Regional Data-Driven Modeling of Levee Failure Due to Overtopping

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ABSTRACT

There are growing concerns regarding the increase in flood risk due to climate change and land use/land cover changes. In light of these changes, levees play an increasingly critical role in safeguarding communities, infrastructure, and the natural environment. However, the average age of levees in the United States is 60 years, with the majority operating under marginal conditions. The most common failure mode of earthen levees is breach due to overtopping. Existing methodologies evaluate the site-specific probability of levee overtopping and do not provide a holistic view of flood risk across a wider area. Here we present a regional-scale overtopping model for levees using a data-driven overtopping model that uses five variables: (1) levee construction classification, (2) overtopping depth, (3) overtopping duration, (4) erosion resistance classification, and (5) duration of levee loading before overtopping. The overtopping model is applied to levee systems in Wilton, California. The probability of breach due to overtopping is presented for three distinct scenarios (overtopping duration) during a 50-year flood event. The results show the probability of breach for the Wilton Levee ranges from 0.32 to 0.91 for overtopping durations of 6 hours and between 6 to 24 hours. For durations exceeding 24 hours, the probability of breach increases to a range of 0.73 to 0.98. The proposed framework offers a viable tool for performing regional-scale levee risk assessment, offering broader implications for enhancing preparedness, response, and recovery strategies in the face of escalating flood risks.

INTRODUCTION

Levees constitute the backbone of flood risk management globally. They are predominantly earthen embankments that control, divert, and contain water flow. Levee systems are found across the globe, including Asia, North America, Africa, and Europe; the global database of levees reports 19,248 km of levees safeguarding 42,343 km^2 across 153 river deltas (Nienhuis et al., 2022). In the United States alone, the National Levee Database (NLD) reports 6,814 documented levee systems extending over 38,000 km, protecting an estimated 23 million people and $2 trillion in properties (NLD, 2024). Notably, 97% of the levees in the U.S. are earthen embankments, with the remaining 3% comprising floodwalls. Despite the critical role, the average age of levees is 60 years old, most of which are under marginal conditions (ASCE, 2021). Compounding the issue, climate change projections show exacerbating patterns in the frequency and intensity of floods, further burdening aging levees (Mallakpour & Villarini, 2015; Mallakpour et al., 2020; Vahedifard et al., 2020). Intensified precipitation, sea level rise, and tropical storms can increase the likelihood of levee failure by overtopping, placing millions of people and critical infrastructure systems in leveed areas at heightened risk.

Levees can fail through several mechanisms, each with its distinct characteristics. Common failure modes include under-seepage, piping, slope instability, and overtopping (USACE, 2000; Van et al., 2022, USACE, 2024). Overtopping represents one of the most common failure mode for earthen levees (Foster et al., 2000; Hui et al., 2016; USACE, 2024). Within the USACE portfolio of levees, approximately 500 levee systems experienced overtopping, 100 of which were breached due to overtopping (USACE, 2018). A breach occurs when overtopping leads to substantial loss of the levee section due to erosion. In contrast, non-breach overtopping refers to scenarios where water overflows without causing a substantial loss of the levee system (USACE, 2024).

The increasing availability of data from past levee breaches, such as hydraulic loading conditions, levee materials, and levee construction standards, due to advancements in sensing and stream gauge monitoring, has led to the development of several databases, including the international-level performance database and levee loading and incident database (Ozer et al., 2019; Flynn et al., 2021). These databases facilitate the construction of models to calculate the probability of a levee breach by applying data-driven techniques (e.g., logistic regression or machine learning). Consequently, regional-scale analyses have become both essential and more feasible. However, the majority of existing studies on levee failures focus on individual levee sections (Vahedifard et al., 2020; Jasim et al., 2020) and thus lack a holistic view of flood risk across broader geographical regions.

The main objective of this study is to develop a scalable methodology for regional-scale levee risk assessment using publicly available datasets. For this, we implement the data-driven overtopping model of Flynn et al. (2022) into a GIS-based regional framework to identify sections across an entire levee system that are under heightened risk of breach. This proposed methodology enables iterative refinements of the probability of breach based on evolving climatic conditions. The study offers broader implications for improving preparedness, response, and recovery strategies in the context of escalating flood risks.

