NATIONAL ACADEMIES Sciences Engineering Medicine

TRB TRANSPORTATION RESEARCH BOARD

TRB Webinar: Improving Geotechnical Asset Resilience—Design, Monitoring, and Modeling

November 14, 2024

12:00 – 1:30 PM

PDH Certification Information

1.5 Professional Development Hours (PDH) – see follow-up email

You must attend the entire webinar.

Questions? Contact Andie Pitchford at TRBwebinar@nas.edu

The Transportation Research Board has met the standards and requirements of the Registered Continuing Education Program. Credit earned on completion of this program will be reported to RCEP at RCEP.net. A certificate of completion will be issued to each participant. As such, it does not include content that may be deemed or construed to be an approval or endorsement by the RCEP.

ENGINEERING RCEP REGISTERED CONTINUING EDUCATION PROGRAM

Purpose Statement

This webinar will cover current geotechnical asset resilience practices and advancements in the broader framework of transportation asset management (TAM), project planning, and life-cycle analysis.

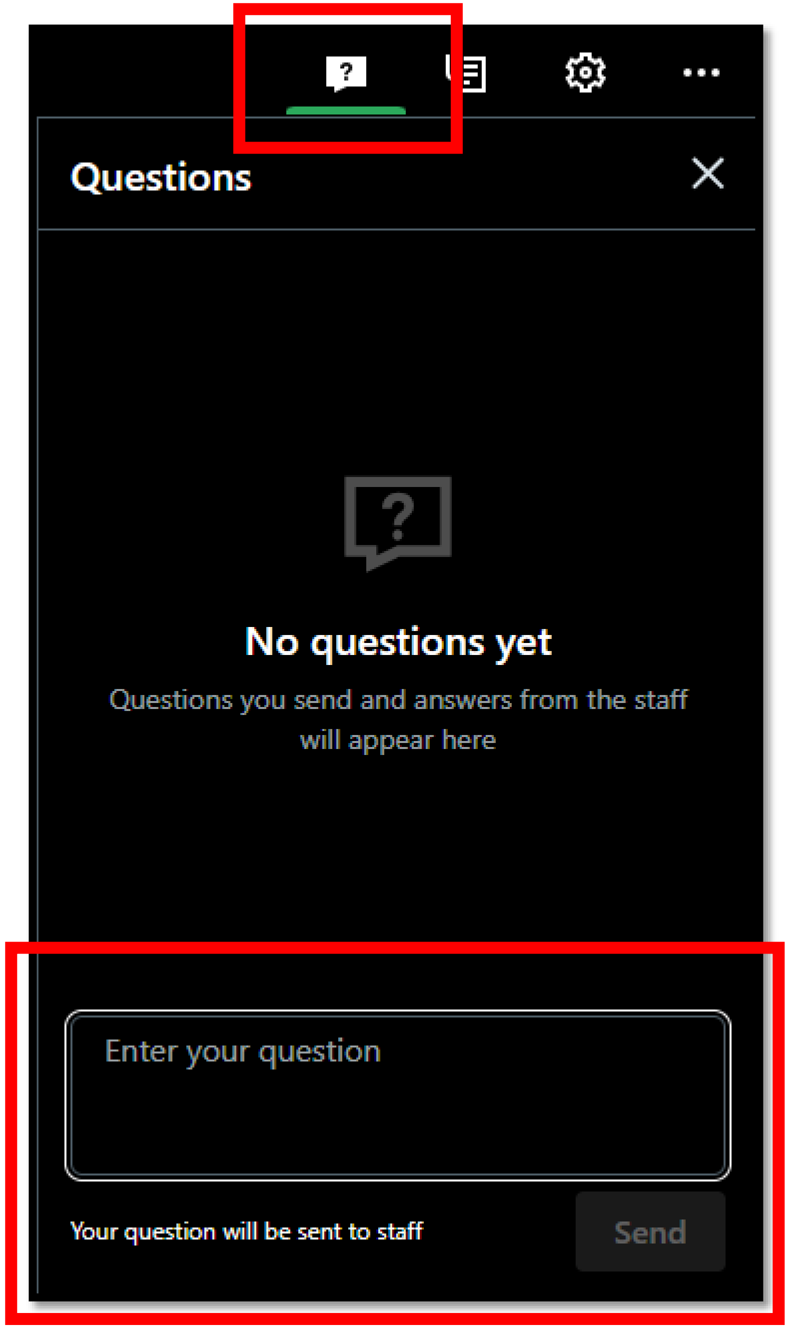
Learning Objectives

At the end of this webinar, you will be able to:

- Identify FHWA activities related to resilience of pavement and embankment assets
- Speak to the concept of resilience-based design for geotechnical assets and practices
- Understand the utility and implications of modeling through the examples of cascading failures of levees and power grid due to flooding in changing climate

Questions and Answers

- Please type your questions into your webinar control panel
- We will read your questions out loud, and answer as many as time allows



Today's presenters

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Progress Toward More Resilient Roadways

FHWA Resilience Efforts

Amir Golalipour, Ph.D., P.E., M.ASCE.

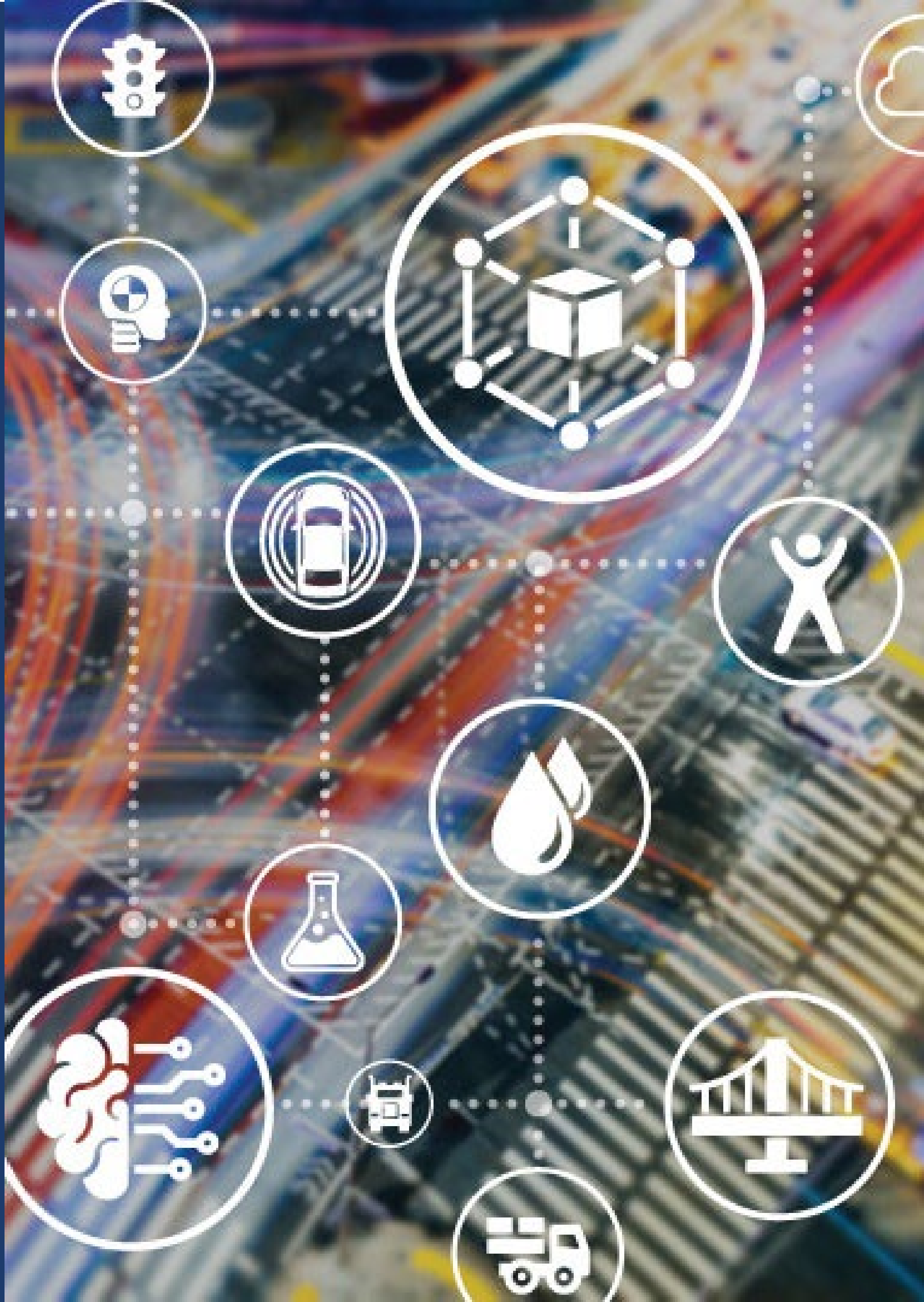
Office of Research, Development, and Technology

Khalid Mohamed, P.E., PMP

Office of Infrastructure

Federal Highway Administration (FHWA)

TRB Webinar November 14th, 2024
Improving Geotechnical Asset Resilience



What Is Resilience?

Resilience: The ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions, FHWA Order 5520 (FHWA 2014c).

1. (i) to resist hazards or withstand impacts from weather events and natural disasters; or (ii) to reduce the magnitude or duration of impacts of a disruptive weather event or natural disaster on a project; and
2. to have the absorptive capacity, adaptive capacity, and recoverability to decrease project vulnerability to weather events or other natural disasters. (Bipartisan Infrastructure Law, 2021)

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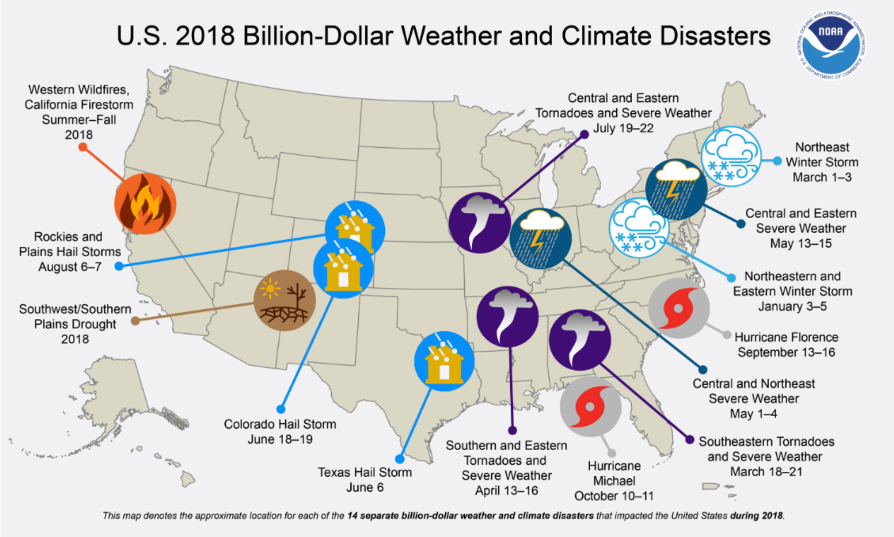
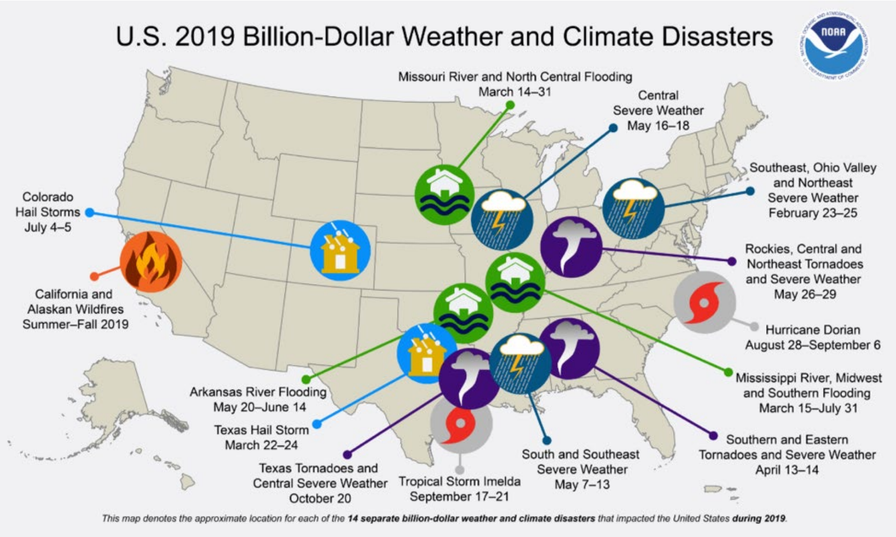
The Need for Resilience!





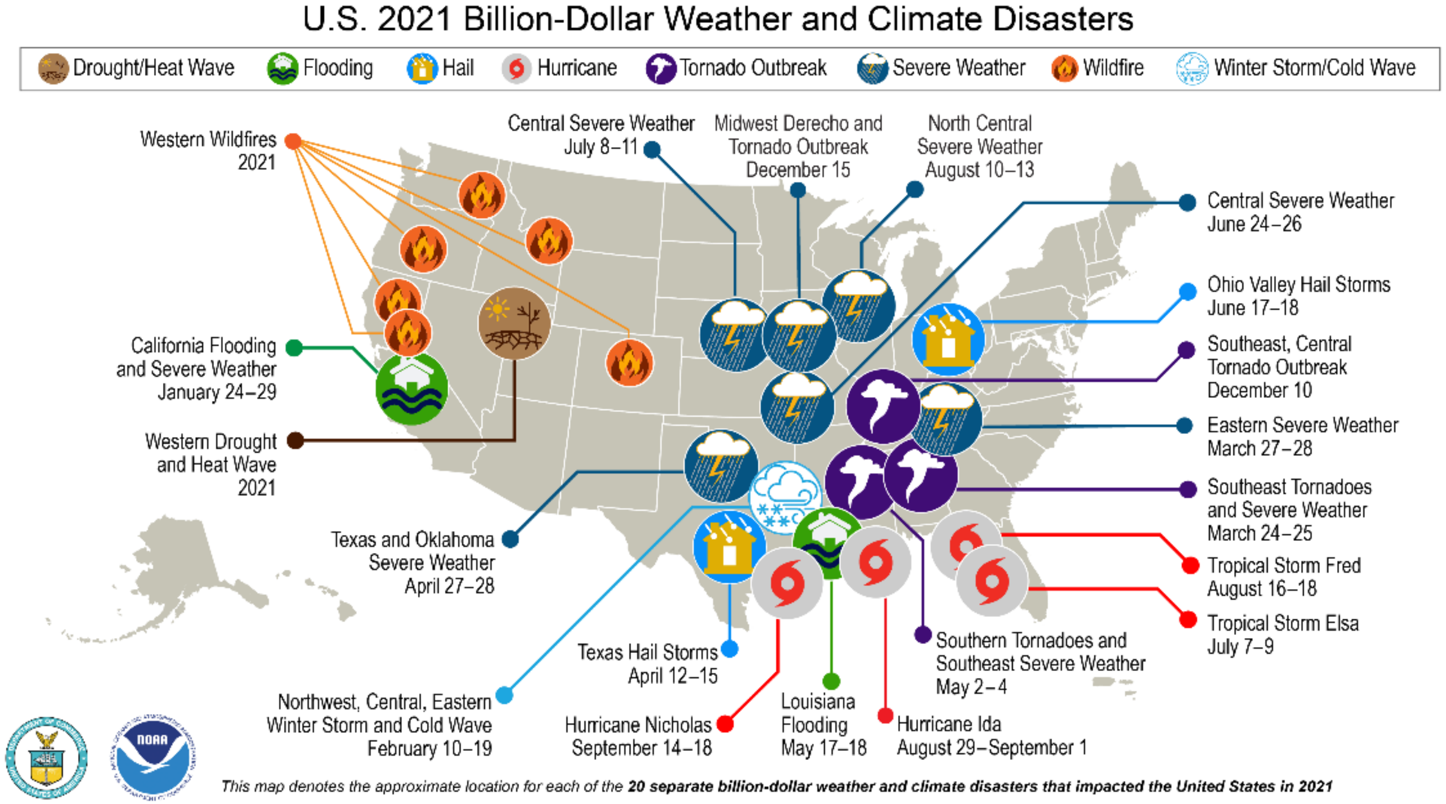


Image credit: NOAA

Resilience in TAMPs in Regulation

23 CFR Part 515.7

State DOTs are required to develop a risk-based asset management plan to include specific minimum processes, including the following section on lifecycle planning identified in subsection (b)*:

> A State DOT shall establish a process for conducting lifecycle planning for an asset class or asset subgroup at the network level (network to be defined by the State DOT). As a State DOT develops its lifecycle planning process, the State DOT should include future changes in demand; information on current and *future environmental conditions*, including **extreme weather events**, **climate change**, and seismic activity; and other factors that could impact whole-life costs of assets.

*Similar requirements are in subsection (c), which addresses risk management plans.

(Office of the Federal Register, National Archives and Records Administration 2018)

Addressing Resilience in TAMP Risk Management Analysis

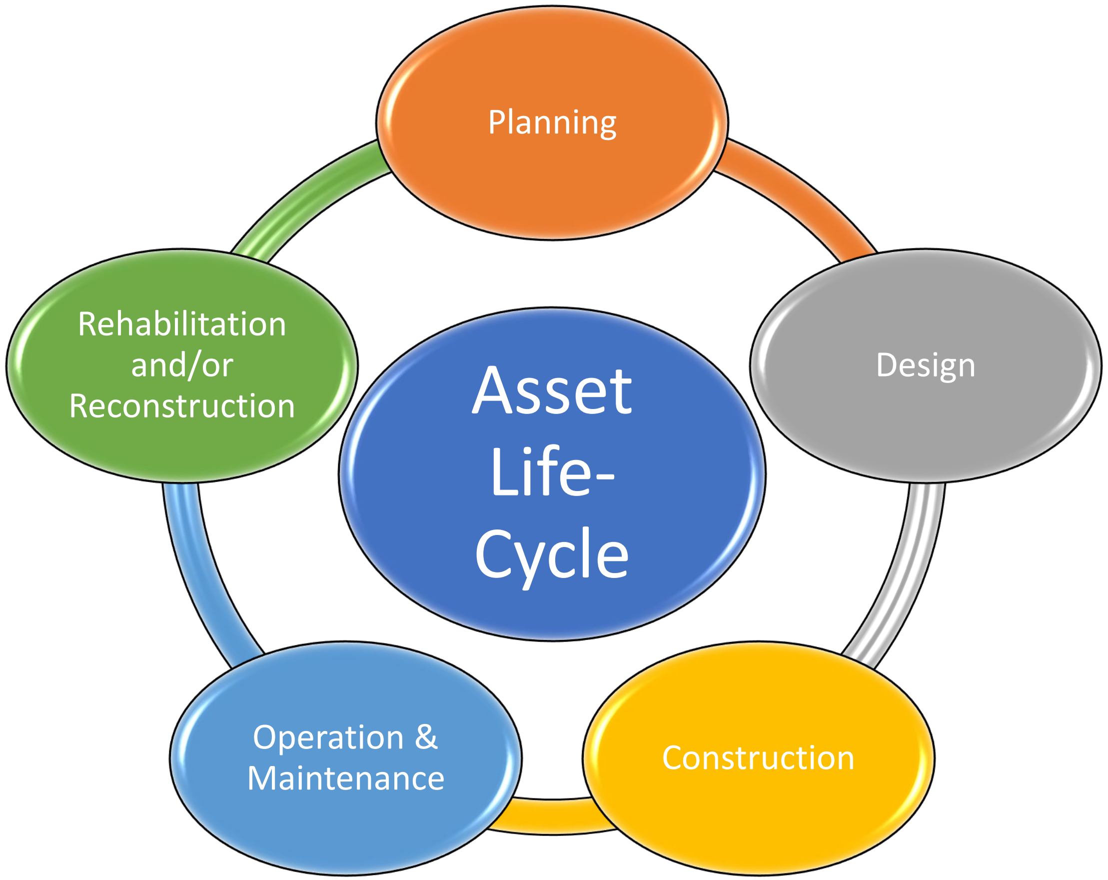
What can States do to address risks associated with extreme weather and climate change?

Three steps for success:

1. Leverage results from existing (or new) vulnerability and engineering assessments focused on resilience.
2. Identify hazards affecting each asset class.
3. Assess strategies/costs for making each asset class resilient.

Adaptation Strategies:
1. Monitor Trends

Most predicted changes to environmental variables are projected to occur relatively slowly in relation to a typical infrastructure lifecycle (FHWA 2015).



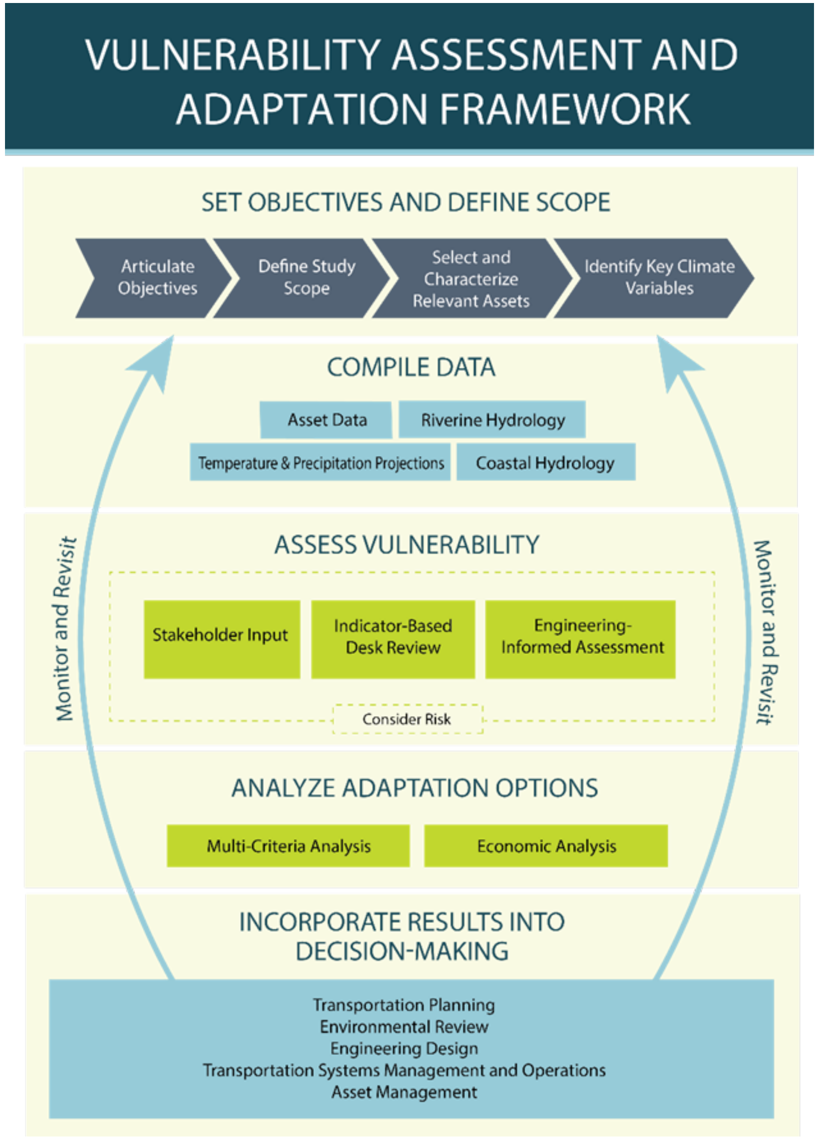
2. When Trends Differ, Evaluate Vulnerability

Objectives:

- Identify whether an asset is more vulnerable than other system assets.
- Prioritize potential vulnerabilities for the system.

