remote connectivity to office using data network (wireless) or ability to offload data for email or external data transfer.
- Has user interface with dropdown menus to minimize typing.
- Has ability to append data daily as features change.

The NLD is the national repository for all levee performance data. The Levee Inspection System is integrated with the NLD, and data collected using this tool is automatically associated with the levee in the NLD; however, if manual data collection or other commercial tools are used, manual upload of that data would be needed. Users of the Levee Inspection System should be prepared for computer issues and lapses in internet service during an emergency. Non-electronic means of data collection will likely need to be used in these instances.

4.3 Floodfight Actions

There are a wide range of floodfight actions that can be implemented depending on the failure mode that has initiated and the location and severity of the incident. The appropriate response actions will also depend on the availability of materials, equipment, staff, volunteers, and time. Incident response consistency and efficiency can be improved by assigning a single individual the responsibility of evaluating incidents, determining their severity, and prescribing floodfight actions to address them. Best practices to help ensure adequate personnel and resources are available during floodfight events are included in section 2.9 and 2.10.

Failure to react in a timely manner and apply proven floodfight actions greatly increases the likelihood of levee breach. Although each flood is unique, there are many common elements from one flood to the next, and proper implementation of floodfight actions will improve response time and chances of successfully managing consequences. Pre-defined incident classifications with associated pre-planned response actions as discussed in sections 2.6 and 2.7 are an excellent tool for facilitating fast communication and decision making during an incident.

Coastal flooding is significantly different in that the wind and wave action make floodfight during a storm very difficult, so the best response for a coastal levee is to make preparations before the storm, and act once a storm is predicted but before it arrives. A list of references to help aid the development of pre-planned floodfight actions is available in the callout box titled "Reference Materials" in section 2.7.3. Typical incidents observed during a flood on a levee with typical actions to address them are provided in Table 10-6.

Table 10-6: Typical Floodfight Actions

Incident	Typical Floodfight Actions
Individual sand boils	• Raise water level over boil. Most common method is to build a ring of sandbags around the boil that stops soil migration out of the boils but allows water to continue to flow.
Large area with many sand boils	• Raise water level over area by building a water berm. Water berms are constructed by building a 1- to 2-foot-tall soil embankment around the seepage area and filling it with water. • Reinforce the landside slope or the area landside of the levee by building an emergency seepage berm. Berm soils should be less permeable than levee and foundation soils. See the discussion on seepage berms in **Chapter 7**.
Landside slope failure	• Minor sloughs typically do not impact levee stability and can be covered with plastic sheeting or riprap to prevent erosion of exposed levee soils during the flood. These areas should be monitored for throughseepage. • Deeper slides often require the placement of soil or rock on the levee toe to prevent additional slope movement. Monitor for seepage emerging from the slide as this can indicate a progressing failure mode.
Waterside erosion	• Wave wash can usually be managed by the deployment of plastic sheeting to protect the areas where wave wash is occurring. • Sever wave wash or deeper erosion due to currents may require the placement of rock to protect the levee.

Incident	Typical Floodfight Actions
Overtopping – Outside of designed overtopping sections	• Evacuate the leveed area. • Overtopping can sometimes be prevented by raising the levee using methods for earthen assembled closures discussed in **Chapter 7**. However, this action can transfer risk to other levee systems and areas outside of levees. Raising a levee also subjects the levee and its foundation to water levels greater than those used to design the levee.
Leaking floodwall joints	• Expanding foam can be used to stop moderate leaks. • Extreme leakage may be a sign of a progressing failure mode and a structural or geotechnical engineer should be consulted.
Leaking closure structure	• Deploy plastic sheeting against the waterside of the closure. • Place sandbags along the seals on the landside.

4.4 Emergency Communication

It is important to ensure timely, consistent, and clear communication during an emergency. Specifically informing emergency management agencies and local jurisdictions of the condition of the levee and providing ongoing situational updates following the pre-developed notification flowcharts and messages discussed in section 2.7.1 keeps all partners aware, engaged, and ready to respond.

Throughout the U.S., the National Weather Service has the primary responsibility for issuing flood warnings to the impacted community. The National Weather Service will often decide when to issue flood warnings to the public based on the weather forecast and information from the levee owner or the emergency management agency concerning levee conditions. This makes timely and accurate delivery of information to the National Weather Service about levee conditions—particularly imminent breach, overtopping, or high flow conditions—very important.

It is critically important that proper coordination and communication occurs among personnel in the field, public information officers, and emergency personnel at the emergency operations centers to ensure a successful response to an emergency. Thoroughly testing these activities during emergency action plan exercises, and making necessary modifications, can help communication flow smoothly during an emergency.

4.5 Evacuation

If floodfight actions are not successful or if conditions worsen, it may become necessary to initiate an evacuation of the threatened area. Often, the levee owner/operator will not have the authority or resources to perform an evacuation. Evacuations are typically ordered and conducted by a local or state emergency management agency.

Typically, the levee owner/operator's role in an evacuation is to provide the information necessary for responsible entities to make an informed decision regarding evacuation. However, in some cases, the levee owner/operator may be a municipality or other organization with the responsibility to call for and/or execute an evacuation. It is a best practice for the levee owner to understand their role in the evacuation process and to assign a specific individual within the levee owner's organization the responsibility to make and communicate decisions to fulfill that role. Additional information regarding evacuations is provided in section 2.7.2.

4.6 Termination

Once conditions have stabilized, emergency response will be terminated and a transition to the recovery phase will be initiated. Demobilization and termination are deliberate processes that include all partners in the decision-making process.

It is a best practice for the emergency action plan to describe the termination process, including criteria for determining an emergency at the levee has been resolved, as well as termination and follow-up processes for levee incidents and emergencies. Planned termination activities should include processes to ensure inspection and performance data, debriefings, and after-action reports are documented and organized within the levee's data management system (**Chapter 9**). Components of the termination phase are described in further detail below.

4.6.1 Communication

The first step in transitioning from the emergency phase to the termination phase consists of the levee owner/operator promptly notifying emergency management agencies and other partners that the condition of the levee has been stabilized or the incident classification severity has been lowered.

Government officials are responsible for declaring an end to a public emergency response if one has been previously designated. Emergency terminations will be issued by the level of government from which the emergency declaration was made.

4.6.2 Demobilization

The goal of demobilization is the orderly, safe, and efficient release and return of a resource to its original location and status. Once resources are no longer needed, they can be demobilized by the personnel responsible for the resources. Prompt removal will protect both the resources and the levee from damage.

The termination process can be improved when staff responsible for the planning and logistical functions collaborate prior to demobilization, in order to plan how resources are replenished, disposed of, or returned to operational condition. The management of resources is smoother when levee owner/operators begin planning and preparing for the demobilization process at the same time they begin mobilizing resources, or prior to flood events, if possible.

Demobilization policies and procedures will vary depending on the size of the incident and will be specific to the levee owner/operator based on their fiscal/legal policies, procedures, work rules, and other requirements.

Developing a demobilization plan can help ensure a controlled and cost-effective release process, eliminate waste, and eliminate potential fiscal and legal impacts. A demobilization plan contains the demobilization process, responsibilities for implementation, release priorities, specific release procedures, and travel information.

4.6.3 Transfer of Command

As the incident de-escalates, the size and complexity of the resources needed may be reduced and may lead to a transfer in command. The details of how to execute a transfer in command is thoroughly discussed in FEMA's Incident Command System training materials, which can be accessed through the FEMA website (FEMA, 2015).

4.6.4 Closeout/Debriefing

Incident management team demobilization may include a formal closeout meeting with the responsible agency or jurisdiction for managing the emergency. Including a debriefing as part of the closeout process can help identify areas for improvement. A closeout meeting should be documented and include a summary of the incident, discussion of major events, a discussion of the incident outcome, a voicing of concerns, and a final evaluation of incident management. Closeout meetings are important for major incidents that have attracted media interest, incidents that have drawn public scrutiny, incidents where there will be a need for longer term recovery efforts, and situations where there were important lessons learned for future responses.

4.6.5 After-Action Report

Following an emergency, it is valuable to reflect upon and evaluate the circumstances leading up to the emergency, all activities and actions that took place during the emergency, and the resulting outcomes. It is also beneficial to review the emergency action plan and O&M manual to determine if there are opportunities for improvement and make updates as appropriate.

Preparing an after-action report is the best practice for consolidating all information related to an incident, including response action and levee performance. Detailed information on how to prepare an after-action report along with the standard format is provided in the Department of Homeland Security's Exercise and Evaluation Program (FEMA, 2020).

Coordinating this effort with all organizations and individuals involved in the response efforts will result in a more holistic view of the situation from a variety of perspectives and assist in identifying lessons learned and opportunities for improvement. Depending on the extent of the emergency and partners involved, multiple organizations may produce their own documentation of the emergency.

Assigning the responsibility for implementing each corrective action identified in an after-action report to a specific person, as well as developing and tracking an implementation schedule, will help ensure lessons learned are used to improve future emergency response efforts. Incorporating changes in emergency response procedures into the emergency action plan as appropriate will ensure they are used to improve response during the next flood. Levee owner/operators should store after-action reports in an easily accessible location and upload them to the NLD linked to the respective levee system for ease of access to local emergency management agencies and other levee emergency management partners.

A comprehensive continuous improvement process applied before, during, and after an emergency action plan exercise or actual emergency will improve readiness by identifying and addressing weaknesses. Having an internal process in place to validate previous actions that were successfully implemented can also inform future planning and response.

4.6.5.1 Levee Performance Documentation

Valuable data can be obtained by closely inspecting levees during and after each levee emergency, as well as evaluating and documenting levee performance. Keeping organized records of locations where issues, emergency action, or breaches have occurred can inform O&M, flood operations, and levee rehabilitation projects.

Complete levee performance data includes photos, locations, type and severity of the distress, how the distress point changed during the flood event, and a description of floodfight actions and their effectiveness. The specific date, time, and river level when observations were made is important for levee performance projections for higher hydraulic loads and remediation of observed distress. Including levee performance data as an appendix to the after-action report can be an effective way to organize this data and make it available.

4.6.5.2 Emergency Management Lessons Learned

Lessons learned can provide emergency management agencies and levee owner/operators with valuable information to improve response and recovery actions. A thorough evaluation will include evaluating strengths and weaknesses of significant actions taken on the levee or within the community in response to a levee emergency including the incident management process, resourcing of materials, information sharing, equipment used, and leadership structure. A complete evaluation will result in needed corrective actions, opportunities to improve processes or tools, and a planned course of action to implement recommendations.

This information can also be used to inform public officials and residents about flood and levee risk and to assist in public policy discussions concerning other flood risk management options for the community. Other outcomes of an after-action review could produce either a more effective response during an emergency or improvements to the levee that would reduce the need for emergency response. **Chapter 12** discusses community-based flood risk management measures.

4.6.6 Transition to Recovery

Planning for the transition to recovery is particularly critical in large-scale incidents where an organization, such as an emergency operations center, may be required to assume responsibility for recovery actions and activities.

5 Recovering from a Levee Emergency

A levee emergency may result in impacts to levee infrastructure, critical infrastructure, people, housing, the economy, and the natural environment. **Recovery** of a levee after an emergency is the prompt restoration of the levee to a serviceable condition in the event of damage and/or prompt removal of excess flood water from the leveed area. Including recovery planning in preparedness efforts and starting recovery efforts as soon as the emergency has subsided and it is safe to do so will speed restoration of levee function, minimize economic losses, and minimize the extent of damage progression.

Recovery typically begins after the emergency has ended, but some short-term recovery activities may occur simultaneously with response efforts. This section focuses on the immediate operational actions following a levee emergency. Ensuring short-term recovery actions necessary to return the levee to its pre-flood condition are in the emergency action plan or O&M manual will help ensure a speedy and well-coordinated recovery.

5.1 Post-Flood Inspection

It is important to conduct a post-emergency inspection to document the extent of damage to the levee. Including an inventory of all remaining incident response equipment, sandbags, and other supplies as part of the post-flood inspection can document which materials need to be replenished and the need for equipment maintenance or repair.

A post-flood inspection that includes the type and extent of damage can help determine if short-term repairs or long-term rehabilitation is needed to restore levee integrity. This data can guide the recovery process and help:

- Identify financial requirements for repairs (how much the repairs will cost and who will bear the cost of repairs).
- Determine the priority of necessary repairs.
- Identify key infrastructure that may need to be repaired in coordination with other agencies (e.g., roads).
- Support documentation for state or federal assistance and cost recovery activities.

Documenting the data collected, as well as the inspection findings, in a formal report helps to organize the data and facilitates sharing with appropriate personnel and partners, as further discussed in section 4.6.5.1.

5.2 Immediate Repairs

Once a post-flood inspection has been completed, it is a best practice to prioritize identified repairs based upon risk and to immediately address urgent issues (if safe to do so). Urgent issues are typically those most likely to cause a levee breach during future loadings and/or that have a greater potential to impact populated areas. Immediate repair of high-risk issues will help to prevent conditions from worsening or the occurrence of another levee emergency due to unaccomplished repairs.

The urgency of a repair is dependent upon the unique characteristics of the damage and how it impacts levee risk. The following issues may be urgent depending on what is driving levee risk.

- **Levee crest levels:** Fill any settlement, holes, voids, gullies, and washes in the levee crown with compacted fill material.
- **Levee cross section or foundational damage:** Repair any observed issues that could degrade over time if left unrepaired, increasing the chance for a breach during future floods (e.g., erosion, sloughing). (See Figure 10-13 for an example of a levee slope repair.)

- **Interior drainage systems:** Examine all drainage ditches on the landside of the levee and remove any obstructions. Manually check and repair any damaged gates and remove debris, sediment, or other potential obstructions. Examine the waterside of levee for debris.
- **Access routes and staging areas:** Restore access and repair any damages to transportation routes or locations that will be needed to stage equipment and materials for other levee repairs. Re-establish access security measures, as necessary (e.g., cameras, gates, and locks).
- **Instrumentation system:** Assess and restore levee monitoring systems impacted by incident (e.g., staff gages, stakes, flow meters, water level pressure transducers, and remote cameras).

In some cases, complete repairs will not be possible and **interim risk reduction measures**—actions to reduce levee risk until more permanent repairs are completed—should be implemented. Care must be taken to ensure temporary measures do not block access for O&M, impact levee integrity, or complicate the design and construction of the needed levee rehabilitation project. Completing interim risk reduction measures before conditions worsen or another emergency occurs reduces levee risk until more permanent repairs and rehabilitations can be accomplished.

Figure 10-13: Workers Repair a Levee

Workers using a track hoe to repair levee damage and replace riprap in South Sacramento, California.

5.3 Long-Term Repairs and Rehabilitation

After the emergency has subsided and urgent repairs have been made, levee performance data and post-flood inspection data should be evaluated to determine if additional repairs or large-scale rehabilitation is needed.

In many cases, post-flood repair and rehabilitation needs will exceed immediate resources. It is a best practice for all required repairs identified by flood and post-flood inspections to be tracked and prioritized for action based upon risk. The prioritized list of flood recovery actions should be merged with any pre-existing prioritized list of levee risk management actions to ensure that resources are invested to reduce levee risk as quickly and effectively as possible, as discussed in **Chapter 9**.

In instances where significant performance concerns cannot be addressed immediately, an evaluation may be warranted to see if changes are needed to the O&M manual or emergency action plan. Adjustments to maintenance, operation, inspection, or floodfight procedures may be needed to manage levee risk until permanent repairs can be made. Adjustments to notification and evacuation procedures may also be warranted.

Risk assessment, as described in **Chapter 4**, is an effective method for understanding how damages and performance concerns impact levee risk. Risk assessments result in a list of recommendations to reduce and manage risk. Risk management, as discussed in **Chapter 5**, provides a method for choosing and prioritizing actions. Design and construction of levee rehabilitation projects are addressed in **Chapters 7 and 8**.

5.4 Removing Temporary Floodfighting Measures

Temporary measures deployed during flood emergencies are not permanent solutions. Temporary measures are intended to reduce the likelihood or consequences of an impending levee emergency and are not designed to support a levee in perpetuity. They can cause damage to the levee and increase the levee risk if left in place long term.

Once the emergency conditions have ended and it is safe to do so, it is a best practice to remove temporary measures (e.g., sandbags, flashboards, rock, plastic sheeting, emergency levees) and dispose of them properly to prevent damage and preserve access to the levee. Some temporary floodfighting measures may need to remain in place as interim risk reduction measures until a permanent solution can be designed and implemented.

Additionally, some flood waters impounded by the temporary floodfighting measures may be contaminated with fuel, pesticides, and other contaminants. Due care should be used when entering contaminated water to remove temporary measures. Measures should be taken to ensure the removal of the contaminated water, and the disposal of temporary floodfighting measures that came into contact with the contaminates.

5.5 Recovery Assistance

There are numerous state and federal recovery assistance programs available to levee owner/operators to aid in post-flood recovery efforts. The various programs are discussed in **Chapter 12**.

6 Summary

Emergency preparedness actions outlined in this chapter can reduce potential impacts of emergencies before they occur. Preparation requires communicating with the public, ongoing collaboration between stakeholders, developing and exercising emergency action plans, training levee personnel, and maintaining the appropriate materials, supplies, and operational readiness for when an emergency occurs.

Learning from previous emergencies, constantly revising plans and activities to adjust for changing conditions, and leveraging lessons learned will increase the ability of emergency management partners to navigate future levee emergencies as conditions continue to evolve and change.

Related content associated with this chapter is included in detail in other chapters of the National Levee Safety Guidelines as described in Table 10-7.

Table 10-7: Related Content

Chapter	Chapter Title	Related Content
1	Managing Flood Risk	• Sources of flood hazard
2	Understanding Levee Fundamentals	• Potential failure modes
3	Engaging Communities	• Flood-related communication • Emergency communication
4	Estimating Levee Risk	• Risk assessment • Potential failure modes • Inundation maps
5	Managing Levee Risk	• Levee risk management • Risk-informed decision making
6	Formulating a Levee Project	
7	Designing a Levee	• Levee rehabilitation
8	Constructing a Levee	• Construction of long-term repairs
9	Operating and Maintaining a Levee	• Flood-related inspections and monitoring • Emergency preparedness
10	Managing Levee Emergencies	
11	Reconnecting the Floodplain	
12	Enhancing Community Resilience	• Community flood preparedness • Evacuation planning

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11

Reconnecting the Floodplain

Key Messages

This chapter will enable the reader to:

- **Consider the ecosystem.** Reconnecting the floodplain enhances ecosystem services. Removing a levee is based on ecological and/or flood risk management benefits.
- **Understand the changes.** Levee removal impacts flood risk.


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Other chapters within the National Levee Safety Guidelines contain more detailed information on certain topics that have an impact on reconnecting the floodplain, as shown in Figure 11-1. Elements of those chapters were considered and referenced in the development of this chapter and should be referred to for additional content.

Figure 11-1: Related Chapter Content

CH 1	CH 2	CH 3	CH 4
Understanding the basics of flood risk	Levee form	Engaging for levee-related projects	Estimating hazards, performance, and consequences
CH 5	**CH 6**	**CH 7**	**CH 8**
Risk management activities Risk-informed decision making	Six-step planning process	Design process Site characterization	Construction management General construction activities
CH 9	**CH 10**	**CH 11**	**CH 12**
O&M manuals		**Reconnecting the Floodplain**	Community resilience Mitigation strategies

Contents

1 Introduction 11-1

2 Floodplain Reconnection Overview 11-2

2.1 Drivers for Floodplain Reconnection 11-2

2.2 Project Goals 11-4

2.3 Project Team 11-5

2.4 Community Engagement 11-5

2.5 Regulatory Compliance 11-6

2.6 Documentation 11-6

3 Planning 11-7

3.1 Floodplain Reconnection Considerations 11-9

3.1.1 Levee Removal Risk Management 11-9

3.1.2 Setback Levee Alignment 11-9

3.1.3 Hydraulics and Geomorphology 11-10

3.1.4 Ecology and Restoration 11-11

3.1.5 Recreation 11-12

3.1.6 Existing Infrastructure 11-13

3.2 Plan Formulation 11-13

3.2.1 Identification of Problems, Opportunities, and Constraints 11-13

3.2.2 Inventory Current and Forecast Future Conditions 11-14

3.2.3 Formulate Alternatives 11-16

3.2.4 Evaluate, Compare, and Select Preferred Alternative 11-17

4 Design 11-18

4.1 Site Characterization 11-18

4.1.1 Information Gathering from Available Data 11-19

4.1.2 Additional Investigations 11-21

4.2 Access, Staging, and Hauling 11-22

4.3 Levee and Bank Stability During Construction 11-23

4.4 Post-Removal Inundation and Drainage 11-23

4.5 Extent of Levee Removal 11-24

4.6 Disposal or Re-use of Levee Material 11-26

4.7 Ecosystem Restoration 11-27

4.7.1 Overview of Restoration Approach and Goals 11-28

4.7.2 Geographic Considerations, Available Space, and Surrounding Land Cover/Use Considerations 11-29

4.7.3 Restoration Design 11-29

4.7.4 Climate Change Considerations ... 11-34
4.8 Sequencing the Work ... 11-34
4.9 Unanticipated Conditions ... 11-35
4.10 Operation and Maintenance ... 11-36
4.11 Cost Considerations ... 11-36
5 Construction ... 11-37
5.1 Removal Methods ... 11-37
5.1.1 Earthen Levees ... 11-38
5.1.2 Structures ... 11-38
5.2 Safeguarding Ecosystems During Construction ... 11-39
5.3 Post-Construction Monitoring and Reporting ... 11-39
6 Summary ... 11-40

List of Figures

Figure 11-1: Related Chapter Content ... 11-i
Figure 11-2: Reintroduction of Tidal Waters to Previously Leveed Area ... 11-1
Figure 11-3: Setback Levee Schematic ... 11-4
Figure 11-4: Steps in the Levee Removal Process ... 11-8
Figure 11-5: Floodplain Reconnection Cross Section ... 11-11
Figure 11-6: Plan Formulation Process ... 11-17
Figure 11-7: Lateral Migration of River Channel Observed During Site Reconnaissance ... 11-18
Figure 11-8: Two-Dimensional Modeling Results ... 11-24
Figure 11-9: Potential Removal Extent of Levee ... 11-24
Figure 11-10: Partial Levee Removal ... 11-25
Figure 11-11: Steps to Successful Restoration ... 11-30

List of Tables

Table 11-1: Levee Removal and Associated Ecological Effects ... 11-12
Table 11-2: Restoration Considerations in Different Environments ... 11-27
Table 11-3: Related Content ... 11-41

1 Introduction

Floodplains comprise some of the most valuable ecosystems on the planet. Traditionally situated next to rivers, streams, and coastlines, they are one of nature's best defenses against destructive floods. Natural floodplains provide essential habitat for wildlife, improve water quality, and protect communities of people. They also provide critical ecosystem benefits by retaining sediment, nutrients, and floodwater. In fact, periodic flooding into overbank areas creates unique habitats and provides an exchange of water, sediment, and organisms that drive ecosystem productivity within the waterbody and on the floodplain.

Ecologically functional floodplains are less common in today's increasingly developed and engineered landscape, and this is to the detriment of people, wildlife, and the waterbody. Where a floodplain has been disconnected from a waterway and converted to other uses, its ability to provide an array of natural and beneficial functions is inhibited, curtailing benefits to both human and ecological communities (American Rivers, 2016).

Figure 11-2: Reintroduction of Tidal Waters to Previously Leveed Area

Inter-tidal partial levee removal as part of Napa Plant Site Salt Pond Restoration project near American Canyon, California.

The decision to remove a levee and reconnect the floodplain to the waterbody is typically based on ecological and/or flood risk management benefits (Figure 11-2). Other potential drivers may include managed community retreat, flood managed aquifer recharge, existing levee deterioration, and/or the original need for the levee may no longer exist. When a levee is no longer needed to reduce the risk of inundation, the levee may be intentionally breached in localized areas or removed entirely. Refer to **Chapter 5** for more information related to levee risk management activities.

Often times, an existing levee can be moved back (or setback) from the watersource, allowing the opportunity to reintroduce more acreage within the floodplain to be directly connected to the waterbody. This also allows for the incorporation of natural or nature-based features into the floodplain design, and these type of features (e.g., dunes, wetlands, reefs, islands) can provide independent benefits for risk reduction, as well as other economic, environmental, and social benefits. In the context of these guidelines, best practices associated with planning, design, and construction of the levee setback are applicable to the content addressed in **Chapters 6, 7, and 8** for a new levee.

The primary result of typical levee removal or setback is expansion of the river, creek, or coastal inundation area into adjacent (often shallower) areas. One of the main benefits is the return of more natural hydraulic and geomorphic processes, habitats, and ecosystems; however, levee removal could have significant impacts to flood risk. Because former leveed areas may become exposed to inundation after a levee is removed, conducting a comprehensive study is essential to ensure no increased risk to human life and critical infrastructure will occur. Robust community engagement may also be necessary if the levee removal or setback project has the potential to impact public safety and/or areas of community interest (**Chapter 3**).

This chapter presents best practices related to levee removal, with the overarching goal of floodplain reconnection. Potential drivers for levee removal are discussed, along with unique planning considerations, especially if the intent is to setback the existing levee. Appropriate site characterization activities are also covered, along with recommended design criteria and analyses, and construction practices, particular to levee removal.

2 Floodplain Reconnection Overview

Reconnection of a waterbody to the adjacent floodplain through levee removal or setback can have numerous benefits to natural resources including wildlife, vegetation, groundwater, and in some cases, flood risk reduction. However, floodplain reconnection through the lens of removing an existing levee requires a comprehensive understanding of existing and future flood risk, as well as other ancillary impacts and benefits. Refer to **Chapter 1** for related information on the basics of flood risk. While there are numerous drivers that could initiate a floodplain reconnection project, successful implementation will be tied directly to early establishment of clearly defined goals, selection of a qualified team of planners and designers, and early community and regulatory engagement.

2.1 Drivers for Floodplain Reconnection

The impetus for a floodplain reconnection project may stem from an opportunity to benefit the community, a public safety concern, or an environmental issue. These overarching objectives can provide useful context throughout all phases of project development. In many instances, levee construction throughout the nation has resulted in the loss of riparian, wetland, and other floodplain and coastal habitats. More than 50% of the wetlands in the United States are estimated to have been lost (Dahl and Allord, 1982), and 90% of the floodplains in Europe and North America have been cultivated and now are functionally extinct (Tockner and Stanford, 2002). Although levee construction is not the primary reason for the extent of these losses, levee removal and floodplain reconnection present an opportunity to help restore these areas to their natural state and reverse the trend of declining natural ecosystems. Some examples of potential drivers for floodplain reconnection projects include:

For some agricultural areas, infrequent flooding may be beneficial for both crops and groundwater.

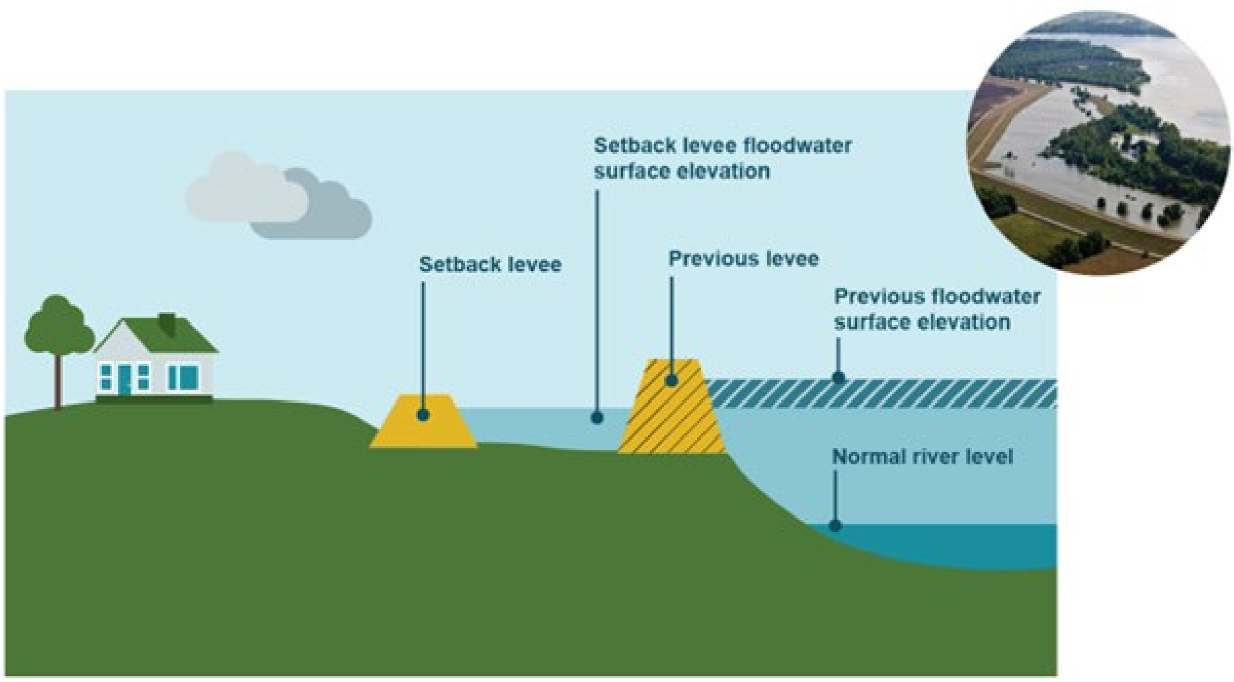
- **Floodplain storage during flood events**: Floodplain storage during large storms can reduce river flood elevations and possibly reduce flooding in other problem areas.
- **Managed community retreat**: Managed retreat involves the strategic relocation of structures or abandonment of land to manage flood risk to communities. Relocation of communities or structures away from a river or coastal area to avoid flood risk may provide the opportunity for floodplain reconnection.
- **Existing levee is being rerouted or replaced (setback levee)**: When a decision is made to realign or replace an existing levee with a new flood risk reduction feature, an opportunity may exist to remove the existing levee after the new feature is in place. Setting levees back a certain distance from their current location along a riverbank or coastline can be associated with managed community retreat or with the reclamation of former agricultural or other open space land into the floodplain (Figure 11-3).
- **Other flood risk reduction features have made the levee functionally obsolete**: When other features have been implemented to reduce the risk of flooding at lower water surface elevations, the need for a levee may become obsolete, potentially allowing subsequent removal and reconnection of the floodplain.
- **Existing levee is in a state of failure**: Although levee vulnerability alone may not necessarily warrant levee removal because of lingering flood risk, it may help lead to one of the other drivers listed above, ultimately resulting in levee removal and floodplain reconnection after the flood risk has been addressed.

Other ecological and environmental drivers for floodplain reconnection include:

- **Groundwater recharge and/or flood-managed aquifer recharge**: Degraded or lowered aquifers can affect the water supply for domestic and agricultural users. Allowing dry weather flows or flood flows to pond over larger areas can help them to infiltrate to the aquifer. Flood-managed aquifer recharge is an integrated and voluntary resource management strategy that uses flood water resulting from, or in anticipation of, rainfall or snow melt for managed aquifer recharge on agricultural lands and working landscapes, including refuges, floodplains, and flood bypasses. Flood-managed aquifer recharge may be implemented on multiple scales, from individual landowners diverting flood water with existing infrastructure, to using extensive detention/recharge areas and modernizing flood management infrastructure/operations (California DWR, 2015).

- **Ecological restoration**: Degraded habitat on the landside of levees can be a driver to increase hydraulic connectivity between the waterbody and adjacent areas leading to opportunities for ecological restoration. Extensive restoration may not be possible on all levee setback or removal projects, but at a minimum, the former levee footprint should be covered with native vegetation.

