ASSOCIATION OF STATE
DAM SAFETY OFFICIALS

THE JOURNAL OF Dam Safety

VOLUME 21 | ISSUE 2 | SPRING 2024

MAKING LEVEE SAFETY DECISIONS IN THE CONTEXT OF FLOOD RISK MANAGEMENTS

EMPIRICAL EQUATIONS FOR LEVEE BREACH PARAMETERS BASED ON RELIABLE INTERNATIONAL DATA

LEVEES: AN OPPORTUNITY TO ADVANCE STRATEGIC CONNECTIONS IN FLOOD RISK MANAGEMENT AT ALL LEVELS OF GOVERNMENTS

Stantec

Flood Risk Management

Stantec's team worked with the USACE Sacramento District to provide design and engineering services during construction for seepage and stability improvements along the Sacramento River East Levee.

Sacramento River East Levee, downstream of the American River confluence | California

Volume 21 | Issue 2 | Spring 2024

ISSN 1944-9836

THE JOURNAL OF Dam Safety

Association of State Dam Safety Officials

We are excited to publish another topic-focused issue of the *Journal of Dam Safety*. This issue is all about levees and levee safety. Our nation's levees reduce flood risk to over 17 million people, protecting nearly $2 trillion in property, including some of our most critical infrastructure. Dams and levees have a lot in common, with similar technical issues and overlaps in the expertise required to evaluate, construct, maintain, and rehabilitate the infrastructure. We can learn from one another – sharing knowledge will benefit both the dam and levee communities. This is particularly timely now as we build a National Levee Safety Program (to learn more, visit leveesafety.org).

To make sound engineering decisions that improve communities, it's important to weigh the benefits and risks associated with dam and levee infrastructure. By definition, all levees have a primary benefit of reducing flood risk. Our first article discusses how levee risk should be considered in the context of the flood risk reduction benefits the levee is intended to provide.

For the second article, Kaveh Zomorodi presents approaches for estimating levee breach parameters, with some key concepts that differentiate levee and dam breach characteristics.

The third article illustrates the need to work across various levels of government toward integrating our management of flood risks. It also delves into some of the specific similarities and differences between dams and levees and highlights the roles states can play in levee safety moving forward.

The development of the National Levee Safety Program is being led by the U.S. Army Corps of Engineers and FEMA. We provide a summary of recent and ongoing activities of the program, including the publication of first-ever *National Levee Safety Guidelines,* available at leveesafety.org. We encourage our readers to review and provide input on the guidelines. Feedback is due by July 31st.

The Volunteer Spotlight highlights the work of ASDSO's Speakers Bureau volunteer Russ Hicks. Our Regional Spotlight is on the Michigan Dam Safety Program and strides the program has made following the 2020 Edenville and Sanford Dam failures. We round out the issue with ASDSO news.

The *Journal of Dam Safety* is a quarterly publication dedicated to sharing technical content to benefit engineers, owners, operators, and others involved in dam and levee safety. Topics are presented from various geographic regions, relate to all types of dams, and represent different perspectives. Articles are selected to share important information, lessons to be learned, and to promote new technologies that can benefit the dam safety community. The journal is also a valuable source for industry news, organizational updates, and upcoming events.

We cannot stress enough that the Technical Journal Committee is always looking for articles of interest to our community. If you have an exciting project or topic to share with your peers, please contact Greg Paxson or others on the Technical Journal Committee to begin the process with a short abstract. Articles must be original work and appropriate for the readership. Please feel free to email gpaxson@schnabel-eng.com for more information on authorship or to provide feedback on recent articles.

ASDSO DAM SAFETY JOURNAL

The Journal of Dam Safety welcomes articles from any writer, but the opinions expressed in those articles do not necessarily reflect the opinions and policies of ASDSO.

EDITORIAL COMMITTEE

ASDSO REVIEW TEAM & CONTRIBUTORS

Lori C. Spragens, Executive Director: lspragens@damsafety.org

Katelyn Riley, Communications Director: kriley@damsafety.org

Brittany Lewis, Executive Office Manager/ Programs Support: blewis@damsafety.org

Association of State Dam Safety Officials

The Journal of Dam Safety is compiled, written and edited by the Association of State Dam Safety Officials

239 S. Limestone Street, Lexington, KY 40508
Tel: (859) 550-2788
Fax: (859) 550-2795
Email: info@damsafety.org

www.damsafety.org

ASDSO 2023-2024 BOARD OF DIRECTORS

ASDSO Disclaimer for Journal of Dam Safety

The material presented in this ASDSO publication has been prepared in accordance with generally recognized engineering principles and practices, and is for general information only. This information should not be used without first securing competent advice with respect to its suitability for any general or specific application. The contents of this publication are not intended to be and should not be construed to be a standard of the Association of State Dam Safety Officials (ASDSO) and are not intended for use as a reference in purchase specifications, contracts, regulations, statutes, or any other legal document.

No reference made in this publication to any specific method, product, process or service constitutes or implies an endorsement, recommendation, or warranty thereof by ASDSO.

ASDSO makes no representation or warranty of any kind, whether express or implied, concerning the accuracy, completeness, suitability or utility of any information, apparatus, product, or process discussed in this publication, and assumes no liability therefore. Anyone utilizing this information assumes all liability arising from such use, including but not limited to infringement of any patent or patents.

TABLE OF CONTENTS

ASDSO TRAINING CALENDAR

View additional information including agenda and registration details at **www.damsafety.org/training**.

July 16-19

» *Basic Soil Mechanics Related to Earth Dams*
Virtual Seminar

August 6-8

» *Inspection & Assessment of Dams*
Virtual Seminar

August 13

» *Using the Cone Penetrometer Test (CPT) for Evaluation of Dams and Levees*
Webinar

September 10

» *Hydraulic Tour of Standard NRCS Inlet Risers*
Webinar

September 22-26

» *Dam Safety 2024*
Annual Conference - Denver, CO

ASDSO Webinars Available in On-Demand Format

ASDSO provides a comprehensive library of over 130 On-Demand Webinars for dam safety professionals.

On-Demand webinars allow the registrant to access the webinar on-demand (any time 24/7) for up to one year following the date of purchase. On-Demand webinars allow registered participants to complete the quiz at the end and receive PDH credit.

In addition, all live webinars are added to the On-Demand library shortly after their live broadcast.

» **Visit https://portal.damsafety.org/asdso-webinars to view all On-Demand Webinars.**

Southport Levee Improvement Project, West Sacramento Area Flood Control Agency, City of West Sacramento, California *HDR, 2020*

Making Levee Safety Decisions in the Context of Flood Risk Management

Elena Sossenkina, P.E. | Jonathan Simm, Ph.D., C.Eng | Greg Paxson, P.E., BC.WRE | Michael K Sharp, Ph.D., P.E.

This article includes several concepts developed by the authors for the April 2024 draft of the *National Levee Safety Guidelines*. Some of the narrative and most of the graphics are included in various sections of the *National Levee Safety Guidelines.* The authors would like to acknowledge the *Guidelines Management Team and the Publications Support Team*, including representatives from the U.S. Army Corps of Engineers and HDR. The current draft of the *National Levee Safety Guidelines* is located at **www.leveesafety.org/pages/nlsg**

ABSTRACT

Levees provide vital flood risk reduction in the United States and throughout the world. It is important to understand that levees reduce, but do not eliminate, flood risk. Levees are just one component of a holistic flood risk management strategy, which typically includes a combination of structural and nonstructural approaches. Decisions related to all aspects of the levee life cycle, from planning to removal, should be made in the context of overall flood risk management strategies. Differences between levee risk management and flood risk management actions and decisions should be well understood, with clear goals and objectives to inform risk management approaches that are aligned with both the flood risk reduction provided by the levee and the risks posed by the levee.

This article describes the relationship between flood risk and levee risk; explains the often-confusing concepts such as residual risk, non-breach risk, breach prior to overtopping, and overtopping with and without a breach; and discusses how these terms are used to properly characterize the flood risk reduction benefits provided by a levee. The authors acknowledge that there are other terms used to describe these concepts, both in the United States and internationally, which can sometimes make the understanding of these concepts more difficult.

Comparing levee risk reduction benefits, levee risk, and flood risk can help in selecting the appropriate level of effort (rigor) and focus for levee risk management activities. This paper presents strategies and approaches that help inform decisions related to day-to-day activities and major investments to address levee safety concerns or to increase flood risk reduction benefits associated with the levee.

Levee Basics

A levee can be defined as follows: Humanmade (as opposed to natural) barriers along a watercourse (i.e., a river or a coastline) with the principal function of excluding floodwaters from a portion of the floodplain for a limited range of flood events.

To function as intended, levees must form a continuous physical barrier against floodwaters. Levee features that work together to create such a barrier include, but are not limited to, embankments, floodwalls, and closure structures. Engineered structures, such as highway and railroad embankments, may also make up a portion of the levee system. These structures are considered part of the levee when they are integral to the performance of a flood risk reduction system. In addition, the levee may tie to a natural high ground or a natural feature (e.g., a dune), which are also considered part of the levee, if they are integral to the performance of a levee system. In this paper the term levee and levee system are used interchangeably.

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

The function of levees in reducing flooding in the leveed area is illustrated in Figure 1, which portrays flood stage on the waterside of the levee versus flooding elevation in the leveed area (landside). When there is no levee (dashed line), the flooding elevation in the leveed area is equal to the flood stage on the waterside. The introduction of a levee and the resulting flood risk reduction is depicted as a solid line. The solid line traces the flooding on the waterside of the levee from the levee toe to the levee crest and beyond. Following the line from left to right illustrates that there is no flooding in the leveed area for flood stages on the waterside of the levee up to the levee crest elevation when the levee performs as intended. As water exceeds and overtops the crest of the levee, the levee continues to provide some benefits during overtopping, until a point where there is so much water in the leveed area that the levee no longer provides any flood risk reduction benefits (solid line meets and follows dashed line). Figure 1 illustrates a levee that is functioning as intended by providing flood risk reduction benefits including excluding flood waters from the leveed area for flood levels up to the levee crest and allowing time for orderly evacuation of individuals within the leveed area.

This figure is a simplification to illustrate the general function of levees to exclude floodwaters. It should be recognized that levees transform the floodplain, and other changes to the water levels for a given flood could be expected.

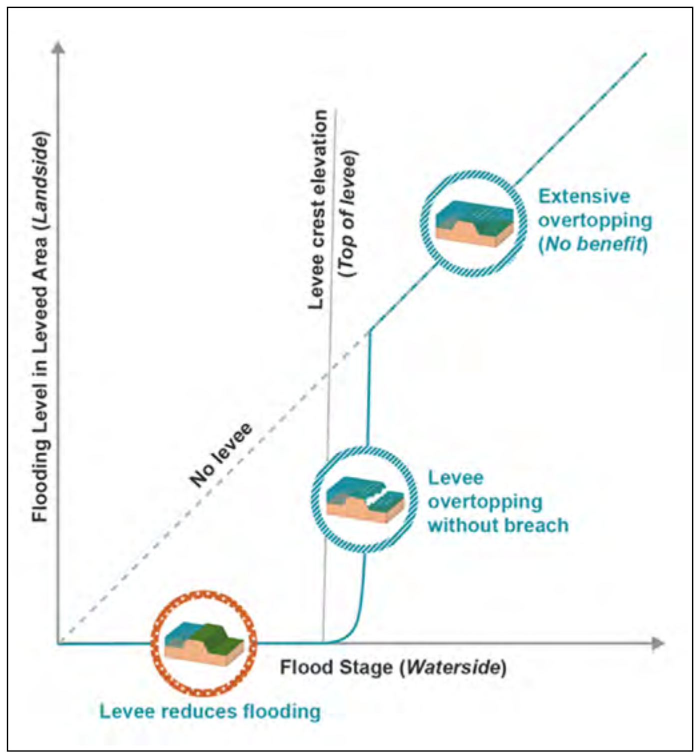


Figure 1 Function of Levees in Reducing Flooding

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

Levee Failure

Despite well intentioned design, construction, operation, and maintenance, a levee, like any infrastructure, may fail. Levee failure, or breach, could result in catastrophic consequences, and, therefore, it is important to understand why and how a breach may develop. The three levee breach situations are described as follows and shown in Figure 2:

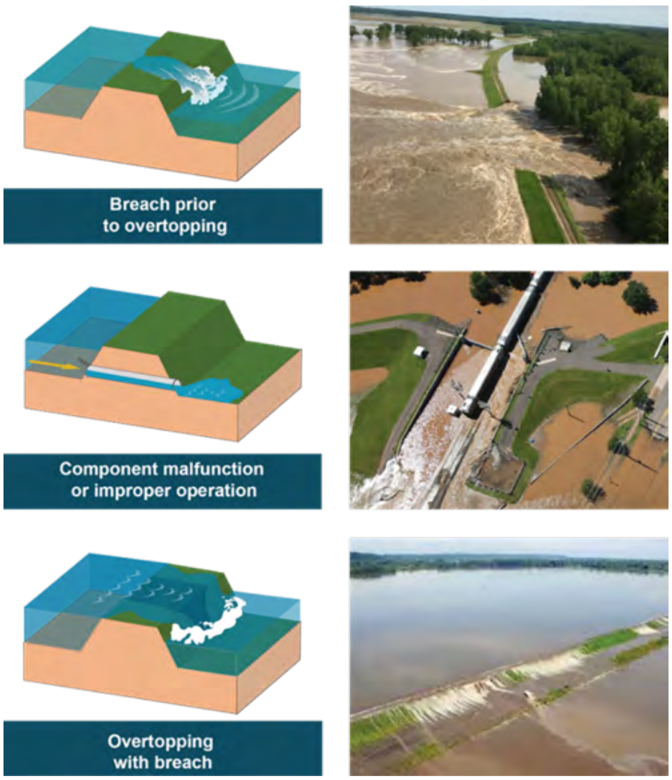


Figure 2 Levee Breach Scenarios

- **Levee breach prior to overtopping**. In this scenario, the levee breaches and floodwaters flow into the leveed area before the levee is overtopped. There are several mechanisms that could cause this failure scenario, including internal or external erosion, slope failure of an earthen embankment, or instability of a floodwall.

- **Malfunction or misoperation of a levee feature.** In this scenario, a levee feature either malfunctions or does not properly operate. This could include situations in which a component of a closure fails, such as a sandbag wall or gate; a pump does not operate; or installation of a closure does not occur in time for the structure to properly exclude floodwaters. These failures can result in an uncontrolled release of floodwater into the leveed area or can lead to more constricted and constrained inundation.

- **Levee breach from overtopping.** This scenario occurs when water overtops the levee and the flows cause erosion sufficient to breach the levee with rapid inundation of the leveed area.

Using the same concept as Figure 1, Figure 3 illustrates how the leveed area could be flooded with each of these breach scenarios. The solid blue line illustrates the levee functioning as intended, including inundation resulting from overtopping of the levee without breach. The orange dashed lines illustrate the levee breach prior to and from overtopping.

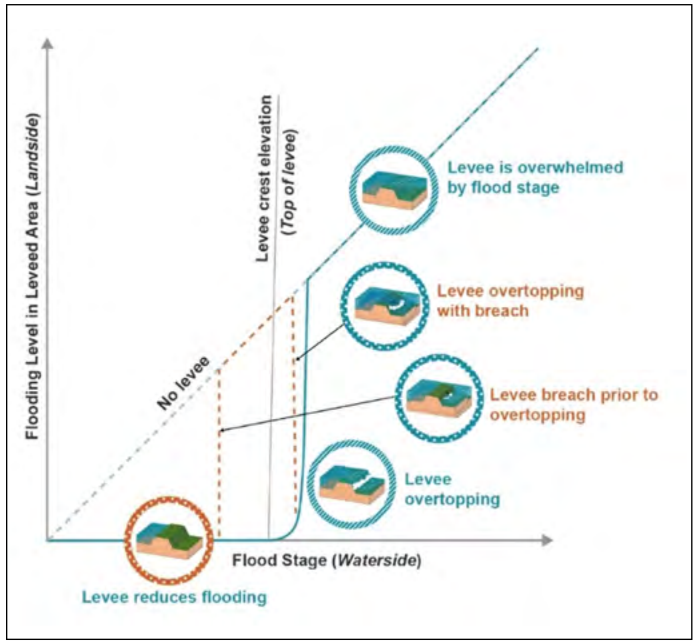


Figure 3 Levee Breach Scenarios

Relationship Between Flood Risk and Levee Risk

Levees are just one of many solutions that may be implemented as part of a flood risk management strategy. There are multiple combinations of structural and nonstructural measures that can be used to achieve the desired level of flood risk reduction. The selection depends on many factors, including, but not limited to, flood risk drivers and the effectiveness of a given measure in addressing them, project physical constraints, availability of funding, existing policies and practices, and community goals. The purpose of flood risk management is to reduce flood risk to as low as practical through integrated implementation of the selected measures.

Decisions associated with levees should be made in the context of flood risk management, and, therefore, it is important to understand the relationship between flood risk and levee risk. The following definitions are fundamental to understanding this relationship.

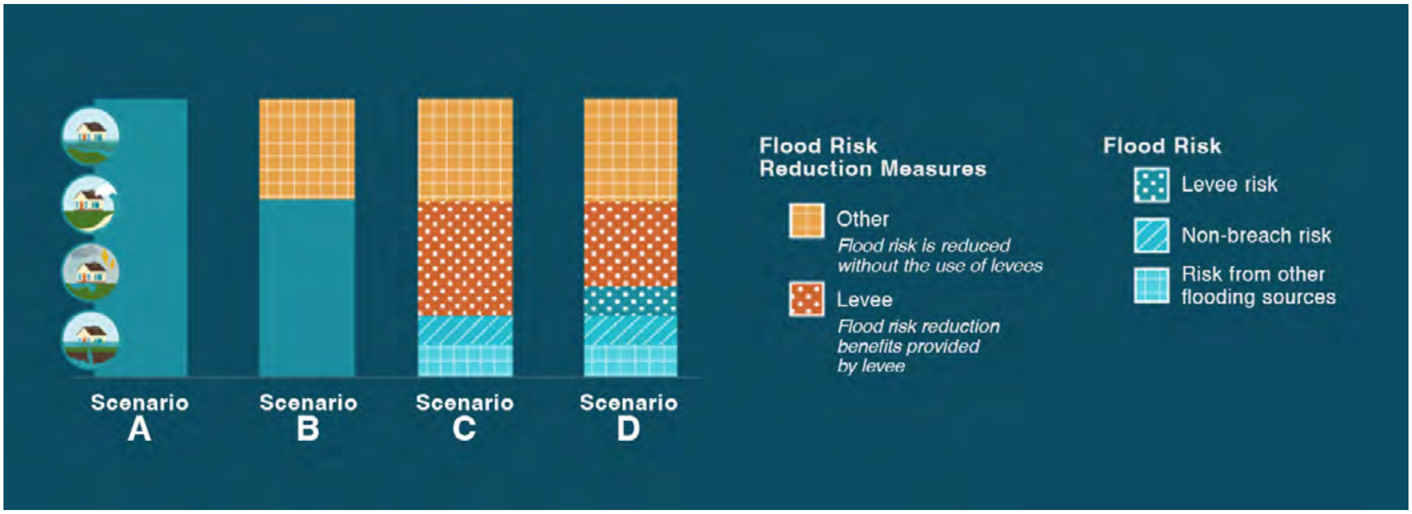


Figure 4 Relationships Between Flood Risk, Levee Risk, and Non-breach Risk

Flood risk. The probability and consequences of flooding in an area. For areas with flood risk reduction infrastructure (e.g., dams, levees, etc.), it accounts for how the infrastructure impacts the subject area, including life, health, and safety impacts; monetary and economic impacts; environmental impacts; and social and cultural impacts. It also includes all sources of flooding.

Non-breach risk. The probability and consequences of flood waters exceeding the top of the levee and flooding the leveed area without levee breach, also known as overtopping without breach risk.

Levee risk. The likelihood of occurrence and potential consequences for the following three inundation scenarios: levee breach prior to overtopping, levee breach due to overtopping, and malfunction or misoperation of levee features.

Flood risk within the leveed area is a sum of non-breach risk, levee risk and flooding from other sources. Flood risk may be addressed by implementing measures singularly or in combination with other measures. Once strategies are implemented, the flood risk for a community is changed and some level of risk is replaced by the benefits of that strategy. When a levee is chosen as a flood risk reduction strategy, the levee will transform some amount of flood risk to levee risk. This is because all levees have some potential for breach prior to overtopping.

Figure 4 depicts several scenarios with regard to flood risk reduction strategies, as follows.

Scenario A: No flood risk reduction strategy. Flooding in the area may occur from any and all potential sources and through the full range of flood events.

Scenario B: Risk reduction measures other than levees. Measures may include nature-based solutions, floodproofing, or zoning. In Scenario B, the flood risk is reduced compared to Scenario A, without the use of levees.

Scenario C: No levee breach. A levee is constructed to provide additional flood risk reduction benefits compared to Scenario B. In this scenario, the likelihood of breach or improper operation is zero for the full range of flood events, and the only potential for adverse consequences is due to inundation from floods that exceed the top of the levee (overtopping without breach, also known as "non-breach risk"). In Scenario C, flood risk in the leveed area—an area behind the levee—is the sum of non-breach risk and flooding from other sources not associated with the levee. For example, for a community with a riverine levee, the riverine (fluvial) portion of the flood risk will go down but flooding in the leveed area may still occur from groundwater recharge or heavy rain and surface water runoff (pluvial).

Scenario D: Typical levee. Building on Scenario C, this situation recognizes the reality that the levee can breach, thereby increasing flood risk. In this case, the flood risk reduction provided by the levee is less than in Scenario C and the flood risk is higher.

INTERCONNECTED DECISIONS

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

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

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

In situations when the flood risk management plan is developed around existing levees, the first step is to estimate the maximum flood risk reduction the levee can provide. Once the maximum risk reduction is understood, the overall strategy can be formulated by considering other measures to supplement flood risk reduction benefits provided by the levee, setting new objectives for the existing levee, modifying the levee accordingly, or combinations of these actions.

In general, flood risk management decisions are broader and deal with overall strategies and floodplain management, whereas levee risk management decisions focus on the levee itself, (including potential consequences a levee breach could cause). As shown in Figure 4, some actions require shared/joint decision making.

Levee Risk Management Overview

The objective of levee risk management is to provide the intended flood risk reduction benefits and ensure that levee risk is tolerable. To accomplish this, levee risk management should focus on (a) making sure the levee performs reliably in accordance with established goals; and (b) managing potential consequences of levee breach or misoperation. The following sections describe concepts associated with levee risk management, which are illustrated similar to Figure 4.

ROUTINE ACTIVITIES ARE ESSENTIAL FOR MANAGING LEVEE RISK

Regular inspections, surveillance and monitoring, and timely maintenance are activities that help prevent deterioration of the levee and ensure proper function. Without routine activities, levee risk can increase over time, diminishing the flood risk reduction benefits associated with the levee, even with all other factors, such as population in the leveed area, remaining unchanged. This is schematically illustrated in Figure 5, which reflects the existing levee condition and the future increase in levee risk and corresponding loss of risk reduction benefits as the levee deteriorates.

