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Identifying Critical Waterway Infrastructure and Managing Risk Associated with Natural Disasters

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1 Project Description

1.1 Introduction

The transportation system in the U.S. is extremely vulnerable to disruptions and delays from natural disasters. Recently, record hurricane and flooding events have impacted urban transportation and strained the coastal and maritime transportation infrastructure like never before and exposed the fact that much of the infrastructure (e.g., levee systems, ports, locks and dams) is well beyond its design life and in need of maintenance, repair, and improvement. Additionally, agencies are looking to ease modal congestion in urban areas (during extreme events, but also in general) by shifting more freight movement to marine "highway" routes. Increased use of these inland waterway routes means an increase in the risk of failure during future extreme weather events. To reduce the risk, proper maintenance and improvements are required; however, there is currently a backlog of maintenance projects due to a lack of funds available and difficulty in identifying and prioritizing the most critical infrastructure. There is a need for an assessment strategy capable of capturing the risk of failure while also accounting for the associated economic impacts for maritime and inland waterway infrastructure subjected to natural disasters.

One particular maritime transportation infrastructure system that has been hit hard in recent years by natural disasters and floods are levees. Levees are earthen embankments and floodwalls that reduce the risk of flooding in an area and they can serve as a perfect test case for risk evaluation and the development of an assessment strategy capable of incorporating maintenance prioritization and resulting economic impacts. The Levee Safety Action Classification (LSAC), as recorded in the National Levee Database (NLD), communicates the risks associated with living or working behind a particular levee. The LSAC serves as a risk classification system or tool and assists local, state, and federal stakeholders in identifying risk and making informed risk-based decisions. The LSAC classification considers the probability of the loading (hazard), the existing condition of the levee and any current or future maintenance of the levee (resistance or performance), and the consequences if a levee were to fail or be overwhelmed (USACE, 2018). The LSAC classification is heavily weighted towards the consequences with two of the main criteria being population and property value. This means that a particular levee that has a densely populated and/or significantly developed leveed area may be deemed high risk despite its performance or infrastructure health. Or, two levees expected to have the same loading and performance may receive two very different LSAC ratings because of the consequences associated with failure. While the LSAC system is a great communication tool, it can cloud some of the aspects related to levee condition and performance and prioritization of maintenance and improvement activities. The LSAC classification also does not consider any economic disruptions (i.e., disruptions to supply chain) that may occur from a breach or overtopping. These are in addition to the property damage, but in some locations the loss of revenue from disruption can have significant costs associated with it.

Multi-criteria decision making (MCDM) methods provide a systematic framework to examine infrastructure failure and evaluate the effects or consequences associated with various scenarios.

This assessment strategy can aid decision makers in determining a weighting for each criterion and then identifying the most critical transportation infrastructure. This prioritization process will assist mitigation and maintenance decision making, ensuring the most efficient use of the available funds.

1.2 Motivation

The U.S. floodway system and flood-related infrastructure have been continuously adapted to respond to changing weather conditions and urban development. Prior to 2005, most of the flood-related failures occurred in low-risk rural areas, primarily affecting agricultural interests. However, Hurricane Katrina in 2005 marked a significant turning point, as it resulted in the first major failure in an urban environment. Over 80% of the city was submerged, leading to an estimated \$16.5 billion in damages and tragically claiming the lives of more than 1,118 individuals (ASCE, 2007). This catastrophe, considered the costliest U.S. natural disaster to date, with over \$167.5 billion in total costs, exposed the vulnerability and increased risk associated with levee systems surrounding rapidly growing urban developments. In 2008, two more flood-related disasters occurred in the Midwest, causing an estimated \$538 million in damages. Then, in 2011, record water levels resulted in over \$2 billion in damages and repairs (ASCE, 2017). Superstorm Sandy in 2012 incurred estimated costs of over \$73.5 billion. In 2017, the U.S. faced a trifecta of devastating storms: Hurricane Harvey, resulting in over \$130 billion in overall costs; Hurricane Maria, totaling over \$93.6 billion; and Hurricane Irma, costing more than \$52 billion (Kiplinger, 2020). Out of the top 10 most costly U.S. natural disasters on record, eight have occurred within the last two decades. As urbanization continues to expand, the costs associated with these types of extreme events will undoubtedly continue to escalate.

In addition to the physical damage inflicted upon infrastructure, a substantial portion of the costs associated with these storm events stems from disruptions to the transportation system. Previous studies have undertaken the quantification of both direct transportation economic impacts resulting from highway network disruptions (Mesa-Arango et al., 2016) and the subsequent indirect economic consequences (Pregnolato et al., 2017; Mesa-Arango et al., 2013). Among all the potential disruptors, natural disasters have emerged as the most formidable, with flooding yielding the most devastating effects to date. While these studies have estimated the direct and indirect economic impacts on the transportation network, including the intermodal freight system, a research gap exists in examining the association between transportation infrastructure, transportation network disruption, and economic impact due to natural disasters. Consequently, there is an imperative need to identify critical transportation modal locations and types vital to the U.S. economy and to comprehend how these nodes will be affected by natural disasters.

Furthermore, there is a pressing need for the development of an assessment strategy capable of gauging the probability of failure and the associated economic impacts for maritime and inland waterways infrastructure when subjected to flooding and other natural disasters. An effective framework should encompass the most critical modal locations for the U.S. transportation system and economy (i.e., consequences of failure) and assess the conditions of the supporting infrastructure (i.e., probability of failure). The research endeavor presented herein aims to foster the creation of a more resilient transportation system overall, ultimately mitigating the economic and societal impact of flooding and other natural disasters.

1.3 Project Goals and Objectives

The overall goal of this research is to develop a risk assessment framework that can be used to prioritize maintenance and identify maritime infrastructure which is most critical to the U.S. transportation system and economy. This study specifically seeks to demonstrate how a multi-criterion ranking framework, integrating Principal Component Analysis (PCA) and Multi-Criteria Decision Making (MCDM) methods (i.e., a CRITIC-TOPSIS approach), can be implemented to identify critical maritime infrastructure that are essential for ensuring safety and reducing economic loss in a given area. The levee systems within the state of Arkansas are used as an example infrastructure set and the criterion were chosen from the National Levee Database (NLD) along with other existing databases.

The following research objectives were achieved:

1. Review and identify the MCDM methods or combination of methods most suitable for infrastructure maintenance prioritization.
2. Evaluate methods for obtaining criteria weighting and develop a survey to incorporate expert opinion.
3. Implement the chosen MCDM methods and set of criteria based on the information collected from NLD to rank levee systems within Arkansas. Parametric studies were also performed to determine how sensitive the ranking system was to different criterion weightings.
4. Recommend a path forward for implementation and further development of the framework and its application to other maritime infrastructure.

2 Literature Review

2.1 Weather and Natural Disaster Databases

Since 1980, the United States has experienced a staggering total of 258 weather and climate-related disasters where damages surpassed the $1 billion threshold (Smith, 2019). This situation is illustrated in Figure 1, which clearly demonstrates a significant increase in both the number of these events and the associated damages over the past decade. Remarkably, in 2019 alone, 14 separate disasters exceeded the billion-dollar mark, marking the fifth consecutive year with 10 or more such events. While there is compelling evidence indicating that more extreme weather events are occurring with greater frequency (NCA, 2018), a substantial portion of the escalation in damage costs can be attributed to the fact that these events are increasingly affecting large urban centers rather than rural areas. As a result, not only will a larger portion of the population be exposed to natural disasters in the near future, but the impact on infrastructure and the economy will also intensify.

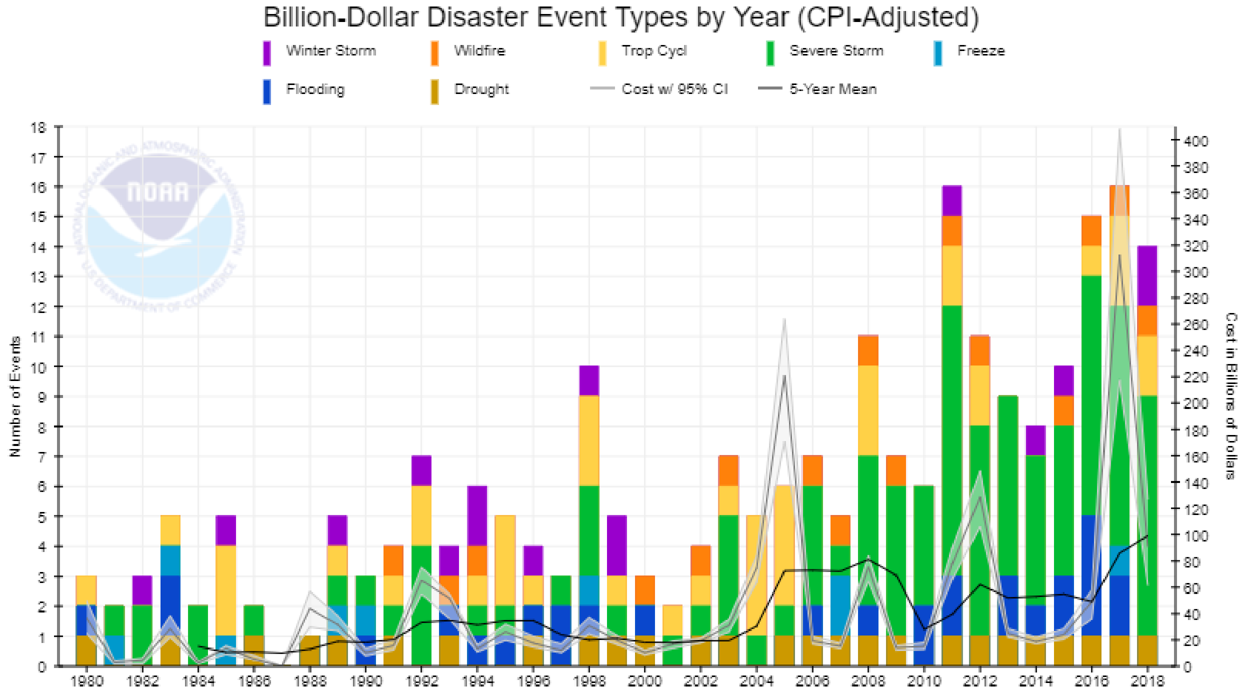
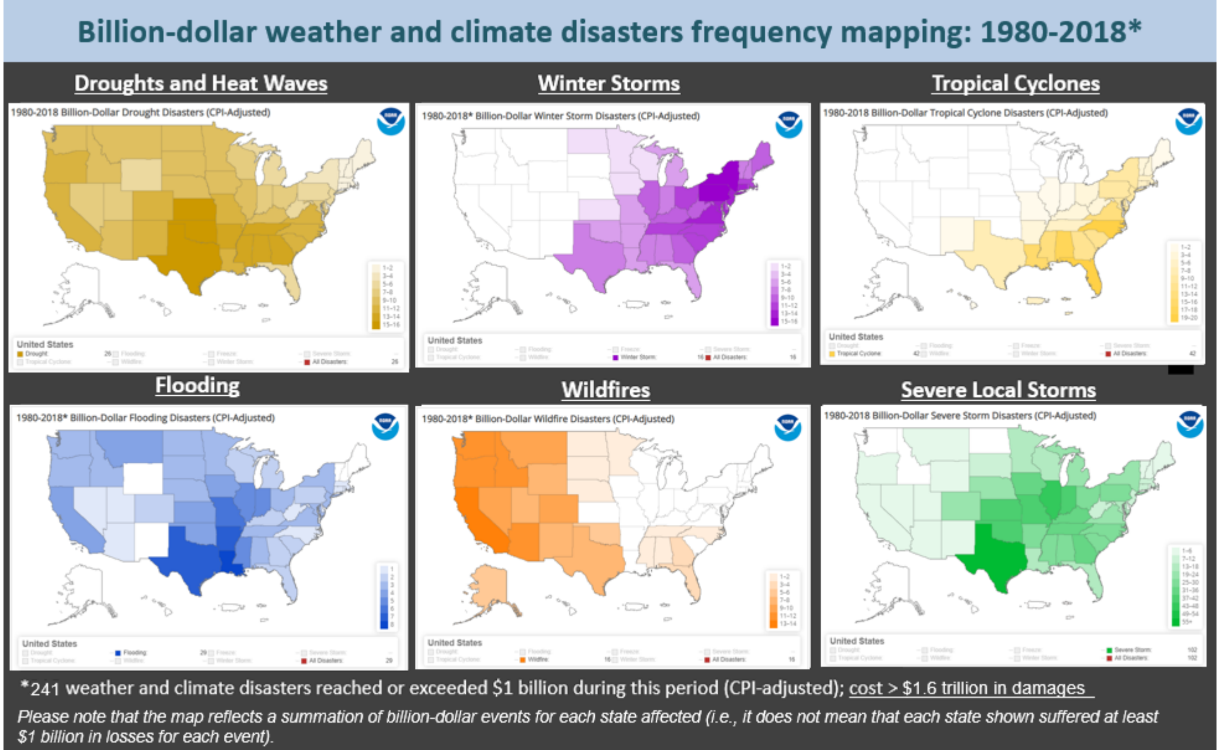


Figure 1 Summary of Events between 1980 and 2018 which totaled over $1 billion in losses (Smith, 2019)

To effectively assess and prepare for the future, it is imperative to develop risk assessment strategies capable of accommodating the evolving climate, urbanization patterns, and economic dynamics. Often, conventional natural disaster risk assessments treat the three core components (hazard, exposure, and vulnerability) as static entities. In reality, these components are highly dynamic, and a risk assessment that remains fixed in the present can swiftly become obsolete (GFDRR, 2016). Francis Ghesquiere, Head of the Global Facility for Disaster Reduction and Recovery, emphasizes the importance of shifting towards risk assessments that guide decision-makers toward a resilient future. What is needed is a framework that can incorporate these dynamic changes and facilitate mitigation and preparedness strategies.

Assessing risk and understanding the probability associated with hazards necessitates the ability to quantify the spatial occurrence (i.e., frequency) of severe weather events and natural disasters. Figure 2 presents spatial frequency plots categorizing billion-dollar natural disasters from Figure 1 into droughts, winter storms, hurricanes (i.e., tropical cyclones), flooding, severe storms, and wildfires. Both figures highlight that hydraulic and wind-related events, such as severe storms, flooding, and hurricanes, constitute the majority of events and damage costs. This invaluable data can be sourced from organizations like the National Oceanic and Atmospheric Administration (NOAA), the National Weather Service, and the U.S. Geological Survey (USGS). Geographical Information System (GIS) software like ArcGIS facilitates the compilation of this data into visually informative maps and figures, which can also be made interactive. While there are numerous examples of such plots and maps in the literature, they often focus on specific years, disaster types, or, as seen in this figure, a limited set of disasters. Consequently, there is an urgent need for a comprehensive database that consolidates data from multiple sources, offering yearly hydraulic and disaster data nationwide. Spatially understanding this data is also immensely valuable for informing the other two components of risk assessment: exposure and vulnerability. These components are closely linked to the consequences of risk and are directly tied to the layout of infrastructure and the urban environment, as well as their susceptibility to natural hazards.



*241 weather and climate disasters reached or exceeded $1 billion during this period (CPI-adjusted); cost > $1.6 trillion in damages

Please note that the map reflects a summation of billion-dollar events for each state affected (i.e., it does not mean that each state shown suffered at least $1 billion in losses for each event).