Figure 11-3: Setback Levee Schematic



2.2 Project Goals

As with any infrastructure project, it is important to identify overarching project goals of floodplain reconnection as early as possible, since they will serve as a guide for activities that follow through planning, design, and construction. Engagement with the community is essential when identifying and refining project goals, and clear communication with those responsible for implementing the work is critical to the project's success.

Specific goals associated with the prospect of either keeping or removing an existing levee should be clearly defined. Possible goals may include any of the following:

- Maintaining or reducing the risk to human life.

- Maintaining or reducing the risk of economic damage to businesses, residences, manufacturing facilities, and critical infrastructure (e.g., agriculture, medical centers, schools, roads, rail corridors, bridges, and energy production and distribution facilities).
- Minimizing the need for long-term maintenance.
- Maximizing multiple opportunities/benefits, such as recreation, aquifer recharge, geomorphic processes, and agricultural.
- Maximizing ecological benefit.
- Incorporating climate change and sea-level rise considerations.

2.3 Project Team

The project team is typically comprised of professionals with similar engineering expertise as a levee design team, with the exception of including others with specialized discipline backgrounds. Since floodplain reconnection projects traditionally include restoration of more natural hydraulic and geomorphic processes, habitats, and ecosystems, it is important to ensure that the project team includes a geomorphologist, ecologist, landscape architect, and regulatory specialist.

2.4 Community Engagement

Robust community engagement may be necessary if the floodplain reconnection project impacts public safety and/or areas of community interest. **Chapter 3** describes best practices for community engagement in four distinct phases throughout the life of a levee. The best practices outlined for the phase entitled "engaging for future levee projects" are most applicable for removing or setting back an existing levee.

Community engagement is essential for removing or setting back an existing levee.

Although the themes (i.e., flood risk, public safety, ecosystem health) remain the same, many of the engagement specifics will vary for floodplain reconnection. For instance, instead of discussing the flood risk reduction associated with a new levee, engagement for floodplain reconnection may focus on benefits such as increased floodplain storage and hydraulic connectivity, ecosystem restoration, or aquifer recharge. In addition, education and awareness is important to assure community members that the levee removal will not result in increased flood risk.

Inclusivity should be a key consideration during the planning process and when implementing community engagement. In many areas across the country, underserved community members may live in low-lying areas that are prone to flooding. The community's characteristics and capabilities—and any potential impacts to the population—should be clearly understood prior to entering the design phase for a floodplain reconnection project.

2.5 Regulatory Compliance

Activities related to regulatory compliance touch every phase of the floodplain reconnection process. As described in **Chapter 6**, regulatory permit requirements help ensure proposed project impacts to existing natural resources are limited, and for unavoidable impacts to critical resources, appropriate mitigation is provided.

Identifying federal, state, and local permit requirements—and consulting with key agencies to confirm regulatory constraints and specific requirements—are essential for floodplain reconnection projects with a large ecosystem restoration component. This best practice helps to ensure the proper incorporation of elements into planning and design that conform to individual agency requirements.

Several examples of regulatory processes and permits are listed in **Chapter 6**, including the National Environmental Policy Act, which requires the potential environmental impacts of the project be assessed and several alternative approaches be evaluated. As a best practice, an alternatives analysis should be completed that is consistent with the plan formulation process discussed in section 3.2.

As the floodplain reconnection planning and design phases progress, permit applications should be prepared and submitted, often after a 30% design is complete. A 30% design typically provides an adequate level of detail to assess impact to existing resources, which is a key part of many regulatory permit processes. Recurring meetings with regulatory agencies serve as excellent opportunities to discuss project details, review approaches for compliance with applicable regulations, and refine the understanding of likely permit conditions related to post-construction monitoring and reporting.

It is imperative that required permits are in hand prior to construction, and it is ideal if they are in hand prior to bidding the project. This allows for incorporation of regulatory-related best management practices into the contractor's scope and work plan, to alleviate the risk of change orders after permit acquisition.

2.6 Documentation

Documenting floodplain reconnection projects is similar to other types of design and construction projects and should be completed in accordance with the established requirements of the project owner and regulatory agencies. **Chapter 6** highlights the importance of project documentation, lists types of documentation, and describes several factors that inform the appropriate level of documentation.

If a floodplain reconnection project results in a change to flood risk or to existing flood maps, this information should be documented and reported to the appropriate organizations. For example, regulatory agencies—the U.S. Army Corps of Engineers (USACE), Federal Emergency

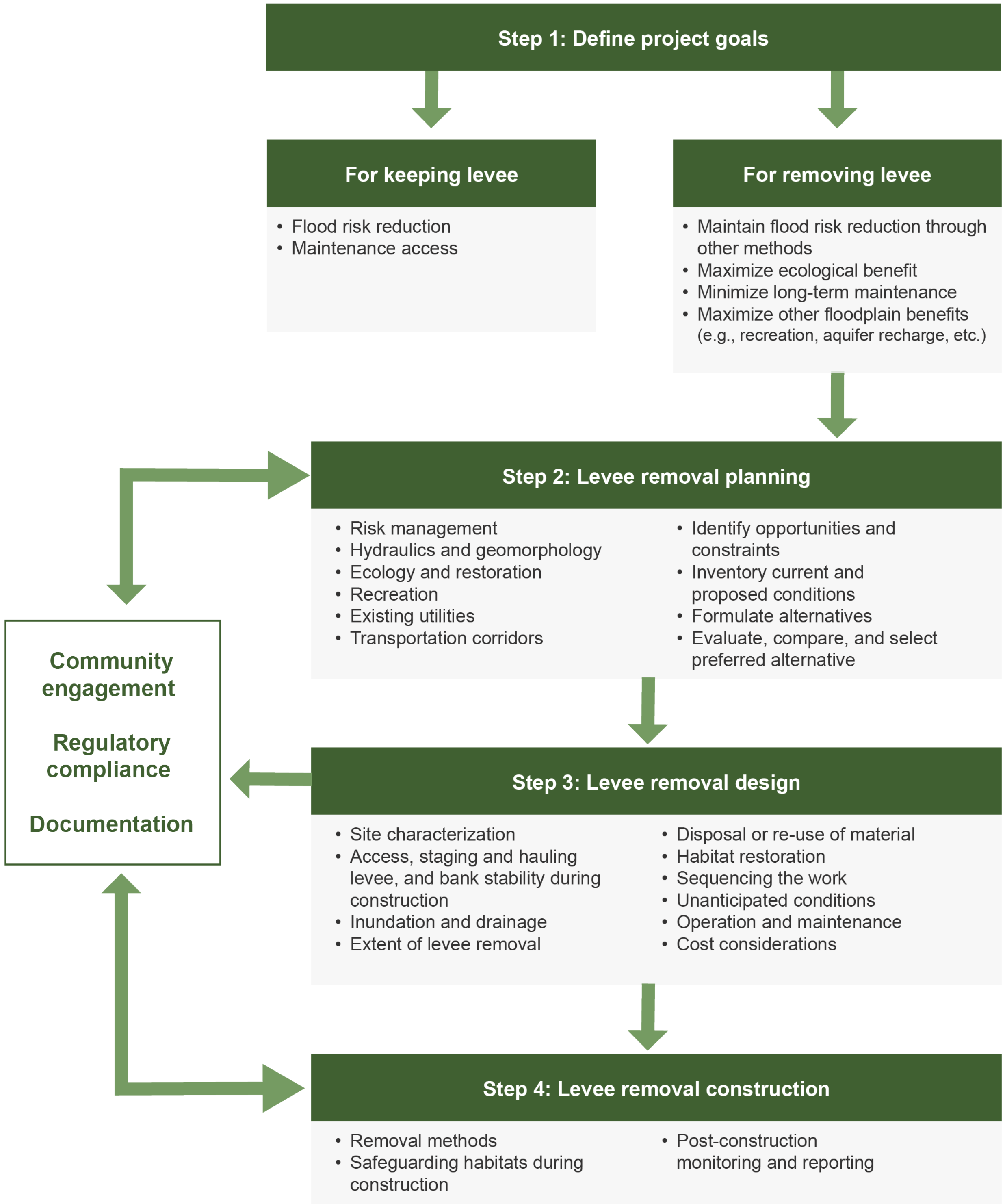
Management Agency (FEMA), state agencies, and local entities—may require documentation of the changed flood risk-reduction conditions. This may include removing the levee from the National Levee Database, updating flood insurance rate maps, or removing the levee, or portions of it, from public records.

3 Planning

A well thought out and comprehensive planning process will help with the transition to more efficient and streamlined design and construction phases. Although the steps and general process outlined in **Chapter 6** are the same for floodplain reconnection, project objectives, opportunities, and constraints may vary considerably from a new levee project to one that involves the removal or setback of an existing levee to initiate floodplain reconnection.

Reconnection of the floodplain involves sequential steps, as depicted in Figure 11-4 and described throughout the remainder of the chapter. During each step of the process, a number of individual tasks should be accomplished while engaging with the community, ensuring regulatory compliance, and documenting decisions.

Figure 11-4: Steps in the Levee Removal Process



3.1 Floodplain Reconnection Considerations

Due to the unique nature of levee removal or setback, there are a number of considerations that should be taken into account during the planning phase, as described in the following subsections.

3.1.1 Levee Removal Risk Management

Levee removal and subsequent risk management activities differ from new levee projects since levee removal involves the expansion of areas exposed to flooding and new levee projects result in the reduction of areas exposed to flooding. It is not advisable to implement a levee removal project that increases flood risk to human life and/or critical infrastructure. Therefore, it is a best practice to confirm there is no increase in flood risk at the beginning of the planning process. After this is confirmed, risk assessment and management activities can focus more on other non-flood related risks associated with design, construction, and post-construction. These may involve risks associated with meeting project objectives related to other features, such as stability during construction, erosion control, drainage, and habitat establishment.

Chapter 4 outlines relevant risk concepts and risk assessment best practices for levee projects, and describes how to estimate risk hazards, performance, and consequences. Multiple data sources, tools, and methods for determining flood consequence for both riverine and coastal environments are available for flood risk, which is most pertinent to levee removal. These tools and methods are the same ones that should be used during the planning phase to inventory existing and forecast future conditions for flooding (section 3.2.2).

MISSOURI RIVER LARGE-SCALE LEVEE SETBACK

Having suffered repeated flooding in past years, the Atchison County, Omaha Levee District #1 in consultation with the USACE Omaha District and the impacted landowners, determined that a levee setback—moving the levee inland which allows more room for floodwater conveyance—combined with a modern design, was in the best interest of their community now and for future generations.

The levee setback allowed for over 400 acres of new wetland and 1,040 acres of reconnected floodplain, providing significant benefits for macroinvertebrate production, native fish growth, increased groundwater recharge, and improved water quality.

https://www.nature.org/content/dam/tnc/nature/en/documents/L-536factsheet.pdf.

3.1.2 Setback Levee Alignment

For levee setback projects, determining the setback levee alignment will ultimately determine the extent of floodplain reconnection possible. In general, real estate or cost limitations will often limit the setback distance before the maximum ecological or flood risk reduction benefit is met. The objective should be to maximize the distance from the channel or water source to allow for natural sediment transport, increased conveyance during high water events, and the establishment of native vegetation along channel banks to minimize or prevent bank erosion.

Lands waterward of the setback should be used to encourage native vegetation growth to maximize ecological benefits.

The alignment determination is often a function of available landside property and associated topography. If the levee owner also owns the adjacent lands, then the extent of floodplain reconnection and associated natural resource benefit can be maximized. In this case, the setback levee would be aligned along the outer landside edge of the property. If the levee owner does not own the adjacent lands and community retreat is not a component of the project, then landowner engagement and property or right-of-way acquisition will drive the setback levee alignment location. The process of landowner engagement, land appraisal, and property acquisition can be very time intensive and should begin early in the planning process.

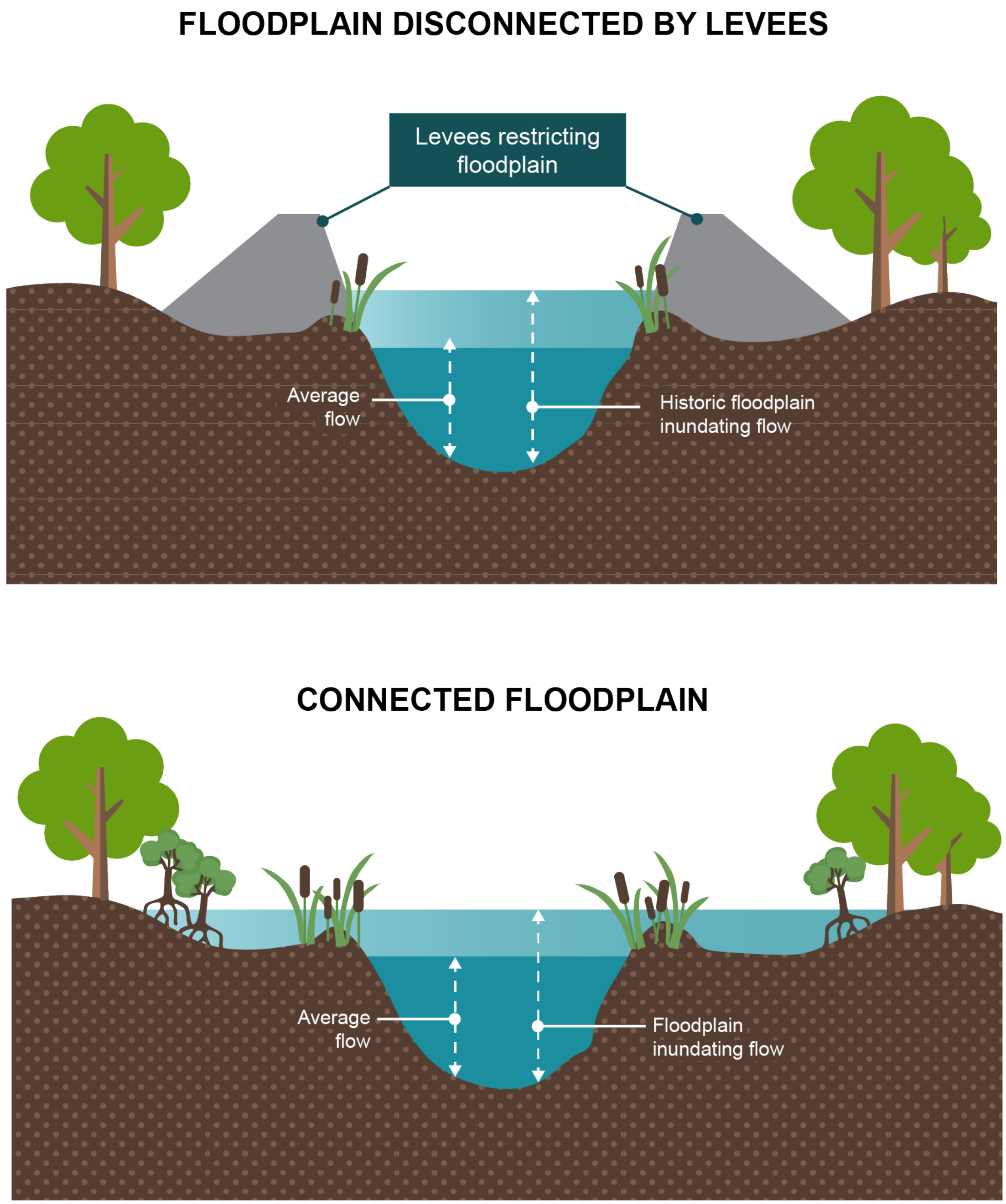
3.1.3 Hydraulics and Geomorphology

Floodplain reconnection may alter the hydrodynamics of the river or coastal area, which in turn may have an effect (positive or negative) on water surface elevations, velocities, erosion, scour, sediment transport and deposition, vegetation, habitat composition and quality, aquifer recharge, and surface drainage pathways (Figure 11-5). In addition, some effects may occur at a limited distance upstream or downstream (or upcoast and downcoast) from the actual project extents.

All of these potential effects should be evaluated during the planning phase, to determine whether the levee removal or setback will be consistent with the overall flood risk management strategy, project objectives, and river navigation, where applicable. Many of the hydrodynamic parameters (e.g., water surface elevation, velocity) listed above can be assessed using the same tools and methods discussed later in section 4.4 and presented in **Chapter 4** for determining flood consequence.

Potential impacts should be mitigated through design to the extent possible, and any unavoidable impacts associated with levee removal or setback should be discussed with regulators to confirm project feasibility from a regulatory approval perspective.

Figure 11-5: Floodplain Reconnection Cross Section



3.1.4 Ecology and Restoration

Levee removal and the resulting hydrodynamic changes may present opportunities for ecosystem restoration and associated ecological benefits. One example of this is when a levee is removed in a riverine system, allowing river flood flows to inundate adjacent areas with no increased flood risk to human life or critical infrastructure. Depending on the frequency of inundation, substantial ecological benefits can be achieved in the reestablishment of post-removal floodplain and wetland habitat. Although not all levee removal projects will have restoration opportunities, most will have some level of impact on existing vegetation and habitat within the levee removal footprint.

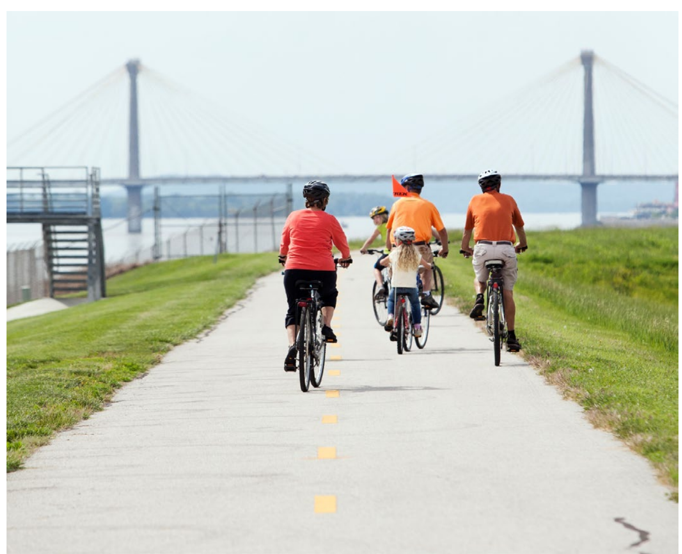
Potential effects of levee removal and associated ecological benefits and risks are summarized in Table 11-1.

Table 11-1: Levee Removal and Associated Ecological Effects

Potential Effects	Ecological Benefit	Ecological Risk
Decrease in velocity	Reduced scour and bank erosion, improved riverine fish passage and aquatic habitat, increased sediment bedload deposition.	Sedimentation of existing habitat.
Increase in overbank flows and inundation area	Increasing post-removal riparian, wetland, and other floodplain habitat.	Negative impacts of inundation on existing upland habitat and vegetation in overbank areas.
	Increased aquifer recharge in freshwater systems.	
Improve upland habitat and wildlife connection	Improved access and connectivity between upland habitat and the waterbody.	Increased wildlife and human interaction with negative consequences.
Disruption to existing drainage pathways	Development of new drainage pathways, designed to maximize ecological benefit.	Impacts on existing habitat along drainage pathways.

3.1.5 Recreation

Natural riverine and coastal areas are highly valued for public recreation because of the close proximity to water, native vegetation, and wildlife. Because levee removal involves the removal of human-made features resulting in the potential restoration of natural processes and habitats, there may be community interest in incorporating public recreation features into a levee removal or setback project. Typical recreation features may include trails, benches, kiosks, water access, interpretive signage, water fountains, parking, and restrooms. Another good example of a recreation feature that is compatible with a reconnected floodplain is athletic fields.



Trails along rivers and coastal areas provide opportunities for the public to experience nature and wildlife.

Many existing levees already include trails for public access. Refer to **Chapter 2** for details on basic levee form. In these cases, the trails may simply be lowered or realigned to incorporate any newly restored areas.

3.1.6 Existing Infrastructure

Municipal infrastructure may exist near levees and these features—such as bridges, roads, recreational trails, water or sanitary sewer mains, power distribution lines, telecommunication lines, and pump stations—need to function during and after a levee removal project. Refer to **Chapter 12** for details associated with community resilience. During the planning phase, existing infrastructure that might be affected by the project should be identified and solutions should be incorporated into the plan formulation process.

Existing utilities and other types of infrastructure may cross, be adjacent to, in-line with, or embedded within a levee. If this situation occurs at or near the location where a levee is being removed, the utility or other infrastructure type may be affected. For example, if a road or powerline is on the crest of a levee and the levee is removed, the road and powerline will need to be rerouted. Similarly, transportation (road), rail corridors, and underground pipeline crossings may need to be modified or relocated.

Design and record drawings, aerial photographs, and survey data may be used to identify utilities and other types of infrastructure that may be affected by the levee removal project. Field reconnaissance should be completed to document the location and size of utilities. Affected utilities within the removal footprint may require improvement, relocation, or abandonment to accommodate the levee removal. Coordination for accomplishing the design and construction related to these activities should be coordinated with the facility owners.

3.2 Plan Formulation

3.2.1 Identification of Problems, Opportunities, and Constraints

In order to achieve the overarching project goals, it is essential to identify and clearly understand the problems to be alleviated, possible opportunities to be realized, and constraints to be managed for the entire area affected by the project. This refers both to the specific geographic region where levee removal or setback is contemplated, in addition to any new regions where the possibility exists for inundation as a result of levee removal. The potential affected area should include the geographic scope necessary for analyzing the nature and extent of potential problems, opportunities, and constraints. Throughout this process, the potential affected area may be adjusted to accommodate new understandings of physical, biological, and economic relationships.

When considering removal of a levee and associated floodplain reconnection, the problem is likely related to the various project drivers, described in section 2.1.

Opportunities present themselves when a set of circumstances make it possible to address an existing problem or realize a benefit. Since floodplains support diverse habitats with direct benefits for both aquatic and terrestrial wildlife, one opportunity resulting from levee removal is the potential to create or enhance native habitats within the previous leveed area. Other potential opportunities include the identification of funding resources and incorporation of aquifer recharge, open space development, or recreational features and public spaces into the project. Community engagement may be helpful to uncover opportunities through the context of the local residents and stakeholders.

Constraints are obstacles to meeting the specified objectives. Constraints for levee removal or setback projects may include land acquisition, disturbance of protected environmental habitat or species, laws or regulations, risk transfer and risk transformation considerations, inadequate resources, and funding.

With the overarching goals being established at the onset of the project, it is a best practice to re-evaluate each goal after the problems, opportunities, and constraints have been clearly identified. Objectives that directly relate to the project goals should then be established, including specific actions and measurable steps to be taken to achieve the objective. An example associated with restoring a floodplain would be setting an objective to plant and establish specific native species that will naturally thrive under the proposed hydraulic condition to meet the goal of minimizing long-term maintenance. Measuring habitat and vegetation establishment and coverage post-construction against previously established thresholds that could trigger further action helps to ensure the objective is met.

SAN JOAQUIN RIVER RESTORATION PROGRAM

The San Joaquin River Restoration Program is a comprehensive long-term effort by the U.S. Bureau of Reclamation to restore flows to the San Joaquin River from Friant Dam to the confluence of Merced River and restore a self-sustaining Chinook salmon fishery in the river, while reducing or avoiding adverse water supply impacts from interim and restoration flows. A key aspect of the project involved the removal of existing levees and the construction of new setback levees to accommodate increased flows to reconnect the floodplain in certain reaches of the river.

River and levee photo of the San Joaquin River restoration.

3.2.2 Inventory Current and Forecast Future Conditions

Estimates of historic, existing, and future conditions are necessary to assess flood risk to the potential affected area. Considerations for inventorying these conditions should include:

- **Historic topography or aerial photography:** Historic topography may be available from original levee as-built drawings and historic aerial photography may be available from local geographic information system (GIS) databases.

- **Current and future topography:** This should include existing and any future anticipated changes to topography of the project area, such as inclusion of any planned infrastructure or transitions from developed areas to open space.
- **Geological and geotechnical characterization**: Geologic and geotechnical conditions should be included to understand key characteristics and data to be used in channel bank or coastal stability analyses, both during construction and post-construction. Geologic parameters and geotechnical stability analyses are important and similar to levee design and are discussed in more detail in **Chapter 7**.
- **Current and future morphology**: An understanding of existing and future morphology is needed to develop a comprehensive design for levee setback or removal. Existing morphology should be assessed and documented by a qualified geomorphologist based on field reconnaissance, survey, and an understanding of watershed sediment budget and transport. To attain the desired morphology with the goal of maximizing the overall system's functionality, projected hydraulics should be factored into the assessment. For rivers and creeks, the potential for lateral migration, as depicted in Figure 11-7, should also be considered using appropriate methods such as the Bank Erosion Hazard Index (Rosgen, 2001) or the U.S. Department of Agriculture's Bank Stability and Toe Erosion Model (Langendoen and Ursic, 2016).
- **Exposure (property, people, environment, cultural)**: Areas of planned or anticipated inundation should be assessed to identify sensitive biological areas, possible pollution or contamination, and the existence of cultural resources. Property or parcel data and habitable structure locations are often available through local GIS databases, but may also be identified through field surveying. Information and data pertaining to property ownership, habitable structures (people), environmental, and cultural resources are necessary to assess potential impacts and develop an approach for community and regulatory outreach.
- **Hydraulics**: Hydrologic and hydraulic analyses will be required to estimate channel water surface levels, velocities, and potential floodplains caused by the removal of a levee. Additional information about appropriate hydraulic analysis methods is presented in section 4.4.

WHY REMOVE A LEVEE?

Numerous drivers exist for why a levee may be considered for removal, such as the following:

- Ecological restoration.
- Floodplain storage during flood events.
- Managed community retreat.
- Groundwater recharge and/or flood-managed aquifer recharge.
- Existing levee deterioration.
- Existing levee rerouting or replacement (setback levee).
- Other flood risk mitigation features making the levee functionally obsolete.

Section 2.1 contains a more detailed discussion of potential drivers for floodplain reconnection:

Levee removal in USACE's New Orleans District.

- **Climate**: Climate change effects should be considered when forecasting future conditions. This may be done as a sensitivity analysis to give context to selected design parameters and components, or could be selected to drive the proposed design, depending on specific project objectives or regulatory requirements. Trends and potential impacts to consider for river systems include changes in total precipitation and precipitation frequency, increases in precipitation rates and duration, changes to snowpack, and changes to runoff timing, duration, and magnitude. For coastlines, relevant trends and impacts include increases to sea level, storm surge, wave height, and groundwater elevations.

Because the future is unknown, a level of uncertainty should be included with forecasted future conditions. Uncertainty should be characterized—quantitatively and/or qualitatively—for all levee removal projects. Key assumptions used in the projections should be stated explicitly. When uncertainty may affect investment decisions, multiple baselines may be used with a clear explanation of the basis and assumptions underlying each.

An analysis to inventory and define current and future conditions may be costly and time-intensive. The scale of an analysis should fit the study area and align with the resources and data available.

3.2.3 Formulate Alternatives

Consideration should be given to a broad spectrum of alternatives, ranging from no action to the most robust of alternatives. Alternatives should consider no action, nonstructural solutions, nature-based solutions, levee removal or setback, and structural solutions (where appropriate) that address specific project objectives. Nothing should be eliminated or screened at this step. If alternatives are eliminated too early, certain biases may be given to the remaining alternatives. This will be an iterative process, considering combinations of all feasible measures that address different objectives. Some alternatives may be better at addressing one objective versus another.

Alternatives should consider life safety, economic and environmental benefits or impacts, social equity, and underserved populations. For example, enhancements that advance environmental goals may include infrastructure that reduces greenhouse gases, limits sediment deposition, or enhances habitat.

STEIGERWALD RECONNECTION PROJECT

The Steigerwald Reconnection Project involved more than two miles of levee removal and created four direct connections between the Columbia River and adjacent U.S. Fish and Wildlife National Wildlife Refuge areas. The 2021 construction enhanced seasonal flooding and provided unfettered access to the refuge area for salmon and lamprey.

Construction crew breaching the old levee to reconnect the refuge to the Columbia River. https://www.estuarypartnership.org/our-work/habitat-restoration/steigerwald-reconnection-project.

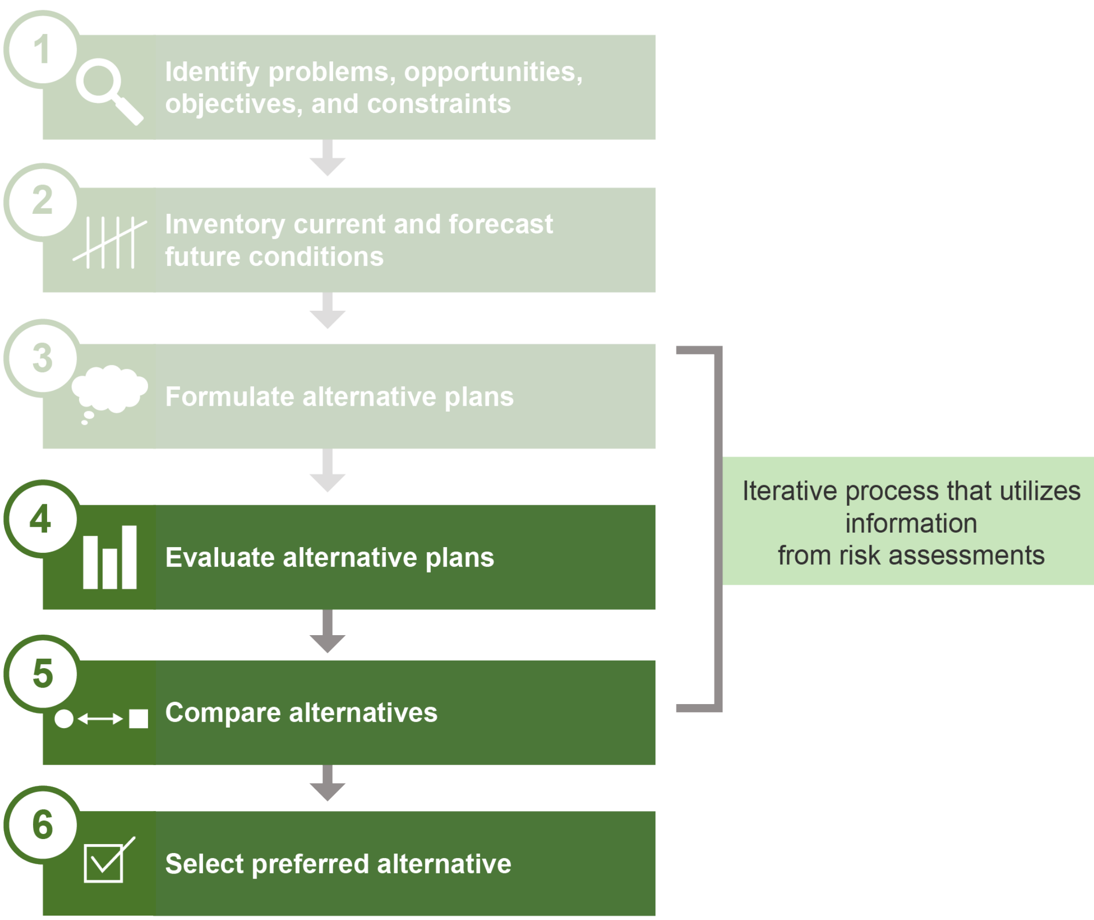
Considerations when formulating alternatives specific to levee removal should include the following:

- Determine the extent (vertical and horizontal) of levee removal required to meet project objectives.
- Identify disposal locations to place the excavated levee material.
- Identify potential ecological opportunities within the new inundation area.
- Identify drainage features to safely convey drainage from adjacent areas to a waterbody.
- Identify ecosystem restoration features, including seeding, planting, and irrigation (if needed to meet project objectives).
- Identify multi-benefit features.
- Minimize future maintenance requirements.