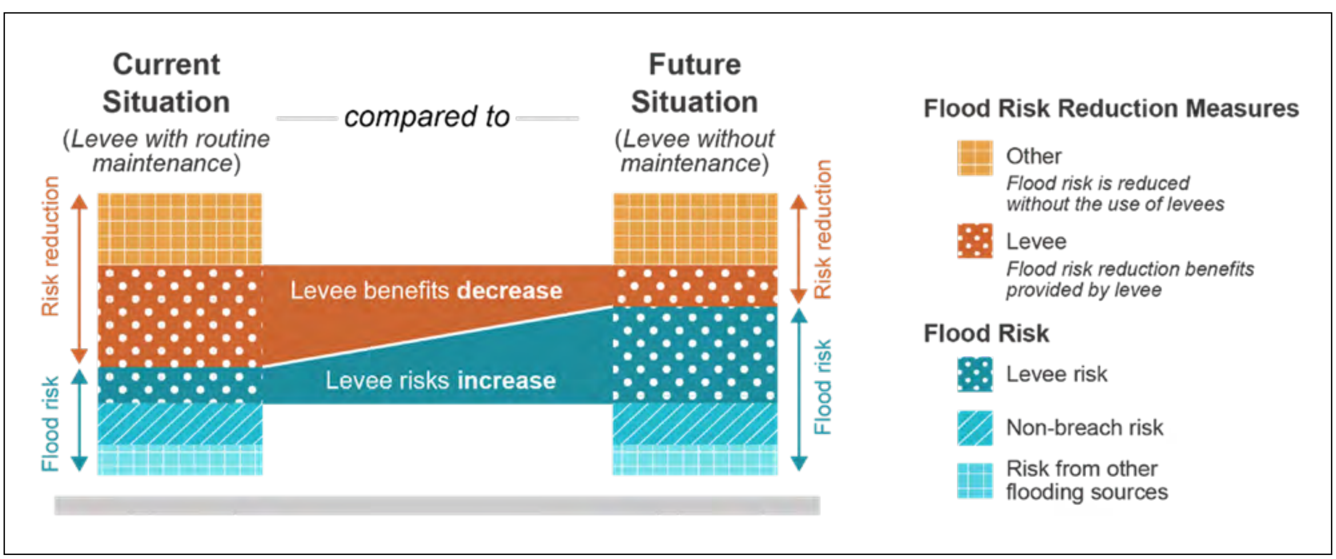


Figure 5 Increase in Levee Risk Over Time with No Maintenance

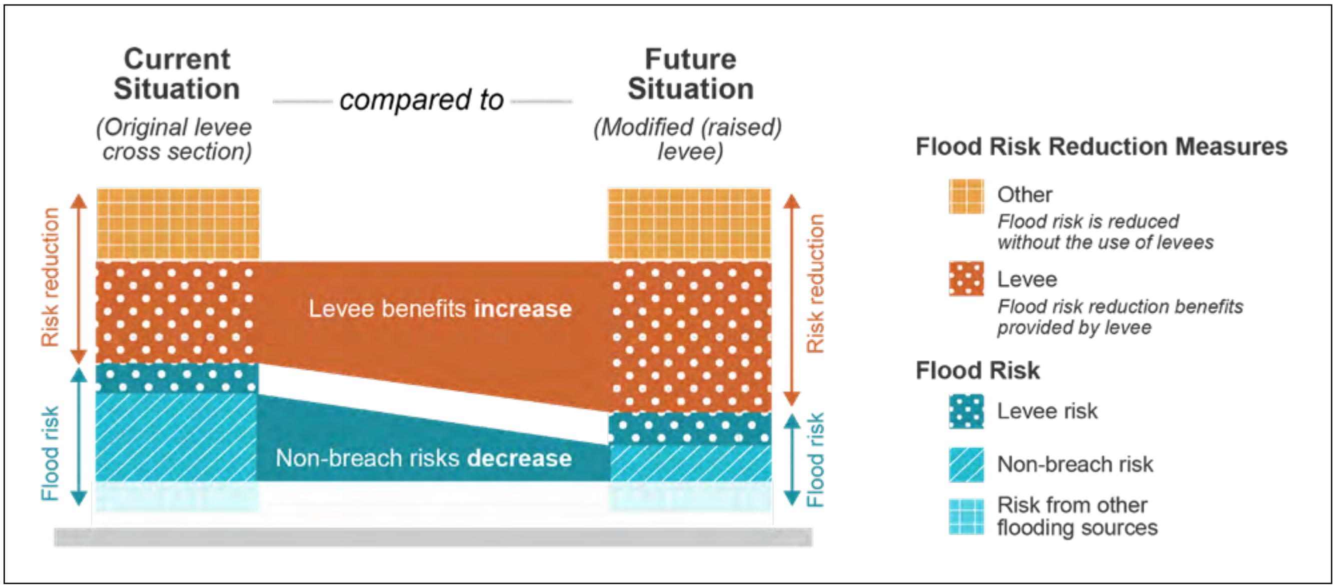


Figure 6 Change in Levee Risk with Levee Modifications

LEVEE RISK CANNOT BE ELIMINATED

Levees can be raised (modified), widened, or hardened (rehabilitated) to provide additional risk reduction benefits. However, even if it were feasible to make levees so high as to eliminate any possibility of overtopping, levee risk will remain. This concept is schematically shown in Figure 6. The existing levee is compared with a modified (raised) levee. With the modification, the "levee risk reduction benefits" increase and the flood risk in the leveed area is reduced, but it is still a sum of levee risk, non-breach risk, and flooding from other sources (Figure 6).

Further, in modifying a levee, the potential to inadvertently increase risk compared to current conditions must be considered. This increase could be from the introduction of a new potential failure mode or by increased consequences associated with a levee breach (e.g., higher depth and velocity of flooding). The goal of levee risk management is to ensure that levees do not contribute significantly to flood risk in the leveed area and levee risk remains tolerable.

RISK IS DYNAMIC

Both flood and levee risks are dynamic and can evolve with time due to changes in flood hazards (including climate change), structure condition, and changes in land use and development in the leveed area. In addition, the understanding of the levee risk can change through advances in engineering approaches to understand the structure and/or estimate the risks. These changes should be periodically assessed and the corresponding risks proactively managed.

It is important to recognize that despite proactive levee risk management, the flood risk in the leveed area can increase with time. For example, economic development in the leveed area and increase in population living and working behind the levee results in an increase in non-breach risk. In addition, these changes in the leveed area would result in increased risk reduction benefits provided by the levee and increased levee risk. This scenario is schematically illustrated in Figure 7, which compares the existing levee to a future condition with additional development in the leveed area, resulting in increased non-breach risk, along with increases in both risk reduction benefits and levee risk. Although not shown in Figure 7, levee risk may also increase due to the increased potential consequences of a levee breach.

There are approaches to compensate for the increase in levee risk for this scenario, primarily through improved evacuation effectiveness. However, even if the levee risk remains the same, the flood risk in the leveed area increases. Strategies for addressing or accepting this increase should be made jointly between levee owners and the community.

Because community needs and the associated flood risk management strategies evolve, levees should evolve and change accordingly. For example, with the desire to shift to nature-based solutions or to provide additional storage in the floodplain, existing levees may need to be removed and new setback levees constructed to meet the revised flood risk management strategy. Conversely, with additional development in the leveed area and the associated increase in flood risk, the strategy may shift to more robust structural measures. Levees may need to be raised or modified to incorporate reaches of managed overtopping and floodways away from urban areas.

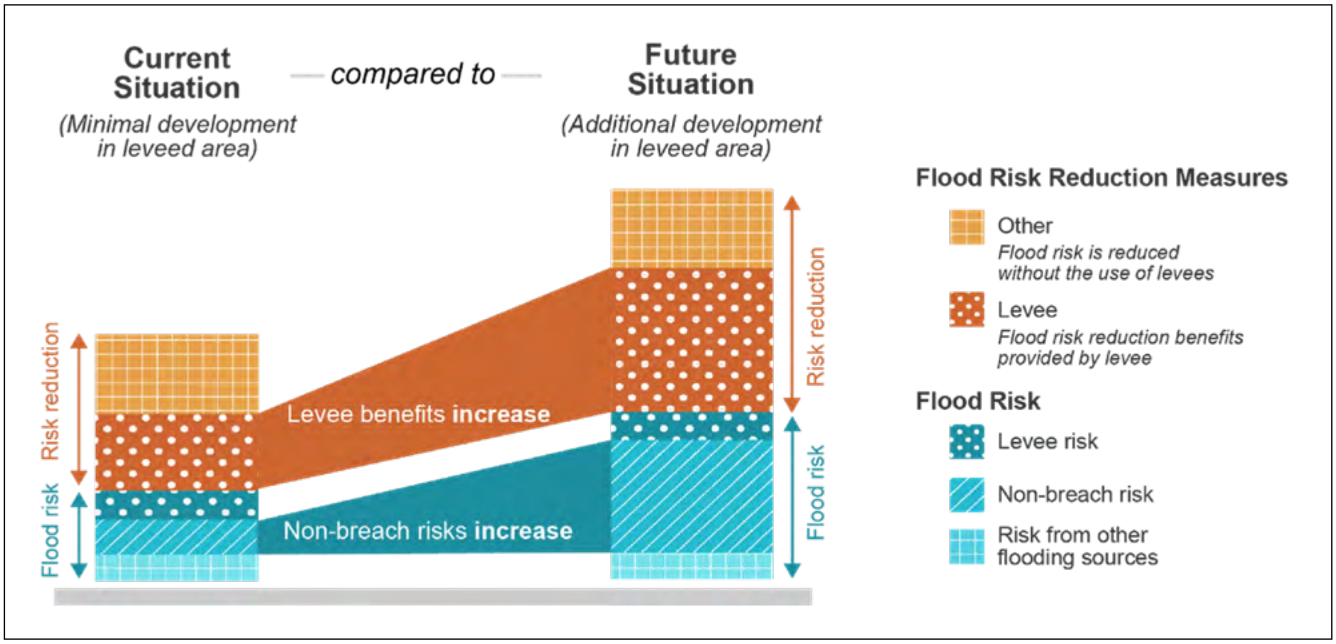


Figure 7 Increase in Flood Risk Over Time

Levee Safety

Levee safety is the art, science, and practice of managing levee systems as an integral element to a community flood risk management strategy. The current best practice for levee safety management is to use risk-informed decision making supported by engineering standards. This approach is based on a set of principles that have evolved to reflect the best understanding, management practices, and technology available to reduce levee risks and guide decisions. The following principles apply to levee safety:

- Life safety is paramount. Prioritizing actions to reduce the risk to life loss is the most important responsibility within the levee safety management.
- Levee safety is a shared responsibility. To be effective, levee safety must include all levels of government, businesses, and the public working together in a coordinated fashion.
- Levees should exist in balance with social, environmental, cultural, and economic interests within the floodplain.
- Levee risk should not contribute significantly to the overall flood risk.
- Transparent, proactive, and continuous engagement with community members and other stakeholders is essential.
- Levees exist within a dynamic environment influenced by both natural and human-made factors. Levee risk should be periodically reevaluated and proactively managed.
- Floods do not impact all communities and individuals equally. Levee risk management practices should strive to achieve equity by addressing unique challenges that may be experienced by socially vulnerable and underserved communities behind levees.

Levee Risk Management Responsibilities

Responsible levee risk management requires continuous and proactive monitoring of risk and taking actions to reduce it as low as practicable. Levee risk management responsibilities are:

- understanding risks associated with levees
- taking actions to reduce risk
- building risk awareness
- fulfilling daily responsibilities

Fulfilling these responsibilities throughout the levee life cycle is essential for ensuring levee risk is tolerable. Tolerable risks are defined as: (a) risks that society is willing to live with so as to secure certain benefits, (b) risks that society does not regard as negligible or something that it might ignore, (c) risks that society is confident that are being properly managed by the owner, and (d) risks that the owner keeps under review and reduces still further if and as practicable. Levee risk is considered tolerable if it is understood to commensurate with the benefits provided by the levee and risks have been reduced to as low as reasonably practicable. The evaluation of tolerability is subjective and is not intended to be a checklist or a pass/fail grade.

UNDERSTANDING RISKS ASSOCIATED WITH LEVEES

A risk characterization documents and depicts risk for use in risk management and decision making. It can be supported by various products portraying the risk. Understanding the risk includes:

- understanding the basis for risk estimates, including primary sources of uncertainty as well as confidence in the estimates
- knowing where a levee risk estimate plots on the life safety matrix and other ways risk is portrayed and visualized
- understanding what is driving the risk
- understanding how levee risk compares to flood risk reduction benefits provided by the levee, the non-breach risk, and the flood risk in the leveed area.

TAKING ACTIONS TO REDUCE RISK

Actions to reduce risk should be considered in the context of the flood risk. Principles of risk reduction and approaches or strategies to be evaluated in reducing risk are presented in the following sections.

As Low as Reasonably Practicable

Levee owners should identify and implement cost-effective and socially and environmentally acceptable approaches to achieve flood risk reduction benefits and manage levee risks. Even if risks are below the societal risk guidelines, actions may still be justified. A responsible approach to levee ownership requires that cost-effective approaches to reduce risk further are identified, explored, and implemented as appropriate.

This guideline is met if those responsible for operation and maintenance, as well as those involved with safety assessments, identify approaches to reduce risk and the solutions are implemented in a timely manner. This should be part of the culture of those involved with day-to-day activities as well as those completing the periodic activities.

All activities should consider what additional risk-reduction efforts could be easily and economically implemented and their impact on the risk. When assessing how far to reduce risks below the societal tolerable risk guideline, the as-low-as-reasonably-practicable (ALARP) considerations should be followed.

The fulfillment of ALARP considerations is usually assessed as a matter of judgment and considers the following:

- the level of risk in relation to the tolerable risk guidelines
- the cost effectiveness of the risk reduction measures
- relevant recognized good practice and a precedent of comparable decisions on other projects
- the chance of success of an action
- societal concerns as revealed by engagement with the community and other stakeholders

Investment Strategies

Understanding, evaluating, and comparing levee risk reduction benefits, levee risk, and non-breach risk can help in selecting appropriate focus and level of effort for risk management activities. It can also help inform decisions on whether to invest in modifications to increase flood risk reduction benefits associated with the levee. Consider the five scenarios illustrated in Figure 8 and described here.

The five scenarios portrayed in Figure 8 are described as follows.

Scenario 1. The levee provides limited risk reduction benefits and flood risk in the leveed area is mostly managed through other measures so that the remaining flood risk is low. Because the levee is not heavily relied upon for flood risk reduction, its condition and satisfactory performance are not as critical. Therefore, the benefit of expending resources on reducing levee risk is limited. Scaled-back levee risk management activities may be sufficient for this structure. There is also no strong justification to invest in rehabilitation or modification (raising the levee) because the flood risk is primarily managed through other solutions.

Scenario 2. The levee is a major part of the flood risk reduction strategy and provides significant flood risk reduction benefits. Further, the levee is in good condition and is proactively managed so that the levee risk is low. In this scenario, levee risk management activities are of paramount importance to ensure levee risk remains low. Robust inspection, maintenance, and surveillance and monitoring programs, and strong emphasis on building risk awareness in the community as well as emergency preparedness and planning, are justified. On the other hand, there is no strong justification to invest in rehabilitation or modification because the flood risk is low.

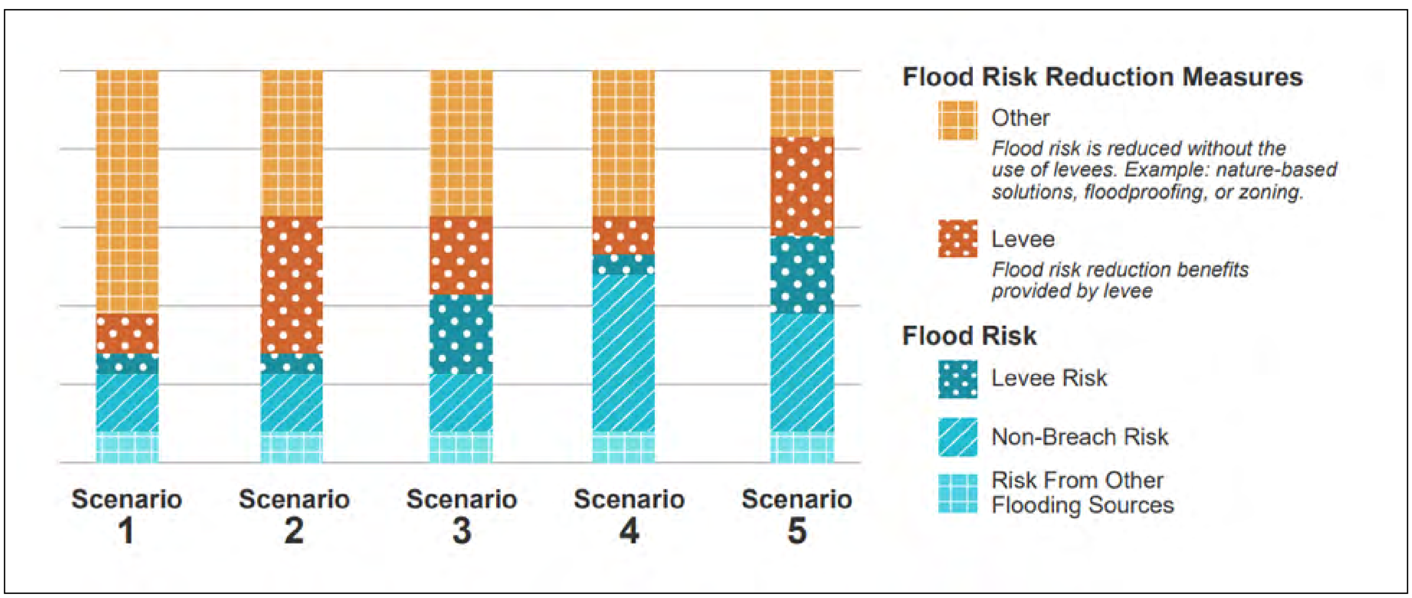


Figure 8 Scenarios Informing Levee Risk Management Activities

Scenario 3. The levee is a major part of the flood risk reduction strategy, but in its current condition, the levee risk is high, particularly relative to the benefits provided by the levee. In this scenario, there is justification to reduce levee risk by rehabilitating the levee. In addition, robust inspection, maintenance, and surveillance and monitoring programs, and strong emphasis on building risk awareness in the community as well as emergency preparedness and planning, are justified. On the other hand, there is no strong justification to modify the levee because flood risk due to overtopping without breach (non-breach risk) and flooding from other sources is low.

Scenario 4. The levee provides limited flood risk reduction benefits. Flood risk in the leveed area is high and is driven by non-breach risk and/or other sources of flooding. There may be relatively little benefit gained by rehabilitating the levee to reduce levee risk. Scaled back levee risk management activities may be sufficient for this structure. On the other hand, modifying the levee (e.g. raise the crest) may offer a significant overall flood risk reduction benefit. With modifications, changes in levee risk should be evaluated.

Scenario 5. The levee is a major part of the flood risk reduction strategy, but in its current condition, the levee risk is high. Non-breach risk and/or flooding from other sources in the leveed area is also high. This scenario represents the highest overall flood risk of all five scenarios. In this scenario, there is justification to reduce levee risk by rehabilitating the levee. In addition, robust inspection, maintenance, and surveillance and monitoring programs, and strong emphasis on building risk awareness in the community as well as emergency preparedness and planning, are justified. There is also justification for modifying the levee (e.g., raise the crest) or implementing other measures to provide additional flood risk reduction.

BUILDING RISK AWARENESS

Risk awareness is foundational to successful risk management. Although awareness alone does not guarantee individuals and communities will take protective actions, it is essential to providing those entities the option to safeguard things of value to them. An open and transparent exchange of information improves knowledge and understanding of risks and helps others understand options available to manage those risks. The following questions should be considered with regard to risk awareness:

- Do all parties responsible for levee risk management, collectively called the levee owner, have a common understanding of levee risk? This requires all entities participating in a risk assessment and decision making understand the risks, along with clear and complete documentation of risk estimates and risk characterization.
- Can those responsible for levee operation and maintenance activities describe levee vulnerabilities and explain how the operation and maintenance plan considers site-specific risks?
- Has the community in the leveed area been provided the best available risk information associated with the levee, including potential changes to flood risk over time? Examples include public engagement activities, media stories, or a current community website.

FULFILLING DAILY RESPONSIBILITIES

Routine activities such as inspections, periodic reassessment of risk, proactive maintenance, surveillance and monitoring, and emergency preparedness and planning are critical elements of levee risk management. Daily responsibilities are considered fulfilled when (a) routine inspections are taking place, (b) risks are routinely evaluated, (c) issues arising that result in increased risk are addressed in a timely manner, (d) levee safety-related operation and maintenance activities are performed in a timely manner, (e) a surveillance and monitoring plan is in place and includes the expected performance for each instrument and area to be observed, and (f) an emergency action plan exists and is current.

Conclusions

Levees are just one component of a holistic flood risk management strategy, which typically includes a combination of structural and nonstructural approaches. Decisions related to all aspects of the levee life cycle, from planning to removal, should be made in the context of overall flood risk management strategies. Although flood risk management and levee risk management are closely related and in some instances are implemented by the same entity, it is important to understand the difference between levee risk management and flood risk management actions and decisions. Clear goals and objectives help inform effective risk management approaches that are aligned with both the flood risk reduction provided by the levee and the risks posed by the levee. It is also important to recognize the public may not be aware of the difference between flood risk and levee risk and how they may be impacted by one or both. Therefore, communication strategies should be formulated accordingly.

Make your plans now to join us in Denver for Dam Safety 2024

Join us September 22-26, 2024 at the Colorado Convention Center in Denver, CO for Dam Safety 2024! This year marks the 40th Anniversary of ASDSO's national dam safety conference, and we are ready to celebrate the occasion with dam and levee safety professionals from across the country. Dam Safety 2024 will offer 44 concurrent sessions with over 130 unique presentations, the always popular poster-lightning talks, 100+ exhibitors and sponsors, and numerous networking opportunities throughout the week. Make your conference experience even more valuable by adding one of our conference workshops or field trips to your week.

LEARN MORE

AGENDA

REGISTER NOW

REGISTRATION TYPE	EARLY BIRD RATE (On or Before August 31)	REGULAR RATE (Starting September 1)
Member Full Conference Registration	$1,040	$1,140
Non-Member Full Conference Registration	$1,195	$1,295
Honorary Member Full Conference Registration	$150	$150
Student Full Conference Registration *Eligibility Guidelines Apply	FREE	FREE
Member (Single Day)	$565	$615
Non-Member (Single Day)	$720	$770
Guest Registration	$150	$150
Exhibit Booth Staff Registration	$325	$375

A Limited number of exhibit and sponsorship opportunities remain.
Please visit **www.DamSafety.org/DS24esa** to learn more!

View the floor plan at **https://damsafety2024.eventscribe.net**.

DAM SAFETY
DENVER, COLORADO

Elena Sossenkina, P.E.

Levees Practice Leader, HDR

1670 Broadway, Suite 3400, Denver, CO 80202 • (303) 318-6282 • elena.sossenkina@hdrinc.comv

Elena Sossenkina is a professional engineer with 24 years of experience in dam and levee safety. Elena specializes in geotechnical engineering and risk assessment for dams and levees. She is currently vice chair of the ICOLD Technical Committee on Levees and has served as chair of the USSD Levee Committee and US Levee Safety Coalition, a group of six professional organizations dedicated to advancing levee safety in the United States. This group currently includes ASCE, ACEC, ASDSO, DFI, NAFSMA, and USSD in partnership with FEMA and USACE. She was a contributor and reviewer for several chapters of the *National Levee Safety Guidelines.*

Jonathan Simm, Ph.D., C.Eng

Technical Director, HR Wallingford

Howbery Park, Wallingford, OX10 8BA, United Kingdom • +44 7718 153374 • j.simm@hrwallingford.com

Jonathan Simm is a UK civil engineer who specializes in flood and coastal risk management. He has been the principal author, editor, or major contributor for more than 20 industry guidance documents. Jonathan was the technical lead for the production of the *International Levee Handbook,* is acting as international advisor on the production of the US *National Levee Safety Guidelines,* and is the lead editor for the international *Handbook on Emergency Management of Flood Defences.* He recently retired from HR Wallingford where he worked for over 30 years as a technical director.

Greg Paxson, P.E., BC. WRE

National Practice Leader for Dams, Schnabel Engineering

300 Union Blvd., Suite 530, Lakewood, CO 80228 • (720) 798-1880 • gpaxson@schnabel-eng.com

Greg has nearly 30 years of experience in dam and levee safety, with a focus on dam rehabilitation, hydraulics and hydrology, and risk informed decision making for dams and levees. He was a contributor to several chapters of the *National Levee Safety Guidelines* and has supported the National Levee Safety Program on several initiatives.

Michael K Sharp, Ph.D., P.E.

Lead Civil Engineer, Risk Management Center, U.S. Army Corps of Engineers

12596 W Bayaud Ave, Suite 400, Lakewood, CO 80228 • (601) 831-9119 • michael.k.sharp@usace.army.mil

Dr. Sharp is currently supporting the Levee Safety Center, U.S. Army Corps of Engineers (Vicksburg, MS) in development of the *National Levee Safety Guidelines* for the National Levee Safety Program. Dr. Sharp is a geotechnical engineer with over 39 years of experience in dam and levee safety with the U.S. Army Corps of Engineers.

ASDSO Peer Reviewers

This article was peer reviewed by Bryant Robbins, Ph.D., P.E. (U.S. Army Corps of Engineers), Jim Gallagher, P.E. (NH Office of Dam Safety, Retired) and Robrecht Schmitz, Ph.D., G.E. (Technische Hochschule Georg Agricola).