METHODOLOGY

Data-driven Overtopping Model

The overtopping model employed in this study was developed by Flynn et al. (2022) using a subset of the Levee Loading and Incident Database (LLID), consisting of qualitative and quantitative data on USACE levees (Flynn et al., 2021). The model is based on data from 185 levee overtopping incidents and utilizes a logistic regression model to predict the probability of levee breach due to overtopping (Flynn et al., 2022). The model incorporates five key inputs of numerical and categorical values, as shown in Table 1.

Here, the probability of breach (Z) is calculated as a probability of occurrence ranging from 0 to 1, with a threshold of 0.5 as a cutoff between breach and non-breach. The linear component (Z) is shown in Equation 1, and the logistic function is applied to Z as presented in Equation 2. It was validated using the k-fold cross-validation method, yielding a model accuracy of 80.7%, suggesting a good fit (Landis et al., 1977).

$$Z = 0.93 - 1.13 \cdot X_{X_3=2} + 0.87 \cdot X_{X_4=2} + 1.27. X_{X_4=3} + 0.08. X_{X_5=2} + 1.85 X_{X_5=3} - 1.74 \cdot X_{X_6=2} - 3.93 \cdot X_{X_6=3} - 0.42 \cdot X_{X_7=2} + 0.17 \cdot X_{X_7=3} + 2.18 \cdot X_{X_4=2,X_7=2,} + 2.65 \cdot X_{X_4=3,X_7=2} + 0.60 \cdot X_{X_4=2,X_7=3} + 2.29 \cdot X_{X_4=3,X_7=3} + 1.35 \cdot X_{X_3=2,X_6=2} - 0.51 \cdot X_{X_3=2,X_6=3} \tag{1}$$

$$P(breach) = \frac{1}{1 + e^{-z}} \tag{2}$$

where all variables are defined in Table 1. For example, $X_{x_{4=3}}$ refers to overtopping depth level 1, which is of greater than 0.305m, $X_{x_{7=2}}$refers to duration of levee loading prior to overtopping level 2, which is between 3-14 days and $X_{X_4=2,X_7=2,}$ is an interaction term between level 2, overtopping depth and level 2, duration of levee loading prior to overtopping. The model incorporates the interaction effects between X_4 and X_7 as well as between X_3 and X_6.

Table 1. Summary of model input parameters

Code	Variable	Definition	Type	Levels (units)
X_3	Levee construction classification	Construction entity, reflecting the quality of construction and maintenance	Categorical	1: Local 2: Federal
X_4	Overtopping depth	height of the water level above the levee crest	Categorical	1: <0.152m 2: 0.152 – 0.305m 3: >0.305m
X_5	Overtopping duration	duration of overtopping until a breach occurs or for non-breach scenarios; it represents the duration in which water level exceeds levee height	Categorical	1: <6 hours 2: 6 – 24 hours 3: >24 hours
X_6	Erosion resistance classification	ability of the levee to resist erosion when subject to overtopping load	Categorical	1: Low 2: Moderate 3: High
X_7	Duration of levee loading prior to overtopping	duration, the levee was subjected to hydraulic load above the riverside toe prior to overtopping	Categorical	1: <3 days 2: 3 – 14 days 3: >14 days

Study Area

California is home to 1,705 levee systems extending over 7,700 km, safeguarding critical infrastructures and an estimated 11 million people (Vahedifard et al., 2023). Notably, 25% of California earthen levees have experienced structural failures over the last century (Florsheim & Dettinger, 2007). This study focuses on 11 earthen levee systems spanning 44.4 km along the Cosumnes River in Wilton, California, which fall under Reclamation District 800, shown in Figure 2. Wilton, home to an estimated 5200 residents (ACS, 2019), was selected for two primary reasons: (1) a recent double levee breach in December 2022 corresponding to a 50-year flood event indicating the vulnerability of these levee systems, and (2) the opportunity to demonstrate the performance of the proposed regional-scale approach in rural areas with limited levee information.