Approach:

- Use the Vulnerability Assessment Scoring Tool (FHWA 2017e).
- Input local asset data.
- Output the relative vulnerability scores per asset.



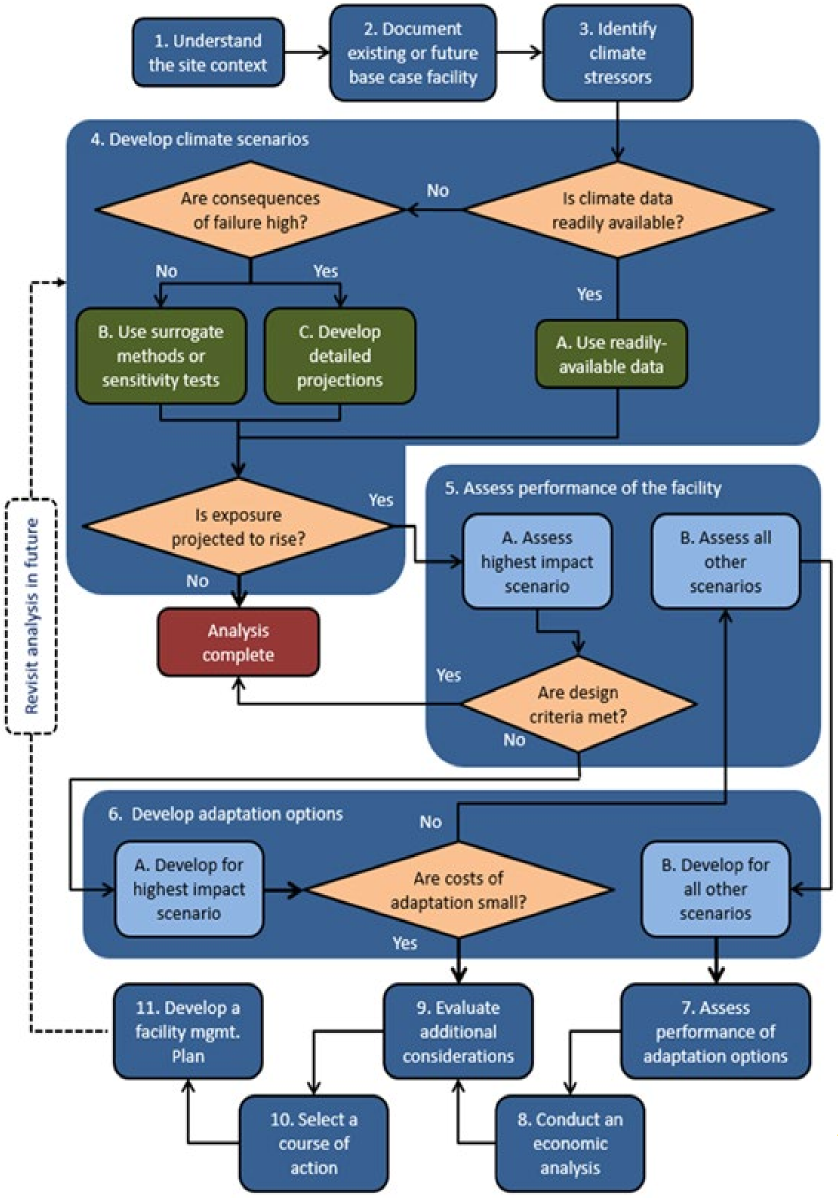
Source: FHWA.

(FHWA 2019)

3. Plan and Design Infrastructure to Meet Future Conditions:

- Use the adaptation decisionmaking assessment process (ADAP).
- Use a risk-based approach for planners, designers, or engineers.
- Tailor to each State.
- Aid decisionmakers in determining which project alternative is best (lifecycle costs, resilience, and regulatory and political settings) (FHWA 2021b).

Decision Tree of the ADAP Steps



Source: FHWA.
(FHWA 2016a)

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FHWA Resilience

Geohazards

U.S. Department of Transportation
Federal Highway Administration

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GEOHAZARDS

"Geohazards, such as *landslides, liquefaction, rock falls, subsidence, expansive/collapsible soils, and erosion* can pose major threats to transportation assets. *Extreme weather events* can also *trigger and/or exacerbate geohazards*, and the increasing incidence of such events is a growing potential concern in certain regions of the United States."

Foreword

Geohazards, Extreme Weather Events, and Climate Change Resilience Manual

https://www.fhwa.dot.gov/engineering/geotech/pubs/hif23008.pdf

Future Climate Effects on GEOHAZARDS Events and Transportation Infrastructure!

- Climate stressors (*Temperature*, *Precipitation*, *Freeze/Thaw cycles*) affect geohazards events in the following aspects:
  - ***Frequency*** – Increase in the occurrence of extreme weather and geohazards events over time
  - ***Intensity*** – Increase in the force of the geohazards
  - ***Severity*** – Increase in the impact of the geohazards

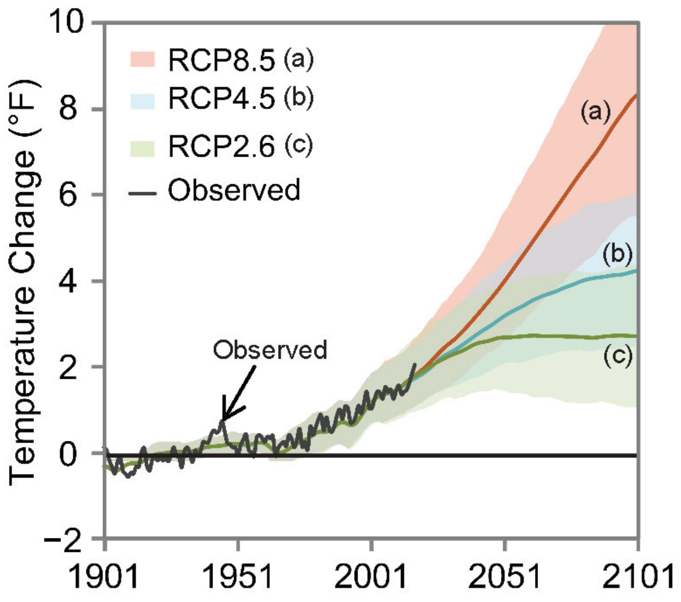
Glen Canyon Debris Flow (I-70)

Shiloh National Park, TN

Recent Climate Trends

How do we know how the climate might change in the future?

Representative Concentration Pathways (RCP) are scenarios for *potential trajectories* for atmospheric GHG levels over the remainder of the 21st century and beyond. Each RCP is based on different assumptions.



Projected Global Temperatures

Projected changes in global annual mean surface temperature for various RCPs relative to a 1901–1960 baseline. The solid lines indicate the mean projections and the shaded areas indicate the uncertainty range (+/- two standard deviations) across 20+ global climate models.

Source: USGCRP 2017

Static Versus Future Climate Inputs

Stationary Climate Inputs:

- Based on historical data: Previously observed and measured.
- Grounded in well-established methods for design consideration.
- Based on the fundamental assumption: Historical data = future climate.

Future (Nonstationary) Climate Inputs:

- Generated by climate models: Partially incorporating historical inputs.
- Built on assumptions of greenhouse gas emission sources and levels.
- Based on the explicit assumption: Historical data ≠ future climate.

Data Sources for Future Climate Projections (Including Sea-Level Rise (SLR))

Resource	Description
Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections (DCHP) database (U.S. Federal Government 2021)	A database that contains publicly available, downloadable, downscaled climate projection data for temperature and precipitation in the contiguous United States.
USGS Geo Data Portal (U.S. Geological Survey 2022)	A web portal that provides access to a suite of climate datasets for temperature and precipitation, including climate projections using different downscaling techniques.
U.S. DOT CMIP Climate Data Processing Tool 2.0 (FHWA 2021a)	An Excel®-based tool to process data from the DCHP database to provide temperature and precipitation projections for climate variables relevant to transportation planners. The updated version uses the localized constructed analog dataset and incorporates several new variables.
U.S. Army Corps of Engineers Sea- Level Change Curve Calculator (U.S. Army Corps of Engineers 2021)	A web-based tool that accepts user input to produce a table and graph of the projected sea-level changes at the project site, including vertical land movement.
National Oceanic and Atmospheric Administration's (NOAA's) SLR Viewer (NOAA 2022)	A web mapping tool to visualize community-level impacts from coastal flooding or SLR that contains downloadable SLR data for many locations.

CMIP = Coupled Model Intercomparison Project; USGS = U.S. Geological Survey; DOT = department of transportation.

Types of Geotechnical Assets

- **Geotechnical assets** include:
  - Structural foundations
  - Retaining walls
  - Slopes
  - Embankments
  - *Subgrades* that contribute to the ability of an infrastructure component to perform its strategic mission

Bridge 8, Foothills Parkway, TN

New River Gorge National Park, WV

Risk: Geotechnical Assets Impact on Performance

- **Risk:** Probability of occurrence (%) X consequence ($$$)

- Failure of geotechnical assets *surrounding and supporting pavements and bridges* present a major risk that should be assessed and managed.

July 26-31st Debris Flow at I-70 through Glenwood Canyon, CO
(Source: CDOT)

Benefits of Establishing a Geotechnical Assets Management Program

- Provides a *data-driven* *process* to measure and manage *risks* and *save costs* over lifetime.
- Develops understanding of current risk exposure levels and ability to manage those risks.
- *Improves operational performance* with fewer unscheduled delays and closures.
- Demonstrates *stewardship*, *protects environment*, enhances agency reputation, and improves sustainability.

Inspection of Bridge Approach Embankment Washout during Flooding, New River George National Park, WV

Benefits of Establishing a Geotechnical Assets Management Program – Cont.

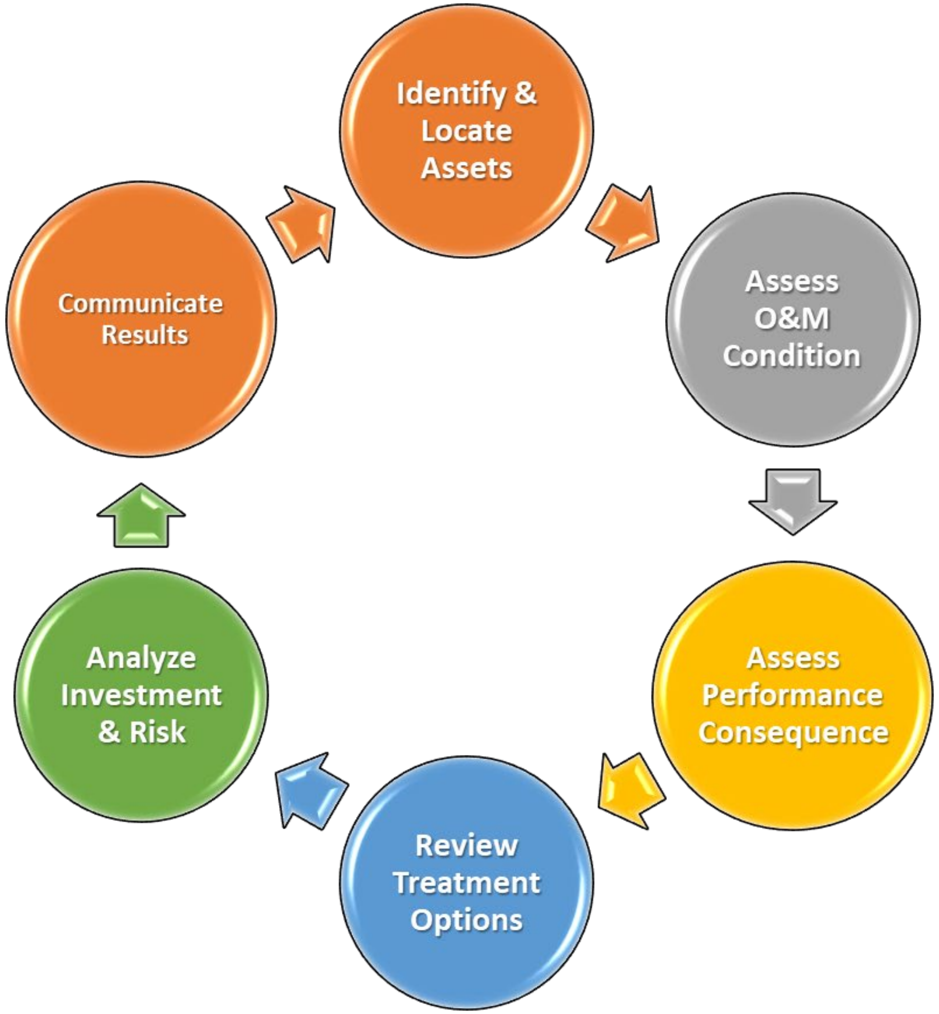
- Supports *informed decisions* that align with agency objectives for investment and performance.
- Process provides insights into system *vulnerability* and *resilience*.
- Process can *start as very simple and be adapted over time* as challenges are identified and economic benefits realized.

Monitoring of Culvert Washout Repair on Waldo Canyon, CO

Tools for Starting GAM Program

Available sources for starting and building a GAM Program:

- **NCHRP Research Report 903** Geotechnical Asset Management for Transportation Agencies, two volumes
- **Unstable Slope Management Programs** (Federal Lands Highway and many DOTs)
- **TRB Subcommittee on GAM** – website
- **Other Federal Tools**:
  - Risk-Based Protocol for MSE Walls – FHWA-HIF-18-065
  - Unstable Slope Management Protocol – FHWA-FLH-19-002
  - Geohazards Manual – FHWA-HIF-23-008
  - Many TAM documents



Steps for Implementing GAM

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FHWA Resilience

Case Studies

U.S. Department of Transportation
Federal Highway Administration
Turner-Fairbank
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Roadway: Adaptation Case Studies

These are some examples of recent projects.

Study Name	Location	Stressor(s) Studied
Transportation Engineering Approaches to Climate Resiliency (TEACR) Pavement Shrink-Swell (FHWA 2020)	SH 170, near Dallas, TX	Temperature, precipitation
TEACR Pavement Freeze-Thaw (FHWA 2016a)	SR 6/SR 15/SR 16, Guilford, Piscataquis County, ME	Temperature, precipitation
Gulf Coast Study Phase 2 (GC2) Pavement (FHWA 2014b)	Mobile, AL	Temperature
WFLHD/Alaska DOT and PF Pilot (FHWA 2016a)	Dalton Highway Mile Post (MP) 9 to MP 11, Alaska	Temperature, precipitation
TEACR Slope Stability (FHWA 2016a)	I–77, MP 1.8 to MP 6.3, Carroll County, VA	Precipitation, temperature

SH = State highway; SR = State route; WFLHD = Western Federal Lands Highway Division.

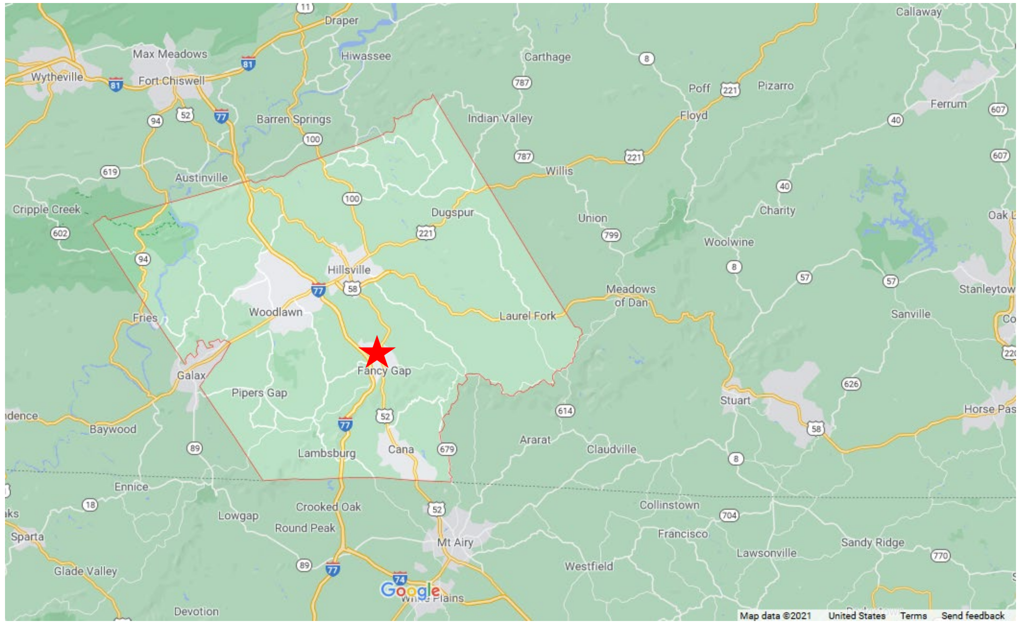
VIRGINIA – CASE STUDY

- Study Focus
  - Soils and Slopes.
- Project Scope
  - I-77, Carroll County, Virginia
- Approach
  - Sensitivity to Climate Change: Accelerated rock slope weathering and decreased slope stability from precipitation changes
  - FHWA TechBrief on Climate Change Adaptation for Pavements

VA – PRECIPITATION AND TEMPERATURE IMPACTS ON ROCK AND SOIL STABILITY

Carroll County, Virginia
https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/va_slopes/index.cfm

Soil slope slide along I-77. Source: VDOT



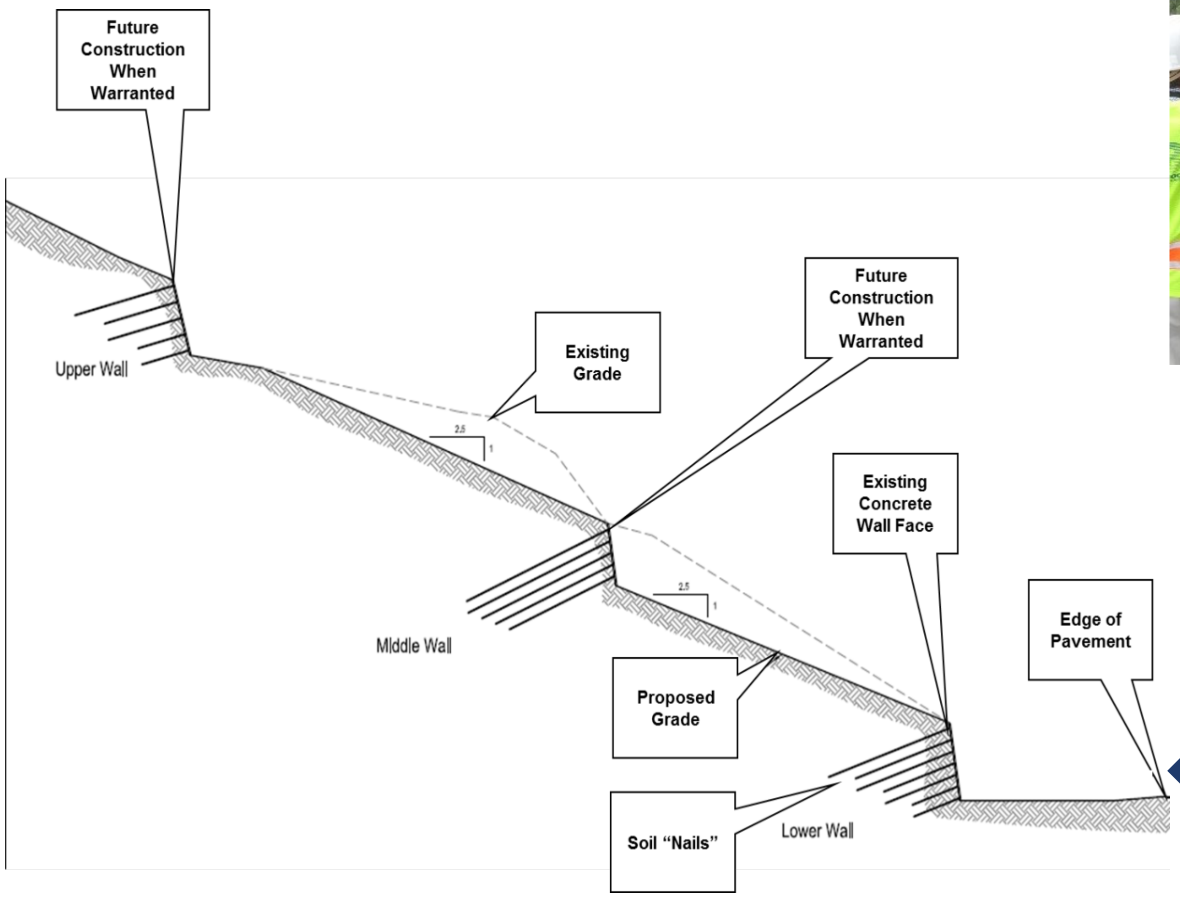
Red star symbol is added to show the map of site area.

VA - ANALYTICAL APPROACH

- Moderate increases in rainfall during10-, 50-, and 100-year storms projected

- Suggested preliminary steps to determine if climate change may impact soil slope stability:
  - Determine the steepness of the slope. Slopes steeper than 2 (horizontal) to 1 (vertical) should be initially suspect
  - Perform a field inspection to detect physical clues such as soil bulges at the toe of the slope, deformed tree trunk growth, depressed elevation of the slope face
  - Perform a parametric analysis (i.e., vary the groundwater elevation and soil unit weight) to see how the slope would respond under a wide range of conditions. Doing so could save considerable time and expense in instrumentation and data collection.

