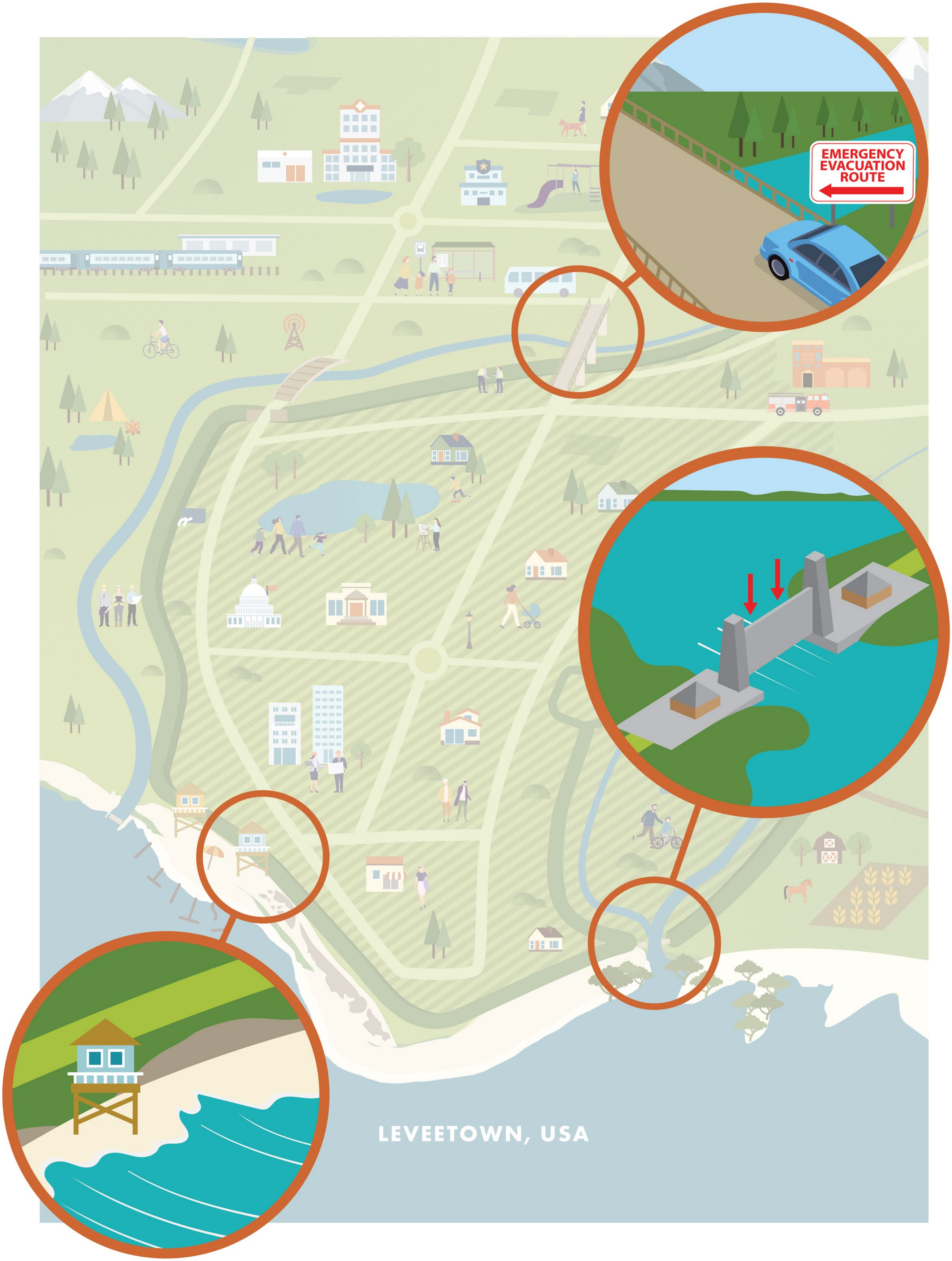
4

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.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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

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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.

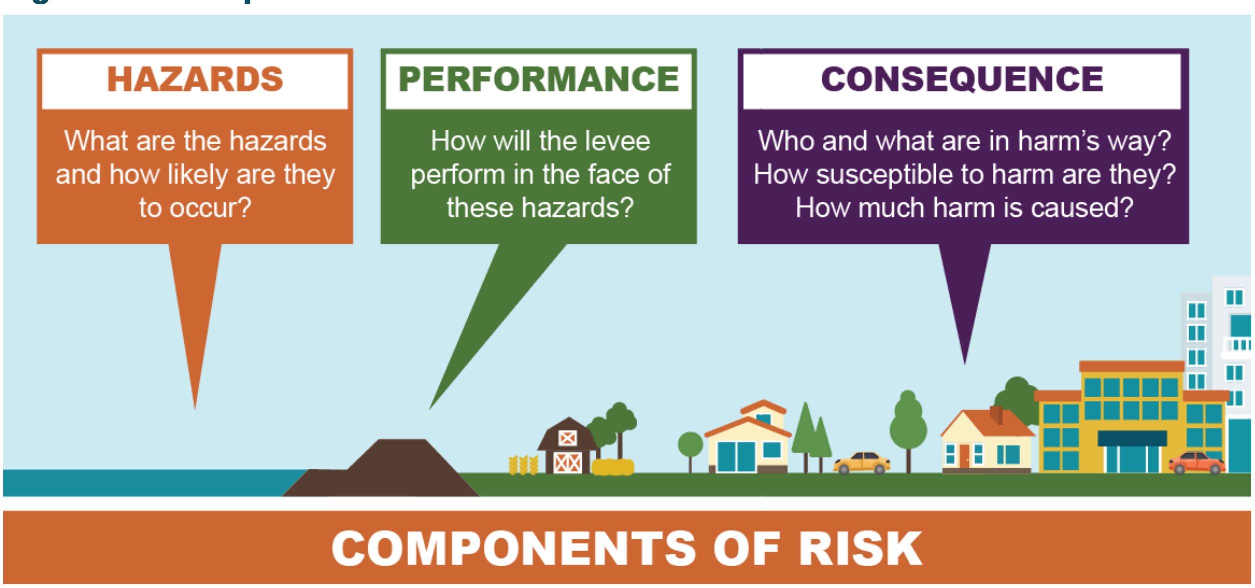
Understanding what is driving the risk estimate is just as important, if not more important than the estimate itself. There could be two situations that seemingly have the same risk, but what is driving the risk for each of the two situations can be very different. A high consequence/low probability 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

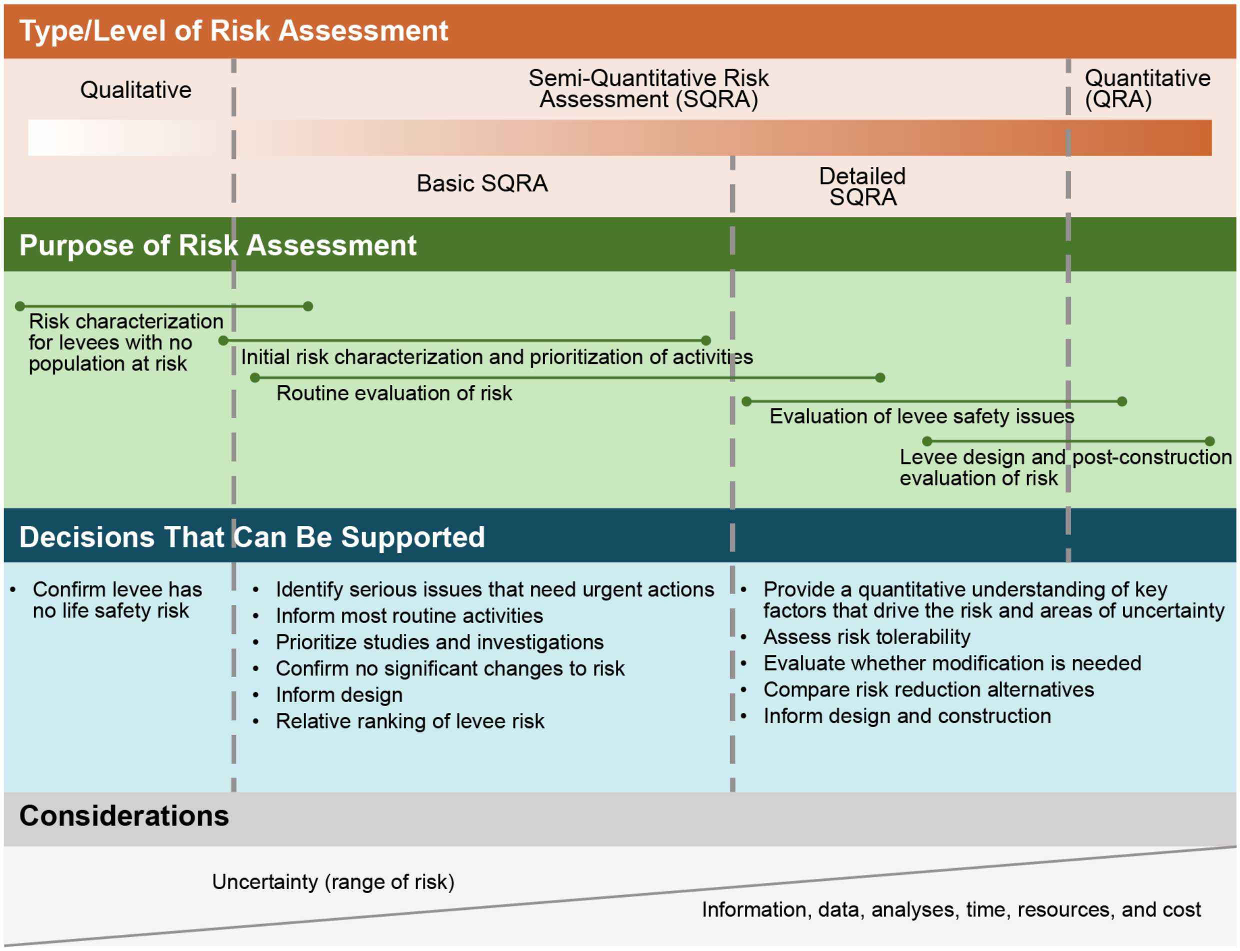
The Levee Screening Tool is a web-based tool developed and maintained by the U.S. Army Corps of Engineers (USACE). Initially developed to facilitate screening of the USACE levee portfolio, the Levee Screening Tool now has additional capabilities to facilitate basic and detailed semi-quantitative and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