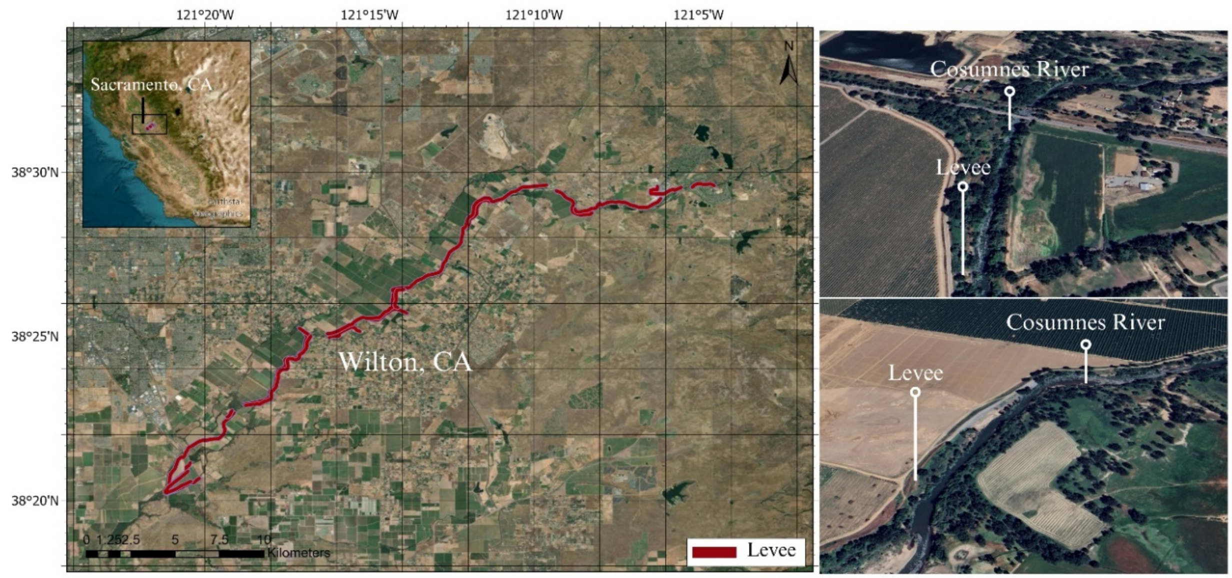

Figure 1. Map showing the study area of 11 levee systems in Wilton, California.

Regional-Scale Analysis

The regional-scale analysis was conducted using ArcGIS Pro. The levee system was imported from the NLD. Levees, represented as a line feature, were transformed into point features at 3-meter intervals. This resulted in 14,800 points representing the entire Wilton levee system. Subsequently, the input parameters, such as the elevation and soil map, were imported as raster layers and extracted for each levee point. Hydrological variables were computed for the entire levee system through stream gauge data. The input parameters were then used to compute the probability of breach by overtopping for each point. A comprehensive overview of the proposed methodology is presented in Figure 2.