ADAPTIVE MANAGEMENT



Completed Toe Wall at the Base of the Sliding Mass.
Source: WSP

VA - LESSONS LEARNED

- Increased precipitation may not increase the likelihood of slope failure. A slope that is suspected of being vulnerable should be analyzed before drawing conclusions.

- Detailed climate data are not necessary for an initial, general assessment of climate change impacts on soil stability.

- Rather than screening detailed climate change projections, the “worst case scenario” can be analyzed first without specific climate data.

FHWA Resilience

Ongoing Efforts

U.S. Department of Transportation
Federal Highway Administration
Turner-Fairbank
Highway Research Center

PROTECT Discretionary Grant Program Overview

- **Promoting Resilient Operations for Transformative, Efficient, and Cost-Saving Transportation** (PROTECT) Discretionary Grant Program: Established under the Bipartisan Infrastructure Law, Section 11405; 23 U.S.C. 176.

- **Program purpose**: To plan for and strengthen surface transportation to be more resilient to natural hazards, including climate change, sea level rise, flooding, extreme weather events, and other natural disasters through competitive discretionary grants.

- **Total available in FY 2022 and FY 2023**: $848 million (Discretionary Grant Notice of Funding Opportunity, April 2023 NOFO))

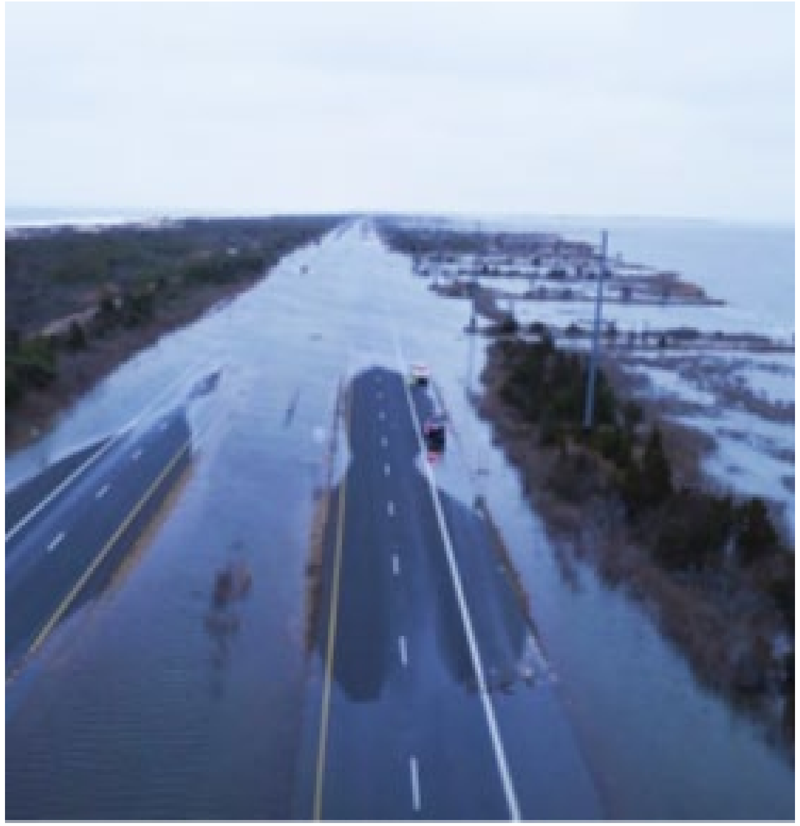
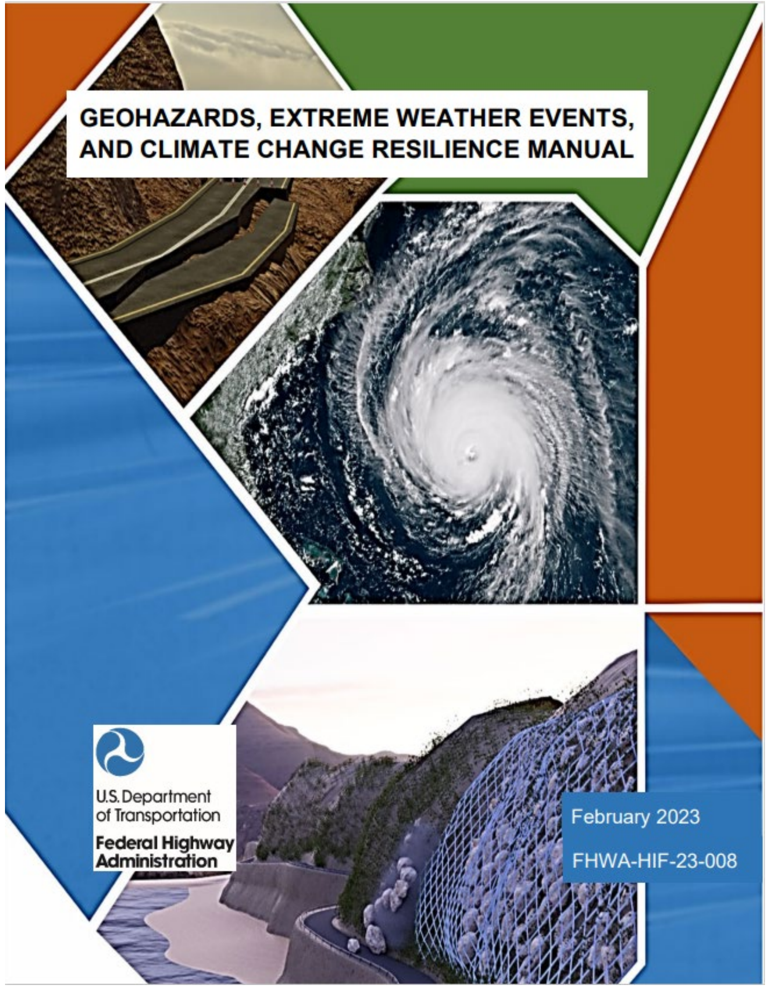


Photo credit: Delaware DOT

Infrastructure Resilience Roadmap

- What are the current gaps and future needs?
  - Resilience peer exchanges.
  - Highway resilience to wildfire events.

- What education resources are available to incorporate more resilient practices?
  - Geohazards, Extreme Weather Events, and Climate Change Resilience Manual (Published).



Assessing Flooded Roadway Project

- Project objectives:
  - Develop methods to assess flooded pavements.
  - Assess the capacity to carry traffic during/after flooding.
  - Evaluate emergency or heavy equipment.
  - Evaluate normal traffic.
  - Determine the tradeoff between the user costs of road closure (and detours) versus the costs of increased road damage.
  - Develop a decision support tool.

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- Project deliverables: Two techbriefs are published.

National Oceanic and Atmospheric Administration Project: Effects of Sea Level Rise

- Joint project with the National Centers for Coastal Ocean Science.
- Project goal details: Facilitate informed adaptation planning and coastal management decisions through a multidisciplinary research program that results in integrated models and tools of dynamic physical and biological processes capable of evaluating vulnerability and resilience under multiple SLR, inundation, and management scenarios.

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NOAA Project (Continued)

Two focus areas:

- Coastal resilience.
- **Surface transportation** resilience:
  - Quantify the vulnerability of surface transportation systems to SLR and inundation.
  - Quantify the social, economic, and/or ecological benefits.
  - Predict the effects of SLR and inundation on surface transportation infrastructure under varying risk mitigation and management strategies.

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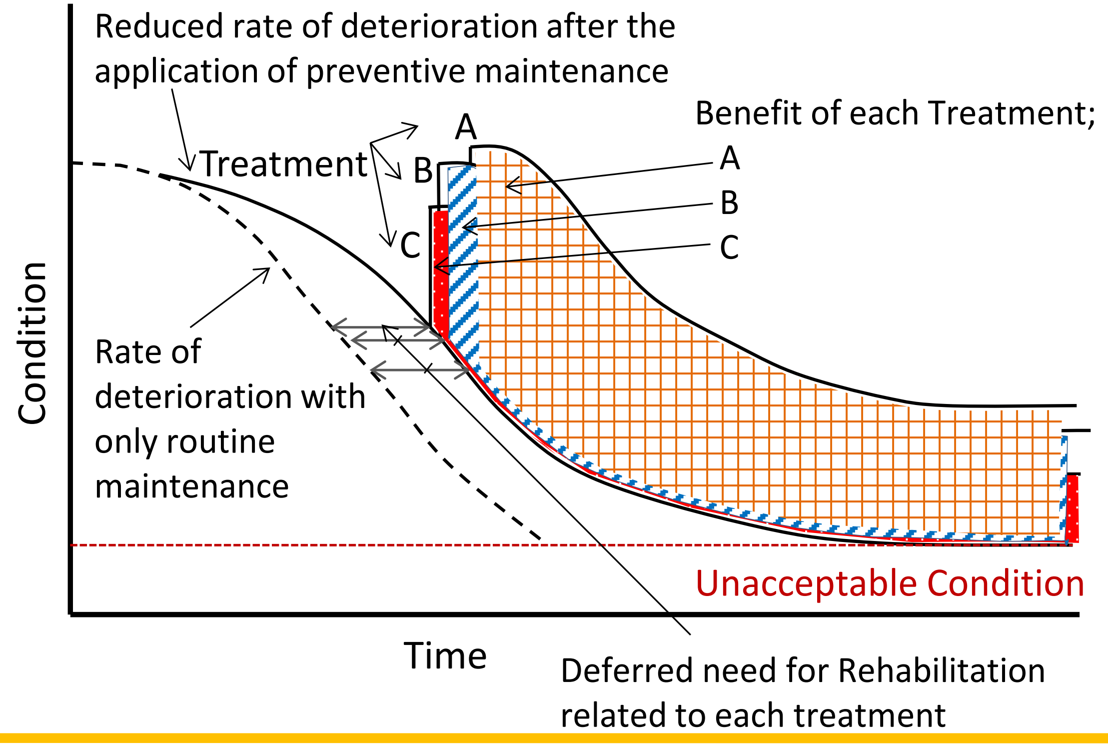
Impacts of Wildfires on Transportation Assets

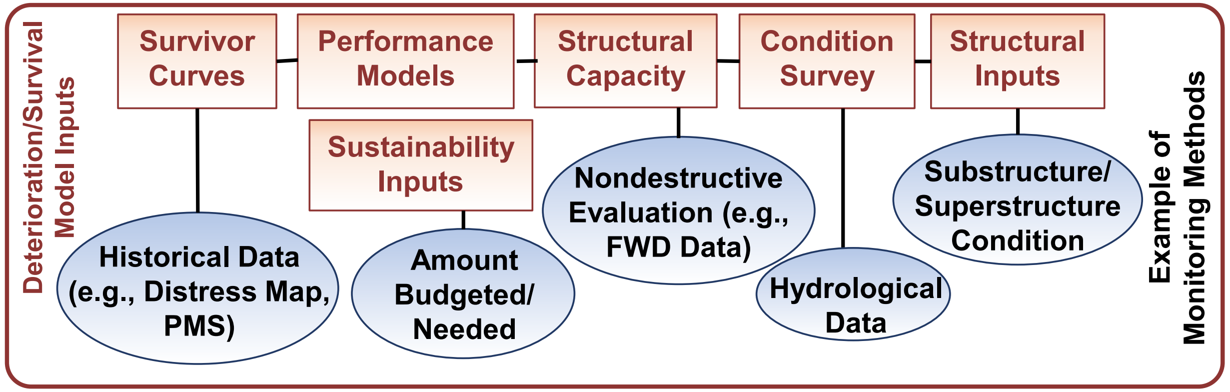
- Project objectives:
  - Determine the state of knowledge of wildfire impacts on roadways and other assets.
  - Define direct and indirect impacts.
  - Identify research gaps and needs.
- Project deliverables:
  - Determine the state of knowledge.
  - Identify how State DOTs deal with this issue:
    - Conduct detailed interviews.
    - Gather information on their experiences, observations, and challenges.

Wildfire Impact - Indirect

Upcoming Projects/Efforts

- Impact of Environmental Factors on Transportation Infrastructure—Different datasets will be used for the development of deterioration models.





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Transportation Pooled Fund on Resilience

New Pooled Fund Project (TPF-5(512)):
Resilience Approaches for Roadway Assets

TRANSPORTATION POOLED FUND

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Transportation Pooled Fund - Study Detail

Home › Studies › Resilience Approaches for Pavements and Geotechnical Assets

Resilience Approaches for Pavements and Geotechnical Assets

Print

General Information

Study Number:	TPF-5(512)
Former Study Number:	
Lead Organization:	Virginia Department of Transportation
Solicitation Number:	1590
Partners:	FL, HI, MDOT SHA, PADOT, TX, VA, WA
Status:	Cleared by FHWA
Est. Completion Date:	
Contract/Other Number:	
Last Updated:	Apr 27, 2023
Contract End Date:	

Financial Summary

Contract Amount:	
Suggested Contribution:	
Total Commitments Received:	$660,000.00
100% SP&R Approval:	Approved

Contact Information

Lead Study Contact(s):	Shabbir Hossain Shabbir.Hossain@VDOT.Virginia.gov Phone: 434-293-1989
FHWA Technical Liaison(s):	Amir Golalipour amir.golalipour@dot.gov Phone: 2024933089

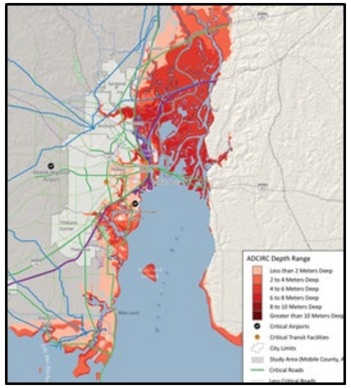
National Highway Institute (NHI) Course:
Addressing Resilience in Highway Project Development and Preliminary Design (2022)

Four 1-h web-based prerequisite courses and one 2.5-d instructor-led course (NHI 142085):

- **Content:**
  - Addressing resilience in engineering decisionmaking (pavements and geohazards, inland flooding, coastal hydraulics).
  - Accessing and using climate projections.
  - Integrating resilience into project development.
- **Audience:**
  Engineering, design, project development/environmental staff, and others.
- **Source material:**
  - *Synthesis of Approaches for Addressing Resilience in Project Development* (FHWA 2015).
  - Project assessments.
  - Hydraulic Engineering Circulars 17 and 25 (Kilgore et al. 2016; Douglass and Webb 2020).

FHWA Resilience Resources

Gulf Coast 2 Study

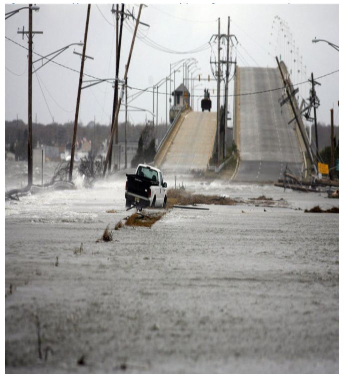


(FHWA 2019)

Resilience Pilots with State DOTs and MPOs

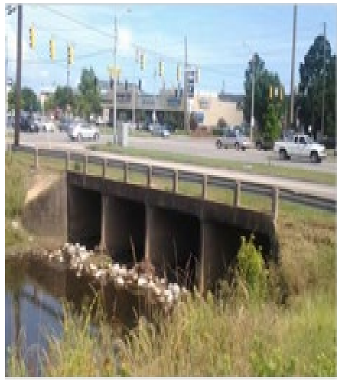
(FHWA 2021c) MPOs = metropolitan planning organizations.

Hurricane Sandy Project



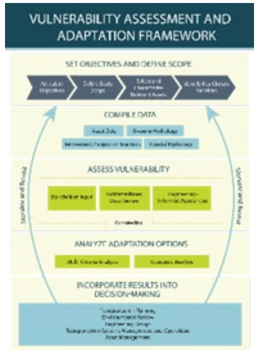
(FHWA 2017c)

Engineering Assessments



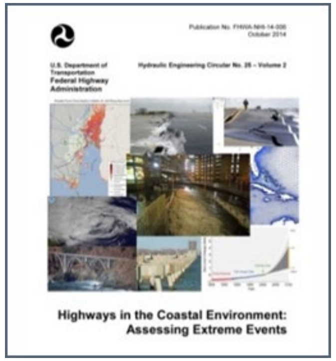
(FHWA 2017d)

Vulnerability and Adaptation Framework



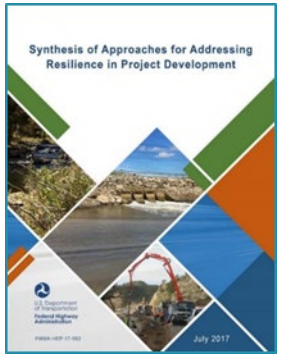
(FHWA 2019)

Engineering Guidance (HEC-25 & 17)



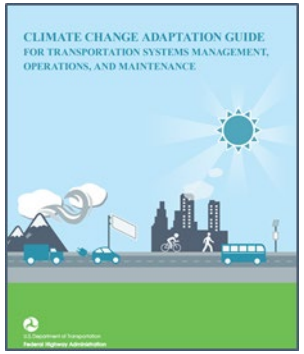
(FHWA 2014a)

Project Development



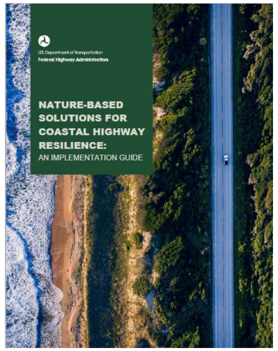
(FHWA 2015)

Operations and Maintenance



(FHWA 2017a)

Nature-Based Solutions



(Buckingham and Torossian 2021)

All photos source: FHWA.

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U.S. Department of Transportation
Federal Highway Administration

Turner-Fairbank
Highway Research Center

Resilience-Based Design and Management of Geotechnical Assets

Ahmad Alhasan

November 14, 2024 | 12:00–1:30PM ET

TRB

ARA

Outline

- **Resilience and its Role in Geotechnical Practice**
- Design Philosophy
- Load and Resistance During Asset Life
- Concluding Remarks and Future Directions

Why Resiliency?

- Increasing numbers of extreme weather events are affecting assets (climate change).
- Extreme events will accelerate the deterioration of assets.
- Increased demand and vulnerability.
- Aging Infrastructure is more susceptible to damage
- Design and management of assets are becoming more integrated.

British Columbia Ministry of Transportation

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Teton Pass Mountain Highway in Wyoming

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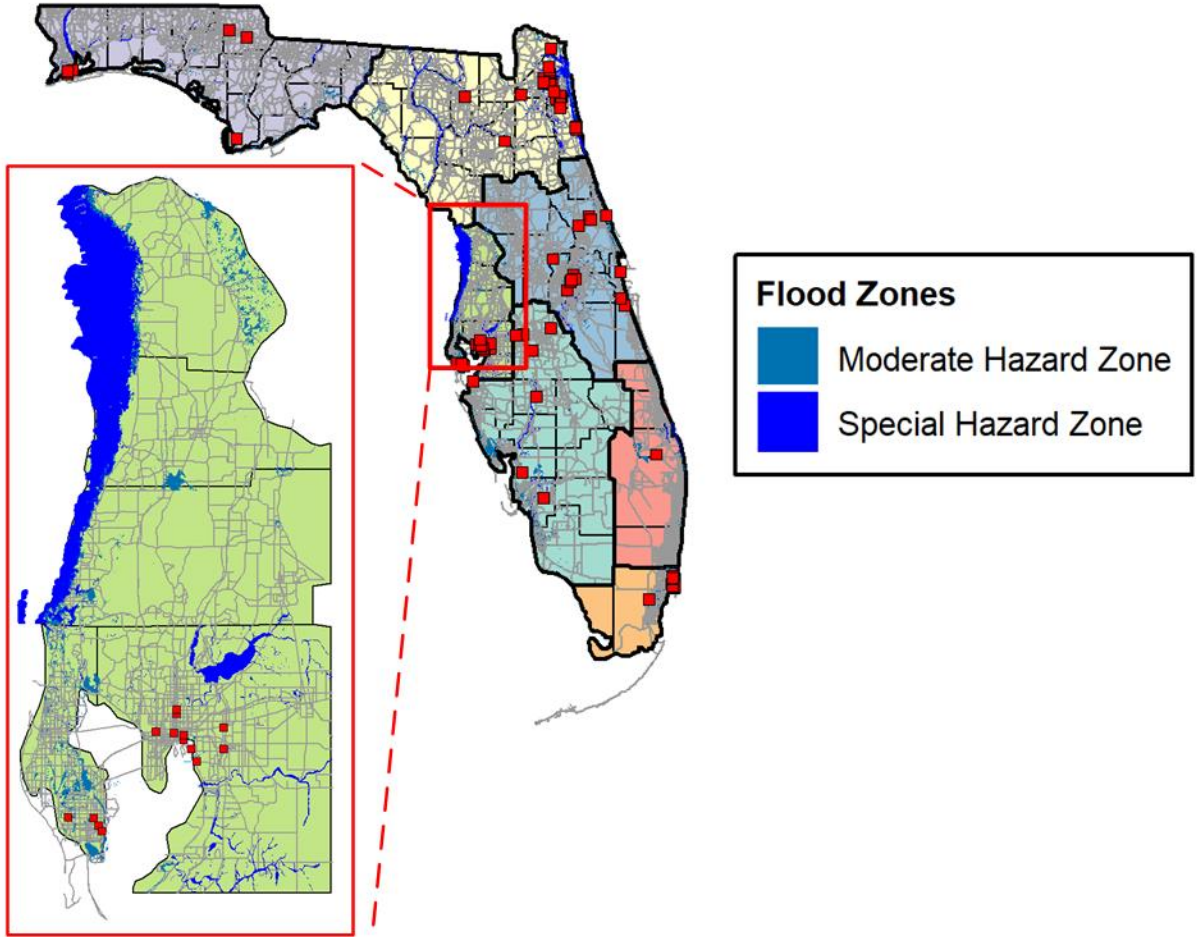
Teton Pass Mountain Highway in Wyoming

Defining Scale

- Resiliency was originally developed to describe systems.
- Network resilience has different measures and requirements.
- The next level of detail is localized system (Asset) resilience.
- If we zoom in it could reach an element level.
- A grand scheme should be able to capture all levels.