Figure 2 Frequency plot showing spatial distribution of $1 billion disasters from 1980-2018 (Smith, 2019)

2.2 Infrastructure in the U.S. and Available Databases

2.2.1 U.S. Transportation System and Freight and Commodity Databases

The U.S. transportation system comprises several vital components, including coastal ports and waterways, inland waterways, rail networks, and highway routes. The United States boasts approximately 25,000 miles of inland, intracoastal, and coastal waterways and channels, with the U.S. Army Corps of Engineers (USACE, 2024a) responsible for maintaining roughly 12,000 miles of this extensive system. Within these navigable waterways lie numerous locks and dam systems, along with essential offload and terminal facilities that play a crucial role in facilitating the movement of goods across the nation. At these terminal facilities, commodities are unloaded from barges and transferred to rail and truck transport for further distribution. Similar to many elements of infrastructure in the United States, several locks and dam systems and port facilities have considerably surpassed their intended design life and are thus increasingly susceptible to natural disaster events.

The Federal Highway Administration (FHWA) has developed a sophisticated Freight Analysis Framework that integrates multimodal freight flow data from diverse sources, offering a comprehensive overview of freight movement throughout the United States. This framework incorporates freight data from various sectors, including agriculture, extraction, utilities, construction, and services. Users can readily download and analyze this data to generate customized traffic flow maps and figures. A notable example of the utility of this framework and data can be found in the work of Tang and McHale (2016), who produced the map featured in Figure 3. This map illustrates the tonnage of goods transported across the various transportation networks within the United States. Intriguingly, the primary routes responsible for carrying the majority of tonnage across the nation frequently intersect with regions that are more susceptible to disaster events. In other words, the maps depicting flooding, cyclone, and storm frequencies from Figure 2 closely correspond to the areas with the highest tonnage (indicated by the thickness of lines) on the map in Figure 3. One critical dataset not visualized in either of these figures pertains to the current health assessment and condition of the associated transportation infrastructure, including its vulnerability to the aforementioned hazards. While a map providing this overlay data is not currently available, such a comparison and overlay would prove immensely valuable for decision-makers, and this research study presented herein suggests many benefits of its development.

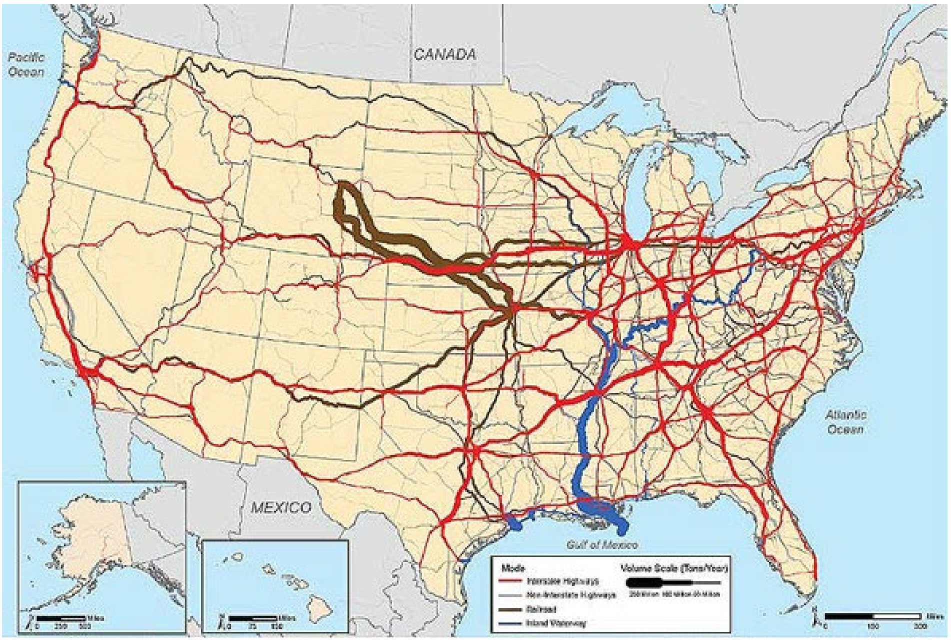


Figure 3 Map of tonnage transported on inland waterways, rail, and interstate highway (after Tang and McHale, 2016)

A number of port related databases also exist which contain information regarding the locations, tonnage, and types of commodities transferring through the U.S. navigable waterways and ports. The USACE maintains the Transportation Operational Waterborne Statistics (TOWS) database which provides information on the movement of foreign and domestic vessels and commodities within the U.S. (USACE, 2024b). Figure 4 presents an example of TOWS data which include information on navigation points, the usage of waterway ports, and USACE projects. They also manage the Lock Performance Monitoring System (LPMS) which tracks the vessels moving through Corps-owned or operated lock structures. Data is reported near real-time in 15 minute intervals and provides a snapshot of the U.S. and foreign vessels operating in U.S. waterways. While the specific companies and commodities are not available to the general public, they are available to the USACE and can serve as a very useful dataset on economic disruptions due to weather or disaster events. The Department of Transportation Bureau of Transportation Statistics (BTS) and the USACE facilitate the development and management of National Geospatial Data Asset (NGDA) datasets which depict various transportation networks within the United States and Puerto Rico. The maritime transportation related assets include the Freight Intermodal Facility, Intermodal Passenger Connectivity, North American Rail Lines, North American Rail Nodes, Waterway Locks, Ports, Navigable Waterway Routes, and Navigable Waterway Nodes (FGDC, 2024). The Ports NGDA (ArcGIS, 2022) for example utilizes data from the BTS to depict on a GIS layer the major ports in the U.S. and Puerto Rico by total tonnage summaries for the year (total tons, domestic, foreign, imports and exports). This type of data can be extremely valuable in aiding the quantification of economic impact along a waterway; however, much of this information is not currently used in a levee risk assessment.

Figure 4 Example of map from the Transportation Operational Waterborne Statistics (TOWS) database

In many cases, exposure and vulnerability can be viewed as economic impacts related to either the costs of damages or repairs, or the disruptions to the system. Some of the most substantial impacts on the economy during and after natural disaster events stem from damages to transportation infrastructure and interruptions in supply chains and services. To comprehensively assess this aspect of risk, it is essential to quantify and analyze the health and vulnerability of the transportation system and associated infrastructure in conjunction with the hazard data previously described.

2.2.2 Levee Systems

Transportation waterways are often lined with levee systems that have endured significant stress over recent decades. A levee is an embankment, or a floodwall built along the banks of rivers, lakes, or other bodies of water to prevent water from overflowing onto adjacent land (National Geographic, 2023). Levees play a crucial role in mitigating flood risks and protecting human lives and infrastructure in flood-prone areas. Across the USA, approximately 17 million individuals reside or work in areas protected by these structures. Levees act as risk reduction structures, shielding valuable infrastructure, which amounts to $2.3 trillion in property value, along with 4,500 schools attended by over 2 million students, and various industries (ASCE, 2021). According to the most recent risk assessment, the current findings indicate that a mere 4% of levees within the USACE portfolio are classified as high or very high-risk. However, it is worth noting that while most levees in the portfolio are deemed low-risk, approximately 45% of the population resides or works in areas protected by high- or very high-risk levees. In fact, the reason these levees are deemed as high- or very high-risk is because of the significant percentage of the population that would be affected by a failure.

The effectiveness of levee systems heavily relies on regular and appropriate maintenance practices The USACE estimates that improving and maintaining the moderate to high-risk levees within their portfolio, which account for only 15% of the estimated 100,000 miles of levees in the country, would require an investment of $21 billion (ASCE, 2021). Even worse, the condition of the remaining 85% of levee systems in the U.S. is largely unknown. Given the rising occurrence of extreme weather events that result in increased flooding, such as the $20 billion worth of damages caused by the Midwest flooding in 2019, it is imperative to identify the critical levees and to establish a maintenance prioritization plan based on the limited available resources. Consequently, there exists a compelling need for a comprehensive risk assessment system or framework capable of incorporating the condition, or "health," of maritime infrastructure alongside the probability of encountering a hazard.

2.2.2.1 Levee Management Datasets

The National Levee Database (NLD) is a congressionally authorized database that is maintained by the USACE. The NLD contains information about the location and characteristics of approximately 2,000 levee systems that fall under the USACE and FEMA programs. The NLD contains levee characteristic data such as length and height, as well as values related to the risk associated within a particular leveed area calculated by the USACE such as property value, annual exceedance probability (AEP), and population.

Table 1 presents a list of some of the publicly available levee attributes contained in the NLD that are most relevant to this study. Appendix A contains tables detailing the full sets of attributes available for various data category types. Note that many of these attributes do not have data recorded and it is not clear in many of these categories whether there is zero occurrence (or issues) or if there is just missing data.

Table 1 Example list and description of attributes found in the National Levee Database (NLD)

Attribute	**Description**
Levee System ID	Unique ID number given to each levee system
Name	Name of the levee system
Segment Count	Number of segments comprising the levee system
Levee Length	Length of levee in miles
Closure Count	Number of closures along levee system length
Population	Number of people estimated to live and/or work in the leveed area
Number of Buildings	Number of buildings estimated within the leveed area
Property Value	Property value of infrastructure estimated within the leveed area
Annual Exceedance Probability (Overtopping)	Probability of a flood overtopping the levee in any given year
Distress Points	Number of distress points identified
Encroachments	Number of encroachments through levee system
Year Constructed	Year levee was constructed
LSAC Rating	Levee Safety Action Classification Rating (communicates risk)
Risk Assessment Date	Date of LSAC determination
Last Inspection Date	Last date of inspection
Pump Stations	Number of pump stations within leveed area
Flood Walls	Number of flood walls along levee system
Relief Wells	Number of relief wells installed within leveed area
Toe Drains	Number of toe drains along levee system
Pipes	Number of pipes located within levee system
Flood of Record Date	Date of historical flood on record
FEMA Accredited	Identifies whether levee system is accredited by FEMA
Leveed Area	Area in square miles behind or adjacent to the levee system (“protected” area)
Rehabilitation and Inspection Program (RIP) Status	Identifies whether the levee system is active in a RIP
Last Edited	Date for last edits to levee NLD record

2.2.2.2 Current USACE Risk Classification Methods

The Levee Safety Action Classification (LSAC) is a part of the NLD that communicates the risks associated with living behind a particular levee and assists local, state, and federal stakeholders in identifying and prioritizing funding needs. LSAC is a classification system that identifies risk by considering three different criteria: hazards (the probability of a levee being breached), performance (how a levee system performed in the past, also how it is expected to perform in the future) and consequences (the number of people and infrastructure that would be impacted when an event exceeds design capacity). Figure 5 shows a schematic describing the components of risk used in the LSAC rating determination (USACE, 2023).

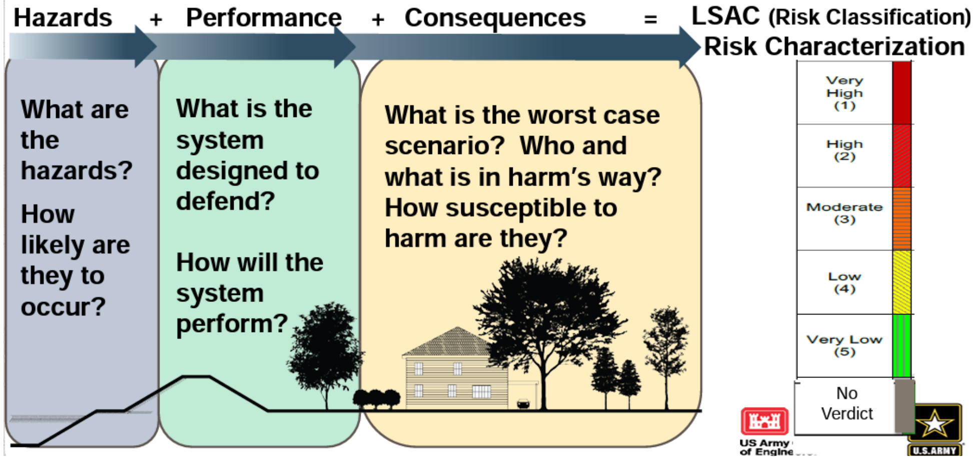


Figure 5 Schematic describing the three components of LSAC risk determination ratings (USACE, 2023)

There are six levels of the LSAC classification system, as described in Table 2. A levee that reduces the risk for a dense population will receive a different classification from another similarly constructed levee with a smaller population because its consequences of failure are more significant. Very Low or Low LSACs indicate extremely low consequences of failure. It is still possible, however, for a levee system with these ratings to have performance and maintenance issues. They just are not considered high risk because there are relatively low potential consequences. In contrast, a well-maintained levee system with perfect performance can often be assigned a high-risk rating if the area adjacent to the levee is populated, developed, or has critical infrastructure (e.g., first responder or emergency services, hospitals, water treatment plants, schools). It is expected that the LSAC rating will decrease as flood risk decreases. However, in some cases, the LSAC rating for a particular levee may remain the same despite its performance or infrastructure health when the leveed area is densely populated or significantly developed.

Table 2 LSAC definitions

Level	Description
Very High (1)	Likelihood of inundation due to breach and/or system component malfunction in combination with loss of life, economic, or environmental consequences results in very high risk.
High (2)	Likelihood of inundation due to breach and/or system component malfunction in combination with loss of life, economic, or environmental consequences results in high risk.
Moderate (3)	Likelihood of inundation due to breach and/or system component malfunction in combination with loss of life, economic, or environmental consequences results in moderate risk.
Low (4)	Likelihood of inundation due to breach and/or system component malfunction in combination with loss of life, economic, or environmental consequences results in low risk.
Very Low (5)	Likelihood of inundation due to breach and/or system component malfunction in combination with loss of life, economic, or environmental consequences results in very low risk.
No Verdict	Not enough information is available to assign Risk

It is notable that USACE uses the LSAC as a basis to prioritize funding needs and proceed with further actions related to levees (USACE, 2023). Due to a limited maintenance budget, the levees with high failure consequences may take up most of the budget, leaving others that might need maintenance to be degraded until they fail. The LSAC also does not account for any economic impact or disruptions to the transportation network and supply chain that may result from a failure. Therefore, we are motivated to develop indicators that are more robust than LSAC for assessing maintenance needs and funding.

2.2.3 Risk Management Frameworks and Methods

Many studies have been conducted regarding different types of maritime infrastructure, such as ports, locks & dams, etc., which face continuous exposure to harsh environmental conditions, posing significant challenges to their maintenance and durability. Several aspects of maritime infrastructure maintenance are explored, including methodologies, technologies, and best practices for ensuring these vital assets' structural integrity and operational efficiency. Mokhtari, et al. (2011) proposed a Risk Management (RM) framework specifically tailored for seaports and offshore terminals operations and management (PTOM). The study incorporated a generic bow-tie-based risk analysis framework as the backbone of the risk assessment phase. Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) techniques were employed to analyze the risk factors associated with PTOM. This process enables port professionals and risk managers to conduct a detailed investigation into the identified risk factors. Kurth, et al. (2019) discussed the importance of a strategic corrosion management plan for owners and operators of ports and other maritime facilities. Maritime infrastructure is at high risk for corrosion-related damage over its service life due to harsh exposures and heavy usage that can degrade ordinary protective measures for reinforced concrete and steel elements. A corrosion management plan begins with understanding a few key items: identifying what infrastructure elements are present and should be inventoried, identifying what construction materials and corrosion protection measures are already in place, and understanding the nature and severity of environmental and usage-related exposures and impact on corrosion. Guignier et al. (1999) developed a Markov decision model that enables the joint optimization of maintenance and improvement activities. This model improves the budget allocation among facilities within the network, considering both sets of activities. Additionally, it allows for not fully utilizing the annual budget, enabling more efficient allocation in subsequent years. The paper included a case study of bridge deck maintenance, reconstruction costs, and transition matrices. There are two alternatives for maintenance (do-nothing and rehabilitation) and two for improvements (do-nothing and reconstruction). The results demonstrate that substantial cost savings can be achieved by jointly optimizing maintenance and improvement policies. This highlights the benefits of considering these decisions integrated, leading to improved resource allocation and overall network performance. Molina et al. (2017) proposed a Bayesian network for port operation planning and management. This research incorporated a comprehensive database comprising over 40 variables classified in the four sustainability port dimensions: environmental, economic, institutional, and social. A non-cyclic conducted graph was constructed using Bayesian

Networks to visualize the relationships between these port variables. Notably, economic variables emerge as the primary drivers in most cases, playing a central role in shaping the interdependencies among various port-related factors. Using Bayesian Networks provided insights into these relationships, enabling a better understanding of port operations and facilitating informed decision-making.