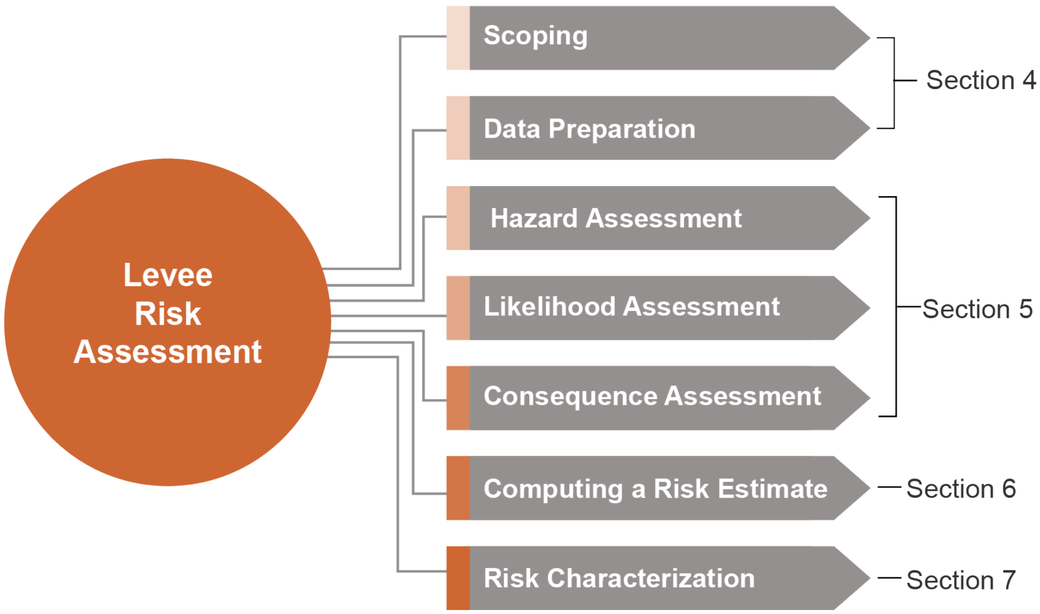
Figure 4-3: Scalability of Risk Assessments



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.

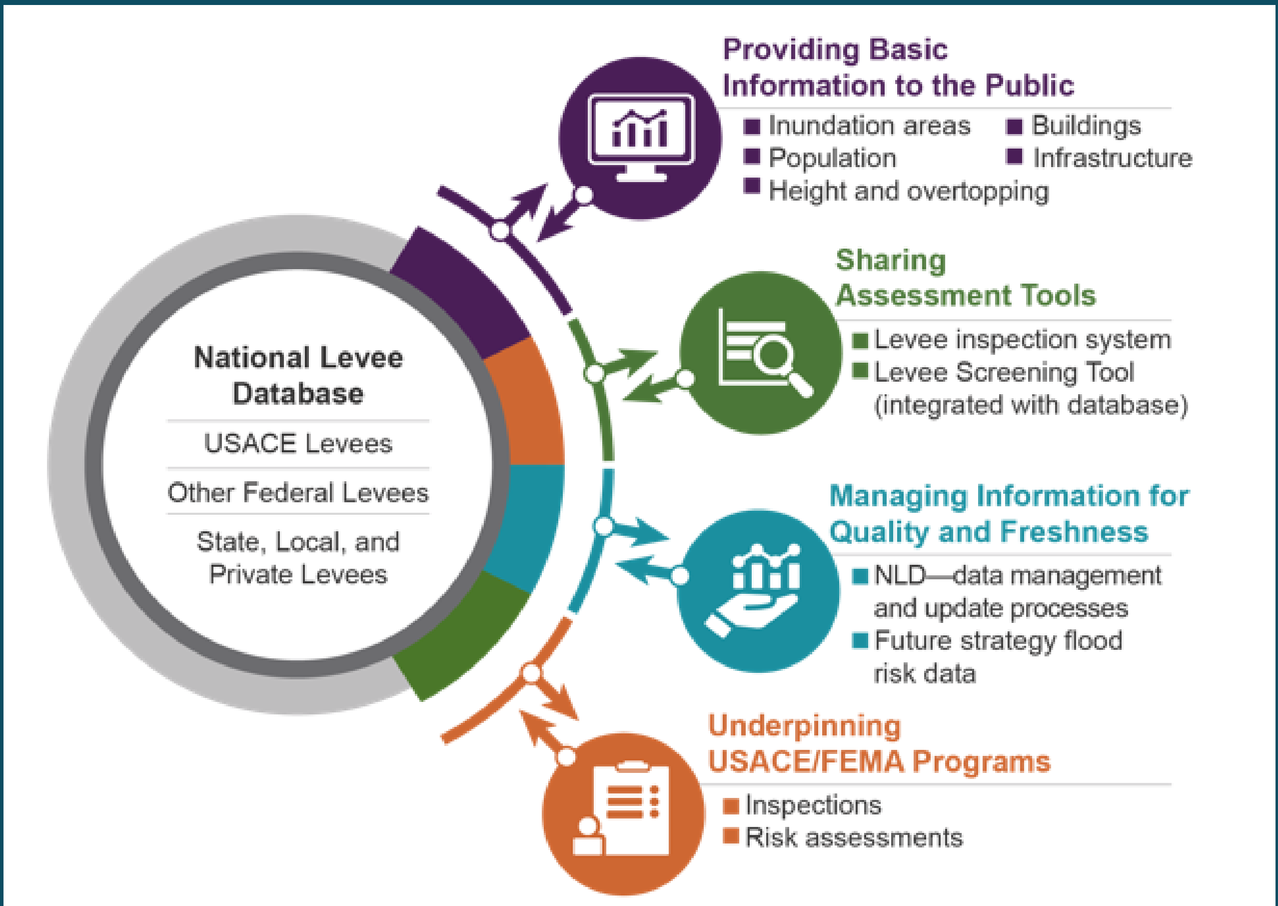
- Levee location and alignment
- Levee profile, including levee crest and landside toe
- Feature types and location
- Leveed area

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.

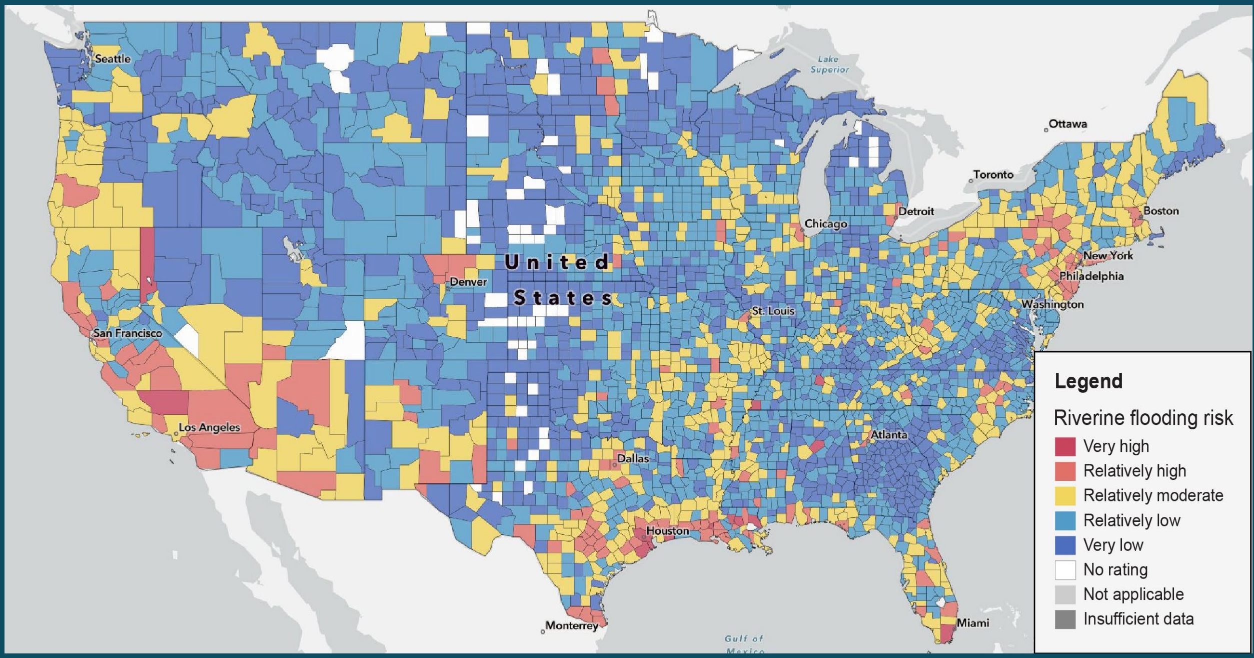
Other hazards that can damage levees are impacts from ice, debris, and boats, and should be considered when applicable.