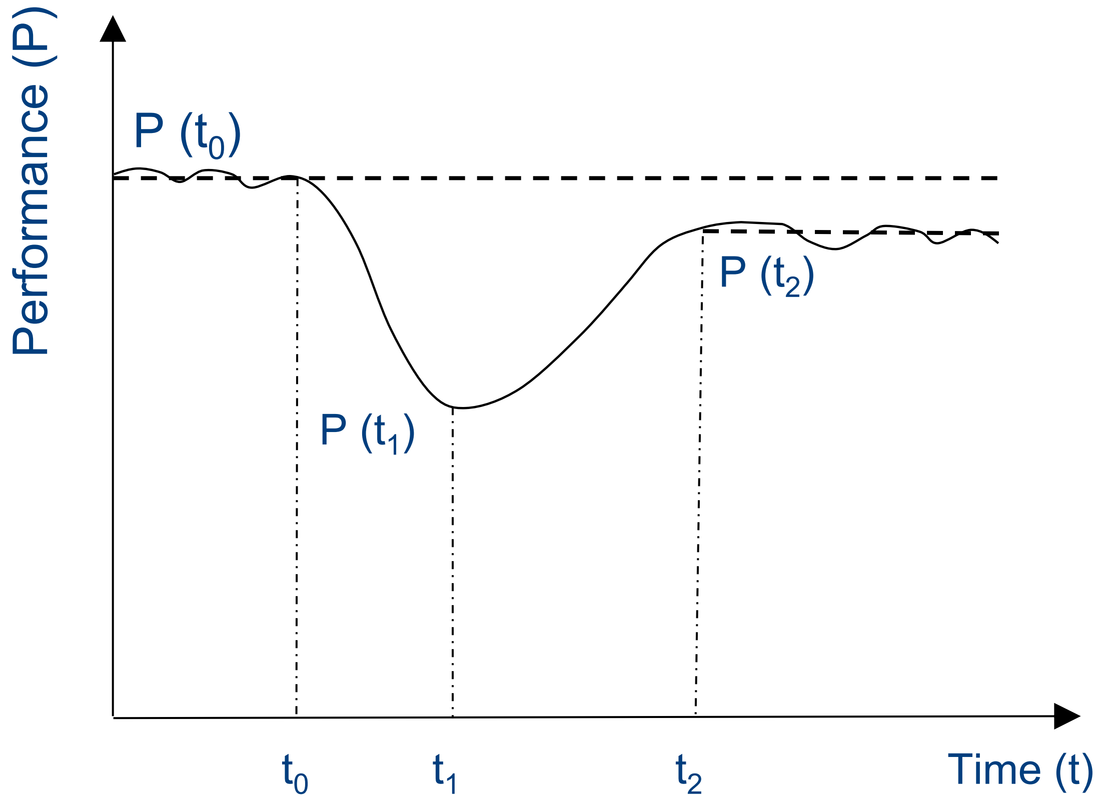
FDOT Project: Slope Stabilization Using Drilled Shafts Design Methodology and
Jamal Nusairat: Improved Resilience of Rigid Pavement Systems (Hyung Lee, ARA)
Case History, DFI, 2019

Geotechnical Assets and Foundations

- Geotechnical assets can include earth retaining structures, embankments, slopes, tunnels, culverts, and foundations of other transportation assets.
- Resilience of geotechnical assets is the foundation of the overall network resilience.

Defining Condition, Performance, and Capacity

- Condition reflects the physical condition of the asset in relation to its degradation from the newly constructed condition.
- Performance relates to the intended asset of the asset or network and their functionality.
- Capacity is how much load (could be force related loads or traffic levels) can the asset withstand before reaching the service or ultimate limit states



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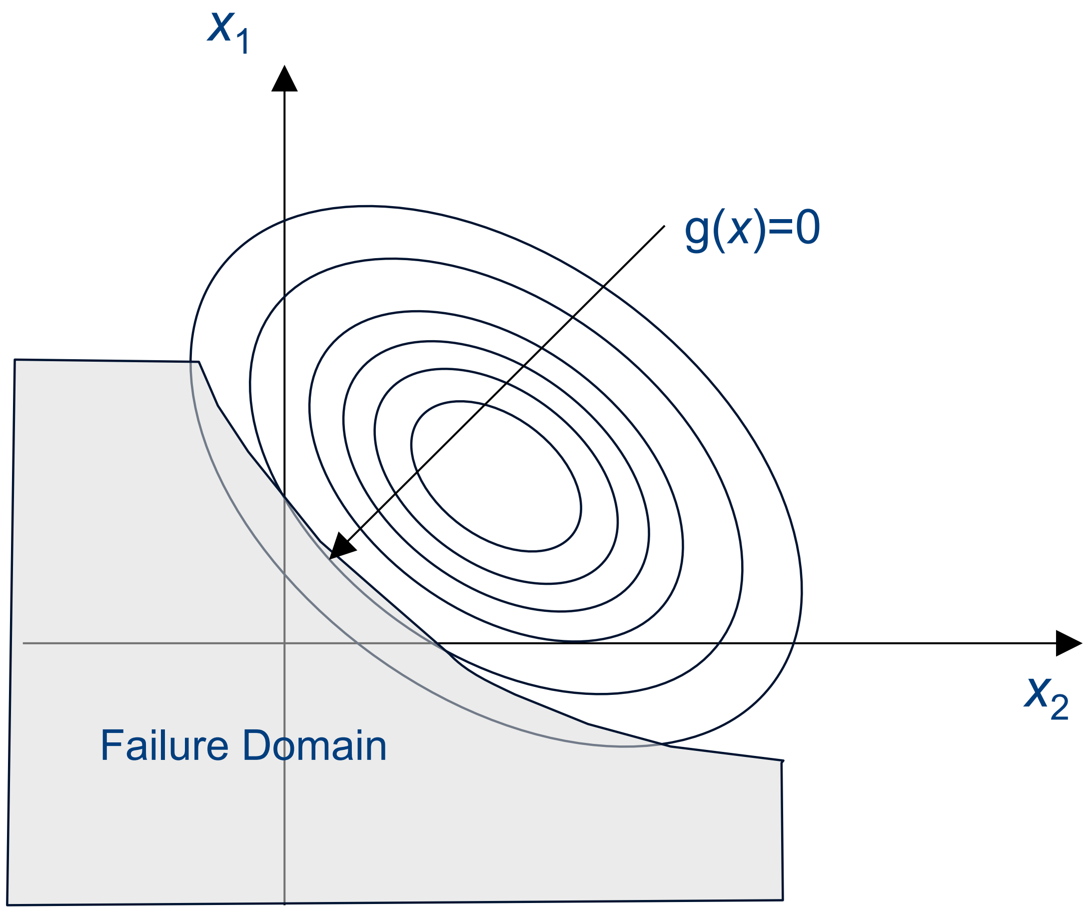
Design Objectives (Allowable Stress Design and Load and Resistance Factor Design)

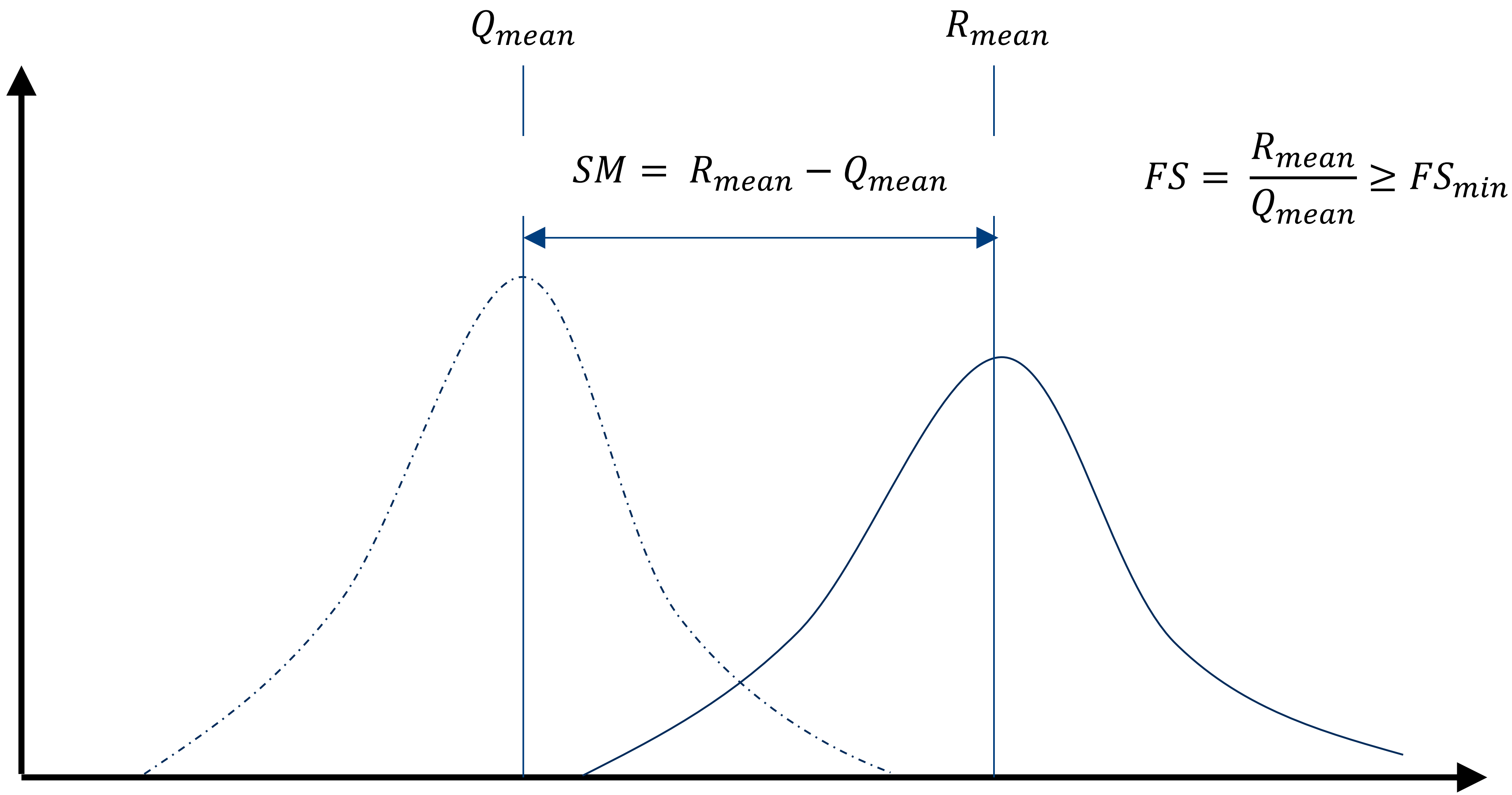
- Provide acceptable performance levels to serve the intended function of the asset at a minimum feasible cost.
- In some cases, we translate performance requirements to limit states and how far the design is from that limit state!
- In few cases, we think of cumulative damage, performance, and benefits.

Limit States and Failure

- Failure is the state where the asset or the localized system no longer serves its intended function.
- We need to revisit our limit state definitions especially in relation to serviceability.

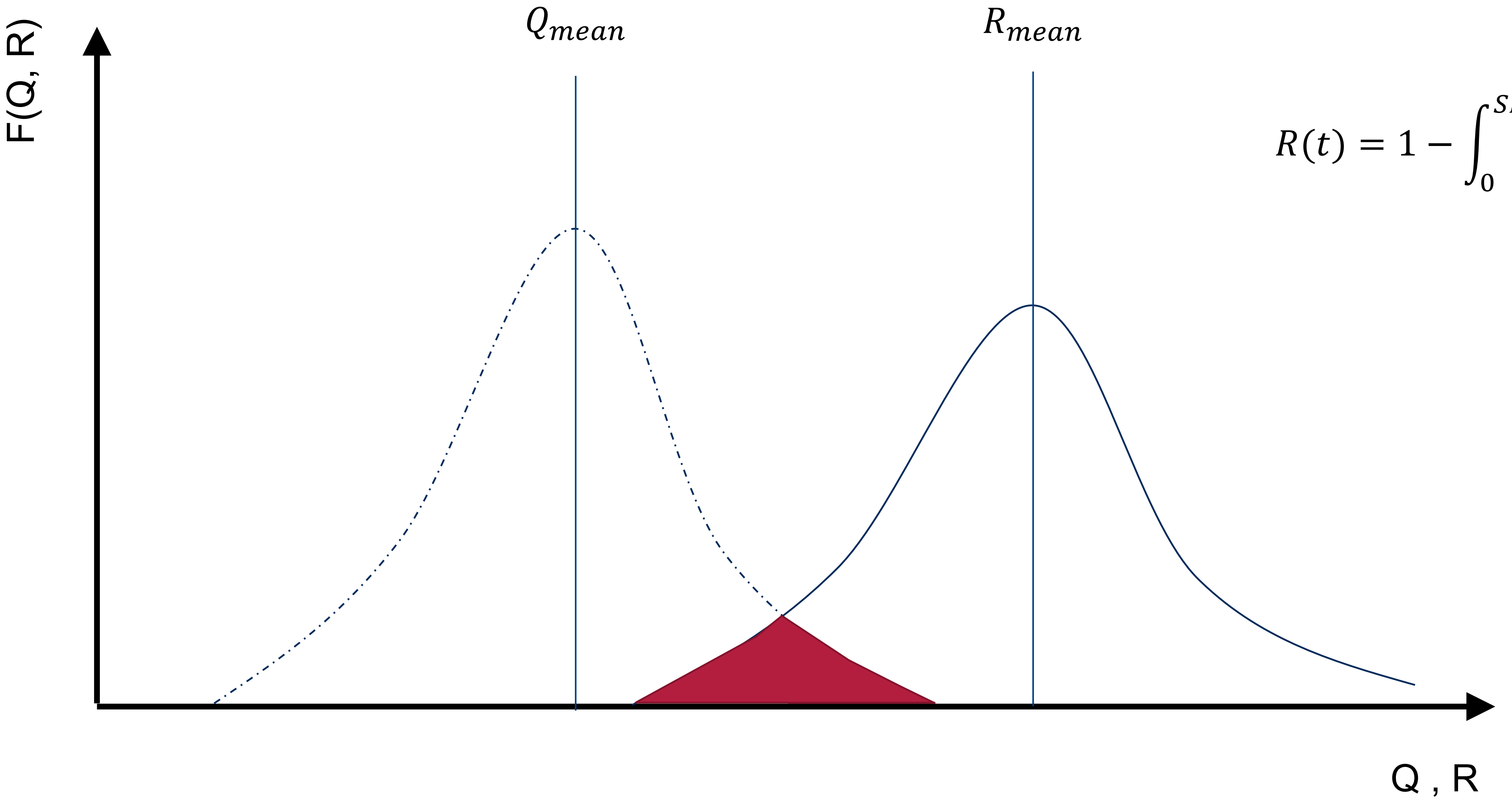


Generation 1: Deterministic Design



$$FS = \frac{R_{mean}}{Q_{mean}} \geq FS_{min} \approx \{2, 3, 4\}$$

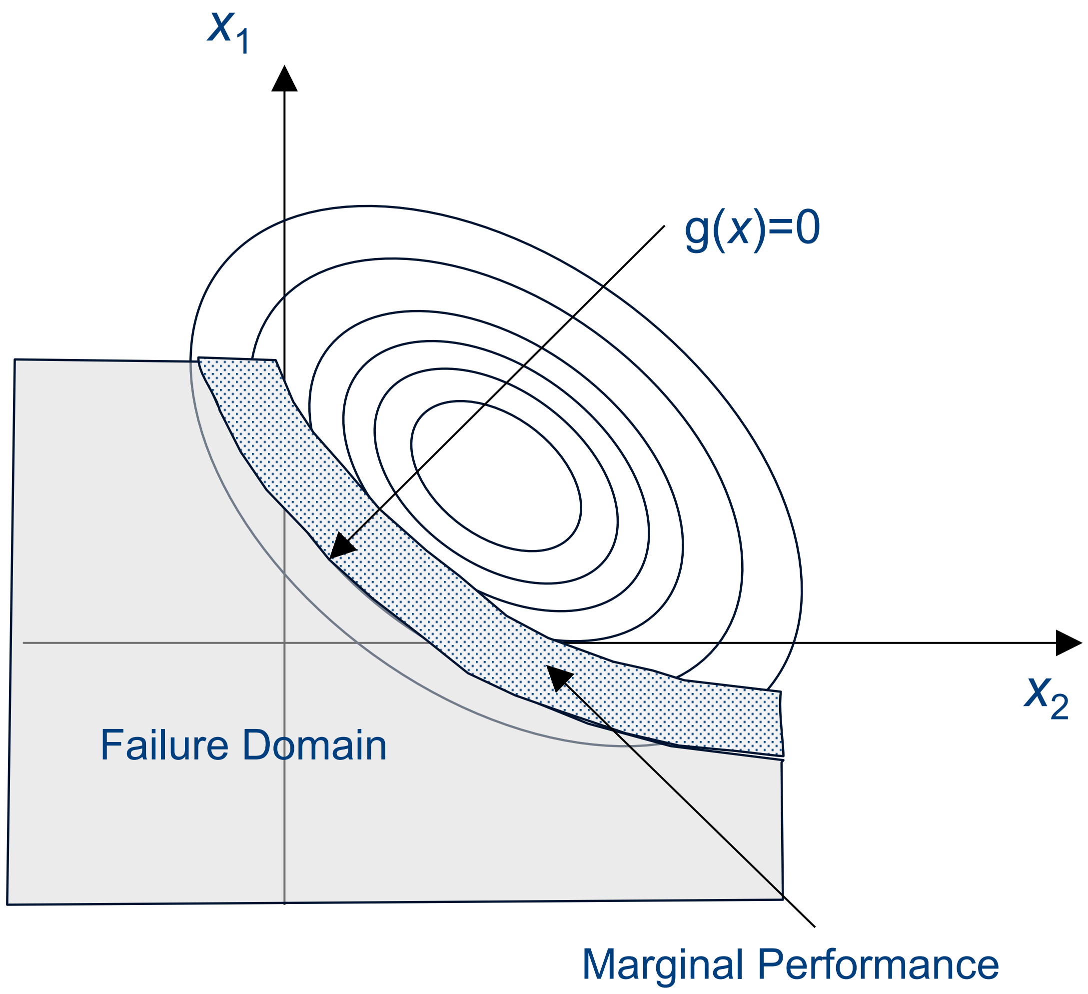
Generation 2: Reliability-Based Design



$$R(t) = 1 - \int_0^{SL} P(R \leq Q)\, dt \geq R_{min}$$

Design Objectives (Geotechnical Resilience Based Design)

- Achieve acceptable capacity levels throughout the asset life (design Life).
- Maintain acceptable asset condition, to avoid accelerated deterioration and progressive failure throughout the asset life (service life).
- Provide acceptable performance levels to serve the intended function of the asset in a network throughout the asset life (service life).
- Incorporate potential corrective activities during the asset life (service life).



Outline

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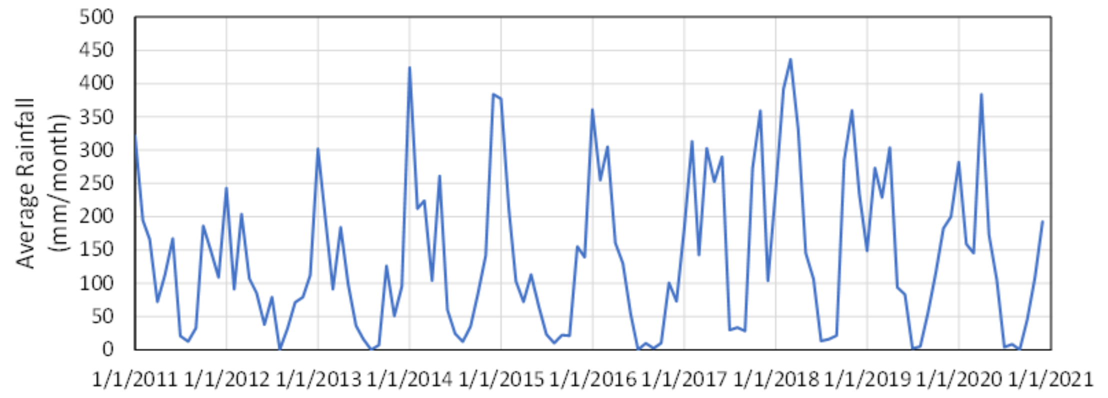
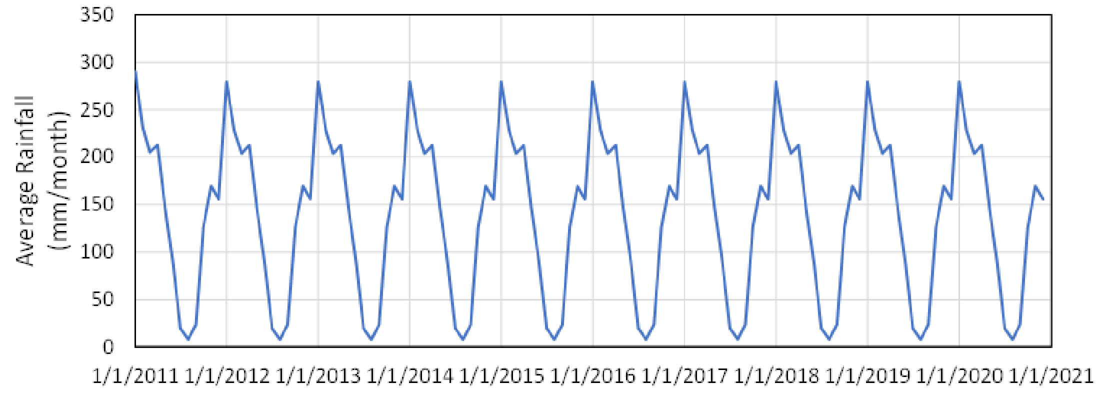
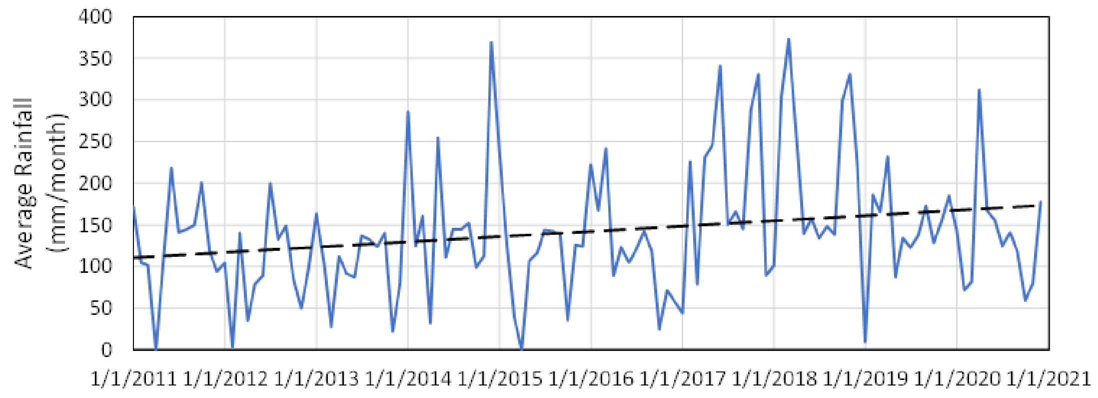
Define Disruptive Events

- Consider stochastic and non-stationary models.
- The sequence of events matters since they accumulate damage.
- The story does not end here.
- We have been looking into the past to design for the future.
- Learn from the past and forecast for the future!