3.2.4 Evaluate, Compare, and Select Preferred Alternative

The final three steps in the plan formulation process (Figure 11-6), are identical to the steps taken for a new levee, described in **Chapter 6**.

Figure 11-6: Plan Formulation Process



4 Design

While some aspects of levee removal or setback design are similar to new levee design projects (site characterization, access, staging and hauling, bank stability), others are unique, such as determining the extent of levee removal to meet project goals, disposing all or re-using excavated material, and ecosystem restoration. Best practices outlined herein are intended to supplement information presented in **Chapter 7**, which focuses on investigations, technical analyses, and design of new levees, levee modifications, and levee rehabilitation. Although levee removal design is a unique subset of levee design, many of the design practices discussed in that chapter are also relevant to levee removal.

4.1 Site Characterization

The purpose of site characterization is to develop a comprehensive understanding of existing conditions on the ground, relevant subsurface conditions (e.g., geologic, hydrogeologic, utilities) and adjacent waterbody characteristics and hydraulics. This information and data will set a baseline condition for the project and will feed into the identification of opportunities and constraints.

When considering a levee removal project, it is important to understand the characteristics of the flood source, the levee, and the leveed area (Figure 11-7). Understanding the existing levee risk may support the refinement of project objectives and design solutions.

Figure 11-7: Lateral Migration of River Channel Observed During Site Reconnaissance

Lateral migration of river channel noticed during site reconnaissance in a Sacramento, California, levee area.

Existing data should be evaluated to characterize the site and additional investigations may be necessary to improve design confidence, reduce construction costs, and better understand flood and levee risk. This should be an iterative process and is most efficient when performed in phases. For instance, an initial limited geotechnical investigation during the planning phase would allow for some level of understanding of underlying geologic conditions to support alternatives development. Depending on the consistency and extent of information and data obtained—in addition to the results of preliminary stability analyses—it may be necessary to complete a more comprehensive geotechnical investigation during the design phase.

Characterization activities generally will include existing information gathering and review, interpretation, and data gap analysis. These activities will not be linear because existing information gathering and review will be a one-time process, while interpretation and investigation frequently will need to be performed in phases, sometimes correlated to the design phases (i.e., conceptual, feasibility, final).

4.1.1 Information Gathering from Available Data

Developing an understanding of the existing levee and conditions will be a necessary first step when beginning levee removal design. Information from three primary areas is necessary: (1) the existing levee that is to be removed, (2) the previous area behind the levee (leveed area), and (3) the river or coastal area that presents the flood risk. This information should be used to understand site opportunities and constraints, and to develop or refine project goals and objectives.

Information from the original levee design and as-built conditions will be important to understand pre-levee conditions, fill material, placement specifications, interior drainage, utilities, and intended performance. Typical documents to review include:

- Design drawings.
- Basis of design reports.
- Technical specifications.
- Construction testing results.
- Geotechnical investigation reports.
- Record drawings.

Existing site information and data on current topography, vegetation, habitat, and utility locations (i.e., water, gas, sanitary, power, telecommunications) will be critical to develop the project base map and understand baseline conditions. After the design approach and preferred extent of removal are determined, the base map and other baseline condition data will allow calculation of key quantities, such as the extent for clearing and grubbing, levee removal material volume, identification of potential impacts on existing natural resources, and determination of what type of ancillary structures may need to be removed or relocated.

In addition to the physical characteristics of the levee, existing information on the actual performance of the levee should be investigated. This may include information on historic flooding, recreational uses, and past or present issues with levee stability, erosion, and ancillary infrastructure.

Typical documents to review for performance information include:

- Inspection reports and photographs.
- Historical aerial photography.
- Existing topography data.
- Operations and maintenance (O&M) manuals.
- New site reconnaissance.
- New geotechnical investigation (if warranted).

Existing information on the former leveed area is needed to understand potential effects of expanded inundations, and to identify opportunities for ecosystem restoration. Understanding the historical land cover/use (including the potential for pollution/contamination of soil and/or groundwater), current land cover/use, and the changes that have occurred can guide the restoration approach, if an opportunity exists. Information and data on the geology, soils, climate, climate change predictions, and demographics will affect the approach to restoration after the levee has been removed. Depending on past land use, the previously leveed area to be inundated may contain soil or groundwater contamination, and a site assessment by a qualified professional may be needed. The potential for wider environmental damage by spreading harmful substances should also be taken into account.

Typical documents and data to review include:

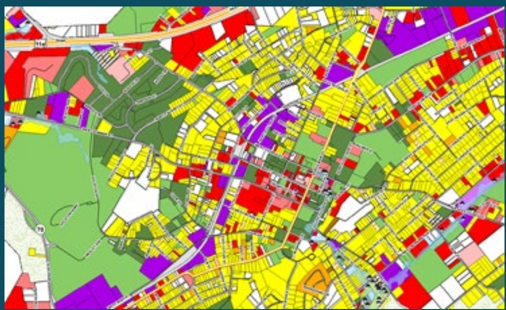
- Land cover/use databases or mapping.
- Photographs, environmental maps, and natural resource documents, such as wetland, agricultural, and fishery reports describing pre-levee conditions.
- Geotechnical, geologic, and morphologic maps and reports.
- Climate and climate change assessments.
- Management plans.

The purpose for removing a levee often is related to the hydrology and hydraulics of the area. Thus, understanding the hydrology of the leveed area and hydrology and hydraulics of the waterbody presenting the flood risk will be important to the removal design. An enhanced understanding of the hydrology and hydraulics

LAND USE VERSUS LAND COVER

Land use is the term used to describe the human use of land. It represents economic and cultural activities—mining, agricultural, residential, industrial, and recreational uses—that are practiced at a given place. Public and private lands frequently represent very different uses. For example, urban development seldom occurs on publicly owned lands (parks, wilderness areas), while privately owned lands are infrequently protected for wilderness uses.

Land cover is the term used to describe the surface components of land that are physically present and visible, provides a means to examine landscape patterns and characteristics, which are important in understanding the extent, availability, and condition of lands; ecological system extent, structure, and condition; and potential for dispersion and effects of chemicals and other pollutants in and on the environment.



Land Cover - U.S. Environmental Protection Agency.

is critical, so the flood risk is not increased, restoration of the former leveed area is consistent with the future hydraulics and impacts on the waterbody (river or coast) are considered and mitigated.

Existing information on these aspects of the site and waterbody can be found in:

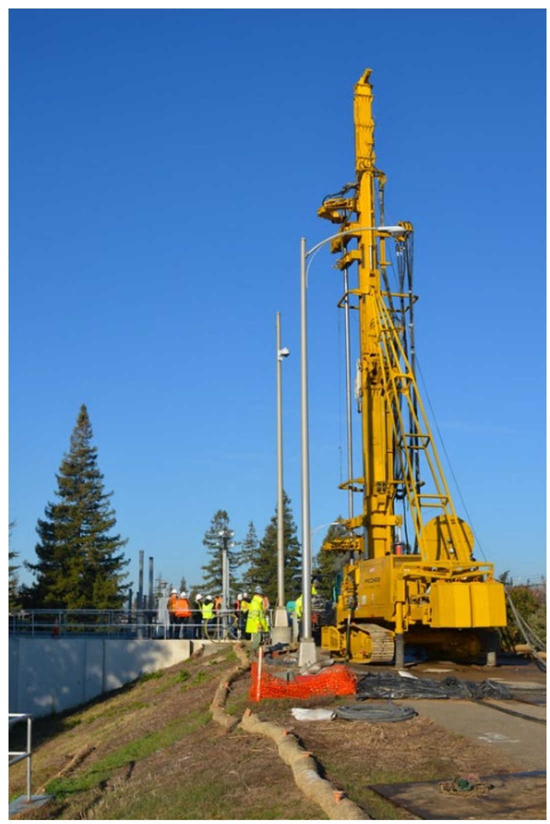
- FEMA flood zone maps.
- Hydrologic and hydraulic models and associated reports.
- Interior drainage maps.
- Storm drainage infrastructure maps or data.
- Land cover/use databases or mapping.

Reviewing the available information related to the levee, previous leveed area, and hydrology and hydraulics of the site will provide insight into how the area has been modified and is directly related to developing a successful levee removal project. For example, this information can define the quantity of material, physical properties of the material, the type and number of utility structures that will need to be removed and relocated, and potential disposal locations. The pre-levee land cover can be a useful guide when considering restoration alternatives. This information should be utilized when determining the preferred design alternative.

4.1.2 Additional Investigations

The data required to complete technical analyses and develop levee removal drawings and specifications is similar to that needed for a new levee and restoration design (**Chapters 6 and 7**). Investigations for levee removal projects can include many different aspects, but the most common are as follows:

- **Topographic survey and bathymetry**: See **Chapter 7** for further details.
- **Geologic and geotechnical investigations**: The extent of geologic and geotechnical investigations is likely to be less when removing levees compared to designing new levees because the information and data will be used primarily to confirm temporary stability during construction, as opposed to long-term levee stability for flood risk reduction. The project geologist and geotechnical engineer should be consulted to confirm investigation needs. See **Chapter 7** for further details.
- **Inspection and testing of existing levee features**: The extent of existing levee inspection and testing are likely to be less when removing



Geotechnical investigation may involve drilling borings to understanding underlying geology.

levees compared to designing new levees because the information and data will be used primarily to confirm temporary stability during construction, as opposed to long-term levee stability for flood risk reduction. The project geologist and geotechnical engineer should be consulted to confirm investigation needs. See **Chapters 7 and 9** for further details.

- **Hazardous materials surveys**: See **Chapter 7** for further details.
- **Utility surveys**: See **Chapter 7** for further details.
- **Hydrologic and hydraulic data collection, water level gage, and tide gage data**: Depending on the extent of previous studies and available information to inform model calibration and verification, some amount of gage installation and data collection will be helpful to support model development. Stream and river data are available through the U.S. Geologic Survey surface water data online repository and stream stats online tool (USGS, 2023). Tidal data is available through the National Oceanic and Atmospheric Administration tides and currents online database (NOAA, 2023).
- **Geomorphic reconnaissance and mapping**: If modeling indicates potential changes to river or coastal hydraulics, geomorphic reconnaissance, assessment, and mapping may be required to assess existing planforms and determine potential impacts. The project geomorphologist should be consulted to confirm investigation and assessment needs.
- **Environmental baseline conditions surveys**: Surveys to identify and document wetlands, vegetation, habitat, and threatened and endangered species should be completed during the planning phase. This information will be used to support restoration design if such an opportunity exists, and to assess impacts on existing natural resources related to project construction activities.
- **Access and haul routes**: Reconnaissance and assessment of access and haul routes should be completed during the planning phase to determine whether existing conditions will support construction access and material transport.
- **Sources of construction material**: The amount of construction materials brought to a levee removal project site are likely to be a function of restoration and recreation opportunities, which may require seeds, plants, irrigation materials, plant protection materials, large wood for habitat features, and trail gravel. See **Chapter 8** for more details.

4.2 Access, Staging, and Hauling

Construction access, material and equipment staging, and hauling are important aspects of any construction project, but particularly so for levee removal projects. This is primarily due to limited access on the waterside of the existing levee (unless by barge), and restricted access along the landside of the levee due to ecological protection and/or property ownership restrictions. Although some existing levees include maintenance roads on the levee crown, that will not always will be the case.

For the same reasons stated above, space and access may be limited to establish material and equipment staging areas. Thus, a thoughtful approach to access and staging should be completed early in the design phase to confirm whether there are existing feasible access routes, or conversely, if construction access requires additional planning and design efforts.

For hauling excavated levee material off site (in the event on-site disposal is not feasible or preferred), condition issues and/or weight and stability restrictions associated with existing roads and bridges may occur. In such cases, coordination with the road owner (e.g., county, state) may be necessary to determine the requirements, criteria, and regulatory approval associated with temporary or permanent improvements.

4.3 Levee and Bank Stability During Construction

Slope stability of the remaining levee embankment, after a partial removal, during interim conditions, or at the final configuration (if any portion of the levee will remain) should be analyzed to ensure safety during construction. This analysis should verify that the interim and final conditions are stable. In some cases, the existing levee may be on the edge of an existing channel or other slope, which should also be inspected and analyzed for undercutting and stability during construction.

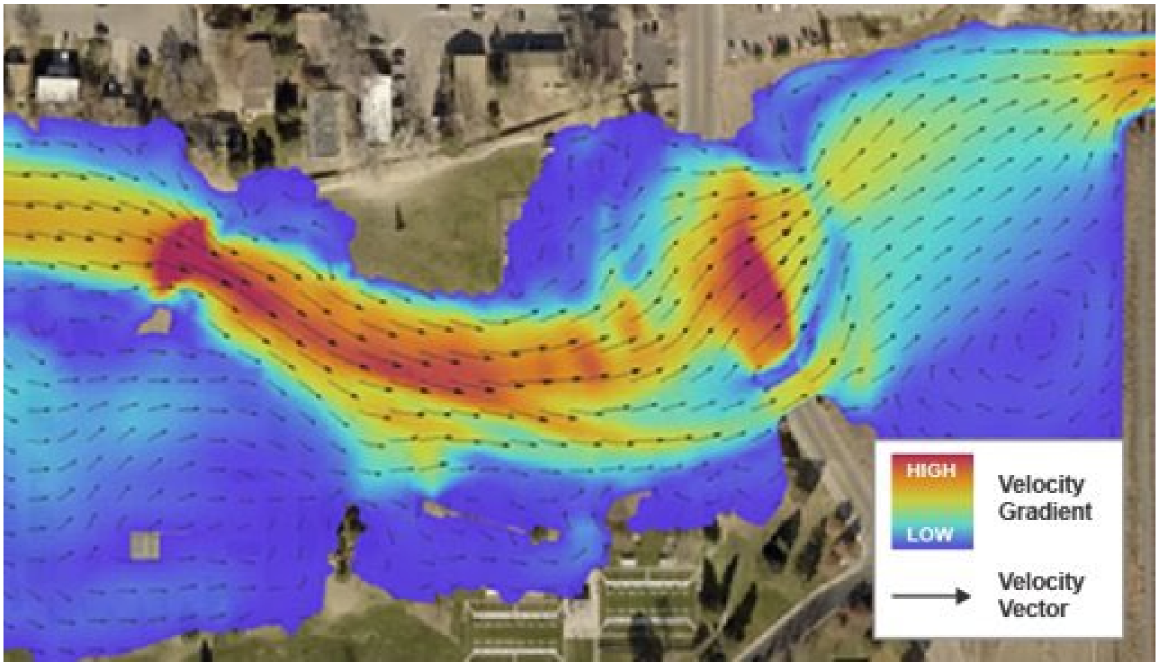
The level of analysis will depend on the size of the levee and structures, consequence of failure, and sequencing of construction. This analysis should be completed by a licensed geotechnical engineer and may be accomplished by the design team or the contractor who develops the means, methods, and sequencing of construction. The purpose of the analysis will be to evaluate the stability of the structure during and after removal.

Chapter 7 presents the design analysis for new, rehabilitated, or modified levees. These same considerations should be completed for a levee removal project, with the ultimate goal being whatever portion of the levee remains should be consistent with good levee design practices.

4.4 Post-Removal Inundation and Drainage

An understanding of post-levee removal inundation (e.g., magnitude, duration, and frequency), hydraulics (e.g., velocity, shear stress), and internal drainage will be necessary to effectively design erosion protection (as needed), ecosystem restoration, and for river systems with fish communities to prevent stranding fish while flood waters recede from floodplain areas. One- or two-dimensional hydraulic modeling should be completed for a range of storm return frequencies to build an appropriate understanding of post-removal hydraulics. Figure 11-8 shows two-dimensional modeling results, providing insight into inundation extents, depths, and velocities of newly inundated areas post-removal.

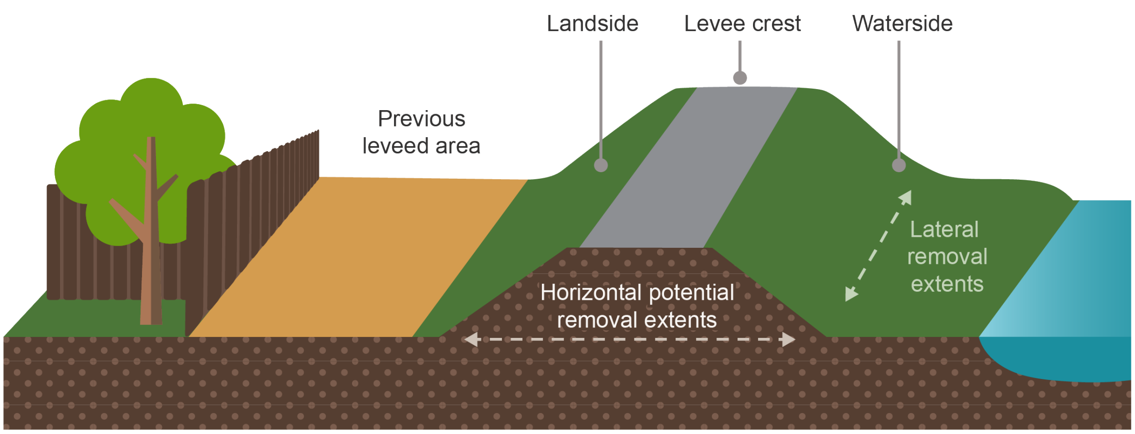
Figure 11-8: Two-Dimensional Modeling Results



4.5 Extent of Levee Removal

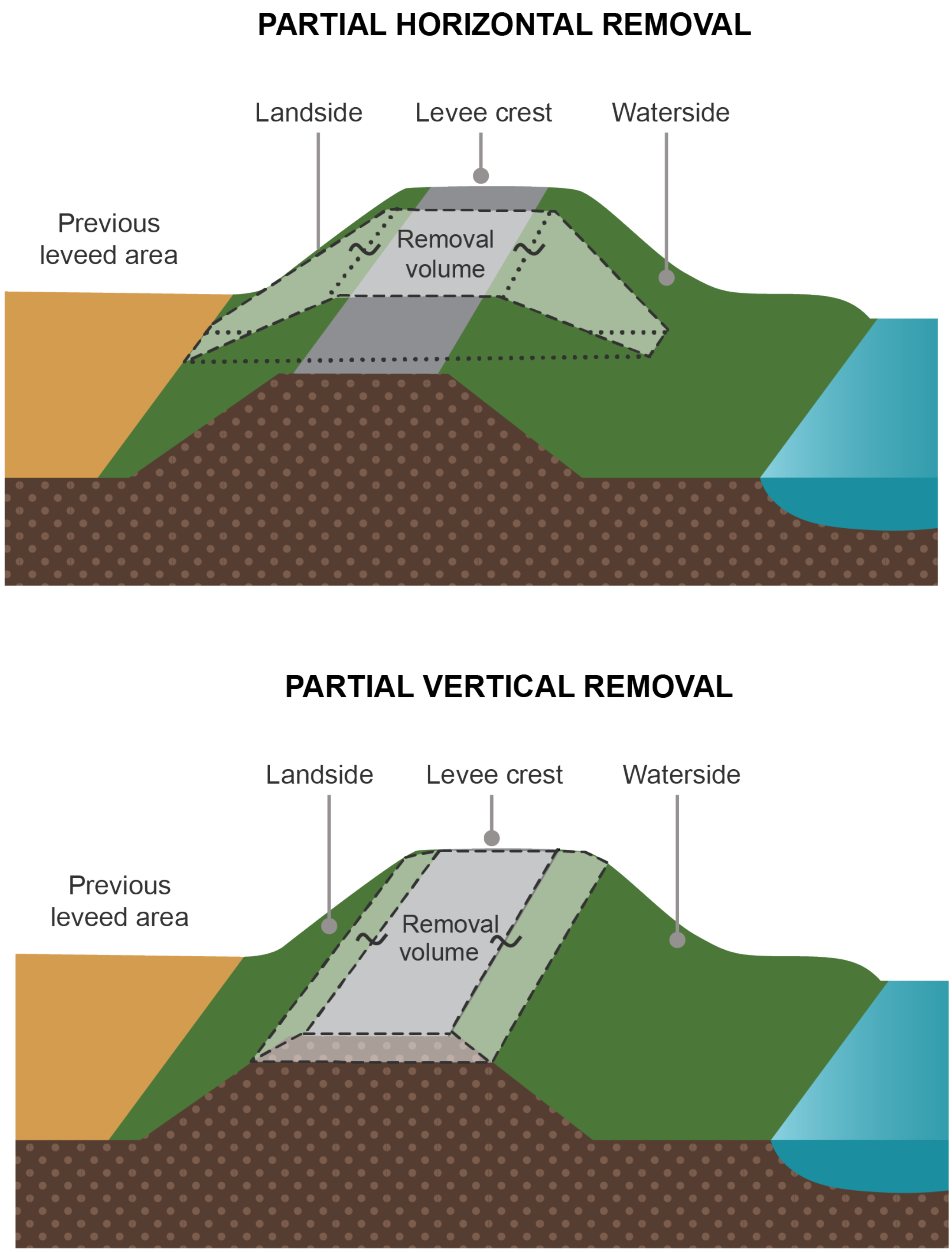
The extent of existing levee and erosion protection materials should be considered early in the design process. Hydraulic modeling can help determine whether or not full levee removal will be needed to achieve acceptable floodplain connectivity. Reconnection of the floodplain requires full removal of a section of levee to allow water to flow into the leveed area. Both the vertical depth and the lateral length of the section to be removed will depend on the project goals and the unique characteristics of each site (Figure 11-9).Because levee material excavation, hauling, and disposal can constitute a substantial portion of the levee removal project cost, leaving portions of the existing levee in place can reduce cost and aid native species recruitment while vegetation is reestablished post-removal. Figure 11-10 shows options for partial vertical and horizontal levee removal.

Figure 11-9: Potential Removal Extent of Levee



Some levees have existing erosion protection on the waterside of the levee to prevent erosion that can affect levee stability. This type of hardened feature can affect the natural processes of the waterbody, particularly river systems, as interruption of lateral migration may have impacts upstream and downstream. Careful consideration should be given to removal of these hardened features to understand the potential benefits and impacts.

Figure 11-10: Partial Levee Removal



4.6 Disposal or Re-use of Levee Material

After the volume of material to be removed is known, an assessment of potential on-site disposal options should be completed, and if none exist, off-site disposal locations should be identified and confirmed. For setback levee projects, the removed levee material could potentially be used to construct all or a portion of the new setback levee. However, the timing of re-use in this case may be inconsistent with the principle of no increase to flood risk above pre-construction levels, which would necessitate that the setback levees be in place prior to removing the existing levee.

Material hauling and disposal can be one of the more expensive activities of any construction project, and thus a thorough examination of disposal options will be important to provide a cost-effective solution. In addition, material hauling has the potential to affect local traffic, road conditions, and greenhouse gas emissions.

Re-use of excavated levee materials may be beneficial from a cost and environmental standpoint. Therefore, quantification and characterization of materials intended for re-use should be decided early in the design phase. Potential re-use options may include new levees, new dams, levee raises, on-site upland fill, and fill needed from off-site locations. If the material will be kept on site and integrated into the restoration process, care should be taken to blend the material into the existing topography. Material that cannot be re-used must be disposed of at an approved off-site facility, such as a landfill.

Because levee removal projects may generate large quantities of material, a wide variety of circumstances or conditions of the material should be taken into consideration. The following list of best practices is common to all projects that generate large quantities of material for re-use or disposal:

- Disposal requirements should be set in accordance with local ordinances. This process should be coordinated with the contractor, who may use the materials at another project or site, if the materials do not pose environmental hazards.
- Site surveys and testing may be necessary for identification of potential hazardous materials. Materials determined to be hazardous will require special handling and disposal at approved facilities.
- Suitable disposal sites should be identified in the specifications or may be located by the contractor within a reasonable haul distance for all waste materials.
- Some disposal sites may necessitate special separation of materials before disposal, such as removal of reinforcing steel from concrete, separation of combustible and non-combustible materials, separation of topsoil/organics from mineral soil and removal, treatment, and disposal of water.

Re-use or permanent placement on site can reduce overall project costs considerably. Thus, sufficient time should be dedicated during the planning phase to develop a well-defined plan for material disposal.

4.7 Ecosystem Restoration

Restoration aims to recreate an ecosystem that has been destroyed or to initiate/accelerate the recovery of an ecosystem that has been disturbed. Removal or repositioning of large flood risk reduction structures, such as levees, berms, tidal barriers, or floodwalls, presents an opportunity for ecological restoration within the footprint of the structure and potentially within land areas adjacent to the structure. Refer to Table 11-2 and **Chapter 6** for detailed information related to vegetation management best practices for setback levees.

Levee removal or setback provides a unique opportunity to meaningfully restore ecological functions and values at the interface between land and water. Design drawings to restore the former leveed area and newly connected floodplain or other ecological features should be part of the overall design package.

These drawings will establish habitat zones based on topography and inundation frequency, native plant species and seed mixes, plant locations and details, habitat feature location and details (e.g., large wood, boulder erosion protection), and irrigation system location and details. For example, certain habitat zones or features may require fine or detailed grading to ensure successful, long-term survival of plant species. The entity with overall authority for the project should ensure personnel charged with plant selection and habitat creation—and those charged with geotechnical considerations—are coordinating appropriately during the design process. Refer to **Chapter 6** for detailed information related to vegetation management best practices for setback levees.

Table 11-2: Restoration Considerations in Different Environments

Waterbody	Surrounding Land Use/ Wave Action	Ecosystem Restoration Considerations
River/ canal	Rural	Greater potential opportunity for overbank area habitat creation incorporating various cover types (e.g., wooded, scrub shrub, herbaceous, and open waters) and also creating unique habitats (e.g., vernal pools, backwater sloughs).
	Urban	The available area from the water edge to urban development, may not be sufficient to support a full, diverse habitat development, but placing select plantings (e.g., species for pollinators, trees for bats or migrating birds) can still provide some level of benefit to ecological resources. Stormwater inputs and needs from the surrounding area should also be considered.
Estuary/ bay/harbor	Rural	Greater opportunity for leveed area habitat creation, depending on potential lateral extent of tidal reach, palustrine, and estuarine environments.
	Urban	If existing vegetated habitat (e.g., emergent wetland, mangrove) is waterside of the levee, consideration should be given for increasing the habitat into or past the levee footprint, including planting complementary shoreline supratidal/shoreline vegetation. However, implementing ecosystem restoration measures are secondary to ensuring that the levee continues to provide the intended risk reduction benefits.

Waterbody	Surrounding Land Use/ Wave Action	Ecosystem Restoration Considerations
Marine shoreline	Calm wave energy	Shoreline or intertidal vegetated habitats may be an option, considering future sea-level rise and future inundation.
	Wave-driven energy	In turbid environments, leaving a portion of the seawall as a reef structure should be evaluated. Placing reef structures or hard bottomed or coarse-grained habitats are other options.

4.7.1 Overview of Restoration Approach and Goals

Restoration planning should conform to a set of general restoration design principles. The proposed restoration should strive to accommodate the regional context, as well as nearby land uses. The restoration design should maximize ecological uplift, yet minimize the number of artificial structures and amount of off-site fill materials needed to create the restored habitat. The goals and objectives are summarized as follows:

- Planning on a regional scale:
  - **Applying landscape ecology theories**. The design should consider and reflect analyzing structure, function, and changes in a landscape.
  - **Integrating watershed hydrology**. The design should consider not only the local project area but also potential effects on hydrology upstream and downstream from the project area.
  - **Accommodating land use and development**. The restoration plan should consider existing and future land uses to ensure the long-term success of the restoration.
- Establishing a self-sustained ecosystem:
  - **Allowing self-design**. Design of the habitat should encourage the self-organizing ability of an ecosystem, in which natural processes allow species succession and functional development of an ecosystem.
  - **Minimizing engineering techniques**. The long-term success of a designed ecosystem should not be heavily dependent on engineering. In essence, engineering inputs should be the minimum amount necessary to stabilize the restored environment to allow natural development of the ecosystem.
  - **Performing temporal planning**. An ecosystem, depending on its vegetative coverage selection, can vary in time to maximize its ecological uplift. For instance, a forested wetland will take longer to develop than an herbaceous habitat. The design, monitoring, and management should reflect the temporal needs of a planned ecosystem.
- Incorporating natural and nature-based features:
  - **Using a systems approach**. Leverage existing components and projects and their interconnectivity. Systems thinking means considering physical, biological, and social processes, and their interactions, in evaluating flood risk problems and solutions, and

identifying ways to reduce conflict and maximize synergies to produce sustainable solutions.

  - **Striving for multiple benefits**. Identify sustainable and resilient solutions that produce multiple benefits.
  - **Incorporating risk management**. Anticipate, evaluate, and manage risk in project or system performance.
- Designing for cultural and natural sustainability:
  - **Considering cultural and natural sustainability**. Designer collaboration with government entities and local communities is highly recommended to seek their input. **Chapter 3** outlines various phases of community engagement throughout the life of a levee and summarizes engagement best practices.

4.7.2 Geographic Considerations, Available Space, and Surrounding Land Cover/Use Considerations

Ecosystem restoration is not a one-size-fits-all application. For a potential restoration project, geography, available space, and surrounding land use are important considerations that should be reflected in the design. For instance, a levee in an urban environment may provide limited opportunities for ecosystem restoration, compared to a levee in a more rural setting with considerable open space. Conversely, setting back a levee in an urban environment can present an opportunity to alleviate stormwater drainage issues. The restoration area can provide temporary storage in an urban environment in which stormwater systems currently are undersized because of development and/or changes in rainfall patterns.

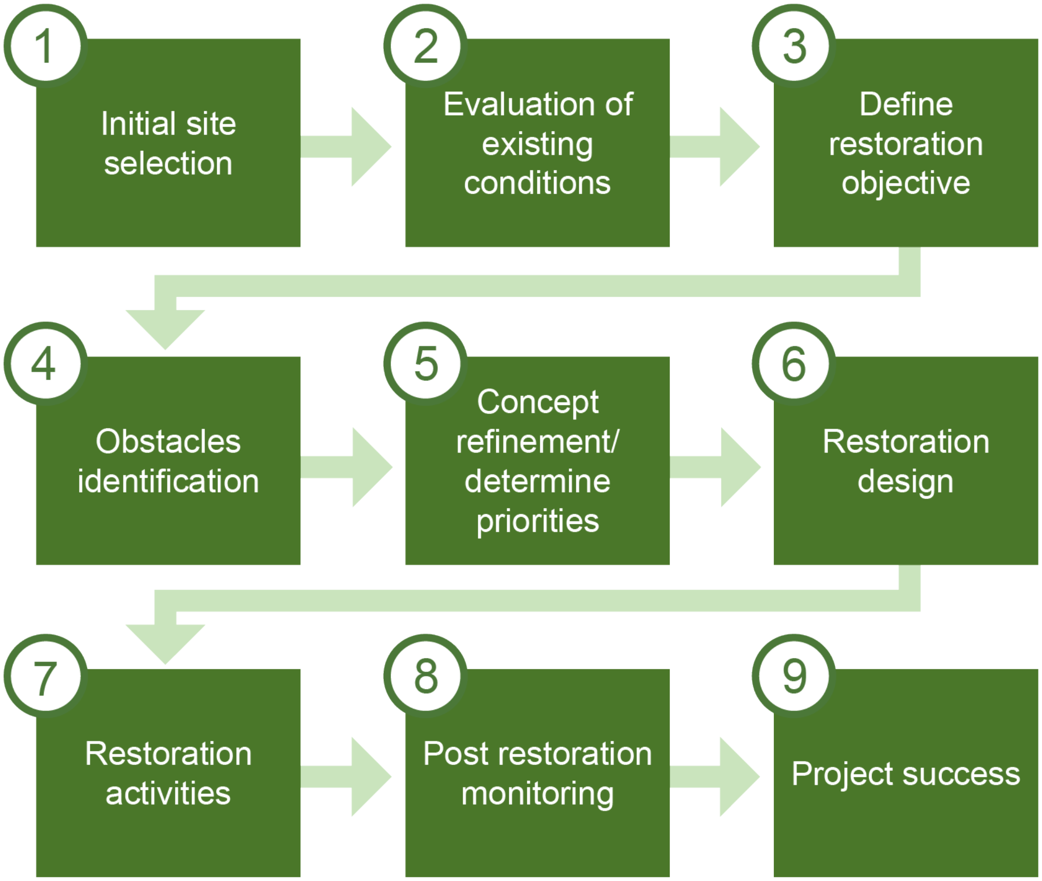
Tidal barriers and floodwalls in estuaries and along coast lines also need to account for space and land use developments, tidal action, and wave activity, the latter of which can vary dramatically, depending on geographic conditions. For example, the surf action on the Atlantic and Gulf coasts of the U.S. varies dramatically compared to locations in Alaska, where tide ranges can be greater than 20 feet. Also, islands such as Hawaii, the Aleutians, Florida Keys, and U.S. territories like the American Samoa are situated in vastly different climatological and oceanographic settings, likely to result in differing restoration approaches and considerations.