AECOM
Delivering sustainable legacies
AECOM draws upon our network of dam, hydropower, levee and mining experts to provide technical excellence for the most complex project. Our network of global experts work collaboratively with our clients to provide tailored and innovative solutions to meet their unique needs.
Dennis J. Hogan, P.E.
Americas/Global Dams & Hydropower Market Sector Leader
dennis.hogan@aecom.com
aecom.com
Delivering a better world

Missouri River levee L550 breached on June 23, 2011, near Watson, Missouri

USACE Ohama District, Eileen Williamson

Empirical Equations for Levee Breach Parameters Based on Reliable International Data

Kaveh Zomorodi, PhD, P.E., CFM

ABSTRACT

Levee breach prediction and modeling requires an estimate of the breach characteristics, including the final breach width and lateral erosion rates. Currently, there are no widely accepted empirical equations for levee breach dimensions, lateral erosion rates, or breach development time. Previous empirical equations relied on limited, inaccurate, or incomplete data sets, including data from very old levee failures. In some cases, levees with specific features or levee failures governed by uncommon circumstances were included in equation development. The main objective of this study was to establish empirical equations to predict idealized levee breach geometric parameters for engineering analysis and design. The study process emphasized using reliable data from the relatively recent river levee failures and data from well-controlled physical model tests. Through research and personal contacts, I gathered and examined data for many international levee breaches. Data quality control identified reliable data sets that were more consistent with typical and expected field and design conditions. I applied further data control and correction, and finally selected 55 data sets for levee failures in the United States, France, Italy, Germany, Belgium, Dutch–Belgian border, China, and Japan. I used this data to develop empirical curves and equations for levee breach width and lateral erosion rates.

For each parameter, I provide the design level, the upper limit, and the lower limit curves and equations. The expected range of parameters can aid in better defining the range of flooding and damages to expect for levee failure. I also developed approximate equations for peak flow rate through levee breach by combining the weir flow equation with the new equations for the breach geometry. This paper includes all the resulting curves and empirical equations.

Introduction

One approach to evaluate the expected levee breach geometry and dimensions is to use a breaching algorithm based on physical processes and parameters. For example, the U.S. Army Corps of Engineers' HEC-RAS software (Hydrologic Engineering Center River Analysis System) includes an option named "DLBreach" that computes breach development through a lateral structure for overtopping and piping failures through cohesive, cohesionless, or composite structures. The HEC-RAS version of DLBreach combines the breach development algorithms from Wu (2013) with HEC-RAS hydraulics. This approach requires extensive data and information about levee embankment and core, soil parameters, and type of erosion.

This study focuses on estimating levee breach parameters based on new empirical equations that require only basic information about the levee. Few empirical equations for estimating levee breach dimensions or development time have been proposed in the past. These equations either rely on dam-break data or historical levee breach data that are mostly old and unreliable, and exhibit considerable spread. Traditional dams and levees are both constructed of earthen materials with similar cross-sectional shapes, and both experience many of the same failure mechanisms such as overtopping, piping, and so forth. However, levees differ from dams in some important aspects.

- Unlike dams, levees are sometimes constructed from local materials without much compaction and may even be built onto existing legacy old levees.
- The water depth behind a dam is typically much larger than the water depth behind a levee.
- Levees run longitudinally with a river rather than laterally across the river like a dam. Hence, a dam breaches in a perpendicular direction to the main flow, whereas levee breaches almost in the parallel direction to the river flow.
- Levee breach outflow typically flows freely out and spreads in every direction. This limits the water elevation on the land side unless road embankments or other features block the flow. In contrast, the outflow from dam breach is usually constrained by the downstream valley, which may result in considerable backwater impacts.
- During the dam break, the hydraulic head usually quickly drops as the storage water is released, but during levee breach, the incoming flood hydrograph could keep the hydraulic head elevated a relatively long time.
- Dam breach development usually stops when the breach is completed in a vertical direction. However, for most river levees, after the breach has reached its full depth, the breach will continue to widen due to continued shear stress from the floodwaters in the river. Levees generally breach with much wider breach bottom widths than dams relative to the height of the embankment.

Because of these differences between the dam and levee breach, previous studies such as Resio et al. (2009) and SERRI Report 70015-001 (Saucier et al., 2009) concluded that using dam breach methods does not usually correlate well with observed levee breaches. Danka and Zhang (2015) compared relevant factors of a dike, man-made dams, and landslide dam breaches and showed that the models for man-made dams and landslide dams should not be used for dike breaching analysis.

FEMA (2013) acknowledges that, "If available, historic levee breach information is an important tool in determining breach shape and development time. Currently, there is no nationwide compendium of historic breach information to reference." Previous empirical equations for levee breach dimensions relied on approximated data and some involved parameters that are not easily available or are only relate to noncohesive embankments. For example, as described in URS (2013), the researchers analyzed data from 96 breaches to develop relationships between levee parameters and breach geometry and size. They considered levee height, soil type, geographic location, and breach mechanism. However, only the levee height and soil type showed a statistically significant correlation with breach length. The researchers developed separate regression equations to predict breach length from levee height for sandy levees and clay levees. Unfortunately, the correlation coefficients for these equations were very low, leading the researchers to conclude that the prediction of breach length for an individual levee would be highly uncertain. Nagy (2006) presented a figure showing a general relationship between the head over the weir and the breach length. The correlation coefficient for Nagy's data was also very low. Previous studies such as URS (2013) and Nagy (2006) may not have carefully vetted data quality. Typical errors include not considering the final breach width or ignoring the impact of intervention measures. Therefore, in this study, the focus is on selecting reliable levee breach data that are not too old and are representative of the typical field and design conditions. Rather than exclusively using historical breach data from a particular country or region, data from observed levee failures or lab tests from many different countries are identified and used. Data obtained for newer cases of levee breaches are likely to be more accurate due to new and improved measurement or surveillance and imaging techniques available. For example, Brauneck et al. (2016) reported on experiences of using unmanned aerial vehicles (UAVs) for monitoring levee breaches.

Study Objective and Relevant Levee Breach Parameters

The main objective of this study is to establish empirical equations to predict idealized levee breach parameters for engineering analysis and design. The following definitions and symbols identify the levee breach parameters relevant to this study.

W_b: Final breach dimension in the direction of flow through the breach

H_b: Final breach height

H_l: Levee height from the toe of the levee to levee crest elevation

H_w: Water height from the toe of levee during breach enlargement (same as hydraulic head if tailwater depth is minimal)

T_b: Total breach development time from onset of breach formation to cessation of lateral breach growth

LE_a: The average lateral erosion rate calculated by the final breach width divided by total breach development time

According to Michelazzo et al. (2018), results obtained from the levee breach experiments seem to indicate the existence of a final equilibrium stage in the breaching process. W_b is this equilibrium or final breach dimension. Some researchers refer to the dimension of levee breach in river flow direction as breach length, and some call it breach width. In this research, we use levee width, understanding that occasional reference to levee breach length means the same thing. The dimension of breach width may be different from bottom to the top of the levee if the levee breach shape is not rectangular. Most observed levee breaches are almost trapezoidal in shape, with the top levee width slightly larger than the bottom width. Unfortunately, the available sources for breach width data usually do not specify if the bottom or top width is reported. However, it is likely that mostly the top breach is reported because it is easier to estimate from aerial pictures. Therefore, in this study, the breach width refers to the length of the breach at the top of the levee. The bottom width can be inferred from the top width by knowing or assuming breach side slopes. For large width to depth ratios, the total breach area does not vary significantly with the side slopes of the breach opening. Therefore, as a practical and reasonable simplification, the side slopes of a levee breach may also be assumed to be nearly vertical, resulting in rectangular rather than trapezoidal breach shape.

The final breach height (H_b) refers to the length of the breach in the vertical dimension. For an idealized or model levee failure, the levee breach is complete in the vertical direction, meaning the breach height represents the difference of elevation between the top of levee and bottom of the levee at the stream ground elevation. Under this situation, $H_b = H_l$ and any scour hole at the levee toe on the riverside or protected side is not considered part of breach height. In some research papers or historical levee breach accounts, water height during levee breach (H_w) is reported. If the levee overtops, then H_w would be larger than H_l. Otherwise, generally, H_w is smaller than or equal to H_l.

Most field observations, as well as experiments by Michelazzo et al. (2018), indicate that the breach development process takes place mainly downstream of the point where the breach starts. For an engineering design purpose, it may be assumed that the breach develops along the river only downstream of the breach initiation point.

Breach development time refers to the time duration from the initiation of the breach until the breach reaches its final width. The average lateral erosion rate (LE_a) refers to the final breach width divided by breach development time (T_b). The average vertical erosion rate refers to the height of the levee divided by the time it takes for the entire height of levee to be eroded or collapsed down to stream elevation. Some investigators include what they call Stage 1 of breach formation in the total breach time. Stage 1 refers to the time from erosion of the embankment, the grass cover, and crown to the onset of breach widening. In many cases, the reported development time starts from the onset of overtopping or any visible erosion. Because no lateral widening of the breach takes place during Stage 1, the time period for Stage 1 should not be included in T_b.

Previous Relevant Studies and Data

The final breach width may depend on many factors, including levee embankment height, levee material, crest width, depth and duration of overtopping, longitudinal river velocity, the area protected by the levee, and duration of river stage. The breach erosion process is commonly described as being a complex multistage process. Zhu (2006) describes the breach erosion process in clay dikes by five stages, and Visser et al., (2006) also described five stages of breaching of sand dikes. Recent work by Elalfy et al. (2018) involved both physical and numeric modeling of the mostly noncohesive earthen levee in studying breach-shape evolution. The failure process of noncompacted and noncohesive earthen levees, which mainly includes surface erosion, was considered in that study. But the report concludes that further investigations are required to simulate the breaching process of cohesive levees, including surface erosion and headcut erosion. The levee breach process is further complicated by the fact that the breach size depends on local soil parameters as well as local flow availability. Small scale physical model experimental study by Silva Araya (2010) showed that cohesive behavior is present in soils with clay content as low as 15%. Hence, unless clay percentage in the levee material is extremely low and the material is not compacted, the levee material may be viewed as cohesive. Chapter 8 of the *International Levee Handbook* (2010) presents a comprehensive treatment of physical processes and tools for levee assessment and design.

Various investigators have reported a wide range of breach widths from a few meters to hundreds of meters. As stated in URS (2013), an early estimate of the breach width was set to 50 times the levee height based on data from California Central Valley. According to Britton (2011), the USACE sets the width to height ratio to 22 for noncohesive levees and 15 for cohesive levees for the Columbia River Treaty levees. They set the breach side slope to 2V:1H and use 1 hour for initial breach formation time and lateral erosion rate to 35 m/hr. Therefore, the full breach development time is set to 1 hour plus breach width divided by 35 m/hr.

Liquet and Moiriat (2016) wrote a comprehensive research report on levee breaches and models. They analyzed the characteristics of 18 breaches that occurred within an area close to Tonneins and Jusix in France during the floods of the Garonne River in December 1981. In some cases, the breach width published in reports was checked and updated using aerial photos taken 1 day after the failures. Most of the breach data included in Liquet and Moiriat (2016) with breach lengths between 10 and 100 m were deemed reliable and usable in the development of empirical equations. Some of the breach widths reported in this study are relatively small, possibly due to the fact that some levees were adjacent to storage areas by the river and not the river itself. Longer breach lengths (300 to 600 m) have been reported in France for Loire River, but reliable data were not available for those cases which date back to the mid-19th century. It is likely that the reported extremely long levee lengths were the result of overlapping adjacent failures.

Ideally, empirical equations should identify a range of possible levee breach dimensions. An estimate of the lower limit for breach width could prevent underestimating the outflow rates and volumes. FEMA (2013) in Pages 28-29 states, "The minimum breach width will be 100 feet for clay levees and 500 feet for sand levees. This is based on a qualitative review of historic breach width information." However, this generalization by FEMA ignores the levee height, and it is not clear which historic breach width information was used by FEMA to reach this conclusion. The data from SERRI Report 70015-001 (2009) suggest the range of breach width to levee height ratio of 5 to 40. Having an upper limit for breach width helps prevent overestimating breach dimensions and outflow rates. Data points used to establish the upper limit of breach size should preferably belong to extreme measured cases. Rogers and Meehan (2008) reported that during the 1986 Linda levee breach in California, the breach of the Linda Levee along the south side of the Yuba River near its mouth was only 170 feet (52 m) wide, even after floodwaters had poured through the opening for 5 days. However, this levee breached when water elevation reached only up to 2.13 m below the top of the levee, and the observed breach width may not be a good data point in deciding the upper limit of breach width.

Nagy (2006) reports on a large number of levee failures in the 19th and 20th century as well as a few more recent cases on

Tisza and other rivers in Hungary. According to the recorded events, the majority of the longest levee breaches occurred in the 19th century, when levees were very much smaller. Extremely large breach widths belong to very old levees that are not relevant to our study. From Figure 3 in Nagy (2006), it is seen that "Head over the Weir" in his paper is equivalent to the levee height minus a bar with a height of over 0.3 m that remained at the waterside of the levee toe. Figure 12 in Nagy (2006) indicates a general relationship between the head over the weir and the breach length. As overflow height increases, so does the length of the levee breach, but the correlation is weak due to the multitude of factors that are at play. All in all, the results do not contradict the physical law that raising the height of overflow will increase the boundary shear force of the water, which corresponds to the increase of the breach width as a result of dike failure.

Nagy and Toth wrote the conclusions from the analysis of dike breach data in IMPACT (2005-b). They concluded from data provided by Czech colleagues that breach length versus the height of overflow and river flow rate indicated very poor correlations. They also provided a graph for 49 other levee breach cases that plotted the height of dike versus length of the breach for different soil types in the levee structure. They concluded that the hazard of shifting particles, erosion, and, hence, increasing the length of a levee breach is higher with fine particulate soils that offer no cohesion than with clays and with gravel of rougher grain.

Bodi et al. (2014) presented an updated report on levee failures in Carpathian Basin in Hungary and five neighboring countries. The predominant cause of reported failures was overtopping. Unfortunately, numerical data from levee failures reported in Nagy (2006) or Bodi et al. (2014) are not available to include in this study.

Hopf (2011) wrote his PhD dissertation on the subject of levee failures in the Sacramento–San Joaquin River Delta in California, USA. Hopf (2011) examined the history of 265 failures of levees dating back to 1868 that have occurred in the Legal Delta, CA, and pointed out the gap in data availability stating that details of most levee failures are missing.

Risher and Gibson (2016) applied three embankment models developed for dam breach analysis to two historic levee breaches with observed (or estimated) breach rates. For each of the two historic leveebreaches, Risher and Gibson (2016) describe several stages. This indicates that the failure process may be different at each location depending on the makeup of the levee material, history of repair, and flooding characteristics.

Michelazzo (2014) wrote his PhD dissertation on breaching of river levees studied using analytical flow modeling and experimental hydromorphodynamic investigations. In this research, the river-breach system was analyzed by two series of laboratory experiments and an analytical model of the river flow. A simple overall picture of the hydrodynamic processes and a new interpretation of the breaching at the equilibrium stage was offered. Based on the majority of the studies found, Michelazzo (2014) reported a typical case assuming a fully developed breach with a trapezoidal shape for which the breach length (width in streamflow direction) generally varies from 0.5 to 10 times the depth of the breach. The side slopes of the breach typically vary from essentially vertical to 1V:1H to the most common slope of approximately 2V:1H. This study pointed out that the final breach length is linearly governed by the water discharge of the river, and breach discharge is strongly correlated with the breach length. Backwater effects from the floodplain could have significant effects on the lateral outflow, and they limit the breach flow and, consequently, the final breach length. An earlier version of this study (Michelazzo & Paris, 2012) reported more specific conclusions regarding the hydraulic limitation of the breach length. Preliminary results showed that the maximum length a breach can reach is dependent on the flow characteristics. As the ratio between downstream and upstream Froude numbers tends to zero, breach length seems to attain an upper limiting value, which is in the order of river width. They reported the existence of a "hydraulic limitation" of the breach length as 1.5 times the wetted width of the cross-section (channel width at the water surface). However, in his final version of the dissertation Michelazzo (2014) did not include these conclusions.

Viero et al. (2013) conducted mathematical modeling of levee breaching and collected data from several levee breach cases in Italy. According to this study, the final width of the breach is mainly related to the magnitude and the persistence of water-level difference across the levee, which controls the flow velocity sediment transport rate. The growth rate of the outer water level plays a leading role in determining the final breach width. For this reason, very large breaches can be produced if topographical conditions of the rural areas adjacent to the river promote a rapid expansion of the flow downstream of the breach, thus preventing outer water levels from increasing.

Islam and Tsujimoto (2015) reported findings from small-scale laboratory experiments and numerical analyses for the same scenario. They concluded from their laboratory tests that for a given elevation of the top of levee and flood discharge, higher bed level (lower levee height) brings more rapid propagation of the levee breach and widening, but they do not discuss the impact on the final breach width.

Peeters et al. (2015) reported on large-scale dike breaching experiments in Belgium. During the experiments, headcut migration and breach growth in width were monitored and results were recorded. The results from this breach experiment confirm the breach stages described in the literature.

The setback distance from the main channel could also impact the breaching of a riverine levee. Levee setbacks are constructed at a greater distance from the river channel than traditional levees, and they allow a river to occupy a portion of its historic floodplain. Levees that are built closer to the main channel are more easily exposed to the longitudinal scour forces of faster flows in the main channel compared to slower flow in the floodplain. Recognizing this fact, the U.S. Army Corps of Engineers has recently published a report (ERDC/EL SR-17-3, 2017) to explain the advantages of levee setback. Accordingly, levee setbacks are a relatively recent innovation in Corps flood risk management practice to reduce rehabilitation costs and reduce flood stages and velocities.

Data Selection Process

The process of collecting or estimating breach parameters revealed many special conditions that would limit or dismiss the applicability of a case to this study. For example, in some cases, interventions (repairs, riprap dumping, engineered, or controlled relief breach) prevent the breach width from reaching its ultimate length. In other cases, levees breached due to reasons not related to flooding of the river or piping. These cases do not fit the engineering design requirement of a conservative breach estimate.

Several databases for historic breaches were considered. For example, the International Levee Performance Database is a comprehensive data depot for levee failure maintained by researchers at Technical University Dresden, Germany (http://leveefailures.tudelft.nl/). More cases can be looked up from other databases available from Delft University, Netherlands: https://dataverse.nl/dataset.xhtml?persistentId=hdl:10411/20639. However, many of the cases included in these databases are too old or the breach dimensions included could not be verified. These databases were deemed as basically not suitable to use in this study.

In some cases (especially older cases in the Sacramento–San Joaquin River Delta), extremely wide breaches, upward of a 1600 m long, have been reported. The unusually wide breaches are likely the result of multiple breaches overlapping. In some cases, breach length is from undocumented anecdotes or are caused by nontraditional causes such as seepage from a large landslide on an irrigation ditch, which aggravated stability of the steep riverside berm. Yet there are other cases where the length of sloughing is reported as the breach length or the gap in embankment is due to landslide. These cases will not be included in this study.

In some physical-model experiments, conditions are intentionally varied to get a sense of the impact of different parameters on the levee breach and outflow. Some data from inconsistent test runs may still be used to better establish lower and upper bounds of breach dimensions. For example, Kakinuma and Shimizu (2014) conducted physical model experiments using a large-scale flume to simulate riverine levee breach for four cases. However, Case 2 experiment was conducted using half of the inflow rate of other cases, which was not adequate to sustain a high head over levee breach. Also, Case 4 levee was built much wider than the other three cases with larger cross-sectional volume of the levee to be eroded. The results from Cases 2 and 4 were utilized in this study to help with considering variable breach conditions.

Some investigators hint to the fact that one of the parameters that could control the final breach size is the top width of river. This makes sense in terms of water supply driving the breaching process forward. Data considered by Michelazzo et al. (2018) mostly showed a positive relationship between the top width of river associated with the water level during breaching and the breach length. However, in view of the inadequate data available, I did not include top width of river as a parameter in developing empirical equations.

The following points summarize the conditions for ideal historical or physical test breaches selected for this study:

- The cause of levee failure is known with reasonable certainty. Breach formation may be due to overtopping or near overtopping conditions (breach during extreme flooding without water flowing over the levee). But levees could also fail during sunny days due to piping or other nonhydraulic causes.

- Breach formation, progress rate, and final shape and size are not significantly restrained by insufficient discharge or flood duration in a river or by human intervention. An ideal design breach is fully developed in the vertical and lateral direction.
- No major build-up of backwater occurred on the land side to significantly reduce breach outflow and breach size.
- The lateral erosion rate associated with the reported levee failure should be within a reasonable design range. For example, the lateral erosion rate of the floodwall on Inner Harbor Navigation Canal in New Orleans, Louisiana, during Hurricane Katrina (August 2005) was reported to be 280 m/hr. This rate is extreme and an outlier compared to other levee failure data. The erosion mechanisms at this failure were likely altered by the presence of a large vertical drop at the floodwall. Therefore, data from this failure would not be included in the analysis.
- Basic knowledge about levee material is available to categorize the levee as cohesive (clay levees typical of river levees) or noncohesive (sand levees typical of coastal flood barriers).
- Levees included no atypical structural component that would impact the breaching process significantly. For example, the floodwall on London Avenue Canal and the floodwall on Metairie Outfall Canal, New Orleans, both had a reinforced concrete cap approximately 2.44 m tall when they failed during Hurricane Katrina (2005). Therefore, the data from these failures would not be included in this analysis.
- The breach record should ideally not be very old as it tends to reduce the data reliability.

Based on the previous criteria, several sets of data were used in this study:

1. Table 2.16 of SERRI Report 70015-001 (2009). This table includes observed levee breach geometries and growth rates for six recent riverine and three hurricane related failures in the United States. Only the riverine cases were selected for this study. Data for Truckee Irrigation Canal Levee near Fernley, Nevada (January 2008), was not used as an overtopping case because a USBR report indicated that the levee failed by piping due to rodent activity.

Also, levee breach width for Pin Oak Levee on Mississippi River near Winfield, Missouri (June 2008), was adjusted from 46 m to 100 m considering additional information found in Storesund et al. (2009) and Bernhardt et al. (2011).

2. Data for two dikes included in Tables 7.4 to 7.6 in Zhu (2006), which are based on the EC IMPACT Project laboratory experiments (IMPACT, 2005-a).

3. Data found through internet search and breach parameters estimated and inferred from various sources for the following cases:

    a. Elsberry (Norton Woods) Levee,
    b. Hamburg, IA June 14, 2011 levee failure,
    c. The Union Township Levee,
    d. Tyler Island-Delta, CA,
    e. Pocahontas Black River levee breach, AR.

4. International data on historic levee failures or physical laboratory models gathered through other references and personal contacts, including cases in France, Italy, Germany, Belgium, Dutch–Belgian border, China, and Japan. For example, several Italian cases were listed and explained in Michelazzo (2014) and Viero et al. (2013) or obtained through correspondence with Davide Persi of Po River authority, Italy (see Persi, 2012), and Danish Hydraulic Institute and Andrea Defina of Padova University, Italy. Additional information on levee failures in Japan was obtained from Professors Kakinuma and Shimizu from Hokkaido University, Japan. Also, valuable additional information regarding the French levee failures reported in Liquet and Moiriat (2016) was obtained from these researchers through personal communications.

Development of New Empirical Equations

This research focused on developing empirical equations to predict the breach parameters most commonly needed for engineering design and analysis of levee failure. By its nature, a design parameter needs to be conservative in terms of the predicted flooding and damages. Ideally, the new levee breach equations should have a simple, practical format. The outcomes from the equations need to be reasonable for a wide range of input parameters, and the equations should provide lower and upper bounds for the results. The lateral erosion rate associated with the equation predictions needs to be within the reasonable range to represent usable design conditions.

TABLE 1 PARTIAL LIST OF THE LEVEE FAILURE CASES SELECTED FOR THIS STUDY

CASE NO.	DATA SOURCE	LOCATION AND DATE	FLOOD SOURCE	MATERIAL	MAT. CODE	FAILURE MECHANISM	FAILURE MODE CODE	LEVEE H_l (M)	WATER HEIGHT H_w (M)	WATER HEIGHT-LEVEE HEIGHT (M)	BREACH WIDTH W_b (M)	LATERAL EROSION RATE (M/HR)
16	D.P. Viero et al (2013) & Defina Personal Comm.	Loreggia Breach (breach L) Muson dei Sassi River, Italy January 21, 2009	River	Cohesive	C	piping	P	4.2	1.95	-2.25	20	
17	D.P. Viero et al (2013) & Defina Personal Comm.	Due Ponti di Caldogno (breach C1) Timonchio River, Italy November 1-3, 2010	River	Cohesive	C	overtopping	O	3.4			90	
18	D.P. Viero et al (2013) & Defina Personal Comm.	Boschi di Caldogno (breach C2) Timonchio River, Italy November 1-3, 2010	River	Cohesive	C	overtopping	O	2.3			50	
19	D.P. Viero et al (2013) & Defina Personal Comm.	Veggiano levee failure (breach V) Tesina Padovano River, Italy November 2010	River	Cohesive	C	overtopping	O	2.2			35	
20	D.P. Viero et al (2013) & Defina Personal Comm.	Ponte San Nicolò levee failure (breach P), Bacchiglione River, Italy November 2011	River	Cohesive	C	piping	P	3.1			40	4.44
21	Orlandini. et al (2015)	San Matteo breach on Secchia River, Italy January 19, 2014	River	Non-cohesive	C	piping/ burrowing animals	P	3.5			80	
22	Michelazzo (2014) & Personal Comm.	Versilia River, Italy (1996 flood)	River	Cohesive	C	overtopping	O	5.0			68	90.67
23	Michelazzo (2014) & Personal Comm.	Serchio River, Italy (2009 flood)	River	Cohesive	C	piping	P	6.0			160	80
24	Michelazzo (2014) & Personal Comm.	Calice River, Italy (2009 flood)	River	Cohesive	C	piping	P	4.0			30	30
25	Michelazzo (2014) & Personal Comm.	Ombrone River (Tuscany – Italy) December 2009	River	Cohesive	C	piping	P	4.0	3.4	-0.60	20	20

Equations for Levee Breach Width

Empirical equations are needed to establish a relationship between the levee height and the final breach width. The average lateral erosion rate may simply be estimated as the final breach width divided by the breach development time. The change of the lateral erosion rate with time is not considered in this study. This is because there are many complicating factors that may control the progress rate of breaching in time. These factors include the history of the levee structure (impacting the variability of soil layers and compaction in lateral and vertical direction), slumping and sudden mass waste of large chunks of the levee, the variability of flow supply in the riverside, and so forth. Hunt et al. (2005) evaluated the time rate of breach widening of three large-scale earthen embankment tests. They concluded that rates of widening were strongly influenced by the compaction water content. Measured soil properties were judged only as "promising" in characterizing the development of a breach.