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.

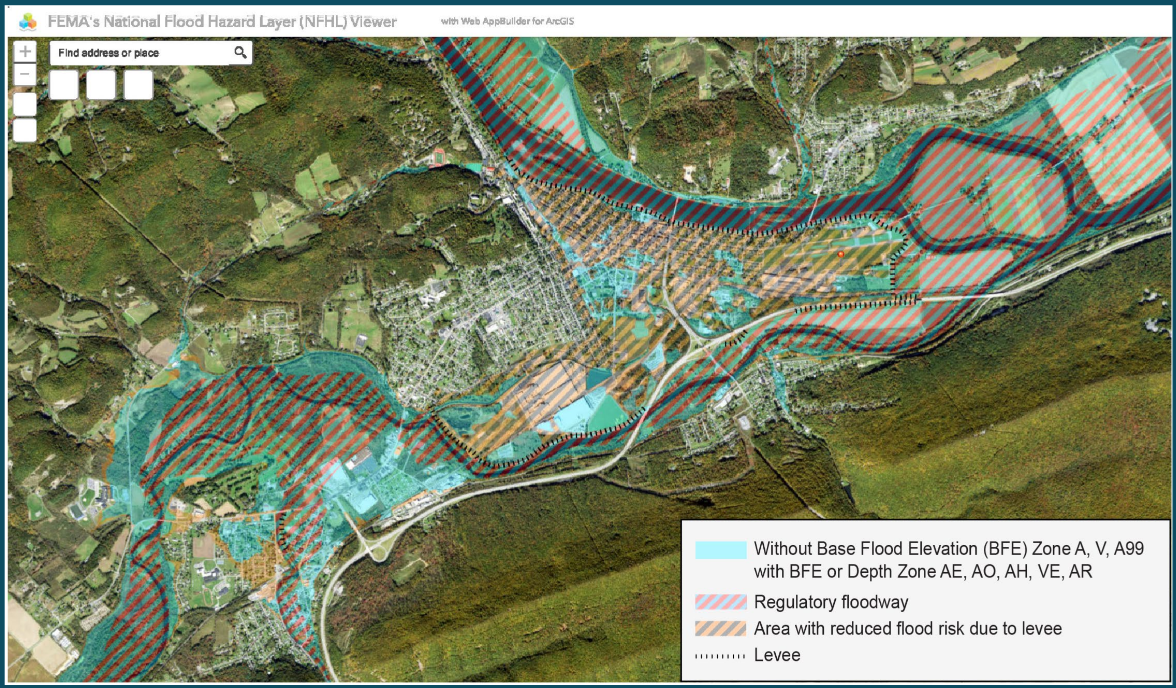
Rainfall and groundwater hazards are only included in the levee risk estimate if they could lead to a malfunction or misoperation of a levee feature. However, while not typically part of the levee risk estimate, rainfall and groundwater flooding should be evaluated in sufficient detail to ensure the 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

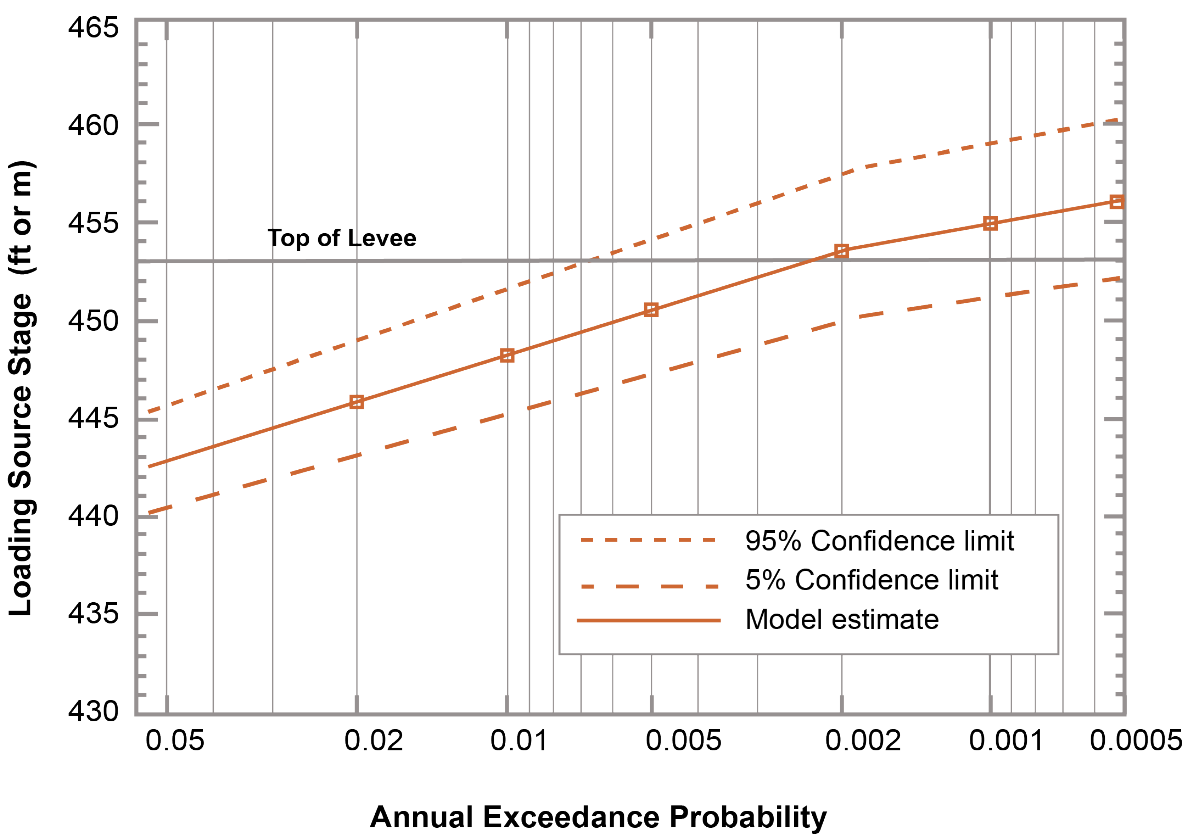
When a flood study is completed for FEMA's National Flood Insurance Program, the information and maps are assembled into a flood insurance study. The flood insurance study report contains detailed flood elevation data in flood profiles and data tables. Flood insurance rate maps are the official community 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:

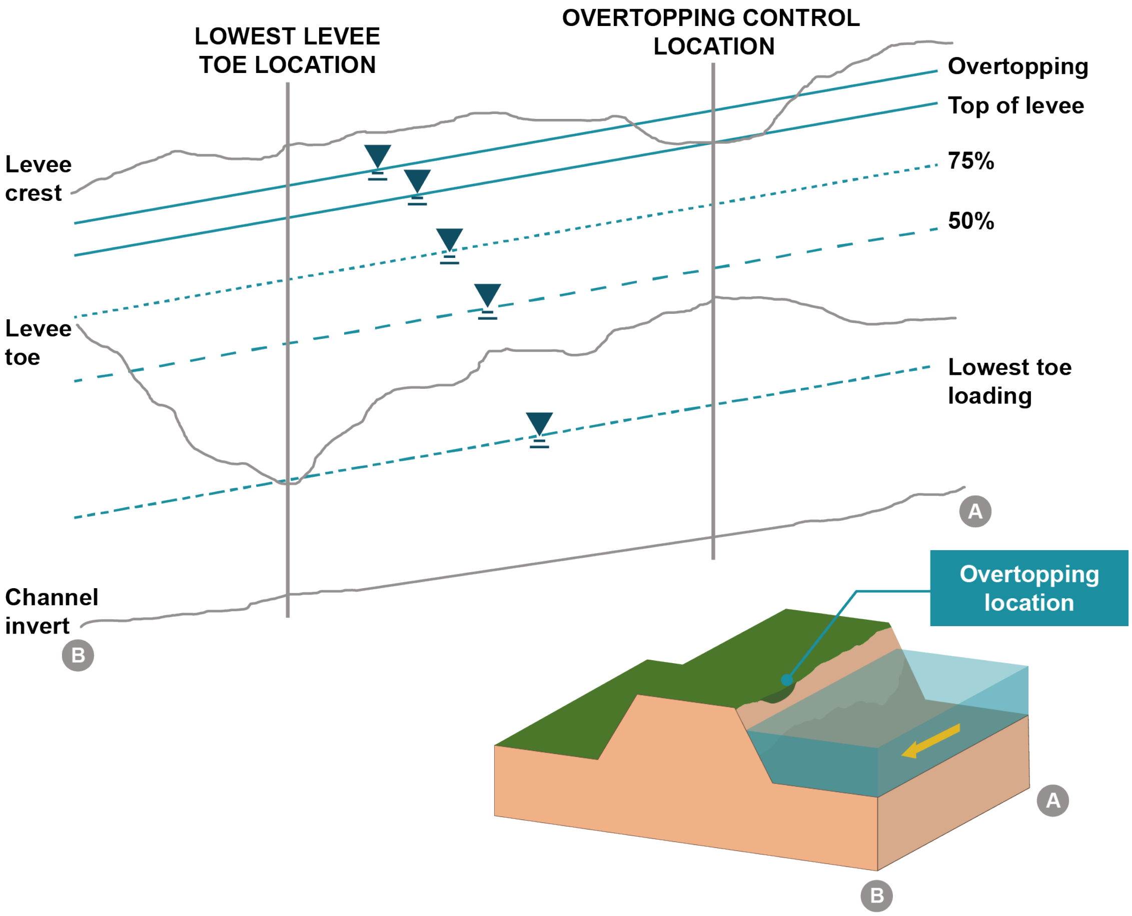
- Location where the levee is loaded first.
- Location of first overtopping.
- Location subject to the maximum loading.