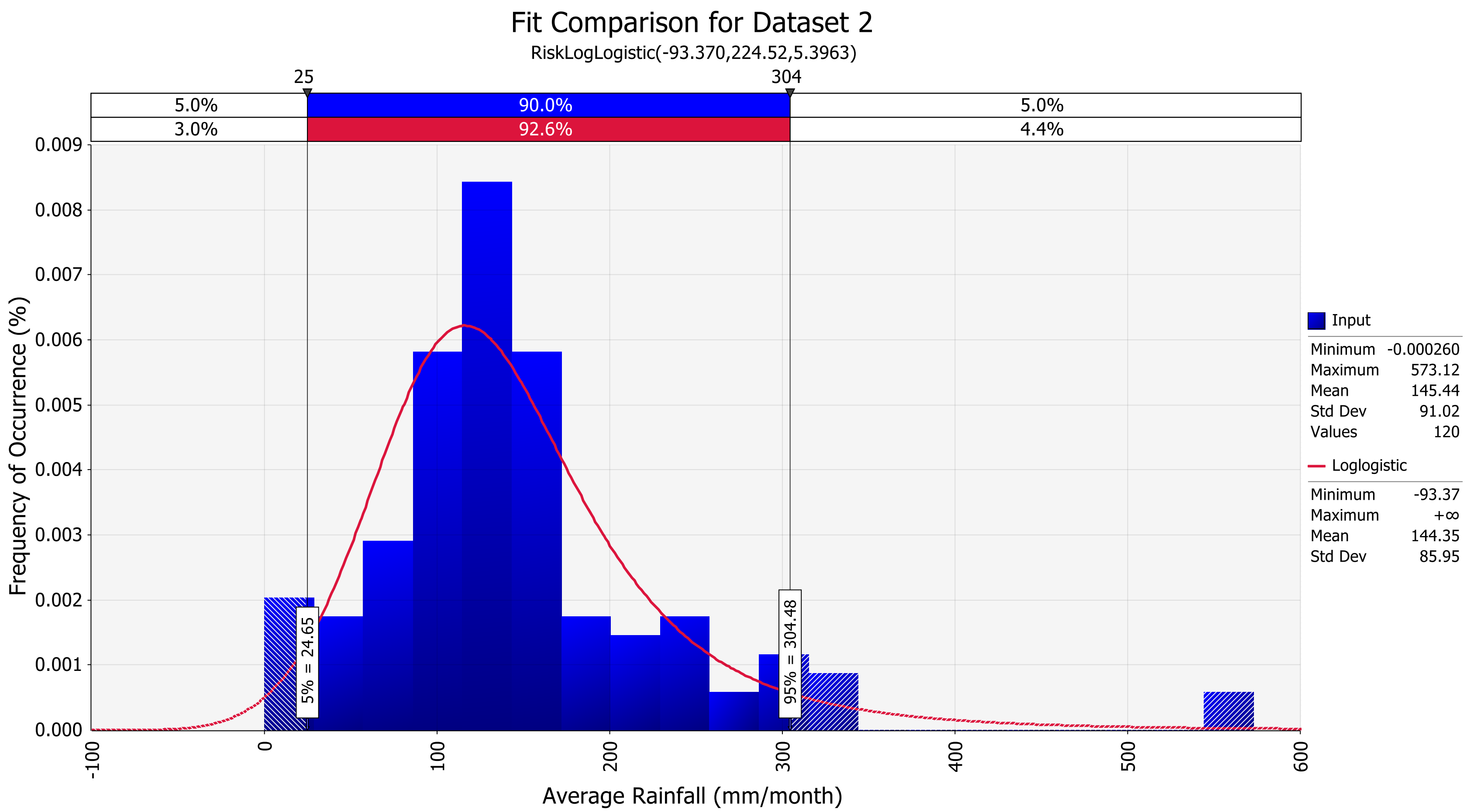






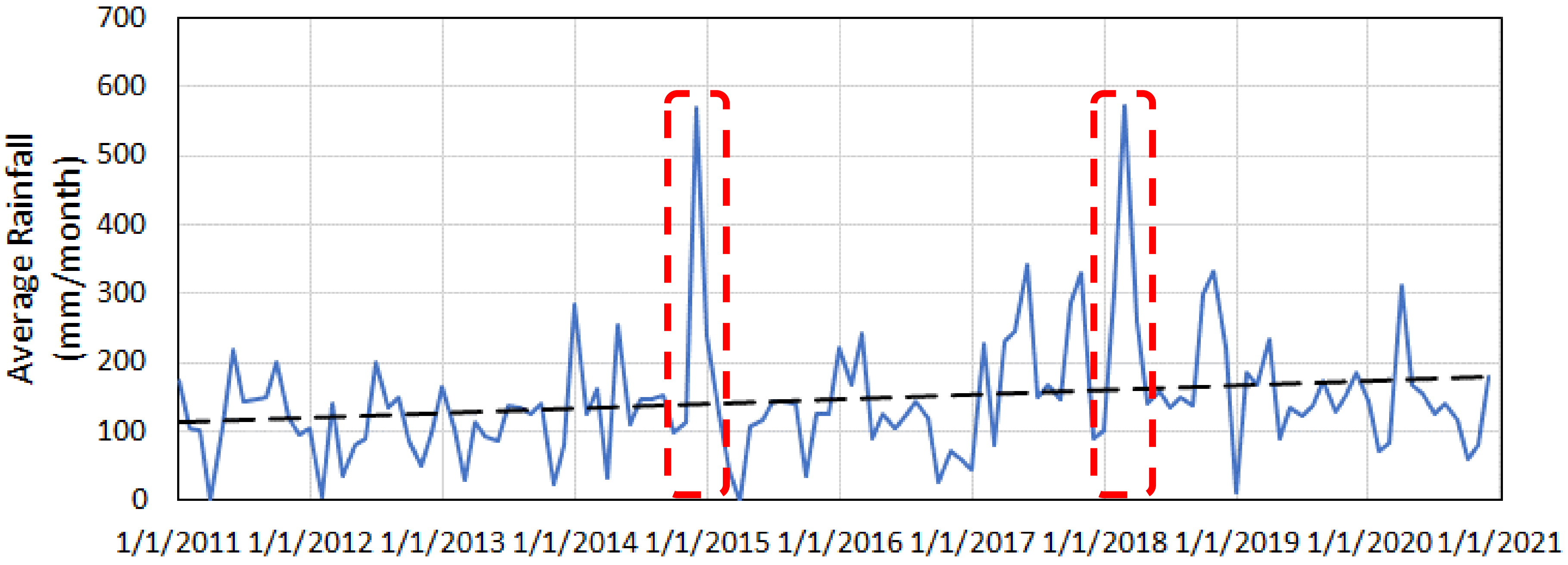
Disruptive Events in Time Series

- Traditional probabilistic analysis collapses the time series into a distribution.

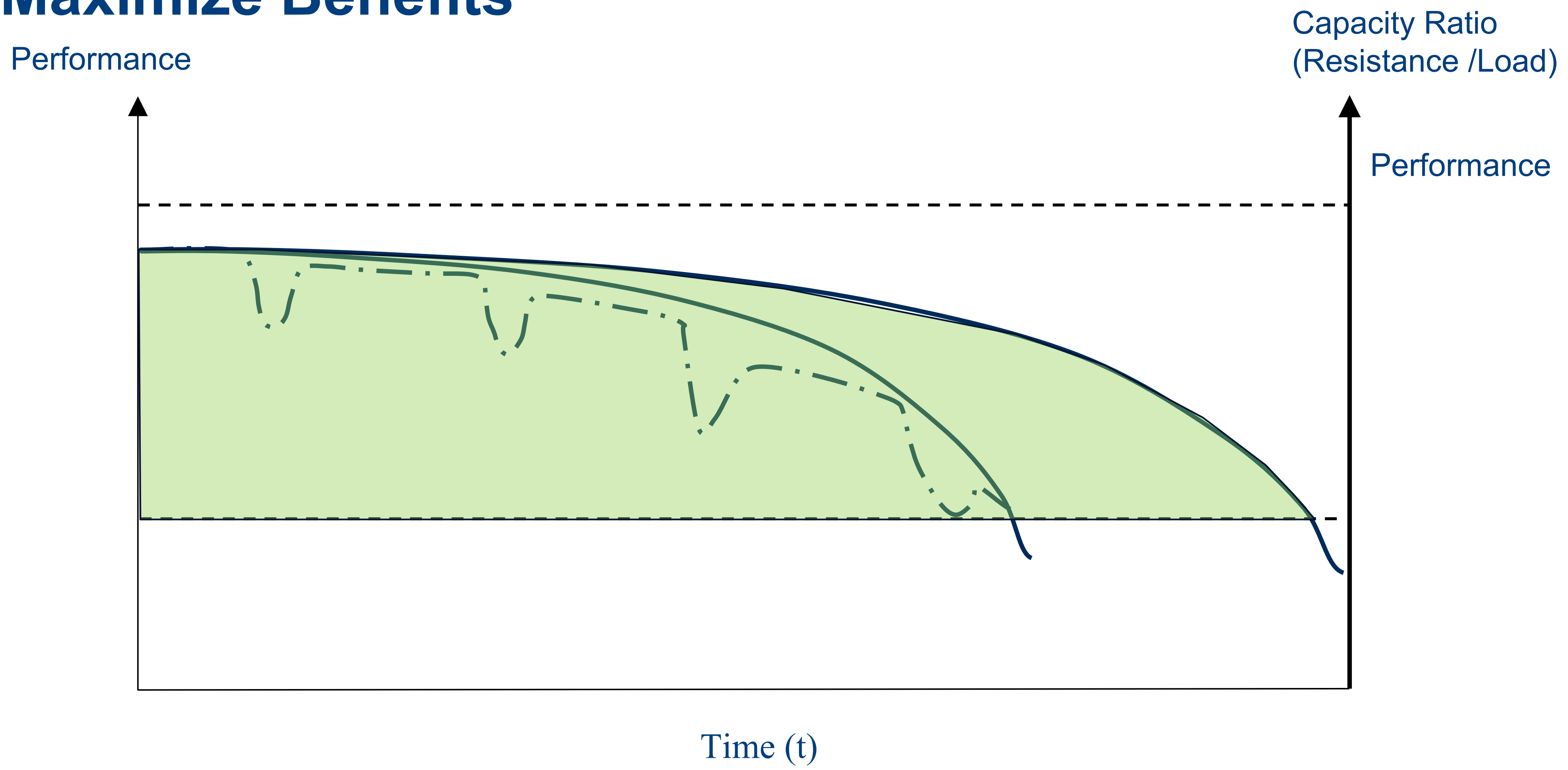


Disruptive Events in Time Series

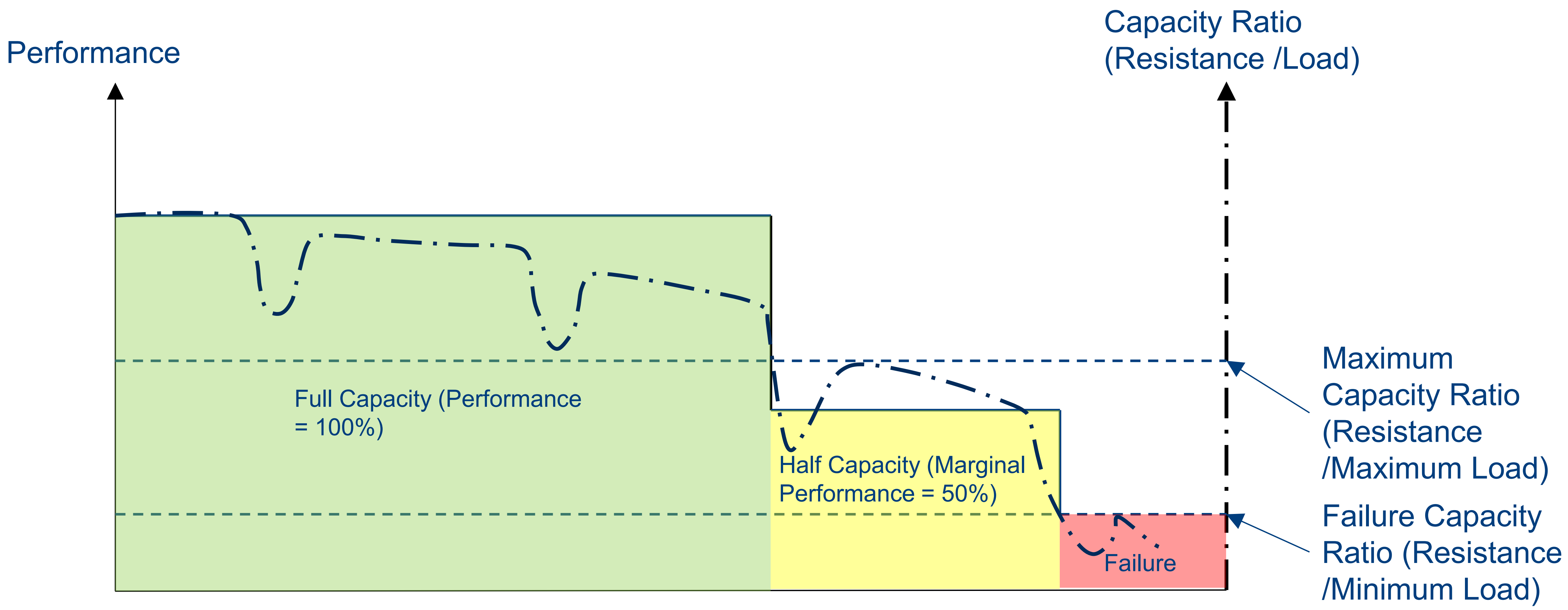
- Traditional probabilistic analysis collapses the time series into a distribution.
- Traditional time series analysis cannot incorporate extreme.
- Exploring the use of modified Deep Neural Networks (DNN) memorizing extreme events in historical data with Extreme Value Loss (EVL) function.



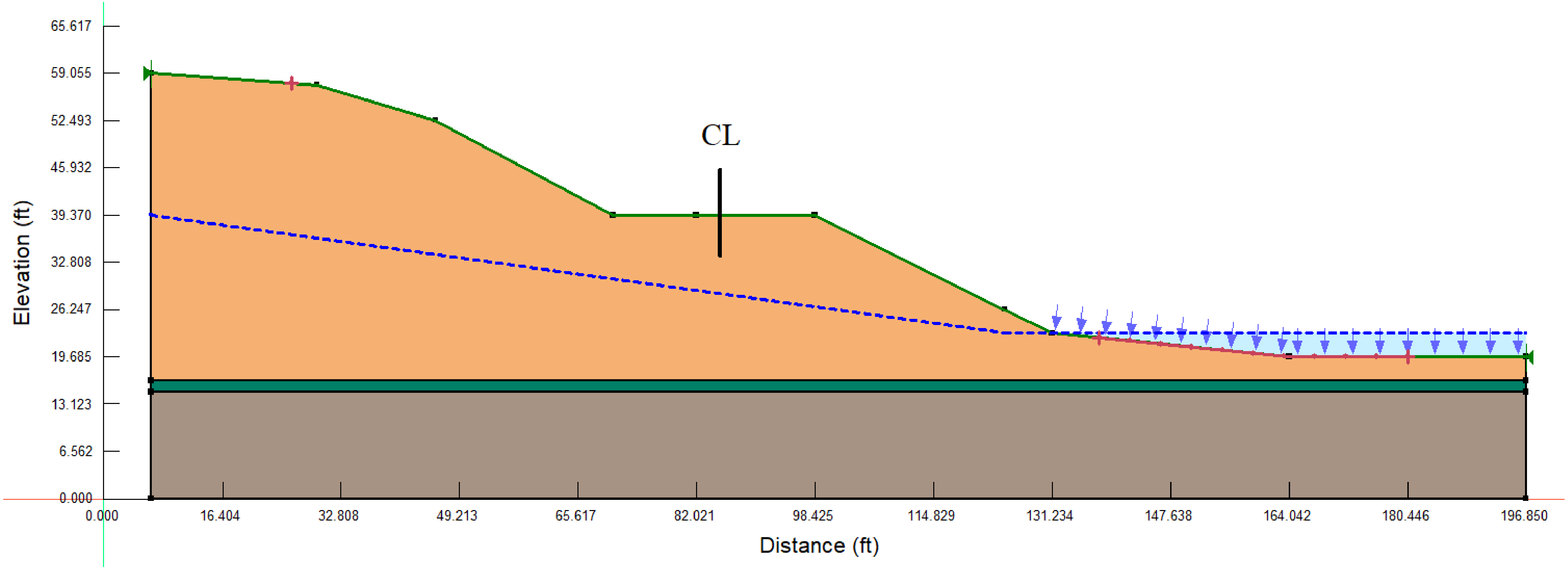
Generation 3 (GRBD): Consider the Full Life Under Uncertainty and Maximize Benefits



Impact of Time and Repeated Events

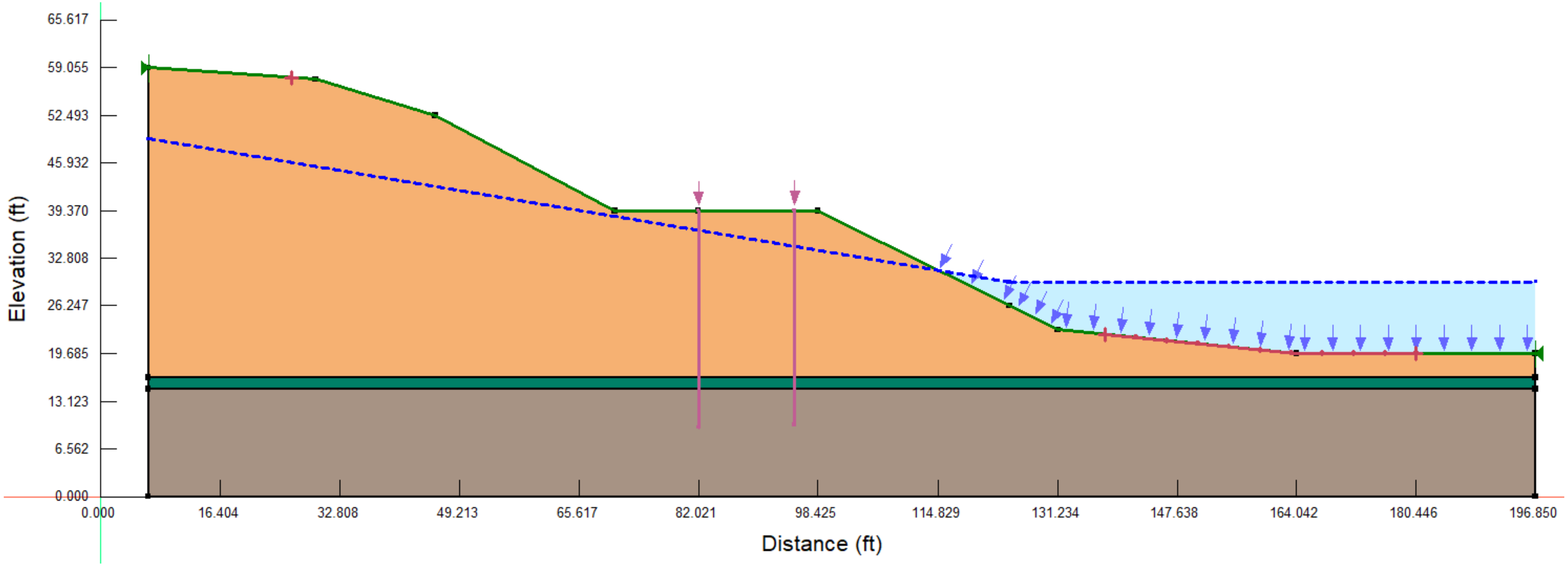


Case Study: Cut Slope Stabilized Using Drilled Shafts



Improving Resiliency

- This solution brought the reliability index to 3.00 from 1.37 and a probability of failure to 0.10% from 7.8%.



Outline

- Resiliency and its Role in Geotechnical Practice
- Load and Resistance During Service Life
- Design Philosophy
- **Concluding Remarks and Future Directions**

Concluding Remarks and Future Directions (1 of 2)

- Traditionally we have evaluated loading conditions by investigating the past events. With the changing conditions and climate impacts, loading conditions should be properly modeled and forecasted into the future using proper data driven procedures.
- Loading conditions have been showing non-stationary trends and increased frequency, which should not be ignored or oversimplified, even if using probabilistic analysis.
- The most appropriate tool to consider the loading conditions is to simulate future time series scenarios with extreme events and identify the most critical loading conditions and sequence of events.

Concluding Remarks and Future Directions (2 of 2)

- It is important to consider the condition and performance of geotechnical assets in addition to their capacity using response functions to a given time series scenario.
- Life cycle analysis (part of asset management) plays a significant role to develop more adaptive designs with planned maintenance and rehabilitation activities.
- A proper GRBD should also consider the serviceability and economic impacts of geotechnical asset during their service life, and the ability of the asset to rebound after extreme events.