As explained previously, restrictions and controls were applied in selecting reliable data for developing levee breach empirical equations. As a result, only 55 cases of levee failures were selected for this study. To show the data structure used, Table 1 summarizes the 10 selected cases of dam breach in Italy. In Table 1, the material code "C" refers to levees mostly built with cohesive material that is engineered to resist breaching. The material code "S" refers to noncohesive (sandy) levees or nonengineered material susceptible to faster erosion. Failure model "O" refers to failure due to levee overtopping or near overtopping caused by extreme flooding and high water levels. Failure mode "P" refers to failure due to piping or other factors when water levels could be relatively low.

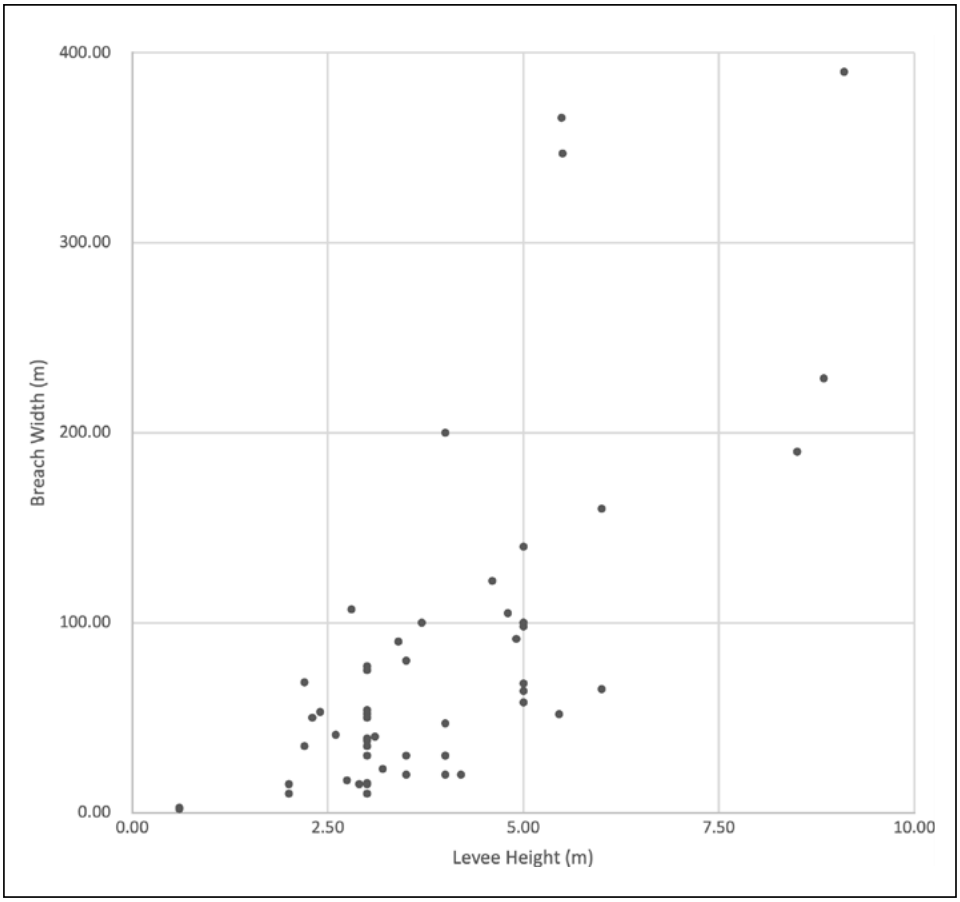


Figure 1 Final Breach Width Versus Levee Height for all Cases

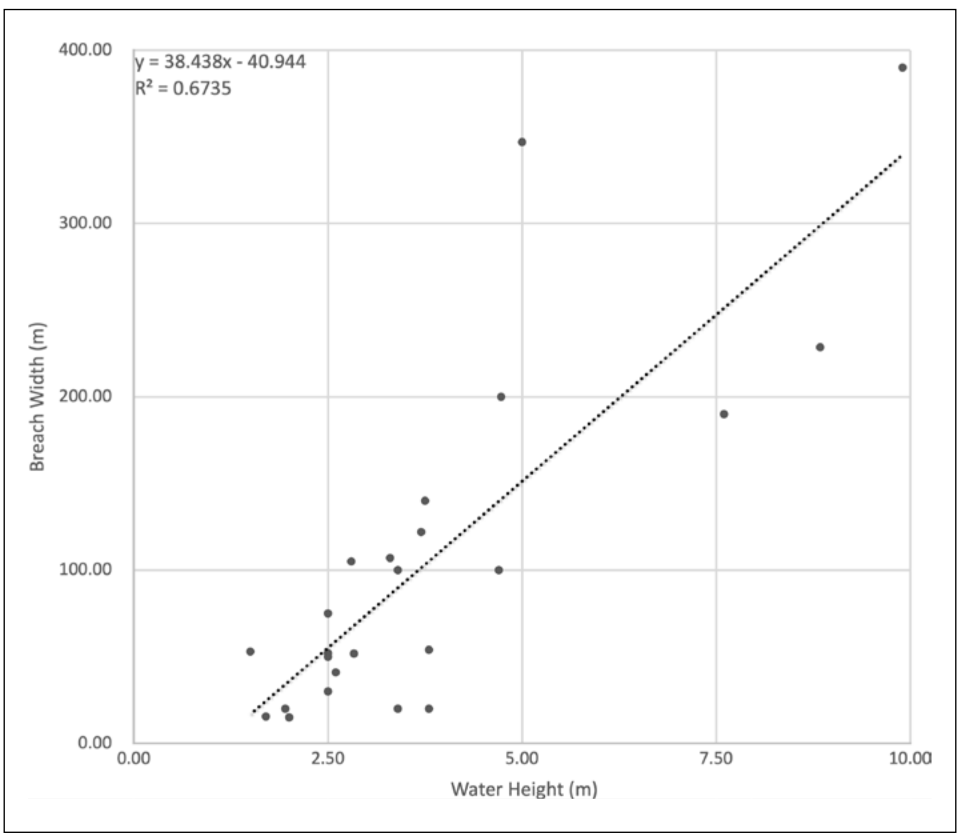


Figure 2 Final Breach Width Versus Water Height

In Figure 1 the final breach width is plotted against the levee height for all cases. The data point labels identify the case number, levee material code, and failure mode code.

Figure 1 shows a general trend of increasing final breach width with increasing levee height. The water height behind levee is an indicator of hydraulic loading and the force driving the breach development. Water height was available for 24 failure cases. Figure 2 plots the final breach width as a function of water height behind the levee, showing considerable scatter of points around the best fit line. Apart from inaccuracies in measurement or reporting of data, the scatter could also be explained by the fact that I included cases with different failure modes and levee material.

Figure 3 shows that the relationship between final breach width and water height can be improved by considering only the levees with cohesive material. The correlation would be even stronger if only the cohesive levees subject to overtopping failure are considered (see Figure 4). Figure 4 shows that under extreme flooding conditions resulting in overtopping and failure of the levee, the final breach width would be directly predictable by knowing the maximum water height.

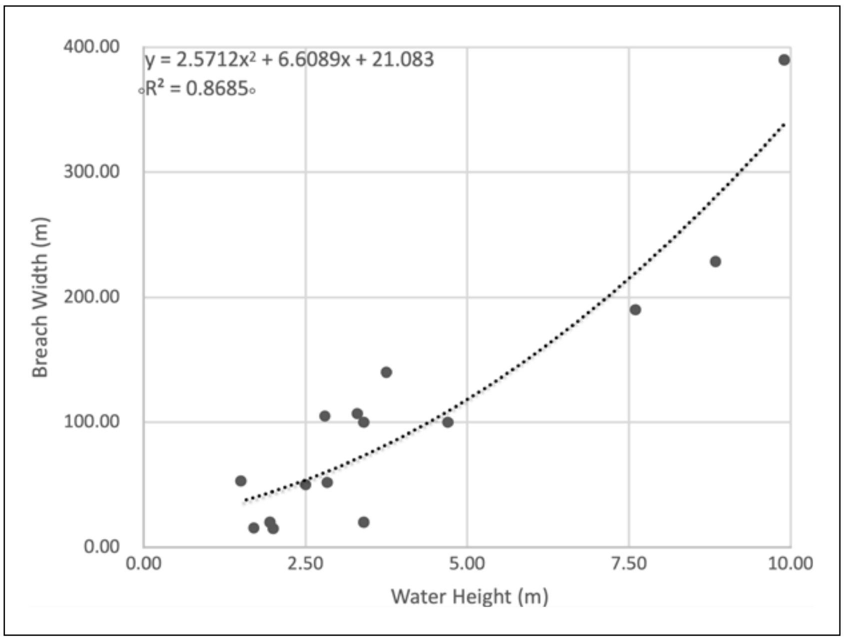


Figure 3 Final Breach Width Versus Water Height for Cohesive Levees

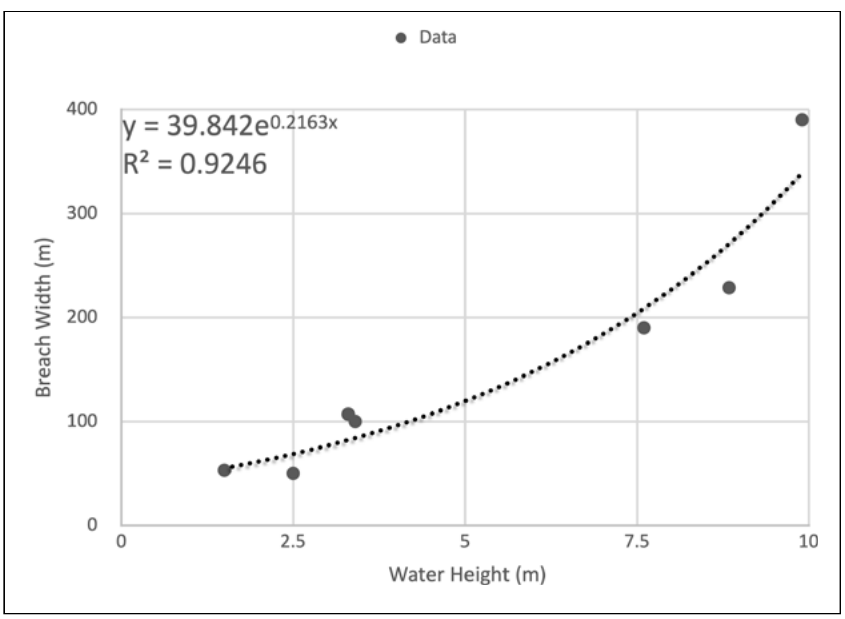


Figure 4 Final Breach Width Versus Water Height for Cohesive Levees Subject to Overtopping

Most modern levees are built with cohesive material and are not expected to fail unless the levee is overtopped. The breach width equations and curves were initially developed using regression analysis in Microsoft Excel and then, if needed, adjusted by visual fit to be conservative while also considering reports on some extreme cases of failure not included in this study. As seen in Figure 4, the best-fit trend line (dashed curve) is an exponential curve with a large R^2 (coefficient of determination) value of 0.9246. The corresponding approximate fit curve with rounded coefficients is:

$$W_b = 40\, e^{(0.21\, H_w)} \qquad (1)$$

Where both W_b and H_w (water height) are in meters. If the water height is known, then Equation 1 provides a good design approximation of the final breach width for cohesive levees within the water height limits of 1.50 m to approximately 10 m. Adequate data were not available to set upper and lower bounds for Equation 1.

The water height is not an easily measured or defined parameter to be considered in a levee breach equation. Practically, the levee height would be the better parameter to include in a levee breach geometry equation. The scatter of points shown in Figure 1 is expected to diminish by considering points with the same material type and/or failure modes separately. Initially, data points with common levee material code and/or failure mode code were grouped together. This effort only had limited success due to a limited number of data points in each group. Moreover, it was difficult to maintain consistency between equations developed for various data groups. Therefore, the main equations to relate breach width to levee height were developed considering all data. As seen in Figure 1, the largest observed breach widths on Y-axis show a consistent trend up to a levee height of 5 m. Taller levees belonging to Cases 36, 30, and 28, which appear to be high outliers, were used in establishing the upper limit of breach width. For example, the breach width of 366 m for Case 36 represents the Bois Brule Levee failure near Perryville, MO. This failure, which occurred during the 1993 Mississippi River flooding, resulted in an overall breach depth in the vertical direction almost three times the levee height in less than 2 hours. To better include the extreme cases into the analysis, separate upper and lower bound equations were developed for very tall levees (over 5.0 m high). Figure 5 shows the design curve, as well as the upper and ww limit curves. Notice that despite different lower and upper equations for tall levees, these curves are plotted as continuous curves in Figure 5, showing consistency among the equation results for all levees.

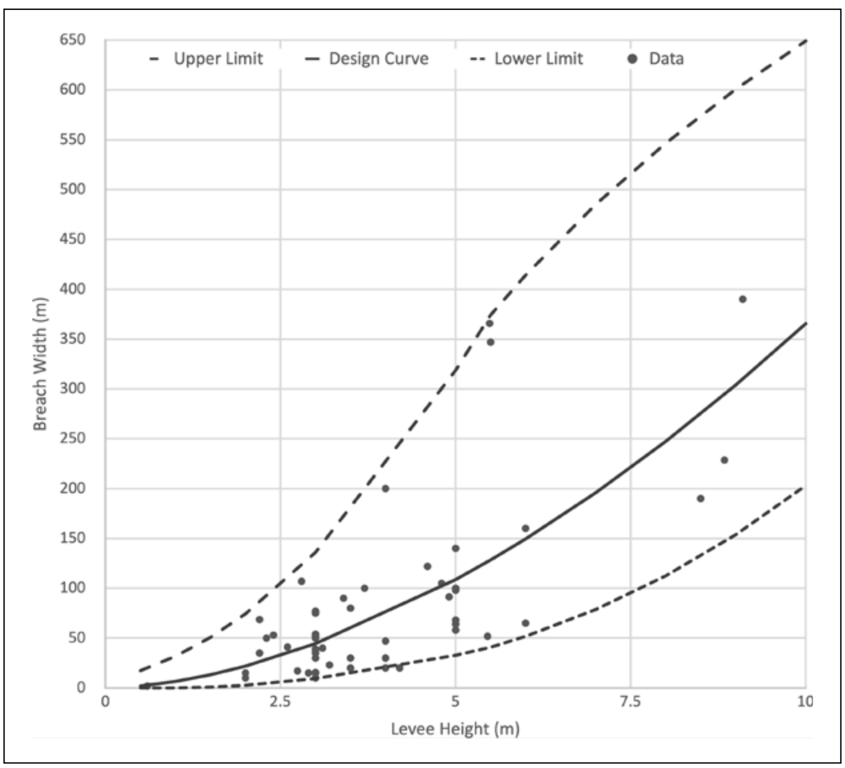
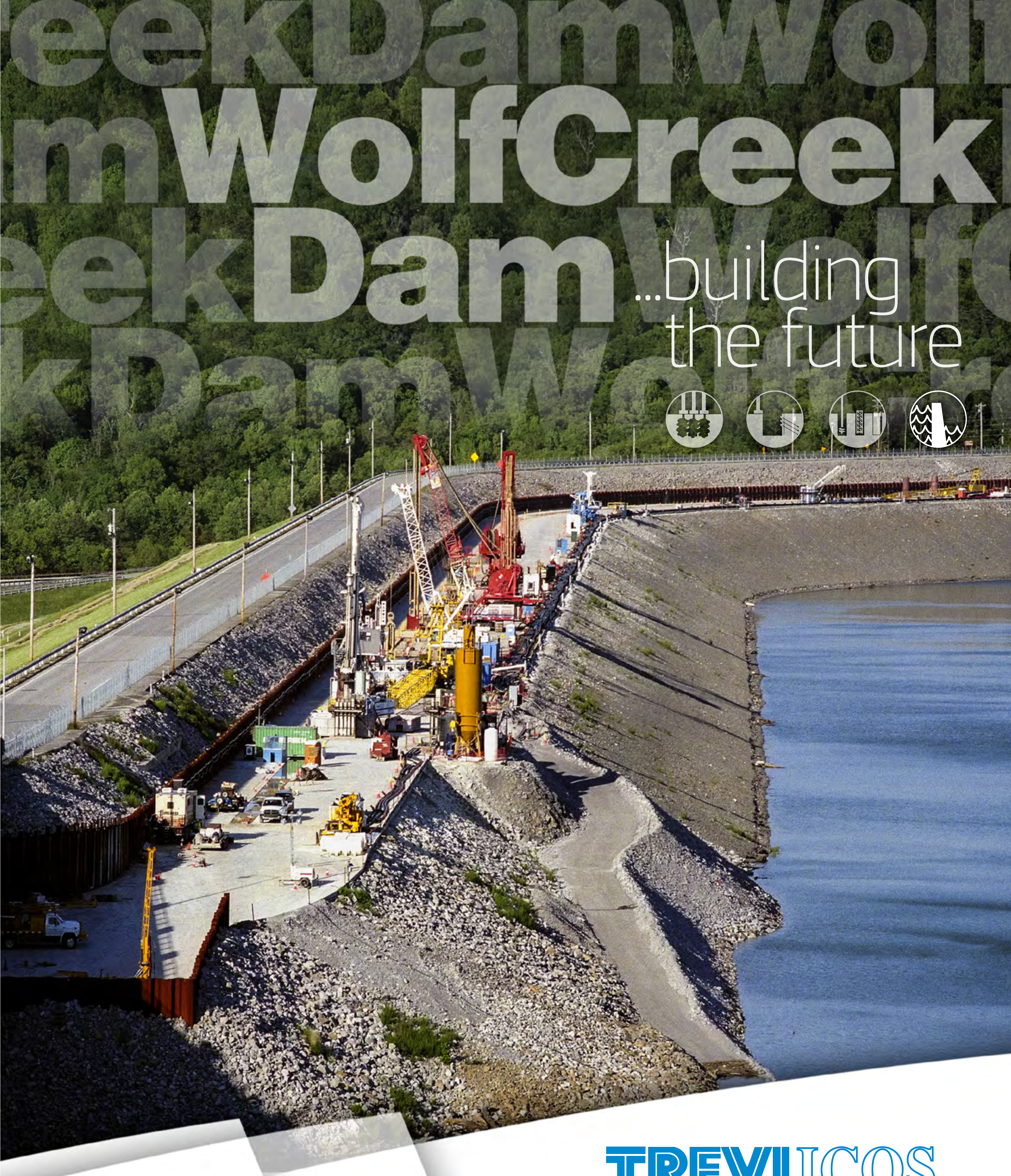


Figure 5 Design Curve and Upper and Lower Limits of Final Breach Width as a Function of Levee Height


WolfCreekDam
...building the future

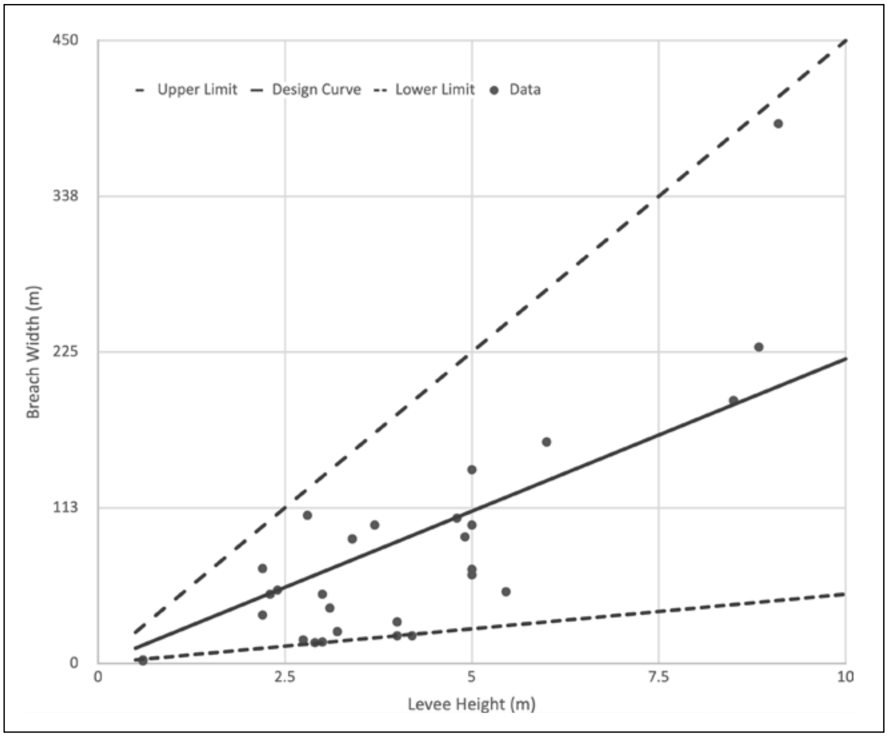


Figure 6 Design Curve and Upper and Lower Limits of Final Breach Width of Cohesive Levees as a Function of Levee Height

The following equations represent the breach width estimate as a function of levee height corresponding to the Figure 5 curves. W_b is the final breach width, and Hl is the height of levee, both in meters.

The following is the design equation corresponding to the middle curve in Figure 5 for a reasonably conservative breach width for levee heights from 0.5 to 10 m:

$$W_b = 6.5\,(H_l)^{1.75} \qquad (2)$$

The upper limit curve in Figure 5 is more applicable to nonengineered or noncohesive levees subject to a breach by significant overtopping and long duration flood. The upper limit equation for levees heights of 0.5 to 5.0 m is:

$$W_b = 7.4\,(H_l + 1)^{2.1} \qquad (3)$$

The upper limit curve for levees heights larger than 5.0 m up to 10.0 m is:

$$W_b = 460 \ln\left(H_l\right) - 410 \qquad (4)$$

Where "ln" is the symbol for natural logarithm.

The lower limit curve is more applicable to engineered or cohesive levees subject to a breach by piping or flooding that does not overtop the levee for a long time. For levee heights less than 3 m, the breach width can be approximated as three times the levee height. The equation for the lower limit curve for levees heights of 3.0 m to 5.0 m is:

$$W_b = 2.7\,(H_l - 1)^{1.8} \qquad (5)$$

The equation for the lower limit curve for levees heights larger than 5.0 m up to 10.0 m:

$$W_b = 0.73\,(H_l - 0.5)^{2.5} \qquad (6)$$

If we only consider the levees built with cohesive material, some of the extreme cases (e.g., cases 30 and 36) will drop out, and the breach width will be somewhat shorter (see Figure 6) and can be expressed with simpler linear equations.

