



Assessing Climate Change Impacts on Flood-Protection Infrastructure and Marginalized Communities: Insights from the Pajaro Levee

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ABSTRACT

Historically underserved and socially vulnerable communities in the United States are often located behind levees, exposing them to compounded risks from deteriorating flood-protection infrastructure and intensifying climate change-driven extreme events. This study uses a methodology to quantify climate change impacts on flood-protection infrastructure resiliency as a first step to evaluate how flood risk assessments serve disadvantaged communities, focusing on a case study levee in Pajaro, California.

Peak flow frequency changes, based on parameters linking current design recurrence intervals to future requirements, are used to adapt designs to evolving hydrologic conditions. A simplified, physically-based breach model is employed to construct fragility functions to estimate failure probabilities. These functions incorporate parameter variations without requiring system reanalysis, advancing risk assessment and planning processes.

The findings highlight critical vulnerabilities and offer insights to inform mitigation, planning, and preparedness strategies. This research underscores the importance of incorporating environmental justice principles into proactive climate adaptation practices to build resilient communities and sustainable flood-protection systems. Engineering decision-making must extend to consider and engage in a multidisciplinary conversation on the broader consequences of where and how we build, whom we protect, and how infrastructure either mitigates or amplifies social inequities.



1 INTRODUCTION

Flood-related damage to infrastructure in the United States has escalated significantly in recent years, driven by the intersection of increased exposure, aging infrastructure, and the intensifying frequency and severity of extreme weather events, resulting in concerns with respect to the reliability of levee systems. These concerns are most elevated where historically underserved and socially vulnerable communities (HUSVCs) live behind these structures, as the capacity to mitigate risks and disaster recovery is substantially lower. Understanding and preparing for the future impacts of climate change demands an evaluation of how critical infrastructure, like levees, will perform under extreme conditions (Vahedifard et al. 2020) and how the risks of infrastructure failures for HUSVCs may be reduced.

Flood hazard mitigation efforts have traditionally emphasized prevention, with flood control infrastructure (FCI) serving as the principal line of defense. However, a changing climate is altering precipitation patterns and flood frequencies, which directly threatens the stability of both natural and constructed earthen embankments such as levees (U.S. Army Corps of Engineers 2018).

Despite their vital role, many levees face substantial challenges. Although the majority of the U.S. Army Corps of Engineers (USACE) levee portfolio is classified as low-risk, nearly 45% of the protected population is situated behind levees deemed high- or very high-risk, raising concerns of environmental and climate justice, or the idea that environmental benefits and burdens are equitably distributed. At the same time, about 80% of these high-risk levees exhibit performance issues that could result in failure even before overtopping occurs (ASCE, 2021). Compounding these concerns is the fact that many levees were constructed over 150 years ago, often without engineering standards and frequently on weak, compressible soils. Given these vulnerabilities, ensuring that levees can withstand severe floods is crucial for the resilience of surrounding communities.

Traditionally, the design and risk assessment of FCI has relied on historical records of extreme rainfall and flood events, assuming relative stationarity in the behavior of such extremes over time. However, advances in the understanding of the frequency of extreme events and changes in the magnitude and recurrence of natural hazards with anthropogenic climate disruption challenge these assumptions, raising urgent questions about the adequacy of aging flood protection systems under future climatic conditions (Milly et al, 2008).

In response to these emerging challenges, this study proposes a methodology to quantify the impacts of climate change on the resilience of flood protection infrastructure. Focusing on a case-study levee in Pajaro, California, we examine shifts in peak flow frequency by linking current design recurrence intervals to future hydrologic demands. To assess levee vulnerability, a simplified, physically-based breach model is employed to simulate critical breaching processes and to develop parameterized fragility functions estimating failure probabilities. Through this approach, the study identifies critical vulnerabilities and provides insights that can inform more adaptive mitigation, planning, and preparedness strategies.

2 METHODOLOGY

When evaluating flood hazards in levee systems, overtopping remains the most prevalent failure mechanism, followed by internal erosion (piping) and slope instability (Jasim et al., 2017). These failure modes are highly dependent on the levee’s geometric configuration, material characteristics, and the prevailing hydraulic conditions at the site. The methodology employed in this study consists of four primary steps: (i) Development of a numerical levee model to simulate structural response under overtopping conditions, incorporating the geometric and material properties of the levee cross-section; (ii) Flood hazard characterization, involving the analysis of hydrologic data to define peak flows for different recurrence intervals; (iii) Generation of various flood loading profiles for different recurrence intervals, accounting for uncertainties in hydraulic parameters through probabilistic sampling; (iv) Fragility function fitting using the outcomes of the simulations to estimate the probability of levee failure under different flood scenarios, (v) understanding the effects of the 2023 flooding through interviews with affected Pajaro residents. The following sections describe the site and each step of the methodology in detail.