Maintenance of infrastructure systems is complex and requires careful allocation of limited resources. Levee maintenance prioritization specifically is inherently a multi-criteria problem because it involves consideration of various criteria when deciding which levees to prioritize for maintenance. These criteria can include the condition of the levees, their designs and past performance, their vulnerability to failure, and the potential consequences of failure. Each criterion carries a different weight or level of importance and decision-makers need to consider all the factors together to make informed decisions about which levees should receive maintenance first. Multi-criteria decision making (MCDM) methods can be used to prioritize infrastructure maintenance activities based on multiple criteria and MCDM techniques enable decision-makers to consider multiple factors simultaneously, such as asset condition, criticality, cost, environmental impact, and social considerations. By incorporating these diverse criteria, the method provides a comprehensive framework for evaluating and comparing maintenance alternatives objectively. This helps owner-operators make informed choices based on a holistic assessment of infrastructure needs. As a result, MCDM plays a pivotal role in project selection, leading to improved resource allocation and offering a range of additional benefits.

Broniewicz and Ogrodnik (2020) aimed to choose the most environmentally favorable option among variants of expressway sections in North-Eastern Poland. They proposed a hybrid approach in which both classic Analytic Hierarchy Process (AHP) and Fuzzy Analytic Hierarchy Process (FAHP) were used for factor weighting, while two other methods were used to develop final rankings: Technique for Order Preferences by Similarity to Ideal Solutions (TOPSIS) and Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE). The results of the conducted multi-criteria analysis almost overlap with the choice made in the analyzed environmental impact report.

Tee et al. (2016) proposed using Principal Component Analysis (PCA) and AHP as two alternatives for interpreting oil test data for transformer insulation in place of the traditional empirical formula (EF) used by asset managers. PCA demonstrates its potential in working directly with data to explore parameter relations as well as ranking transformers according to their conditions. AHP, on the other hand, presents a way to coherently aggregate criteria in a flexible hierarchical setup for identifying the weightage of the oil test parameters before the interpretation of measurements. The interpreted conditions based on PCA and AHP, along with a track-record proven EF, are similar, particularly for transformers at the extreme end of the insulation condition. Babatunde and Ighravwe (2019) aimed to determine a hybrid renewable energy source (HRESs) for a rural community using technical, economic, and techno-economic criteria, which combines the importance of criteria by linking the Criteria Importance through Inter-criteria Correlation

(CRITIC) and TOPSIS as a solution method. It is proposed that a combination of these methods may lead to the most robust decision making framework. Table 3 provides a list of each MCDM method proposed along with the pros and cons.

Despite the application of MCDM in some infrastructure maintenance applications, there remains a significant gap in research focusing specifically on utilizing MCDM to prioritize levee maintenance. This study aims to fill the research gap by focusing on levee maintenance, specifically by (1) examining different levee attributes and their importance rating as criteria, (2) exploring new techniques for ranking and prioritization, and (3) propose practical solutions for robust and sustainable levee maintenance practices.

Table 3 Pros and cons of each MCDM method

Methods	Pros	Cons
PCA	Reduces the noise in the data and produces independent, uncorrelated variables	The new variables created will have different meanings than the original dataset. (Loss of interpretability).
CRITIC	Assign a higher weight to a criterion with a higher contrast intensity and a higher conflict with other criteria.	Has a shortcoming in properly capturing the conflicting relationships between criteria, since it merely utilizes the Pearson correlation for this purpose. Studies indicate that this correlation does not always denote the actual relationships between criteria.
AHP	Easy to use; scalable; hierarchy structure can easily adjust to fit many sized problems; not data intensive.	In case the number of criteria or alternatives is high, the demanding pairwise comparisons may increase the complexity of the problem and decrease the consistency of pairwise comparisons
TOPSIS	Has a simple process; easy to use and program; the number of steps remains the same regardless of the number of attributes.	Its use of Euclidean Distance does not consider the correlation of attributes; it is difficult to weigh and keep consistency of judgment.

3 Methodological Approach

3.1 Levee Maintenance Assessment

The primary data used in this study came from the National Levee Database (NLD). As described previously, the NLD is published and maintained by the USACE and it includes information for approximately 2,220 levee systems across the United States. To conduct a more focused initial case study, we pulled information on approximately 115 levee systems, totaling approximately 2,060 miles of levees, within the state of Arkansas. Due to large gaps of missing data and the database's high level of non-standardization; however, only 76 levees were ultimately used, as they had the most complete information across a number of attributes.

This study considers 11 criteria relevant to flood fighting, design, construction, operation, maintenance, repair, and inspection. Note that more than 245 attributes are potentially recorded in the NLD, however, many fields are blank with no data. On inspection, the 24 attributes listed in

Table 1 were determined to be most relevant to levee maintenance, with 11 of these attributes being selected due to the completeness of the data. The levee attributes used, and their corresponding descriptions are presented in Table 4.

Table 4 Descriptions of the levee attributes used as the criteria in this study

Criteria	Abbreviation	Description
1. Average Height	H	The average height, in feet, of the entire levee system.
2. Buildings at risk	B	The estimated number of structures in the leveed area.
3. Days since last inspection	I	Days since the last time inspection was performed.
4. Levee length	L	The length, in miles, of the entire levee system.
5. Leveed Area (SQ miles)	SQ	Estimated area of a flood plain from which flood water is excluded by the levee system.
6. Population at risk	P	The estimated population within the leveed area.
7. Levee segment	S	A discrete portion of a levee system that is operated and maintained by a single entity. S represents the number of segments in the levee system.
8. Overtopping AEP	AEP	Probability of overtopping in a given year based on a hydrological interpretation of the likelihood of occurrence.
9. Property Value	PV	An estimated sum of the structure value, structure contents and vehicles in the leveed area. This value does not include land value, economic productivity loss or transportation infrastructure value (i.e., bridges, runways, roads.)
10. FEMA Accreditation Rating	AR	A rating by FEMA to determine whether the levee system meets the design, data, and documentation requirements
11. Inspection rating	IR	The rating is based on the levee inspection checklist, which includes 125 specific items dealing with operation and maintenance of levee embankments, floodwalls, interior drainage, pump stations, and channels.

We first examined the 11 criterion and their relationship to the LSAC rating using very simple multinomial logistic regression. The Levee Safety Action Classification (LSAC) provides a systematic, evidence-based estimation of the likelihood and consequence of existing and future risks associated with levee systems. LSAC ratings are used by USACE to prioritize resources across the portfolio and to organize widespread levee-related risk information into reasonably commensurate groupings for action. As described previously, the LSACs range from Very High risk (immediate action recommended) to Very Low risk (maintain routine activities) based on the combined assessment of probability of occurrence and the consequences of failure (e.g., population and property value). Although the levee safety tool is used to determine LSAC assignments, it was important as an initial evaluation to examine whether these criteria had an effect on the LSAC rating assigned by the USACE.

Table 5 Multinomial logistic regression results comparing the criteria to the USACE assigned LSAC rating

	LSAC	Coef.	Std. Err.	z	$P > \lvert z \rvert$	[95% Conf. Interval]	
High	Intercept	-174.50	8.10	-21.54	0.00	-190.373	-158.622
	Segment count	0.08	0.08	1.01	0.31	-0.07	0.23
	Miles	1.28	0.64	1.99	0.05	0.02	2.54
	Overtopping AEP	-0.27	0.27	-1.00	0.32	-0.80	0.26
	Leveed Area SQ Mile	-2.79	1.43	-1.95	0.05	-5.60	0.01
	Days since inspection	0.36	0.16	2.16	0.03	0.03	0.68
	Population	4.64	3.46	1.34	0.18	-2.14	11.42
	Property value	2.67	1.25	2.15	0.03	0.23	5.11
	Building risk	-3.78	3.32	-1.14	0.25	-10.29	2.72
	Average height	-0.26	0.14	-1.85	0.06	-0.53	0.01
	Inspection rating (Unacceptable)	129.64	10.60	12.24	0.00	108.88	150.41
	FEMA -Accredited	11.50	5.28	2.18	0.03	1.16	21.85
	FEMA - PAL	18.15	1.04	2.66	0.01	4.76	31.55
Moderate	Intercept	-2.77	2.35	-1.18	0.24	-7.37	1.83
	Segment count	-0.014	0.039	-0.362	0.72	-0.09	0.06
	Miles	0.205	0.113	1.817	0.07	-0.02	0.43
	Overtopping AEP	-0.010	0.057	-0.177	0.86	-0.12	0.10
	Leveed Area SQ Mile	-0.91	0.61	-1.49	0.14	-2.10	0.28
	Days since inspection	-0.006	0.019	-0.32	0.75	-0.04	0.03
	Population	0.76	0.78	0.98	0.33	-0.76	2.29
	Property value	0.06	0.41	0.15	0.88	-0.75	0.87
	Building risk	0.13	0.60	0.22	0.83	-1.05	1.31
	Average height	0.01	0.03	0.54	0.59	-0.04	0.07
	Inspection rating (Unacceptable)	-0.87	0.93	-0.93	0.35	-2.69	0.95
	FEMA -Accredited	1.24	6.83	1.19	0.24	-0.81	3.28
	FEMA - PAL	1.02	1.49	0.69	0.49	-1.90	3.93
(LSAC == low is the base outcome)			AIC: 108.4906		Residual Deviance: 56.4906		

From Table 5, the test statistic z is the coefficient ratio to the respective predictor's standard error, and the p-value describes how likely it is to find a particular set of observations if the null hypothesis were true. For a given alpha level, z and p values determine whether the null hypothesis that there is no relationship between the X variables and the Y variables can be rejected. For levees with LSAC ratings of high relative to low, for an *alpha* level of 0.05, we would conclude that criteria such as miles, leveed area square mile, days since the inspection, property value, inspection rating, and FEMA accreditation rating do affect the LSAC rating since their p-value is less than 0.05. For levees with LSAC ratings of moderate relative to low, none of the criteria have an effect on the LSAC rating since their p values are higher than 0.05. We would expect the same variables to have a similar effect for both categories of LSAC ratings; however, it is clear that the determination of LSAC value for a given levee is either more complex or has a level of subjectivity not captured in the multiple logistic regression analysis.

To test the multinomial logistic regression model's accuracies, we created a confusion matrix (Table 6) and calculated model accuracy (Table **7**) to categorize the predictions against the actual values. We can see that this model has a very fair accuracy of 83.58%, and only 16.42% of the time it misclassifies the LSAC rating. More specifically, the multinomial logistic regression model can correctly predict a low LSAC at 95% and a high LSAC at 86%; however, it does a poor job of predicting moderate LSAC ratings (accuracy of only 50%). In short, we can conclude that the levee safety tool used to determine the LSAC rating does not utilize many of the criteria provided in the NLD, and the exact algorithm for assigning the LSAC may require additional information that is not publicly available. We propose instead to determine a raking for the Arkansas levee systems through the use of PCA, as well as a combination of CRITIC and TOPSIS methods. The purpose of ranking is for maintenance prioritization using the given dataset. The final rankings will be compared to each other as well as with the LSAC rating. The proposed flowchart is presented in Figure 6.

Table 6 Confusion Matrix

	Low	High	Moderate
Predicted Low	42	1	8
Predicted High	0	6	0
Predicted Moderate	2	0	8

Table 7 Model Accuracy

	Low	High	Moderate
Predicted Low	0.95	0.023	0.18
Predicted High	0.0	0.86	0
Predicted Moderate	0.13	0	0.5

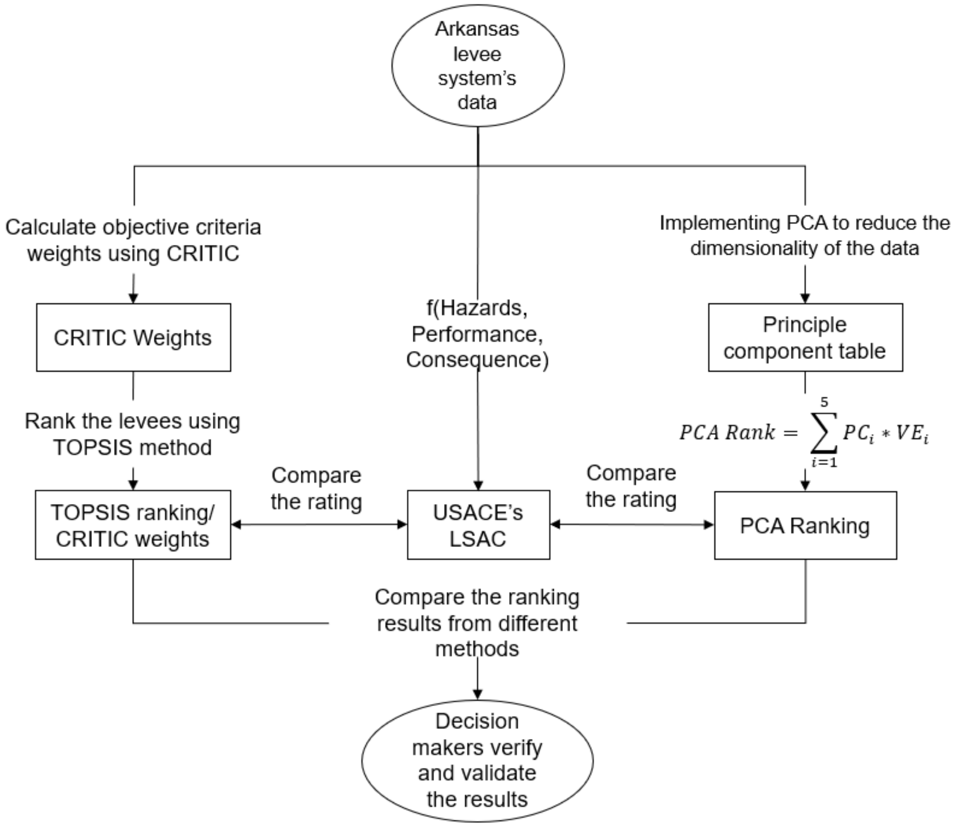


Figure 6 Flowchart detailing the proposed approach

3.2 Principal Component Analysis (PCA)

The PCA method is a multivariate technique that reduces the dimensionality of a set of interrelated variables while retaining the maximum possible variations present in the data set (Black et al. 2010). In this study, we used PCA to identify independence among different criteria (i.e., the distribution of one does not depend on the others). PCA transforms the columns of a dataset into a new set of features called principal components (PC). The principal components are obtained from a linear combination of the original variables. The first component has the largest possible variance; the second component is computed with the requirement of being orthogonal to the first components. The same requirement applies to the other components. The inertia assigned to each principal component is in decreasing order from the first component. Generally, the number of principal components coincides with the number of variables in the data set. Nevertheless, the magnitude of inertia carried by each component is used as a criterion to discard those components that do not describe much of the data variability. Therefore, the variable space is reduced to the significant, or relevant, feature space (Nema and Hussein, 2019). Combining the data from each column of the PC table with their corresponding amount of variance, we can complete an objective ranking for the levee systems in Arkansas and then compare it with rankings computed using other methods.