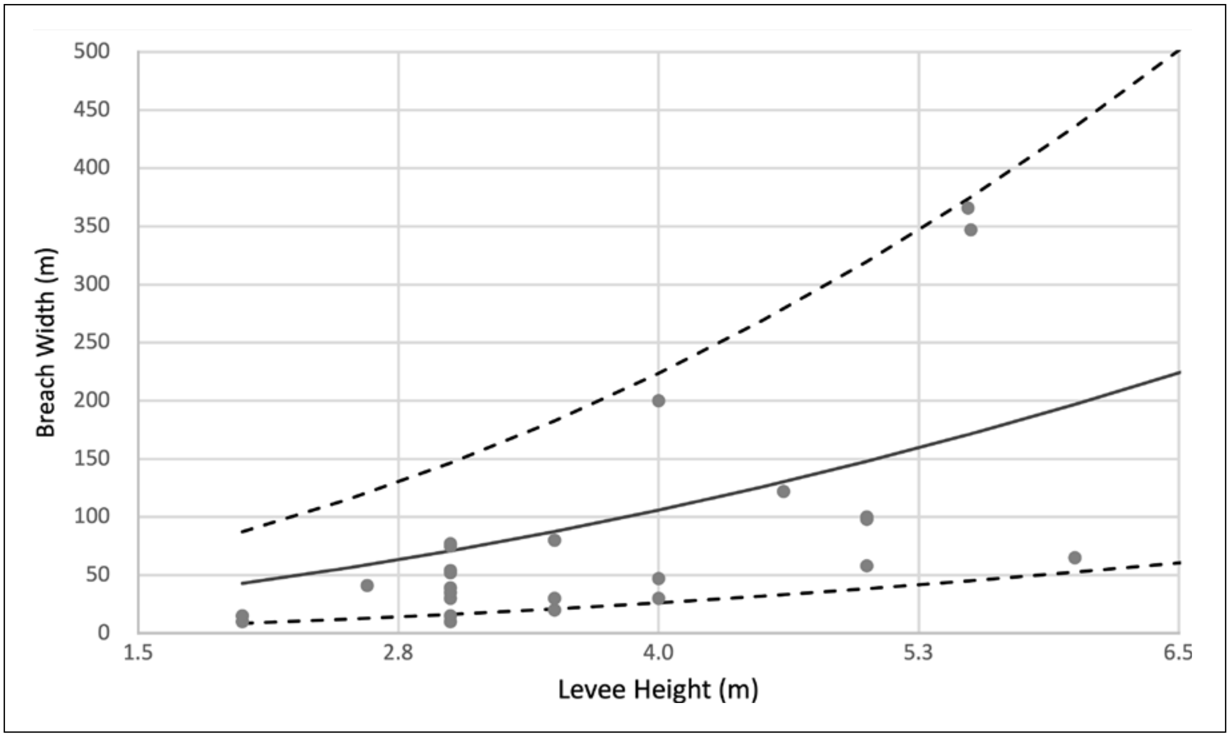


Figure 7 Design Curve and Upper and Lower Limits of Final Breach Width of Noncohesive Levees as a Function of Levee Height

The equation for the design line for the breach width for cohesive levees with heights from 0.5 to 10 m is:

$$W_b = 22\ H_l \qquad (7)$$

The equation for the breach width upper limit for cohesive levees with heights from 0.5 to 10 m is:

$$W_b = 45\ H_l \qquad (8)$$

The equation for the breach width lower limit for cohesive levees with heights from 0.5 to 10 m is:

$$W_b = 5\ H_l \qquad (9)$$

Figure 7 shows the relationship between the breach width and levee height for noncohesive (sandy) levees. These levees are more representative of coastal levees or older nonengineered riverine levees. The middle, upper, and lower level curves and equations for noncohesive levees were developed to give larger breach widths than for cohesive levees, especially for levees taller than 3 meters.

The equation for the design line for the breach width for noncohesive levees with heights from 2.0 to 6.5 m is:

$$W_b = 3.5\ (\ H_l + 1.5)^{2.0} \qquad (10)$$

The equation for the upper limit for the breach width for noncohesive levees with heights from 2.0 to 6.5 m is:

$$W_b = 3.5\ (\ H_l + 2)^{2.32} \qquad (11)$$

The equation for the lower limit for the breach width for noncohesive levees with heights from 2.0 to 6.5 m is:

$$W_b = 1.5\ (\ H_l + 0.5)^{1.9} \qquad (12)$$

According to Britton (2011), for the Columbia River Treaty levees, the USACE sets the width to height ratio to 15 for cohesive levees and 22 for noncohesive levees. The range of levee heights is 3–5 meters, with most levees around 3.3 m high. Equation 7 gives a breach width to height ratio of 22, which is higher than the USACE ratio for cohesive levees. Using a levee height of 3.3 m, Equation 10 gives a breach width of 81 m resulting in a width to height ratio of 24.5, which is slightly larger than the USACE ratio of 22 for noncohesive levees. The SERRI Report 70015-001 (2009) suggests the range of breach width to levee height ratio of 5 to 40. The previous equations indicate a range of 5 to 45 for cohesive levees, which are close to the cohesive levees in the SERRI report.

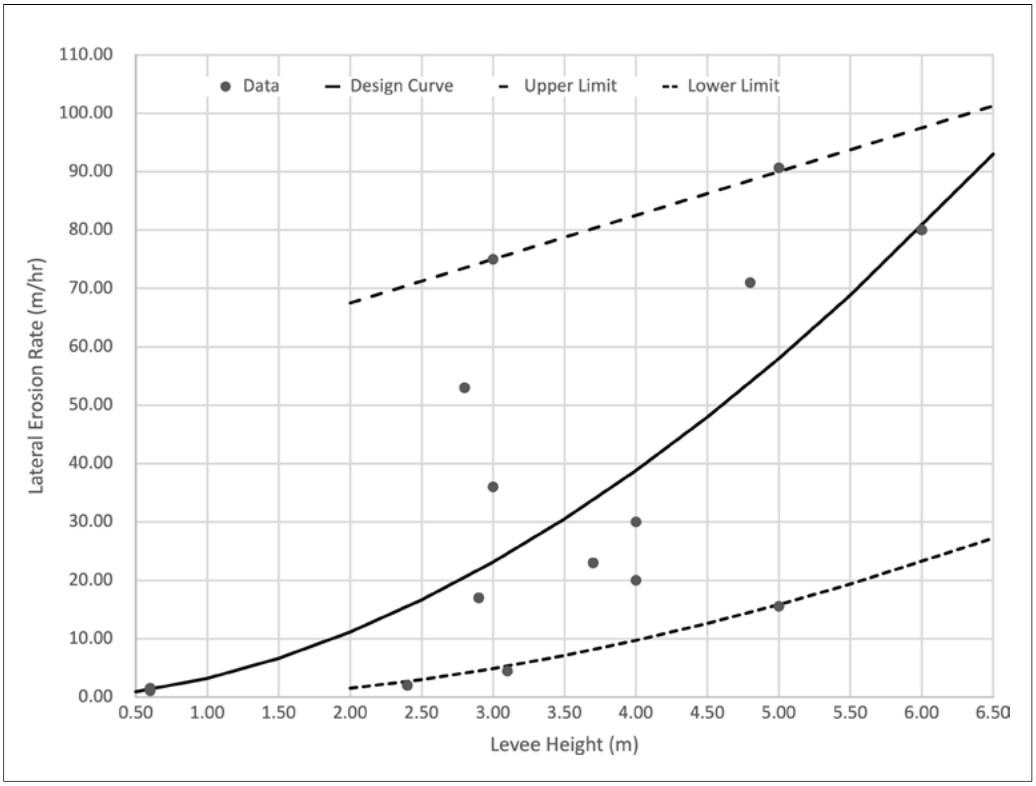


Figure 8 Lateral Erosion Rate as a Function of Levee Height for Cohesive Levees

Equations for Lateral Erosion Rate

In general, the noncohesive levees would be subject to faster breach development and longer final breach widths than cohesive levees.

The relationship between the average levee lateral erosion rate and the levee height was investigated. In reality, it is the depth of water flowing through the breach, which is the critical factor controlling the rate of breach widening. However, this parameter is rarely measured or reported in levee failure data. Levee height is more widely available (or obtainable) and is a good approximation of head or depth of water for many levee failure cases, especially breaches during large floods. The assumption that the hydraulic head is equivalent to the levee height implies little tailwater impact during peak discharge from the levee. Only 21 cases of the selected data included a value for lateral erosion rate (or breach development time that can be used to estimate erosion rate). The observed average lateral levee erosion rates may be heavily controlled by factors such as multilayer levee structure, degree of compaction, and duration of elevated flood levels. In some cases, mass slumping of levee material led to short development time, whereas in other cases, gradual erosion process under falling water levels made breach development time longer. With the limited available data, efforts to develop empirical equations for the breach development time or average lateral erosion rate applicable to all levee material types did not produce credible results. However, 15 out of 21 points belonged to cohesive levees with a height of 6 meters or less. Cohesive levees are expected to show slower erosion rates than noncohesive levees. Figure 8 shows the data for cohesive levees and the fit design curve as well as the upper limit line and lower limit curve.

The equation for a reasonable conservative value of the average breach lateral erosion rate in m/hr for cohesive levees with heights from 0.5 to 6.5 m would be:

$$LE_a = 3.2\,(H_l)^{1.8} \qquad (13)$$

Not enough data points were available to establish an upper limit curve. I simply connected the two highest points resulting in the following line that may be applied to cohesive levee heights of 2.0 to 6.5 m:

$$LE_a = 52.5 + 7.5\,H_l \qquad (14)$$

The equation for the lower limit curve for cohesive levees heights larger than 2.0 m up to 6.5 m is:

$$LE_a = 1.5\,(H_l - 1)^{1.7} \qquad (15)$$

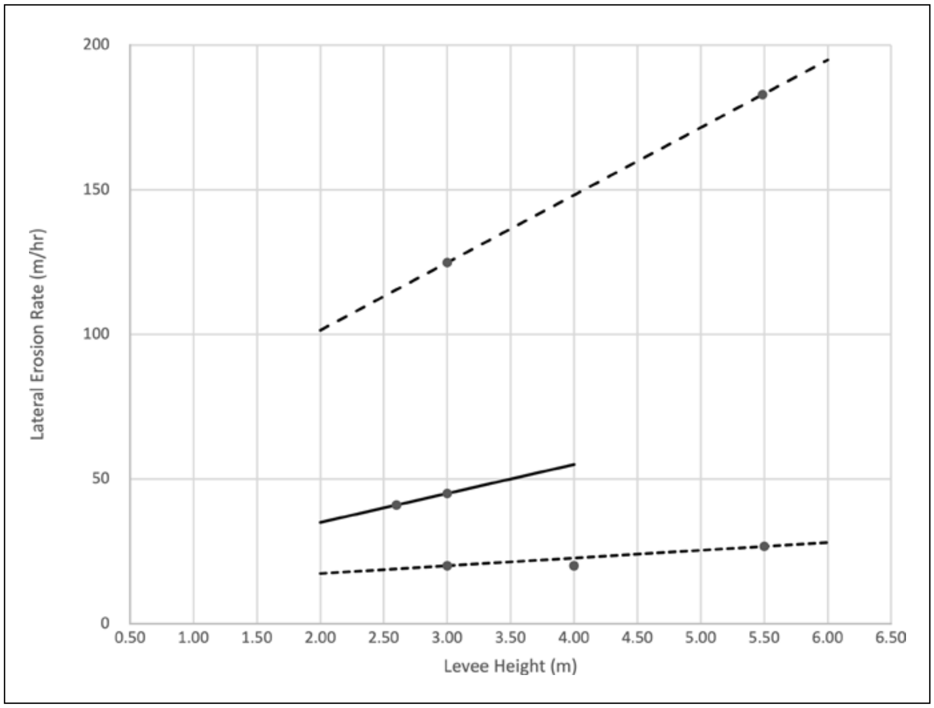


Figure 9 Lateral Erosion Rate as a Function of Levee Height for Noncohesive Levees

For noncohesive levees, only seven data cases were available with estimates of lateral erosion rate or duration of breach development. This was not sufficient to develop general relationships, but as shown in Figure 9, the points were used in the same fashion as Equation 14 to give approximate linear equations for noncohesive levees:

The following is the equation for a reasonable conservative design value of the average breach lateral erosion rate for noncohesive levees in m/hr for levee heights from 2.0 to 4.0 m:

$$LE_a = 15.0 + 10.0\,H_l \qquad (16)$$

For the upper limit of the lateral erosion rates for noncohesive levees, the following linear equation may be used for levee heights of 2.0 to 6.0 m:

$$LE_a = 54.7 + 23.4\,H_l \qquad (17)$$

For the lower limit of the lateral erosion rates for noncohesive levees the following linear equation may be used for levee heights of 2.0 to 6.0 m:

$$LE_a = 12 + 2.7\,H_l \qquad (18)$$

The previous equations proposed for the noncohesive levees generally show a higher later erosion rate than the equations for the cohesive levees. According to Britton (2011), the USACE uses 35 m/hr for lateral erosion rate for the Columbia River Treaty levees. The range of levee heights is 3–5 meters, with most levees around 3.3 m high. For a levee height of 3.3 m, Equation 13 gives a lateral erosion rate of 27 m/hr for cohesive levees, and Equation 16 gives a lateral erosion rate of 48 m/hr for noncohesive levees. Given that the Columbia River Treaty levees include both cohesive and noncohesive levees, the rate of 35 m/hr is consistent with the previous equations.

Approximate equations may be composed for breach development time as a function of levee height by dividing the levee breach width equations by the breach lateral erosion rate equations. Care must be exercised to match the levee types and also to make sure the upper limit of breach width is divided by lower limit of erosion rate and vice versa to put upper and lower limits on breach development time. This procedure was followed for cohesive levees, and the results are shown in Figure 10. Logarithmic scale is used for the Y-axis to better show the upper and lower curves. The general trend of decreasing breach development time with increasing levee height may indicate that the impact of the hydraulic head on accelerating lateral erosion rate outweighs its impact on making the final breach width longer. This seems to be the case for the upper limit and design curves in Figure 10. However, the trend is reversed for the lower limit curve, which maybe more associated with weaker levee structure.

Equations for Peak Discharge Through Levee Breach

Data on measured discharge through a major levee breach are scarce, which makes it impractical to develop an empirical equation. Discharge through a levee breach changes as the breach development progresses toward its ultimate shape and size. If the hydraulic head is maintained when the breach reaches its final size, the peak discharge through the breach would coincide with that moment and will continue in time until the hydraulic head across the breach drops due to a decrease in flood levels or backwater build-ups on the land side. Riahi-Nezhad (2013) wrote his PhD dissertation on the subject of experimental investigation of steady flows at a breached levee. The objective of the research was to offer a better understanding of the hydraulics of steady flow at a breached levee.

Visser et al. (2006) used a weir equation considering the depth of the backwater on the landward side to estimate discharge through the breach for when the breach is completed. A more conservative approach is to estimate the maximum breach discharge for the final width of the breach, assuming no build-up of backwater on the landward side. A more elaborate approach requires a more comprehensive treatment of breach flow as weir flow provided by studies such as Ren's Thesis (Ren, 2012). The broad crested weir equation for a rectangular opening subject to a head equivalent to the levee height may be combined with any of the above breach width equations to develop the approximate peak discharge equation. The area through which water could flow from the riverside to the landward side could be larger than the levee breach area if a large erosion hole is developed below the levee base. This possibility is not considered in the following equations.

Peak discharge through a levee breach may be estimated by the general equation for rectangular weir:

$$Q = \frac{2}{3} C_D W_b \sqrt{2g}\, H^{\frac{3}{2}} \qquad (19)$$

Where

Q = Peak discharge (m^3/s),

C_D = Discharge coefficient,

W_b = Final breach dimension in the direction of flow (m),

G = Gravity acceleration= 9.81 (m/S^2),

H = Elevation head, which is equivalent to the height of water measured from levee base (could be approximated by levee height), ignoring any depth of erosion hole at the levee base (m).

The discharge coefficient for levee breach flow is a very complex parameter, and there is no widely accepted value for it. Lee et al. (2019) recently studied the levee breach discharge coefficient and concluded that the ratio of the head above the bottom of an opening and the opening width as well as the approach Froude number should be considered for a river type approach. Lee et al. (2019) did not propose a specific number for C_D, but they made the following general statement: "A theoretical discharge coefficient over a typical

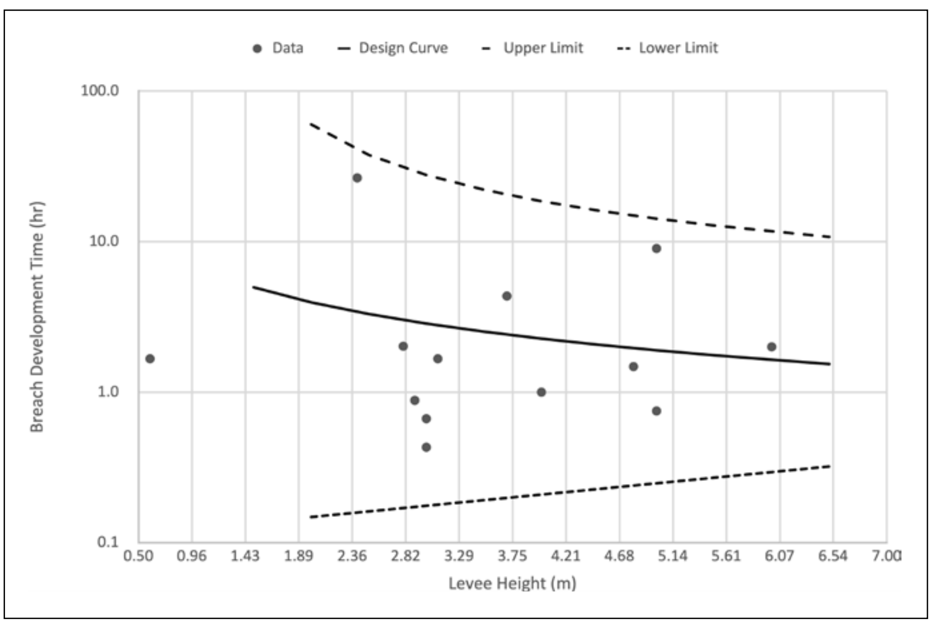


Figure 10 Breach Development Time as a Function of Levee Height for Cohesive Levees

broad crested weir is 1.0, but friction losses reduce the value of the discharge coefficient, C_D, to 0.848." Multiplying all the constants in Equation 19 by a value for C_D results in a constant known as the weir coefficient. Based on the information in Lee et al. (2019), it seems that the value of 0.848 should be used for the weir coefficient and not for the discharge coefficient. This would be consistent with user guidelines for the U.S. Army Corps of Engineers HEC-RAS model. Table 3-1 in HEC-RAS 2-D modeling user's manual (USACE, 2016) recommends a weir coefficient range of 0.83 to 1.43 for levees. Riahi-Nezhad (2013) experimental measurements gave C_D values ranging from 0.833 to 0.919. Using an overall weir coefficient 0.9 in Equation 19 results in:

$$Q = 0.90\ W_b H_l^{1.5} \qquad (20)$$

If the breach width is not known, Equation 20 may be combined with any of the equations in this study that express breach width as a function of levee height. For example, when we take W_b from Equation 2, the design peak discharge for levee heights from 0.5 to 10 m tall can be evaluated by:

$$Q = 5.85\ H_l^{3.25} \qquad (21)$$

For example, for a levee height of 3.3 m, the peak discharge would be approximately 283.4 m_3/s. Given the breach height of 3.3 m and the breach width of 52.5 m, the average velocity of flow through this breach during peak discharge would be approximately 1.63 m/s. In practice, the build-up of tailwater on the downstream side may decrease the discharge and velocity compared to the calculated values. On the other hand, the formation of a significant erosion hole at the levee base may increase discharge over the estimated value. For a cohesive levee with a height of 3.3 m, Equation 10 gives a lateral erosion rate of 27 m/hr, suggesting a breach development time of close to 2 hours from the onset of breach formation.

Measured peak discharge from levee breaches is generally not available. Sometimes the discharge is estimated after the event by the size of the breach. According to Risk Nexus (2014), the 2002 Fischbeck levee failure on the Elbe River was one of the biggest river levee breaches ever recorded in Germany. The flow through the breach was estimated at 1,000 m^3/s—equal to approximately one fifth, or even one quarter of the Elbe's total discharge at this point during the floods. Given the levee height of 5 meters, Equation 21 gives a discharge of 1,093 m^3/s.

Summary and Conclusions

This study utilized relatively reliable data on historic levee failures or physical test levees to derive empirical curves and equations for the levee breach parameters. The results indicated a direct relationship between the final breach width and the height of water at the levee. The correlation between the two parameters increased when only levees built with cohesive material were considered. The correlation maximized for overtopping failure cases for cohesive levees. Empirical equations were developed to express breach width as a function of levee height. Separate equations were developed for the design level, the upper limit and lower limit of the final breach width, as well as breach lateral erosion rates. The equations were further refined by offering a separate set of equations for cohesive and noncohesive levees. The design breach geometry values used in practice could be improved by using the range of breach parameters offered in this study. Finally, a simplified approach was proposed to estimate the peak discharge from a levee breach. The general discharge equation can be combined with any of the empirical equations for the breach width to estimate the peak discharge through a levee breach as a function of levee height. One such equation was included for the design level discharge estimate. Future studies could focus on verification and/or improvement of the equations developed in this study. Reliable data from new levee failures could be used to better define the range of possible breach geometry, lateral erosion rate, and discharge through the breach.

Acknowledgement

This study was partially funded in its early stage by Federal Emergency Management Agency (FEMA) through the funds FEMA provided Dewberry for "Probabilistic Modeling, Mapping, and Structure-Level Risk Assessments" as part of the Innovation Task of Standard Operations 3 (SO3).

References

Bernhardt et al. (2011). Mississippi River levee failures: June 2008 flood. *International Journal of Geoengineering Case Histories, 2*(3), 127 –162. https://www.engr.colostate.edu/~pierre/ce_old/classes/ce717/Mississippi%20Levees.pdf

Bodi L., Nagy L., & Takacs, A. (2014). Review of historic floods in Hungary and the extent of flooded areas in case of levee failures. Paper No. 118 presented at the 6th Canadian Geohazards Conference, Kingston, Canada.

Brauneck , J., Pohl, R., & Juepner, R. (2016, June). Experiences of using UAVs for monitoring levee breaches. *6th Digital Earth Summit, IOP Conf. Series: Earth and Environmental Science, 46.* http://iopscience.iop.org/article/10.1088/1755-1315/46/1/012046

Britton, J. (2011). Columbia River treaty levee fragility curves. [PowerPoint presentation].

Danka, J., & Zhang, L. (2015, October). *Evaluation of empirical methods for estimating breaching parameters of dikes.* Paper in *Geotechnical Safety and Risk V*, Fifth International Symposium on Geotechnical Safety and Risk (ISGSR), Rotterdam, The Netherlands.

Elalfy, E., Tabrizi, A.A., & Hanif Chaudhry M. (2018). Numerical and experimental modeling of levee breach including slumping failure of breach sides. *ASCE Journal of Hydraulic Engineering, 144*(2), 04017066-1 to 18.

ERDC/EL SR-17-3. (2017, June). *Levee setbacks: An innovative, cost-effective, and sustainable solution for improved flood risk management.* Vicksburg, MS: U.S. Army Corps of Engineers, Engineering Research and Development Center.

Federal Emergency Management Agency (FEMA). (2013, September). Operating guidance 12-13, non-accredited levee analysis and mapping guidance.

Hopf, F. (2011). Levee failures in the Sacramento–San Joaquin River Delta: Characteristics and perspectives. Submitted to the Office of Graduate Studies of Texas A&M University in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Hunt, S.L., Hanson, G.J., Cook, K.R., & Kadavy, K.C. (2005). Breach widening observations from earthen embankment tests. *Transactions of the ASAE, American Society of Agricultural Engineers, 48*(3), 1115–1120.

IMPACT. (2005a). Investigation of Extreme Flood Processes and Uncertainty." Final Technical Report. By HR Wallingford, UK.

IMPACT (2005b). "Investigation of Extreme Flood Processes and Uncertainty", W.P. 6: Monitoring and Case Study, Detailed Technical Report on the collation and analysis of dike breach data with regards to formation, process and location factors, Conclusions by L. Nagy - S. Tóth, H-EURAqua Ltd., Szentendre, Hungary, Project Coordinator: HR Wallingford, Howbery Park, OX10 8BA, U.K.

International Levee Handbook. (2010). "Physical processes and tools for levee assessment and design." http://webissimo.developpement-durable.gouv.fr/IMG/pdf/J_Chapter_8_cle6febc5.pdf

Islam Md. S., & Tsujimoto, T. (2015). "Levee breaching process of a river and disaster risk on floodplain." *American Journal of Civil Engineering and Architecture, 3*(2), 39-44. http://pubs.sciepub.com/ajcea/3/2/1/index.html

Kakinuma, T., & Shimizu, Y. (2014). "Large-scale experiment and numerical modeling of a riverine levee breach." *Journal of Hydraulic Engineering, 140*(9). https://eprints.lib.hokudai.ac.jp/dspace/bitstream/2115/57527/1/JHE140-9%2004014039.pdf

Lee, S.O. Yoon, K.S. Lee, J.S. & Hong, S.H. (2019). "Estimates of discharge coefficient in levee breach under two different approach flow types." *Sustainability, 11*, 2374.

Liquet M., & Moiriat D. (2016). “Review for levees, breaches and models–application to breaches of Garonne’s levees. Institut de Radioprotection et de Sûreté Nucléaire (IRSN), France. Research report n° PRP-DGE n°2016-00012.