Resilience-Based Design of Geotechnical Assets

Q & A

Ahmad Alhasan
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Modeling Cascading Failures of Levees and Power Grids Due to Flooding in Changing Climate

Farshid Vahedifard, Ph.D., P.E., F.ASCE
Professor and Louis Berger Chair
Department of Civil and Environmental Engineering
Tufts University

Lead, Resilient and Equitable Infrastructure
United Nations University
Institute for Water, Environment and Health (UNU-INWEH)

Levees: Critical Infrastructure Systems

- More than 38,000 miles of levee in the U.S., with an average age of 60 years
- Over 36 million people live behind levees*
- Protecting over $2.0 trillion of property
- ASCE Report Card Garde: D (marginal/poor),

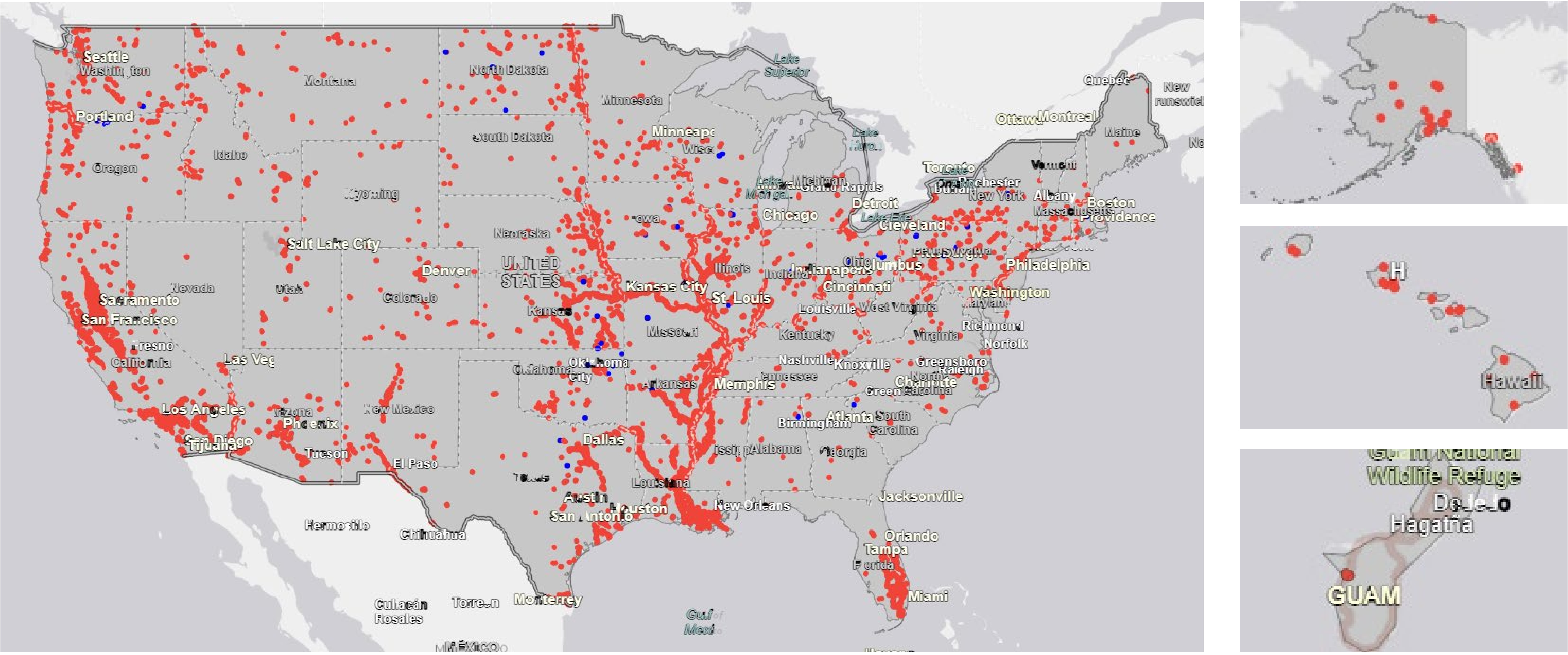
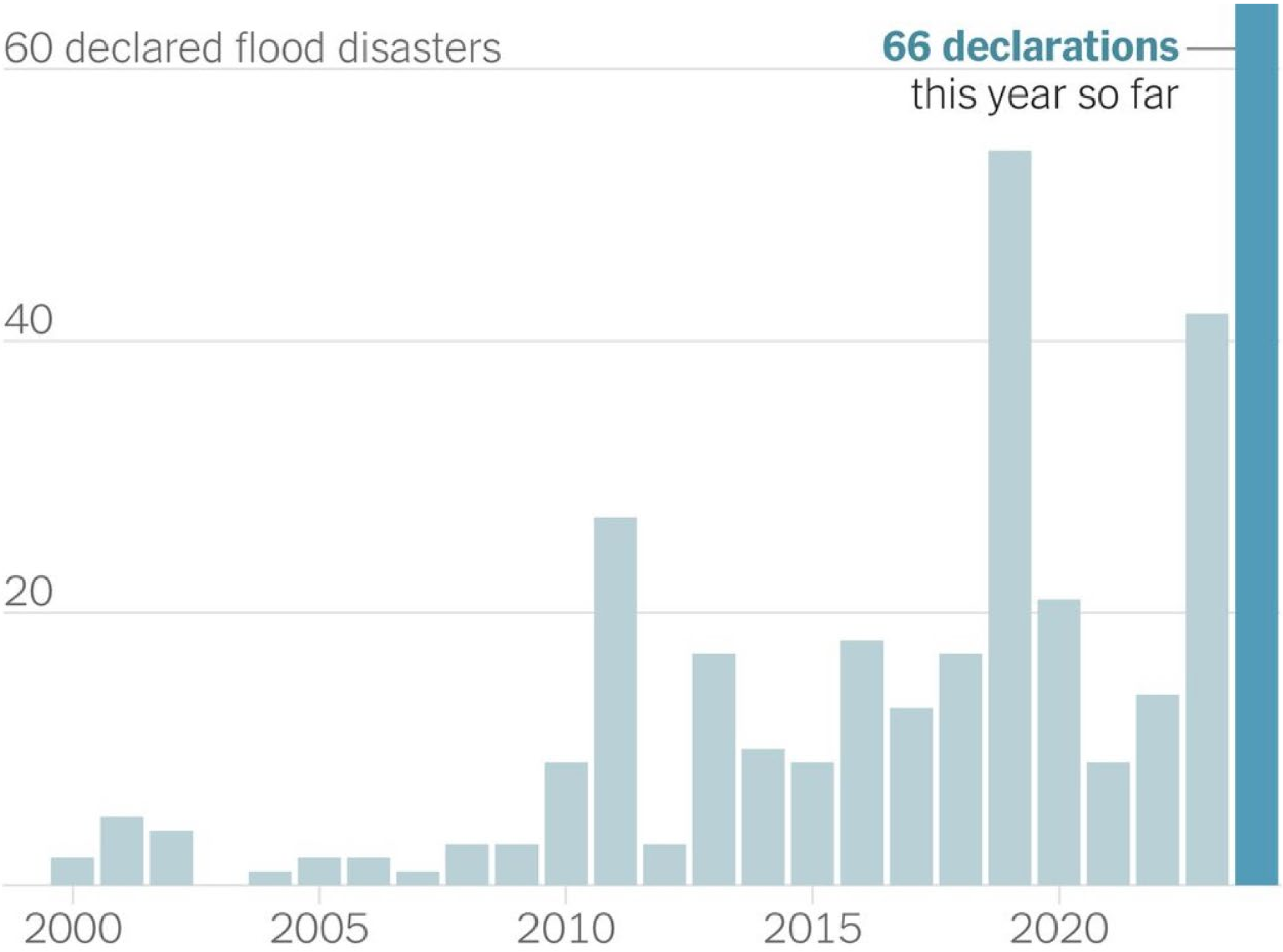


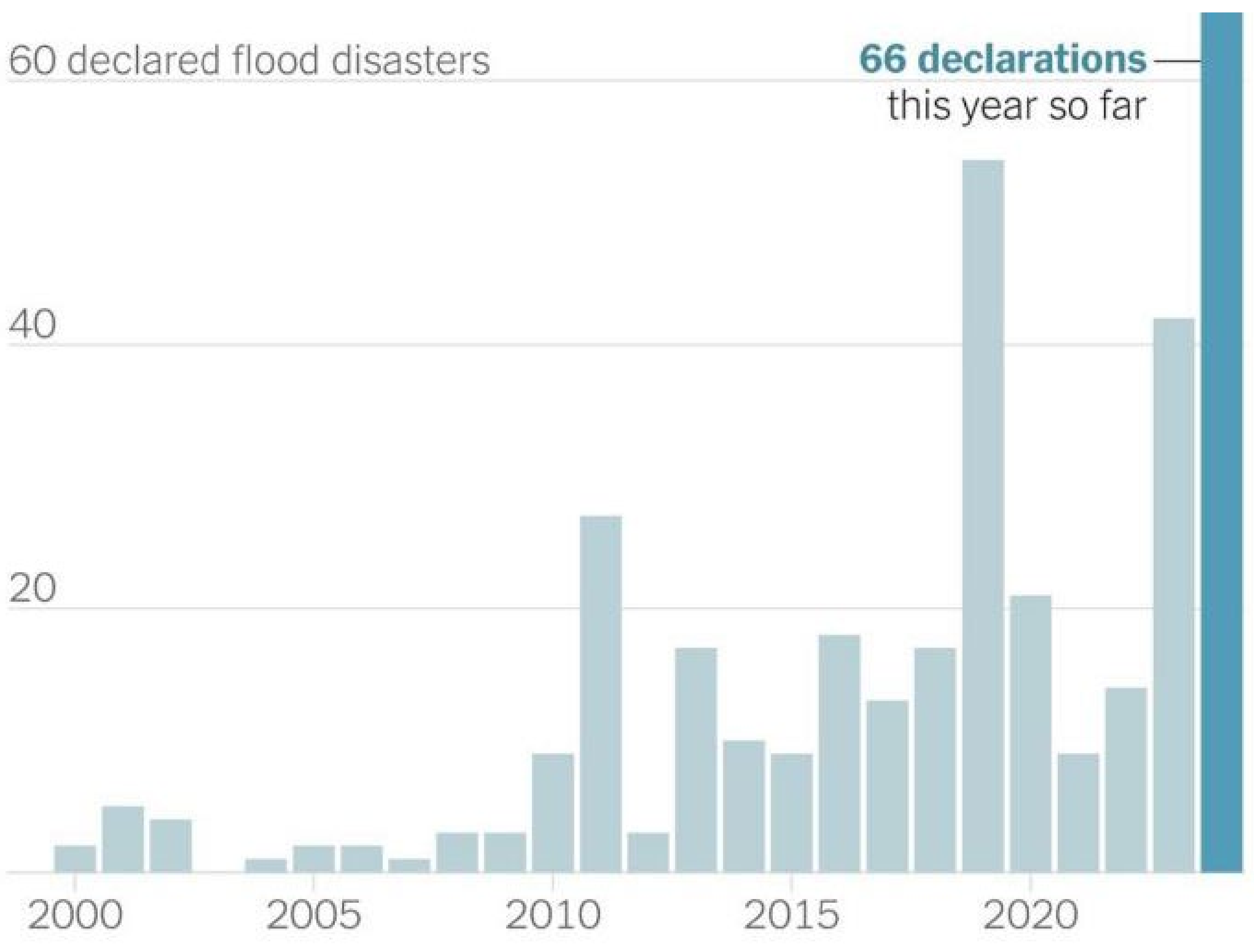
Image modified from USACE National Levee Database (2024)

A Surge in U.S. Flood Disasters



America's Flooding Problem, New York Times sourced from the Federal Emergency Management Agency
https://www.nytimes.com/2024/10/22/briefing/americas-flooding-problem.html

Critical Infrastructure at Risk of Failure due to Flooding



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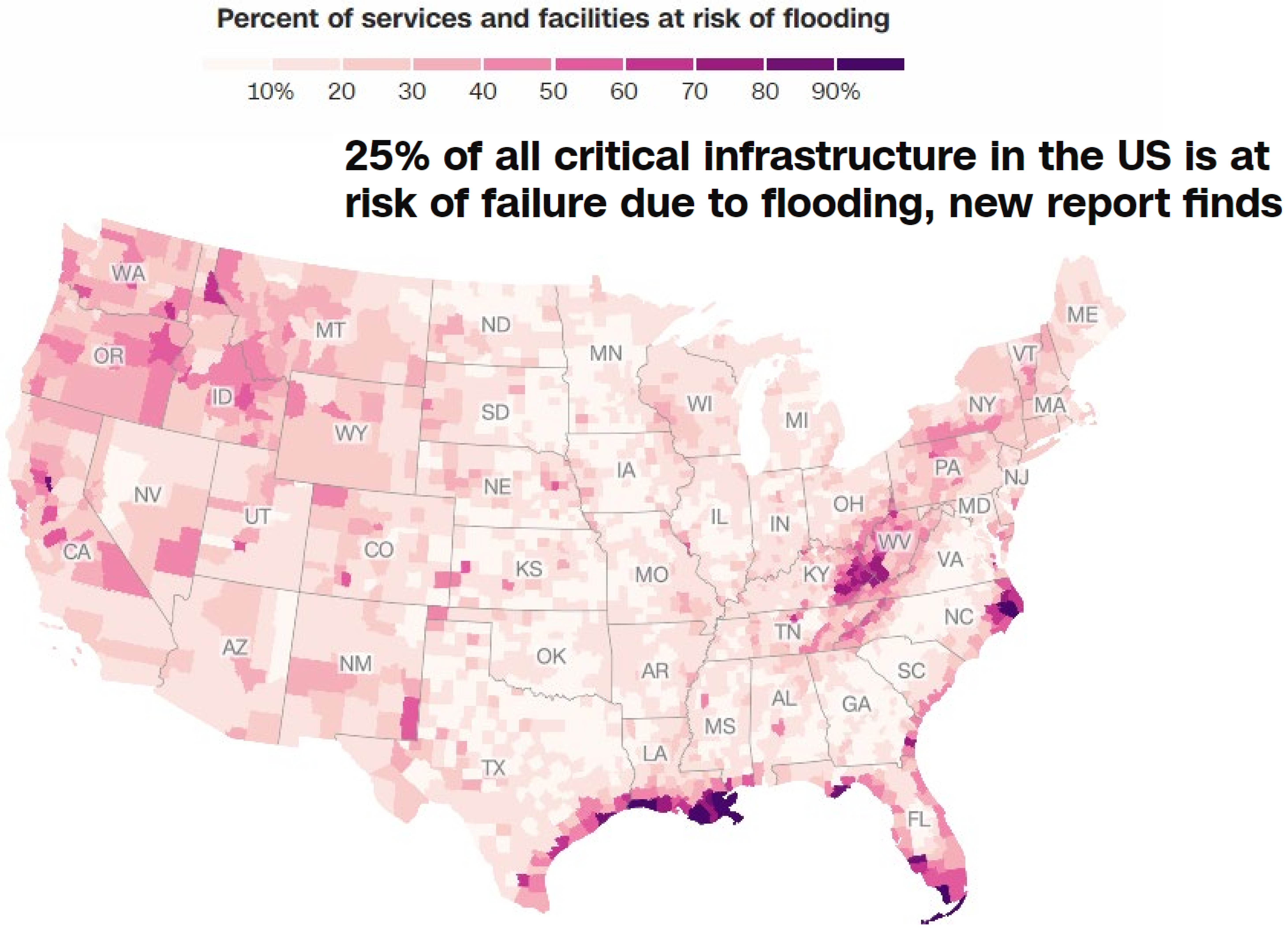
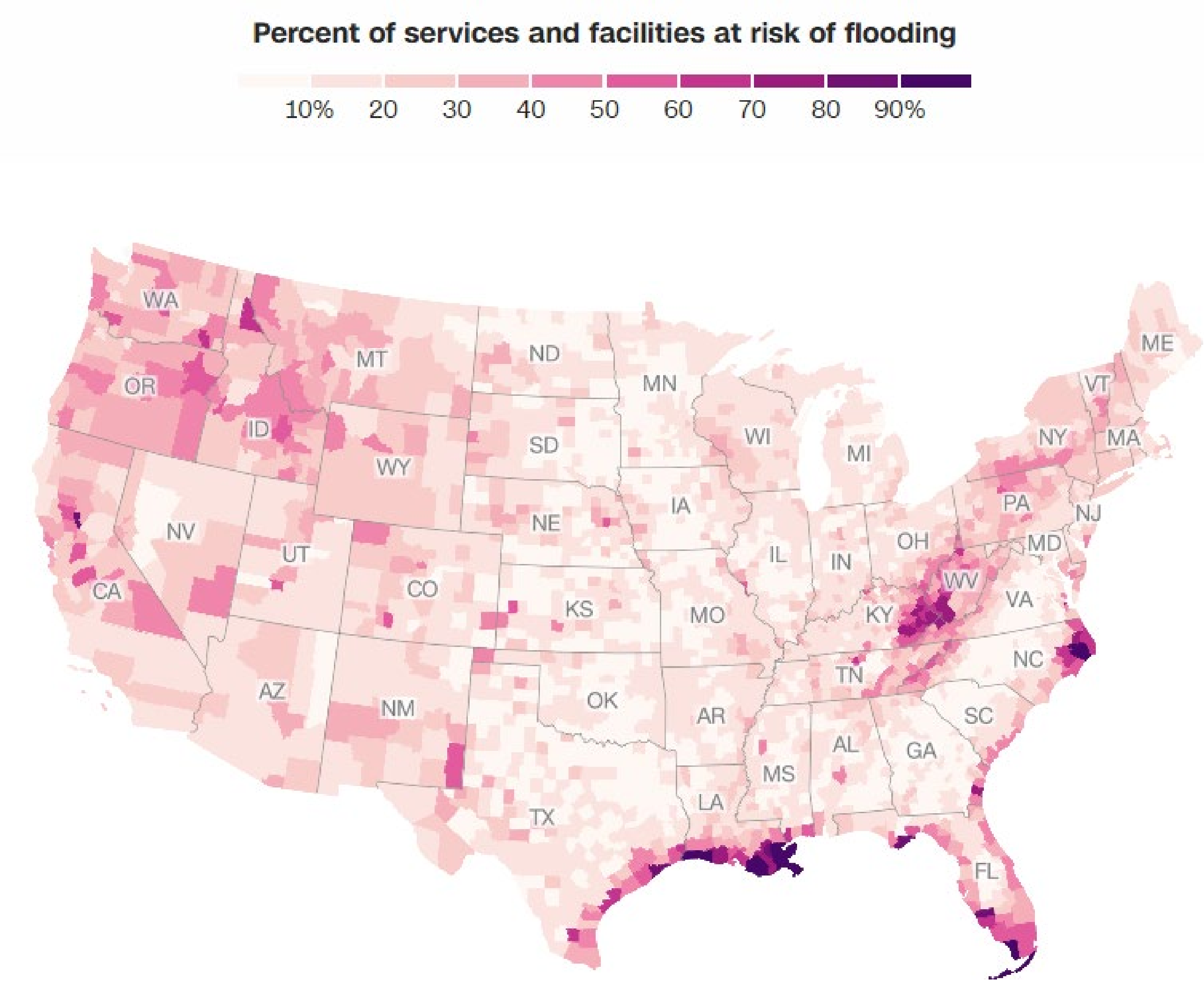


25% of all critical infrastructure in the US is at risk of failure due to flooding, CNN sourced from First Street Foundation
https://www.cnn.com/2021/10/11/weather/infrastructure-flood-risk-climate-first-street/index.html

Aging U.S. Levees: Final Line of Flood Defense



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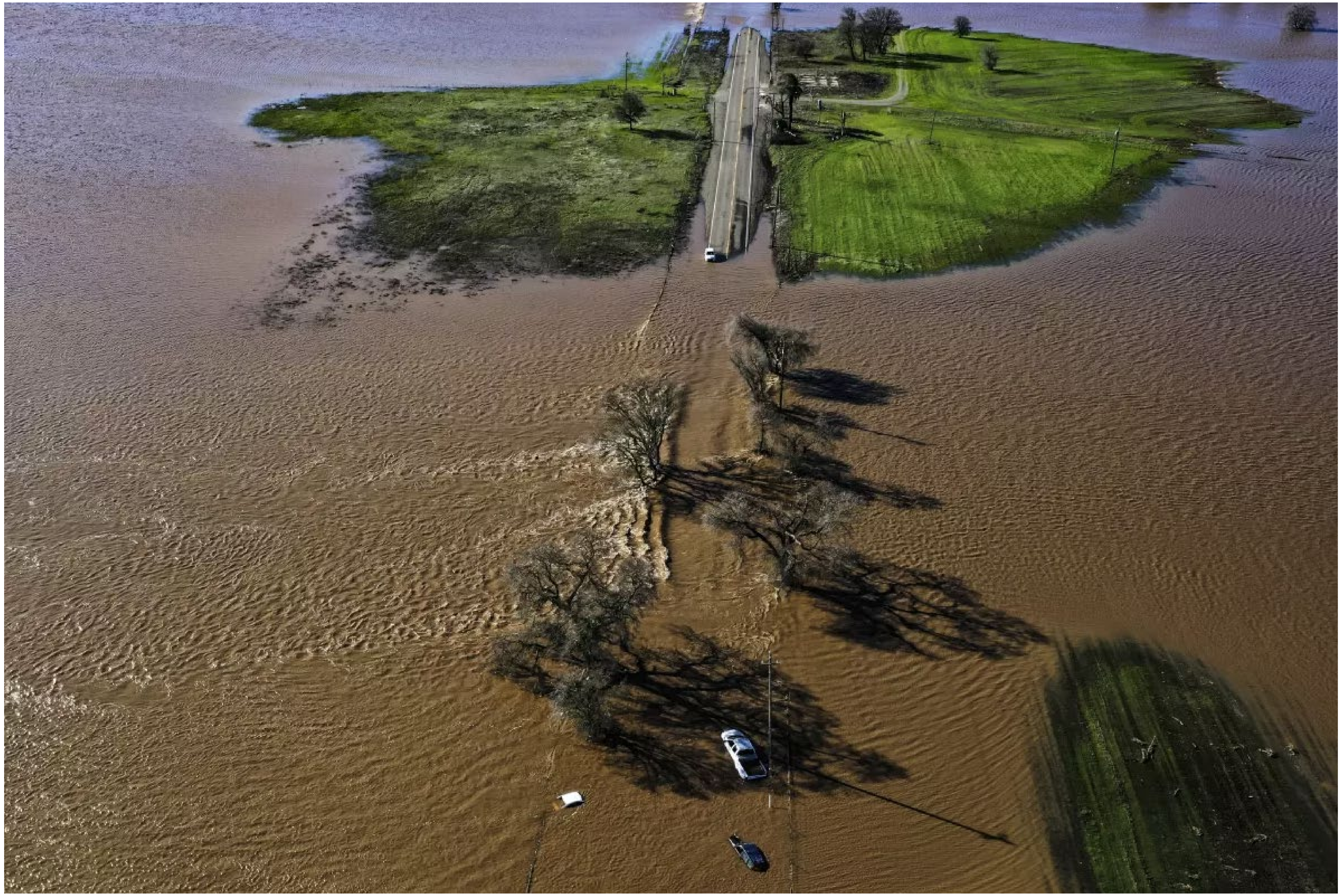