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.

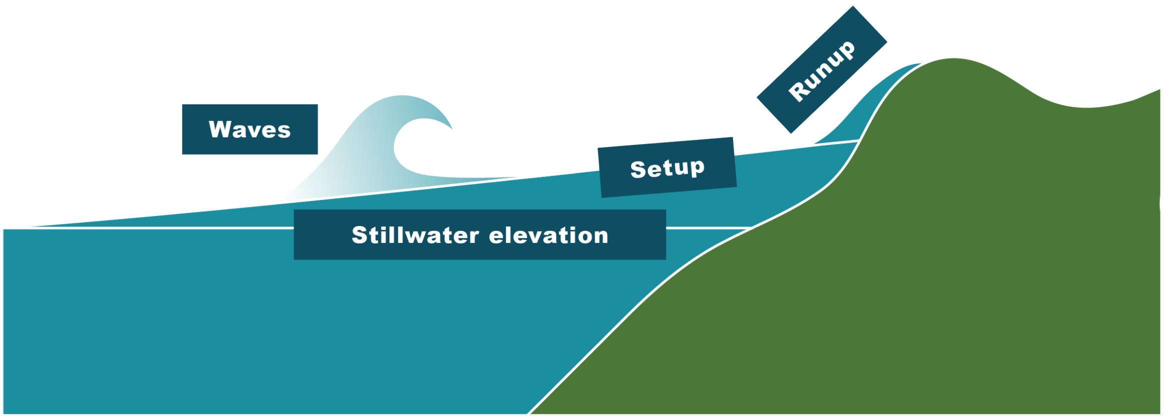
Coastal models are used to predict storm surge and flooding, model tides, and wind driven circulations. The models focus on the amount of water that is pushed towards the shore during a storm, combined with tidal effects. However, due to the regional nature of coastal hydraulic conditions used for design 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



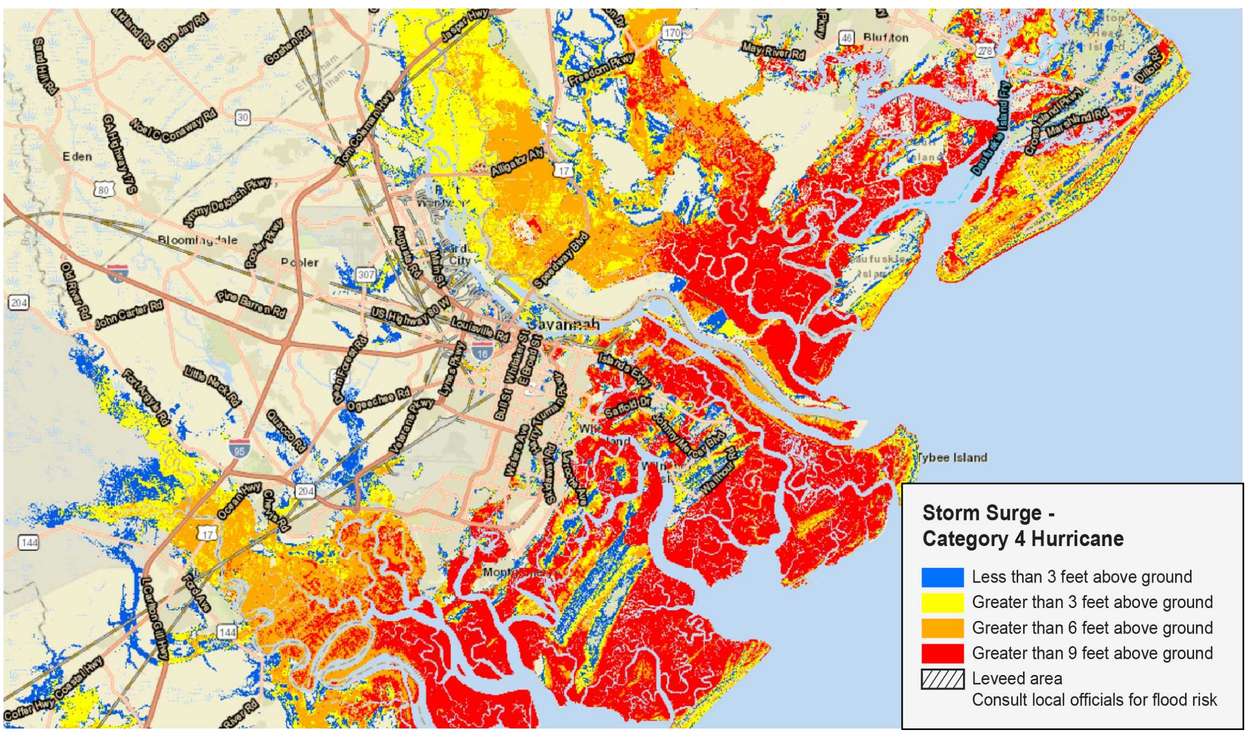
Setup and runup computation methods are provided in USACE's EM 1110-2-1100 (USACE, 2002), and Engineer Circular (EC) 1110-2-6067 (USACE, 2010). Additionally, Guidance for Flood Risk Analysis and Mapping: Coastal Wave Runup and Overtopping (FEMA, 2018) provides support requirements and recommends approaches 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).

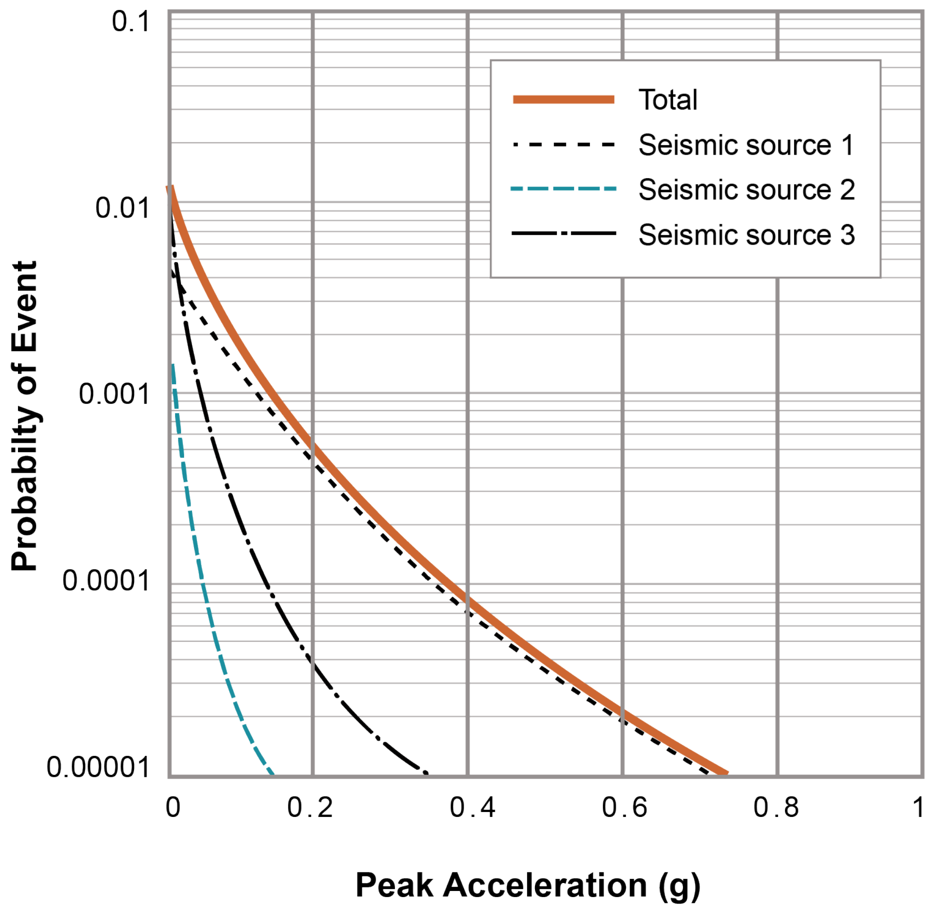
Seismic hazard information is used to evaluate levee performance under earthquake loading. It usually applies to levees that are continuously or frequently loaded, such as those at the coast or in an estuary or bay. They can also apply when there is insufficient time to repair or rebuild the levee after 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.