3.3 CRITIC Weights and TOPSIS Ranking

The CRITIC method is based on the standard deviation proposed by Diakoulaki et al. (1995), which uses correlation analysis to measure the value of each criterion. CRITIC is used as our primary method to calculate the objective weights of each criterion and eliminate possible bias associated with subjective evaluation. In addition, CRITIC considers both the contrast intensity and the conflicting relationship held by each decision criterion. In the CRITIC method, the standard deviation is used to measure the contrast intensity of each criterion, then distribute more weight to the one with a higher contrast intensity. The rationality is that it is reasonable to assume that a criterion whose scores differ more from one alternative to another will provide more exciting or meaningful information. So, from a decision-making perspective, such a criterion should be given more weight than criteria with homogeneous scores.

The criteria used in MCDM are often contradicting each other. The CRITIC method addresses the conflicting relationships among criteria using the Pearson correlation coefficient (Durmaz, 2020), which ranges between -1 and 1. When the coefficient is zero, it implies that the two criteria are independent of each other. Meanwhile, two criteria with a high positive coefficient share too much redundant information, thus not delivering extra value (Tus and Adali, 2019) and playing a smaller role in the decision-making process. By adhering to this principle, based on certain formulas, the CRITIC method ensures that a criterion with a higher degree of conflict or a lower degree of redundancy is assigned with a higher weight.

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method was first developed in 1981 by Yoon and Hwang on the assumption that there is an ideal and non-ideal solution. The chosen alternative should have the shortest distance to the positive ideal solution and the farthest distance to the ideal negative solution (Yoon and Hwang, 1981). The TOPSIS method has been applied in a wide variety of fields, including supply chain management, project management, decision making, risk analysis, and facility location, etc. For example, Wu et al. (2020) developed a safety risk evaluation model for building bridges in the marine environment. They used the CRITIC and TOPSIS methods to create this model. The authors established a system of 16 secondary indexes for evaluating construction safety risks in marine bridges, based on expert opinions and literature research. They used the CRITIC model to calculate the importance of each index and the TOPSIS model to assess the overall construction safety risk. The study focused on the Tangshan Zhongshan Bridge Project and identified the key technology scheme and important technologies with the highest significance. The bridge's construction safety risk was classified as medium, and the risk level was highest in spring. The findings from this case analysis aligned with real-world engineering practices, confirming the effectiveness of their proposed method. We propose that combining the TOPSIS method with the objective criteria weights from the CRITIC method will achieve a robust weighting and ranking scheme that can be compared to the PCA ranking method.

3.4 Subjective Weighting

Objective methods such as PCA and CRITIC-TOPSIS provide a way to analyze the problem based on features of the data and are not biased by any personal opinions. While this is often a useful option and important baseline, an analysis may also benefit from having expert opinion and input from personnel experienced in that area. For levee safety specifically, historical events and lessons learned could be very valuable in understanding the relationships between maintenance and risk. One goal of the project was to develop a survey that could be sent out to levee safety personnel, levee owners and operators, and engineers with expertise in this area. The feedback gathered in the survey can be used to develop weighting factors for the different criteria and develop a mechanism so that the framework can be updated with expert opinions and lessons learned from historical events. The preliminary set of survey questions are provided here and implementation of the survey will be an ongoing task as we continue future research in this direction.

Levee Maintenace Survey

Introduction and Purpose: Levee systems are intended to reduce flooding risk for urban and rural communities. Recurring flooding and levee failures have highlighted the need to take a proactive approach to maintenance, yet funding is limited, and the prioritization of repair or improvement activities is a complex balance of probability of occurrence and the associated consequences of failure. Our study seeks to develop a multi-criteria decision-making framework capable of prioritizing levee maintenance and identify critical levee systems based on criteria related to the (1) likelihood of flooding, (2) anticipated performance or condition of the levee, (3) consequences of failure, and (4) economic impacts associated with flooding and levee failure. A key aspect in developing this framework is identifying the importance of each criterion as they relate to maintenance decisions and maintenance prioritization (i.e., allocation of funds for repairs or improvements as well as annual maintenance expenditures). We would like to request your help as a levee expert in completing this survey. Thank you in advance for your time and for helping us advance our understanding of levee management.

Many of the criteria of interest in this study come from the National Levee Database (NLD) because of its availability and common use by levee owners/operators, the Federal Emergency Management Agency (FEMA), and the U.S. Army Corps of Engineers (USACE). Definitions of these criteria are given for clarity. Several additional criteria related to potential economic impacts are also included with their corresponding definitions or descriptions.

Name:

Organization:

Job Title:

Email:

Criteria Rating

Please rate the importance of the following criteria in terms of maintenance decisions and maintenance prioritization (i.e., allocation of funds for repairs or improvements, as well as annual maintenance expenditures). In other words, how important is each criterion in determining the urgency of repairs or improvements or setting the annual maintenance budget allocation to a given levee system?

Rating

- Not important
- Minimally important
- Neutral
- Somewhat important
- Very important

<u>Likelihood of Flooding/Failure</u>

Overtopping Annual Chance Exceedance (ACE) or Annual Exceedance Probability (AEP): The probability that in a given year the water level is higher than the height of the levee. Derived from the minimum overtopping event from a single segment of the system.	1	2	3	4	5
Days Since Record Flood Date: The number of days since the highest flood stage registered.	1	2	3	4	5
Levee Height: The height of the levee crest.	1	2	3	4	5
Freeboard: Increment of levee height above the design flood height to reduce likelihood of overtopping during a design event.	1	2	3	4	5
LSAC Risk Rating: The risk associated with the levee system based on the hazard, levee performance, and potential lost benefits.	1	2	3	4	5
Days Since Risk Assessment Date: The number of days since the risk rating was assigned to the levee system.	1	2	3	4	5
RIP Status: Rehabilitation and Inspection Program Status in which “active” projects meeting the USACE criteria at the time of a flood or storm event may receive federal rehabilitation assistance.	1	2	3	4	5
FEMA Accreditation Rating: Rating given by FEMA indicating whether or not the certification and adopted operation and maintenance plan provided by the levee owner are adequate.	1	2	3	4	5

Anticipated Performance or Condition of the Levee

Levee Miles: The length, in miles, of the entire flood control system.	1	2	3	4	5
Inspection Rating: The rating of the last inspection.	1	2	3	4	5
Days Since Last Inspection: The number of days since the last inspection of the levee system.	1	2	3	4	5
Has Evacuation Plan: Whether or not the system has an evacuation plan on record.	1	2	3	4	5
Segment Count: The number of segments the levee system is divided into.	1	2	3	4	5
Floodwall Miles: The length, in miles, of floodwall within a levee system.	1	2	3	4	5
Closure Structure Count: The number of closures (e.g., vehicular, railroad, pedestrian, or other openings) in the flood control system.	1	2	3	4	5
Crossing Points: Locations on a levee or floodwall where crossings occur.	1	2	3	4	5
Year Constructed: The year the levee system was constructed.	1	2	3	4	5
Pump Stations: The number of stations to pump water from the interior of a levee.	1	2	3	4	5
Relief Wells: The number of wells installed to reduce interior pore pressures.	1	2	3	4	5
Gravity Drains: The number of structures designed to allow the flow of water from the interior of a levee unit to the waterside.	1	2	3	4	5
Toe Drains: The number of trenches that run parallel to the levee/floodwall at the landside edge to provide a positive outlet for local under seepage and check for controlling piping and/or excessive uplift pressure.	1	2	3	4	5
Number of flood fighting points: The number of locations where flood fighting measures have been applied to the control of flood waters.	1	2	3	4	5
Number of sand boil locations: The number of sand boils documented for the levee system.	1	2	3	4	5
Distress points: The number of closure structures, levee, or floodwall sections that have been eroded, breached, or failed by flood waters. **(Animal burrows)**	1	2	3	4	5
Encroachments: The number of locations where utilities or other structures or pipes pass through the levee or levee foundation.	1	2	3	4	5

Consequences of Failure

Leveed Area SQ Mile: Estimated area of a flood plain from which flood water is excluded by the levee system.	1	2	3	4	5
Population at Risk: The estimated population within the leveed area.	1	2	3	4	5
Property Value: An estimated sum of the structure value, structure contents, and vehicles in the leveed area.	1	2	3	4	5
Buildings at Risk: The estimated number of structures in the leveed area.	1	2	3	4	5
Critical Infrastructure: Sewage treatment, water treatment, schools, first responder stations	1	2	3	4	5

Economic Impacts (not contained in current consequences criteria or NLD)

Business Closures: The number of businesses and business-related activity within the leveed squared area that would be disrupted due to flooding and levee failure.	1	2	3	4	5
Port Economics: The quantity of goods/commodities transferred through ports along the length of the levee system that would be disrupted due to flooding and levee failure.	1	2	3	4	5
Roadway Closures: The number of road crossings or bridges that would be disrupted by flooding or failure.	1	2	3	4	5
Traffic Counts: The daily traffic count that would be disrupted by flooding or failure within the leveed square area.	1	2	3	4	5
Supply Chain Hubs: The number of transfer hubs, distribution centers, or multi-modal facilities within the leveed square area (Rail, Highway, etc.).	1	2	3	4	5
Factory or Industrial Facilities: The number of factory or industrial facilities or the quantity of goods produced within the leveed square area.	1	2	3	4	5

4 Results/ Findings

4.1 PCA Ranking Results

PCA is a technique that reduces the dimensions of a dataset while keeping the original data variation. PCA transforms the original correlated variable into a new set of uncorrelated variables known as principal components (PCs) (Wang, et al. 2008). The principal component table computed based on the data set of Arkansas levee systems can be found in Appendix A. Principal Components are new variables that are constructed as linear combinations or mixtures of the initial variables. These combinations are done in such a way that the new variables (i.e., principal components) are uncorrelated and most of the information within the initial variables is squeezed or compressed into the first components. So, eleven-dimensional data gives eleven principal components and PCA tries to put the maximum possible information in the first component, then maximum remaining information in the second and so on, similar to the plot shown in Figure 7.

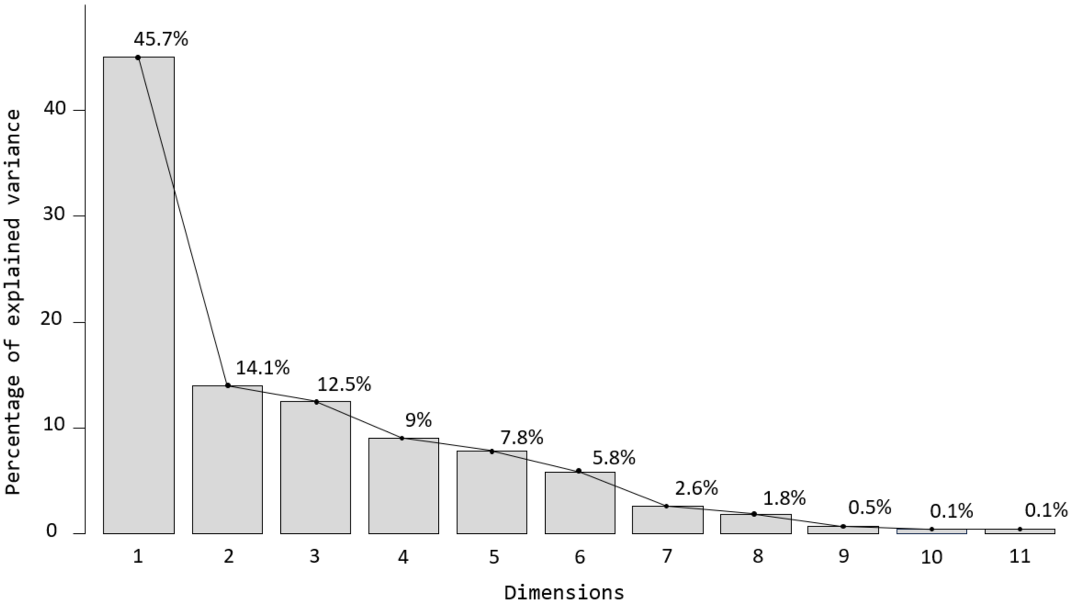


Figure 7 PCA scree plot diagram

Organizing information in principal components this way will allow us to reduce dimensionality without losing much information, as components with low information can be discarded and the remaining components are considered as the new variables. An important thing to note is that the principal components are less interpretable and do not have any real meaning since they are constructed as linear combinations of the initial variables.

After performing PCA, eleven PCs were obtained, which individually explain different percentages of the variance in the original dataset. Both the individual and cumulative percentages of the variance explained (VE) by each PC are also shown in Figure 7. The result of the scree plot shows that PC1 + PC2 + PC3 + PC4 + PC5 + PC6 explains 94.9% of the variance in the data set.

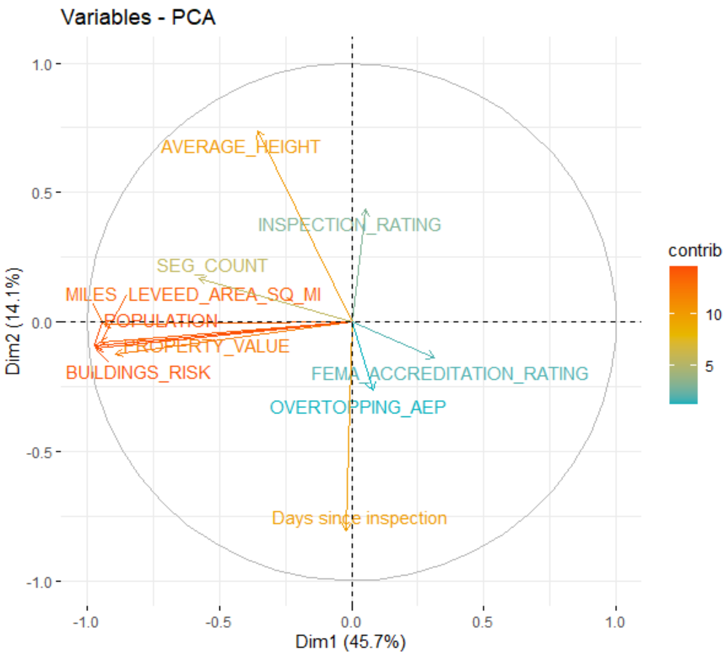


Figure 8 PCA correlation plots

From the correlation plot in Figure 8, PC1 is on the *x*-axis and PC2 is on the *y*-axis. Within the circle, the arrows represent the criteria of our dataset. It is clear that there are high correlations between population and other criteria such as building risk, levee length, property value, and leveed area square miles. These criteria are also positively correlated with the number of levee segments, although that is not a physical trend that is required. The levee average height is negatively correlated to the overtopping AEP meaning that a higher levee would have a lower AEP which makes sense. The number of days since inspection is also negatively correlated to the inspection rating, and the FEMA accreditation rating is negatively correlated to the levee segment count (another trend that is not physically required).