4.7.3 Restoration Design

While specific guidance on ecosystem restoration design is outside the purview and goals of the National Levee Safety Guidelines, it is important when reconnecting a floodplain to an active waterbody to follow appropriate industry and regulatory agency standards for restoration design. Input and guidance from key federal agencies—including the U.S. Fish and Wildlife Service and the National Oceanic and Atmospheric Administration’s National Marine Fisheries Service—should be sought. In addition, state fish and wildlife agencies, as well as some local agencies, often have specific guidance or protocols for ecosystem restoration design that should be followed.

The removal or setback of levees and subsequent selection and implementation of successful ecosystem restoration measures is a multi-step process, as shown in Figure 11-11 and defined in more detail below.

Figure 11-11: Steps to Successful Restoration



1. Initial site selection. Initial site selection involves identifying an opportunity to remove or setback a levee and determining the extent to which removal/setback will occur (section 4.5). It is important to help ensure levee removal or setback does not increase flood risk to life or property during the identification process. In addition, areas outside the levee removal extents should be considered for ecosystem restoration, as a function of the post-removal hydraulic conditions adjacent and inland of the former leveed area.

2. Evaluation of existing conditions. As with any restoration project, an evaluation of existing conditions should occur. An understanding of existing soil chemistry and organic content, invasive species, inundation frequency and duration, hydrodynamics, geomorphology, site constraints, and reference site conditions are useful information to inform restoration of native habitats at a levee removal site. The scope and level of effort of the evaluation will vary from site to site, but at a minimum should include the following to inform ecosystem restoration. Many of these overlap with data gathering and investigations summarized in section 4.1, or hydraulic analyses described in section 4.4:

- Hydrological analysis (frequency and duration of flood/inundation events) for both existing and post-removal conditions.
- Existing geology and soil characteristics.
- Habitats on and adjacent to the site.

- Identification of a reference site to aid in determining success criteria.
- Existing infrastructure (e.g., stormwater systems on the landside or through the levee, groundwater dams, utilities) and surrounding land uses.
- Historical use associated with cultural resources.
- Contamination.
- Identification and coordination of upstream and downstream actions and activities that may affect or be affected by the proposed restoration.

3. Define restoration objectives. A clear understanding of existing conditions and site characteristics will allow practical development of achievable restoration goals and objectives. Objectives may focus on acreage of certain habitat types or features, vegetation coverage, invasive species control, erosion protection, and minimization of long-term maintenance requirements.

4. Identify obstacles. Obstacles to restoration should also be identified at this stage. Potential obstacles may include infrastructure to remain, engineered stability requirements, soil characteristics or chemistry, non-native and invasive vegetation, or funding constraints.

5. Concept refinement/determine priorities. After the existing conditions assessment is completed, concept refinement will commence and should be closely coordinated with the proposed hydraulics at the site. Frequency of inundation, elevation, and seasonal shading will determine which habitats can thrive where, and whether earthwork is needed to meet project objectives. Other key considerations include an evaluation of potential seed banks, likelihood of introducing invasive species, and an understanding of surrounding land uses. Moreover, and perhaps most importantly, the restoration should not result in a net increase in flood elevations or velocities in areas where critical infrastructure or habitable structures are located. After a conceptual restoration plan is developed, a functional assessment of the proposed actions should be conducted to validate the concept.

After feasible solutions are identified, a clearer picture will be possible of where and ultimately what type of restoration can be implemented. At this point, priorities may be identified based on ecological needs, funding limitations, and regulatory constraints, and a preferred site plan should be selected to achieve project goals.

6. Restoration design. After a preferred concept is selected and types and sizes of habitats are identified, the design of each habitat can begin in detail. Design details will include size, number, and spacing of plants, plant species and seed mix selection, large-scale earthmoving and microtopography (ground scoops to simulate tree falls), irrigation (if needed), and planting elevations.

- Regarding the establishment of surface elevations, bio-benchmarking, which is a method to validate the anticipated survivability of a plant species, is a key activity to identify planting elevations, especially in intertidal settings.
- Also, important to plantings is the identification of known invasive pests (e.g., emerald ash borer), and species selection should consider the likelihood of infestation. If infestation is likely, the selection of other non-host species should be considered.

- The design and plan should include a detailed approach to control of non-native and invasive species (e.g., tamarisk/salt cedar, kudzu). This should consider best practices before, during, and post-construction.
- Once the quantity and type of plant and seed species are known, a collection and procurement plan should be developed to safeguard that the required plants and seeds will be available for construction. Refer to **Chapter 6** for detailed information related to vegetation management best practices for setback levees.
- After the design work is completed, this should be reviewed by knowledgeable personnel (e.g., engineers, ecologists).

7. Restoration activities. Restoration activities should be carried out in accordance with the drawings and specifications developed in the design phase. The seed and plant species required for a successful restoration should be sourced from the nearby sites or the same watershed to ensure compatibility. These species may not be available at local nurseries and may require seed and plant collection and propagation prior to construction. This can be a lengthy process so it should be contemplated and initiated prior to bidding the restoration project.

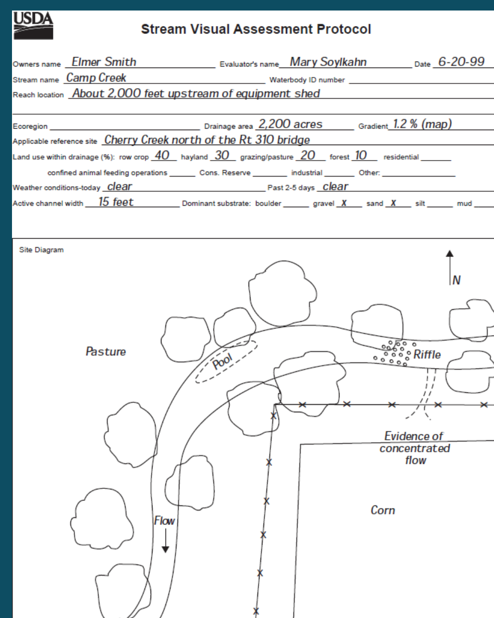
Maintenance of the restored area during the plant establishment period may include ongoing and routine activities, such as temporary irrigation, invasive species control, and/or periodic functional evaluations of the project that assess whether project goals are being met. These functional evaluations will vary based on the project goals, but may include vegetation assessments, habitat assessments, and species monitoring.

Restoration activities should be conducted by experienced and knowledgeable personnel who have demonstrated knowledge, skills, and the ability to perform restoration activities and conduct the requisite oversight. The best designs will be of little use if they are not implemented properly in the field. Since ecosystem restoration involves a unique skillset that is different from typical general contractors, it may be appropriate to prequalify restoration contractors or subcontractors based on an adequate amount of experience on similar projects.

8. Post-restoration monitoring. Restoration should include construction and post-construction monitoring activities, metrics, and triggers for adaptive management actions to measure and maintain project success. Also, before implementing the restoration, the principal parties who will be responsible for conducting the restoration and, if necessary, reporting monitoring studies and metric success to the regulatory agencies, should be clearly established.

EXAMPLE FOR FUNCTION ASSESSMENTS OF HABITAT

Programs such as USACE's Evaluation of Planned Wetlands (Bartoldus, Garbisch and Kraus, 1994) or the U.S. Department of Agriculture Natural Resources Conservation Service's Stream Visual Assessment Protocol (USDA and NRCS, 2009) can be used or modified to conduct an initial analysis of the restoration area and adjacent habitats.


USDA
Stream Visual Assessment Protocol

Owners name Elmer Smith Evaluator's name Mary Soylkahn Date 6-20-99
Stream name Camp Creek Waterbody ID number ____
Reach location About 2,000 feet upstream of equipment shed

Ecoregion ____ Drainage area 2,200 acres Gradient 1.2 % (map)
Applicable reference site Cherry Creek north of the Rt 310 bridge
Land use within drainage (%): row crop 40 hayland 30 grazing/pasture 20 forest 10 residential ____
confined animal feeding operations ____ Cons. Reserve ____ industrial ____ Other: ____
Weather conditions-today clear Past 2-5 days clear
Active channel width 15 feet Dominant substrate: boulder ____ gravel X sand X silt ____ mud ____

Site Diagram

After restoration is completed, the restored location should be monitored. Monitoring should include plant survival, abundance, diversity, distribution of species, soil stabilization and erosion, site responses to flooding, and establishment of invasive species. In addition to the monitoring, certain metrics should be established to take measurements and further ensure success. The metrics can vary from project to project, depending on activity; however, often for projects that require federal and state permitting for plant survival, a mortality rate of less than 15% is required. If the mortality increases above 15%, replanting usually is the required solution.

9. Measure project success. Restoration projects should employ an adaptive management program, (Williams, 2011), to increase the likelihood of achieving desired project outcomes based on the identified uncertainties. Adaptive management, within the context of floodplain restoration, is a multi-step iterative process to manage natural resources in the face of uncertainty. It provides an organized, coherent, and documented process for promoting learning that improves decision making years after the removal has taken place.

FISHER SLOUGH ESTUARY RESTORATION AND LEVEE SETBACK PROJECT

The Fisher Slough Estuary Restoration Project is a nature conservancy tidal marsh restoration project in Skagit County, Washington, that reconnected natural freshwater tidal hydrology to approximately 56 acres of leveed floodplain. Fisher Slough and the surrounding farmland had been highly modified from historic conditions as a result of channelization, levee construction for flood risk reduction, drainage, and agricultural development of the Skagit River delta for the past 150 years. In 2009, fish-friendly floodgates were installed, providing improved fish passage and tidal exchange. In 2010 and 2011, the levee was set back and the emergency spillway improved to provide an additional 300 acre-feet of flood storage and restored estuary.

The project excavated channels and restored historic freshwater tidal marsh vegetation communities, providing rearing habitat for juvenile Endangered Species Act-listed Chinook salmon. It also removed fish passage barriers and improved fish passage to miles of tributary spawning areas, increased watershed connectivity for coho, chum, and other native fish species, and improved flood and sediment storage conditions for the tributary levee system (*Model Restoration Project is Working for Salmon and for Farmers*, 2017).

Within the context of restoration, adaptive management includes:

- Implementing corrective actions, when necessary, to projects that are not trending toward established performance criteria.
- Making adjustments over time to projects that require recurrent or ongoing decision making.
- Informing the selection, design, and implementation of restoration projects.

Affected areas of concern include increased shoaling or erosion in rivers and channels that may increase flooding and impact floodplain management, wildlife, the community, and/or river navigation.

People with specialized degrees, specialized training, and demonstrated experience may be needed to perform monitoring and adaptive management activities. The specifics will depend on the type of restoration, requirements of the geographic area and locality, and permit conditions. Examples include:

- Degrees in academic disciplines relevant to the restoration, such as botany, landscape architecture, ecology, geomorphology, soil science, forestry science, environmental science, and/or environmental engineering.
- Special training in invasive species monitoring and control and evaluating the functional ecological performance of habitat—possibly including plant identification provided by an arborist, professional wetland scientist, soil scientist, or person with advanced stream restoration training.
- Demonstrated experience in projects pertaining to botanical investigations, restoration ecology, stream restoration, geomorphology, and other disciplines providing the requisite experience.

4.7.4 Climate Change Considerations

Often, restoration activities are considered to have an initial lifecycle of a number of years before a natural succession of ecological communities exists. For instance, herbaceous habitats become vegetated with volunteers of woody species, and the habitat ultimately transitions into a forest. However, with the climate changes predicted to occur in the next 50 years, these transitions may not be as predictable as they have been in the past. Previously predictable temperatures, storm activity, and sea levels are being replaced with new normal conditions to which restoration projects will have to adapt.

For example, with temperatures warming across the U.S., ecologists have seen species' home ranges moving northward (Pastorok *et al.*, 1997). Plant selection should reflect the predicted temperature changes, and species that will survive should be selected. Also, based on changes in storm intensity, rainfall, and sea-level rise anticipated to occur in the next 50 years, restoration efforts should consider changes in the local area from climate change, developing a restoration process to work with changing climate and water levels to the greatest extent practicable.

Many of the environmental regulations that govern restoration activities were authored decades ago. Based on the anticipated changes in the climate, in the upcoming years, new regulations and laws may be enacted to reflect the new reality. Entities wishing to perform restoration projects should keep abreast of current and proposed regulations.

4.8 Sequencing the Work

Construction sequencing may be critical to levee removal design to minimize the risk of flooding during the removal process and facilitate re-use of materials. The sequencing may be dictated by permitting agencies, the design team, or may be done in coordination with the contractor to optimize costs.

The priority when developing the sequencing should be to maintain the desired level of flood risk reduction during construction. Factors such as interior drainage, seasonality, length of the construction period, and the desired level of flood risk reduction should be evaluated using a risk-based approach. When dictating sequencing, the distance between excavation areas and disposal or re-use sites should be carefully considered. Failure to appropriately account for these knowns can result in a construction site vulnerable to flooding or double handling of materials, both of which may have costly implications.

4.9 Unanticipated Conditions

Levee removal may encounter unanticipated conditions or materials. The design should include provisions for change management and cost options for unanticipated conditions. Planning for the unexpected may save the project time and money and avoid potential claims.

Because the levee being removed may have been constructed decades earlier and documentation may not exist on the materials that were used for its construction, uncertainty may exist about the material that will need to be removed. This uncertainty can be reduced by performing a geotechnical investigation that characterizes the material, but even the most robust geotechnical investigation cannot eliminate the risk of encountering unanticipated materials or conditions.

Examples of unanticipated conditions that may be encountered with levee removal include finding construction debris within the levee, abandoned utilities, or unidentified or mis-dimensioned cutoff walls, contaminated materials, levee foundations, and erosion protection.

Approaches to mitigating the risk of unanticipated conditions should include having a construction contingency in accordance with standard cost estimating practices and informed by local and project-specific considerations. Another approach to address the risk of unforeseen conditions is to include additional optional pay items that could be incorporated into the project later to address a certain construction risk. For example, pay items can be included for a cutoff wall on an earthen embankment, even if one is not known to exist. This will 'lock in' a unit cost for the material during the bidding phase and reduce cost uncertainty if such an item is identified during construction.

NAPA-SONOMA MARSH RESTORATION PROJECT

The Napa-Sonoma Marsh Wildlife Area is located along the northern portion of the San Pablo Bay, approximately 45 miles north of San Francisco, California. The marsh was originally comprised 25,000 acres, but agriculture and development reduced it by 64%. In 1994, the Cargill Salt Company ceased production and sold over 9,800 acres of land in the project area to the state of California, managed by the California Department of Fish and Wildlife. The Napa Salt Marsh Restoration Project restored approximately 4,500 acres of the 9,800 acres of the Napa-Sonoma Marsh Wildlife Area by breaching some and removing other levees to restore tidal waters to the formerly leveed salt pond areas.

Thriving shorebirds at the salt marsh restoration site.

4.10 Operation and Maintenance

O&M manuals should be updated to reflect a changed project condition. This will be particularly important if the levee is setback or if only a portion of a larger levee system is removed, and the remaining levee still provides a flood risk reduction purpose. In that situation, it is likely that two O&M manuals will be needed. One manual should focus on modified inspections of the remaining levee (**Chapter 9**) and the second should cover periodic evaluation of the restoration in the former leveed area. Furthermore, some regulatory agencies may require periodic monitoring for a defined period, to meet permit conditions.

4.11 Cost Considerations

Construction costs for a levee removal project should be developed during the design phase using typical cost estimating procedures. Following standard practices should be sufficient to generate an appropriate cost estimate. Accurately accounting for the quantity and quality of levee material to be moved, extent of revegetation required, and amount of utility relocation needed, is critical since these factors may substantially contribute to the overall project cost, reflecting large quantities or challenging procurement issues.

A unique aspect to a levee removal project is the excavation, transport, and disposal of levee material, which often is a significant proportion of the cost. The quantity and quality of this material will determine how it may be moved, disposed of, or re-used, and its ultimate placement location and procedures will influence the cost. Because the quantity may be large, assumptions should be made for demolition/excavation methods and rates, labor, and equipment resource requirements, expected transportation methods and capacities, and proposed waste disposal or re-use locations, as these factors will have the largest impact on the cost. Fluctuations in the price of fossil fuels will also influence costs, as most equipment used for heavy civil construction is powered by diesel engines.

Establishment of vegetation may also be a large part of the project cost, depending on the spatial area of restoration and the design approach for re-vegetating the site. Active restoration—when seeding or seedlings are included in the design—provides better and quicker coverage of the desired vegetation, but is more costly than passive restoration. Passive restoration occurs when no action is taken and native seed banks self-establish. These approaches result in different vegetation characteristics, but each may achieve project goals. Cost implications should be considered when evaluating which approach best meets project goals.

The relocation of public and private utilities required by levee removal may be a project cost. As discussed in section 3.1.6, utilities requiring rerouting should be identified in the planning phase to allow sufficient time for coordination during the design and construction phases. The timeliness of utility relocation may affect removal construction and may require phased construction. The type and quantity of utilities influence the overall project cost. Because some levees have been in place for many years, infrastructure often is designed on the assumption that it always will remain. Thus, water, sanitary, gas, power, telecommunications, and transportation infrastructure may need to be modified to accomplish the goals of the levee removal project.

5 Construction

During the construction and post-construction phases, material disposal and ecosystem restoration present unique challenges due to the possibility of hauling route issues/impacts and the duration and effort associated with establishing native vegetation to meet coverage and growth requirements. This section presents principles and best practices unique to the floodplain reconnection construction process. This discussion is intended to supplement information presented in **Chapter 8**, which gives an overview of construction practices relevant to a new levee project, as well as construction closeout activities and risk management during construction. These topics also are relevant to a floodplain reconnection project.

Levee removal construction is a unique subset of levee construction. This section describes specific aspects of levee removal construction, including the following:

- Removal methods.
- Safeguarding ecosystems during construction.
- Post-construction monitoring and reporting.

In general, the physical act of deconstructing a levee is similar to many other types of earthwork—intensive, heavy civil construction. Site conditions, site locations, and volume and type of materials for removal, transport, and disposal, along with flood risks during construction, influence the contractors' methods, total cost, and schedule. Adding a restoration component to this type of construction increases the complexity of the project and expands the type of experience needed by the contractor. This experience may involve performing restoration-specific activities, which might include vegetation selection and installation, and monitoring surface water and groundwater levels. In addition, because levee removal projects take place near a waterbody, such as a river, lake, or coastal zone, the contractor should have experience with excavation in these environments, ecological restoration, work near water, and with all the complexities these environments entail.

5.1 Removal Methods

A demolition method should be selected for project planning and cost estimating purposes, but the design should define the removal limits and any pertinent constraints or restrictions, thereby allowing alternative demolition methods to be submitted by the contractor for approval. Individual work items should be well-defined and quantified.

Typical excavation and demolition methods are used for levee removal projects. These include use of excavators, scrapers, backhoes with bucket or hydraulic hammer, bulldozers, graders, loaders, and dump trucks. Use of explosives and various attachments to excavators may be used to loosen material before transport, depending on site-specific restrictions and local regulations. The type of equipment to be used generally depends on the size and configuration of the levee, its location, volume of material, and schedule for removal because each of the excavation methods has different rates of work.

5.1.1 Earthen Levees

Earthen levees may be removed using common excavation methods and earth-moving equipment, and can provide a source of clay, sand, gravel, cobbles, and rock for site restoration or local commercial use.

Stability of the earthen and adjacent features should be maintained during removal. Slopes should be monitored visually, and instrumentation to monitor slope stability may be required for larger projects.

Removed materials should be separated to the degree practical for re-use. Examples include topsoil, berm drain materials, structural fill, nonstructural fill, and aggregate surfacing.

5.1.2 Structures

Structures to be removed may include concrete or other floodwalls, engineered erosion protection, gates, pipes, asphalt, or recreation-related infrastructure, such as trails, bathrooms, benches, or interpretive signs. During construction, the contractor will determine the type and size of equipment to be used. The selected equipment should:

- Meet the permit requirements.
- Achieve the desired removal rates.
- Support other “means and methods” to attain the intended objective.
- Have the ability to demolish the structure.
- Be able to access the construction site.
- Accommodate the removal, re-use, and disposal of materials.

The approach selected by the contractor should be approved by the designers, so it meets the intent of the overall project.

Typical removal methods include the following:

- Conventional concrete removal is an older method, but still constitutes a large percentage of demolition, and includes the use of jackhammers, rig-mounted hydraulic hammers, and breaking balls. High-pressure water-cutting and wire saws can cut through concrete walls accurately, including reinforcement. Wire saws may be used underwater.
- Demolition using expansive grout requires drilling a series of holes, but this method eliminates the need for explosives and reduces noise and vibration. (Drilling is typically percussive, which generates some noise and vibration.)
- Blasting can facilitate and expedite concrete demolition on sites with difficult equipment access and existing large structures. Vibrations and noise levels affecting adjacent buildings and communities should be considered and mitigated, if they exceed the thresholds set by the designers. Use of explosives as part of a demolition project may require an elevated level of permitting and licensure. While local licensing and permitting requirements vary, controlled blasting generally requires federal and state licenses, and

project specifications typically require the contractor to submit detailed blasting and safety plans for approval.

- Bulk demolition can be accomplished with large breaker balls and explosives, with conventional clamshell and bucket cranes used for removal.
- Pile foundation removal likely will be performed with a vibratory hammer. When seepage and cost are concerns, piles should be cut off a minimum of 2 feet below the final grade and not removed.
- In the case of underwater demolition, the use of a dive team and associated safety controls add to the project cost. Underwater concrete piles can be pulverized, and steel piles can be cut by a dive team. When seepage and cost are concerns, piles should be cut off a minimum of 2 feet below the final grade and not removed.

5.2 Safeguarding Ecosystems During Construction

For sites where ecosystem restoration will occur within the footprint of the former levee, work should be planned so the levee removal does not inadvertently compromise the planned restoration. For instance, vehicles and equipment should be staged to avoid unnecessarily compacting soil. Moreover, vehicles should be cleaned prior to coming on site to reduce the risk of introducing seeds of non-native species from other sites.

Care should also be taken to protect vegetation and habitat adjacent to the work area. As part of the on-site restoration, ongoing maintenance activities such as temporary irrigation, invasive species control, and/or periodic functional evaluations of the project will be needed until the native vegetation is established. Additional information related to ecosystem restoration implementation is discussed in section 4.7.

5.3 Post-Construction Monitoring and Reporting

Post-construction monitoring may be needed to quantify and evaluate the effectiveness of a floodplain reconnection project, to ensure project objectives are met, and in some cases, may be required to comply with federal, state, or local regulatory permits. Monitoring plans should be developed specifically for the project and cover all of the aspects the designers require to evaluate functional performance and adherence to the design. Thus, monitoring typically includes a topographic survey of the site; periodic monitoring of erosion, sedimentation, and scour; growth and success of vegetation; and assessment of terrestrial and/or aquatic life.

Projects that parallel a river or channel should include a site survey. The surveying effort should include channel cross sections to identify where shoaling or scour is occurring. This information may be used to assess the impact on project functionality. Survey methods in channels include conventional transect surveys and multibeam or sounding bathymetry.

Monitoring is helpful to document project performance and provide scientific data to improve the understanding of levee removal effects for future projects of a similar nature. For example, a performance monitoring program may be developed to document what is likely to happen to the channel, floodplain, or adjacent wetlands after levee removal. A written monitoring plan, a summary of accomplished work, and a schedule of anticipated work are generally recommended to provide a description of completed and proposed future monitoring. Prescribed monitoring should be explicitly funded to the extent possible. Some smaller projects have relied on engagement and involvement by the community at various stages by completing a periodic visual assessment of the stream corridor and collecting water quality data, at minimal cost. When utilizing this type of approach, an appropriate level of oversight and quality assurance should be performed to confirm conformance with industry best management practices.

6 Summary

This chapter focuses on the unique aspects involved with removing or setting back a levee and reconnecting the adjacent floodplain areas. While the primary benefit—and possibly the primary driver—is often associated with ecosystem restoration, there are numerous ancillary benefits and opportunities associated with groundwater recharge, floodplain storage, and associated flood risk reduction, recreation, and waterway function.

It may be possible to meet project objectives with partial levee removal to limit the construction footprint and need for material off-hauling. Since material off-hauling is a key cost component, on-site disposal is preferred, and there may be ways to incorporate fill and upland ecosystem restoration into the design.

Ecosystem restoration brings numerous complexities into the project planning, design, construction, and post-construction phases. Some examples include non-native invasive species control, sourcing of native seeds and plantings, temporary irrigation, establishment periods, and post-construction regulatory monitoring and reporting.

As with all chapters throughout these guidelines, assessment of flood risk and maintenance or improvement of flood risk reduction is essential and will often govern the overall scope of the project.

Related content associated with this chapter is included in detail in other chapters of the National Levee Safety Guidelines as described in Table 11-3.

Table 11-3: Related Content

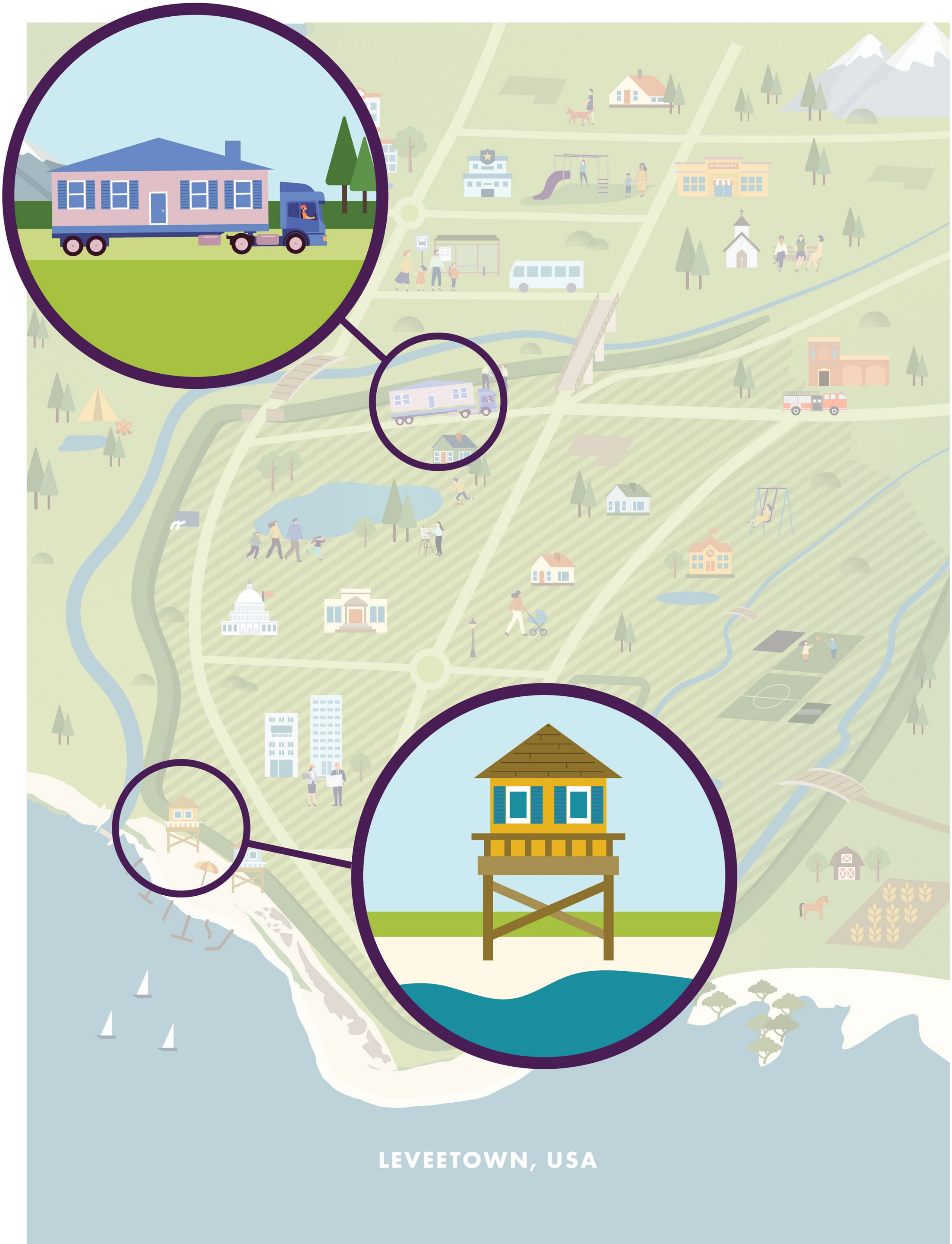
Chapter	Chapter Title	Related Content
1	**Managing Flood Risk**	• Understanding the basics of flood risk
2	**Understanding Levee Fundamentals**	• Levee form
3	**Engaging Communities**	• Engaging for levee-related projects
4	**Estimating Levee Risk**	• Estimating hazards, performance, and consequences
5	**Managing Levee Risk**	• Risk management activities • Risk-informed decision making
6	**Formulating a Levee Project**	• Six-step planning process
7	**Designing a Levee**	• Design process • Site characterization
8	**Constructing a Levee**	• Construction management • General construction activities
9	**Operating and Maintaining a Levee**	• O&M manuals
10	**Managing Levee Emergencies**	
11	**Reconnecting the Floodplain**	
12	**Enhancing Community Resilience**	• Community resilience • Mitigation strategies

12 Enhancing Community Resilience

Key Messages

This chapter will enable the reader to:

- **Build resilience.** There are other meaningful flood risk management options that can supplement the role of the levee in building a community's resilience to flooding.
- **Be adaptive.** Communities should evaluate their progress in building resilience and adapt activities to reflect changing needs and conditions.
- **Perform inclusive engagement.** Whole community engagement helps achieve more equitable flood resilience consistent with broader community goals.


LEVEETOWN, USA

Other chapters within the National Levee Safety Guidelines contain more detailed information on certain topics that have an impact on enhancing community resilience, as shown in Figure 12-1. Elements of those chapters were considered and referenced in the development of this chapter and should be referred to for additional content.