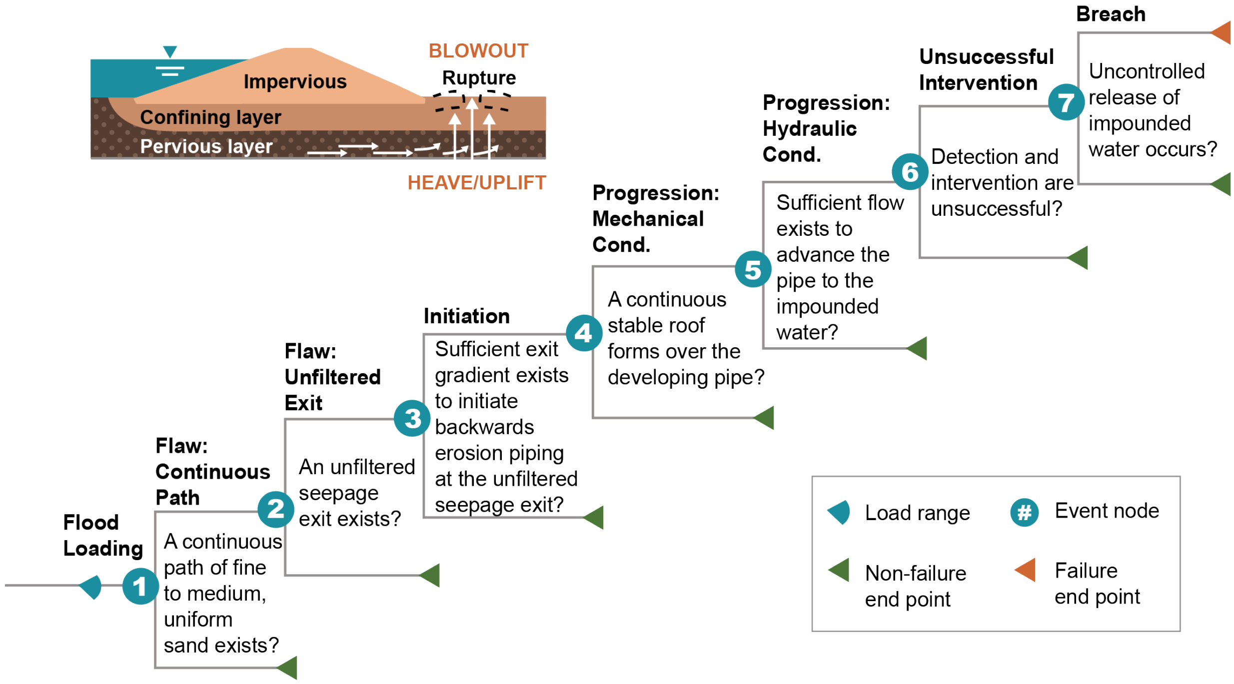
Potential failure modes should be described with enough detail to adequately estimate the probability of failure or justify screening out the potential failure mode. The team should consider each failure mode in increasing levels of detail until it is either screened out (i.e., excluded) or carried forward 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

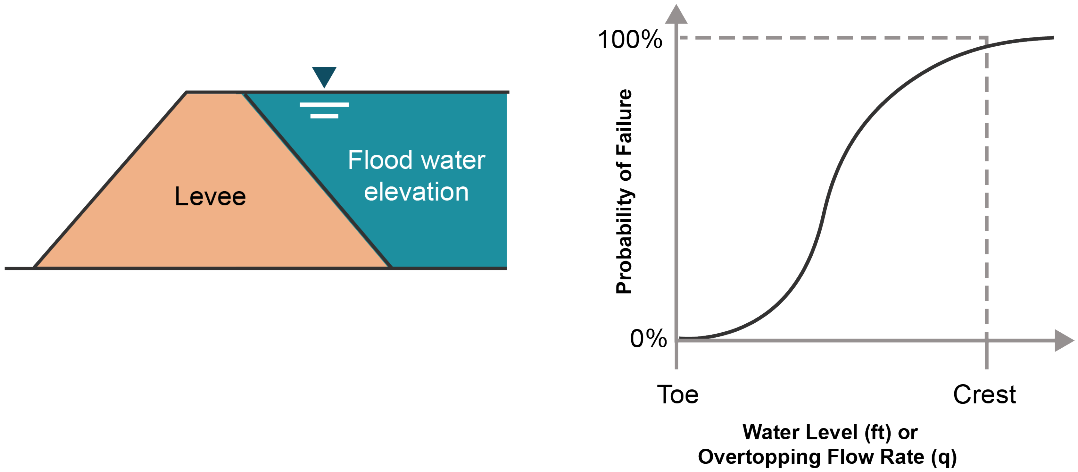
One tool that can be used in conjunction with expert elicitation or as a statistical model input is a system response curve established from case studies.

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

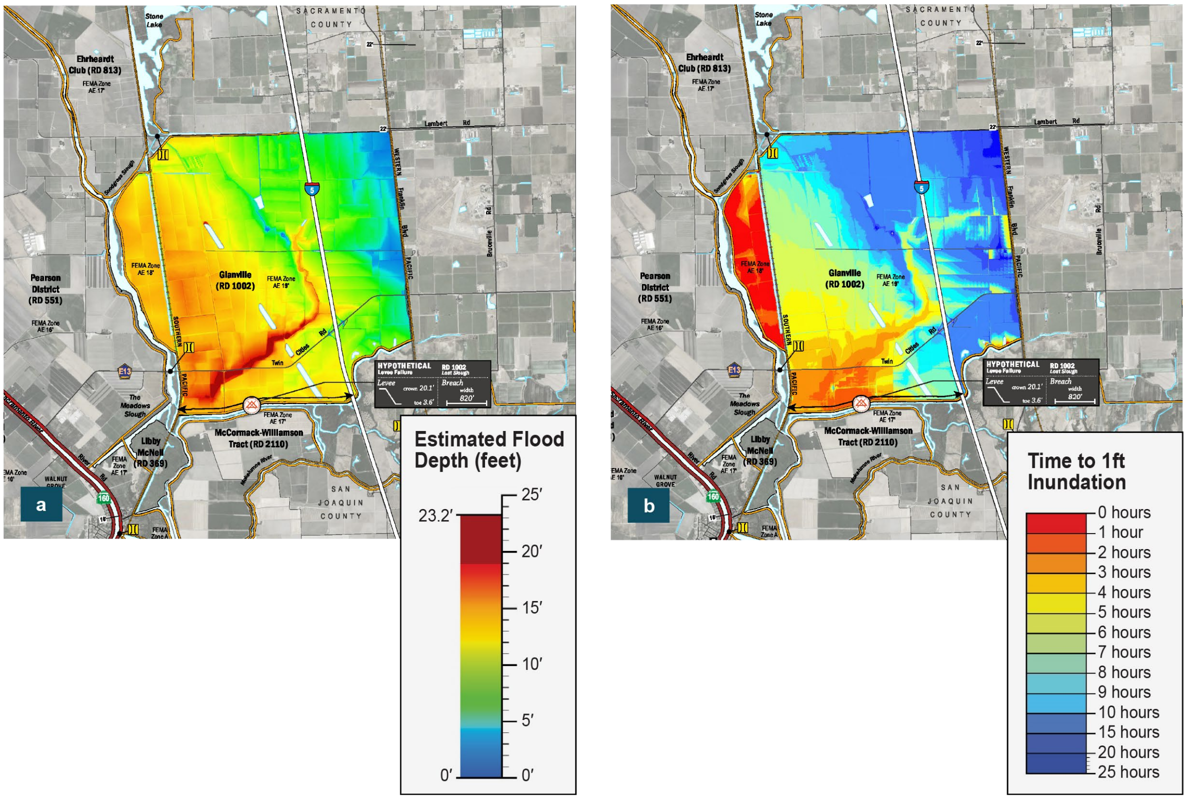
The levee breach modeling is an input to hydraulic modeling used to estimate inundation in the leveed area. For some levees, the configuration of the levee and topography of the leveed area may be such that overtopping or breaching of the levee would fill up a finite volume, similar to a bathtub or pond, 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