To complete the ranking for Arkansas levee systems using PCA, we calculated the PCA ranks using Equation 1, which aggregates the normalized and scaled version of the six PCs with respect to their variance explained (VE) as illustrated in Figure 8. It should be noted that this PCA rank calculation could have incorporated all eleven PCs. Nevertheless, the difference in results would be small; thus, the PCA rank based on six PCs is deemed sufficient.

$$PCA\ Rank = \sum_{i=1}^{6} PC_i VE_i \tag{1}$$

Table 8 Arkansas levee rankings calculated with PCA

Rank	System Name	Rank Value	PC1	PC2	PC3	PC4	PC5	PC6
1	West of Morrilton	1.058	0.77	-1.69	5.11	1.50	3.82	-2.20
2	Sainte Genevieve Levee System No. 2	0.706	0.84	-1.18	1.57	0.74	2.92	-0.03
3	Kaskaskia Island Drainage & Levee District System	0.648	0.79	1.99	0.88	-1.47	0.26	0.14
4	Bois Brule Levee & Drainage District System	0.635	0.49	2.25	1.10	-1.18	0.67	0.17
5	Red River LB AR	0.567	0.64	2.23	0.78	-1.75	0.07	0.25
6	Des Arc Levee System	0.544	1.00	-2.19	1.72	0.21	2.32	-0.33
7	Columbia Drainage & Levee District No.3 System	0.522	0.80	1.1	0.96	-1.21	-0.16	0.04
8	Festus Crystal City Levee System	0.501	0.31	3.44	-0.63	-0.49	0.66	-0.94
9	Prairie du Rocher / Edgar Lake System	0.480	0.18	2.46	0.37	0.01	0.11	-0.08
10	Hempstead County AR	0.476	0.81	1.98	0.13	-1.57	-0.17	-0.60
…	….	…						
70	North Little Rock to Gillette	-0.140	0.05	-0.65	-1.08	0.91	-0.11	-0.17
71	Mississippi and White Rivers Below Helena System	-0.148	-0.31	-0.39	-0.65	1.19	0.41	-0.15
72	Little River Drainage District Levee of Missouri System	-0.174	0.33	-1.05	-1.40	0.40	-0.16	-0.43
73	West Bank St. Francis Floodway System	-0.421	-1.07	0.16	1.27	-0.86	-0.55	0.12
74	St. Francis East to Big Lake West System	-0.440	-1.02	0.28	0.28	1.1	-1.22	-0.90
75	Big Lake and St. Francis Floodway East System	-0.569	-2.30	1.20	-0.25	3.01	0.07	1.17
76	Commerce MO - St. Francis River System	-0.919	-1.89	1.05	-1.58	-0.96	1.18	-0.19

Table 8 shows the ranking for the levees in Arkansas and the PC values for each. Note that the central ranking levees have been removed for brevity. As discussed, the principal components are combinations of the variables which limits interpretation of the results in terms of direct relationship to any one attribute or criterion. The PCA ranking is based simply on the data, relationships, and VE, and it does not consider any weighting or importance of any given attribute. An objective method like this is valuable as a tool, but it may not fully consider attributes that normally receive higher weighting or importance by experts in the area. For example, based on conversations with USACE personnel, a high weighting is placed on population because life safety is of upmost importance. The PCA analysis method does not have the ability to incorporate such a weighting or expert opinion.

4.2 CRITIC Objective Weights /TOPSIS Rankings Results

CRITIC is a correlation-based technique that uses analytical testing to extract underlying information in the decision criteria. It determines weights by exploiting the contrast intensity and the conflicting nature of the criteria. The CRITIC method introduced the concept of conflict to MCDM. It is commonly used to generate objective weights for MCMD techniques. CRITIC was used in this study to calculate the objective weights for the 11 criteria including levee segment (S), levee length (L), Overtopping AEP (AEP), leveed area square mile (SQ), days since inspection (I), population (P), property value (PV), building risk (B), inspection rating (I), FEMA accreditation rating (AR), and average height (H). CRITIC also enabled calculation of the Pearson correlation coefficients to measure the strength of the relationships among all criteria (Table 9).

Table 9 Correlation coefficients of each of the 11 criteria examined in this study

	S	L	AEP	SQ	I	P	PV	B	IR	AR	H
S	1	0.69	0.04	0.44	0.13	0.43	0.34	0.40	0.17	-0.11	0.38
L	0.69	1	-0.03	0.88	0.08	0.88	0.77	0.86	0.05	-0.18	0.30
AEP	0.04	-0.03	1	-0.05	0.14	-0.07	-0.06	-0.06	0.07	0.24	-0.07
SQ	0.44	0.88	-0.05	1	0.03	0.98	0.79	0.94	-0.09	-0.20	0.28
I	0.13	0.08	0.14	0.03	1	0.03	0.01	0.01	-0.23	-0.03	-0.43
P	0.43	0.88	-0.07	0.98	0.03	1	0.89	0.98	-0.08	-0.25	0.25
PV	0.34	0.77	-0.06	0.79	0.01	0.89	1	0.94	-0.07	-0.26	0.15
B	0.40	0.86	-0.06	0.94	0.01	0.98	0.94	1	-0.09	-0.25	0.22
IR	0.17	0.05	0.07	-0.09	-0.23	-0.08	-0.07	-0.09	1	0.20	0.05
AR	-0.11	-0.18	0.24	-0.20	-0.03	-0.25	-0.26	-0.25	0.20	1	-0.3
H	0.38	0.30	-0.07	0.28	-0.43	0.25	0.15	0.22	0.05	0	1

Table 9 shows population (P) continues to have a strong positive relationship with other criteria such as levee length (L), with a correlation of 0.88; leveed area SQ mile, with a correlation of 0.98; property value, with a correlation of 0.89; and building risk, with a correlation of 0.98. All the remaining criteria have negligible correlation with population. Combining the information from Table 6 with the calculated standard deviation, *σ,* for each criterion, we can calculate the information given by a criterion using equation 2.

$$c_i = \sigma_i \sum_{k=11}^{11} 1 - r_{ik} \tag{2}$$

where c_i is the information given by the i^{th} criteria and r_{ik} is the linear correlation between indicators *i* and *k*. The weights are computed by Equation 3 and the objective weight for each criterion is shown in Table 10.

$$cw_i = \frac{c_i}{\sum_{i=1}^{11} c_i} \tag{3}$$

Table 10 Standard deviation, conversion of preference values and weights of criteria

	σ_i	c_i	cw_i
1. Levee Segment	0.26	1.85	8.19%
2. Levee length	0.14	0.82	3.61%
3. Overtopping AEP	0.14	1.35	5.98%
4. Leveed area Sq Mile	0.12	0.74	3.27%
5. Days since inspection	0.29	2.99	13.21%
6. Population	0.13	0.79	3.50%
7. Property Value	0.14	0.94	4.14%
8. Building risk	0.15	0.90	4.00%
9. Inspection rating	0.50	5.00	22.09%
10. FEMA Accreditation Rating	0.48	5.29	23.36%
11. Average Height	0.21	1.96	8.65%

In the next step, criteria weights are used with the TOPSIS method for the determination of the levee system ranking. The weight assessment of the criteria defines the importance of one criterion over the other criteria. The final ranking of the Arkansas levees can be found in Table 11. Si^+ calculates the L^2-norm distance of each alternative to the best solution, and Si^- shows the distance to the worst solution. The final ranking is determined using the "similarity to the worst condition" measure, i.e., $Pi = Si^-/(Si^- + Si^+)$. Note that the central ranking levees have been removed for brevity.

Table 11 Arkansas levee ranking with CRITIC-TOPSIS

Rank	System Name	Si^+	Si^-	Similarity Pi
1	West of Morrilton	0.067	0.073	0.523
2	Commerce MO - St. Francis River System	0.072	0.068	0.484
3	White River Levee System	0.075	0.056	0.428
4	Dardanelle Levee/Carden Bottom Levee	0.077	0.057	0.426
5	Grand Tower / Degognia Levee System	0.079	0.057	0.418
6	East of Morrilton	0.081	0.057	0.411
7	Bois Brule Levee & Drainage District System	0.081	0.056	0.408
8	Point Remove Creek Drainage and Levee District	0.081	0.056	0.407
9	Village Creek White River Mayberry Levee District	0.082	0.056	0.406
10	McKinney Bayou - Mid - North	0.082	0.055	0.403
…	…	…	…	…
70	Faulkner County Levee District No. 1	0.100	0.013	0.114
71	North Little Rock Levee and Floodwall	0.100	0.013	0.114
72	Rock Creek Levee	0.099	0.013	0.112
73	Sainte Genevieve No. 3 Levee System	0.099	0.012	0.104
74	Des Arc Levee System	0.099	0.011	0.103
75	Clarendon Levee System	0.099	0.011	0.098
76	Cape Girardeau Flood Protection System	0.100	0.008	0.070

As discussed, the TOPSIS method ranks the levees based on the “distance” from the ideal solutions, such that the first ranking levee is closest to the positive ideal solution and the last ranking levee is furthest from the positive ideal solution. One interesting observation from the ranking is that the first ranked levee is the same for the PCA and CRITIC-TOPSIS analyses. The second ranking levee in the CRITIC-TOPSIS ranking; however, is the last ranking levee in the PCA-based ranking. Hence, there is clearly some discrepancy in these methods and how they objectively rank the data.

4.3 Comparison of the Results

The ranking results of all suggested methods are plotted in Figure 9, together with the LSAC assigned by the USACE shown by color. To see how closely the ranking from the two different methods compares to each other, a linear regression analysis was performed. The analysis results show a multiple *R* square of 0.6734, which means that the ranks from the PCA fit well to the ranking from CRITIC-TOPSIS overall, although there are some discrepancies as discussed above.

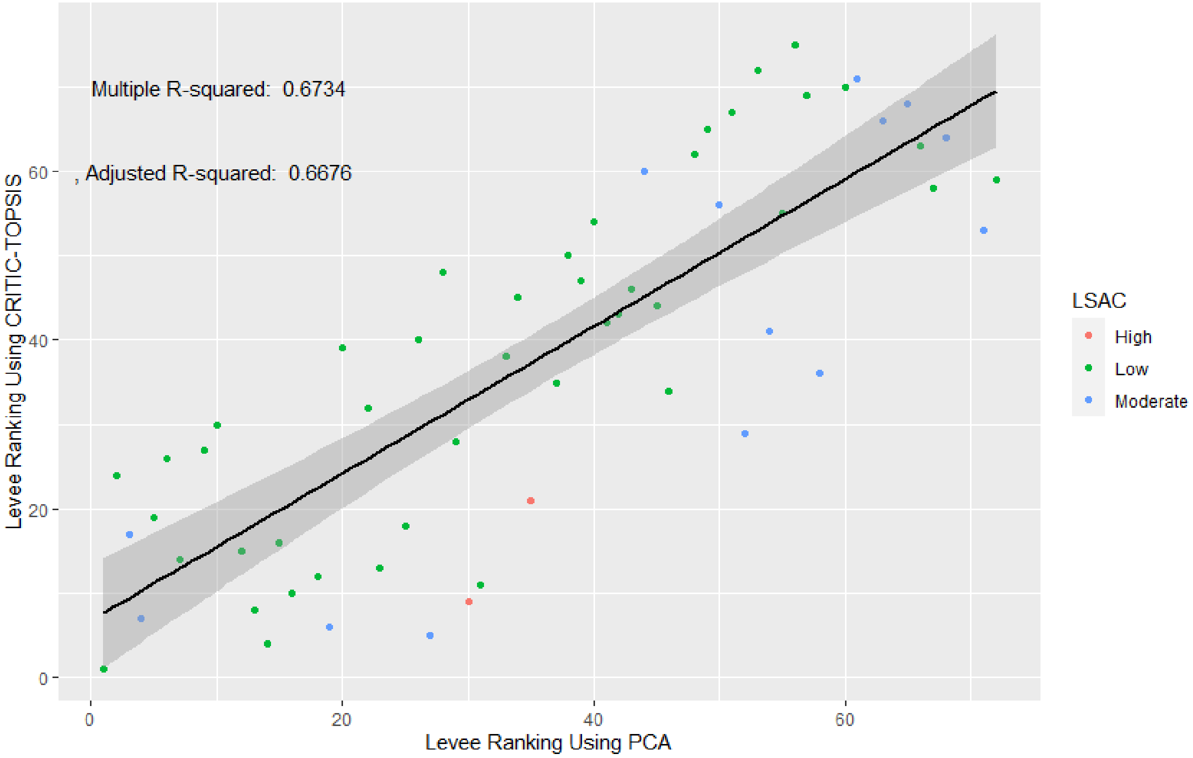


Figure 9 Linear regression plot for PCA and CRITIC TOPSIS rankings

Both approaches are suitable for taking advantage of the criteria available in the NLD since the rankings from each method are not significantly different from each other. Moreover, the top-ranking levee systems obtained using the PCA or CRITIC-TOPSIS ranking method often have a low to moderate LSAC. Therefore, these levees are most likely viewed by the USACE as low priority in terms of maintenance despite having a higher ranking in the MCDM methods examined herein. It should be noted, however, having design and performance issues is not directly considered by specific criteria in the MCDM methods here, as they are simply ranking based on features of the data as a whole. A more subjective weighting, such as what is likely used in the USACE algorithm can provide a way to incorporate expert opinion to highlight the criterion that engineers and levee overseers know are directly related to the risk associate with failure. As future research related to this study, the levee criteria ranking survey we developed can be used to gather the opinions of experts in levee risk and maintenance (e.g., levee owner/operators, USACE levee personnel, geotechnical engineers) so that subjective weightings can be created. The levee rankings using the subjective weighting could then be compared to the rankings from the objective methods to assess if any improvement is gained. It should be noted that the goal of this research was not to exactly match the USACE LSAC ratings, but to use them as a baseline for which to compare the rankings obtained by the MCDM methods evaluated herein. As shown by the multinomial logistic regression results, there was no clear set of criteria or weightings that covered all of the LSAC ratings, so it is likely that there is additional subjectivity built into the LSAC determination.

One important benefit of using MCDM methods such as the CRITIC-TOPSIS combination is the ability to easily include a large number of parameters in the evaluation of risk and maintenance prioritization. The current LSAC rating does not account for economic factors such as disruptions to the transportation network and supply chain, yet these can often be as or even more costly than the resulting property damage. For example, if a leveed area were to contain a port with an offload facility and multimodal hub, the flooding may not only contribute to a loss of property, but also a large disruption to the economic activities of the area. Significant agricultural areas may also be flooded which can disrupt the food supply and economy of rual locations. These are difficult to incorporate in the algorithm within the levee safety tool currently used by the USACE. A framework using MCDM; however, is very flexible and robust and could be continuously expanded to include new data and criteria as it became available. These data could be incorporated without having to rework any algorithm or rethink the framework and weightings could be assigned and/or varied to accommodate changing economic climates or changing urbanization or development. This type of framework could also be expanded to other maritime infrastructure and adapted based on the criteria or attributes that make sense for that particular set of infrastructure and application.

4.4 Cost-benefit Analysis

Once the list of ranking results is obtained, the next step can include performing a cost-benefit analysis to facilitate the maintenance decisions. The cost-benefit analysis involves comparing the operating and maintenance (O&M) costs with the benefits associated with the levee system to determine whether the levee should be prioritized for maintenance. However, detailed cost estimates for levee repair, operation, and maintenance costs are not always readily available in public documents and they are not available in the NLD. Collecting and verifying such information can be time-consuming, but accurate information on these costs is urgently needed to support maintenance decisions.