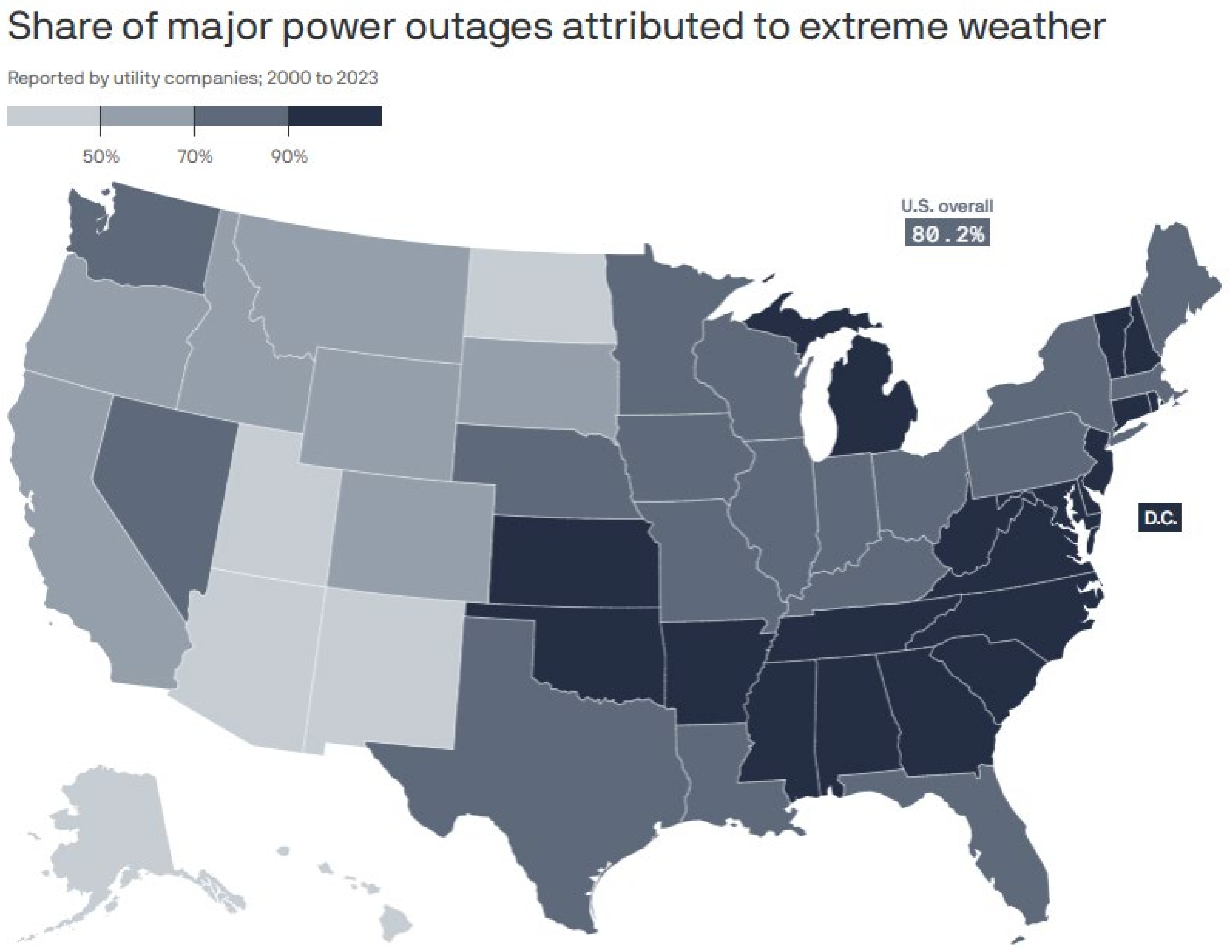
Can California's aging levees cope with extreme weather?, CNN
https://www.latimes.com/environment/story/2023-01-05/can-aging-california-levees-cope-with-exterme-weather

When Levees Break: Cascading Failures

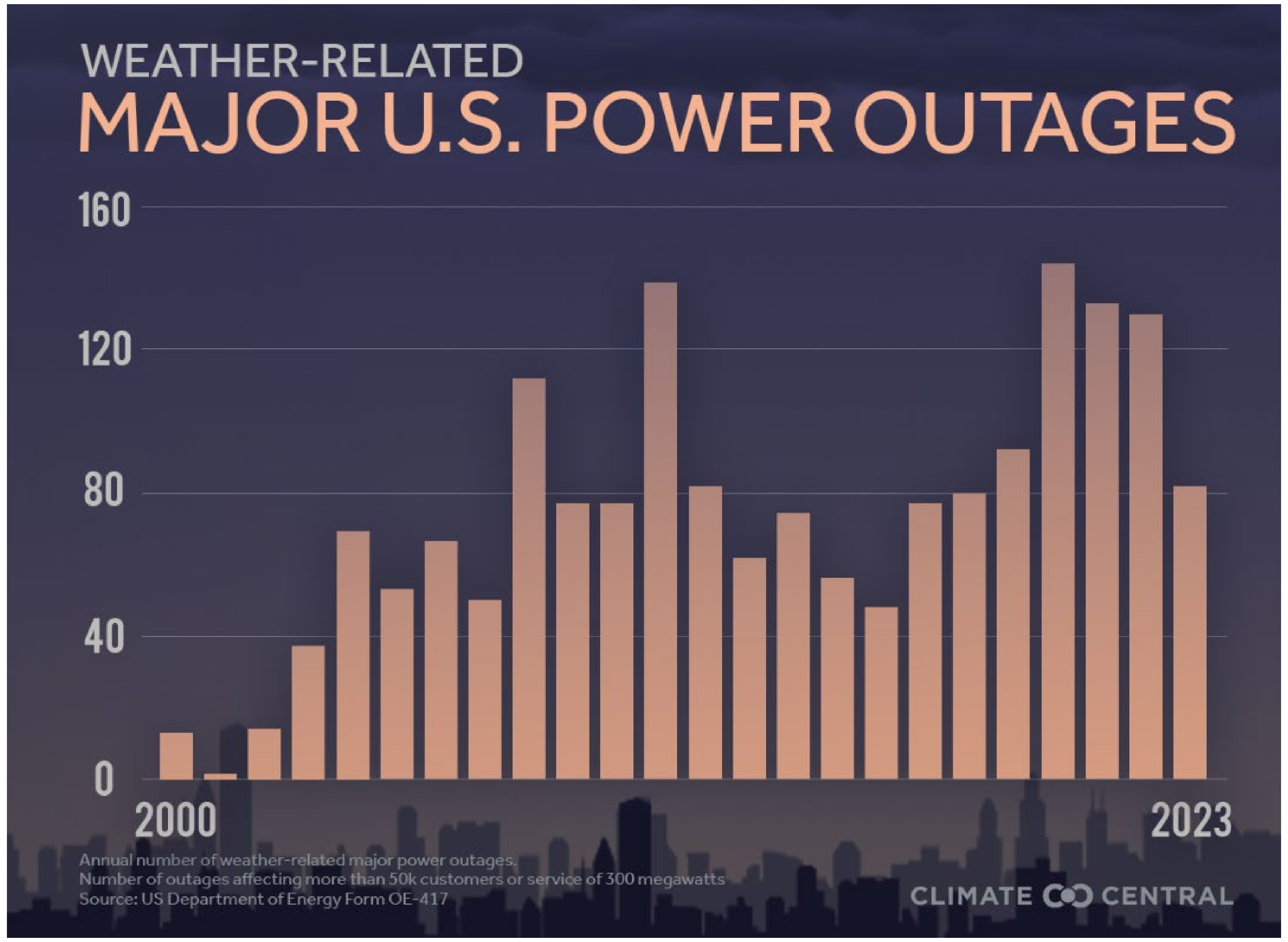
https://youtu.be/BtlfbhMp02Q?si=4o8qzN7WkSybhBnr

Increasing Power Outages due to Weather Events

- Power outages cost the U.S. economy $28-169B annually.
- Between 2000 and 2023, 80% of reported major outages due to weather events.
- The average annual number of power outages increased by roughly 116% during 2011-2023 compared to 2000-2010.
- From 2000-2023, there were 1,755 weather-related power outages. Winter weather (23%), tropical cyclones (14%), and other severe weather (58%).



Climate Central via U.S. Department of Energy
https://www.axios.com/2024/04/24/us-grid-outages-extreme-weather



Power outages 2000 to 2023
https://www.climatecentral.org/climate-matters/weather-related-power-outages-rising

Goal and Objectives

Goal

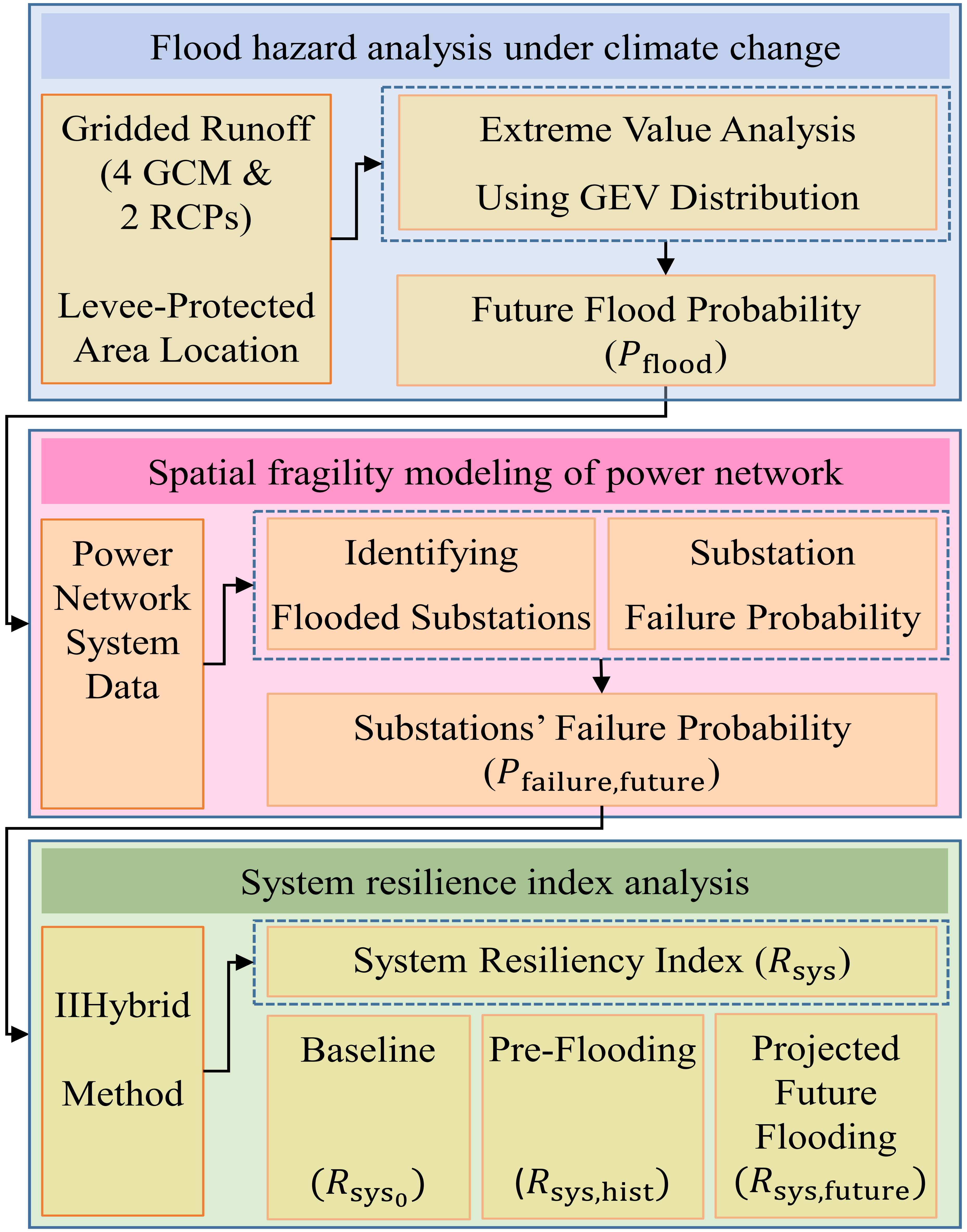
Enhancing the resiliency and developing adaptation strategies for levees and levee-protected electric power networks to flooding under a changing climate.

Objectives

To establish a methodological and multi-disciplinary framework by integrating climate science, hydrology, and electric power network to quantitively asses the resiliency of levee-protected electric power networks to flooding in a changing climate.

- How does climate change affect reoccurrence intervals of flooding?
- How does the integrity of levees will be affected by changes in flooding patterns?
- How will these changes affect the resilience of levees and a power grid located in levee-protected areas?

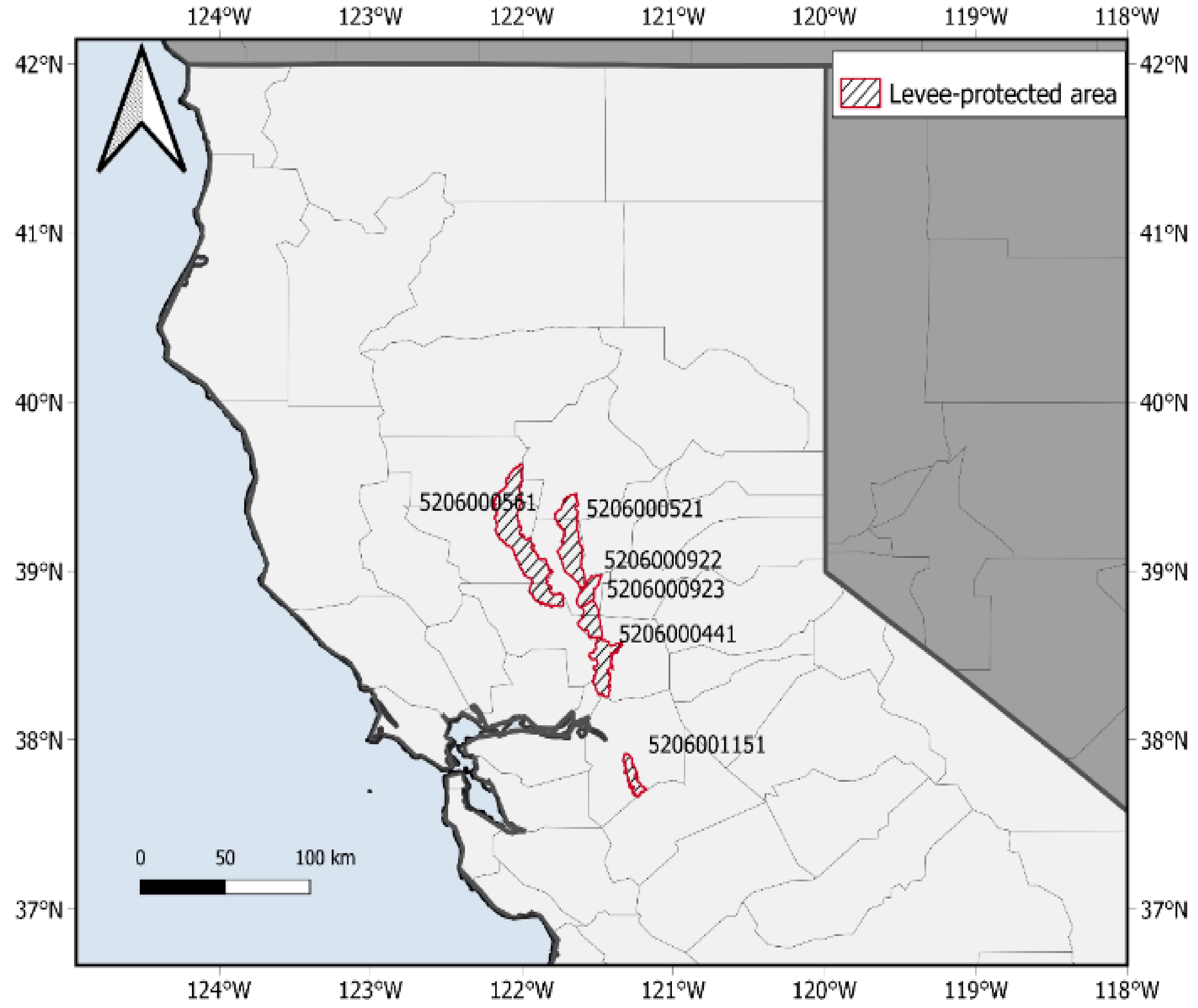
Proposed Modeling Framework

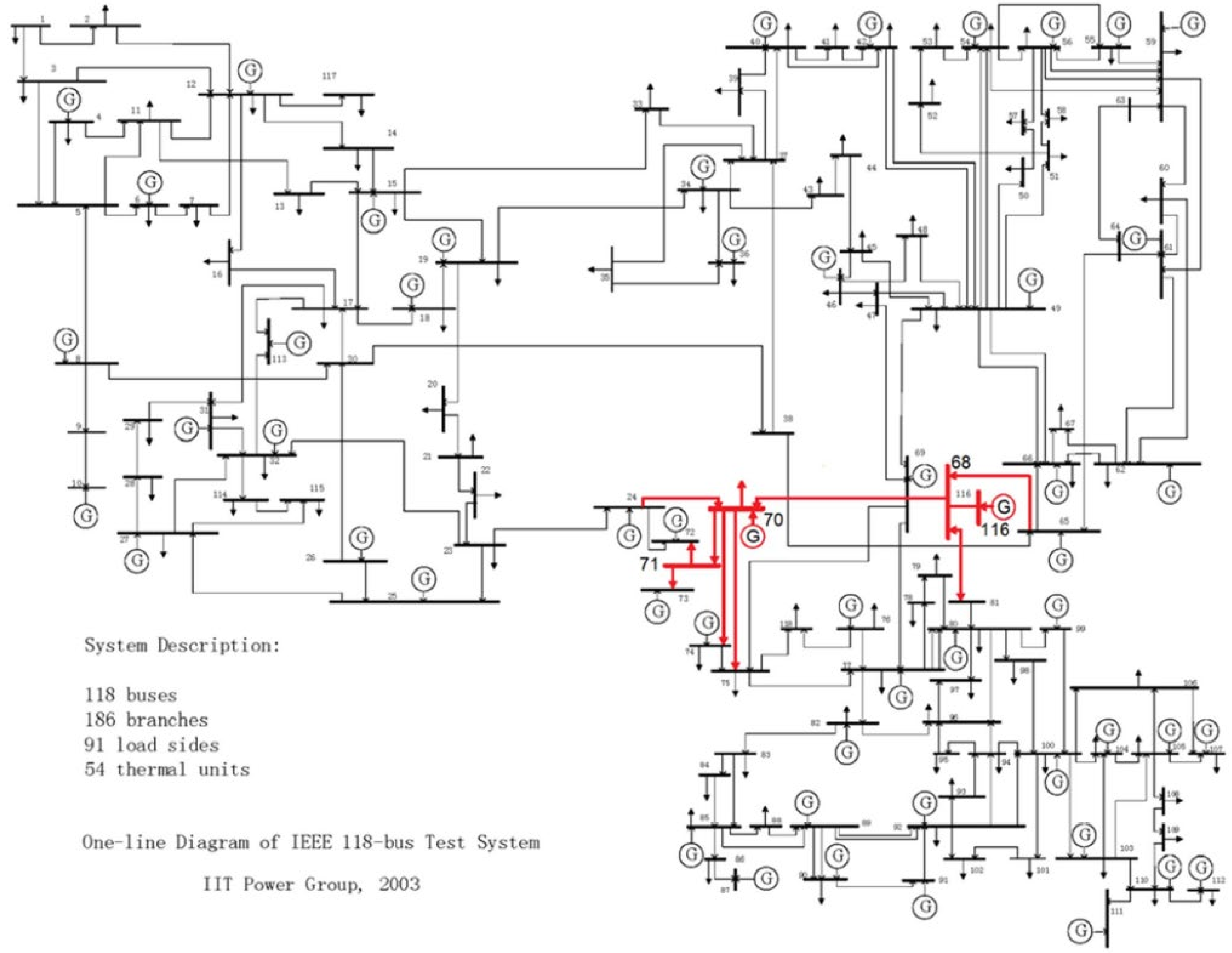


Miraee-Ashtiani et al. (2022)

Study Area: Northern California

- There are 3242 levee systems in California with an average age of 57 years, protecting over 6 million people and an estimated $8 billion in property.
- 82% of CA's counties have at least a levee system with a 1 km length.
- Test Power Network: IEEE 118-bus system.