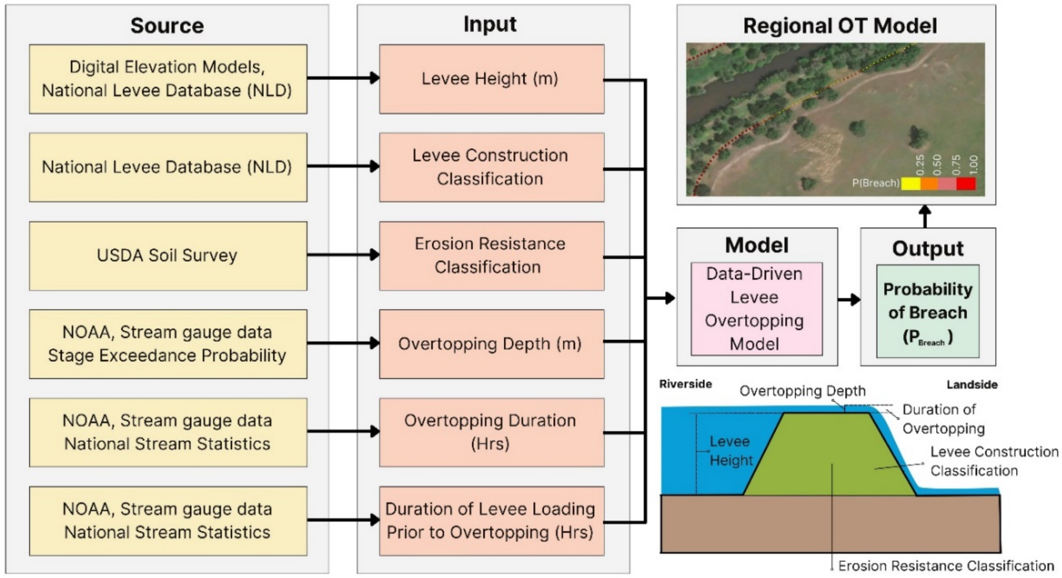

Figure 2. Overview of methodology for the regional-scale overtopping model.

Input Parameters

Levee Construction Classification

The levee data were obtained from the NLD, which includes information on the location, length, height, and construction classification of both federal and non-federal levees. Here, we specifically extract the construction classification data. The study area comprised 11 non-federally constructed and maintained levee systems spanning 44.4 km. Table 2 provides a summary of levee systems included in the study area.

Table 2. Summary of levee systems

No.	Segment ID	Levee name	Construction Classification	Length (km)
1	1905048054	Levee 132	Locally constructed/ maintained	1.72
2	1905048053	Levee 29	Locally constructed/ maintained	2.90
3	1905048039	Levee 99	Locally constructed/ maintained	7.23
4	1905048043	Levee 82	Locally constructed/ maintained	0.43
5	1905048034	Levee 103	Locally constructed/ maintained	5.84
6	1905048035	Levee 83	Locally constructed/ maintained	5.78
7	1905048045	Levee 81	Locally constructed/ maintained	0.55
8	1905048050	Levee 50	Locally constructed/ maintained	1.67
9	1905048049	Levee 18	Locally constructed/ maintained	14.92
10	1905048051	Levee 45	Locally constructed/ maintained	1.35
11	1905048036	Levee 41	Locally constructed/ maintained	2.01

Overtopping Depth

Risk assessments of flood protection infrastructure typically rely on historical extremes of rainfall and flood records. In this study, we use the annual peak flow data from gauge ID 11335000 on the Cosumnes River, covering a period from 1913 to 2023. Initially, the annual peak flows were sorted in descending order and assigned ranks. Subsequently, we calculated the exceedance probability (P) using Equation 3.

$$P = \frac{m}{n+1} \tag{3}$$

where *m* represents the rank of discharge, and *n* is the total number of years in the record.

To model the distribution of extreme values, we fitted a log-Pearson type III distribution, a widely used approach for extreme values, as shown in Figure 3. The distribution was selected primarily for its flexibility in fitting skewed datasets typically observed in hydrological records. We also constructed 95% confidence intervals to capture the uncertainty in the estimates of flood probabilities. Furthermore, the discharge was then translated into stage heights using rating curves provided by the USGS water watch (USGS, 2024). The stage height for varying recurrence intervals (H_{RI}) was then corrected for the difference in datums using a correction factor (D), and the overtopping depth (OT_{RI}) for each point (n) along the levee system was calculated, as shown in Equation 4. The correction factor is obtained through the vertical datum conversion tool, VDatum (NOAA, 2024)

$$OT_{RI,n} = (H_{RI} + D) - H_{levee,n} \tag{4}$$

where, $H_{levee,n}$ represents the height of the levee crest at point (n) along the levee system.

The NLD typically provides the average height of federal levees. However, the height data on non-federal levees, including the Wilton levee systems, was missing. To address this gap, we utilized the digital elevation models (DEMs) from USGS Earth Explorer (USGS, 2024), featuring a one-arc-second equivalent to approximately 30 m resolution.