Michelazzo, G., et al. (2018) “New hypothesis for the final equilibrium stage of a river levee breach due to overflow.” *Water Resources Research, 54*(7), 4277-4293. https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2017WR021378

Michelazzo, G. (2014). “Breaching of river levees: Analytical flow modelling and experimental hydro-morphodynamic investigations.” PhD Dissertation, Faculty of Architecture, Civil Engineering and Environmental Sciences University of Braunschweig–Institute of Technology and the Faculty of Engineering University of Florence, Italy. https://flore.unifi.it/retrieve/handle/2158/873126/29051/2014_Michelazzo_Dissertation.pdf

Michelazzo, G., & Paris, E. (2012) “Hydrodynamic analysis of river levee breach: Preliminary results.” Preliminary results for PhD dissertation, University of Florence, Italy. https://wrr-submit.agu.org/wr_files16b/2012/03/06/00722791/00/722791_0_art_file_2327259_m0h4wj_convrt.pdf

Nagy, L. (2006). “Estimating dike breach length from historical data.” *Periodica Polytechnica Civil Engineering, 50*(2), 125–138. https://pp.bme.hu/ci/article/view/563

Orlandini, S., G. Moretti, and J. D. Albertson (2015), Evidence of an emerging levee failure mechanism causing disastrous floods in Italy, Water Resour. Res., 51, 7995–8011, doi:10.1002/2015WR017426.

Peeters, P, et al. (2015). "Large-scale dike breaching experiments at Lillo in Belgium." In *Scour and erosion-proceedings of the 7th International Conference on Scour and Erosion.* Taylor & Francis Group. DOI:10.1201/b17703-36

Persi, D. (2012) "Levee Risk Assessment along the River Po", Presented by Eric Foneno of DHI, http://www.floods.org/Files/Conf2013_ppts/F5/F5_Fontenot.pdf

Ren, Y. (2012), "Breach flow modeled as flow over a weir." Master of Science thesis.Department of Hydraulic Engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Netherlands.

Resio, D., Boc, S., Maynord, S., Wal, D., Abraham, D., Dudeck, D., & Welsh, B. (2009), "Development and deployment of rapid repair of levee breaching technology." Report to Southeastern Regional Research Initiative, Department of Homeland Security.

Riahi-Nezhad, C. K. (2013). "Experimental investigation of steady flows at a breached levee." Doctoral dissertation, University of South Carolina. https://scholarcommons.sc.edu/etd/646

Risher, P., & Gibons, S. (2016). "Applying mechanistic dam breach models to historic levee breaches." E3S Web of Conferences, 03002 (2016), FLOODrisk 2016-3rd European Conference on Flood Risk Management. https://www.e3s-conferences.org/articles/e3sconf/ref/2016/02/e3sconf_flood2016_03002/e3sconf_flood2016_03002.html

Risk Nexus. (2014). "Central European floods 2013: A retrospective." Flood Resilience Review. Zurich, Switzerland: Zurich Insurance Company.

Rogers, J.D., and Meehan R.L. (2008, November 13). "Site characterization and levee failure modes: With special reference to the Paterno flood case." ASCE-AEG Joint Meeting, Berkeley, CA. http://web.mst.edu/~rogersda/levees/Rogers-Paterno%20Overview-March%202008-compressed.pdf

Saucier, C. L. Howard, I. L., & Tom, J. G. (2009). "Levee Breach Geometries and Algorithms to Simulate Breach Closure, Mississippi State University." SERRI Report 70015-001. http://www.cee.msstate.edu/assets/documents/(2009)%20SERRI%20Report%2070015-001%20(Levee%20Breach).pdf

Silva Araya, W. (2010). "Experimental Study of Levee Breach." ASABE-21st Century Watershed Technology: Improving Water Quality and Environment. 2010. 10.13031/2013.29445.

Storesund et al. (2009, March 16), "2008 Midwest Levee Performance Investigation, Summary of Initial Field Reconnaissance." Report to the National Science Foundation. www.geocasehistoriesjournal.org/pub/article/download/IJGCH_2_2_3/124

URS Corporation. (2013). "Memorandum on DWR Levee Breach Database." Developed by Z. Islam, N. Malyala, & R. Kulkani. Submitted to MWH Americas, Inc.

US Army Corps of Engineers (USACE). (2016). "HEC-RAS, River Analysis System, 2D Modeling user's manual." Version 5.0, February 2016. https://www.hec.usace.army.mil/software/hec-ras/documentation/HEC-RAS%205.0%202D%20Modeling%20Users%20Manual.pdf

Viero et al. (2013). Mathematical modeling of flooding due to river bank failure. *Advances in Water Resources, 59*, 82–94.

Visser, P.J. et al., (2006). Breaching of dikes. Coastal EngineeringConference. DOI:10.1142/9789812709554_0244

Wu, W. (2013). Simplified physically based model of earthen embankment breaching. *ASCE Journal of Hydraulic Engineering, 139*(8).

Zhu, Y. (2006). *Breach growth in clay-dikes.* [PhD thesis]. Delft University of Technology, Delft, The Netherlands.

Kaveh Zomorodi, Ph.D., P.E., CFM

Principal Engineer, Dewberry
8401 Arlington Boulevard, Fairfax, VA 22031 • (703) 849-0336 • kzomorodi@dewberry.com

Dr. Kaveh Zomorodi is a principal engineer at the Dewberry Companies. He received a Ph.D. in civil and environmental engineering (hydrology and water resources) from Utah State University in 1988. He has over 36 years of work experience in academic and consulting engineering work dealing with surface water, groundwater, transportation engineering, and hazard mitigation. Dr. Zomorodi has published or presented over 60 technical papers in various journals and conference proceedings and numerous R&D and project reports.

ASDSO Peer Reviewers

This article was peer reviewed by Art Miller Ph.D., P.E., and Craig Findlay, Ph.D., P.E. (Findlay Engineering).

The Wyoming Valley Levee System, located in Wilkes-Barre, PA, June 2020 *USACE/Baltimore District*

Levees: An Opportunity to Advance Strategic Connections in Flood Risk Management at All Levels of Government

Tammy L. Conforti, P.E. | Linda I. Manning

As flooding becomes more complex due to sea level rise, coastal erosion, wildfires, and changes in precipitation patterns, we no longer have the luxury to think about mitigation programs individually. To manage flood risk in a well-coordinated, efficient, and cost-effective manner requires collaboration at all levels. This article asks the question about how levees fit into this changing scenario, sets the stage for areas to explore, and discusses the roles states can play.

Levee Systems: An Overview

Periodic flood events continue to shine light on the importance of levees and the need for a consistent national approach to better predict levee performance and manage them in the broader community context. Today, levee systems play a critical role in managing flood risk throughout the United States. Yet levees are built by various governmental agencies or by private property owners, often using different standards, materials, and flood scenarios to inform their design. With over 24,000 miles of levees throughout the nation reducing flooding to about 2,400 communities, over 23 million people, and $2.4 trillion in property value (Figure 1), there exists a national need for gaining a more consistent understanding and management of this important infrastructure.

Figure 1 Levee Statistics, National Levee Database

It is important to consider not only the flood risk reduction benefits afforded to the communities behind levees but to also understand how levees interact within the broader watershed: how levees are affected by the operation of upstream dams; how levees influence water elevations upstream and downstream; and how levees may impact the natural environment. States are in a key position to align dams and levees with floodplain management to support community flood resilience in a way that is unique to each state. States also have the authorities and visibility to forge broader strategic connections with national approaches to flood risk management, resiliency, natural resources protection, and equity.

Why Levees and Dams Can't Be Treated the Same Way

Both types of infrastructure are tools in flood risk management and are similar in their technical approaches and practices. However, looking at the landscape a bit more closely, significant differences emerge:

- Levees are part of the fabric of a community (Figure 2). They occupy the floodplain and are a dominant part of the daily landscape, visible from land and water for tens or hundreds of miles. Dams are often (although not always) out of the everyday public view. In addition, levees are recognized by communities as having a more direct impact on flood insurance and floodplain management requirements for the National Flood Insurance Program.
- Societal expectations are somewhat different for levees and dams. Although both dam and levee safety professionals look to prevent catastrophic failure and hold public safety paramount, levee professionals are frequently called upon to manage the impacts of overtopping both on the levee and in the floodplain. Through activities such as reducing pool levels or releasing water, dams can reduce risk of infrastructure failure and uncontrolled overtopping. Typically levees have no such mechanisms and communities rely more often on evacuation, floodproofing, or elevating critical structures and acquiring flood insurance to manage financial vulnerabilities.
- Dams and levees both have flood risk management objectives, but dams are often also constructed to generate hydropower, store water for human use and irrigation, and provide recreational opportunities. Levees are more singular in focus; they exist to allow for use of the floodplain to support a density of economic activity and protect economic investment. Because of their location adjacent to communities, levees are often relied on to reduce the risk of flooding to other types of public infrastructure and lifelines such as water and wastewater infrastructure, energy production, emergency services, schools, local roads, and highways.
- The length of levee systems makes their ownership and operations complicated. Levee systems often comprise multiple sections, each with their own owner/operator. Because they extend for such long distances near transportation routes, there are quite often openings for traffic and pedestrians that need to be closed during high water and pumps started to remove rainwater trapped on the dry side of levee. Inspection, instrumentation, and monitoring is more challenging for levees due to their length and encroachments (e.g., pipes, signs, buildings, human encampments) more difficult to identify and address. One example of a complicated levee is the New Orleans East Bank levee system; it is about 180 miles in length, has 323 closures and seven communities behind it, requiring a complex operational and emergency response plan during flood events. Many rivers have levees on both sides, and there are multiple levees that cross two states.

Figure 2 The View Across the Galena River in Illinois From the Top of the Levee, Including Community Walking Trail

TABLE 1 SOME SIMILARITIES AND DIFFERENCES BETWEEN DAMS AND LEVEES
(Source: National Levee Database and National Inventory of Dams)

SIMILARITIES		DIFFERENCES	
Levees	**Dams**	**Levees**	**Dams**
Average age–60 yrs.	Average age–65 yrs.	Number of Levees: ~7,000	Number of Dams: ~90,000
97% are earthen embankments	80+% greater than 50' tall are earthen embankments	~24,000 miles	~16,000 miles[1]
		70% owned by government entities	65% privately owned
		~700 levees have emergency action plans	Over 12,000 high hazard dams have emergency action plans

[1] This includes the 79,000 dams that have length recorded in the National Inventory of Dams.

The National Levee Safety Program: The Missing Piece to a More Integrated Flood Risk Management Approach

Under the National Levee Safety Program, the U.S Army Corps of Engineers (USACE) and the Federal Emergency Management Agency (FEMA) are developing tools and resources that promote common and consistent best practices for levees.

Not only will the National Levee Safety Program fill a long-needed gap for levees (e.g., national inventory, best practices, levee safety programs) , but it is also intended to work in conjunction with the National Dam Safety Program and the National Flood Insurance Program to improve the overall flood resilience of communities (Figure 3). This triad of programs can work together to support flood risk management for the nation by reducing risk to human life, property, and the environment from dam-related and levee-related hazards (National Dam Safety Program and National Levee Safety

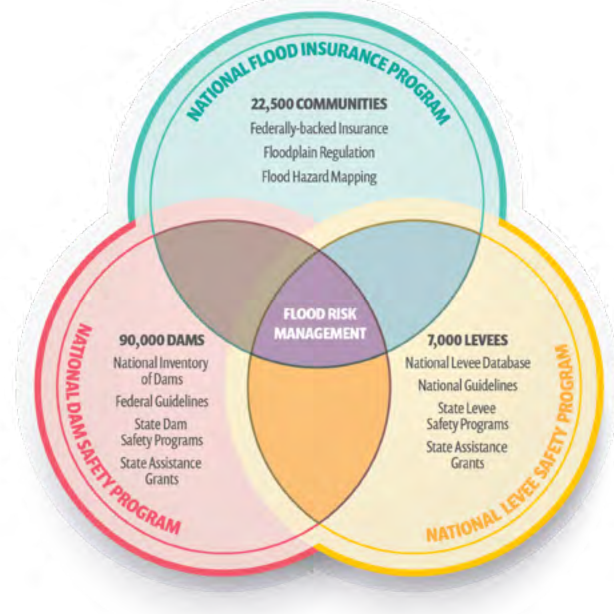


Figure 3 Federal Programs Supporting a More Aware, Prepared, and Flood-Resilient Nation

TABLE 2 ACTIVITIES TO CONSIDER WHEN CREATING A COMPLEMENTARY ROLE FOR THE NATIONAL LEVEE SAFETY PROGRAM

NATIONAL DAM SAFETY PROGRAM	NATIONAL FLOOD INSURANCE PROGRAM
Provide assistance to states to strengthen their state dam safety programs to: • Conduct dam safety training • Increase the number of dam inspections • Increase development, testing and use of emergency action plans • Review and issue permits in a timely manner • Improve coordination with state emergency preparedness officials • Identify dams to be repaired or removed • Conduct dam safety awareness activities	• Ensure communities have legal authorities necessary to adopt and enforce floodplain management regulations • Establish minimum state regulatory requirements consistent with the National Flood Insurance Program • Provide technical and specialized assistance to local governments • Coordinate the activities of various state agencies that affect the National Flood Insurance Program • Provide insurance to homeowners and businesses

Program), mitigate future flood risk and transfer of flood risk through floodplain regulations, and make insurance available to reduce financial vulnerability and help individuals and businesses recover more quickly from floods when they do occur (National Flood Insurance Program). Table 2 summarizes key activities that can be considered when identifying the most important activities that a National Levee Safety Program should promote at all levels in a manner that is complementary and non-duplicative.

This effort is coming at an opportune time. Following several decades of implementation of the National Flood Insurance Program and the National Dam Safety Program, the National Levee Safety Program can take advantage of a lot of experience and lessons learned. Advanced technology in imaging, modeling, databases, and risk estimation has provided a snapshot of levees in just a few years. A combination of available information including databases, surveys, and digital terrain algorithms has identified almost 7,000 levee systems. This information has been overlayed with available data sets to estimate people, property, critical infrastructure, and environmental resources behind and near levees. This levee information can also be easily compared to information in the National Inventory of Dams, FEMA's mapping products, agricultural land, critical wildlife habitat, highway, and public infrastructure locations, and many other interests. Figure 4 shows a screenshot for a levee as seen in the National Levee Database which allows visualization of multiple national datasets allowing information to be more accessible to the public.

Technology Used to Build the Levee Inventory

- *A digital terrain algorithm was first used to identify possible levee structures on the terrain.*
- *A semiautomated tool uses top of levee and cross section data from digital terrain data to confirm the presence of a levee, then combines several possible methods to create leveed area polygons.*

Because all states participate in the National Dam Safety Program and the National Flood Insurance Program, there exists a solid governmental and organizational foundation on which to incorporate levees into activities and governance. **The question is, how can existing programs or governance frameworks integrate with or be adjusted to include levees in a**

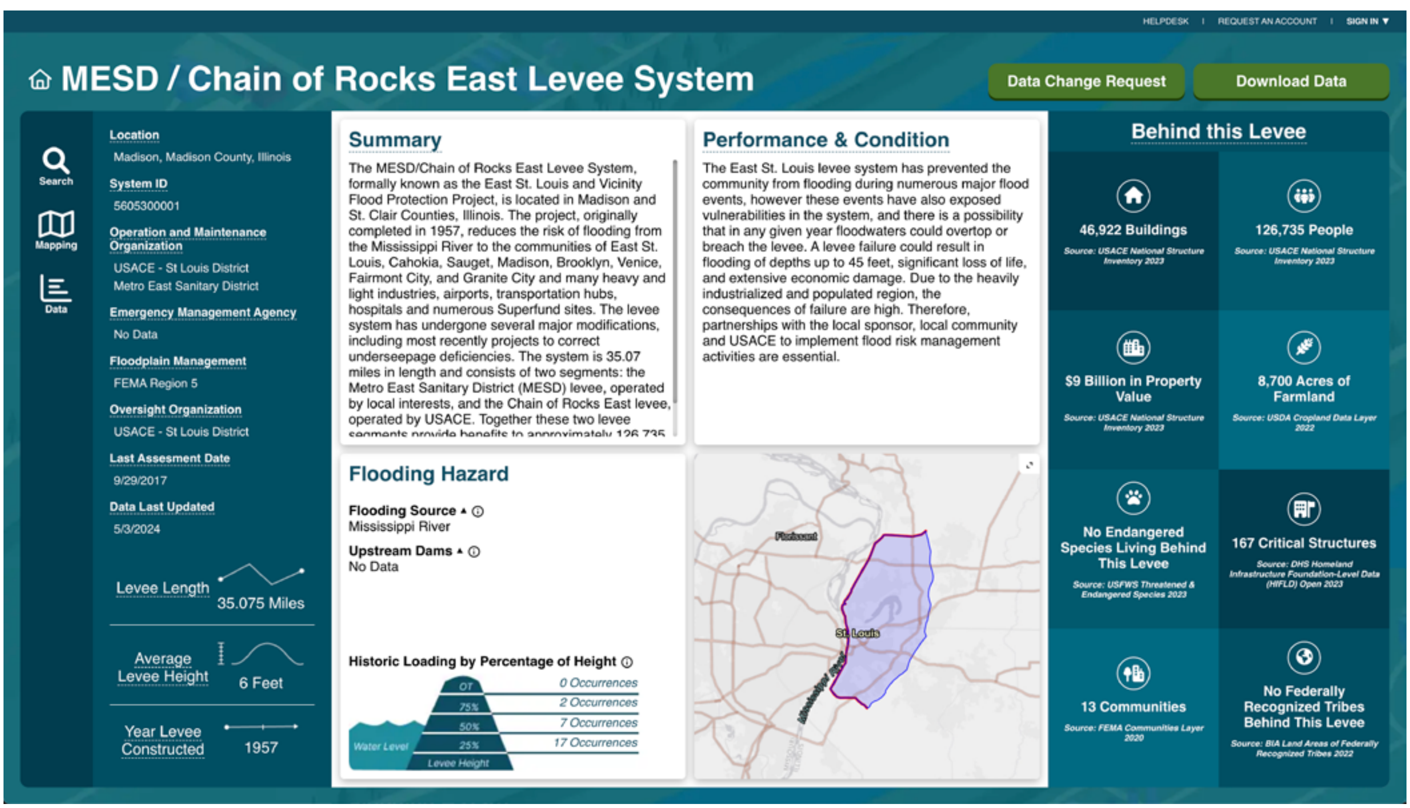


Figure 4 Example of the Main Landing Page of a Particular Levee System

STATE	MILES OF LEVEES	STATE	MILES OF LEVEES	STATE	MILES OF LEVEES
CALIFORNIA	5,069.7	OHIO	196.7	WEST VIRGINIA	37.4
LOUISIANA	3,282.4	SOUTH DAKOTA	182.2	WISCONSIN	33.7
ILLINOIS	2,095.1	NORTH DAKOTA	182.1	NEVADA	29.5
MISSOURI	1,919.6	PENNSYLVANIA	160.0	CONNECTICUT	25.0
ARKANSAS	1,482.3	KENTUCKY	140.1	MARYLAND	22.1
TEXAS	1,242.2	NEW YORK	113.7	GEORGIA	21.8
FLORIDA	1,055.6	MICHIGAN	97.1	VIRGINIA	16.1
MISSISSIPPI	968.7	OKLAHOMA	86.4	SOUTH CAROLINA	15.2
IOWA	730.8	NORTH CAROLINA	77.9	HAWAII	14.3
KANSAS	710.4	NEW JERSEY	77.9	ALABAMA	13.4
WASHINGTON	620.3	TENNESSEE	76.6	RHODE ISLAND	3.8
NEW MEXICO	394.2	UTAH	74.7	NEW HAMPSHIRE	3.7
INDIANA	380.1	MONTANA	74.0	DISTRICT OF COLUMBIA	3.3
NEBRASKA	335.5	COLORADO	70.0	DELAWARE	1.9
ARIZONA	330.7	PUERTO RICO	65.3	MAINE	1.9
OREGON	315.4	ALASKA	53.0	VERMONT	1.0
IDAHO	243.4	MASSACHUSETTS	51.9	GUAM	0.8
MINNESOTA	222.4	WYOMING	49.0	US VIRGIN ISLANDS	0.3

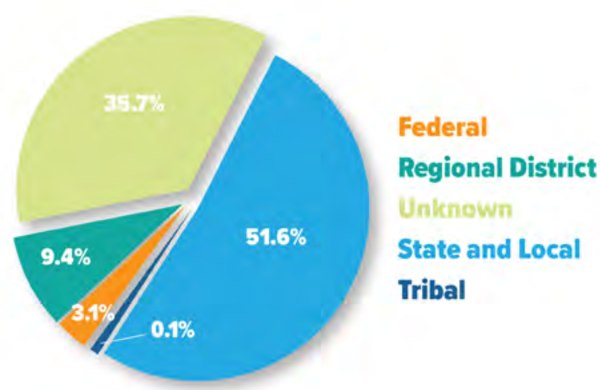
Table 3 Levee Miles per U.S. State and Territory

A Snapshot of Levees from a State Perspective

There are levees in every state (Table 3), but there is considerable variation not only in the total number of levees but the number of people and the amount of property they protect.

The Varied Activities of Levee Owner/Operators

Entities that operate and manage levees are found at all levels of government, with tribes, and in the private sector (Figure 5). Because many entities that operate levees also have other duties related to state or local laws or authorities, there is no such thing as a typical or standard levee operator. A short list of duties that owner/operators such as states, tribes, regional districts, and local governments may have also include floodplain regulation, land use management, communications and outreach, emergency planning, alerts, warnings and evacuations, and floodproofing critical infrastructure and



National Levee Database

Figure 5 Percent Distribution of Levee Ownership

STATE	TOTAL # OF LEVEES IN THE STATE	TOTAL # OF LEVEES OPERATED BY REGIONAL DISTRICTS	STATE	TOTAL # OF LEVEES IN THE STATE	TOTAL # OF LEVEES OPERATED BY REGIONAL DISTRICTS
CALIFORNIA	1,707	99	NORTH DAKOTA	198	6
MISSOURI	287	95	MISSISSIPPI	108	4
ILLINOIS	557	91	SOUTH DAKOTA	99	4
FLORIDA	89	75	MINNESOTA	133	3
ARKANSAS	99	46	OHIO	147	3
TEXAS	231	42	TENNESSEE	17	3
WASHINGTON	334	27	COLORADO	60	2
OREGON	213	21	KENTUCKY	34	2
LOUISIANA	273	20	OKLAHOMA	72	2
KANSAS	345	17	PENNSYLVANIA	200	2
IOWA	177	16	UTAH	45	2
INDIANA	112	15	MICHIGAN	54	1
IDAHO	139	14	NEW MEXICO	127	1
NEBRASKA	126	13	NORTH CAROLINA	22	1
ARIZONA	141	9	WYOMING	31	1
MONTANA	75	6			

Table 4 States Where Regional Districts Operate and Maintain a Portion of the Levee Systems

community lifelines. For the purposes of this paper, those other roles and responsibilities will be discussed separately from the basic set of responsibilities listed here that are common to nearly all levee owner/operators, which include:

- Maintain and repair
- Inspect and assess
- Operate during flood
- Develop a levee emergency action plan and share with local emergency responders
- Plan for rehabilitation and capital improvements

The Role of States

A short survey the Association of State Dam Safety Officials (ASDSO) sent to states in 2006 indicated that 23 states had some involvement with levees. As with dams, state levee program activities are housed within many different types of state organizations, including water resources or environmental organizations, public safety-related programs, or state agencies with broader floodplain management responsibilities. Based on more recent informal conversations, state approaches to levees can generally be grouped into the following high-level categories:

- States that have added "levee" to state dam safety authorities, either through legislation or more informally treating the two types of infrastructure largely the same regarding activities and oversight.
- States that are gathering information to better understand the levee situation in their state. This includes information not only on the levee itself, but financial health of levee districts, assessment technologies, and so on.
- States that have incorporated the needs of levee owners and communities into broader state programs and/or have levee-specific authorities and approaches. This could include technical assistance, emergency planning and response, qualification for state funding programs, incorporating levees into state hazard mitigation plans,[2] and so forth.

In 33 U.S.C. Chapter 46, a term "regional district" is introduced as a subdivision of a state government, or a subdivision of multiple state governments, which is authorized to acquire, construct, operate, and maintain projects for the purpose of flood damage reduction.

The Role of Regional Districts

To make matters more complicated, many states have created regional districts to assist in the management and oversight of levees within their states. Rough estimates[3] indicate there are 643 levee systems across 31 states that are operated and maintained at least partially by regional districts (Table 4). Some states use regional districts more than others, with five states containing more than 60% of the regional districts. About half of the regional districts serve as local sponsors for levees under the jurisdiction of the USACE. The remaining regional districts operate and maintain levees constructed by state and local governments, private entities, and so on.