Figure 12-1: Related Chapter Content

CH 1	CH 2	CH 3	CH 4
Flood risk management strategies Climate change impacts	Levee fundamentals Potential failure modes	Community engagement	Potential failure modes Estimating consequences Social vulnerability
CH 5	**CH 6**	**CH 7**	**CH 8**
Taking actions to reduce risk Building risk awareness			
CH 9	**CH 10**	**CH 11**	**CH 12**
Access corridor	Emergency preparedness Evacuation planning	Floodplain restoration	**Enhancing Community Resilience**

Contents

1 Introduction 12-1
2 Building Community Resilience 12-1
2.1 Resilience Planning 12-4
2.2 Understanding Community Capabilities 12-6
2.3 Integrating Environmental Justice 12-7
3 Understand Risk 12-9
3.1 Flood Hazards within the Leveed Area 12-9
3.2 Remaining Flood Risk within the Leveed Area 12-10
3.2.1 Overtopping 12-11
3.2.2 Rainfall and Groundwater 12-11
3.3 Levee Performance 12-11
3.4 Consequences 12-11
4 Explore Options 12-12
4.1 Prepare 12-13
4.1.1 Community Education and Awareness 12-13
4.1.2 Individual Actions 12-14
4.1.3 Community Emergency Planning 12-15
4.2 Absorb and Resist 12-21
4.2.1 Land Use Planning 12-21
4.2.2 Building Codes 12-23
4.2.3 Natural and Nature-Based Solutions 12-23
4.2.4 Property Acquisitions 12-28
4.2.5 Structure Elevations 12-29
4.2.6 Floodproofing 12-29
4.2.7 Improve Stormwater Drainage System Capacity 12-31
4.2.8 Harden or Elevate Infrastructure 12-31
4.3 Restore and Recover 12-32
4.3.1 Recovery Planning 12-32
4.3.2 Flood Insurance 12-33
4.3.3 Grants and Emergency Funding 12-33
5 Prioritize and Implement 12-34
5.1 Prioritization 12-34
5.2 Implementation 12-38
6 Evaluate and Adapt 12-40
6.1 Evaluate Using Indicators 12-40

6.1.1 Capitals to Measure a Community Flood Resilience 12-41
6.1.2 Evaluate Results 12-46
6.2 Adapt to Change 12-47
7 Summary 12-48

List of Figures

Figure 12-1: Related Chapter Content 12-i
Figure 12-2: Resiliency Expressed as Functionality Over Time Following a fFlood 12-2
Figure 12-3: Enhancing Community Resilience Approach 12-3
Figure 12-4: Sources of Flooding 12-9
Figure 12-5: Flooding Sources to Leveed Area 12-10
Figure 12-6: Remaining Flood Risk Contributors 12-11
Figure 12-7: Flood Risk Management Options 12-13
Figure 12-8: Graduated Land Use Strategy 12-22
Figure 12-9: Dry Floodproofed Building with Aluminum Shield Temporary Closure 12-30
Figure 12-10: Wet Floodproofed Building with Flood Openings 12-31
Figure 12-11: Example Spider Chart Showing Measurement Per Capital 12-47

List of Tables

Table 12-1: Common Flood Risk Management Options with Environmental Justice Concerns 12-8
Table 12-2: Emergency Evacuation Lessons Learned and Informed Best Practices 12-17
Table 12-3: Example Resilience Project/Program Prioritization 12-36
Table 12-4: Example Indicator in the Natural Capital Maturity Matrix 12-42
Table 12-5: Example Indicator in the Built Capital Maturity Matrix 12-42
Table 12-6: Example Indicator in the Financial Capital Maturity Matrix 12-43
Table 12-7: Example Indicator in the Health and Human Capital Maturity Matrix 12-44
Table 12-8: Example Indicator in the Social and Cultural Capital Maturity Matrix 12-44
Table 12-9: Example Indicator in the Institutional and Governance Capital Maturity Matrix 12-45
Table 12-10: Related Content 12-49

1 Introduction

Flooding adversely affects many communities across the nation, resulting in loss of life, destruction of property and infrastructure, environmental harm, and significant recovery costs. In this publication, community flood resilience refers to the ability of a community to persist and recover from the impacts of flooding. Communities which are highly resilient can withstand flooding impacts to a greater degree and more rapidly recover from flooding than those which are less resilient. Flood resilience can be achieved through a combination of structural and nonstructural flood risk management options. As previous chapters have focused on the levee's role as a structural option to build flood resilience, this chapter focuses on nonstructural options that may be implemented to reduce a community's exposure to flooding, minimize losses, and enhance recovery capabilities.

Best practices described within this chapter directly align with the National Levee Safety Program's overarching vision of reducing the impacts of flooding and improving community resilience in areas behind levees. This material is intended to help communities of all sizes and financial capabilities to implement solutions promoting resilience to flooding. Understanding the reality that some level of risk is always present, and flooding may still occur in communities behind levees, the goal is for communities to take tailored actions and consider their unique situations that will result in the best possible outcome for those living and working in the community.

The content outlined within this chapter presents a roadmap to enhance community resilience guided by inclusive and equitable community engagement that involves all those affected by floods and flood risk management decisions in the decision-making process. Once the community sets its vision and establishes overall objectives for flood resilience, an iterative approach to progress towards those objectives may be followed. This approach is guided by continuous engagement of the community and includes the following activities:

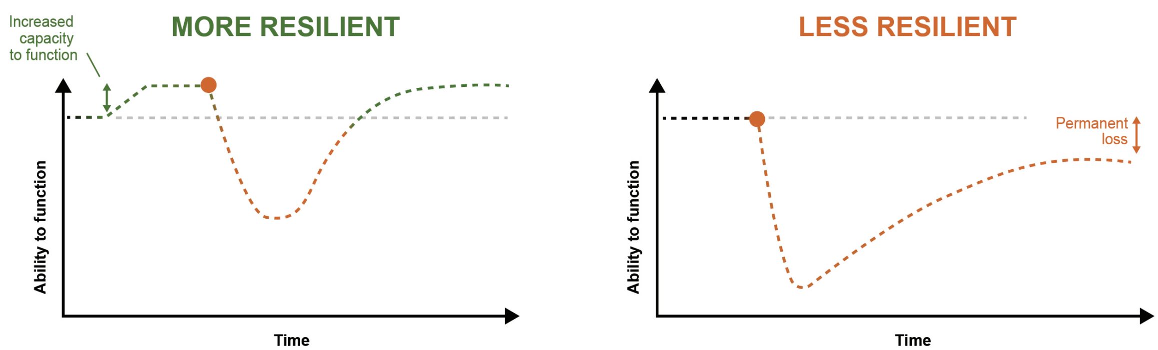
- Understanding the community's flood risk.
- Exploring options to enhance the community's flood resilience.
- Prioritizing and implementing actions to enhance community resilience.
- Evaluating progress and adapting to changing conditions.

2 Building Community Resilience

Each person, business, organization, or government agency can contribute towards building resilience across the entire community, with the intent to improve quality of life and community well-being despite the risks of floods. A community's flood **resilience** is defined by its ability to anticipate, prepare for, respond to, and recover from floods with minimal damage to social well-being, the economy, and the environment.

Figure 12-2 depicts the concept of resilience in terms of a community's ability to function versus the time to recover after a flood, shown as the orange dot (U.S. Department of Commerce and National Institute of Standards and Technology, 2016). In this generalized description, functionality is a measure of how well a community meets its intended services. A resilient community still requires a period of recovery but is able to rebound quicker and to the same level or greater, than its original functionality. In comparison, a less resilient community may not be able to recover to its original level of functionality after a flood. For example, a more resilient community may have a wastewater treatment plant able to quickly return to operation after a flood, minimizing the impact to the quality of life of the people in the community.

Figure 12-2: Resiliency Expressed as Functionality Over Time Following a fFlood



To enhance resilience, communities should understand flood risks and manage those risks with appropriate measures to successfully reduce future impacts of flooding. To do this, community resilience relies on continual improvement through a holistic vision that includes:

- Taking a whole systems approach by considering integrated efforts to improve quality of life, durable systems, economic vitality, and conservation of resources for present and future generations.
- Working together to better understand the community's resilience needs and identify partners who can support them in meeting those needs.
- Embracing community wisdom and respecting and elevating the voice and expertise of those individuals who have been systematically left out of decision making. A more inclusive path to societal security and resilience is built when decisions and solutions are implemented taking the entire community into consideration and reflecting the input of all individuals.

PEOPLE: A COMMUNITY RESILIENCE FOUNDATIONAL CONCEPT

The power to define community values and create an inclusive and resilient vision for the future resides with community members. This requires the active engagement of all people, including typically underrepresented groups, in the resilience conversation.

Denham Springs Resilience by LSU Coastal Sustainability Studio (LSU Coastal Sustainability Studio, 2021).

- Strengthening community lifelines. The community lifelines are the most fundamental services in the community that, when stabilized, enable all other aspects of society to function. Lifelines include, but are not limited to, critical infrastructure such as water systems for drinking water and wastewater, transportation infrastructure, communications infrastructure, energy grid and fuel, and health and medical facilities. Community members rely on the services that support daily living and serve as the foundation of the community's social and economic fabric such as access to clean drinking water, electricity, health, food, and appropriate elimination of waste.

Approaches used to enhance community resilience should be grounded by the principles of including and listening to the whole community, understanding risk, exploring options to reduce risk, prioritizing and implementing those options based on the unique characteristics and needs of the community, and monitoring and adapting to changing conditions. In short, a best practice is for community decision makers to decide the desired level of resilience. The step-by-step process, depicted in Figure 12-3 and described throughout the remainder of this chapter, begins by establishing the community's vision through engagement of the whole community.

UNITED STATES CLIMATE RESILIENCE TOOLKIT:

This toolkit was created as a problem-solving process communities can implement to prioritize options for reducing risk. The steps to resilience provide a framework for reducing climate-related risks. Communities can use the framework to identify valuable assets, determine which climate-related hazards could harm them, and then identify and take effective actions to reduce risk (NOAA, 2021).

Figure 12-3: Enhancing Community Resilience Approach

Key elements that will improve the outcome of this approach to building resilience are engaging in deliberate planning for resilience, understanding current community capabilities, and seeking opportunities to incorporate environmental justice into resilience planning, as described in section 2.3. These elements will help provide an initial understanding of how resilient a community is to flooding, which then guides the iterative process of enhancing resilience, including which options to explore, select, and prioritize. Developing a reference point of initial community resilience is crucial to all steps of the approach and fundamental to effectively carrying out the fourth step of evaluating effectiveness of activities and making adaptions, as necessary. Principles, strategies, and tools for this evaluation are further detailed in section 6.

2.1 Resilience Planning

Resilience planning sets out a strategic and transparent approach to achieving a community's resilience goals. Plans alone do not increase resilience, but they provide a foundation for implementing actions and should establish a framework with metrics for evaluating their success. The planning process should be used to clearly articulate the values and vision for community resilience that will then guide selection, prioritization, and implementation of resilience building actions.

Some communities develop stand-alone resilience plans or refine existing community planning documents to articulate the overall flood resilience objectives and describe approaches for enhancing flood resilience. At a minimum, it is a best practice for communities to integrate activities that contribute to building resilience into community planning efforts such as:

- Engaging with all members of the community.
- Incorporating the best available flood risk information.
- Identifying and reconciling conflicts with hazard mitigation activities.
- Acknowledging and seeking ways to address impacts of the changing climate.

For example, community-based master plans—sometimes referred to as comprehensive plans—guide the decision-making process for growth and development, economics, housing, and transportation. These efforts present opportunities for communities to address flood hazards, climate change impacts, and inequities in flood risk exposure. Additionally, these plans offer opportunities for communities behind levees to identify gaps in community capabilities and to implement actions to minimize those gaps and make improvements.

PLAN INTEGRATION FOR RESILIENCE SCORECARD™

This tool was created to advance community resilience by helping communities understand and discuss inconsistencies across their networks of plans, the connection between plans and vulnerability to natural hazards, adjustments to current plans, and policy tools to improve integration. One of the innovations is a spatial evaluation of plans, particularly the overlaying of hazard zones with planning districts. This allows communities to understand in a visual way where updates to their land development policies can have the most impact on resilience and where to encourage more resilient development practices. The tool was developed by a team of researchers at Texas A&M University's Institute for Sustainable Communities.

(Malecha, 2019)

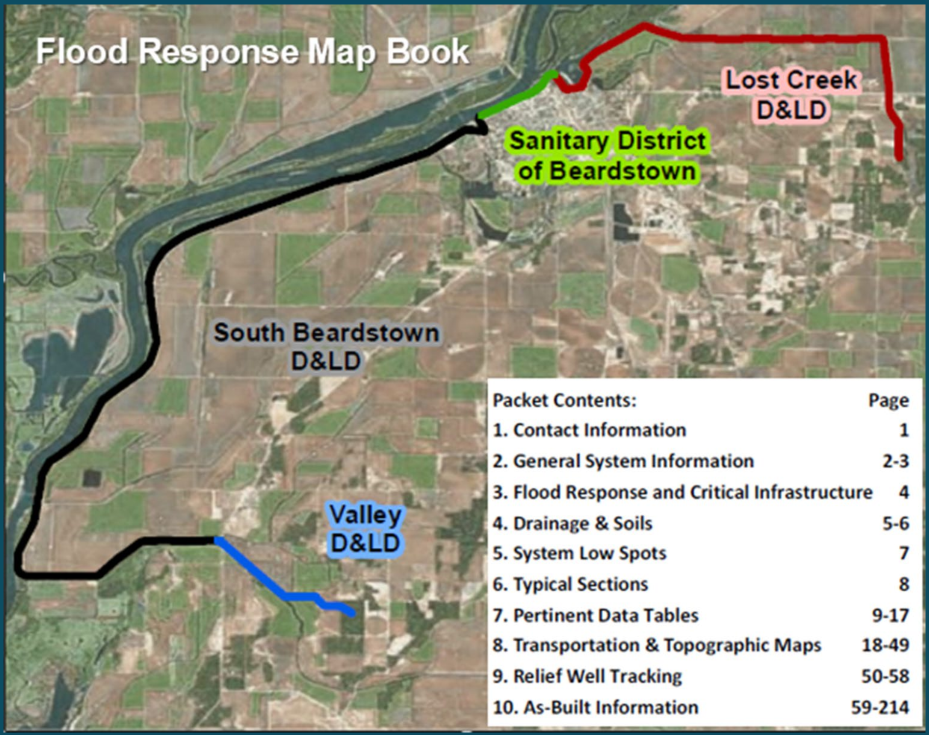
State and federal agencies offer grant programs to assist communities with the cost of preparing plans such as disaster preparedness, hazard mitigation, and emergency action plans—all which can feed into community resilience planning. Local agencies, including emergency management, economic and community development, and environmental protection are good sources of information about funding programs.

CASE STUDY: FLOOD RESPONSE MAP BOOK

The Illinois Flood Risk Management Team brings together federal and state agencies to focus on four themes to reduce flood risk in Illinois: hazard mitigation, emergency response, structural flood reduction measures, and policy evaluation. The team establishes and strengthens intergovernmental partnerships within the state that serve as a catalyst to develop and implement comprehensive and sustainable solutions to flood risk challenges.

For example, the Sid Simpson Levee located along the Illinois River provides flood risk reduction to the city of Beardstown. A levee breach analysis was performed to identify inundation and arrival time for possible breach locations. The intent of this analysis was to inform flood emergency management planning efforts, improve evacuation planning, and reduce future life and safety risks for nearly 6,200 people. Additionally, there is an estimated $1.4 billion of property value within the leveed area.

The team developed an easy-to-use flood response “map book” for the Sid Simpson Levee District. The information and data visualizations collected in the book supports decision making by officials, facilitates communication, and improves interagency coordination for a more efficient flood response. The book includes information such as flood impacts, datum conversion factors, as-built engineering drawings, and river gage information, as well as interior drainage layouts, soil information, and a contact list for local officials. Maps of the entire drainage area show features such as levees, floodwalls, pump stations, and relief wells, as well as aerial photography, evacuation routes, emergency services, and locations of critical infrastructure. This information, when compiled into a single, easily accessible source like the map book, becomes a useful tool for prompt and accurate responses to flooding situations. The map book was most recently used during the near-record Illinois River flood in May 2019.



2.2 Understanding Community Capabilities

Communities have various levels of capabilities to manage flood risk. These capabilities may be influenced by available funding, local technical expertise, or community values and priorities. Understanding what current capabilities exist is key to building an effective flood resilience strategy. The evaluation of capabilities will identify gaps that need to be filled for improved resilience, as well as inform the selection and prioritization of activities based on the resources available for successful implementation. Community capabilities that should be evaluated to assess their current flood resilience—alongside opportunities for strengthening the resilience of a community—include:

- Flood risk management actions:
  - Identify hazards and assess risk.
  - Adopt and enforce land development policies and building codes.
  - Protect natural and cultural resources.
- Public engagement/communication:
  - Conduct equitable public engagement.
  - Test and utilize public information and warning systems.
- Funding and economics:
  - Fund and implement infrastructure projects.
  - Implement economic development programs.
  - Provide affordable housing.
  - Apply for and administer grants to fund projects and programs.
- Community assistance:
  - Provide public health and social service facilities and programs.

CASE STUDY: COLORADO RESILIENCY FRAMEWORK

Following the devastating floods in 2013 and record wildfires in 2010, 2012, and 2013, the state of Colorado developed the 2020 Colorado Resiliency Framework–the first of its kind in the state to serve as a roadmap for helping communities prepare for a more resilient future. It outlines the state's resiliency vision and goals and explores risks across three themes: understanding risks from natural and other hazards, addressing social inequities and unique community needs, and pursuing economic diversity and vibrancy–all within the context of an ever-changing climate. The framework provides 29 strategies across six priority focus areas the state will implement to reduce risk and be adaptive to changing environmental, social, and economic conditions. The six priority focus areas of the framework include community, economic, health and social, housing, infrastructure, and watersheds and natural resources.

Throughout the framework, risks are analyzed, and specific strategies are identified that will strengthen the state's capacity to adapt and support local communities on their path toward resiliency. Two overarching strategies—establishing a statewide resilient and sustainable community/regional program and attracting and leveraging resiliency funding opportunities—are foundational activities that will connect and strengthen all the resiliency priorities.

(Colorado Resiliency Office, 2020)

  - Participate in mutual aid and community assistance charters.
- Emergency preparedness and response:
  - Plan for and conduct emergency preparedness and response activities, including evacuation and sheltering.
  - Invest in hiring and training personnel to support resilience-building strategies.

Federal agencies offer technical assistance to support communities that may not have the resources to begin community resilience planning and engaging the public and stakeholders in exploring and selecting resilience strategies.

2.3 Integrating Environmental Justice

The process of building community resilience should include an evaluation of how equitably the benefits delivered by flood risk management options are distributed throughout a community. Community members most impacted by floods and flood risk management decisions should be meaningfully involved in the decision-making process. Exclusion from this process could cause further harm or put some individuals at greater flood risk than existed before options are implemented.

Environmental justice refers to the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies. In many communities, a disproportionate number of underserved populations reside in areas historically prone to flooding due to a combination of housing costs, housing policy, land use policy, residential mortgage lending practices, and insurance practices.

Similarly, vulnerable populations are often left out of community conversations where critical needs and strategies are decided. Both groups can include children, women, pregnant women, elderly, racial or ethnic minorities, underinsured persons, those who are economically disadvantaged, unhoused individuals, persons with medical conditions that predispose them to disparate impacts, and those with limited access to human and social services or infrastructure (e.g., transportation, healthcare, food, potable water).

ENVIRONMENTAL JUSTICE TOOLS:

EJ Screen, EnviroAtlas, and the Climate and Economic Justice Screening Tool are several tools produced by federal agencies that can help communities in areas with historically underserved populations to identify geographic areas of concern using key health, climate, and infrastructure indicators. The data available in these tools are presented spatially and can be overlayed with flood risk data to highlight locations with additional vulnerabilities to flood risk.

Community resilience strategies should recognize the inequalities and inequities which exist and seek to integrate environmental justice into the planning process through exploring flood risk management options that achieve the same degree of risk reduction from flood hazards and equal and equitable access to the decision-making process for all members of the community. Conversely, it is important that all potential negative impacts of options are considered through collaboration with members of the community (**Chapter 3**). Options which can negatively impact the environment, health, or well-being of community members should be avoided.

Table 12-1 provides common flood risk management options and potential environmental justice concerns that could be associated with their implementation. A community should consider conducting a comprehensive benefit analysis to select the appropriate measure to minimize or avoid these impacts. Engagement with affected populations is essential to identify measures and to monitor needs and preferences of communities.

Table 12-1: Common Flood Risk Management Options with Environmental Justice Concerns

Option	Potential Environmental Justice Concern	Actions to Avoid Concern
Structural measures (dams, levees, channels)	Redirection of floodwaters that disproportionately impact underserved communities who may lack resources to prepare for and/or recover from flood-related damage.	Identify historically underserved communities and vulnerable populations in the study area and include representation of both in planning and decision- making efforts.
Traffic mitigation in flood response and recovery plans	Road closures that divert traffic primarily through underserved community neighborhoods.	Plan for the safest and quickest evacuation routes for all community members. Coordinate with emergency management and health departments to fully understand needs and resources.
Relocation of public facilities (e.g., hospitals, fire stations, parks)	Disproportionate changes in environmental and health impacts from relocated facilities, such as vacant sites or reduced greenspace, or decrease in accessibility of relocated facilities.	Consider dry floodproofing instead of relocating facilities that are important to underserved populations.
Residential buyouts of flood prone properties	Lack of affordable housing to relocate; stress of relocation; broken community social ties; destruction or degradation of property with cultural significance; creation of vacant lots.	Provide affordable housing with access to public transportation, parks, and social services.
Temporary housing strategies in flood recovery plans for displaced residents	Placing housing in an area with existing environmental health hazards or limited access to employment opportunities, public schools, or community lifeline services.	Provide temporary housing in areas where wrap-around services exist (i.e., medical/ dental clinics, behavioral health, employment services).

3 Understand Risk

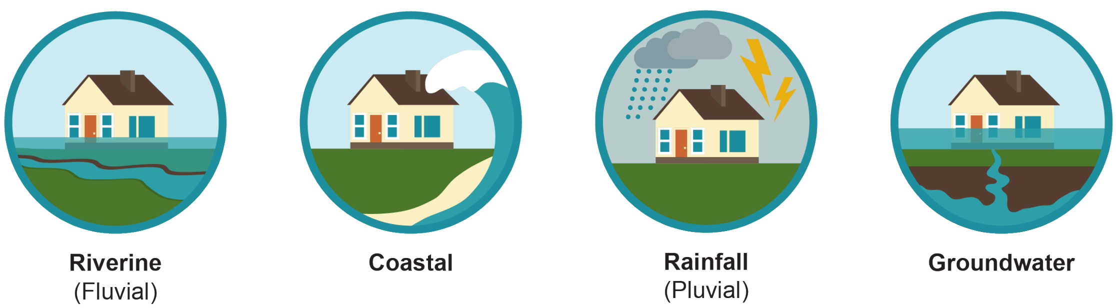
A comprehensive understanding of how flood hazards, expected levee performance, and potential consequences contribute to risk in the leveed area is vital. This understanding helps to inform the selection and prioritization of viable flood risk management options to build or enhance a community's resilience. **Chapter 1** describes the sources of flood risk and options to manage that risk, highlighting the levee as one option that may be implemented. Subsequent chapters—2 through 11—provide best practices related to a levee as the flood risk reduction option.

3.1 Flood Hazards within the Leveed Area

Common sources of flood hazards (Figure 12-4) are described in **Chapter 1** including:

- Riverine (fluvial)
- Coastal
- Rainfall (pluvial)
- Groundwater

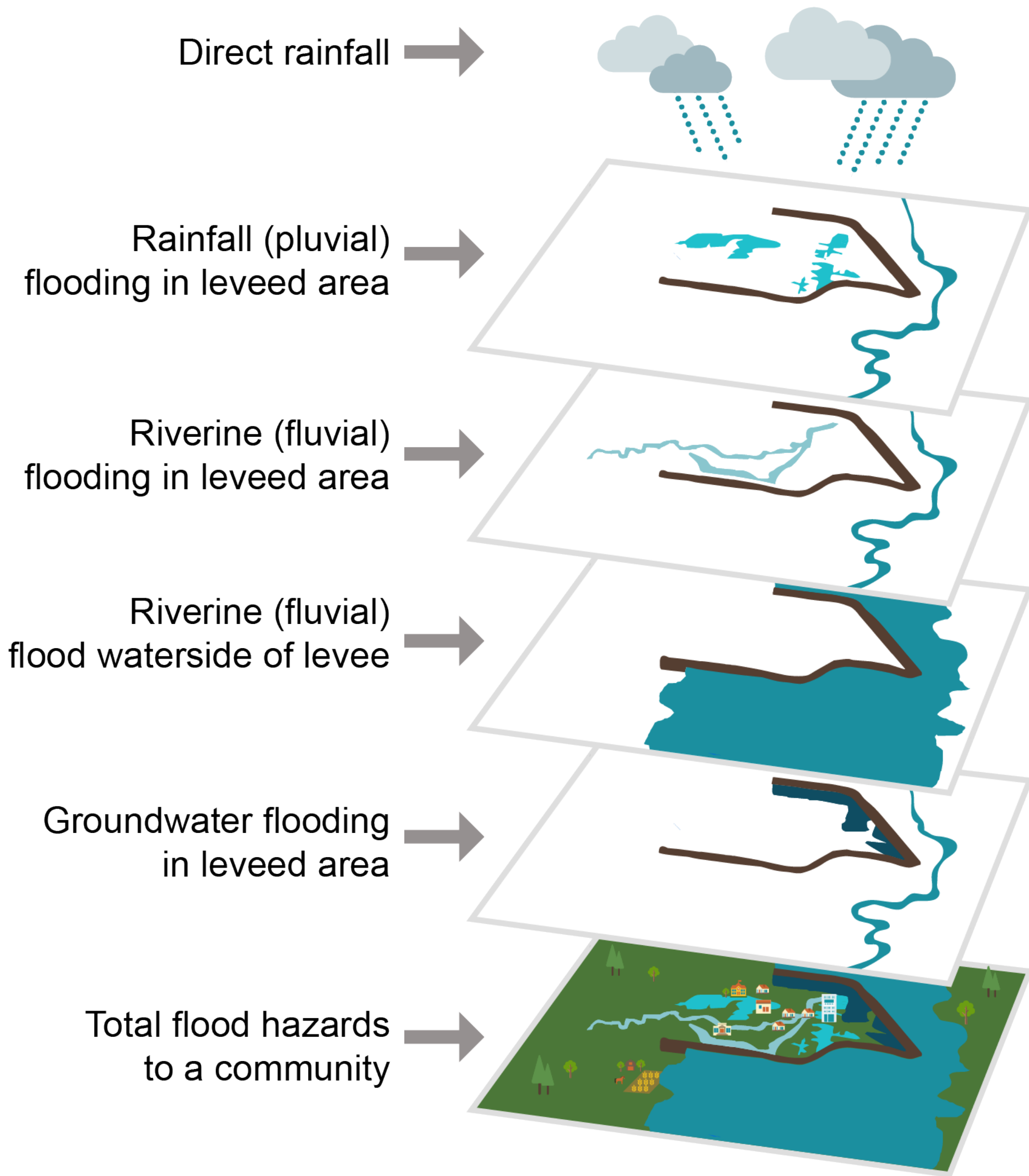
Figure 12-4: Sources of Flooding



Floods may occur from a singular source or multiple sources in combination with one another, as shown in Figure 12-5. Flood hazards will change over time, requiring regular monitoring of conditions to understand if and how risks have changed, and as community resilience needs evolve. As discussed in **Chapter 1**, changes to weather patterns and other natural processes from a warming climate and human activity will impact hazards and how they influence a community's flood risk.

It is important to understand the various sources of hazards and ensure current flood risk management measures are in place to address the hazards, as well as understand their limitations, when exploring additional community resilience building options.

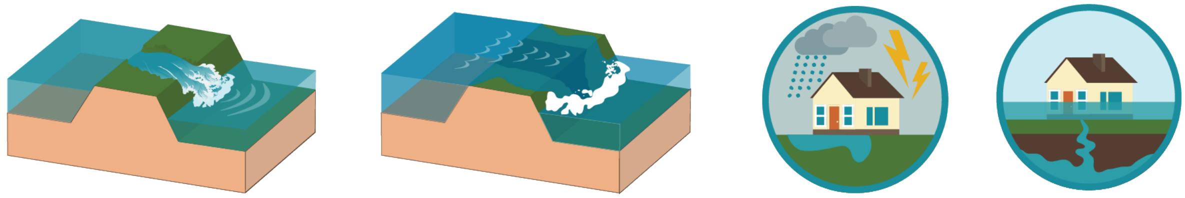
Figure 12-5: Flooding Sources to Leveed Area



3.2 Remaining Flood Risk within the Leveed Area

Levees reduce flood risks to communities but do not address all flood hazards, nor do they eliminate all flood risks. The flood risks that remain in a community with a levee in place are the overtopping (with or without breach), rainfall, and groundwater (Figure 12-6). **Chapters 4 and 5** discuss the evaluation and management of flood risk associated with levees and how the overtopping (with or without breach) contributes to flood risk. The following focuses on remaining flood risk within the leveed area.

Figure 12-6: Remaining Flood Risk Contributors



Overtopping without breach **Overtopping with breach** **Rainfall** *(Pluvial)* **Groundwater**

3.2.1 Overtopping

Levees are designed to reduce flood risks associated with a limited range of certain riverine or coastal hazards. Levees may be overwhelmed by these flood hazards with water flowing over the top of the levee (overtop) leading to flooding of the leveed area.

3.2.2 Rainfall and Groundwater

A levee's primary function does not address the risks associated with rainfall and groundwater hazards, though levee features may be designed to provide some limited capacity to evacuate their associated flood waters through or over the levee. Therefore, even with a levee in place, flood risk in the leveed area from rainfall and groundwater must be accounted for.

3.3 Levee Performance

Risk assessments identify how the levee performance contributes to the flood risk of a community. Understanding **potential failure modes**—mechanisms that, once initiated, could progress to the breach of a levee or inundation of the leveed area and their likelihood of occurrence—will assist in identifying effective resilience building options. The five most common potential failure modes for a levee are introduced in **Chapter 2** and are discussed in more detail in **Chapter 4**.

In some situations, levees may be very vulnerable to certain potential failure modes during a flood, but permanent repairs are not financially or physically viable. In this case, community-based flood risk management options—such as developing and practicing sophisticated plans for emergency response and evacuation should the issue lead to levee breach—are the best ways to manage the associated risks and build resilience to potential flooding in the community. Best practices for emergency response planning are discussed in **Chapter 10**.

3.4 Consequences

Flood consequences broadly refer to short- and long-term impacts attributable to flooding. Consequences of flooding can include immediate or long-term life safety and health impacts, monetary and economic impacts, environmental impacts, and social and cultural impacts. Consequences of levee breach or overtopping are evaluated in levee risk assessments, detailed in **Chapter 4**. These consequence assessments typically focus on the exposure and vulnerability of people and infrastructure in the leveed area, with life safety considered paramount. Understanding the ways communities may be impacted by potential flooding is critical to developing effective resilience strategies.

Keeping life safety paramount, the ability of those living and working within the leveed area to prepare for and respond to floods should guide communities in their exploration and selection of options that successfully and equitably reduce flood risk. A number of factors, including wealth, access to transportation, and affordable housing, may either strengthen or weaken a community's ability to prevent human suffering and financial loss in a disaster.

Social vulnerability refers to the susceptibility of social groups to adverse impacts from a variety of hazards, including flooding. Understanding and giving intentional consideration to social vulnerability and how it may amplify consequences during flooding can lead to solutions that build resilience of the whole community. For example, a community that contains a senior living facility in an area susceptible to flooding should focus on how to successfully protect the individuals living in the facility during a flood. This may result in a focused effort on evacuation or shelter-in place planning for individuals with varying medical access and functional needs, and a more deliberate consideration of vulnerabilities community-wide. Additionally, it may result in the development of more effective means of evacuation from which the whole community may benefit, thereby improving evacuation effectiveness for all community members. Additional considerations and best practices for evacuation planning are discussed in section 4.1.3.2.