3 CASE STUDY: PAJARO RIVER LEVEE

The Pajaro River flood protection project was developed in 1949 to reduce frequent flooding in Watsonville, the town of Pajaro, and surrounding communities. Located along the Santa Cruz–Monterey County border (Figure 1), the system primarily consists of earthen levees designed to prevent overtopping during high-flow events. This levee was selected due to its well-documented flood history, including six major events between 1955 and 2023, and its high social vulnerability (OEHA 2021, FEMA 2023, USACE 2024).

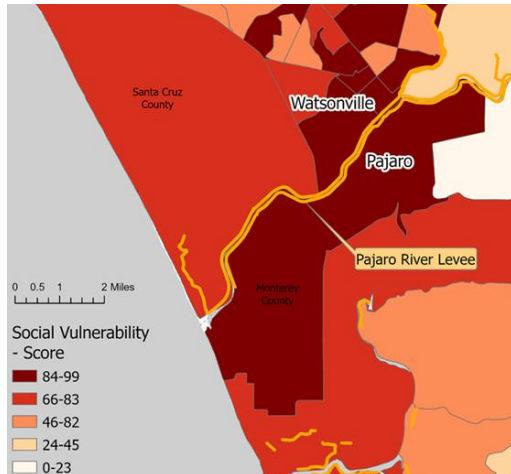


Figure 1 - Pajaro Levee location and Social Vulnerability Score

3.1 Numerical breach model

This study evaluates two levee cross-section configurations: the existing (or old) design and an alternative configuration aligned with current USACE design standards (USACE 2017). For the purposes of comparison, the crest elevation in the USACE-conforming configuration was assumed to be 4 feet higher than the existing design, as detailed in Table 1.

The analysis focuses on overtopping-induced failure in homogeneous levee embankments of non-cohesive soils. In this failure scenario, progressive surface erosion dominates the breaching process, typically initiating at the downstream face and progressing through lateral widening and localized mass failures along the breach sides due to geomaterial instability (Rahimi et al., 2023). To model this behavior, the software DLBreach (Wu, 2016) was used to implement a simplified, physically-based breach simulation. The model represents the levee as a trapezoidal cross-section (Figure 2) and treats overtopping flow as passing over a broad-crested weir. For inland levees, such as those studied here, the breach is modeled as one-way, where erosion is confined to the downstream slope, while the upstream slope remains largely intact.

Table 1 - Comparison of Existing Levee Cross-Section and USACE-Conforming Alternative Design Parameters

Parameter	Current design	Alternative Design
Waterside Slope, sUS	1V:2.5H	1V:3H
Landside Slope, sDS	1V:2H	1V:3H
Crest Width, bTOP	12 ft	20 ft
Crest Elevation, H	11 ft	15 ft

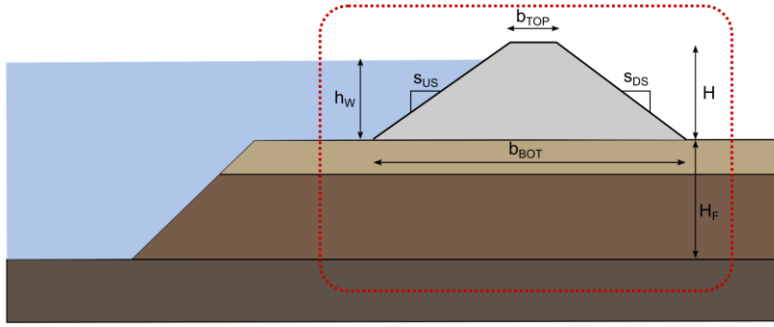


Figure 2 - Simplified levee cross-section and geometric parameters

3.2 Probabilistic demand models

The Natural Resources Conservation Service (NRCS) unit hydrograph shown in Figure 2 will be used for the analysis. The initial water height behind the levee can theoretically range from 0% to 100% of the levee height. However, data from the National Levee Database (USACE 2024) for the Pajaro River Left Bank indicate that, historically, water levels have most frequently reached around 25% of the levee height. Based on this information, a probability density function (PDF) was developed to represent the distribution of historical loading levels as a percentage of levee height. This PDF was then used to randomly sample initial water heights in the simulations, capturing the variability in historic loading conditions.