A review of publicly available documents (e.g., legislation, executive orders, and agency websites) related to the formation and authorities of identified regional districts located in five states[4] revealed that regional districts participate in a variety of authorities and activities. This research indicated that most regional districts can be grouped into two main categories (although care should be taken in extrapolating this information to all states or regional districts).

- The large majority (over 95%) have authorities that focus on upkeep, maintenance, operations, and flood fighting. These entities have authority to collect taxes from those being protected by the levee for those purposes. Some regional districts blend responsibilities for levee upkeep with agricultural drainage purposes. These regional districts are often called levee districts, drainage districts, and/or diking districts.
- A few (less than 5%) have broader responsibilities that include levee operations and maintenance, and have additional responsibilities for floodplain management, natural resources protection, recreation, and other purposes. These regional districts often have names of water management districts, flood protection boards, water agency/authority, flood control and conservation districts, and so on.

The geography and responsibilities of regional districts within a state can also vary (Figure 6). Of the 31 states that have created regional districts with at least some levee management responsibilities, some have districts that cover the entire geography of the state, whereas some states have districts in parts of the state. There are 16 levee systems that cross state lines that include at least one regional district. Not all regional districts within a state have the same authorities and responsibilities.

To get a more current and comprehensive picture of state levee-related activities, ASDSO and the Association of State Floodplain Managers (ASFPM) recently sent a survey to states to better understand the status of authorities, programs, and activities underway at the state level. This survey will provide an updated and more detailed baseline understanding of levee management at the state and regional district levels including:

- Legislation, statutes, and authorities;
- Activities or programs that support levee owner/operators and communities;
- Role and authorities of regional districts within and between states;
- State budgets and funding available to levee owner/operators and communities; and
- Identification of state needs for levee management.

---

[2] Hazard mitigation plans exist at the state, tribal, and local community level and identify natural disaster risks and vulnerabilities that are common in their area. After identifying these risks, they develop long-term strategies for protecting people and property from identified events. They are required to apply for certain types of nondisaster assistance from FEMA (42 U.S.C. 5121).

[3] Estimates of probable regional districts were created by searching the National Levee Database on owner/operator names including levee/drainage/diking districts, water management, flood control, and other combinations. These regional districts have not been independently verified except for the 5 states where additional research was conducted. The total number of unique regional districts may be higher as some portion of the segments that have no named sponsors are likely to be regional districts. On the other hand, there may be some duplicates with variations in owner/operator spelling and truncation of names in the National Levee Database.

[4] The five states included in this analysis are Washington, Iowa, Louisiana, Missouri, and Florida, chosen for their geographic distribution and diversity in type and scope of their regional districts.

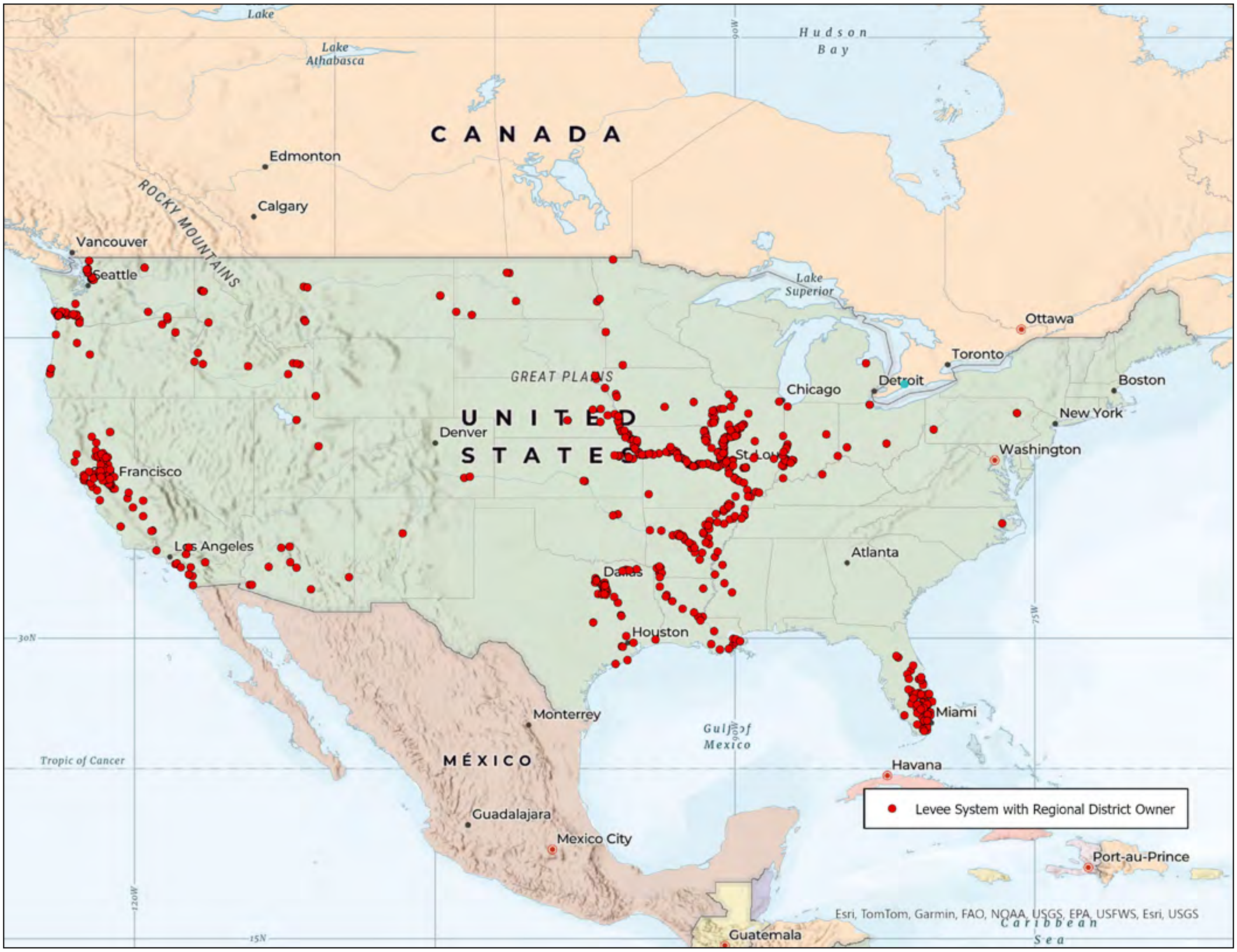


Figure 6 Geographic Distribution of Regional Districts

What's Next for Levees

The purposes of the National Levee Safety Program as envisioned by Congress include encouraging the use of appropriate technical and emergency preparedness practices for levees; supporting public education and awareness related to levees and flood risk; and establishing effective levee safety programs to be the means for accomplishing these purposes.

Suite of Best Practices. The National Levee Safety Program has spent the last several years developing a suite of best practices based on the priorities of stakeholders to improve levee literacy and help achieve nationwide consistency in improving the reliability of levees and resilience of communities behind levees. Once finalized, the first edition of the National Levee Safety Guidelines will provide an up-to-date comprehensive set of best practices that serves the following purposes:

- Levee owner/operators will have a readily available resource to use as a reference for specific levee activities.
- Communities and local officials may better understand the benefits and risks of levees and can integrate reliable levees with overall flood risk management, emergency planning, and public awareness.
- States, regional districts and tribes may incorporate best practices into a variety of state efforts including hazard mitigation, flood risk management, resiliency, and natural/water resources management strategies.

List of Best Practices and Other Resources Being Developed by National Levee Safety Program

- *National Levee Safety Guidelines*
- *Levee Management Guide*
- *Emergency Action Plan Template*
- *Operations and Maintenance Template*
- *Levee Inspection Checklist*
- *Best Practices for Managing Vegetation on Levees*

A Discussion of Roles and Responsibilities to Support Effective Levee Safety Programs. In addition to developing best practices, the National Levee Safety Program is working to move the nation towards an integrated, coordinated set of levee safety programs/practices at the federal, state, regional, and tribal levels to:

- Support levee owner/operators in inspection, assessment, repair, and rehabilitation of levees.
- Work with communities, emergency managers, businesses, and individuals to understand relevant levee-specific information and use that information to raise awareness of and manage flood risks.
- Work collaboratively across programmatic and political jurisdictions to ensure that all communities with levees have access to any needed support.
- Ensure that services are applied in a fair and equitable way across the landscape with special attention to underserved communities, tribes, and individuals particularly vulnerable to flooding.

As in dam safety and floodplain management, states are thought to have a critical role in helping national programs be more efficient by assisting in coordinating among all levels of government and integrating levees in meaningful ways across state strategic investments and related programs such as flood risk management, community resiliency, climate change, natural resources management, and transportation. To begin the national, in-depth discussion to develop an integrated, efficient, and clear framework, the following conceptual roles and responsibilities of government levels could be considered as a starting point (Table 5).

SOME EXAMPLES OF LEVEE ACTIVITIES AND APPROACHES AT THE STATE LEVEL

- Arizona manages hazard mitigation assistance grants for specific levee projects through its Department of Emergency and Military Affairs.
- In early 2024, the state of Arkansas entered into a partnership agreement with USACE to conduct a detailed identification and inventory of levees within the state.
- The California Department of Water Resources integrates levees within a more comprehensive flood risk management program that includes planning, prioritization, and support of projects; emergency planning and response; research and standards development; and operations and maintenance activities. California has grant programs for levee improvements, operations, and maintenance. One such program is the Small Communities Flood Risk Reduction Program, which covers 75–100% of the cost share for projects in communities with populations under 10,000.
- Kentucky, among other states, has included levees and dams as eligible projects under their Clean Water State Revolving Loan Fund.
- In 2023, Iowa adopted new legislation that stood up an Office of Levee Safety and created a $25 million Levee Improvement Fund. They are currently creating a prioritization system to identify the most at-risk levees.
- The Association of Levee Boards of Louisiana educates members about state and federal assistance programs, and helps low-income levee districts apply for grant funding, conduct inspections, and write reports.
- In response to the damaging storms in the mid-2000s, the state of New Hampshire modified its definition and interpretation of a “dam” so that levees around the state (i.e., those that meet a certain height threshold) would have the same regulation requirements as dams. Some of these requirements include frequency of inspections, permits for modifications, condition assessments, and emergency action plans.

FEDERAL AGENCIES	STATES	REGIONAL DISTRICTS	LOCAL GOVERNMENTS
• Develop and track progress against national goals • Develop best practices • Maintain national datasets • Conduct training • Provide funding assistance • Coordinate activities on federal levees	• Coordinate at watershed and interstate levels • Integrate levees into state investment and strategic plans • Regulate floodplains • Coordinate federal assistance • State-level emergency management • Support public awareness • Include levees in state hazard mitigation plans • Assist with levee information/fill gaps	• Implement state-delegated authorities in their area of responsibility • Coordinate regionally • Share information with states	• Manage land use • Enact floodplain ordinances • Conduct warnings and evacuations • Increase community flood awareness • Identify and serve disadvantaged communities • Incorporate levees into community resiliency efforts • Include levees in local hazard mitigation plans

Table 5 High Level Roles in Levee and Flood Risk Management

A Unique Case for Tribes. Discussion and feedback from tribes to date indicate that tribal governments have little interest in developing formal programs like states. Out of 574 federally-recognized tribes, only 5 own/operate levees. Approximately 53 tribes have levees that cross tribal land – these are operated and maintained by a variety of entities including federal agencies and states. Even though they do not play a large role in construction or maintenance, tribes have a keen interest in levees. In addition to universal interests of public safety and reducing flood damages, levees have sometimes been built on or near sacred sites, or in places where traditional foods or medicines grow. Tribes are also actively involved in advocating for the modification, set back, or removal of levees to restore migratory fish and other aquatic species on which they depend and sometimes have treaty rights.[5]

Starting the National Dialogue. The development of the National Levee Safety Program presents the ideal forum to address these challenging topics and questions and start a national dialogue on approaches that integrate levees into flood resiliency goals while remaining scalable to local situations. The following are some of the many questions to be wrestled with as we endeavor to create a framework that raises the level of levee awareness promoting increased stewardship of these important pieces of flood management infrastructure.

- What are the minimum components or best practices that should be encouraged for states, regional districts, and tribes? Where can federal agencies best support?
- Given the complexities of roles and responsibilities across those entities, should a common set of activities be promoted for each level of government, or should activities be more distinct yet coordinated?
- How can we ensure that activities are clear and work in concert with each other while reducing duplication?

[5] These "contracts among nations" recognized and established unique sets of rights, benefits, and conditions for the treaty-making tribes who agreed to cede millions of acres of their homelands to the United States and accept its protection. Like other treaty obligations of the United States, Indian treaties are considered to be "the supreme law of the land," and they are the foundation upon which federal Indian law and the federal Indian trust relationship is based (U.S. Department of Interior, Indian Affairs).

- What is a productive relationship among federal agencies, states, and tribal governments that recognizes tribal sovereignty and treaty rights and supports tribal values, cultures, and interests?
- How do we encourage adoption of consistent, high-level best practices while maintaining the flexibility needed?
- What strategies can we use to ensure equity and access to government programs is incorporated into the National Levee Safety Program?

Conclusion

More work is needed to develop a vision for effective and consistent approaches to levee safety and to articulate the roles levees play in flood risk management and community resiliency. Effective flood risk management requires an integrated effort because responsibility is shared among multiple entities within a complex set of programs and authorities. Levees are no exception. The National Levee Safety Program provides an opportunity to look hard at the status quo. Multiple sources of flooding can impact the same community and increasing recognition of the importance of naturally functioning floodplains reinforces the fact that levees cannot be the only flood risk management solution most communities consider. Costs to maintain, repair, and improve levees continues to rise, making it challenging to maintain or improve levees. Changing weather patterns mean we can no longer rely on levees in the same way we did in the past; this reality is coming at a time when there are more people and property behind or near levees than ever before. How will states help support an effort to accomplish a unified approach that recognizes their varying legal mechanisms, governance, funding, capabilities, and political realities? Even though the nation has been grappling with flooding for a long time, in some respects the conversations about levees are just beginning.

Tammy Conforti, P.E.

Special Assistant for Levee Safety, U.S. Army Corps of Engineers

441 G Street, NW, Washington, DC 20226 • (202) 761-4649 • tammy.conforti@usace.army.mil

Ms. Conforti has worked for the U.S. Army Corps of Engineers for 33 years in a variety of areas related to flood risk management. In her current role as the special assistant for levee safety, she is responsible for overseeing the development of the National Levee Safety Program, which is intended to improve public awareness and management of levee systems. Ms. Conforti has a B.S. in civil engineering from Virginia Tech and a M.S. in risk management from Notre Dame of Maryland University. She is a registered professional engineer and a certified floodplain manager.

Linda I. Manning

President, The Council Oak, LLC

6544 Mapledale Court, Falls Church, VA 22041 • (703) 395-3570 • lmanning@thecounciloak.com

Linda is the president and founder of Council Oak, a small consulting business focused on water resources, infrastructure, and natural resources topics. She has an interdisciplinary background in public policy, facilitation, stakeholder engagement, collaborative problem-solving, program evaluation, and strategic communications. For three decades, her work has assisted government agencies make scientifically-informed decisions, meaningfully engage stakeholders, design and implement effective programs, and communicate program benefits and outcomes.

ASDSO Peer Reviewers

This article was peer reviewed by Ian Maki, P.E. (California Division of Safety of Dams).


CANARY
Start typing...
Help
Database / Image Windows / Goover Dam (Scene)
Cancel
Save
3D View
View Date: 09/20/2023 09:07:06.478 AM
Home
Status
Dashboards
Water Elevation vs. Headwater (Daily Avg)
(2D Histogram)

NATIONAL LEVEE SAFETY PROGRAM NEWS

First Ever *National Levee Safety Guidelines* Currently Under Review

This spring, the National Levee Safety Program released the first-ever draft comprehensive guidelines for the nation's levees (Figure 1). The *National Levee Safety Guidelines* are intended to provide best practices and serve as a resource to help achieve nationwide consistency in improving the reliability of levees and resilience of communities behind levees.

The National Levee Safety Program developed the guidelines through a comprehensive literature review process, gathering input from stakeholders, and using a multi-disciplinary author team of technical subject matter experts from private sector firms. Topics range from basic levee concepts and terminology to strategies for reducing flooding impacts to people, property, and the environment. Considerations for climate change impacts on levees, integrating natural and nature-based features, and needs of underserved communities are woven throughout the document.

Feedback on the scope of the *National Levee Safety Guidelines* from stakeholder engagement efforts over the past two years also included the need for levee vegetation management practices. High-level best practices have been incorporated into several *National Levee Safety Guidelines* chapters and will be expanded in the future. Until then, a companion document to the draft guidelines, "Best Practices for Vegetation Management on Levees," is also available for review. This document provides detailed information about the current thinking related to practices for vegetation management on or near levees.

Figure 1 Cover of the Draft 1st Edition of the *National Levee Safety Guidelines*

Stakeholders, tribes, community members, and others who have an interest in levees are encouraged to provide comments on both documents which are available for download at: **https://www.leveesafety.org/pages/nlsg.** Comments are due by July 31, 2024.

Once public comments are incorporated, the 1st Edition of the *National Levee Safety Guidelines* will be published and available for use later this year.

A detailed strategy for updating future editions of the guidelines will also be developed and shared with stakeholders and the public. Finally, in early 2025, the National Academies of Science will conduct an independent review of the document and a formal report of their findings will be publicly available.

New *Levee Management Guide* in Development

During the first phase of stakeholder engagement for the National Levee Safety Program, feedback on the scope of the *National Levee Safety Guidelines* identified a need to consolidate practical information for levee owner/operators in one location and, in some circumstances, provide additional detail on procedures and methodologies as well as supplemental resources to support the safe operation and maintenance of levees. The *Levee Management Guide* is being developed, with stakeholder input, as a supplement to the *National Levee Safety Guidelines*. The purpose is to consolidate the information needed by anyone who has a responsibility for some or all aspects of the operations, maintenance, and management decisions on levees.

The *Levee Management Guide* will assist users with understanding and carrying out responsibilities for operating and maintaining a levee from the time it is constructed through its useful life. The content in the *Levee Management Guide* can also help users develop specific products, such as operations and maintenance manuals and emergency action plans, to document and communicate information specific to an individual levee.

Additional resources are being developed to further support levee owner/operators with levee management activities. These products, which are supplemental to the *Levee Management Guide*, would be adaptable for any user and include:

- operations and maintenance manual and emergency action plan templates
- levee inspection checklist
- floodfight techniques document

These resources, including the draft *Levee Management Guide*, will be available for public review in early 2025. More information will be available at **https://www.leveesafety.org/pages/imsp**.

Launch of User-Friendly Features in the National Levee Database

USACE recently launched an updated National Levee Database to improve the user experience and ease of access to key data. The database – available at **https://nld.sec.usace.army.mil** – has been publicly accessible since 2011 and is a dynamic, searchable inventory of information about all known levee systems in the nation that can inform a wide variety of flood risk and levee management activities.

Key changes include:

A new look and feel – Site visitors can quickly access key tools from the landing page. For example, users can now input their address to see if their property is behind a levee (Figure 2). More advanced searches can be completed using the mapping or data tools.

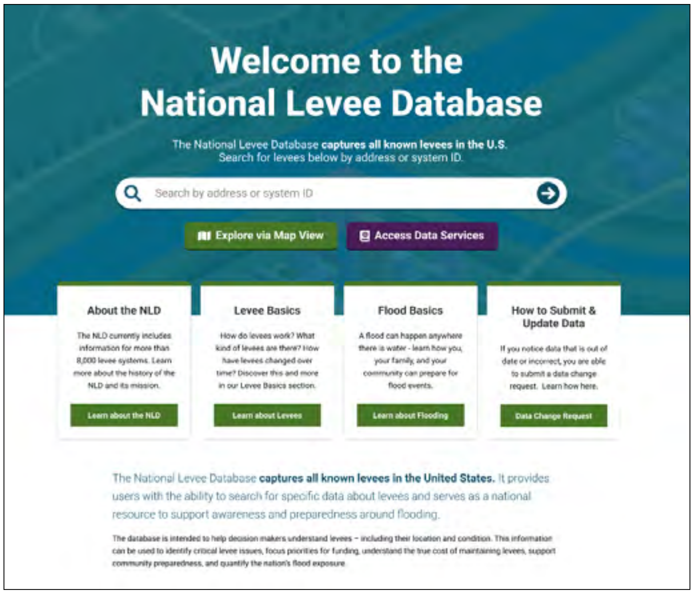


Figure 2 New Landing Page for the National Levee Database

Timely data updates – New or updated data can be submitted more easily. Users can submit new or updated data using the icon on the National Levee Database landing page or from a levee's summary page. Read more about data requirements by clicking on the "**How to Submit and Update Data**" icon.

NATIONAL LEVEE SAFETY PROGRAM NEWS

Helpful resources – People who want to know more about the National Levee Database or about levees can explore newly dedicated informational pages.

- **"About the NLD"** includes information about how the site came to be, how data is populated, and frequently requested information.
- The **"Levee Basics"** icon takes site visitors to a series of webpages that explain the basics of levees including why they are built, how they work, and how they can be used in a community to reduce the frequency and intensity of flooding.
- Visit **"Flood Basics"** to learn how flooding happens and how communities and individuals can be flood ready.

New login procedures - The National Levee Database now includes new procedures for a user account that help differentiate access to information based on the user's role. The following table summarizes access to levee data by role.

USER (ROLE)	LOGIN PROCESS	DATA AVAILABLE FOR ACCESS
PUBLIC USER	No account required	• Informational and levee summary page for all levees. • Search and mapping tools.
ADVANCED USER	Account/role verification by USACE	• All information available to the public. • Additional technical fields for all levees, such as design flow, river gage code, and slope.
LEVEE OWNER OR OPERATOR	Account/role verification by USACE	• All information available to the public. • Additional technical fields for all levees. • Specific reports, analysis, and documents for their specific levee.
REGULATOR/ MANAGER OF MULTIPLE LEVEES	Account/role verification by USACE	• All information available to the public. • Additional technical fields for all levees. • Specific reports, analysis, and documents for levees for which they have a responsibility.

The National Levee Database is an important tool that supports levee and flood preparedness decisions. Data is provided and regularly updated in partnership with a variety of entities responsible for levees – including federal, state, tribal, and local agencies, as well as private organizations.

Opportunity to Learn More About Your Levee Through Levee Review

As part of the National Levee Safety Program, USACE has the authority to conduct a one-time review, known as levee review, of all levees identified in the National

Levee Database to provide a clearer picture of levee-related flood risk nationally and a baseline of levee information. USACE has completed reviews of over 1,600 levees to date. The remaining 5,400 levees in the National Levee Database are eligible for Levee Review under the National Levee Safety Program.

Under this initiative, USACE can facilitate a levee site visit and screening-level risk assessment on levees with the goal of helping states, tribes, and levee owner/operators make informed decisions on managing flood risks associated with those levees.

> *California Department of Water Resources encourages local levee owners to volunteer for this program. It is beneficial for levee owners to update their levee data in the NLD, receive information that can assist with operation and maintenance activities, better understand levee conditions, and get preliminary cost estimates for recommendations based on the levee review results.*

Benefits of Participating in Levee Review

- Provide a comparable basic risk measure across all levees in the National Levee Database.
- Help refine the data in the National Levee Database, where it can be managed and used for multiple purposes.
- Provide a learning/training opportunity for those who participate directly in the levee review process (Figure 3).
- Provide levee owners with information that can help inform operation and maintenance activities.
- Provide communities with information that can be used for emergency planning or land-use decisions.
- Provide states with better information to help levee owner/operators who wish to seek state or federal assistance for levee-related projects.

Figure 3 Multidisciplinary Team Conducts a Risk Assessment with Levee Owners in California in the Spring of 2024

Through the site visit and screening-level risk assessment process, participants develop a basic understanding of levee components along with the flood hazard, expected levee performance, and consequences of levee failure. In preparation for conducting these levee reviews, USACE partnered with levee owner/operators in a series of pilots. These pilots were used to develop and document consistent procedures for the remaining levee reviews. Feedback from the levee owner/operators and other local participants was especially helpful in increasing efficiencies and better ensuring a value-added levee review process.

How to Participate in a Levee Review

For more information about the levee review process or to sign up, please email **hq-leveesafety@usace.army.mil**.

VOLUNTEER SPOTLIGHT

Each quarter, ASDSO recognizes one ASDSO volunteer or volunteer group in the *Journal of Dam Safety*. Through this recognition, ASDSO hopes to spotlight some of the outstanding efforts being made by our members and thank them for their contributions. The ASDSO Annual Awards Committee oversees this effort, and the Board of Directors selects honorees.