SOCIAL VULNERABILITY INDEX:

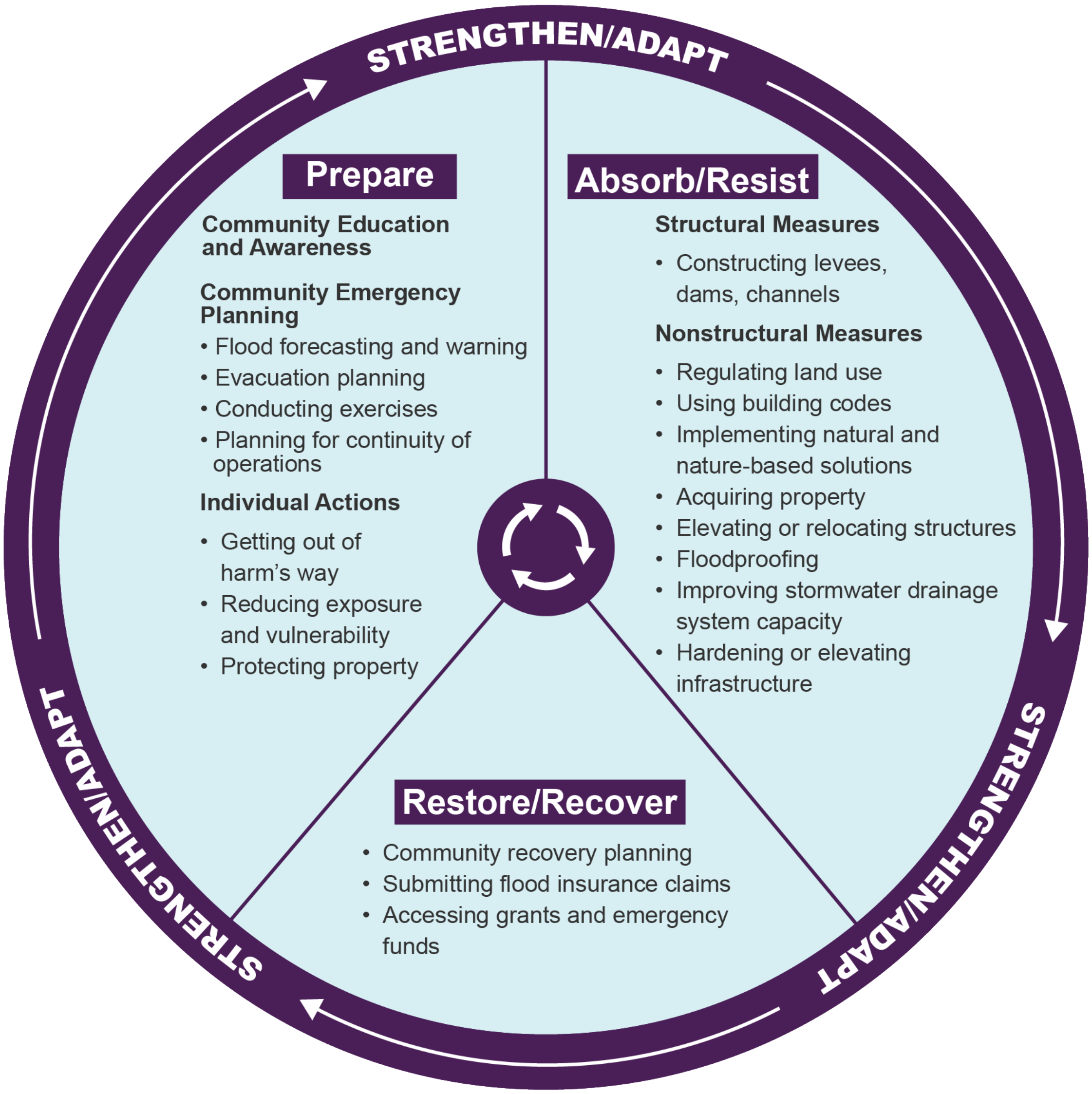
The Social Vulnerability Index published by the Centers for Disease Control utilizes 15 variables from the U.S. Census to identify populations that may need additional support before, during, and after disasters (CDC, 2022).

4 Explore Options

Understanding a community's exposure to flood risk, its greatest vulnerabilities, and its vision for community resilience should guide the exploration of options to most effectively sustain or increase a community's flood resilience. A variety of options exist that can support a community's goal.

These guidelines consider those options through commonly understood principles of community resilience—prepare, absorb and resist, restore and recover, and strengthen and adapt. The latter principle, strengthen and adapt, refers to the continual assessment of resilience and identification of new or improved ways to achieve resilience goals. Therefore, the following options are categorized into the three principles of prepare, absorb and resist, and restore and recover, as shown in Figure 12-7.

Figure 12-7: Flood Risk Management Options



4.1 Prepare

Proper planning for and education about flood risks prior to a flood can build and sustain the capabilities needed to prevent or manage the effects of flooding. This principle includes all elements needed to be ready before, during, and immediately after a disruption or changing condition. Preparedness includes activities such as understanding risks, developing emergency plans, and training based on those plans. The principle of 'prepare' considers all other principles—what is needed to absorb and resist and to restore and recover from flooding.

4.1.1 Community Education and Awareness

Important characteristics of resilient communities are that residents are knowledgeable about their risk of flooding and are aware of actions that may be taken to reduce flood risk. As described in **Chapter 3**, knowledge about general flood risk and levee fundamentals is an essential first step. If other dams or levees exist within the watershed, it is important for communities to understand the risk and benefits of other infrastructure and how they may work together to manage flood risks. For instance, upstream dams can regulate flow in the watershed, decreasing the probability of flooding. However, large releases can cause rapid increase in river levels downstream.

A greater understanding of flood risk, combined with increased awareness of how hazards can change over time and the consequences in the leveed area, can motivate leaders and residents to take action to reduce their risk. Communities who understand their flood risks may also feel more comfortable participating in the engagement process for building community resilience and take action on a personal level to reduce their individual flood risk.

4.1.2 Individual Actions

Once individuals have an understanding of flood risks, they can choose to implement actions to protect their property and/or reduce exposure and vulnerability of property to flood risks, such as:

- Purchasing flood insurance.
- Elevating their homes or other structures.
- Flood proofing their homes, businesses, or other structures.
- Accessing grant programs or loans for rebuilding or relocation.
- Participating in a community’s strategy for acquiring flood prone property or relocating flood prone structures.

Individuals can also take actions that improve their ability to safely get out of harm’s way when flooding does occur, such as:

- Assembling emergency supply kits, also known as ‘go-bags,’ which contain essential items in the event community members are displaced from their homes. Kits include items specific to individual needs, such as medication, batteries, food, water, lightweight clothes, and items for young children and pets.
- Developing and practicing family communication plans that include strategies for how to communicate before, during, and after a disaster.
- Signing up for emergency notifications through local jurisdictions or office of emergency management.
- Assembling and protecting personal documents such as birth certificates, passports, medical records, property deeds, and insurance papers. Documents can be stored in a waterproof safe, as digital copies in the cloud, or multiple copies in separate locations such as a safe deposit box.
- Identifying and practicing evacuation routes. Practicing is essential to understanding the safety and practicality of plans, in particular for those in elevated or flood proofed structures.

- Learning the locations of local shelters and aid distribution centers, as well as those in neighboring jurisdictions.

4.1.3 Community Emergency Planning

To effectively enhance resilience, every community should have an emergency response plan specific to flooding. **Chapter 10** details best practices for emergency preparedness, management, and response activities specific to levees. Community-based emergency planning should be done collaboratively and in a manner that is complementary to the levee-specific efforts. Planning should include response activities for when the scope of the incident expands beyond the levee itself and has the potential to impact the surrounding community. These efforts should also acknowledge that flooding can also occur from rainfall or other flood sources not related to the levee, which in some cases pose a greater risk to the community. The community emergency preparedness efforts should include evacuation planning, training and exercises of emergency response plans, and a continuity of operations plan.

4.1.3.1 Flood Forecasting and Warning

Flood forecasting is a process of estimating and predicting the magnitude, timing, and duration of flooding based on known characteristics of a watershed. Flood forecasting can provide communities with the time and information necessary to prepare for potential flooding impacts and take necessary flood risk management measures—such as closing recreational areas, initiating evacuations, and relocating property. A flood warning should be disseminated through an emergency management system or the National Weather Service to the community when the threat of flooding is imminent or already happening based upon flood forecasting.

An effective flood forecasting and warning system requires attention to three basic factors:

- Collect data via the flood forecasting sensing equipment such as rainfall and stream gaging through automated systems, as well as manual observations of field conditions.
- Process data using hardware, software, and manual observations to produce flood hazard information.
- Disseminate the flood hazard information, such as an automated alert, when the processed data indicates a threshold is reached. This flood warning dissemination system should reach communities quickly through sirens, phone calls, and text messages.

To be effective, flood warnings must be understood and received by community members. If actions are required by individuals to receive the warnings, such as registering their mobile phone number, campaigns informing and encouraging community members to take the necessary steps should be carried out.

CASE STUDY: HARRIS COUNTY FLOOD CONTROL DISTRICT'S FLOOD WARNING SYSTEM

The Harris County Flood Control District's flood warning system measures rainfall amounts and monitors water levels in surrounding bayous and creeks on a real-time basis to inform officials and the public of dangerous conditions. The system relies on 188 gage stations strategically placed throughout Harris County bayous and their tributaries. The stations contain sensors that transmit valuable data during times of heavy rainfall and during tropical storms and hurricanes.

When rain begins, data-collecting sensors transmit rainfall amounts and bayou and stream levels to repeaters, which then relay the data to primary and back-up base stations. Harris County Flood Control District staff monitors the data daily to ensure the gages are properly functioning and transmitting accurate data.

This information is used by the Flood Control District and by Harris County's Office of Homeland Security and Emergency Management to inform the public of imminent and current flooding conditions along bayous. It also is used by the National Weather Service to assist in the issuing of flood watches and warnings. The information is provided on a website with an interactive map that can be accessed by community members. The Harris County flood warning system also includes text, email, and social media (Twitter, Facebook, Google) notifications that anyone can register to receive.

Accurate rainfall and bayou/stream level data helps the public and emergency management officials make critical decisions that can ultimately reduce the risk of property damage, injuries, and loss of life. The Flood Control District urges the public to use this information and take the appropriate precautions during times of heavy rain and flooding (Harris County Flood Control District, 2023).

4.1.3.2 Evacuation Planning

Evacuation plans provide strategies to relocate individuals out of harm's way safely and effectively during a hazardous flood. Flood-related evacuation planning must consider a community's unique flood risk and response capabilities, and the potential impacts to a community from a levee breach or overtopping.

Past natural disasters have been widely studied, critiqued, and used as an opportunity to identify lessons learned and subsequent development of evacuation best practices. Many after-action review sessions looked throughout the pipeline of federal agencies to local jurisdictions, including a review of emergency services response efforts such as search and rescue, health and medical services, and key partners throughout emergency evacuation activities.

The reviews highlighted the integrated nature of impacts from flooding. For example, physical damage to infrastructure and the built environment can have immediate and long-term impacts to evacuation, displacement, safety measures, and loss of life. Key understandings from the reviews include the importance of:

- Preparedness by government and other response agencies.
- Effective communication prior to a storm or flood and throughout all activities, both within and across response agencies, hospitals, and other local organizations.
- Coordinated efforts across all entities.
- Tailoring response actions to the unique circumstances of an impacted community, including an understanding of residents' needs, matching efforts to attend to their needs, and protecting residents' life and safety.

Table 12-2 provides a list of lessons learned and associated best practices documented in these reviews. Refer to **Chapter 10** for additional information related to communication before, during, and after a flood.

Table 12-2: Emergency Evacuation Lessons Learned and Informed Best Practices

Lesson Learned	Best Practice
Effective, efficient communications are essential to successful and equitable evacuation.	• Utilize alerts and early warning systems. • Asses needs, develop messages, identify key partners, and select tactics for message delivery as early as possible, and continue throughout response and recovery activities. • Ensure communication content is clear, concise, and timely. • Incorporate redundant platforms. • Ensure content is accessible (e.g., produce in multiple languages for those who are non-English speaking, ensure Americans with Disability Act compliance for those with visual disabilities). • Include all key partners in communications, including hospitals/healthcare facilities, essential services, and community organizations.
Interagency coordination facilitates successful evacuation by improving timely actions, compliance, communications, and resourcing.	• Coordinate activities across sectors that support and enhance evacuation activities. • Include local organizations to improve reach and knowledge of impacted areas. • Integrate platforms within and across agencies for seamless sharing of information and coordinating efforts.
Evacuation plans and plan management can improve successful actions throughout an incident and is key to safety and life-protecting measures.	• Prior to a flood, develop comprehensive, realistic, usable evacuation plans. • Update plans annually, at a minimum. • Provide annual trainings and exercises for response personnel, key partners, and stakeholders. • Provide ongoing educational opportunities for residents to increase awareness of risks, up-to-date evacuation routes, and available resources and services. Updated information should be communicated during a flood if/as resources or available services change. • Prior to a flood, encourage critical facilities to have their own evacuation plans for seamless integration into broader response activities. • Ensure evacuation plans include resource lists with emergency equipment, personnel contact information, evacuation routes and facilities, sheltering needs, and personnel. • Focus on leveed communities, immediate surrounding areas, and neighboring jurisdictions. • Include unique needs and characteristics of vulnerable populations and underserved communities in all evacuation plans.

Lesson Learned	Best Practice
Resourcing across response activities is essential and can be a distinguishing factor between life and death. This is inclusive of material goods, human resources, or financing.	• Ensure resources are sufficient, stockpiled, and funded prior to a flood. • Assess equipment for operability and accessibility prior to a flood; include fuel availability and coordinate with fuel management plans. • Train and staff human resources, including redundant sources of staff such as volunteers. • Coordinate with volunteer agencies and include them in planning activities. • Coordinate with donations management for critical goods, including medical supplies, equipment, and financial assistance. • Review Mutual Aid Agreements/Memorandums of Understanding on an annual basis to ensure agreements are active and up to date.
Timely actions are critical to ensure safety and life protection measures.	• Monitor and assess the situation throughout response activities during a flood and into recovery as necessary. • Activate flood warning systems to the public as early as possible. • Activate interagency coordination protocols prior to an incident as able, or as soon as possible in a no-notice flood. • Ensure resources are available. • Review and secure agency capabilities. • Activate evacuation procedures and orders as early as possible, even prior to an incident, as necessary. • Follow above best practices, as soon as an incident occurs and throughout the incident.
Evacuation routes/improved transportation is a key item for evacuating a community impacted by floods, as the mass disruptions to public transportation mechanisms, road closures, and the inequitable distribution of access to transportation restricts ability for residents to leave.	• Ensure accessible transportation is provided to individuals with access and functional needs. • Build awareness of evacuation routes for at-risk communities through public engagement and educational opportunities prior to a flood. • Communicate updates for evacuation orders to impacted communities throughout a flood. • Monitor functionality of public transportation services and evacuation routes for access throughout response and recovery activities.
Vulnerable populations and underserved communities need to be considered and included throughout the planning process and associated response activities.	• Include the unique resourcing needs and/or specialized assistance for vulnerable populations and underserved communities into all evacuation planning and response activities. • Integrate training and exercise activities to strengthen capabilities and build awareness. • Coordinate government agencies with community organizations and other trusted messengers specializing in accessibility needs, community leaders who have knowledge of and access to immigrant communities, and those populations with differing needs.

Evacuation plans should consider the range of exposure for all members of the community and tailor actions based on the potential flood depths throughout the leveed area, accessibility of transportation systems, and the unique vulnerabilities of community members. Further, impacts of floods to transportation systems should be considered when identifying evacuation routes. The time required for those within the leveed area to evacuate should be considered when establishing flood warning systems so that people can evacuate before roads become impassable and buildings get inundated.

CASE STUDY: NEW ORLEANS CITY-ASSISTED EVACUATION

The city of New Orleans developed the City Assisted Evacuation to help New Orleans' residents and visitors who wish to evacuate during an emergency but lack the capability to self-evacuate. It is meant to be an evacuation method of last resort, and only for those who have no other means or have physical limitations that prohibit self-evacuation.

The City Assisted Evacuation utilizes city facilities, personnel, and other resources to provide the service. The service allows individuals to bring one carry-on sized bag with supplies (not including medical devices, diaper bags, and other necessary personal items). It also provides accommodation for pets to be taken to an animal shelter near where the person is sheltered.

A dedicated center is established as the hub for evacuation for those who can't leave on their own, where individuals are registered for evacuation. From there, evacuees would board a bus, train, or airplane to a state or federal shelter. Multiple options are provided to transport individuals to the dedicated location, including:

- **Evacuspots**: There are 17 pickup locations across the city, called evacuspots, where dedicated shuttle buses will be bringing evacuees to the center. Five evacuspots are specifically for seniors. An example of an evacuspot is shown here at Mary Queen of Vietnam.

- **Bus routes**: Buses run on a Saturday schedule and all bus routes ending at Duncan Plaza will make a final stop at the center.
- **Drop-offs and walk ups**: Evacuees can be dropped off or walk to the center.
- **Rideshare**: Instructions are provided for drop-off locations if evacuees are using a rideshare to get to the center.

If individuals are unable to evacuate on their own because of medical needs, instructions are provided to apply to be picked up from your home. Eligibility requirements apply (City of New Orleans Office of Homeland Security and Emergency Preparedness , 2023).

Evacuation planning efforts should also identify and consider the needs of those who would experience challenges to evacuating, such as those without personal transportation, residents of nursing homes, hospitals and day cares, persons with access and functional needs, those experiencing extreme poverty, and those with pets. Accommodations should be in place to help support evacuation—such as providing transportation suitable to safely accommodate physically disabled persons during evacuation and designating elevated structures to shelter in place.

4.1.3.3 Exercises

Local emergency management agencies typically conduct table-top, functional, and full-scale drills and exercises of their emergency action plans on a regular basis. These exercises mimic real emergency events and are a best practice for training and preparing to activate an emergency plan. Drills and exercises also provide an opportunity for participants to build relationships with partner agencies and identify opportunities to improve emergency capabilities.

While not all exercises will involve flooding, flood-related exercises should consider a community's specific flood risks and incorporate levee and flood emergencies into their exercises to mimic the activation of the levee emergency action plan and the community's evacuation plan.

Drills and exercises present an opportunity for emergency management or other partner agencies to familiarize themselves with the strategies and practice suggested actions, to ensure that access and functional needs are integrated, and the whole community is appropriately included.

CASE STUDY: CITY OF SACRAMENTO, CALIFORNIA FLOOD DEPTH AND EVACUATION MAPS

The city of Sacramento has prepared detailed maps showing hypothetical levee breaches for a 200-year flood. These maps estimate the inundation levels and the time it would take for waters to rise in affected neighborhoods and rescue and evacuation zones after seven days without mitigation. These maps, along with evacuation instructions, are provided to community members. Community members are encouraged to learn possible evacuation routes and heed instructions issued by emergency management personnel during a flood (City of Sacramento Department of Utilities, 2022).

4.1.3.4 Planning for Continuity of Operations

A continuity of operations plan details how an organization will remain operational and perform essential functions following any flood that makes it unsafe or impossible for employees to work under normal conditions or in the normal location. Continuity of operations plans go beyond activities detailed in an emergency action plan including:

- Delegation or transfer of authority.
- Identification of essential functions (information technology, payroll, communications).
- Alternate facilities for performing work.
- Alternate transportation and remote work capabilities.

- Access to and safeguarding of information (physical, local server, cloud).
- Return to normal operations.

The development and execution of these plans for all community lifelines—which are the most fundamental services in the community that, when stabilized, enable all other aspects of society to function—is critical to a community's ability to absorb and recover from flooding impacts.

4.2 Absorb and Resist

To absorb means to receive a stress or endure change with minimal damage and without loss of normal functionality. To resist means to withstand the force or effect of flooding. A range of options can be considered to improve a community's ability to absorb or resist flooding from a full range of hazards, including those not associated with the levee.

Options can vary from small-scale projects on individual properties to large-scale projects on a community level. Small-scale projects on individual properties can typically be taken on at the owner's discretion. While benefits to the property can be significant, they are typically concentrated to a localized area. Large-scale community-level projects require more extensive resources and engagement but can have significant impacts on the community's flood resilience. Because large-scale projects can have such far reaching impacts, community engagement is essential to fully understand potential adverse impacts, select the most meaningful options, and offer community members a voice in the decision-making process. The following sections present options to absorb and resist flooding that can be applied on a community level, as well as by individual property owners.

4.2.1 Land Use Planning

Adopting land development policies or zoning codes which reduce, restrict, or establish standards for development in flood prone areas can effectively enhance a community's ability to absorb and resist impacts of flooding. Communities should consider the likelihood of flooding from all sources and potential consequences in order to adopt policies or codes that are commensurate with their values and tolerability to flood risk.

Many communities adopt a flood damage prevention ordinance which establishes a minimum first floor elevation for houses and buildings to reduce a building's exposure to floods and the subsequent damages if flooding occurs. This designated

CASE STUDY: STATE OF NEW JERSEY MODEL FLOOD DAMAGE PREVENTION ORDINANCES

The state of New Jersey model flood damage prevention ordinance provides a higher standard for development than that which is required for participation in FEMA's National Flood Insurance Program. New Jersey regulates flood hazard areas that are in watersheds measuring 50 acres or greater in size and most riparian zones in the state. The model ordinance requires a comparison of the state-identified floodplains with the FEMA effective flood insurance rate map and FEMA preliminary flood hazard data. The most restrictive of these datasets establishes the flood elevation by which development is regulated.

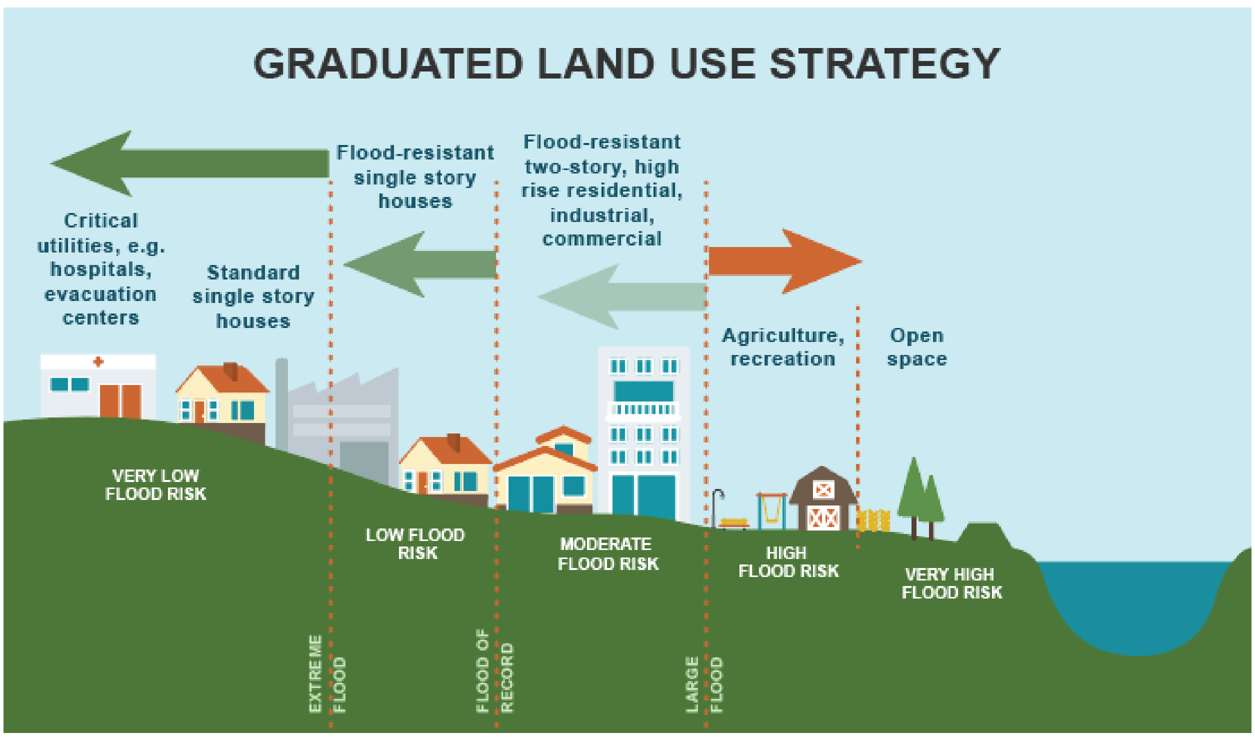
Within the regulated flood hazard area, the model ordinance includes a standard for communities to build the first floor of a building to at least 1 foot higher than this established flood elevation. The first floor of critical facilities must be built to either 2 feet above the flood elevation or the 0.2% annual exceedance probability flood elevation. Because of these higher standards, the regulated flood hazard area in New Jersey is more expansive and more restrictive than FEMA (State of New Jersey Department of Environmental Protection, 2023).

elevation typically correlates to a probability of flooding and is at least 1 foot higher than the 1% annual exceedance flood in most communities. Most states offer a model ordinance to help communities adopt a legally defensible ordinance.

If a levee overtops or breaches, areas immediately adjacent to levees are most susceptible to flood damages due to the velocity and quantity of flow moving through or over the levee. In addition to the access corridor discussed in **Chapter 9**, communities may acquire additional right of way or adopt an ordinance restricting development in areas adjacent to the levee.

Policies may also establish zones based on flood risk that have graduated restrictions on development based on the expected flooding levels and frequency for an area. For example, areas closest to the levee with very high flood risk might only allow recreational or agricultural uses, while areas further from the levee with very low flood risk might allow commercial and industrial uses. In between zones may allow residential and commercial development but require minimum first floor elevations. Figure 12-8 demonstrates the concept of a graduated land use planning policy behind a levee. Not only does this approach reduce consequences of flooding, but can also decrease severity of floods by decreasing runoff and obstructions to flow of floodwaters and increasing the ability of the environment to absorb water.

Figure 12-8: Graduated Land Use Strategy



Stormwater ordinances can also reduce flood risk. Best practices in stormwater ordinances on new construction include requiring ‘zero run-off,’ on-site detention, permeable pavement, vegetative buffers, and erosion and sedimentation control. Similar ordinances can apply to agricultural activity. These practices can improve the environment’s ability to naturally absorb water from rainfall or convey rainfall into drainage systems.

4.2.2 Building Codes

Building codes are laws that set minimum requirements for how structural systems, plumbing, heating, ventilation and air conditioning, natural gas systems, and other aspects of residential and commercial buildings should be designed and constructed. These laws are enforced at a state or local government agency. An example of a flood resistant building code is the requirement for steel exposed to salt water, salt spray, or other corrosive agents to be hot-dipped galvanized after fabrication.

The international codes—developed by the international code council—are a family of 15 coordinated, modern building safety codes that help ensure the engineering of safe, sustainable, affordable, and resilient structures. These consensus-based building codes incorporate the latest technical standards and best practices as published by many different industry groups and stakeholders, such as the American Society of Civil Engineers and the Federal Emergency Management Agency (FEMA). The international codes are updated approximately every three years incorporating the latest technical standards and best practices as published by many different industry groups and stakeholders. Therefore, adopting building codes based on the latest editions of the international codes is one of the best tools communities can use to enhance their resilience to floods in their jurisdictions, particularly for new construction.

Flood resilience provisions in buildings codes require design and construction to be resistant to floods. Two specific examples of flood resilience provisions include:

- Requiring the lowest floors to be elevated 1 foot above the 1% annual chance exceedance probability flood elevation.
- Requiring electrical, mechanical, and plumbing systems and components—if they are located below the pertinent flood elevation—to be designed and installed to prevent water infiltration and resist forces exerted by water depths and flows.

As described in the previous section, communities are encouraged to adopt a flood damage prevention ordinance. These ordinances complement the building codes by including standards for flood resistant design and construction of buildings and structures. In addition to making buildings more resilient, strong building code enforcement can improve competitiveness for resilience grants that are available from state and federal agencies.

4.2.3 Natural and Nature-Based Solutions

Natural and nature-based solutions focus on conserving, restoring, and engineering natural systems for the benefit of people and ecosystems. Natural features (those produced purely by natural processes) and nature-based features (those produced by a combination of natural processes and human engineering) can provide flood risk management benefits along with other economic, environmental, and social benefits. In response to changing natural hazards and to proactively address climate-related risks, many communities are looking for ways to build resilience that yield the most benefit for the least cost. Thoughtfully planned nature-based solutions can contribute to a community's resilience. The International Guidelines on Natural and Nature-Based Features for Flood Risk Management offer a comprehensive guide to identifying, planning, and implementing natural and nature-based features (Bridges *et al.*, 2021).

Natural and nature-based solutions that increase flood resilience for communities with levees can vary widely in size and location. Larger sized solutions on a watershed scale involve interconnected systems of features such as natural areas and open space. These solutions reduce flood risk by keeping flood prone areas clear of development and provide flood storage to lower water surface elevation and velocity which lowers risk to levees and communities. A good source for more information is The Building Community Resilience with Nature-Based Solutions, A Guide for Local Communities (FEMA, 2021). Common solutions include:

- **Land conservation:** Land conservation involves preserving open space through acquisitions and easements to reduce the potential for development. It is most effective on a large scale with a system of interconnecting open space. This enhances community resilience by leaving land undeveloped to store and infiltrate rainwater, slow stormwater runoff, and preserve floodplains from development. These benefits reduce a community's flood risk and conserve habitat for native species.
- **Greenway protection:** Greenways are corridors of protected open space managed for both conservation and recreation. Greenway protection prevents development within corridors along rivers and streams and creates recreational opportunities and improved quality of life by providing access to the water and trail systems. Greenways often follow rivers or other natural features linking habitats. Communities benefit with improved social ties by the presence of nearby natural areas open for recreational public use where individuals are more likely to work together to achieve common goals, exchange information, and maintain informal social controls, which improves community resilience.
- **Wetland restoration:** Reestablishing wetlands will absorb, filter, and store excess water and provide important wildlife habitat. Levee removal is a common method for reconnecting a floodplain to the stream or coastal waters, thereby creating wetland areas. Community resilience is enhanced by having healthier environments with wildlife habitat and recreational opportunities, improved water quality, and open spaces that draw people together.
- **Floodplain restoration:** Reconnecting floodplains to rivers allows their natural functions to return, including storing floodwater and providing wildlife habitat. Community resilience to flood risk is enhanced by lower water surface elevations and slower movement of water. Floodplain restoration also sustains riparian buffers, improves water quality, and supports wildlife habitat diversity. Setback levees are a common example of a way to achieve floodplain restoration. Refer to **Chapter 11** for more information.

CASE STUDY: NAPA COUNTY, CALIFORNIA

In February of 1986, a flash flood took three lives, damaged 245 homes and 120 businesses, caused the evacuation of roughly 7,000 people, and left 25,000 people without power for several days. In total, Napa County suffered an estimated $100 million in property damages. While Napa County has long been plagued by significant floods, the 1986 disaster solidified the importance of enacting a flood risk management strategy.

In 1998, the community opted to pursue a floodplain restoration approach, with a focus on addressing the many environmental issues (water quality, waste disposal, habitat destruction, etc.) throughout the region. The local governments of Napa and surrounding counties backed the initiative to create a more cohesive approach that used many different features and techniques to provide flood risk reduction. The design aimed to create a ‘living river’ returning the river to its natural state and using the river’s natural features to reduce the likelihood of flooding.