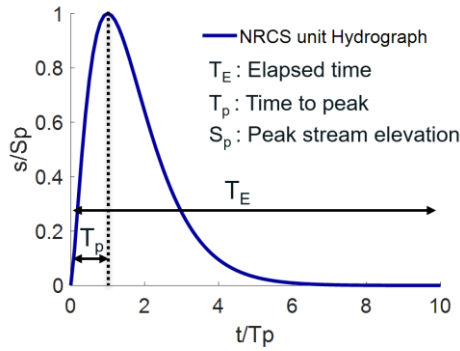


Figure 3 - Schematic NRCS unit Hydrograph

3.3 Climate change-adjusted flood peak frequency

In this study, projected future streamflow simulations are used to estimate changes in peak flows for selected recurrence intervals. The design recurrence interval is estimated using the approach developed by Mailhot and Duchesne (2010), incorporating an adjustment parameter, ρ , calculated across the western U.S. by Maurer et al. (2018). This parameter links the current design recurrence interval to that required under future conditions as expressed in Eq. 1,

$$T_o = T_c \left[\frac{1}{1 - \frac{(1 - \rho)\beta t_d}{100}} \right]$$

where T_o is the design recurrence interval to be used at the time of installation; T_c is the critical recurrence interval representing the target level of protection at a future reference year; t_d is the design life of the levee; ρ is the fractional increase in flood magnitude over a 100-year period; and β is the fraction of the design life at which the flood level associated with T_c is expected to be reached. In this study, we adopt a value of $\rho=0.35$ for both 25-year and 100-year flows in Pajaro, CA, as reported by Maurer et al. A value of $\beta=0.5$ is assumed, indicating that the design flood level corresponding to T_c will likely be reached midway through the levee’s service life. The resulting values are presented in Table 2.

Table 2 - Adjusted design recurrence intervals, T_0 , for Pajaro, CA.

t_d (yrs)	$T_C = 25$ (yrs)	$T_C = 100$ (yrs)
20	27	107
40	29	114
60	32	123
80	33	133
100	37	146

3.4 Flood hazard load profile

The probabilistic flood hazard load profile used in this study is based on the model proposed by Rahimi and Shafieezadeh (2023) and is defined as:

$$h = s + C_h H$$

where h is the total flood demand height, s is the river stage height, obtained from Figure 1, H is the levee crest elevation, and C_h is the initial water elevation in the levee, as a percentage of H . In this study, H takes on two values corresponding to the old and alternative cross-sections, as listed in Table 1. The river stage s is computed as a function of several random variables: the peak flow recurrence frequency (PRF), the time to peak T_E , and the peak flood stage reference S_p . These, along with the parameter C_h , are sampled from the probability distributions summarized in Table 3. This formulation enables a probabilistic characterization of the flood demand on the levee system, capturing the uncertainty inherent in hydrologic loading. The hydrographs generated for this study serve as input to the DLBreach numerical model, effectively covering RI consistent with Table 2.

Table 3. Random variables considered in the Flood hazard load profile

Variable	Distribution	Distribution parameters		Reference
		Mean	Standard deviation	
T_E (yrs)	Normal	72	15.8	(Rahimi et al. 2023)
S_p (m)	Uniform	0.57 (min)	8.4 (max)	(USGS, 2019) and Table 2
PRF	Normal	350	84	(Sheppard and Miller, 2003)
C_h	Lognormal	0.3	0.62	(USACE 2024)

3.5 Fragility analysis

Fragility analysis begins with the identification of performance states that characterize system failure. In this study, two key limit states were considered to assess levee performance during overtopping scenarios. The first event (E_i) marks the initiation of overtopping, defined as the moment when the rising water level exceeds the levee crest elevation. The second event (E_j) corresponds to complete structural failure, occurring when the breach bottom elevation drops below both the headwater and tailwater levels, indicating that the levee materials have been entirely eroded. Figure 4 illustrates the timing of these two events for the March 2023 flood. As shown in Figure 4(a), it took approximately 21.7 hours for the water level to rise from the base to the crest of the levee, marking the onset of overtopping. Complete failure followed 66 minutes later, as seen in Figure 4(b), when the breach was fully developed.

To efficiently explore the range of possible flood and structural conditions while managing computational costs, uncertainty in the model variables (listed in Table 3) was addressed using Progressive Latin Hypercube Sampling (PLHS) (Sheikholeslami and Razavi, 2017). A total of 5,000 simulations were run for the following scenarios: (i) an existing cross section without initial water elevation, (ii) an existing cross section with initial water elevation, (iii) an alternative cross section with initial water elevation. Logistic regression was used to develop fragility curves for each case.