Russ Hicks' Longtime Advocacy for Public Safety at Low Head Dams in Michigan

In June 2016, Russ Hicks thought he was at the end of his journey into the world of dams. He had spent the previous seven years as the chairman of the Return the Rapids to Eaton Rapids campaign, which aimed to remove a dam on the Grand River in Michigan through crowdfunding and local grants. With the dam removed and the rapids restored, he now had the option to focus on other interests. After all, he was a retired English teacher, not a dam safety engineer.

Fortunately, Russ quickly realized he still had a lot more to offer. During his years focused on dam removal, he gained a wide range of knowledge on the removal process. While his efforts began with an interest in conservation and recreation, he now had some insight into first response, grants, the removal process, regulations, and the critical need to address public safety issues. In an effort to share this knowledge and find like-minded individuals, he joined ASDSO.

Since joining in 2017, Russ has been a dedicated speakers bureau volunteer and advocate for public safety at low head dams in Michigan. Russ has staffed a booth at numerous conferences on behalf of ASDSO, including at the Michigan Watershed Summit, the Four Lakes Task Force Symposium, and multiple years at the Quiet Adventures Symposium. His booth typically includes an array of awareness materials, a showing of the *Over, Under, Gone* documentary, and a damaged canoe. The canoe was originally part of a safety demonstration that Russ organized for a previous National Dam Safety Awareness Day. During the demonstration, an empty canoe was sent over the dam to demonstrate the dangers of the hydraulic roller. The demo was attended by local media, first responders, emergency managers, and numerous other local groups.

From working with local organizations and government representatives to address a problem dam to working with students at Michigan State University and the University of Michigan to spark an interest in dam safety engineering, Russ continually finds new ways to share his knowledge. He is truly an example of a local champion and a model volunteer.

Thank you, Russ, for making a difference!

Booth at the 2022 Four Lakes Task Force Symposium

Media Coverage of the 2018 National Dam Safety Awareness Day Demonstration

MIDWEST REGIONAL SPOTLIGHT

Each quarter, the ASDSO Regional Representatives from one region recognize an individual, organization, or group that has made outstanding contributions to dam safety in their region or nationally as a representative from their region. The ASDSO Annual Awards Committee oversees the effort. If you have an idea for a regional spotlight that you would like to be considered, please email **awards@damsafety.org.**

Michigan Dam Safety Program Makes Great Strides

May 2020 Dam Failure Event

On May 16-18, 2020, heavy rainfalls ranging locally from 4 to 8 inches hit mid-Michigan over a 48-hour period, concentrating in Arenac, Gladwin, Iosco, and Midland counties. Swelling floodwaters placed additional stress on many dams in the area, specifically those in the Tittabawassee River basin. Around 5:30 p.m. on May 19, 2020, a portion of the Edenville Dam's earthen embankment failed, causing an uncontrolled release of impounded water to rush downstream toward Edenville, Sanford Lake, and the Sanford Dam. The level of Sanford Lake rose quickly over the next two hours, and around 7:45 p.m. the Sanford Dam was overtopped by floodwaters and also failed. The combined flood waves from these two dam failures rushed through the village of Sanford and toward the cities of Midland and Saginaw, where the Tittabawassee River joins the Saginaw River and ultimately outlets to the Saginaw Bay of Lake Huron.

The resulting flooding forced the evacuation of over 11,000 people and damaged over 2,500 structures. Thankfully, no major injuries or fatalities were reported. Damages are estimated at more than $200 million.


Sanford Dam After Failure on 5/19/2020, Looking Downstream


Edenville Dam After Failure on 5/19/2020, Looking Upstream

Immediately following the dam failures, Governor Gretchen Whitmer issued a directive to the Michigan Department of Environment, Great Lakes, and Energy (EGLE) to complete the three following items:

1. Investigate the cause and contributing factors of/ leading to the failure of the two dams.
2. Perform a full evaluation of the dam safety program, and overall safety of dams in Michigan.
3. Report the findings and recommendations of these efforts to the Governor's office.

Independent Forensic Investigation

In August 2020, EGLE partnered with the Federal Energy Regulatory Commission (FERC) to assemble a team of industry experts to complete a fully independent forensic investigation of the causes and contributing factors leading to the failure of the Edenville and Sanford Dams. A final report (**https://damsafety.org/MI-Final-Report**) of the failures was issued on May 4, 2022. This report determined that causes of the Edenville and Sanford Dam failures were static liquefaction triggered by high water levels and overtopping directly resulting from the upstream dam breach, respectively, and also identified several human and systemic factors that contributed to the failures.

Evaluation of Michigan's Dam Safety Program

In July of 2020, EGLE sent a request to ASDSO to perform a peer review of the dam safety program and dam safety practices in Michigan. The ASDSO Peer Review Committee issued a final report (**https://bit.ly/3V4KF3Y**) of their findings to EGLE on September 4, 2020. This report served as the basis for recommendations of the Michigan Dam Safety Task Force (MDSTF), which was appointed to make final recommendations to the Governor. The MDSTF issued their final report (**https://bit.ly/3QKHkV1**) to Governor Whitmer on February 25, 2021, which contained 86 recommendations as outlined in Table 1.

TABLE 1 SUMMARY OF MDSTF RECOMMENDATIONS TO GOVERNOR WHITMER

NUMBER OF RECOMMENDATIONS	CATEGORY
7	Funding opportunities for dam owners and the Dam Safety Program
11	Legislation and authority
16	General dam safety improvements
6	Compliance and enforcement
7	Emergency Response
33	Dam Safety Program management and funding
2	Safety and security at dams
4	Public outreach and awareness

Michigan Dam Safety Program Updates

Immediately following the release of the MDSTF report, EGLE's Dam Safety Program (DSP) got to work implementing key recommendations of the report. Most notably, the program has increased its budget and staff, currently employing six full-time engineers and one full-time supervisor (up from two engineers and a half-time supervisor), with plans to hire four additional staff in 2024.

Also of note, the DSP has made improvements to its inventory database, performed a preliminary portfolio risk assessment, increased compliance and enforcement actions, created an emergency fund to address deficiencies at dams when an owner is unwilling or unable to do so, and stood up a Dam Risk Reduction Grant Program (DRRGP) to assist dam owners with repair/rehabilitation and removal of dams in the state.

In 2023, EGLE awarded $15.3 million in grants to support sixteen risk reduction projects, including six dam removal projects, four dam rehabilitation projects, and six engineering studies for rehabilitation or removal of dams (**https://bit.ly/4bthmOw**).

On May 6, 2024, EGLE awarded another $14.1 million in grants to support twenty-two risk reduction projects, including eight dam removal projects, six dam rehabilitation projects, and eight engineering studies for rehabilitation or removal of dams (**https://bit.ly/4bn2CAm**).

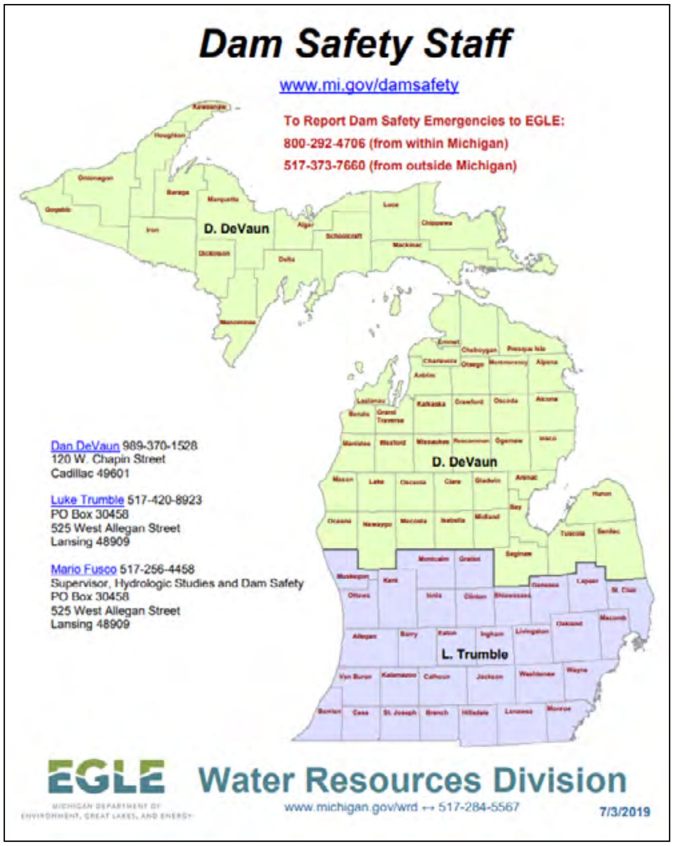


Figure 1 EGLE DSP Coverage Map at the Time of the Dam Failures in 2022

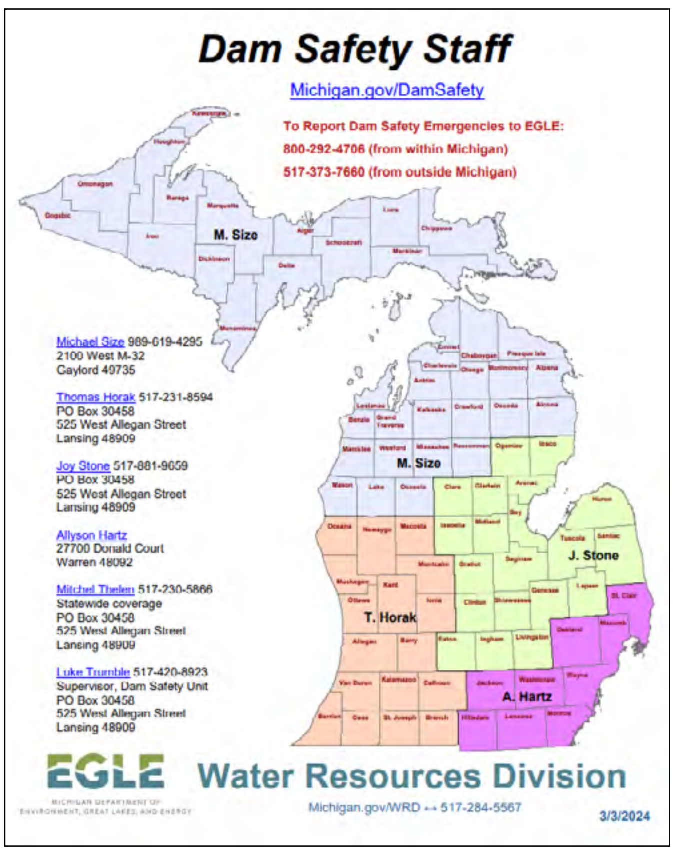
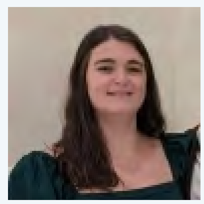


Figure 2 EGLE DSP Coverage Map as of March 2024

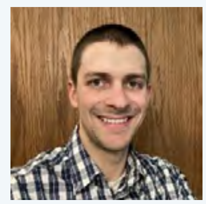
Key MDSTF Recommendations Yet to be Completed

Although Michigan's DSP has made great strides in the past four years to implement recommendations of the MDSTF, there is still some ground left to cover. Most notably, recommendations to strengthen Michigan's dam safety law to meet requirements recommended in the FEMA Model State Dam Safety Program (**https://bit.ly/3K8F864**), specifically those related to inspection frequency and design criteria for high and significant hazard potential dams, have not been completed. In addition, requirements for dam owners to register their dams, exercise Emergency Action Plans, and for the DSP to implement a risk-informed progressive compliance and enforcement program are still in the works.

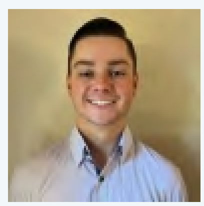
Meet Michigan's DSP



Allyson Hartz
Regional Dam Safety Engineer

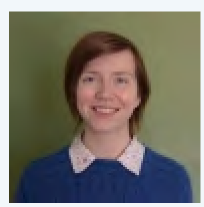


Thomas Horak, P.E.
Regional Dam Safety Engineer

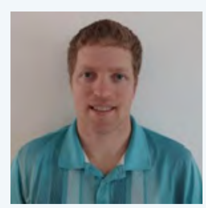


Mason Manuszak
Grants Administrator

Mike Size, E.I.T.
Regional Dam Safety Engineer



Joy Stone, E.I.T.
Regional Dam Safety Engineer



Mitchel Thelen, P.E.
Senior Dam Safety Engineer

Luke Trumble, P.E.
Supervisor

ASDSO Board Approves Recommended Approach to Filling Training and Proficiency Gaps in the Dam Safety Profession

The ASDSO Board of Directors approved "Issue Brief and Recommendation on Developing a Credentialing Program for a Dam Safety Engineering Specialist."

A longstanding issue is a perceived lack of training and proficiency in the fields required to manage dam engineering, dam safety, and related management programs. Consultants, regulators, and owners need to meet a minimum standard of knowledge, coupled with experience in their respective positions. The idea of establishing a credentialing or certification program within ASDSO to address this issue is raised frequently.

The purpose of this paper is to summarize the various certification concepts in practice today by associations, to consider past efforts by ASDSO to define the problem and offer solutions, and to provide a recommendation for the ASDSO leadership to consider.

After many formal and informal discussions and feedback sessions over several years, the ASDSO Board of Directors recommends the following actions:

- ASDSO will not pursue the establishment of a credential or certification program.
- ASDSO will continue to advocate for comprehensive training programs for the dam engineering profession.
- ASDSO will continue to advocate for accredited college and university programs to include dam safety engineering courses.
- ASDSO will continue to provide training courses to fulfill the objectives of the ASDSO Program of Study (DamSafety.org/training-overview) and will launch a program to establish topic-specific certificate tracks, using materials currently available through ASDSO's technical training program.
- ASDSO will continue to provide education programs for dam owners and will launch a program to establish a dam owner training certificate track using materials currently available through the ASDSO Dam Owner Academy program (DamOwner.org).
- ASDSO will continue to build the ASDSO Dam Safety Toolbox (DamToolbox.org), which is a repository for current guidelines and recommendations related to dam safety. The objective of this effort is to fill the educational gap that is the basis of this issue brief.

Read the issue brief at DamSafety.org/Resolutions.

Dam Safety Toolbox Website Continues to Grow

The Dam Safety Toolbox Committee has continued its work to share the new resource with those in the dam safety community and encourage new contributions.

MAY

- Matt Marquis (Ohio Dam Safety) presented at the Ohio Stormwater Conference. He also provided an opportunity for attendees to demo the website at the Ohio Natural Resources booth in the exhibit hall.

APRIL

- Jeremy Franz (Colorado Dam Safety), Greg Richards (Gannett Fleming), and Andy Lynch (Gannett Fleming) hosted a one-hour webinar that provided an overview of existing content, an introduction to making edits, and a breakdown of the content moderation process. The webinar had more than 340 registered attendees. A webinar recording is available on ASDSO's YouTube channel at **Youtube.com/@DamSafety**.

- Keil Neff (U.S. Army Corps of Engineers) helped maintain a website demo area at the ASDSO Southeast Regional Conference.

- Greg Richards presented at the United States Society on Dams annual conference.

FEBRUARY

- Mark Killgore (Virginia Dam Safety) included information about the Dam Safety Toolbox during his keynote speech at the FEMA National Dam Safety Program's Annual National Dam Safety Program Technical Seminar.

Ohio Department of Natural Resources Booth at the Ohio Stormwater Conference

In Memory of Jay Thom

Jason "Jay" Thom passed away on May 2, 2024. Dan Hartel (Engineering Solutions) and Russ Reed (DOWL) shared the following tribute:

"It is with profound sadness we announce that the dam safety community recently lost one of our great engineers - Jay Thom. For those of us who knew Jay, this loss cuts deep. Jay was heavily involved in dam engineering across the western states for over the past 40 years; he was a champion for dam safety in Montana and a contributing member to the national dam safety community, including serving on committees for ASDSO and USSD. He had a gift for filtering through large amounts of data and assessing project sites with challenging topographic constraints to identify creative and elegant solutions. However, despite his undeniable technical strengths, his greatest contribution to society stemmed from his passion for people. Jay always had the time to engage with and mentor those around him. He embraced the concept of knowledge transfer, and his mantra was "we're not in the business of developing projects, we're in the business of developing exceptional engineers, and projects are the vehicle by which we do that." Beyond his professional life, Jay was deeply committed to his family and his faith. As the father of seven children, he made the time to coach sports and be a positive role model for his family. He was also actively involved with his church, including serving on missions to South America to share his faith and work to improve the quality of life in impoverished areas.

His passion, integrity, and strength of character are an inspiration to those of us who had the privilege to know him. The dam safety community is stronger, and our lives are richer, because of Jay's contributions to society. We will miss you, Jay."

ASDSO DAM SAFETY TOOLBOX

LEARN

The Dam Safety Toolbox helps professionals quickly gain an understanding of dam safety basics. Anyone can easily access current state-of-the-practice guidance and resources through the website.

EDIT

The website is maintained by knowledgeable volunteers through open collaboration and a wiki-based editing system. ASDSO members can suggest edits to existing pages or begin the development of a new page.

VOLUNTEER

ASDSO members can volunteer as moderators, subject matter experts, or study group members. Volunteers help develop content, review and approve edits, and help to maintain the reliability and consistency expected from an ASDSO product.

DAMTOOLBOX.ORG

TOOLBOX@DAMSAFETY.ORG

Thanks for Your Support on May 31st

On May 31st, ASDSO recognized National Dam Safety Awareness Day and Membership Appreciation Day. Many of our members, both individuals and organizations, joined us in sharing awareness messages on social media and through emails. Many others helped us celebrate by sharing thoughts on Collaborate and joining our free member webinar, where panelists shared many perspectives on building a career in dam safety. Thank you to everyone who contributed to making this day a success!

Thank you to panelists Ryan Stack, Kate Naughton, Gavin Tasker, Erin Gleason, Michelle Yezierski, and moderator Mia Kannik for an insightful conversation!

The widest range of geophysical and seismic techniques services and technologies to address non-invasive investigation and the maintenance and monitoring of Dams Embankments and Levees

DAM SAFETY GROUP ©

The member companies of the **Dam Safety Group** offer proven solutions for the evaluation and monitoring of safety and subsurface ground characterization issues for new build or existing Dams and related hydrological projects, together with market-leading real-time seismic Earthquake Early Warning Systems supported by a wide range of alerting technologies.

- *Non-invasive or destructive techniques*
- *Regular monitoring of the Dam*
- *Early warning detection of geotechnical problems*
- *Assists the design and build of remedial projects*
- *Assists to assess remedial work after completion*
- *Identifies damaged areas within the body of the Dam*
- *Locates fractures, voids and zones of seepage*

Resistivity Imaging
IRIS INSTRUMENTS

Seismic Tomography
GEOMETRICS
Simplify your search

Ground Penetrating Radar (GPR)
GSSI

Wireline Borehole Logging
ROBERTSON GEO
Unlocking Your GeoData

Seismic Monitoring
KINEMETRICS
Advancement through Innovation

www.damsafetygroup.com

DAM SAFETY GROUP ©

ADVERTISING RATES AND INSERTION

The Journal of Dam Safety accepts advertising. Because of its status as a charitable, educational institution and because of postal laws regarding postage rates for nonprofit organizations, ASDSO cannot accept advertising from insurance, travel, and credit card companies.

ASDSO Sustaining Members receive 25% off Full and Half page ads.

For complete information on advertising rates, visit www.damsafety.org/advertise, or contact Ross Brown, rbrown@damsafety.org, (859) 550-2788.

Advertising Index

Thank You to Our Sustaining Members
& the 50 State Dam Safety Program Members

*As of June 1, 2024

» Learn about becoming a Sustaining Member at **DamSafety.org/Sustaining**

UNIT CONVERSIONS

It is intended that articles in the ASDSO *Journal of Dam Safety* be in English measurements. In order to assist our international partners in dam safety, we also want to include the international SI system of measurements.

Length Conversions

1 Inch (in) = 25.40 Millimeter (mm)
1 Feet (ft) = 30.48 Centimeter (cm)
1 Feet (ft) = 0.3048 Meter (m)
1 Yard (yd) = 0.9144 Meter (m)
1 Mile (mi) = 1.609 Kilometer (km)

1 Millimeter (mm) = 0.04 Inch (in)
1 Centimeter (cm) = 0.03 Feet (ft)
1 Meter (m) = 3.281 Feet (ft)
1 Meter (m) = 1.094 Yard (yd)
1 Kilometer (km) = 0.621 Mile (mi)

Mass Conversions

1 Pound-Mass (lbm) = 453.6 Gram (g)
1 Pound-Mass (lbm) = 0.4536 Kilogram (kg)
1 Ounce (oz) = 28.35 Gram (g)
1 Slug = 14.59 Kilogram (kg)

1 Gram (g) = 0.0022 Pound-Mass (lbm)
1 Kilogram (kg) = 2.2046 Pound-Mass (lbm)
1 Gram (g) = 0.04 Ounce (oz)
1 Kilogram (kg) = 0.07 Slug

Force Conversions

1 Pound-Force (lbf) = 4.448 Newton (N)
1 Kip = 1000 Pound-Force (lbf)
1 Ton = 2000 Pound-Force (lbf)
1 Ton = 4.448 Kilonewton (kN)
1 Kip = 4448.2 Newton (N)

1 Newton (N) = 0.2248 Pound-Force (lbf)
1 Pound-Force (lbf) = 0.001 Kip
1 Pound-Force (lbf) = 1x10^{-4} Ton
1 Kilonewton (kN) = 0.1020 Ton
1 Newton (N) = 2.23x10^{-4} Kip

Pressure and Stress Conversions

1 lbf/Inch^2 (psi) = 6.89 kilopascal (kPA)
1 Atmosphere (atm) = 1.01^{3}x105 Newton/meter^2

1 Pascal (Pa) = 1.45x10^{-4} lbf/Inch^2 (psi)
1 Newton/meter^2 = 9.87x10^{-6} Atmosphere (atm)

Area Conversions

1 Inch^2 (in^2) = 6.451 Centimeter^2 (cm^2)
1 Foot^2 (ft^2) = 0.0929 Meter^2 (m^2)
1 Yard^2 (yd^2) = 0.836 Meter^2 (m^2)
1 Mile^2 (mi^2) = 2.590 Kilometer^2 (km^2)
1 Mile^2 (mi^2) = 640.0 Acre

1 Centimeter^2 (cm^2) = 0.1550 Inch^2 (in^2)
1 Meter^2 (m^2) = 10.76 Foot^2 (ft^2)
1 Meter^2 (m^2) = 1.196 Yard^2 (yd^2)
1 Kilometer^2 (km^2) = 0.386 Mile^2 (mi^2)
1 Acre = 0.0016 Mile^2 (mi^2)

Volume Conversions

1 Inch^3 (in^3) = 16.39 Centimeter^3 (cm^3)
1 Foot^3 (ft^3) = 0.0283 Meter^3 (m^3)
1 Yard^3 (yd^3) = 0.764 Meter^3 (m^3)
1 Pint = 0.473 Liter (L)
1 Gallon = 3.785 Liter (L)
1 Acre-Foot (acre-ft) = 1233 Meter^3 (m^3)

1 Centimeter^3 (cm^3) = 0.0610 Inch^3 (in^3)
1 Meter^3 (m^3) = 35.31 Foot^3 (ft^3)
1 Meter^3 (m^3) = 1.308 Yard^3 (yd^3)
1 Liter (L) = 2.113 Pint
1 Liter (L) = 0.2642 Gallon
1 x106 Meter^3 (m^3) = 811 Acre-Foot (acre-ft)

Velocity Conversions

1 Feet/Second (fps) = 0.3048 Meter/Sec (m/s)
1 Miles/Hour (mph) = 1.609 Kilometer/Hr (km/s)

1 Meter/Sec (m/s) = 3.281 Feet/Second (fps)
1 Kilometer/Hr (km/s) = 0.6214 Miles/Hour (mph)

Flow Conversions

1 Gallons/Minute (gpm) = 0.0022 Foot^3/Second (cfs)
1 Acre-feet/Second = 1233.48 Meter^3/Sec (cms)
1 x10^6 Gallons/Day (mgd) = 1.547 Foot^3/Second (cfs)

1 Foot^3/Second (cfs) = 450 Gallons/Minute (gpm)
1 Meter^3/Sec (cms) = 35.32 Foot^3/Second (cfs)
1 Foot^3/Second (cfs) = 0.65 million gallons per day

Temperature Conversions

n Celsius (°C) = ([°Fahrenheit]-32)/1.8
n Kelvin (°K) = ([°Fahrenheit]+459.7)*(5/9)

n Fahrenheit (°F) = [°Celsius]x1.8+32
n Fahrenheit (°F) = [°Kelvin]x(9/5)-459.7