The Napa River project was completed in 2015 and used more environmentally friendly techniques that have added benefits. One key aspect of the plan removed bridges that blocked the river’s natural water flows. Designers wanted to ensure that the river was reconnected to its historic floodplain, thereby naturally attenuating flood flows, improving instream habitat for native fish, and helping to reduce excess sedimentation and improve water quality. Riverbank terracing allowed the water to spread horizontally into defined areas. Downstream, historic tidal wetlands that had been converted to pastureland were purchased as part of the project and restored back to a wetland habitat capable of holding water. When floodwaters rise to ‘flood stage,’ the water is diverted via a bypass channel that sends fast-flowing water around the sharp turns of the river’s natural banks. Since this bypass can only be utilized once waters reach a certain level, the oxbow of the main river remains connected to the main channel, preserving the existing habitat. Finally, low floodwalls and tiered levees were also constructed to further enhance flood risk reduction.

Although flood risk management is the main goal, the design of this project considered other possible benefits including recreation, access, and environmental restoration. The expanded and restored wetlands provide critical habitat for threatened native birds and other wildlife, social and recreational benefits have been realized through the creation of additional open space areas such as parks, and over six miles of trails have been created–enhancing the river’s aesthetic appeal and increasing riverfront access. Other benefits include potential economic investment as a result of restoring the river and minimizing once flood-prone areas thereby attracting increased and new business development in downtown Napa.

The photo displays the elevated railroad and roadway bridges over the new bypass channel. The bypass channel converges with the more natural river downstream (Napa County Flood Control & Water Conservaton District, 2023).

Smaller sized natural and nature-based solutions can be implemented in localized areas within a neighborhood or individual property. These solutions, often referred to as ‘green infrastructure,’ typically involve distributed stormwater management practices that manage rainwater where it falls, slowing stormwater runoff. These practices can be built into a site’s structure, corridor, or neighborhood without requiring additional space.

These smaller-sized solutions are highly effective for leveed areas in managing flood risk from stormwater and may include:

- **Stormwater parks, rain gardens, and bioretention systems**: A variety of types and scales of vegetated, low areas exist which can effectively collect and absorb stormwater runoff. These elements include attractive landscape features, habitat, and safe environments for walking and biking in urban settings. Stormwater parks are recreational spaces that are specifically designed to withstand flood impacts, store stormwater, promote groundwater recharge, and protect adjacent areas from flooding. Stormwater parks can be a single playground and ball field or a large urban area park with multiple features. Rain gardens and bioretention systems work in the same way, but on a smaller scale. By storing and treating stormwater, these projects can reduce flooding elsewhere and improve water quality.
- **Green roofs**: Green roofs involve planted mediums and vegetation on the top of structures like buildings to absorb rainwater and reduce runoff.
- **Rainwater harvesting**: Rainwater harvesting is the collection and storage of rainfall in man-made or natural basins to reduce runoff. Harvesting can be achieved with projects as large as a retention pond or as small as a household rain barrel.
- **Permeable pavement**: Constructing roadways or walkways with permeable pavement allows rainwater to soak through the top layer into the ground, reducing runoff.
- **Trees**: Natural vegetation reduces runoff by catching rainfall on leaves and branches, which have co-benefits of capturing carbon and reducing urban heat island effect.
- **Green streets**: Green streets integrate multiple green infrastructure features into the design of a street or alleyway to store and filter stormwater. Permeable pavement, bioswales (i.e., long, vegetated trenches), planter boxes, and trees are among the common features that can be woven into street or alley design, while also providing a safer environment for biking and walking.

CASE STUDY: SMART SEWER PROGRAM FOR KANSAS CITY WATER

Kansas City leaders have added nature-based solution elements to traditional infrastructure to reduce stormwater flooding. They have partnered with the Environmental Protection Agency to address its sewer and stormwater overflows during rain events by combining nature-based solutions and traditional infrastructure. When planning these projects, Kansas City Water engages the public at community meetings. By learning about neighborhood needs, project leaders can prioritize different types of nature-based solutions.

The Smart Sewer program is using small-scale solutions like rain gardens, green roofs, and pervious pavers to go with larger projects, which include bioswales, permeable pavement, infiltration trenches, prairies, and detention wetlands. Nature-based solutions help the city meet its stormwater flooding and overflow goals, as well as its goal to have net zero emissions by 2040 (FEMA, 2023).

Green infrastructure at Liberty Courtyard in Kansas City, Missouri.

CASE STUDY: CITY PARK, NEW ORLEANS, LOUISIANA

City Park is a 1,300-acre urban park located in the northern section of New Orleans. Founded in 1854, the park has provided recreational opportunities to the citizens of New Orleans for nearly two centuries. Today the park features athletic fields, two 18-hole golf courses, museums, and restaurants.

A defining feature of the park is the 137 acres of lakes and lagoons that serve as drainage features, while also providing recreation opportunities including boating and fishing. The lagoon system connects to the city of New Orleans drainage system including Bayou St. John and the Orleans Canal. An operable weir allows the city to lower water levels in the lagoons in advance of a rain event. New Orleans relies substantially on pump stations connected to its canal system to drain the city during rain. The rainwater storage provided by City Park allows the city's drainage pump system to catch up before stormwater is released to the system.

Pictured is a graphic of the conceived lagoon cycle on the left and an aerial photo of the lagoon after construction on the right (City Park Conservancy, 2023).

4.2.4 Property Acquisitions

Property acquisitions (or buyouts) can have both immediate and long-term benefits. Through acquisition and demolition of existing flood-prone properties, communities effectively eliminate flood risk for a particular residence, business, or infrastructure. In some cases, property acquisition may create the opportunity to convert high-risk developed areas to open space and natural areas, thereby increasing the ability to absorb flood impacts.

Property acquisition must be done with careful and extensive community engagement, particularly if the property impacted is comprised of residences or has cultural importance to the community. Availability of affordable housing is an important consideration if property that is targeted for buyout includes residences that are rented or owned by individuals experiencing poverty. Pursuing property acquisition without gaining community consensus on the option can have negative impacts on the community's identity and social cohesion and can exacerbate social inequities.

4.2.5 Structure Elevations

Where property acquisition is not a viable option, elevating structures can achieve a similar level of risk avoidance. Elevating structures so that the first floor is lifted above a determined flood elevation will provide individuals with the opportunity to shelter in place during floods to a certain level but may also create a false sense of security that the structures are always safe in all situations. In determining if structure elevation is an appropriate option, communities must evaluate multiple factors including accessibility during a flood, depth of flooding, velocity of flood flows, safety of first responders, and evacuation routes for each structure. Local ordinances and/or building codes which set standards for first floor elevations on new construction should also be considered.

A GUIDE TO BUYOUTS

University of North Carolina's 'Floodplain Buyouts: An Action Guide for Local Governments on How to Maximize Community Benefits, Habitat Connectivity, and Resilience' provides a comprehensive overview of property acquisition for flood-prone structures including potential funding sources and considerations for long-term management (Environmental Law Institute, University of North Carolina Institute for the Environment, 2017).

4.2.6 Floodproofing

Floodproofing involves modifications to structures or equipment to reduce damage caused by inundation and shorten the recovery period after a flood. Flood proofing critical facilities is especially important for reducing the impact and disruption to a community from flooding. These measures can be employed as retrofits to existing structures or designed into new construction. Like structure elevations, accessibility and evacuation capabilities are important factors when considering investments in flood proofing. Floodproofing is not recommended for areas subject to flood depths greater than 3 feet or high velocity flows because pressures exerted by greater depths and velocities can cause walls to buckle or collapse. Two types of floodproofing exist—dry and wet.

Dry floodproofing involves waterproofing exterior walls and closing off penetrations and entry points to prevent flood waters from entering the building. This can be done to residential homes as well as commercial and industrial structures. For buildings with basements and/or crawlspaces prone to flooding, dry floodproofing could be considered to protect upper levels by creating a barrier which makes the first floor impermeable to the passage of floodwater from below. Dry floodproofing is used to enhance the resilience of a building by keeping water out of the building so the building can continue operation. Dry floodproofing is a common strategy for critical facilities such as hospitals. Figure 12-9 shows an example of dry floodproofing of impermeable wall surface and a temporary closure at building entry point (FEMA, 2013).

Figure 12-9: Dry Floodproofed Building with Aluminum Shield Temporary Closure

Wet floodproofing involves a combination of strategies that reduce damage to structures and belongings, while allowing flood waters to enter an uninhabited portion of a building. This is done through relocating or elevating equipment, appliances, or utilities to a higher level, installing flood-resistant materials, such as concrete floors, and providing flood vents, or permanent openings, that allow water to enter the structure, thereby reducing pressure differential between exterior and interior and reducing the likelihood of structural damage or collapse. Structures which are likely to experience flooding, such as riverfront businesses, can more quickly rebound and be functional following a flood if floodproofed. Figure 12-10 shows an example of flood openings that allow water to enter and exit the lower level of the building (FEMA, 2013).

Figure 12-10: Wet Floodproofed Building with Flood Openings

4.2.7 Improve Stormwater Drainage System Capacity

While levees can reduce flood risk from major flooding sources, those same levees can also prevent stormwater from draining out of the leveed area. Stormwater collecting in the leveed area creates flood risk to people and property if it is not managed. In some levees, pumps evacuate water from the leveed area. In extreme floods, pumping systems may struggle to keep up with rainfall. Alternatives to pumping include creating storage and conveyance features that allow stormwater to safely collect during a storm and be drained or pumped out following the storm. This can be accomplished with some of the nature-based solutions discussed earlier or with larger infrastructure projects such as underground storage facilities.

4.2.8 Harden or Elevate Infrastructure

Infrastructure such as roads, bridges, water, and wastewater treatment plants are commonly located in flood-prone areas. Elevating roads and bridges above flood elevation can improve access for first responders and lengthen evacuation windows during floods. Additional hardening measures such as armoring shoulders, embankments, and bridge components (e.g., abutments, piers, approaches) can decrease their risk to flood damage. Flood risks can be reduced for water and wastewater treatment plants and other critical facilities that cannot easily be relocated by elevating important systems critical to the facilities' operation such as control equipment, pumps, and power supplies. Even if the facility gets shut down during a flood, critical equipment that is elevated above flood levels will likely remain unaffected, allowing the plant to come back online sooner, with fewer flood damage-related repairs and costs.

4.3 Restore and Recover

To restore and recover is to return to the previous or improved state of functionality following a disruption or when conditions have changed. This includes re-openings of critical facilities, such as schools or community centers, and building back in a way that allows for less damage or disruption from similar future events.

Small, rural, and low-income communities, as well as others who have been historically marginalized, may need additional support in recovery. Accessing federal assistance programs which can support individuals in their recovery is complex. People from underserved populations have historically received less federal recovery assistance than wealthier and more-resourced communities. Therefore, it is important to identify ways to make the process and distribution of resources more equitable and inclusive.

The following options can build community resilience by focusing on opportunities during the recovery phase.

4.3.1 Recovery Planning

Preparing to recover from flooding can be as impactful on a community's resilience as preparing for the flood itself. Recovery efforts aimed at restoring, redeveloping, and revitalizing the health, social, economic, natural, and environmental fabric of the community often begin while response is still occurring. While a recovery plan should be based on the specific conditions at the time, advanced planning and training can set those immediate recovery efforts up for success, making it more seamless and efficient. This advanced, or pre-flood, planning should include strategies to engage the whole community and to ensure current conditions are well understood to then base recovery actions upon. Recovery planning should also include engagement with partners at the federal, state, tribal, and local levels to establish an understanding of each of their roles and responsibilities.

Seven important elements of recovery planning include:

- **Identify a planning team** pre-flood to oversee the recovery planning process and activities. This should be an inclusive team who can represent or understand the diverse needs of the community.
- **Complete an initial recovery plan** that provides an overall strategy and timeline and integrates socioeconomic, demographic, accessibility, technology, and flood risk considerations.
- **Establish a leadership team** to lead, coordinate, and drive the recovery process.
- **Manage community expectations** through clarity, accuracy, and transparency in recovery plans and actions.
- **Focus on restoring and sustaining essential services** to maintain community functionality.
- **Assess economic issues** and identify potential inhibitors to fostering stabilization of the affected communities.

- **Identify affected populations**, groups, and key partners in recovery. Effective planning can lead to opportunities to advance equity by prioritizing the needs, services, assets, housing, and jobs for people from vulnerable populations and underserved communities.

4.3.2 Flood Insurance

Flood damage is not typically covered under standard homeowners' and renters' insurance policies; a separate flood insurance policy is usually needed. Flood insurance is available for residential and commercial properties and can pay for the costs of repairing damage or rebuilding structures, up to the policy limit. Flood insurance works like other insurance products—the property owner pays an annual premium based on the property's flood risk and the deductible chosen. If the property or its contents are damaged or destroyed by flooding, the policy owner will be paid for the amount required to repair the damage or rebuild the structure up to the policy limit.

Anyone can purchase flood insurance regardless of whether or not the property is situated in a floodplain, since property and structures may be at risk of flooding even if they are not located in a floodplain. Flood insurance can help make the recovery process quicker, easier, and less costly for property owners.

NATIONAL FLOOD INSURANCE PROGRAM

FEMA administers the National Flood Insurance Program. This program offers flood insurance to property owners, renters, and businesses in participating communities through private insurance companies. Participation in the National Flood Insurance Program is voluntary. Communities that join agree to adopt minimum floodplain management regulations that contribute to reduced flood risk for the community.

4.3.3 Grants and Emergency Funding

In the event of a flood, disaster assistance may be limited or unavailable. A variety of local, state, and federal financial assistance may be available, depending upon circumstances of the flooding, as well as the county and state in which a community resides. States typically have a Disaster Emergency Fund to help finance recovery efforts, and some states and counties have additional resources that may be available. Federal disaster assistance may also be available if a disaster declaration is made by the president. It is important communities understand the resources available to them and the process for accessing the funds before a flood occurs. Accessing these resources can present opportunities for communities to implement the various options discussed in this chapter to make communities more resilient.

The American Planning Association has created a list of resources among federal agencies and some national nonprofits which can assist with the recovery process.[1]

[1] The list of resources from the American Planning Association can be accessed at: https://www.planning.org/research/postdisaster/programs.htm.

CASE STUDY: JASPER COUNTY, TEXAS USE OF NATURAL RESOURCES CONSERVATION SERVICE EMERGENCY WATERSHED PROTECTION PROGRAM

Rural areas like Jasper County, Texas, lack the resources for large-scale construction projects when storms like Hurricane Laura cause damage to critical infrastructure within the watershed. The Natural Resources Conservation Service's Emergency Watershed Protection program provides a lifeline for these local communities to recover. The Natural Resources Conservation Service has been doing business with Jasper County for decades supporting the county throughout many storms, including Hurricanes Harvey and Laura. It also includes support for flooding from rainstorms that don't get names. This has been a huge help for Jasper County since the county has limited staff.

The photo shows a segment of the 33-foot by 8-foot sand-cement bag headwall that stabilizes the downstream slope of the road down to the creek channel.

Photo by Adele Swearingen, Natural Resources Conservation Service Public Affairs Specialist, Bryan, Texas (Adele Swearingen, 2023).

5 Prioritize and Implement

Once a broad range of options are considered, community engagement should guide the next steps of determining which options are the most appropriate for the community—in terms of their effectiveness (impact on community flood risks), efficacy (considering community resources and capabilities), and support of community values and vision for flood resilience. Developing a transparent process for prioritizing and implementing the options will increase the likelihood of successful completion. This section introduces common factors communities use in prioritizing options and a set of standard elements found in implementation planning.

5.1 Prioritization

Community engagement plays a key role in the prioritization and eventual selection of flood resilience options that are most appropriate for the community. It is essential that all community members are given equitable opportunity to participate in the process. Examples could include holding community meetings in locations convenient for those who lack access to transportation, enlisting the help of trusted messengers in culturally diverse neighborhoods, and ensuring information is available in different formats and languages. **Chapter 3** describes additional considerations for ensuring equitable engagement.

The common factors communities may use to prioritize flood risk management options include:

- **Feasibility.** This is determined by the community's ability to implement the option and whether or not they have identified and/or secured sufficient funding. Further consideration may be given to the ease or complexity of the proposed option implementation.
- **Equity. This** is determined by the option's ability to advance the community's equity goals and if it directly benefits vulnerable populations and underserved communities.
- **Climate resilience. This** is determined through the option's ability to improve the community's ability to prepare for and adapt to changing climate conditions and withstand and recover rapidly from disruptions.
- **Community values**. These are reflected in prioritization by how well the option aligns with input and ideas received through engagement activities designed to identify community preferences for different types of projects and the issues that concern them the most.
- **Risk reduction**. This includes the economic, social, and environmental losses avoided or benefits gained through the option.
- **Costs**. These are considered in prioritization and include staff time, design, construction, and lifecycle operation and maintenance (O&M) costs. Full benefit-cost analyses are not typically feasible at this point in the planning process, however, may be required when applying for grant funding.

Additional prioritization factors specific to a community may be identified during engagement.

CASE STUDY: ANN ARBOR MITIGATION ACTION PRIORITIZATION

The city of Ann Arbor, Michigan, and its residents place a high value on equity, inclusive engagement, and addressing climate change. When the city updated its hazard mitigation plan in 2022, it wanted to make sure equity and community priorities were addressed in the mitigation actions and in how those actions were prioritized. The prioritization process included five prioritization metrics, weighting factors, and scoring criteria described in Table 12-3. Beyond the typical prioritization metrics of feasibility, risk reduction, and cost, Ann Arbor elected to include equity, community values, and climate resilience (Stantec, 2022).

For equity, the city chose to incorporate an Opportunity Index, which identifies neighborhoods with low access to opportunity. The index measures access to opportunity by combining 16 indicators into five categories: health, job access, economic well-being, education and training, and community engagement and stability. Mitigation actions benefiting areas identified as having ‘very low access to opportunity’ received maximum points for equity. For climate resilience, the criteria and points were based on how well the action helped the city mitigate and adapt to climate change. Finally, for community values, criteria and points reflected the results of the project’s public survey.

The weighting factors chosen for the three metrics also reflect the city’s commitment to equity, inclusive engagement, and addressing climate change. The equity and climate resilience metrics received the same weighting factor as feasibility (20%), while the community values metrics each received weighting factors of 10%, equal to risk reduction/benefits and cost. These weighting factors send a strong message about the city’s priorities. The emphasis on equity allowed the following mitigation action to score highest among the actions included in the hazard mitigation plan:

- Utilize neighborhood asset mapping to improve community mutual aid by identifying residents' resources, skills, and needs.
- Develop a community resilience public engagement strategy that focuses on building partnerships and creating space for vulnerable populations to share their lived experiences and use this information to help shape the city's approach to emergency planning and mitigation.
- Include the Housing Commission and low-income and senior housing entities in emergency action plan updates.

Table 12-3: Example Resilience Project/Program Prioritization

	Prioritization Metric	Weighting Factor	Scoring Criteria	Possible Points
1	Feasibility	20%	5 – Funding identified, easily implemented within five years. 3 – Funding identified, implemented with only moderate complexity or delays. 1 – Funding identified, implementation is complex and faces certain delays for implementation. 0 – Not feasible, no funding identified and/or not able to be implemented.	100
2	Equity (as tied to a city’s opportunity index)	20%	5 – Very low access to opportunity. 3 – Low access to opportunity. 1 – High access to opportunity. 0 – Very high access to opportunity.	100

	Prioritization Metric	Weighting Factor	Scoring Criteria	Possible Points
3	Climate resilience	20%	5 – Very high (Action provides multiple benefits for climate resilience, including greenhouse gas or adaptive measures). 3 – High (Action provides at least one benefit for climate resilience). 1 – Moderate (Action provides limited benefits for climate resilience). 0 – Low (Action does not provide benefits for climate resilience).	100
4	Community values (project type)	10%	5 – Prevention. 5 – Emergency services. 3 – Natural resources protection. 3 – Public education and awareness. 3 – Structural projects. 1 – Property protection. 1 – Social cohesion projects.	50
5	Community values (hazard of greatest concern)	10%	5 – Action addresses one or more hazards identified for the public as of greatest concern (More extreme rain/flood, heat, thunderstorm, tornado, winter weather). 3 – Action addresses one or more hazards identified for the public as of lesser concern (Loss and change of vegetation (including trees), reduced air quality, habitat disruption). 1 – Action addresses one or more hazards identified for the public as of least concern (In-migration of people to the area from areas more severely impacted by climate change).	50
6	Risk reduction/ benefits	10%	5 – Very high (Significant losses avoided and/or significant benefits with consideration to economic, social, and environmental factors). 3 – High (Numerous losses avoided and/or numerous benefits with consideration to economic, social, and environmental factors). 1 – Moderate (Some losses avoided, some benefits with consideration to economic, social, and environmental factors). 0 – Low (No losses avoided, no public benefits with consideration to economic, social, and environmental factors).	50
7	Costs	10%	5 – Project costs are predominantly staff time. 3 – Project costs are estimated between $0-$100,000. 1 – Project costs are estimated between $100,001-$500,000. 0 – Project costs are estimated above $500,000.	50
TOTAL		100%	Sum of parameter scores (max = 500)	

5.2 Implementation

Implementing flood risk management options to reduce flood risk and enhance community resilience involves time, engaged people, and financial resources. Successful completion of actions relies upon deliberate planning for implementation, which includes the following key elements.

- **Champion/responsible entity**: Projects do not implement themselves. Every project or program needs an individual and a department or agency to take ownership, secure funding, and see it through to completion. Project champions find and coordinate partners who will share responsibility for implementation and potentially for funding.
- **Partners**: In addition to the responsible entity, one or more partners may contribute staff time, technical expertise, and funding. Partners may also influence policy decisions or changes necessary for implementation and provide additional leverage needed to get a project funded.
- **Timeline**: The start to a project's timeline can depend on when funding is available and when personnel can support implementation. Sequencing projects based on funding and personnel availability can increase their likelihood for success. Project champions set the timeline based on when funding can/will be available and when the project must be complete.
- **Next steps and milestones**: Successful implementation relies on following a sequential set of actions and milestones. The implementation plan outlines the actions that must be completed by the project champion and partners in the appropriate order to accomplish the project. The project champion assigns completion of these steps to specific individuals along with key milestone dates that follow the project timeline. The steps and timeline require flexibility to adjust to changing conditions while keeping the project moving.
- **Capability needs**: Beyond funding, communities may need additional support and capabilities to implement a project or program. Capability needs may include technical expertise, staff availability, equipment, and supplies. Project champions and partners take responsibility for addressing capability needs and building them into the project timeline.
- **Cost estimates and funding**: Communities must know the cost of their projects and programs and where they will secure the funding. High-cost projects may require significant time to secure necessary funding, which project champions will build into the project timeline. Project champions may also work with partners to combine multiple funding sources. Partners often bring knowledge and expertise in a variety of funding sources and play a pivotal role in securing funds for the project.

CASE STUDY: FUNDING THE FARGO-MOORHEAD METROPOLITAN AREA FLOOD RISK MANAGEMENT PROJECT

The Fargo-Moorhead diversion project will cost roughly $3 billion to provide flood risk management for nearly 260,000 people and 70 square miles of infrastructure in the communities of Fargo, Moorhead, West Fargo, Horace, and Harwood and is being implemented by the U.S. Army Corps of Engineers (USACE), the cities of Fargo and Moorhead, and the Metro Flood Diversion Authority. It includes building a 30-mile diversion channel in North Dakota to include several highway and railroad bridges, as well as two aqueduct structures, and a 22-mile dam embankment with three gated control structures. The total cost of the project is being covered by the federal government, state governments of North Dakota and Minnesota, and local funding through sales taxes.

The Metro Flood Diversion Authority developed a multi-faceted plan to finance their share, utilizing a public-private partnership model that includes a mix of state grants from North Dakota and Minnesota, low-interest loans such as the Environmental Protection Agency Water Infrastructure Finance and Innovation Act loan, the North Dakota Clean Water State Revolving Fund loan, and sales tax revenues. The Metro Flood Diversion Authority also established an ongoing O&M program that will be funded by excess sales and tax revenues, an annual maintenance district levy, and stormwater maintenance fees from Minnesota member entities. The program will also fund any unforeseen mitigation needs that may arise during operation.

The Wild Rice River structure being built as part of the Fargo-Moorhead Metropolitan Area Flood Risk Management project, designed and constructed by USACE (Metro Flood Diversion Authority, 2023).

CASE STUDY: VIRGINIA COMMUNITY FLOOD PREPAREDNESS FUND

In 2020, the Commonwealth of Virginia General Assembly created the Community Flood Preparedness Fund. The fund provides support for regions and localities across Virginia to reduce the impacts of flooding, including flooding driven by climate change. The fund prioritizes projects that are in concert with local, state, and federal floodplain management standards, local resilience plans, and the Virginia Coastal Resilience Master Plan. The fund empowers communities to complete vulnerability assessments and develop and implement action-oriented approaches to bolster flood preparedness and resilience. Eligible activities include flood prevention and protection projects and studies, capacity building, and planning. The following five core principles, known as the Commonwealth Resilience Planning Principles, guide the fund (Virginia Department of Conservation and Recreation, 2023).

- Acknowledge climate change and its consequences, and base decision making on the best available science.
- Identify and address socioeconomic inequities and work to enhance equity through adaptation and protection efforts.
- Utilize community and regional scale planning to the maximum extent possible, seeking region-specific approaches tailored to the needs of individual communities.
- Understand fiscal realities and focus on the most cost-effective solutions for the protection and adaptation of communities, businesses, and critical infrastructure. The solutions will, to the extent possible, prioritize effective natural solutions.
- Recognize the importance of protecting and enhancing green infrastructure in all regions and in the coastal region, natural coastal barriers, and fish and wildlife habitat by prioritizing nature-based solutions.

6 Evaluate and Adapt

As communities implement flood risk management options, climate conditions will change, new information will become available, and community values will evolve. These factors will require communities to adapt to their new reality by understanding any changes to the community's flood risk, understanding how well current flood risk management strategies are meeting their objectives, affirming or adjusting community vision for flood resiliency, and, if necessary, identifying and prioritizing a new set of resilience building actions. Engagement of the whole community is essential to ensure all experiences and perspectives of the community are considered during this process. An important first step is to monitor and evaluate progress in building resilience.

6.1 Evaluate Using Indicators

A community's resilience to flooding can be measured by assessing the impacts of floods. Identifying what indicators to measure, and how to track and evaluate those indicators over time is central to quantifying results. Good measurement indicators provide:

- A baseline that indicates the starting point.
- A target for where the community is going.
- An indication if there is something wrong.

- Highlights when the community achieves its goal.

Further, well designed measurement indicators can help tell a story for why resilience building is necessary, attract political support and funding, and focus efforts while providing a feedback mechanism about whether decisions, investments, and actions to improve resilience are making a difference and can help guide future decisions. Good indicators should be designed to do the following:

- Connect to goals, community values, and desired outcomes.
- Track information required to measure the indicator. Note: When setting an indicator, it is important to keep in mind the ease and cost of obtaining the data required to measure the indicator.
- Provide meaning rather than a count. For example, an indicator that counts the number of people who received training does not necessarily correlate to knowledge gained.
- Provide data for accountability, guiding action, telling a story, and measuring success.
- Be adaptable and scalable with the effort.

6.1.1 Capitals to Measure a Community Flood Resilience

Capitals are assets that add to the long-term resilience of a community. Capitals include various elements, resources, and relationships within a community and their contribution to the overall functioning of the community. Measuring the capitals involves using indicators that are scored on a scale of poor (low) to best practice (high) level of maturity. The maturity matrix should be unique to each community and tailored to align with a community's values and vision for resilience.

The following six capitals[2] are a good way to measure and report on a community's flood resilience:

- Natural
- Built
- Financial
- Health and human
- Social and cultural
- Institutional and governance

MATURITY MATRIX

Adapted from the National Academy of Sciences, Dam and Levee Safety and Community Resilience: A Vision for Future Practice, a maturity matrix is a tool to help gauge the level of resilience practice with respect to an indicator being measured (National Research Council, 2012). The matrix can allow communities to communicate operations in place, identify areas in need of enhancements, and identify the means of meeting goals.

The **natural capital** is described as the natural resources base or environmental conditions within communities. This includes air, land, water, mineral resources, stability and health of ecosystems, natural land cover, and/or indicators of environmental quality. Natural resources, as well as the water and biological resources, combined with the human actions to sustain productivity from these resources enhance resilience to floods.

[2] Adapted from the National Academy of Sciences Building and Measuring Community Resilience: Actions for Communities and the Gulf Research Program.

An example indicator to evaluate the natural capital is the condition of the watershed basin that influences the intensity of the flood hazard in the leveed area. The example maturity matrix for this indicator is show in Table 12-4.

Table 12-4: Example Indicator in the Natural Capital Maturity Matrix

Indicator	Scale	Description
Watershed basin condition that influences the intensity of flood hazard.	Level 1 (Less resilience)	Fully developed watershed with little amount of natural landscape. High amounts of impervious surfaces.
	Level 2	Developed with significantly altered conditions with no purpose of flood resilience.
	Level 3	Partially developed conditions altered to different uses.
	Level 4	Mostly undeveloped with altered conditions maintain flood resilience services.
	Level 5 (More resilience)	Undeveloped watershed or restored natural conditions near perfect as could be expected.

The **built capital** are things produced by economic activity such as buildings and infrastructure systems within communities. This includes critical response support facilities, residential housing, schools, commercial and industrial buildings, and supporting infrastructure such as power, transportation, bridges, roads, communication, water, and wastewater.

An example indicator to evaluate the built capital is the continued functionality of healthcare facilities during and after floods. The measurement should account for the location of the building, the way the buildings are constructed, and how flood risk is managed. There should also be strategies in place to guarantee healthcare service provision to people during and after floods, as well as access to medical supplies. The example maturity matrix for this indicator is show in Table 12-5.

Table 12-5: Example Indicator in the Built Capital Maturity Matrix

Indicator	Scale	Description
Healthcare facilities ability to function during and after floods.	Level 1 (Less resilience)	Facilities are in flood-prone areas with loss of function and no access during floods.
	Level 2	Facilities are impacted by flooding and can provide essential services only. Access is severely limited.
	Level 3	Facilities are located within flood-prone area and are impacted by flooding but can continue to provide essential health services. Facilities remain accessible to the community.

Indicator	Scale	Description
	Level 4	Facilities are located within flood-prone area but managed in such a way that there is no negative impact on healthcare services. The facilities are fully accessible during floods for all relevant vulnerable populations.
	Level 5 (More resilience)	Facilities are located away from flood-prone areas and are not affected in the event of major flooding.

The **financial capital** is the totality of economic assets and livelihoods in a community, including income levels, personal wealth, income equality, overall employment rates, sector-specific employment, and business size and diversity.

An example indicator to evaluate the financial capital is the capability of community members to recover their assets should a flood occur without having to resort to negative coping strategies, such as selling off assets. This could be in the form of accessible savings for emergencies, available credit lines (loans), or having an insurance policy in place. The example maturity matrix for this indicator is shown in Table 12-6.

Table 12-6: Example Indicator in the Financial Capital Maturity Matrix

Indicator	Scale	Description
Household asset recovery capability.	Level 1 (Less resilience)	No households have insurance or savings while located in flood-prone areas.
	Level 2	Less than 20% of households have insurance or there is limited opportunity for households to save.
	Level 3	20% to 50% of households have insurance or have savings to recover their assets.
	Level 4	50% to 80% of households have insurance or have savings to recover their assets.
	Level 5 (More resilience)	More than 80% of households have flood insurance or a way to recover their assets through savings (i.e., an emergency fund).