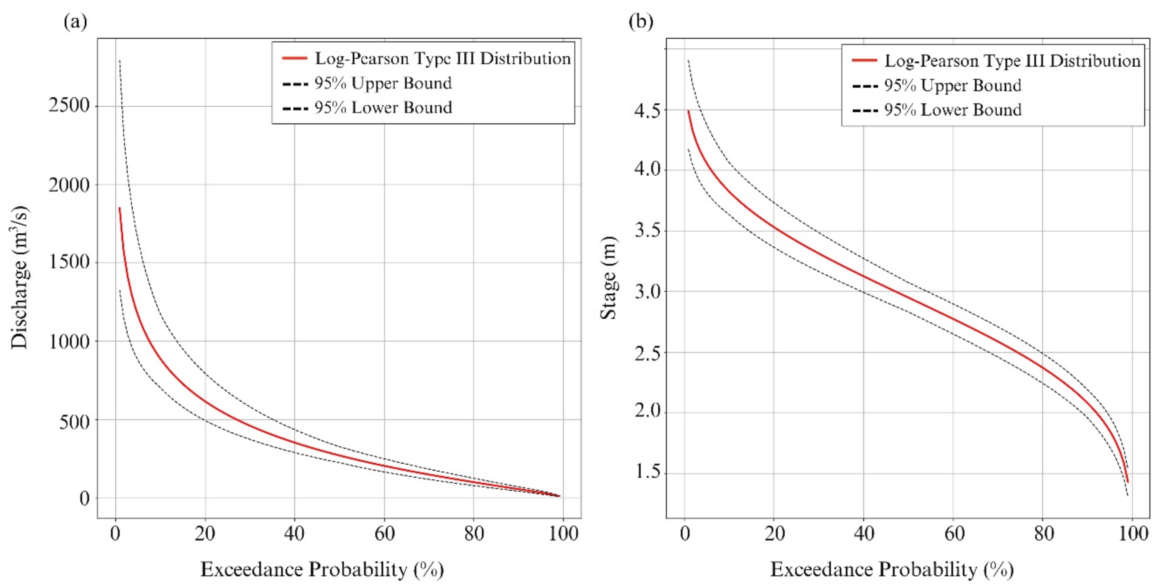

Figure 3. (a) Exceedance probability plot of annual peak discharge for Cosumnes River, based on stream gauge ID 11335000 data, (b) Exceedance probability plot of peak stage for Cosumnes River, based on stream gauge ID 11335000 data.

Overtopping Duration

The overtopping duration is typically derived from hydrographs. A widely used approach involves examining nearby gauge station data to identify peak flow events that approximate the annual exceedance probability, subsequently using the duration of these events. However, this approach is inherently arbitrary. To address this limitation, we defined three scenarios based on categorical variables within the data-driven overtopping model. Here, the model classifies the overtopping durations into three distinct scenarios: less than 6 hours, 6 to 24 hours, and longer than 24 hours. The probability of breach by overtopping was then calculated for each scenario.

Erosion Resistance Classification

The levee material was extracted from a web soil survey conducted by the U.S. Department of Agriculture, Natural Resources Conservation Service (USDA, 2024). This survey provides comprehensive soil data covering over 95% of the U.S. counties. The soil maps show that the Wilton levees composition includes 81.2% silty sand (SM) and 18.8% low-plasticity clay (CL). Subsequently, the levee material types are used to classify the levee into three classes of relative erosion resistance following the methodology established by Flynn et al. (2022).

Duration of Levee Loading Prior to Overtopping

The duration of levee loading prior to overtopping is also a categorical variable of three distinct levels: less than 3 days, 3 to 14 days, and more than 14 days. This variable serves as an indicator of the saturation of the levee prior to overtopping. Here, the 3-day scenario corresponds to flashy loading where the stage increases rapidly, the 3-14-day scenario corresponds to a moderately rising river allowing for more saturation, and the 14-day scenario represents a slow rising stage resulting in the highest saturation levels. Increased saturation leads to increased porewater pressure within the levee, thus reducing its overall strength. In this study, we select the less than 3-day duration for all our analyses, reflecting the duration observed during the most recent 50-year flood event in December 2022.

RESULTS

Figure 4 presents the results for a 50-year flood event under overtopping duration of 6 to 24 hours. The analyses yielded the probability of breach for each 14,800 points along the levee system. Across the entire system, the probability of breach ranged from 0.32 to 0.91 for short and moderate durations. The longer duration shows a substantial increase in the probability of breach, ranging from 0.73 to 0.98. Notably, levee 18 (ID: 1905048049), which was breached in December 2022, shows a higher probability of breach (P=0.91). The results can be iteratively updated based on the evolving hydrological loading scenarios.