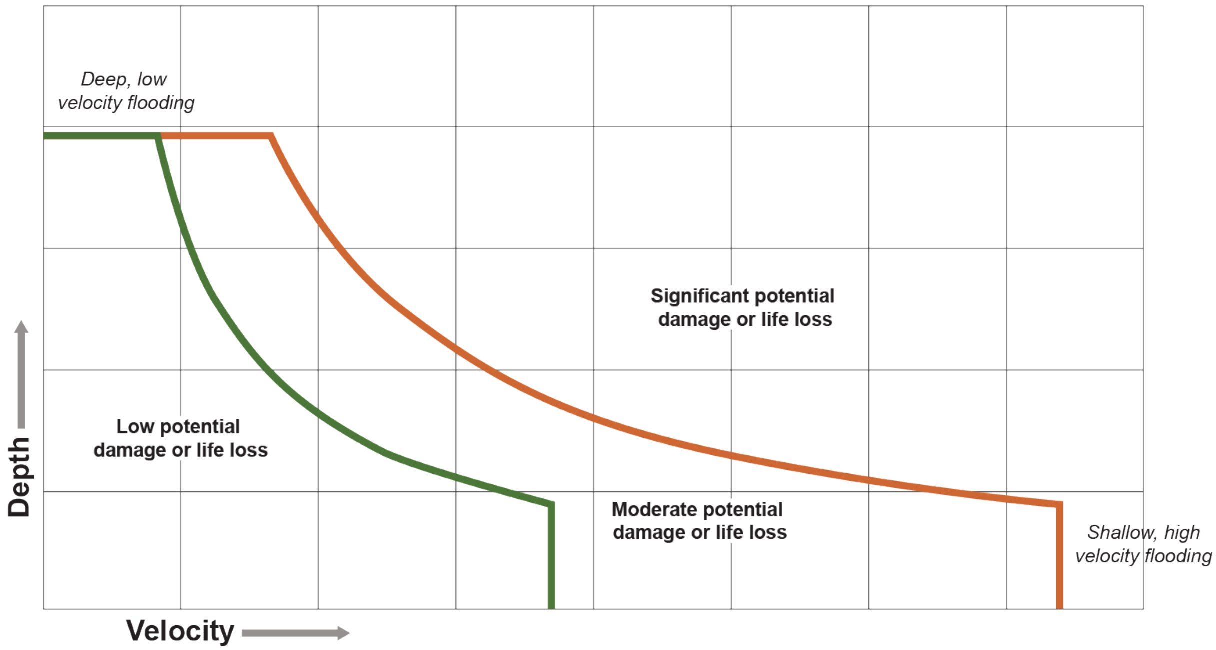
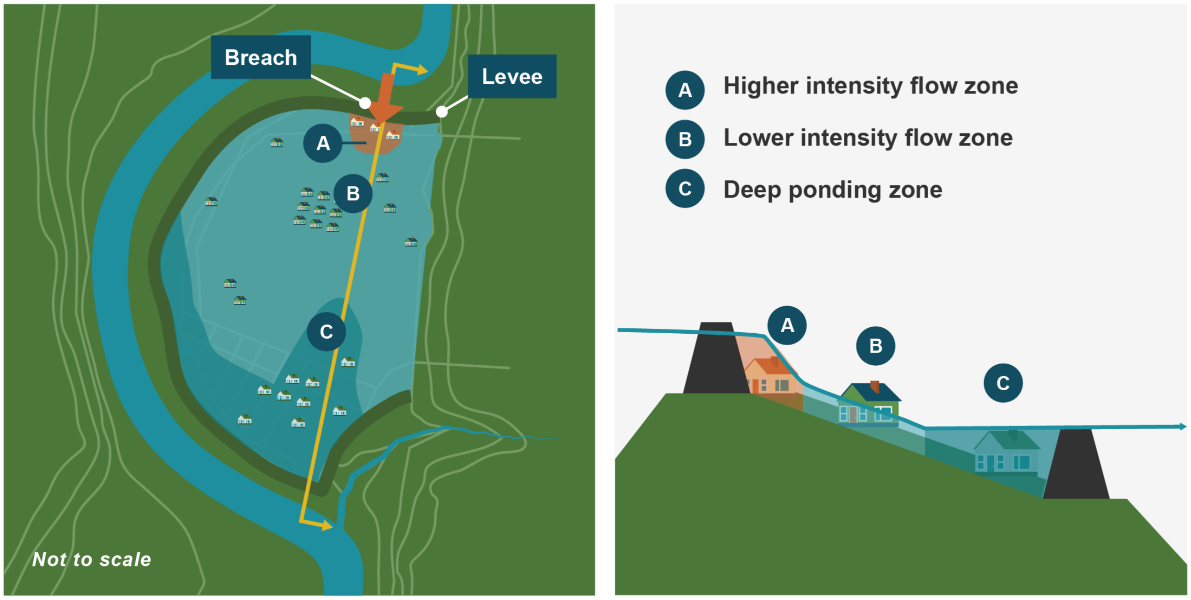


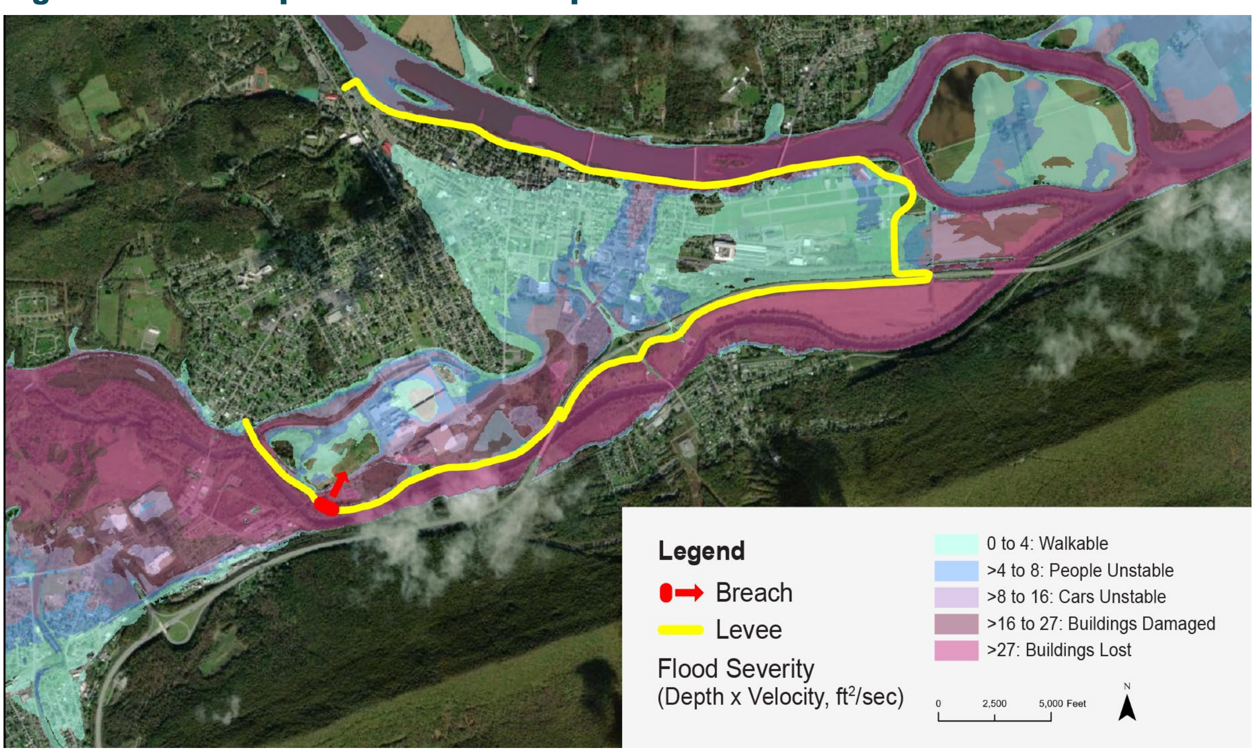
Figure 4-14 illustrates how the same levee breach results in different flood severities depending on location. Zone A is near the breach and is typically not a large area, but has the most damaging flood conditions and is the first to be impacted. Zone B is the next area to be flooded as the water spreads 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:

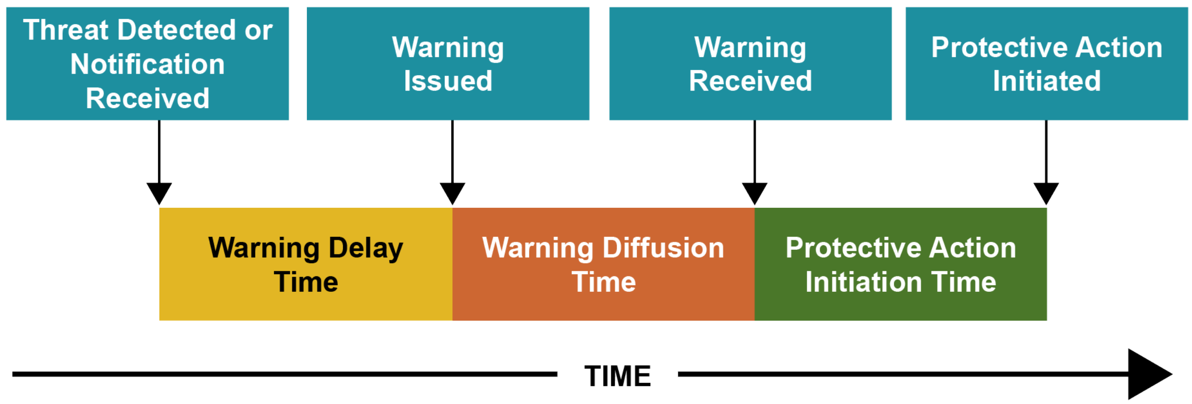
1. Define the leveed area.
2. Model the flood/breach scenarios (based on hazard and performance).
3. Estimate the population impacted by the flood.
4. Estimate the time required for warning and mobilization of the population.
5. Estimate the evacuation efficiency (based on warning time, evacuation time, 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.