Several studies have attempted mathematical modeling for projecting O&M and repair costs. Sohn and Sohn (2019) proposed an optimization model that minimizes damage risks for the levee systems in Arkansas, using the NLD for the majority of their data. Data concerning levee repairs appeared to be related to the height and characteristics of the levees meaning longer or larger cross-section levees will require more maintenance due to their size alone. From Sohn and Sohn (2019), levees are repaired at the following cost:

$$C_i = 5280 * l_i * o_i \tag{4}$$

where l_i*5280 is the conversion of levee length from miles to feet and o_i is the cost of repair based on height, which is shown in the formula below:

$$o_i = \frac{1.5275}{overtopping\ AEP_i} \tag{5}$$

However, this formula assigns a higher repair cost for a low-risk levee with an overtopping AEP of 0.0002 ($7,637.5 per foot) compared to a high-risk levee with an overtopping AEP of 0.1 ($15.275 per foot), which seems counterintuitive.

In another study, Miller (2022) constructed a linear model of O&M expenses for newly constructed hurricane protection infrastructure post Hurricane Katrina using the statistical technique of ordinary least square regression. Their analysis employed detailed information on levee characteristics, such as the acres of right-of-way, numbers of floodgates, and pump stations, combined with historical O&M expenditures by the levee districts. However, it is worth noting that the data on acres of levee right-of-way were not given by the levee district and are not always defined clearly. Therefore, Miller estimated the acres of levees based on the length and height, assuming that all levee systems have a standardized design. Thus, the estimated acres are calculated as follows:

$$\text{Levee right} - \text{of} - \text{way acres} = \frac{5{,}280 * \text{miles} * (10 + 25.4 * \text{height})}{43{,}560} \tag{6}$$

The following regression model was formulated based on the historical data on O&M expenditures from 1996 to 2004, in combination with other measures such as acres and the number of floodgates and pump stations.

$$\text{Exp}_{\text{it}} = \text{a}_{1\text{t}} + \text{a}_2 * \text{acres}_\text{i} + \text{a}_3 * \text{floodgates}_\text{i} + \text{a}_4 * \text{pumps}_\text{i} + \text{e}_\text{i} \tag{7}$$

where Exp_{it} is expenditures on O&M in 2009 constant dollars by levee district *i* in year *t*, acres_i is the number of acres of levee-right-of-way maintained by levee district *i*, floodgate and pump_i is the number of floodgates and pump stations in levee district *i*. e_i is an error term specific to levee district *i*, and a_{1t} is specific to each observation year (1996 – 2004).

The primary strength of the approach outlined above is that it is based on historical costs, which reflect actual costs incurred, local labor, contractor rates, as well as needed supplies and equipment. Unfortunately, we did not have access to such historical data for our study, and infrastructure repair and maintenance cost may differentiate from state to state as well as from one levee district to another. Despite the limitations that may decrease the cost estimation's accuracy, the application of Eq. 7 was used in this study to demonstrate the potential use of such data and model.

The 76 levee systems in Arkansas were down-selected further for the cost-benefit analysis. Levees considered must satisfy at least one of the following conditions to be considered in the cost-benefit analysis. First, they must be ranked in the top ten based on the CRITIC-TOPSIS method and second, they must have an LSAC rating of Moderate or higher. The list of levee systems evaluated is presented in Table 12. Note that several of the levees have a Low LSAC rating, however, they were ranked within the top ten in the CRITIC-TOPSIS analysis.

Table 12 List of Arkansas levees for cost-benefit analysis

Rank	System Name	Estimated Cost	Similarity Pi	LSAC
1	West of Morrilton	$168,192.22	0.52	Low
2	Commerce MO - St. Francis River System	$5,637,618.22	0.48	Moderate
3	White River Levee System	$430,111.83	0.43	Moderate
4	Dardanelle Levee/Carden Bottom Levee	$1,054,394.92	0.43	Low
5	Grand Tower / Degognia Levee System	$879,811.64	0.42	Moderate
6	East of Morrilton	$180,364.04	0.41	Moderate
7	Bois Brule Levee & Drainage District System	$1,079,324.69	0.41	Moderate
8	Point Remove Creek Drainage and Levee District	$207,903.54	0.41	Low
9	Village Creek White River Mayberry Levee District	$525,388.13	0.41	High
10	McKinney Bayou - Mid - North	$72,964.20	0.4	Low
17	Kaskaskia Island Drainage & Levee District System	$155,597.21	0.4	Moderate
20	West Bank St. Francis Floodway System	$1,058,694.83	0.39	High
21	Mississippi and Ohio Rivers Levee System at Cairo & Vicinity	$2,105,813.94	0.39	High
22	St. Francis East to Big Lake West System	$901,672.03	0.38	High
25	Big Lake and St. Francis Floodway East System	$1,388,092.60	0.36	Moderate
29	Big Five Levee System	$590,015.86	0.34	Moderate
31	North Little Rock to Gillette	$1,293,621.70	0.33	High
33	Head of Fourche Island to Pennington Bayou	$697,648.65	0.31	High
36	Memphis - Wolf River Backwater Levee System	$2,556,563.91	0.31	Moderate
41	Inter-River Levee System	$154,266.63	0.31	Moderate
52	Fort Smith Levee District No. 1	$599,362.10	0.3	Moderate
53	Mississippi and White Rivers Below Helena System	$2,636,059.35	0.23	Moderate
56	Butler County Drainage District No. 12	$158,594.76	0.2	Moderate
60	Massey Alexander Levee District	$223,001.22	0.13	Moderate
64	New Madrid-Sikeston Ridge Levee System	$164,607.61	0.13	Moderate
66	Riverdale Private Levee	$609,341.64	0.12	Moderate
68	Newport Levee District	$2,177,405.29	0.12	Moderate
71	North Little Rock Levee and Floodwall	$922,823.14	0.11	Moderate
76	Cape Girardeau Flood Protection System	$537,187.23	0.07	Moderate

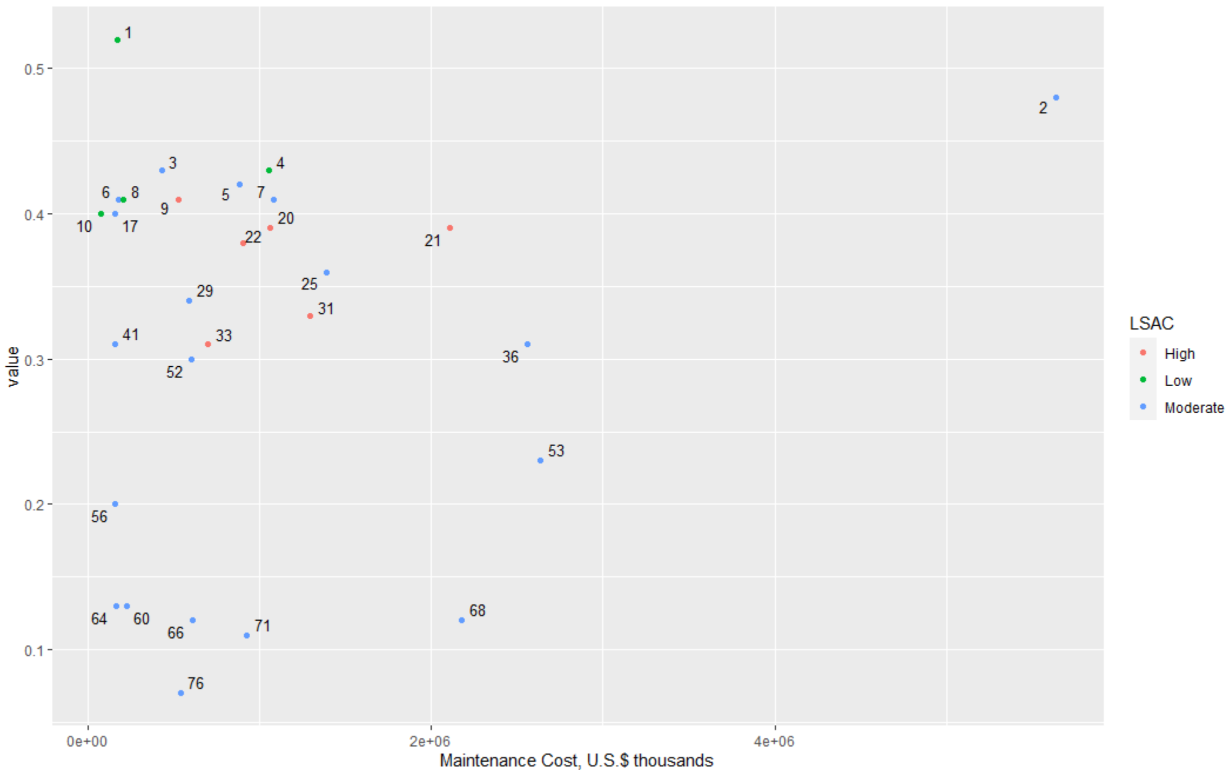


Figure 10 Maintenance cost versus value chart

Figure 10 presents a plot of the maintenance cost versus the value with the LSAC rating shown using color. There are several ways to interpret this data. One option is to consider levees that have a low cost for maintenance, but high impact, meaning they are relatively cheap to maintain or improve and they are higher risk than other levees. For example, the levee systems ranking 3, 6, 9, 17 fit this line of thinking and should have a high prioritization for maintenance since these levees rank high in terms of risk (i.e., high value), have a high to moderate LSAC rating, and relatively low maintenance cost estimates. Although levee system 1 has a low LSAC rating, it also is a very high value option with low maintenance costs. Another way of thinking may suggest that all high LSAC ratings should be prioritized over any other categories working from lowest maintenance costs to highest; however, this does not fully utilize all of the MCDM methods here.

5 Impacts/Benefits of Implementation

The implementation of the multi-criteria ranking system using PCA and CRITIC-TOPSIS methods could provide significant impacts and benefits for prioritizing the maintenance of levee systems in Arkansas, as well as the United States in general. Some of the key potential impacts and benefits include:

- **Improved assessment of maintenance needs**

  The proposed approach enhances the assessment of maintenance needs for levee systems by considering multiple critical factors such as levee condition, performance history, vulnerability to failure, and the potential consequences of such failures. This method offers a comprehensive and nuanced evaluation of maintenance priorities compared to relying solely on the Levee Safety Action Classification (LSAC), which provides a somewhat simplified risk assessment. By considering the condition of the levees, including factors like their structural integrity, inspection ratings, and days since inspection, we gain valuable insights into their current state. Furthermore, our approach evaluates the performance of levee systems by examining their past track record and anticipated future performance, taking into account how well they have functioned in the past and how they are expected to perform in potential flood events. Vulnerability is another crucial aspect that our method addresses, considering the probability of levee breaches and understanding the overall resilience of the levee systems. Lastly, we consider the consequences of levee failures, including the potential impact on people and infrastructure, especially in densely populated areas or regions with significant economic activities. This framework is also very flexible and new criteria can be added without the need to redevelop algorithms or relationships. As more data is available, the prioritization can be reassessed quickly and the influence of various criteria can be evaluated by considering objective and subjective weightings. In summary, our proposed approach offers a holistic and robust framework for assessing levee maintenance needs, enabling decision-makers to make more informed choices when allocating resources for levee maintenance, ultimately enhancing the safety and reliability of flood protection systems.

- **Optimized resource allocation**

  The improved ranking system we proposed for levee maintenance facilitates optimized resource allocation, addressing the challenge of limited funding and resources more effectively. By accurately assessing the maintenance requirements of individual levees based on a broader set of criteria, we can prioritize investments where they are most urgently needed. This approach prevents the deferral of critical maintenance activities on levees with lower LSAC ratings but with significant vulnerabilities or consequences of failure. It ensures that resources are directed towards the levees with the highest risk profiles and those that would yield the greatest benefits in terms of safety and protection of infrastructure and communities. The MCDM methods proposed allow for economic impact to also be easily incorporated into the evaluation. In this way, our optimized resource allocation strategy enhances the overall resilience of levee systems while making the most of available funding, ultimately reducing the potential for flood-related disasters.

- **Enhanced public safety**

  The prioritization of maintenance for levees with higher risks of failure and more significant consequences offers a direct pathway to enhancing public safety. By addressing the maintenance needs of the critical levees first, we substantially reduce the likelihood of failure during flood events, ultimately safeguarding the communities and infrastructure they protect. This is already targeted with the LSAC rating; however, the framework proposed allows greater flexibility and transparency for a large number of criteria. This proactive approach not only reduces the potential for disasters but also significantly enhances community resilience in the face of flooding. Public safety is paramount, and by focusing on the most vulnerable levees, we contribute to a safer environment for those living and working in flood-prone areas, providing them with greater security and peace of mind.

- **Reduced economic impacts**

  Properly maintaining levees is a proactive measure that carries significant economic benefits. By preventing catastrophic failures that could result in extensive damage to communities, infrastructure, and businesses, we effectively reduce the economic impacts associated with flooding events. This approach minimizes productivity losses, preserves property values, and helps sustain the economic stability of the affected regions. Moreover, it saves costs associated with emergency response, recovery, and rebuilding efforts that would be required in the aftermath of a levee failure. Thus, investing in the maintenance of critical levees not only protects communities but also safeguards their economic well-being.

- **Improved levee reliability**

  Regular maintenance and strategic upgrades are instrumental in enhancing levee reliability. By addressing deficiencies and mitigating deteriorating conditions, these measures ensure that levees continue to function reliably as designed. This not only extends the service life of these critical flood control systems but also bolsters their overall effectiveness. The improved reliability of levees contributes to the consistent protection of communities and valuable infrastructure, providing residents with greater peace of mind during flood events. Additionally, it reduces the need for emergency interventions and repairs, ultimately leading to cost savings and more resilient flood management infrastructure.

- **Coordination of stakeholders**

  The ranking system introduced here fosters greater coordination among federal, state, and local decision-makers involved in levee maintenance. By providing a standardized framework for assessing maintenance priorities, it encourages collaborative efforts to address critical levee systems. This coordinated approach ensures that resources are efficiently allocated to levees with the most pressing maintenance needs. Furthermore, it promotes a shared understanding of the levee infrastructure's condition and risks, facilitating informed decision-making and strategic planning among stakeholders. Ultimately, this coordination enhances the collective capacity to manage and safeguard against flood risks, benefiting the communities and regions protected by these levee systems.

- **Adaptability**

  The flexibility and adaptability of the proposed ranking criteria are notable strengths of this approach. The system is designed to accommodate changes over time, enabling adjustments to reflect new data, evolving needs, or shifting priorities. Leveraging Multi-Criteria Decision-Making (MCDM) techniques, the framework readily incorporates diverse factors and considerations, ensuring that the ranking remains relevant and responsive to emerging challenges and information. This adaptability is crucial in the context of levee maintenance, where conditions, risks, and resource availability can change over time. By staying dynamic and open to updates, the ranking system can continue to provide effective guidance for levee maintenance decision-makers in an ever-changing environment.

Overall, the multi-criteria approach offers an effective methodology to determine levee maintenance priorities based on detailed risk assessments. Implementing this systematic framework will enable more targeted upkeep, greater flood protection, and coordination between responsible authorities. This ultimately results in safer communities and avoidance of preventable levee failures.