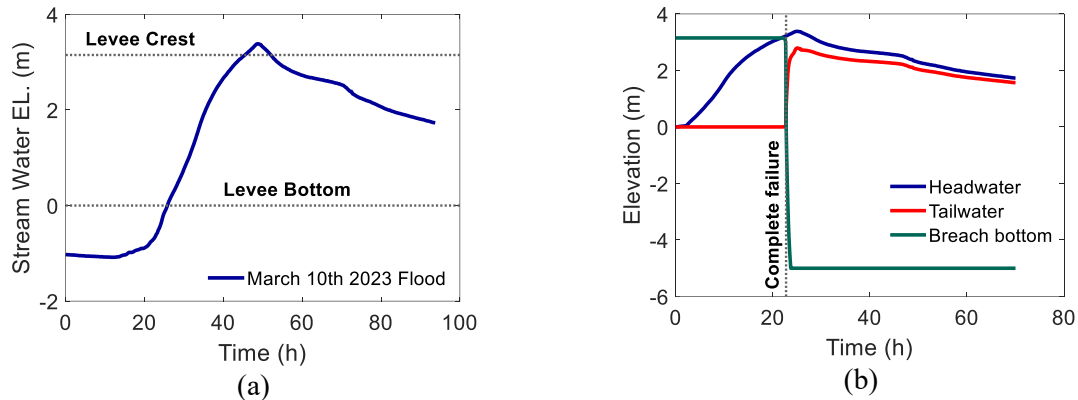


Figure 4 - Time to performance events: (a) overtopping initiation and (b) levee materials washed away

4 RESULTS

The resulting fragility curves for the complete failure event are shown in Figure 5. Across all scenarios, flood events with recurrence intervals exceeding 18 years were found to result in near-certain failure (close to 100% probability). This finding aligns with the real-world outcome of the March 2023 Pajaro levee failure, which occurred during a flood event with an estimated recurrence interval of just 8 years (USGS, 2019). Interestingly, the fragility curve for the alternative cross-section with initial water elevation is very similar to that of the current design without initial water. This suggests that increasing the levee dimensions alone, as proposed in the alternative design, is insufficient to achieve a meaningful improvement in performance, especially under the changes in climate extremes expected from global warming.

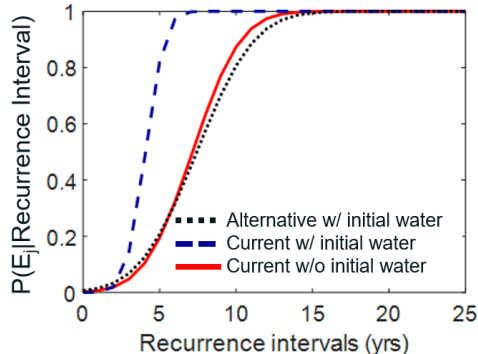


Figure 5 - Fragility curve as a function of the recurrence interval of the flood event for complete levee failure

5 FINAL REMARKS: INTEGRATING ENGINEERING, CLIMATE RESILIENCE, AND ENVIRONMENTAL JUSTICE

This study provides a quantitative framework for evaluating levee performance under future climate scenarios, using a case study of the Pajaro River levee, a system that protects socially vulnerable communities (Figure 1) with a long history of flood exposure. By incorporating probabilistic modeling of overtopping failure and future-adjusted flood hazard profiles, we show that levee performance is highly sensitive to changes in hydrologic loading and geometric configuration.

While infrastructure upgrades may offer incremental improvements, our analysis demonstrates that these alone may be insufficient. As illustrated in the fragility curves (Figure 4), the alternative levee cross-section performs similarly to the current design under certain initial conditions, suggesting that substantial redesign or complementary non-structural measures (e.g., levee setbacks, riprap, floodwalls) are necessary for meaningful risk reduction, as suggested by the USACE.



As climate change drives more intense and frequent flooding, the recurrence intervals used for design must be revisited. Table 2 shows that a levee designed today for a 100-year level of protection may require the equivalent of a 146-year design standard to offer the same future safety. Current guidance by USACE and California DWR recommends a minimum 100-year level of protection, with a long-term target of 200-year protection, especially critical for disadvantaged communities. Designing to outdated recurrence intervals risks institutionalizing inequity in infrastructure safety. Moreover, flood control infrastructure itself reshapes risk, not by eliminating flooding, but by redistributing where and when it occurs. This raises critical questions: who benefits from this protection, and who is left more exposed as a result? In many cases, including in Pajaro, as our interviews with residents showed, vulnerable populations settle in flood-prone zones due to affordability or land availability, only to become more exposed when levees fail. Levees often enable development in previously uninhabitable floodplains, increasing population density and economic value behind them, thereby compounding future flood risk. Engineering decision-making must therefore extend beyond structural design. It must consider and engage in a multidisciplinary conversation on the broader consequences of where and how we build, whom we protect, and how infrastructure either mitigates or amplifies social inequities.

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