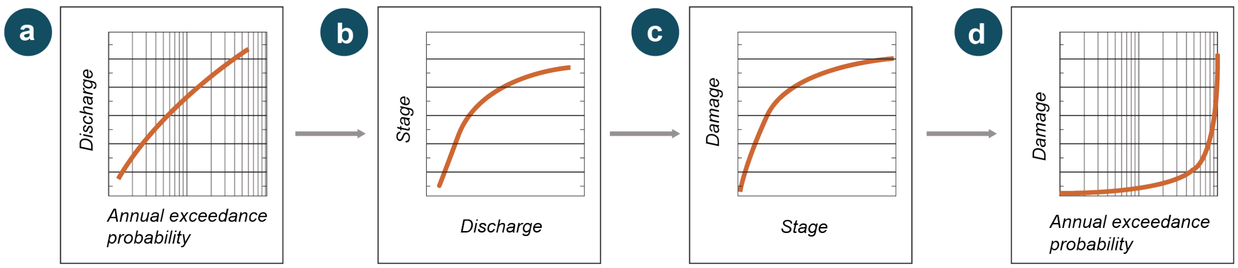
5.3.3.2 Asset Damage and Loss Functions

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.

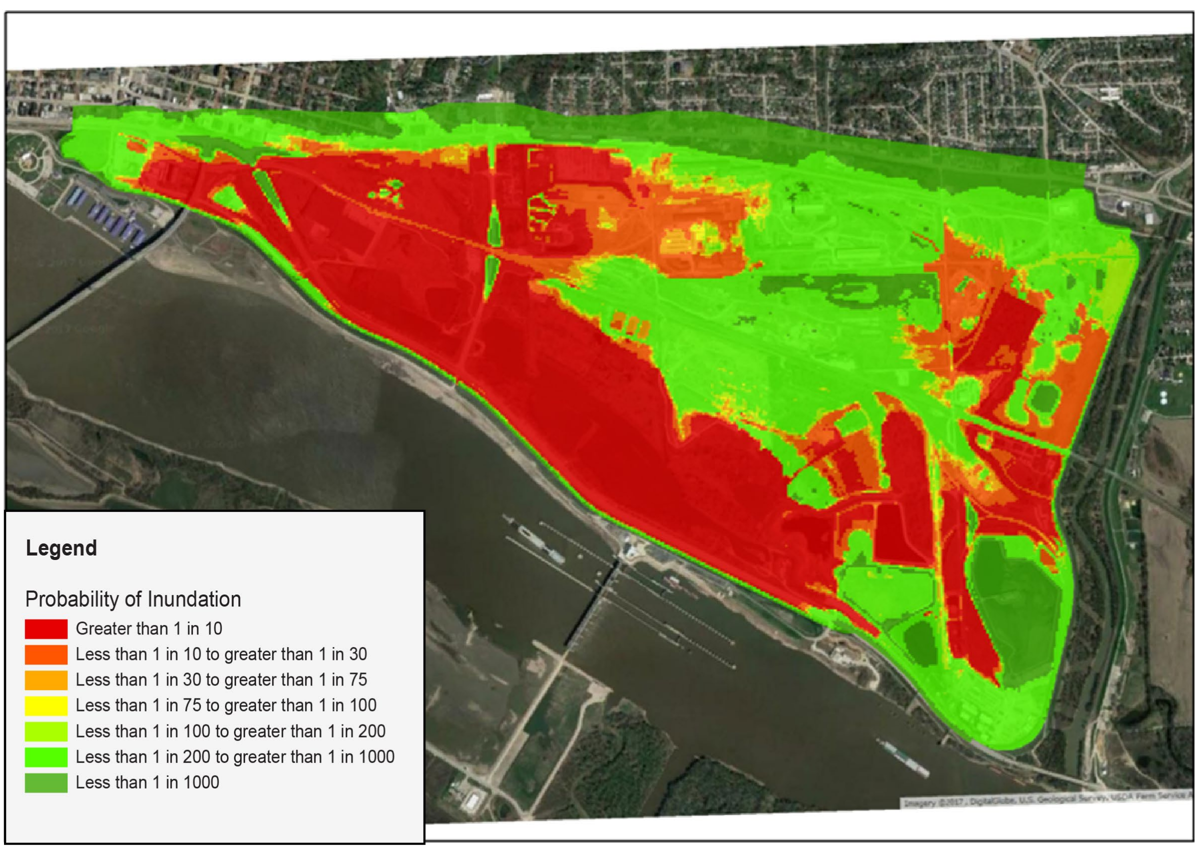
Depth damage curves can be developed for damage to structures, a structure's contents, vehicles, roads, and agricultural crops. Standard curves have been developed by FEMA and USACE for several structure types and vehicles. In detailed consequence models, they can be applied to each structure in the 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

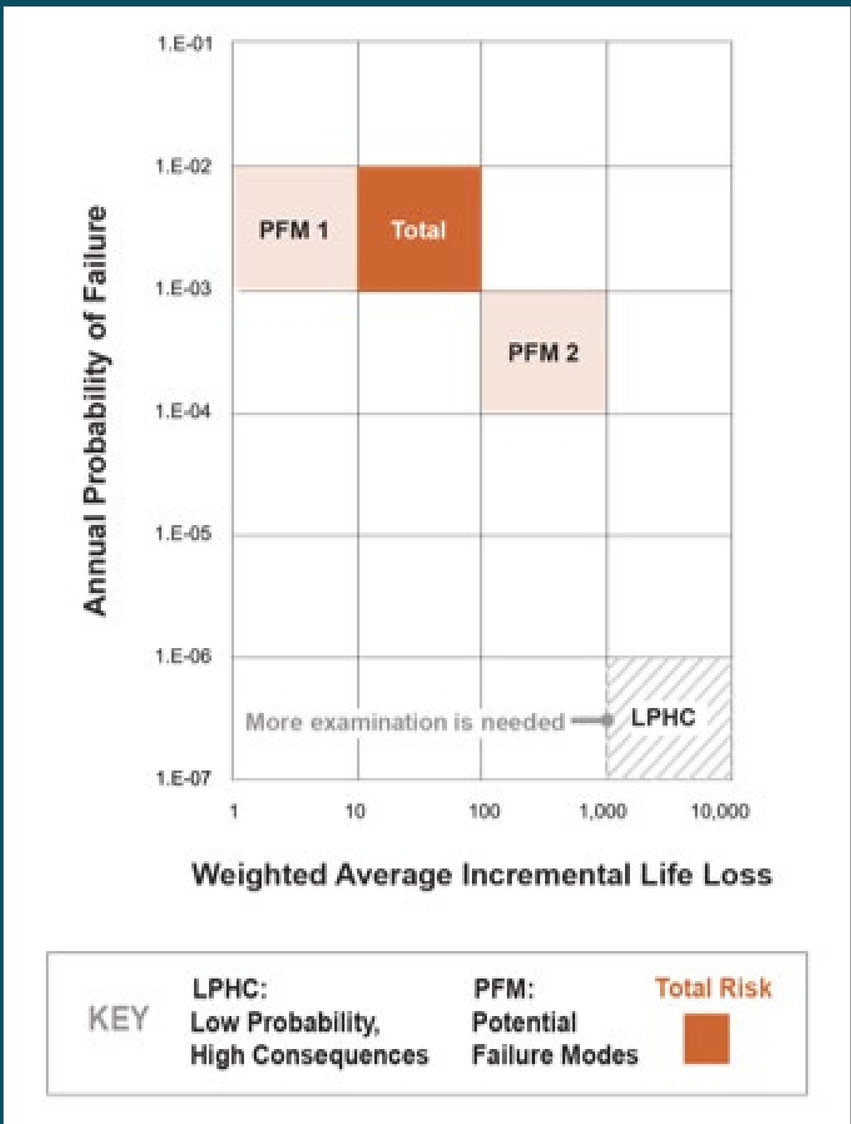
Component malfunction or misoperation could occur prior to or following levee overtopping. An important distinction should be made about how the risk of misoperation/malfunction contributes to levee risk based on the flood source. The levee is designed to prevent flooding from a certain source (or perhaps 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 $\boldsymbol{\overline{N}}$, 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, $\bar{N}$.