6 Recommendations and Conclusions

While the proposed methodology enables flexible and robust multi-criteria decision making for levee maintenance prioritization, there are several limitations. Firstly, our study is currently limited to the data available through NLD. There can be other important criteria in the decision-making process that are not currently contained within the database and there were many attributes and associated data in the NLD that were blank. Therefore, this study serves as a simple example of what could be a much more detailed and criteria rich framework. As such, the ranking results can be described as a snapshot at one particular time rather than a basis for future actions and planning. The maintenance cost data was also very limited and estimates from the literature were used to demonstrate the potential of incorporating this type of analysis into the prioritization task. Given the limitations, there are several opportunities for improvement in future research.

Future research should focus on acquiring more information, since the improved data availability and quality has the potential to greatly increase the effectiveness of the proposed model. In addition, we need to engage experts from USACE in the process of rating the criteria and determining the levee system rankings using the survey developed. Levee system maintenance is a complex problem that requires participation of multiple stakeholders from local, state and federal agencies. One option of incorporating these subjective criteria ratings is the application of the Swing Weight Method (SWM) (Parnel and Trainor, 2009). One important component of the SWM is the swing weight matrix, which is shown in Figure 11.

		Importance of the value measure to the decision makers and stakeholders (intuitive)		
		Low	Medium	High
Impact of the value measure on the decision (factual)	High			
	Medium			
	Low			
	Not relevant			

Figure 11 Swing weight matrix template

Unlike other traditional weighting methods, swing weights are assigned to value measure based on the importance and variation of the scale of the value measures. To be more specific, a criterion should be given a high weight if it is considered to be an important factor in the decision process. However, we also evaluate the weight by “swinging” the value of the criteria from its worst to its best value. If we find out that there is little range of variation in the criteria measure scale, less weight is placed on those criteria during the decision process. The levee system rankings can be obtained using Equation 8

$$v(x) = \sum_{i=1}^{n} w_i v_i(x_i) \tag{8}$$

Each value function $v_i(x_i)$, measures returns to scale on the range of the value measure and converts a score (x_i) to a value. The weights quantify the trade-offs between value measures that assess the achievement of objectives (Miller, 2022). The weights are normalized to sum to 1. Since our values do not depend on the alternative, the additive value model has no index for the alternatives, and we use Equation 4 to evaluate every levee system.

Another improvement is to develop a reliability model applying the Markov Chain Process (MCP) for scheduling and optimization of levee system maintenance. A Markov Chain is a mathematical system stating that the state of the process at time $t+1$ depends on the state of the process at time t, but is independent of the state of the process at any time prior to t. In other words, the probability of a levee system performing as expected in the future is dependent solely on its current state and our decision to perform maintenance or not. Our goal is to find an optimal maintenance plan that minimizes the total cost over the whole period of the decision process. The details of how we can implement MCP are described as:

> $s = \{1, 2, 3\}$ is a set of levee system conditions, 1: Acceptable, 2: Minimally acceptable, 3: Unacceptable.
> $a = \{1, 2, 3\}$ is a set of all possible actions, 1: do nothing, 2: basic maintenance, 3: improvement.
> $r(s, a, s')$ is the reward for taking action a in state s, improve or deteriorate the current state of levee system.
> $p_t(s' | s, a)$ defines a transition probability that when the state is in s and action a is taken, then the next state will be s' with probability $p_t(s' | s, a)$.

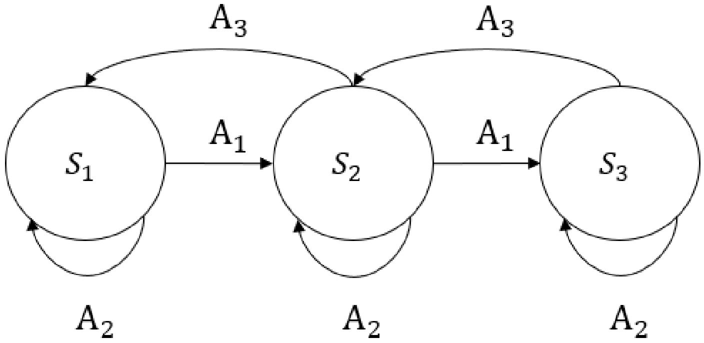


Figure 12 Visualization of Sample Markov Chain

Markov transition probability matrix $p_t(s' | s, a)$ is a matrix whose element of ith row and jth column denotes the transition probability $p_t(s' = j \mid s = i, a)$ It is assumed that the process can move from state i to state j only if $j \geq i$. And the levee can deteriorate only one state of a time:

$$p_t(s' | s, a_t) = \begin{bmatrix} p_t(1|1, a_2) & p_t(2|1, a_1) & 0 \\ p_t(1|2, a_3) & p_t(2|2, a_2) & p_t(3|2, a_1) \\ 0 & p_t(2|3, a_3) & p_t(3|3, a_1) \end{bmatrix}$$

Policy π produce a path (episode):

$\pi 1$: s1; a2, r (1, a2, 1), s1; a1, r (1, a1, 2), s2.

$\pi 2$: s2; a2, r (2, a2, 2), s2; a1, r (2, a1, 3), s3; a3, r (3, a3, 2), s2; a3, r (2, a3, 1), s1.

$\pi 3$: s3; a2, r (3, a2, 3), s3; a1, r (3, a1, 4), s4; a3, r (4, a2, 3), s3; a3, r (3, a3, 2), s2; a3, r (2, a3, 1), s1.

…..

γ is a discount factor; future costs are discounted when converted into present value.

$$V([s1, s2, \ldots, sn]) = \sum_{t=0}^{\infty} \gamma^{t} R(s_t) \quad , \gamma \in (0,1] \tag{9}$$

Objective function for maximizing the total reward:

$$V\pi = \max E\left[\sum_{t=1}^{N} \gamma^{t} R(s_t)\right] \tag{10}$$

The MCDM methods examined show promise in creating a flexible and robust framework for levee maintenance prioritization. While the study was limited to a small amount of data available for a select group of levees within the state of Arkansas, this framework can be extended to other levee systems and levees across the United States in general. This framework can also be extended to other maritime infrastructure where maintenance decisions are difficult and prioritization of limited funding is critical. Future improvements in this research can be made if more complete data across a wider variety of criteria were available. Additionally, the cost-benefit analysis can be greatly improved through incorporation of annual maintenance expenditures and/or maintenance budgets for the levee systems evaluated. Machine learning methods such as neural networks could also be used to evaluate the weightings of the criteria that lead to the LSAC rating and compare those to the objective and subjective weightings determined by the methods discussed herein.

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Appendix

Appendix A. Levee attributes contained in the National Levee Database (NLD).

Attribute Category	System	System (cont.)	Segment	Leveed Area
Attributes	System ID	Segment Count	Segment ID	Leveed Area ID
	Name	System Contains Non Project Segment	Name	System ID
	Type and Sub-type	Division Name	System ID	Name
	Flood of Record Flow (CFS)	District Name	Authorization Category	Leveed Square Miles
	Flood of Record Date	FEMA Region Names	Construction End Year	Levee Station Code
	Closure Structure Miles	Congressional District	Design Flow	Feature Name
	Closure Structure Count	HUC4 Names	Flood Reduction Channel	Min Overtop Event
	Levee Miles	Has Evacuation Plan	Freeboard	Egress Number
	Leveed Area (Square Miles)	Has Warning System	Primary Waterway	Submission ID
	Floodwall Miles	Non-Federal IEI Date	Secondary Waterway	Warning Indicator
	Location	Population	Potential Hazard	Evacuation Plan Indicator
	System Is USACE	Property Value	LIS Alias	Computed Source Date
	Overtopping ACE (Annual Exceedance Probability)	Number of Buildings	Levee Miles	Computed Source
	SWIF Status		Floodwall Miles	Leveed Area Source
	Waterway		Begin Longitude	Feature Class
	Year Constructed		Begin Latitude	
	Rehabilitation and Inspection Program (RIP) Status		End Longitude	
	FEMA Accreditation Rating		End Latitude	
	Sponsors		LSAC Rating	
	States		Non Project	
	Counties		Interested Federal Agency	

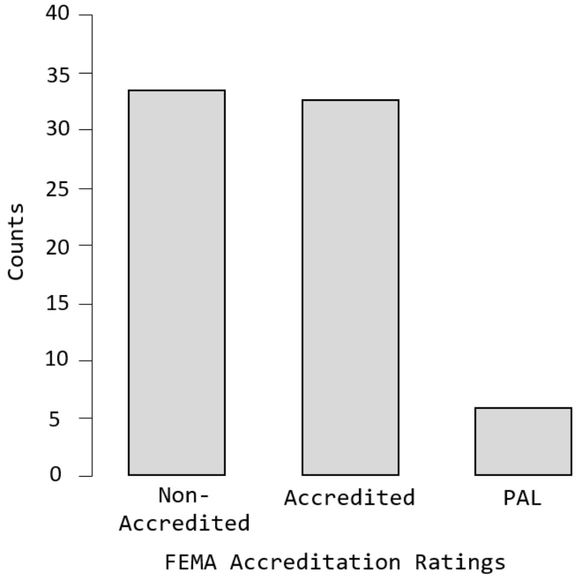
Attribute Category	Closure Structure	Cross Section	Embankments	Floodwall
Attributes	Closure Structure ID	Cross Section ID	Embankment ID	Floodwall ID
	Segment ID	Segment ID	Segment ID	Segment ID
	Levee Station Code or River Mile	Levee Station Code	Up River Mile	Feature Name
	Feature Name	River Mile	Down River Mile	Feature Length
	Closure Height	Horizontal Accuracy	Feature Name	Gage Code
	Closure Width	Vertical Accuracy	Feature Length	Wall Height
	Horizontal Accuracy	Submission ID	Gage Code	Wall Depth
	Vertical Accuracy	Survey Date	Gage Owner	Wall Width
	Submission ID	Coordinate Capture Type	Slope Landside	Foundation Width
	Survey Date	Feature Class	Slope Waterside	Flood Source
	Closure Type		Crest Width	River Basin
	Coordinate Capture Type		Crest Access	Horizontal Accuracy
	Status		Flood Source	Vertical Accuracy
	Feature Class		River Basin	Submission ID
	Operation Frequency		Horizontal Accuracy	Survey Date
	Sill Elevation		Vertical Accuracy	Gage Owner
	Closure Use		Submission ID	Material Type
	Last Operation Date		Survey Date	Bankside Type
	Description of Closure Condition		Coordinate Capture Type	TYCUTO Type
			Bankside Type	Coordinate Capture Type
			TYCUTO Type	Wall Type
			STRMAT Type	Status
			Levee Type	Feature Class
			Status	
			Feature Class	

Attribute Category	**Gravity Drain**	**Levee Crossing**	**Levee Station**	**Piezometer**
Attributes	Gravity Drain ID	Crossing Point ID	Station Point ID	Piezometer ID
	Segment ID	Segment ID	Segment ID	Segment ID
	Levee Station Code	Levee Station Code	River Mile	Levee Station Code
	Feature Name	Date Built	Levee Station Code	Feature Name
	Drain Diameter	Width	Levee Mile	Installation Date
	Design Length	Clearance	Station Elevation	Top Elevation
	Capacity	Submission ID	Submission ID	Tip Elevation
	Inlet Invert Elevation	Permitted Indicator	Survey Date	Location Offset
	Outlet Invert Elevation	Permit Date	Coordinate Capture Type	Submission ID
	Horizontal Accuracy	Permit Number	Status	Survey Date
	Vertical Accuracy	Survey Date	State Levee Type	Coordinate Capture Type
	Submission ID	Coordinate Capture Type	Feature Class	Status
	Survey Date	Crossing Type		Feature Class
	Number of Barrels	Crossing Path		
	Gate Type	Auth Section		
	Pipe Material Type	Feature Class		
	Coordinate Capture Type			
	Status			
	Feature Class			

Attribute Category	**Pipe**	**Pipe (cont.)**	**Pipe Gate**	**Borehole**
Attributes	Pipe ID	Pipe Material Type	Gate ID	Borhole ID
	Segment ID	Coordinate Capture Type	Pipe ID	Segment ID
	Levee Station Code	Status	Gate Type ID	Levee Station Code
	Feature Name	Feature Class	Location	Start Date
	Diameter	Rehabilitation Year	Last Operation Date	Completion Date
	Design Length	Year Inspected	Next Operation Date	Reference Point Elevation
	Inlet Invert Elevation	Next Inspection Year	Description of Gate Condition	Reference Point Description
	Outlet Invert Elevation	Gravity vs Pressurized	Levee Station Code	Gound Surface Elevation
	Horizontal Accuracy	Pipe Function	Operation Frequency	Total Depth
	Vertical Accuracy	Inspection Frequency	Coordinate Capture Type	Description
	Submission ID	Pump Station	Survey Date	Type
	Survey Date	Construction Year		Submission ID
		Description of Pipe Condition		Survey Date
		Grade		Bore Method Type
				Coordinate Capture Type
				Feature Class

Appendix B. Data summary of Arkansas levee systems

	Unit	Min	1st Qu.	Median	Mean	3rd Qu.	Max
1. Average height	Feet	5.5	11.575	14.5	0.20	17.75	33
2. Building risk	Building	1	44	191	34	944	58066
3. Days since last inspection	Days	1197	3198	4444	52	4623	4820
4. Levee length	Miles	0.49	4.0	10.36	0.30	21.62	277.32
5. Leveed area SQ Mile	Sq mile	0.02	1.62	13.95	2.16	46.94	5265.99
6. Population	People	3	90	492	67	2063	135261
7. Levee Segment	Segment count	1	1	1	0.02	2	6
8. Overtopping AEP	N/A	0.0002	0.001	0.002	0.00007	0.005	0.1
9. Property Value	Million $	0.11	10.85	53.89	5.62	230.24	9717.13