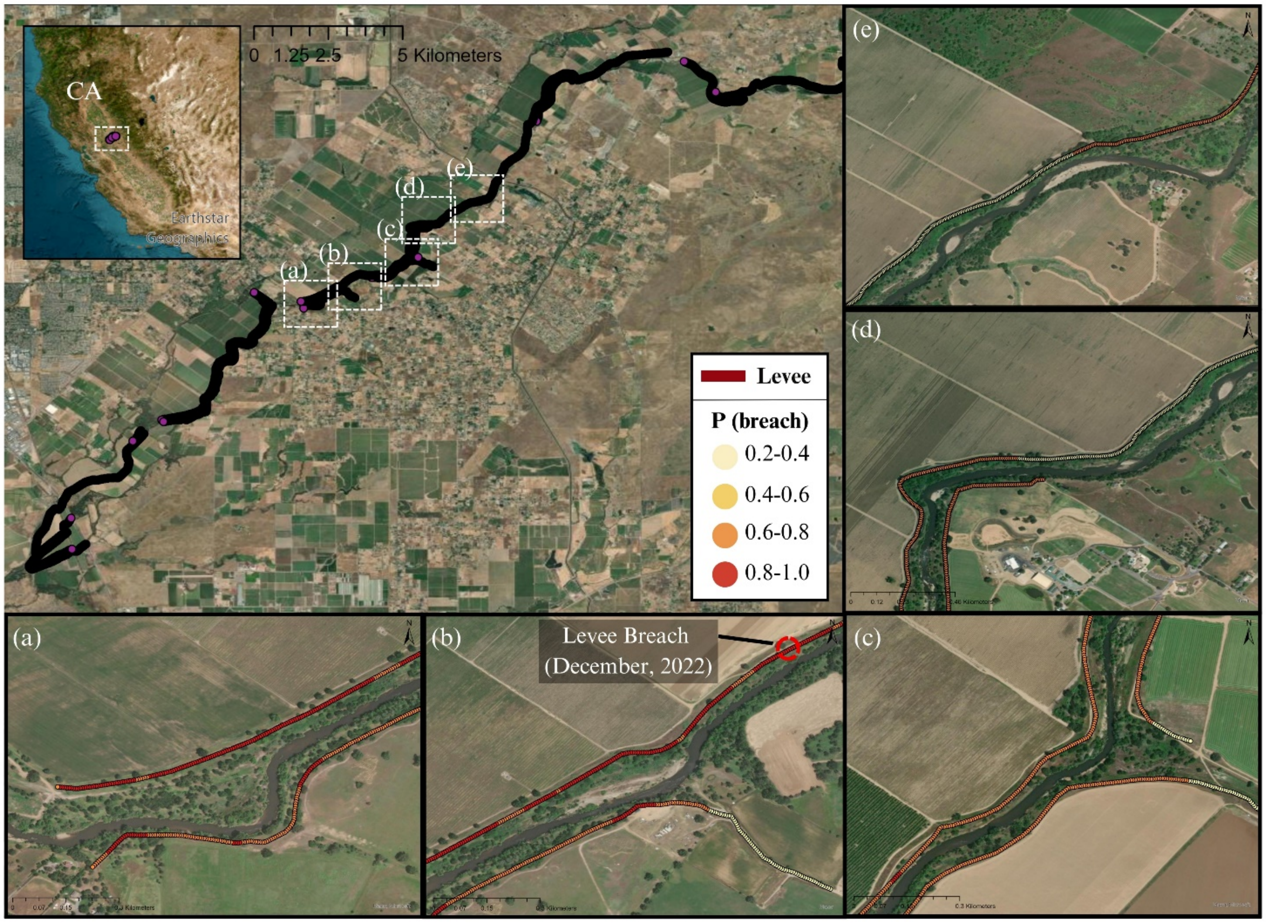

Figure 4. (a) through (e) illustrates the spatial distribution of the probability of breach across the central Wilton levee system for a 50-year flood event and overtopping duration of less than 6 to 24 hours.