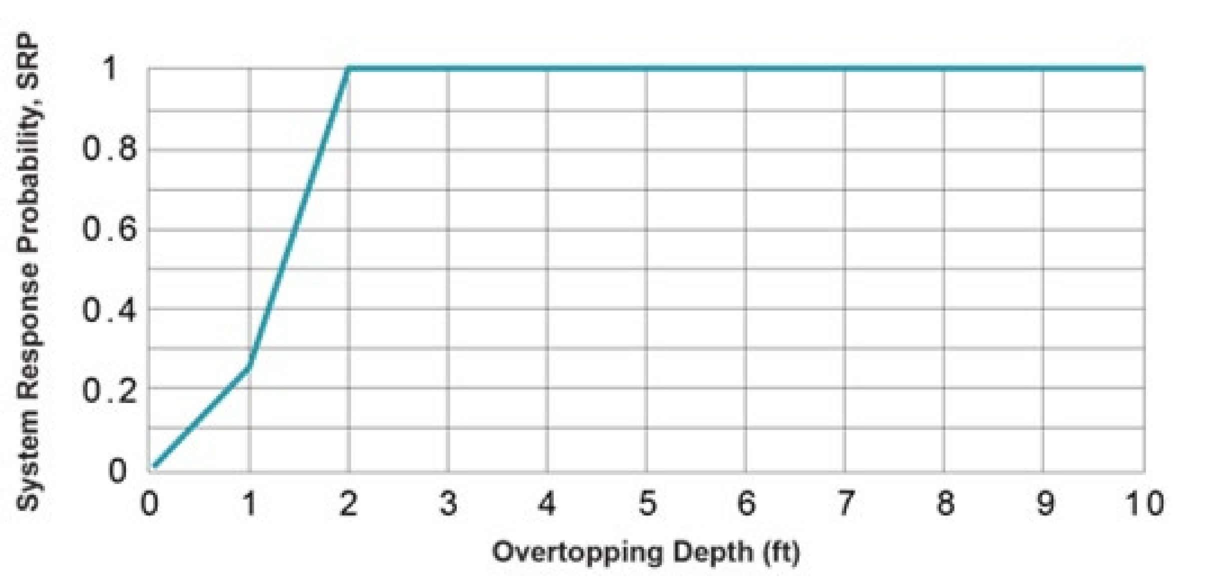
Calculation	$\bar{N}$
$\frac{(4.0\times10^{-3} - 3.8\times10^{-3})\times(\frac{0+0.25}{2})\times(0+595)}{2}$	0.007
$\frac{(3.8\times10^{-3} - 3.5\times10^{-3})\times(\frac{0.25+1}{2})\times(595+700)}{2}$	0.121
$\frac{(3.5\times10^{-3} - 3.0\times10^{-3})\times(\frac{1+1}{2})\times(700+800)}{2}$	0.375
$\frac{(3.0\times10^{-3} - 2.5\times10^{-3})\times(\frac{1+1}{2})\times(800+400)}{2}$	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	$\mathbf{4.0 \times 10^{-3}}$	0
1-ft overtopping	1.00	$\mathbf{3.8 \times 10^{-3}}$	5
2-ft overtopping	2.00	$\mathbf{3.5 \times 10^{-3}}$	100
3-ft overtopping	3.00	$\mathbf{3.0 \times 10^{-3}}$	800
6-ft overtopping	6.00	$\mathbf{2.5 \times 10^{-3}}$	2,000
10-ft overtopping	10.00	$\mathbf{2.0 \times 10^{-3}}$	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.

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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**.

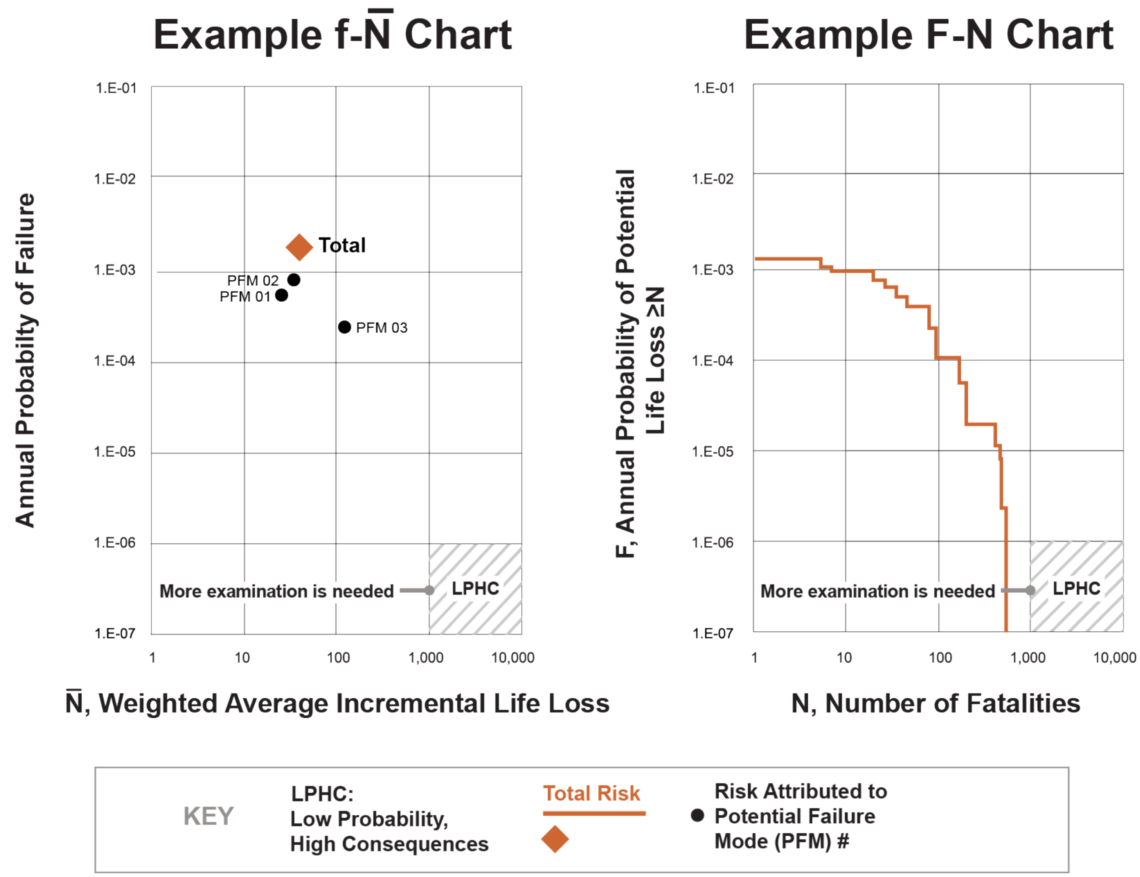
7.2.1 Risk Matrices

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.

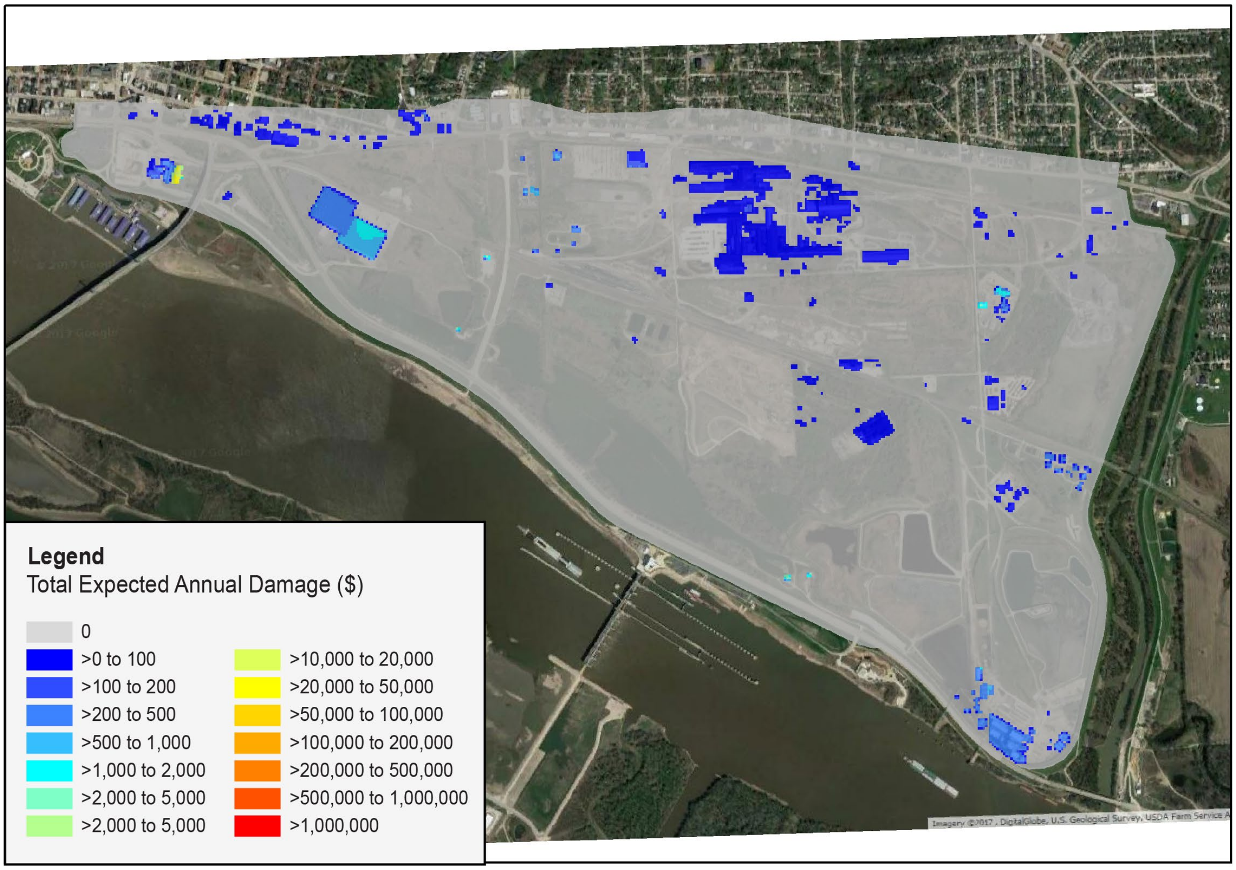
Figure 4-19: Example f-$\bar{N}$ and F-N Charts



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