Appendix C. Principal component table calculated using PCA

System Name	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11
AR River North Bank	-0.99	1.59	1.18	1.16	-0.55	0.24	-0.19	-0.08	0.06	-0.04	0.23
Batesville Levee and Floodwall	0.84	-1.33	-1.35	0.34	-0.31	-0.53	-0.29	-0.31	-0.11	0.01	0.04
Big Five Levee System	-0.68	0.14	0.87	1.70	-0.29	2.13	-0.86	0.32	-0.05	-0.02	-0.03
Big Gum Drainage District	0.42	0.12	-0.04	0.77	-1.06	-1.18	0.23	-0.08	-0.27	-0.03	0.06
Big Lake and St. Francis Floodway East System	-8.49	-1.37	-1.28	-3.34	1.00	-1.53	-0.80	2.49	0.17	-0.01	0.10
Bois Brule Levee & Drainage District System	0.49	2.25	1.10	-1.18	0.67	0.17	0.14	-0.12	0.52	0.01	-0.05
Butler County Drainage District No. 12	0.82	-1.24	-0.75	-0.16	-0.12	0.17	-0.18	-0.10	-0.09	-0.01	-0.03
Cache River Levee System	0.46	-0.86	-0.88	0.13	0.05	0.35	0.43	0.35	-0.06	-0.02	-0.05
Cape Girardeau Flood Protection System	0.49	1.45	-1.57	-0.55	0.97	-0.22	-0.99	-0.39	-0.09	0.13	-0.02
Castor River Levee System	0.68	-0.42	0.10	-1.05	0.77	0.75	-0.60	-0.16	0.07	-0.02	-0.03
Cates Levee System	0.39	-0.39	-1.02	0.97	0.17	-0.20	-0.40	-0.16	-0.15	0.01	0.04
Central Clay Drainage District	0.97	-0.50	0.90	-0.68	-1.08	-0.04	0.64	0.07	0.02	-0.02	0.02
City of Millington Big Creek Levee System	0.74	-1.16	0.04	0.10	-0.18	1.14	-0.04	0.30	-0.40	0.03	-0.02
Clarendon Levee System	0.51	-0.30	-1.43	0.10	0.19	-0.39	-0.39	-0.22	-0.02	-0.01	-0.03
Clarksville Levee and Floodwall	1.12	-1.52	-0.15	-0.76	-0.21	0.79	-0.30	-0.07	-0.18	0.04	-0.03
Columbia Drainage & Levee District No.3 System	0.80	1.10	0.96	-1.21	-0.16	0.04	0.05	-0.14	0.20	0.00	-0.02
Commerce MO - St. Francis River System	-15.13	-0.80	0.33	-0.38	0.42	1.08	1.23	-1.71	-0.26	0.16	0.01
Conway County Drainage & Levee District No. 1	1.02	-1.10	-0.19	-0.39	0.03	0.97	0.22	0.16	-0.08	0.01	-0.01
Conway County Levee District No. 6	0.85	-0.53	-0.29	-0.10	0.29	1.18	0.73	0.41	0.00	0.00	-0.02
Dardanelle Levee/Carden Bottom Levee	0.54	-0.27	1.88	0.24	-0.07	-0.17	0.47	0.11	0.15	-0.02	-0.01
Des Arc Levee System	0.60	-0.07	-1.43	0.27	0.38	-0.33	-0.17	-0.16	-0.08	0.00	0.00
Des Arc Levee System	1.00	-2.19	1.72	0.21	2.32	-0.33	-0.17	-0.20	0.29	0.00	-0.04
East of Morrilton	0.47	0.07	1.34	0.40	-1.22	0.48	0.21	0.29	-0.45	-0.01	0.05
Elk Chute Levee System	0.71	0.12	1.14	-1.36	-0.71	-0.13	-0.37	-0.50	0.57	-0.01	-0.02
Faulkner County Levee District No. 1	0.72	-1.09	-1.35	0.29	-0.21	-0.48	-0.34	-0.32	0.01	0.02	0.05
Festus Crystal City Levee System	0.31	3.44	-0.63	-0.49	0.66	-0.94	0.13	-0.02	-0.10	0.10	0.01
Fort Smith Levee District No. 1	1.07	-0.08	-0.28	-1.46	0.34	0.92	-1.01	-0.29	-0.15	0.04	-0.01

Grand Tower / Degognia Levee System	0.07	0.73	1.24	0.39	-0.40	0.48	1.21	0.48	0.31	-0.06	-0.01
Greenville Harbor	0.81	-0.82	-0.27	-0.10	0.12	1.14	0.69	0.39	0.05	0.00	0.00
Harrisonville / Stringtown / Ft Chartres Levee System	-0.03	1.19	0.24	0.19	0.62	1.77	-0.70	0.10	0.08	0.01	0.00
Head of Fourche Island to Pennington Bayou	0.17	0.02	-0.02	0.67	-1.19	-1.18	0.11	-0.13	-0.04	0.10	0.04
Hempstead County AR	0.81	1.98	0.13	-1.57	-0.17	-0.60	-0.90	-0.57	-0.02	0.04	0.01
Honeysuckle White Levee	1.02	-0.56	-0.29	-0.73	0.17	1.02	-0.10	0.08	-0.13	0.04	0.00
Inter-River Levee System	0.63	-1.61	-0.09	-0.52	-0.36	0.94	-0.02	-0.10	0.42	-0.08	-0.05
Jasper County Levee District No. 1	0.66	-0.62	-1.29	0.66	0.32	-0.42	0.18	-0.05	-0.06	0.00	0.04
Kaskaskia Island Drainage & Levee District System	0.79	1.99	0.88	-1.47	0.26	0.14	-0.13	-0.15	0.11	0.02	-0.02
Little Red River Levee District No. 1	1.08	-1.59	-0.13	-0.48	-0.23	0.86	0.00	0.02	-0.03	0.01	-0.01
Little Red River Levee District No. 2	1.11	-1.95	0.04	-0.60	-0.26	0.69	-0.29	-0.17	0.03	0.01	0.00
Little River Drainage District Levee of Missouri System	-1.89	1.05	-1.58	-0.96	1.18	-0.19	-0.04	-0.65	-0.65	-0.53	0.01
Little Rock Flood Protection	0.71	-0.13	-0.26	0.27	-0.98	-1.43	0.47	-0.19	-0.03	-0.02	0.05
Little Rock to Pine Bluff (Tucker Lake)	0.72	0.22	0.27	0.08	-0.70	-0.59	1.02	0.19	0.02	-0.02	0.02
Long Prairie AR	0.62	0.53	1.10	-0.82	-0.92	0.23	-0.36	-0.19	-0.11	0.02	0.04
Lower Hartman Bottom Levee	0.43	0.06	-1.50	0.83	0.38	-0.10	0.56	0.10	0.17	-0.02	0.02
Massey Alexander Levee District	0.53	-0.34	-1.12	0.78	0.76	-0.46	0.27	-0.02	0.07	0.00	0.01
McKinney Bayou - Mid - North	0.82	0.22	1.27	-0.91	-0.81	0.02	-0.63	-0.30	-0.24	0.02	0.05
McKinney Bayou - South	0.91	0.45	1.00	-1.15	-0.46	-0.07	0.07	-0.17	0.07	0.01	0.02
McLean Bottom	0.10	0.25	-0.42	1.48	0.18	1.05	0.22	0.45	-0.31	0.00	0.03
Memphis - Nonconnah Levee System	0.81	0.68	0.76	-0.99	-0.49	0.05	0.50	0.37	-0.11	0.09	0.09
Memphis - Wolf River Backwater Levee System	-0.13	1.39	-0.47	0.01	-0.19	-1.18	0.78	0.15	-0.16	0.10	-0.39
Mississippi and Ohio Rivers Levee System at Cairo &	-1.06	2.84	1.26	2.09	-0.53	0.82	-0.62	0.72	-1.05	0.03	-0.02
Mississippi and White Rivers Below Helena System	-2.30	1.20	-0.25	3.01	0.07	1.17	-0.26	0.06	0.95	-0.08	0.06
New Madrid Floodway System	-0.31	-0.39	-0.65	1.19	0.41	-0.15	-0.30	-0.48	0.79	-0.05	0.11
New Madrid-Sikeston Ridge Levee System	0.33	-1.05	-1.40	0.40	-0.16	-0.43	0.01	-0.06	0.02	0.00	-0.04
Newport Levee District	0.26	-0.50	-1.47	0.38	0.12	-0.36	0.05	0.15	0.03	0.07	-0.01
North Little Rock Levee and Floodwall	0.82	-1.33	-1.34	0.20	-0.33	-0.56	-0.48	-0.39	-0.09	0.02	0.03
North Little Rock to Gillette	-1.02	0.28	0.28	1.10	-1.22	-0.90	-0.03	0.12	0.22	0.02	0.01

NSA Big Creek Levee System	1.08	-1.76	-0.02	-0.54	-0.12	0.72	-0.10	0.03	-0.14	0.04	-0.03
Point Remove Creek Drainage and Levee District	1.06	-0.48	1.21	-0.62	-0.53	-0.28	0.56	0.06	-0.08	-0.01	0.01
Prairie du Rocher / Edgar Lake System	0.18	2.46	0.37	0.01	0.11	-0.08	0.30	0.16	-0.05	0.00	0.01
Red River LB AR	0.64	2.23	0.78	-1.75	0.07	0.25	-0.44	-0.35	0.37	0.01	-0.01
Riverdale Private Levee	0.60	-1.03	-1.36	0.50	-0.06	-0.47	0.01	-0.07	-0.07	0.08	0.01
Rock Creek Levee	0.82	-1.07	-1.23	0.29	0.05	-0.60	-0.40	-0.35	-0.12	0.01	0.04
Roland Drainage District	0.67	0.27	-0.37	0.29	-0.85	-1.32	0.62	-0.09	-0.09	-0.02	0.05
Running Water Levee District	1.12	-0.82	0.96	-0.97	-1.21	-0.21	0.20	-0.12	-0.12	0.00	0.03
Russellville Dike and Pumping Station	0.31	1.63	-1.60	0.64	1.26	0.08	0.58	0.25	0.03	0.01	0.00
Sainte Genevieve Levee System No. 2	0.84	-1.18	1.57	0.74	2.92	-0.03	0.76	0.32	0.19	-0.01	-0.04
Sainte Genevieve No. 3 Levee System	0.39	1.56	-1.60	0.11	1.09	-0.03	-0.12	-0.08	0.02	0.02	-0.02
Southern Enterprise Private Levee	0.95	-0.99	-0.21	-0.16	0.12	1.05	0.56	0.31	-0.05	0.00	-0.01
St. Francis East to Big Lake West System	-3.79	-0.49	1.01	1.11	-1.81	-0.78	-1.13	0.04	0.21	-0.21	-0.28
Van Buren Levee District No. 1/Crawford County Levee	0.05	-0.65	-1.08	0.91	-0.11	-0.17	-0.37	-0.10	0.02	0.12	-0.08
Village Creek White River Mayberry Levee District	0.75	-0.40	1.07	-0.58	-0.80	-0.08	0.73	0.04	0.22	-0.03	0.03
Village of New Athens System	0.16	3.00	-1.75	0.35	1.85	0.30	0.44	0.28	0.06	0.01	-0.01
West Bank St. Francis Floodway System	-3.96	0.11	1.31	1.90	-1.56	-0.54	-1.24	0.65	0.26	0.07	-0.02
West of Morrilton	0.77	-1.69	5.11	1.50	3.82	-2.20	-0.54	-0.21	-0.41	0.02	0.02
Western Clay Drainage District	0.20	-0.09	-0.28	0.15	-0.98	-1.42	0.50	-0.02	0.15	-0.04	-0.02
White River Levee System	-1.07	0.16	1.27	-0.86	-0.55	0.12	0.38	0.03	-0.23	-0.12	0.01

Appendix D. Estimated maintenance costs for each levee in Arkansas based on models from literature

System Name	Length	Height	Maintenance Cost (Thousand $)
AR River North Bank	56.16	22	$ 542.08
Batesville Levee and Floodwall	0.92	8.5	$ 3.53
Big Five Levee System	54.6	19	$ 456.42
Big Gum Drainage District	8.86	14	$ 54.97
Big Lake and St. Francis Floodway East System	122.47	14.5	$ 786.21
Bois Brule Levee & Drainage District System	33.09	22	$ 319.40
Butler County Drainage District No. 12	4.37	9.5	$ 18.64
Cache River Levee System	5.33	15	$ 35.37
Cape Girardeau Flood Protection System	1.51	17.5	$ 11.65
Castor River Levee System	14.6	11.5	$ 74.85
Cates Levee System	9.89	14.5	$ 63.49
Central Clay Drainage District	12.3	11	$ 60.41
City of Millington Big Creek Levee System	1.51	12	$ 8.07
Clarendon Levee System	6.18	13	$ 35.68
Clarksville Levee and Floodwall	1.16	7	$ 3.70
Columbia Drainage & Levee District No.3 System	19.96	15.5	$ 136.74
Commerce MO - St. Francis River System	277.32	29	$ 3,513.53
Conway County Drainage & Levee District No. 1	2.63	12	$ 14.05
Conway County Levee District No. 6	4.38	17.5	$ 33.78
Dardanelle Levee/Carden Bottom Levee	28.84	15	$ 191.36
Des Arc Levee System	1.42	15.25	$ 0.02
Des Arc Levee System	20.07	10	$ 9.57
East of Morrilton	13.63	14.5	$ 89.91
Elk Chute Levee System	40.66	8.75	$ 87.50
Faulkner County Levee District No. 1	6.73	9.5	$ 160.25
Festus Crystal City Levee System	0.7	27	$ 1.69
Fort Smith Levee District No. 1	1.81	9.5	$ 28.70
Grand Tower / Degognia Levee System	36.57	22.5	$ 8.27
Greenville Harbor	7.86	16	$ 7.72
Harrisonville / Stringtown / Ft Chartres Levee System	34.41	21	$ 360.87
Head of Fourche Island to Pennington Bayou	21.39	13	$ 55.54
Hempstead County AR	9.77	13.75	$ 317.31
Honeysuckle White Levee	0.49	12.5	$ 123.49
Inter-River Levee System	31.13	8.5	$ 59.56
Jasper County Levee District No. 1	1.05	15	$ 2.72
Kaskaskia Island Drainage & Levee District System	14.78	18.5	$ 119.34
Little Red River Levee District No. 1	6.52	8.5	$ 6.97

Little Red River Levee District No. 2	10.81	5.5	$ 120.36
Little River Drainage District Levee of Missouri System	19.29	20.5	$ 24.99
Little Rock Flood Protection	7.51	12.5	$ 27.46
Little Rock to Pine Bluff (Tucker Lake)	8.77	17	$ 173.72
Long Prairie AR	20.23	11.6	$ 41.74
Lower Hartman Bottom Levee	10.23	20	$ 65.75
Massey Alexander Levee District	6.3	17.5	$ 104.58
McKinney Bayou - Mid - North	13.94	9	$ 89.92
McKinney Bayou - South	15.07	12.5	$ 48.59
McLean Bottom	12.29	22	$ 56.44
Memphis - Nonconnah Levee System	3.8	16	$ 83.75
Memphis - Wolf River Backwater Levee System	9.5	21.5	$ 118.63
Mississippi and Ohio Rivers Levee System at Cairo & Vicinity	21.96	28.5	$ 26.85
Mississippi and White Rivers Below Helena System	106.24	28.5	$ 89.65
New Madrid Floodway System	57.01	16	$ 273.49
New Madrid-Sikeston Ridge Levee System	10.48	11.88	$ 1,323.12
Newport Levee District	8.51	15	$ 402.84
North Little Rock Levee and Floodwall	2.97	7.5	$ 55.44
North Little Rock to Gillette	53.27	16	$ 56.47
NSA Big Creek Levee System	2.67	7.5	$ 10.11
Point Remove Creek Drainage and Levee District	7.2	11.5	$ 376.42
Prairie du Rocher / Edgar Lake System	16.5	25	$ 9.08
Red River LB AR	28.09	17.5	$ 36.91
Riverdale Private Levee	2.89	12	$ 180.60
Rock Creek Levee	0.59	9.5	$ 216.65
Roland Drainage District	4.09	15	$ 37.63
Running Water Levee District	7.64	7	$ 15.44
Russellville Dike and Pumping Station	1.2	27.5	$ 2.52
Sainte Genevieve Levee System No. 2	11.06	20	$ 27.14
Sainte Genevieve No. 3 Levee System	3.52	23	$ 24.35
Southern Enterprise Private Levee	3.15	14.5	$ 14.43
St. Francis East to Big Lake West System	112.75	11	$ 97.22
Van Buren Levee District No. 1/Crawford County Levee District	21.51	13.5	$ 35.49
Village Creek White River Mayberry Levee District	22.75	12.5	$ 20.22
Village of New Athens System	1.31	33	$ 553.72
West Bank St. Francis Floodway System	115.9	16	$ 128.81
West of Morrilton	14.05	12.5	$ 126.43
Western Clay Drainage District	20.3	13.35	$ 18.86
White River Levee System	39.31	15	$ 818.97