A Cumulative distribution function was developed under 3 scenarios of overtopping duration, shown in Figure 5. The CDF illustrates that the probability of breach increases rapidly for a duration longer than 24 hours. The figures show that the duration of overtopping has a substantial impact on the probability of breach.

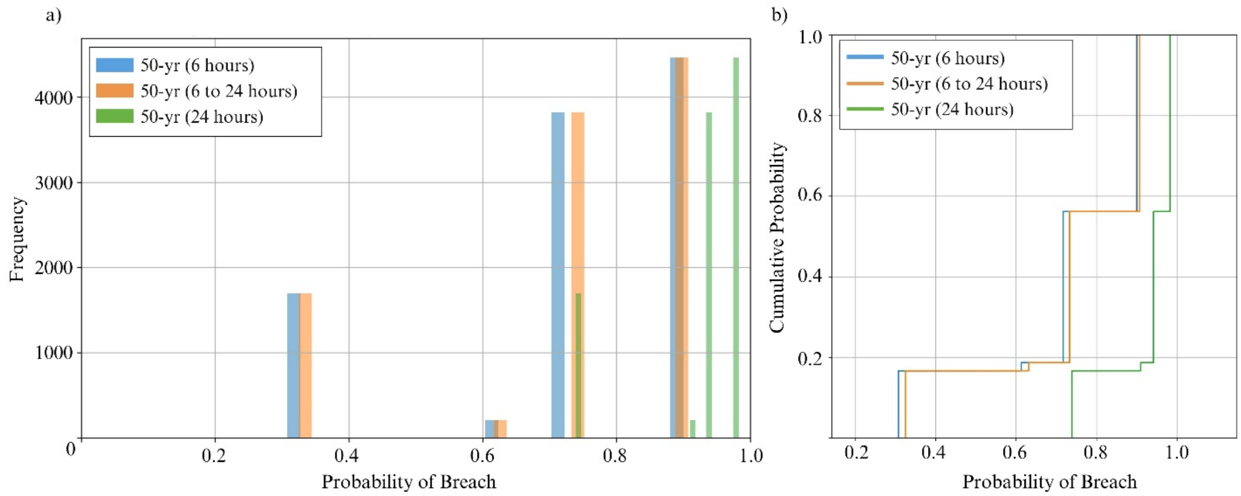

Figure 5. a) Histogram illustrating the breach probability under three scenarios for a 50-year flood event, and b) The cumulative distribution function illustrates the breach probability under three scenarios for a 50-year flood event.

CONCLUSIONS

Our study aimed to develop a scalable approach for regional-scale assessment of levee breaches due to overtopping. Given the increasing availability of levee overtopping data, we propose using data-driven models that employ machine learning algorithms such as decision trees, random forests, support vector machines, and logistic regression models to evaluate the probability of levee breach. Toward this goal, we used the data-driven overtopping model developed by Flynn et al. (2022) to compute the probability of breach for the Wilton levee system under three overtopping duration scenarios. The results indicate that the probability of breach for shorter (6 hours) and moderate (6 to 24 hours) durations, the probability of breach ranged from 0.32 to 0.73, while longer durations showed a substantial increase, ranging from 0.73 to 0.98.

Traditional methods for assessing the vulnerability of individual levee sections provide comprehensive assessments of risk. However, they fail to provide a holistic view of risk across a larger area. This shortfall results in the levee management teams, emergency managers, and decision-makers being uncertain about the distribution of risk. Our proposed approach offers a practical mechanism for addressing these issues. However, our findings are subjected to limitations, including the use of a 30-m resolution for elevation and exclusion of attenuation due to routing. Future studies can employ LiDAR data for finer resolutions and hydrological models to compute the stage at points along the levee.

This research provides insights into the distribution of levee risk at the regional level. For further research, we propose developing robust overtopping models using machine learning techniques and exploring how a regional risk analysis may aid in the allocation of resources for the maintenance and operation of levees, emergency response, and planning. Our analyses of the Wilton levees represent an initial step towards regional-scale assessments of levee overtopping, which has broader implications in enhancing preparedness, response, and recovery.

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