The **health and human capital** is the knowledge, skills, health, and physical abilities of community members. It includes language competencies, cultural symbols, and belief systems. Some specific examples are educational levels, age distributions, health insurance, access to medical and mental health services, food security, special needs populations, and access to transportation and communication services.

An example indicator to evaluate the health and human capital is the community's awareness of flood risk, specifically where in the community it is likely to be flooded. If people in the community do not know which areas of the community are likely to flood, then their lives and assets may be at risk. The example maturity matrix for this indicator is shown in Table 12-7.

Table 12-7: Example Indicator in the Health and Human Capital Maturity Matrix

Indicator	Scale	Description
Flood risk awareness.	Level 1 (Less resilience)	Community's flood hazards are not identified.
	Level 2	Less than 20% of the population know which areas in the community are likely to flood.
	Level 3	20% to 50% of the population know which areas in the community are likely to flood.
	Level 4	50% to 80% of the population know which areas in the community are likely to flood.
	Level 5 (More resilience)	More than 80% of the population know which areas in the community are likely to flood.

The **social and cultural capital** is the social networks and connectivity among groups and individuals within a community. This includes levels of trust and reciprocity, political engagement, length of residency, volunteerism, religious affiliation, and community organizations and services. Also included is the feeling of belonging to and a sense of place about the community.

An example indicator to evaluate the social and cultural capital is the incorporation of a collaborative stakeholder engagement process into the community flood risk management planning process in order to develop a shared vision about future development in the community and strategies to reduce the risk of floods. The example maturity matrix for this indicator is shown in Table 12-8.

Table 12-8: Example Indicator in the Social and Cultural Capital Maturity Matrix

Indicator	Scale	Description
Incorporation of stakeholder engagement in community flood risk management planning.	Level 1 (Less resilience)	No community emergency response plan in place.
	Level 2	A community flood risk management plan is in place and was developed with little or no local participation or inclusion. There is little or no acceptance of it within the community.
	Level 3	A community flood risk management plan is in place and was developed with a moderate degree of local participation and inclusion. It is fairly well accepted within the community.

Indicator	Scale	Description
	Level 4	A community flood risk management plan is in place and was developed with a high degree of local participation and inclusion. It is widely accepted within the community.
	Level 5 (More resilience)	A community flood risk management plan is integrated into the whole community's comprehensive resilience plan. It was developed with a high degree of local participation and inclusion and is widely accepted within the community.

The **institutional and governance capital** is the community's access to public resources and the ability/power to influence the distribution of the resources, as well as the ability to engage entities external to the community in order to achieve community goals. This includes access to disaster insurance coverage (e.g., flood, crop), the degree to which relevant jurisdictions are coordinated or fragmented, experience in flood response and recovery, effectiveness of mitigation spending, and emergency management capacities.

An example indicator to evaluate the institutional and governance capital is the presence of a community disaster fund, which is a budget for members in the community to get emergency funding for response and recovery if their income is disrupted, especially for those that are unable to afford insurance or have no emergency fund savings account. The example maturity matrix for this indicator is shown in Table 12-9.

Table 12-9: Example Indicator in the Institutional and Governance Capital Maturity Matrix

Indicator	Scale	Description
Availability of community disaster fund for response and recovery**.**	Level 1 (Less resilience)	No fund established.
	Level 2	There is a fund, but it does not always function reliably either due to a lack of funding or a complicated bureaucracy. Community members are unaware of the program.
	Level 3	There is a fund but does not always function reliably either due to a lack of funding or a complicated bureaucracy. Community members are aware of the program but do not understand how to access the funds.
	Level 4	There is a functioning fund. Community members are aware of the program but have difficulty accessing the funds in the event of a flood or receiving disbursement.
	Level 5 (More resilience)	There is a functioning fund. Community members are aware of the program and how to access the funds in the event of a flood. Disbursement of the funds is quick and adequate for recovery.

CASE STUDY: ZURICH FLOOD RESILIENCE ALLIANCE FLOOD RESILIENCE MEASUREMENT FOR COMMUNITIES

The Zurich Flood Resilience Measurement for Communities was created by the Zurich Flood Resilience Alliance in 2013 and is an innovation in community flood resilience theory and practice (Zurich Flood Resilience Alliance, 2023). It allows users to generate evidence about the ways in which a given area or community is already resilient to floods, as well as providing a guide to further develop this resilience region.

The Flood Resilience Measurement for Communities framework is also called the 5C-4R framework. It combines a series of indicator, or 'sources of resilience,' on five complementary 'capitals' (5C), as well as four properties derived from resilient system-thinking (4R), that can help communities on their development path and provide capacity to withstand and respond to shocks. The 5Cs comprise human, social, physical, financial, and natural capital. The 5Cs provide greater richness of data about a community's sources of resilience than any single metric.

Each capital group contains a set of generic and discrete sources of resilience. Across the 5Cs there are 44 sources of resilience, each specifically defined. Sources of resilience are grouped under the four headings (4R) of robustness (ability to withstand a shock), redundancy (functional diversity), resourcefulness (ability to mobilize when threatened), and rapidity (ability to contain losses and recover in a timely manner).

This systems-thinking approach considers the assets, interactions, and interconnections at community level, and provides consistency when it comes to identifying and testing sources of resilience. To measure each source of resilience in a given community, data can be collected in four different ways (i.e., household surveys, key informant interviews, focus group discussions, and through the use of secondary sources) according to context and need. After data is collected, a trained assessor grades each of the sources of resilience on a scale from A to D (where A is best practice and D is poor). The grades between A and D awarded to each community are then aggregated in different ways for analysis. Aggregations, or 'lenses' by which resilience can be viewed, include the 5Cs and the 4Rs. Further lenses are the seven themes by which questions are sequenced thematically (such as healthcare, education, livelihoods, etc.), the five steps of the disaster risk management cycle (preparedness, response, recovery, prospective risk reduction, and corrective risk reduction), and many more.

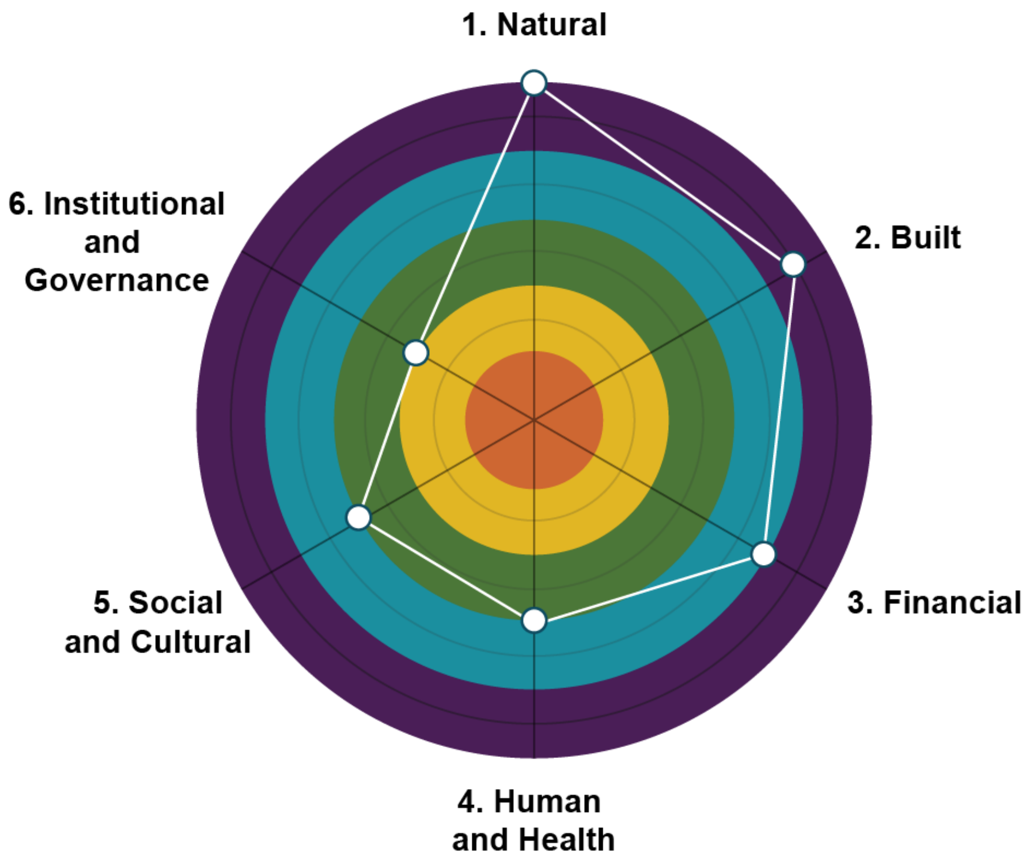
As of year 2022, the Zurich Flood Resilience Alliance has successfully been developing and implementing the Flood Resilience Measurement for Communities process in over 400 communities globally.

6.1.2 Evaluate Results

Evaluating a community's progress in building flood resilience should be an annual activity. This repetition allows communities to demonstrate improvement, identify newly found gaps, and identify the need for new, more effective strategies. Evaluation results should be shared with the community to raise awareness and support for resilience activities and justify continued investment.

The results of the evaluation of indicators using the maturity matrices can be summarized into a total score for each capital. One effective way to present results is with a spider chart, as seen in Figure 12-11. As communities get closer to achieving the maturity for their resilience indicators in each capital, the points on the chart move outward. A more resilient community will have most of its points near the outer edge of the circle and the connecting lines will create a more circular shape. The chart should be compared to prior year's results. When results do not show progress, communities can clearly see where they need to adapt their resilience building activities.

Figure 12-11: Example Spider Chart Showing Measurement Per Capital



6.2 Adapt to Change

The changing environment increases uncertainty in predicting the effectiveness of flood risk management strategies. Adapting to this changing environment requires an iterative process of evaluations to reduce uncertainty about flood risk and improves the potential for achieving desired results from flood risk management options.

Adopting an adaptive management approach to community flood resilience is an effective way to manage the impacts of change. Adaptive management is a multi-step, iterative process for adjusting management measures to changing circumstances or new information about the effectiveness of flood risk management options for the system being managed. Adaptive management reduces uncertainties regarding performance of flood risk management options by developing and using new information and evaluating key uncertainties. Each iteration facilitates the ability for future adjustments or enhancements to existing flood risk management options as necessary to meet or improve expected outcomes.

7 Summary

While levees can help reduce the flood risk, it is important to remember that they do not eliminate the risk. Even levees which are well maintained and operated can overtop or breach when flood hazards exceed the design of the levee.

Flood risk to the leveed area can also come from high intensity or excessive amounts of rainfall directly to the leveed area. This flood source, as well as groundwater flooding that can occur from levee underseepage or from other natural conditions, can exceed the capacity of interior drainage systems meant to evacuate water within the leveed area, thus trapping it behind the levee.

For those living or working near levees, it is important to understand the flood risk and be aware of steps that can be taken to reduce the risk on a community level, as well as an individual level. An iterative process of understanding risks, exploring options to reduce risk, prioritizing, and implementing those options, and evaluating and adapting to changing conditions is essential to building community resilience to flooding. This process revolves around continuous engagement that is inclusive, equitable, and community-driven to help ensure all those affected by floods and flood risk management decisions are part of the planning and decision-making process.

A variety of flood risk management options are available to communities; however, the environment is ever changing from precipitation patterns altering flood hazards, O&M deficiencies altering levee performance, and human behavior and policy changes altering the socio-economic environment of a community. As flood risk changes, a resilient community will monitor, evaluate, and adapt to new information, ensuring their capacity to effectively recover from the next flood, with the same quality of social well-being, economy, and environment as existed before.

Related content associated with this chapter is included in detail in other chapters of the National Levee Safety Guidelines as described in Table 12-10.

Table 12-10: Related Content

Chapter	Chapter Title	Related Content
1	Managing Flood Risk	• Flood risk management strategies • Climate change impacts
2	Understanding Levee Fundamentals	• Levee fundamentals • Potential failure modes
3	Engaging Communities	• Community engagement
4	Estimating Levee Risk	• Potential failure modes • Estimating consequences • Social vulnerability
5	Managing Levee Risk	• Taking actions to reduce risk • Building risk awareness
6	Formulating a Levee Project	
7	Designing a Levee	
8	Constructing a Levee	
9	Operating and Maintaining a Levee	• Access corridor
10	Managing Levee Emergencies	• Emergency preparedness • Evacuation planning
11	Reconnecting the Floodplain	• Floodplain restoration
12	Enhancing Community Resilience	

Glossary

Glossary

Term	Definition
Access Corridor	A defined space needed for maintenance, inspection, and floodfighting, to provide additional room to improve the levee in the future and to prevent excavation and land modifications that might negatively impact the levee performance.
Alignment	A line from the perspective of the top view of the levee that follows along the entire levee length.
Benefits	A qualitative or quantitative description of the positive contributions the levee system has or can provide to the community in the leveed area.
Benefit-Cost Analysis	A systematic process for identifying, quantifying, and comparing expected benefits and costs of an investment or action.
Borrow Area	A region of land from which earthen material is excavated to be used as fill material in another location.
Breach	The formation of a gap in the levee system through which water may flow uncontrolled onto the adjacent leveed area. A breach in the levee system may occur prior to or subsequent to overtopping.
Channel	A general term for any natural or artificial facility for conveying water.
Climate Change	Changes in average weather conditions that persist over multiple decades or longer. Climate change encompasses both increases and decreases in temperature, as well as shifts in precipitation, changing risk of certain types of severe weather events, and changes to other features of the climate system.
Closure	Any movable and essentially watertight barrier, used during flood periods to close openings in levee systems, securing the levee systems' design level of risk reduction. Openings allow for traffic (either vehicular or pedestrian) to pass through during normal conditions.
Co-benefits	The provision for important social, cultural, historical, ecological, and recreational uses beyond the levee's primary purpose of flood risk reduction.
Coastal Flooding	The submergence of exposed coastlines by water from large bodies of open water such as oceans, gulfs, bays, or large lakes. Common causes of coastal flooding include high water levels, wind, waves, storm surge, sea level rise and tsunamis.
Communication	The practice of developing and sharing information with others and is most typically thought of as one-way.
Community	Network of individuals and families, businesses, governmental and nongovernmental organizations, and other civic organizations that reside or operate within a shared geographical boundary and may be represented by a common political leadership. A community can also include stakeholders who are individuals, groups, organizations, or businesses that have an interest in, can affect, or be impacted by the proposed project and other decisions.
Community Assessment	The process of identifying the strengths, assets, needs, and challenges of a community.
Community Resilience	The capability to anticipate, prepare for, respond to, and recover from significant multi-hazard threats with minimum damage to social well-being, the economy, and the environment.

Term	Definition
Component	A discrete element of a levee feature. Examples include rollers, hinges, pumps, motors, etc.
Compound Flooding	A phenomenon in which two or more sources contribute to inundation, simultaneously or within a short period of time.
Consequences	The direct or indirect outcome of inundation as reflected in the potential loss of life, economic losses, and/or adverse environmental impacts.
Crest	The highest elevation of the levee at a specific cross section along the alignment.
Crown	The top, horizontal portion of an earthen levee embankment that is commonly used for access.
Cutoff Wall	A wall of impervious material usually of concrete or steel sheet-piling constructed in the foundation and abutments to reduce seepage beneath and adjacent to the levee.
Dam	An artificial barrier, including appurtenant works, constructed for the purpose of storage, control, or diversion of water.
Design Water Surface Elevation	The flood water surface elevation used to perform deterministic design analyses at a particular point along the levee. The design water surface elevation is used in all deterministic design analyses to determine configurations and features necessary to meet initial deterministic design criteria. The design water surface elevation is determined from the design water surface profile.
Deterministic	An approach that uses limit-state type analyses with corresponding factors to safety to evaluate if a levee will satisfactorily perform under a flood event considering the physical properties of the levee and foundation materials, along with site-specific geologic features.
Embankment	Fill material, usually earth or rock, placed with sloping sides and with a length greater than its height.
Emergency	Any incident, whether natural, technological, or human-caused, that has escalated to the point where life and/or property is at risk.
Encroachment	Any activity on or physical intrusion on, over, through, or under the levee that is not related to the flood risk reduction benefits or other co-benefits the levee is intended to provide. Examples are buildings, fences, pipelines, and other utilities.
Engagement	Active dialogue that allows for meaningful interactions where all those involved feel heard and know their opinions matter.
Environmental Justice	Fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income regarding the development, implementation, and enforcement of environmental laws, regulations, and policies, with no group bearing a disproportionate burden of environmental harms and risks.
Equity	The right of individuals and society to be protected, and the right that the interests of all are treated with fairness, with the goal of placing all members of society on an essentially equal footing in terms of levels of risk that they face.
Erosion (External)	Process by which particles are removed from a surface by the action of wind, flowing water, or waves.
Erosion (Internal)	Movement of soil particles caused by water passing through a body of soil.
Evacuation	A voluntary or mandatory movement of people out of an area to avoid a life safety or health risk.

Term	Definition
Event	An unexpected occurrence or disturbance that is not flood-related that has the potential to cause levee damage. Examples include seismic events; extreme weather events; auto, train, or boat accidents; or even terrorist actions.
Exposure	Describes who and what may be harmed by the flood hazard. Exposure incorporates a description of where the flooding occurs at a given frequency, and what exists in the area. Tools such as flood inundation maps provide information on the extent and depth of flooding; structure inventories, population data, crop data, and habitat acreage provide information on the population and property that may be affected by the flood hazard.
Factor of Safety	The ratio of the required value to the actual value of that quantity.
Failure	Relates to the inability to meet one or more of the desired and declared objectives. See "breach" for failure causing uncontrolled flow within the adjacent leveed area.
Feature	A physical element of a levee system (e.g., levee embankment, floodwall, channel, etc.). Levee systems may have multiple features that function together to exclude water from a defined leveed area.
Flood	An overflow of water that submerges land which is normally dry.
Flood Risk	The probability and consequences of flooding in an area. For areas with flood risk reduction infrastructure (e.g., dams, levees, etc.) it accounts for how the infrastructure impacts the subject area. Flood risk is also known as residual risk.
Flood Risk Management	Activities (risk reduction measures) that aim to reduce the likelihood and the consequences of floods from the various sources.
Floodfight	Measures taken before and during a flood to maintain functionality of a levee system or reduce flood damage. Floodfight actions range from routine, pre-planned actions to non-typical, emergency actions that are required to prevent progression of an issue that could lead to levee breach.
Formulation	An iterative process that establishes planning objectives, evaluates management measures that address these objectives, develops potential alternatives that meet the objectives, screens out plans based on comparison criteria, and identifies plans for implementation.
Emergency Floodfight	Measures taken before and during a flood which require resources and coordination above those typical to a specific system in order to prevent progression of an issue that could damage or lead to breach of the system. Examples are raising the levee where unexpected subsidence has created a low spot and dumping large amounts of materials to create landside ponding over sand boils that threaten levee integrity. Emergency Intervention.
Floodplain	Any land area susceptible to being inundated by floodwaters from any source.
Floodwall	A designed structural wall constructed for the purpose of reducing flooding of property on the landward side of the wall. Floodwalls are normally constructed in lieu of or to supplement earthen levee embankments where the land required for embankment construction is too expensive or not available.
Floodway	The portion of the floodplain that conveys most of the floodwaters.
Fluvial Flooding	An event that occurs when the water level in a river, lake or stream rises and overflows onto the surrounding banks, shores and neighboring land. The water level rise could be due to excessive rain, snowmelt or ice jams.

Term	Definition
Gate	A structure that allows water to drain from the landside to the waterside of a levee while preventing the reverse flow.
Groundwater Flooding	The emergence of water that exists underground in saturated zones beneath the land surface at the ground surface.
Hazard	An event that causes the potential for an adverse consequence.
Inspection	A visual observation and documentation of physical-condition and operability of the levee. This may include operation of mechanical features such as pumps or gates.
Inspection Trench	A foundation excavation in order to inspect the foundation conditions during construction.
Instability	A potential failure mode for a levee involving mass movement of levee and/or foundation material that may result from throughseepage, saturation of soft embankment soils, soft foundation soils, or undermining by erosion.
Instrumentation	An arrangement of devices installed into or near a levee that provide for measurements that can be used to evaluate the structural behavior and performance parameters of the structure.
Interim Risk Reduction Measure	An action to reduce levee risk while more long-term and comprehensive risk reduction and management solutions are being pursued.
Interior Drainage	Natural or modified removal of runoff within an area landward of a levee.
Interior Drainage Systems	Infrastructure that usually include storage areas, gravity pipes, pumping stations, or a combination thereof to manage interior drainage.
Inundation	In the context of this document, this refers to flooding in a leveed area.
Inundation Map	Delineates the specific geographical area(s) that would be flooded due to a hypothetical levee breach, overtopping or component malfunction/accumulation of excess interior water.
Landside	Refers to the lateral location, relative to the levee crown or flood risk reduction structure, nearest to the lands from which flood water is excluded by the levee system.
Levee	A human-made barrier with the primary purpose of reducing the frequency of flooding to a portion of the floodplain. Also known as levee system.
Levee Owner	A federal or state agency, water management or flood control district, local community, levee district, non-public organization, tribe or an individual considered the proprietor of a levee. The levee owner is responsible for administering the operations, maintenance, and emergency preparedness plans for the levee system.
Levee Resilience	The capacity for a levee to withstand degradation or damage.
Levee Risk	The likelihood of occurrence and potential consequences for the following three inundation scenarios: breach prior to overtopping; overtopping with breach; and component malfunction or mis-operation of levee features. Also known as incremental risk.
Levee Safety	The art, science, and practice of managing levee systems as an integral element to community flood resiliency.
Levee Superiority	Concept of designing portions of the levee at higher elevations except in a location where initial overtopping is desired and can occur in a more predictable fashion.
Leveed Area	The lands from which flood water is excluded by the levee system.
Lifecycle	The working life of an asset including planning, design, construction, operation, inspection, maintenance, rehabilitation, replacement or decommission.

Term	Definition
Life Safety Risk	A measure of the probability and severity of loss of life resulting from inundation of a leveed area.
Likelihood	The chance of something happening, whether defined, measured, or estimated objectively or subjectively, or in terms of general descriptors (such as rare, unlikely, likely, almost certain).
Maintenance	Activities required to maintain or restore a system to the desired safety or working condition to function as intended. It includes preventative maintenance, repairs, and replacement of components.
Mitigation	Any sustained action taken by a community to reduce or eliminate long-term risks to people and property from natural hazards or disasters caused by people.
Modification	An activity that changes the original operation and function of a levee, including raising a levee, altering its alignment, or changing features.
Monitoring	The observation and assessment of the levee conditions through collection and evaluation of levee instrumentation and external data.
National Flood Insurance Program (NFIP)	Administered by FEMA, the NFIP is a voluntary program authorized by Congress to mitigate flood losses through community-enforced building and zoning ordinances and to provide property owners with access to federally backed flood insurance.
National Levee Database (NLD)	The NLD, developed by USACE in cooperation with FEMA, is a dynamic, searchable inventory of information for all levee systems in the nation.
Natural and Nature-Based Features (NNBF)	The use of landscape features to produce flood risk management benefits and other economic, environmental, and social benefits (known as co-benefits).
Non-Breach Risk	The risk associated with the scenario of the still-water level and/or associated waves, wind runup, or surge exceeds the top of the levee system, but does not result in a breach of the levee system. Also known as overtopping without breach risk.
Nonstructural Measures	Actions that reduce human exposure or vulnerability to a flood hazard without altering the nature or extent of that hazard.
Operation	Activities or services required for system components to function as intended.
Overtopping	A condition that occurs when the elevation of the still-water level and/or associated waves, wind runup, or surge exceeds the top of the levee system. This may or may not result in a breach of the levee system.
Performance	The measure of how a levee functions when subjected to a hazard.
Permitting	The process by which a formal request for permission to undertake an action is requested, the action is evaluated against predetermined criteria, and a documented decision is provided.
Pluvial Flooding	An event that is caused by persistent, heavy rainfall and independent of an overflowing water body, occurring when the ground cannot absorb rainwater effectively or drainage systems are overwhelmed by excessive water flow.
Population At Risk	The number of people occupying the area inundated due to levee failure prior to the issuance of any warning or evacuation.
Potential Failure Mode	A mechanism that once initiated potentially could progress to breach of a levee system or inundation of the leveed area. It is noted that overtopping without breach is not called a potential failure mode.
Potential Failure Modes Analysis	The process for which potential failure modes are identified and examined for a levee system, conducted by a team of persons who are qualified either by experience and\or education to evaluate levee system.

Term	Definition
Profile	A line that represents the side view of the levee and shows varying elevations of the top of the levee at different locations along the entire levee length.
Pump Station	A structure used to evacuate water from a leveed area through or over a levee system by mechanical and/or electrical components.
Quality Assurance	Processes employed to assure that quality control activities are being accomplished in line with planned activities and that those quality control activities are effective in producing a product that meets the desired end quality. Focuses on providing confidence that quality requirements of a project, product, service, or process will be fulfilled.
Quality Control	Processes used to ensure performance meets agreed-upon requirements that are consistent with laws, regulations, policies, sound technical criteria, schedules, and budget. Focuses on fulfilling quality requirements of a project, product, service, or process.
Qualitative Risk Assessment	A risk assessment that results in nonnumerical expressions for probability of breach and consequence that allows risk ranking or risk discrimination into classes.
Quantitative Risk Assessment	A risk assessment that results in numerical calculations for probability of breach and consequences combined to quantify a numeric risk estimate.
Reach	Discrete lengths of a levee defined such that each length has similar geotechnical, geometric, past performance, construction remedial history, and hydraulic loading.
Recovery/Recoverability	Prompt restoration of a community or levee, to a pre-flood condition in the event of damage, including prompt removal of flood water from the leveed area.
Rehabilitation	Restoring a levee to its original operation and function due to extensive deterioration or deficiencies. Rehabilitation is more substantial than normal maintenance and repair and is not routine in nature.
Relief Well	A vertical drain consisting of a perforated pipe surrounded by granular filter material with the intent to relieve excess seepage pressures in pervious foundation strata beneath the levee.
Removal	An intentional activity that effectively eliminates the flood risk reduction benefits provided by a levee. Removal is not routine in nature.
Repair	Restoring a levee to its original (e.g., as intended in design) operation and function after isolated damage has occurred and a structure's functionality has been reduced. Repair can also be thought of as normal maintenance and routine in nature.
Resilience	(1) The ability of a community or population to anticipate, prepare for, respond to, and recover from significant threats with minimal damage to social well-being, the economy, and the environment. (2) The capacity of a structure to withstand degradation or damage.
Right of Way	The land that has been acquired through fee title or an easement to allow construction, operation, and maintenance of the levee system.
Risk	The measure of the probability (or likelihood) and consequence of uncertain future events.
Risk Assessment	A systematic approach for describing the nature of the risk, including the likelihood and severity of consequences. Risk assessments can be qualitative, semi-quantitative, or quantitative. Risk assessment includes explicit acknowledgment of the uncertainties in the flood risk.
Risk Characterization	Description of the levee system in the context of risk by considering the key drivers of likelihood of performance, potential consequences, and sources of uncertainty.

Term	Definition
Risk Communication	The open exchange of information between risk assessors, decision makers, and those who are affected by the risks and risk management measures to improve decisions.
Risk Driver	Potential failure modes that contribute significantly to the total risk estimate and may require taking a risk management action.
Risk Estimate	The combination of the probability of inundation of the leveed area and the associated consequences and portraying the results as a combined risk estimate typically portrayed in a risk matrix.
Risk Framework	A decision-making process that comprises three tasks: risk assessment, risk management and risk communication.
Risk-Informed Decision Making	The process of using qualitative or quantitative risk information, in conjunction with other considerations, to lead to more complete, transparent, and informed decisions.
Risk Management	The process of problem finding and initiating action to identify, evaluate, select, implement, monitor and modify associated risks.
Risk Matrix	A graphical representation depicting the relationship between the probability of inundation and consequences to help one's understanding of the risk.
Risk Register	A living document created by a project team and updated as the project progresses that tracks and identifies risks and mitigation strategies.
Risk Transfer	Action taken to manage risk that shifts some or all of the risk to another levee system, geographic area, entity, or asset.
Risk Transformation	A situation in which risk is altered as a result of changing conditions, including risk management actions.
Riverine	Relating to, formed by, or resembling a river (including tributaries), stream, brook, etc.
Scalable/Scalability	The action of increasing or decreasing the level of effort or frequency of a levee related activity.
Seepage	The internal movement of water that may take place through the levee embankment (throughseepage) or its foundation (underseepage).
Seepage Berm	A human constructed horizontal step or bench along a levee intended to resist seepage in the levee foundation.
Semi-Quantitative Risk Assessment (SQRA)	A risk assessment that uses a combination of limited numerical estimates with qualitative descriptions that result in risk estimates based on orders of magnitude.
Settlement	Soil movement in the downward vertical direction typically induced by stress changes consisting of three components; immediate settlement, consolidation, and creep.
Site Investigation	The process of methodically observing, sampling and testing for the purpose of characterizing the ground and identifying potential hazards.
Slope	Inclination from the horizontal. Sometimes referred to as batter when measured from vertical.
Stability Berm	A human constructed horizontal step or bench along a levee intended to improve the stability of a levee slope.
Stakeholder	Individuals, groups, organizations, or businesses that have an interest in, can affect, or be impacted by the proposed project and other decisions.
Structural Measures	Infrastructure, such as a dam or levee, that alters the characteristics of floods and is designed to reduce the probability of flooding in the location of interest.

Term	Definition
Subsidence	A process characterized by downward displacement of surface material caused by natural phenomena such as removal of underground fluids, natural consolidation, or dissolution of underground minerals, or by human-made phenomena such as underground mining.
Sustainability	Balancing environmental, economic, and social impacts to meet present needs without compromising the ability of future generations to meet their needs.
Throughseepage	Movement of water through the soils that make up the levee embankment.
Toe	The intersection of the landside or waterside slope of a levee with the ground surface.
Transition	Location along a flood risk reduction system where there is a change in structure type (i.e., levee embankment to closure or floodwall).
Uncertainty	The resultant of imperfect or missing knowledge related to risk or components of risk. In the context of flood risk management, two types of uncertainty in processes are commonly distinguished: natural variability (inherent uncertainty) or limitations in knowledge (epistemic uncertainty).
Underseepage	Movement of water through the foundation soils of a levee embankment, floodwall, or other levee feature.
Underserved Communities/Populations	Groups that have limited or no access to resources or that are otherwise disenfranchised. These groups of people may include those who are socioeconomically disadvantaged; have limited English proficiency; are geographically isolated or educationally disenfranchised; those of color as well as those of ethnic and national origin minorities; women and children; individuals with disabilities and others with access and functional needs; and seniors.
Upstream	In the direction opposite to the flow of the river or stream.
Utility	Any facility producing, transmitting, or distributing a commodity for use by or direct benefit of the public.
Vulnerability	Susceptibility of exposed persons, property and environment to harm from an identified hazard.
Water Surface Elevation	The height, in relation to the National Geodetic Vertical Datum (NGVD) of 1929 (or other datum, where specified), of floods of various magnitudes and frequencies in the flood plains of coastal or riverine areas.
Water Surface Profile	The elevation of the flood water surface along the levee for a specific situation and/or event.
Waterside	Refers to the lateral location relative to the levee crown or flood risk reduction structure nearest to the water source.

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References

References

1 References 1
Chapter 1 1
Chapter 2 1
Chapter 3 2
Chapter 4 3
Chapter 5 5
Chapter 6 5
Chapter 7 8
Chapter 8 11
Chapter 9 13
Chapter 10 14
Chapter 11 14
Chapter 12 15

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Chapter 1

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