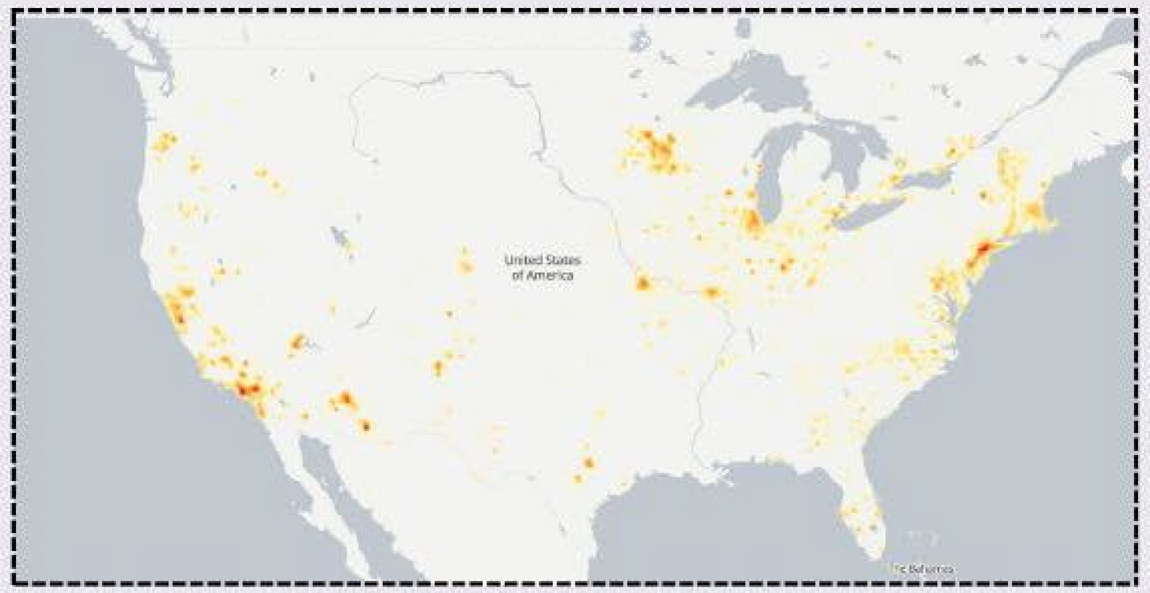


Miraee-Ashtiani et al. (2022)

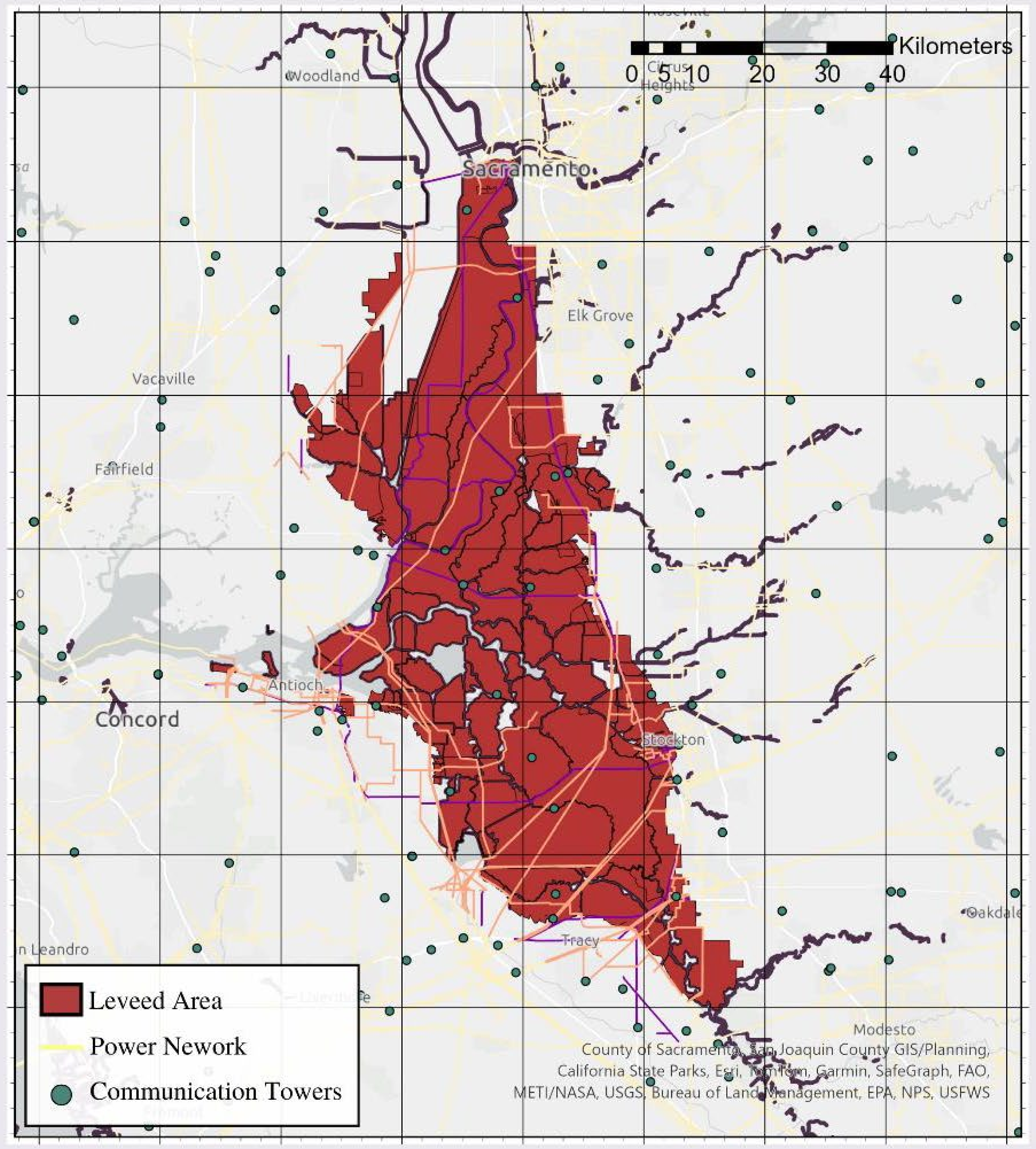
Levee-Protected Infrastructure Systems

Levee System

Power Network



Communication Network



Proposed Modeling Framework: Levees under Climate-Adjusted Flooding

A) Field Monitoring

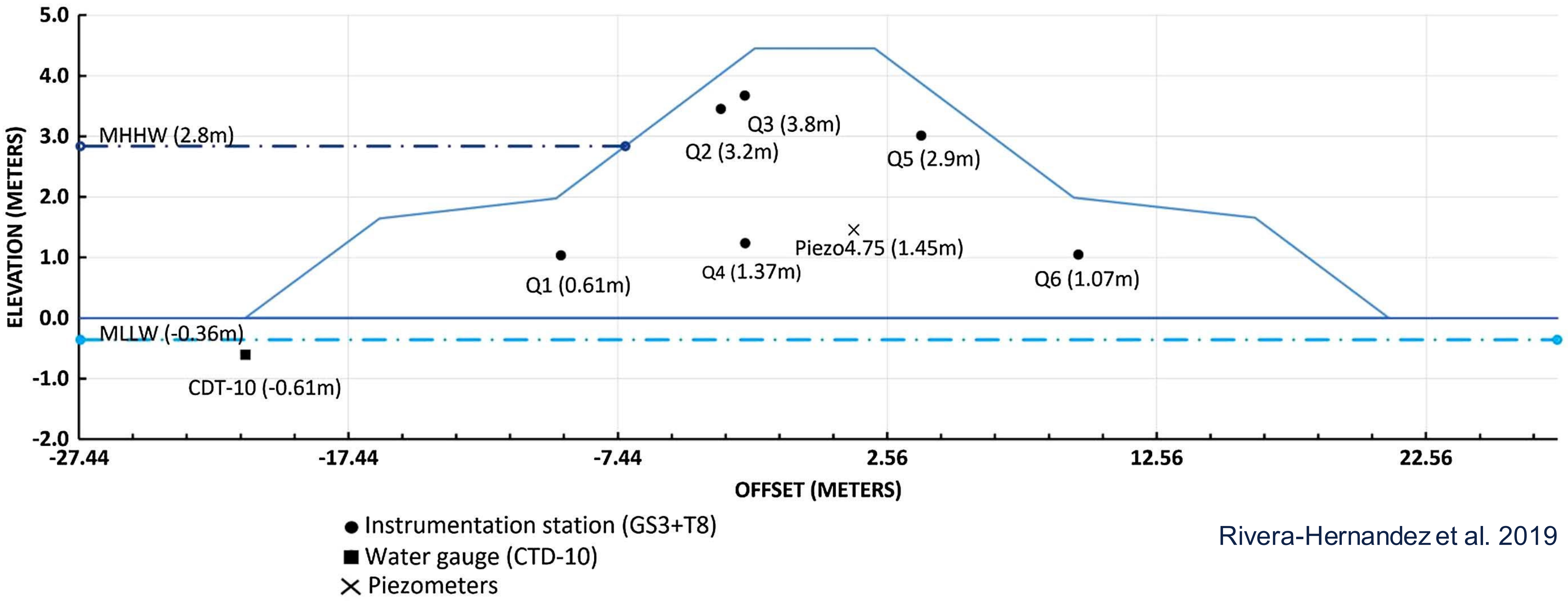
Qwuloolt Levee, WA

Rivera-Hernandez et al. 2019

Proposed Modeling Framework: Levees under Climate-Adjusted Flooding

A) Field Monitoring

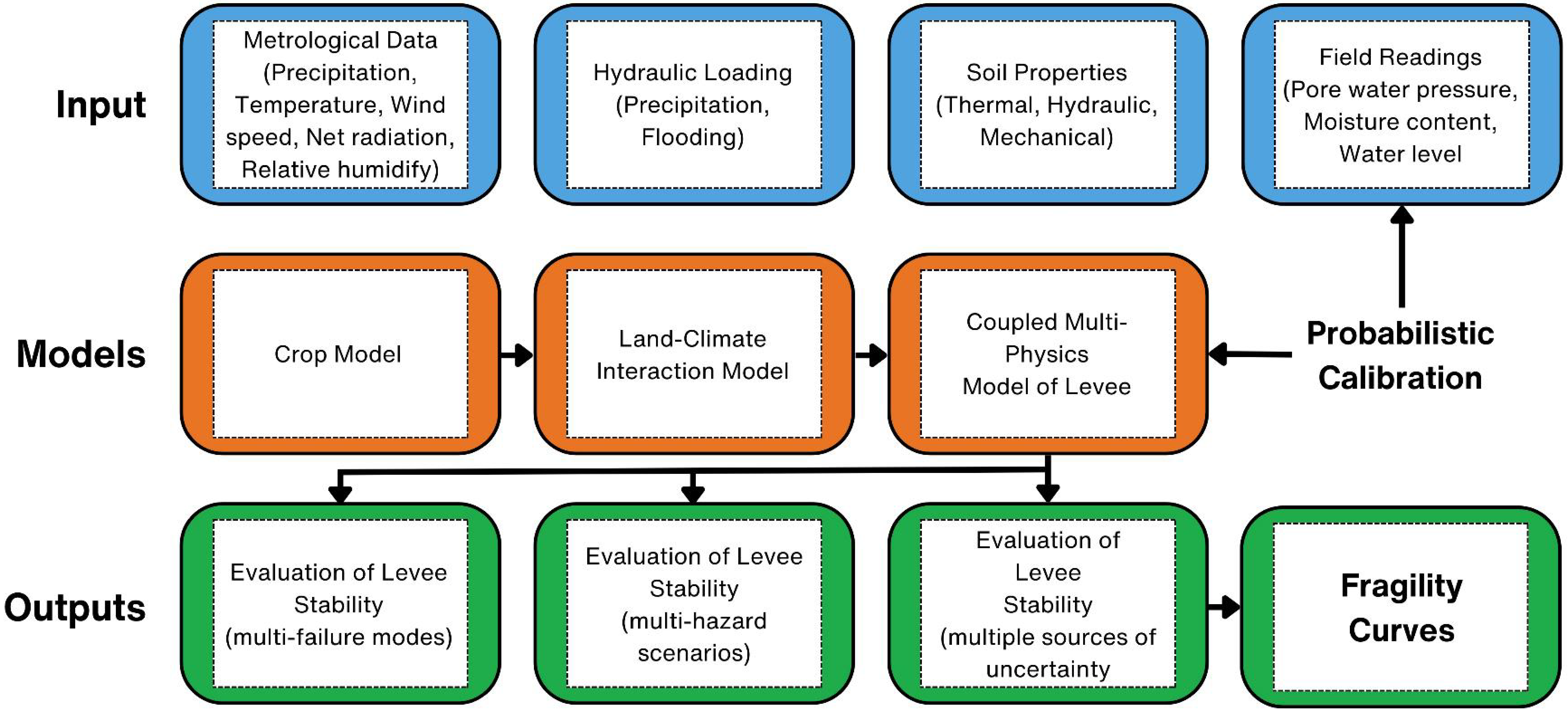
Qwuloolt Levee, WA



Rivera-Hernandez et al. 2019

Proposed Modeling Framework: Levees under Climate-Adjusted Flooding

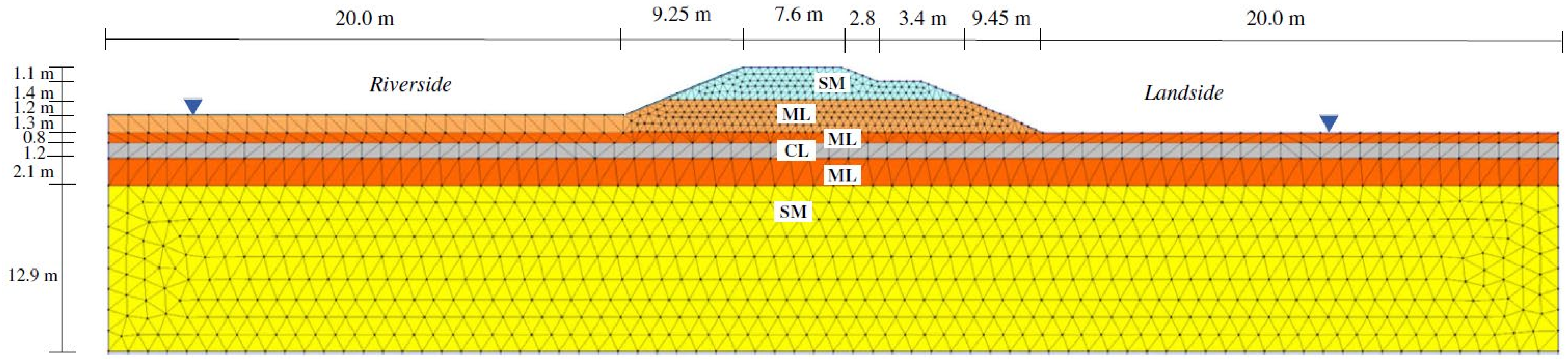
B) Physics-Based Modeling (under seepage, uplift, and slope stability)



Proposed Modeling Framework: Levees under Climate-Adjusted Flooding

B) Physics-Based Modeling (under seepage, uplift, and slope stability)

- The historical and future flood levels were applied in a set of transient coupled finite element seepage and limit equilibrium slope stability analyses to simulate the levee subjected to extreme streamflow
- Variability in hydraulic and mechanical properties of soils was addressed using a Monte Carlo sampling method to evaluate and compare the probability of failure of the levee under different historical and future climate scenarios.
- Three individual modes (under seepage, uplift, and slope stability) along with lower and upper bounds for the combined mode of failure were



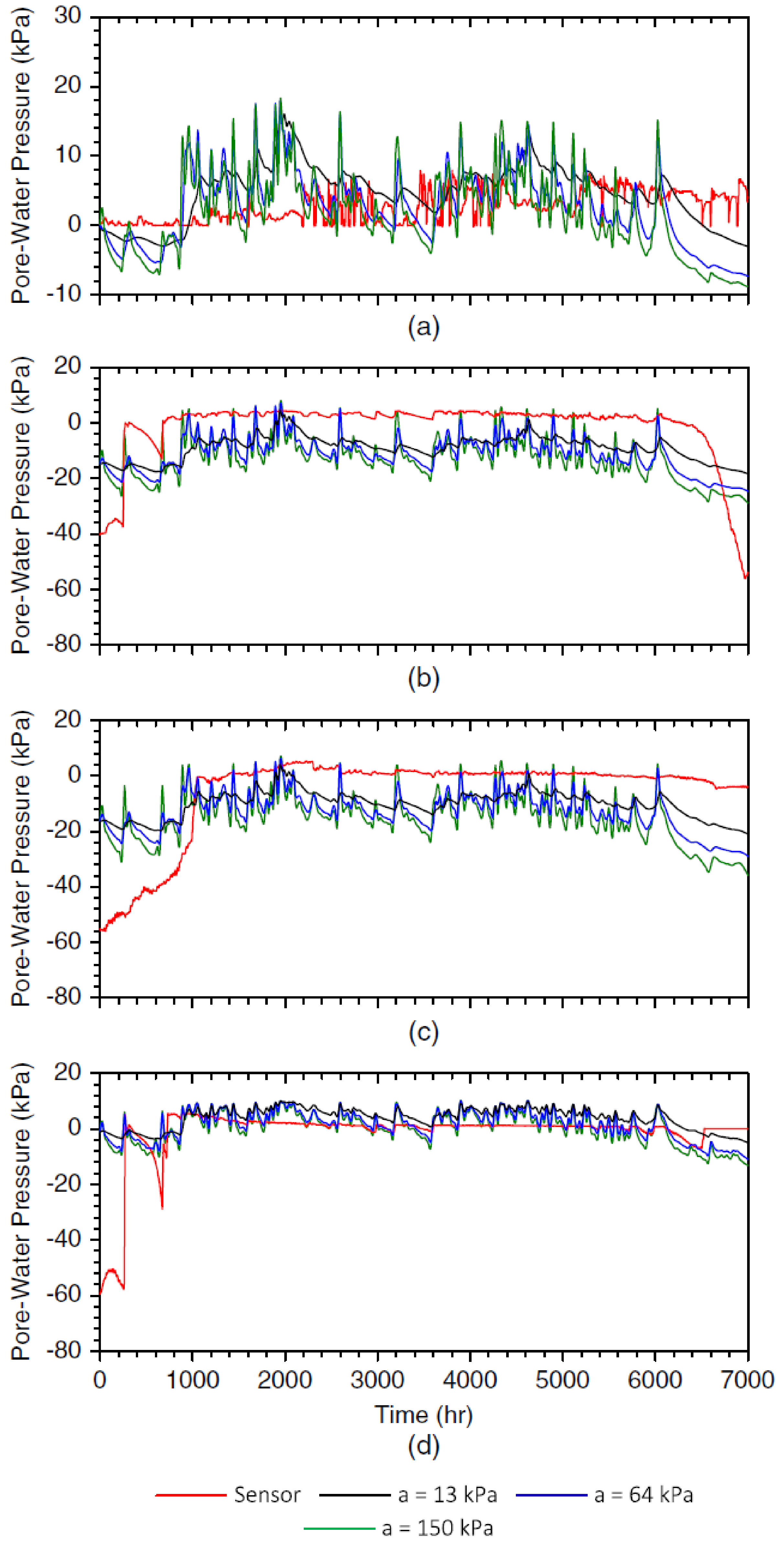
Proposed Modeling Framework: Levees under Climate-Adjusted Flooding

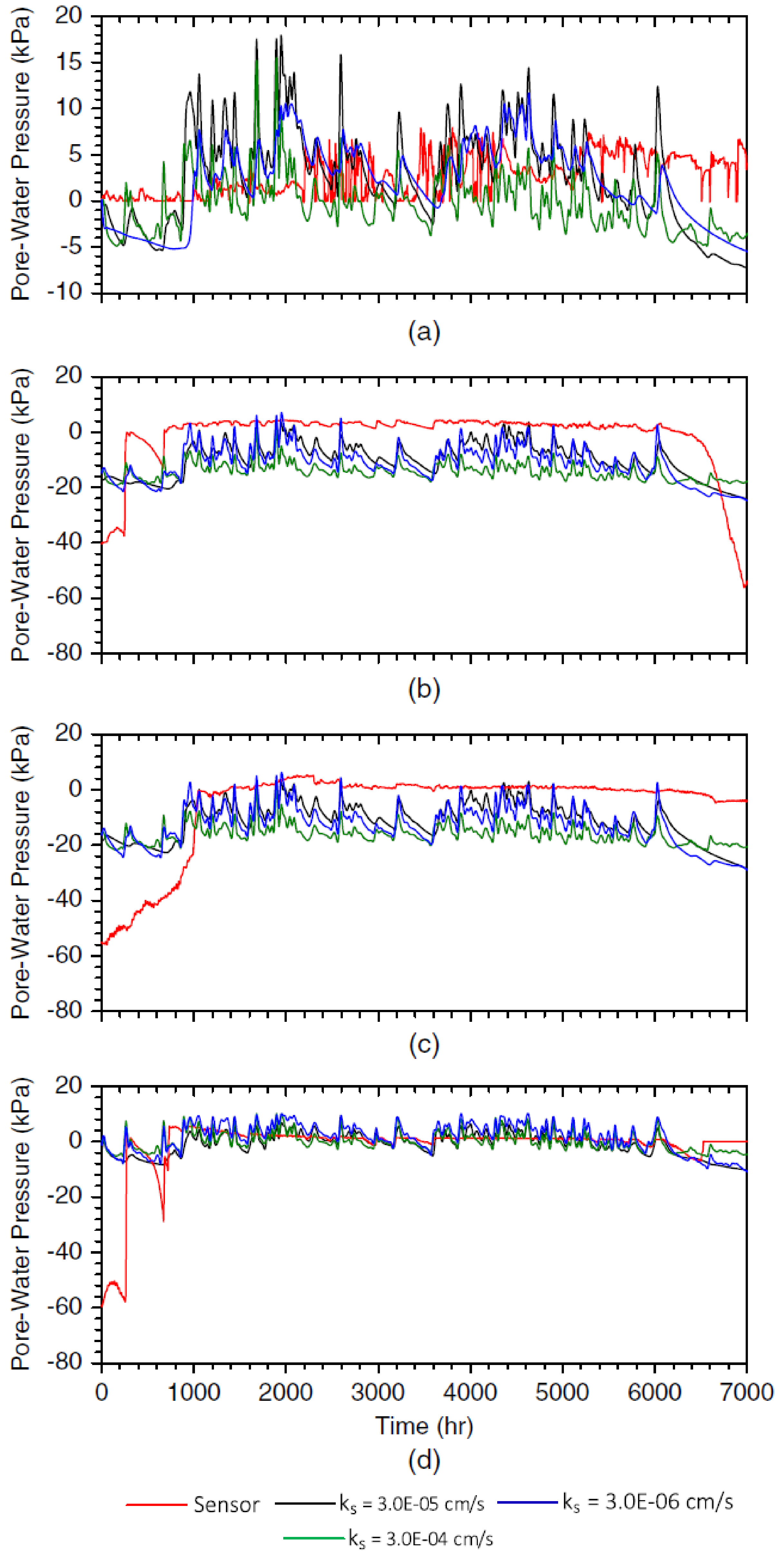
B) Physics-Based Modeling

Model Calibration with Field Data

Numerical model vs. measured field data from September 7, 2016, to July 7, 2017, using (a) Piezo4.75; (b) T8 tensiometer at Q2; (c) T8 tensiometer at Q5; and (d) T8 tensiometer at Q6.

Rivera-Hernandez et al. 2019

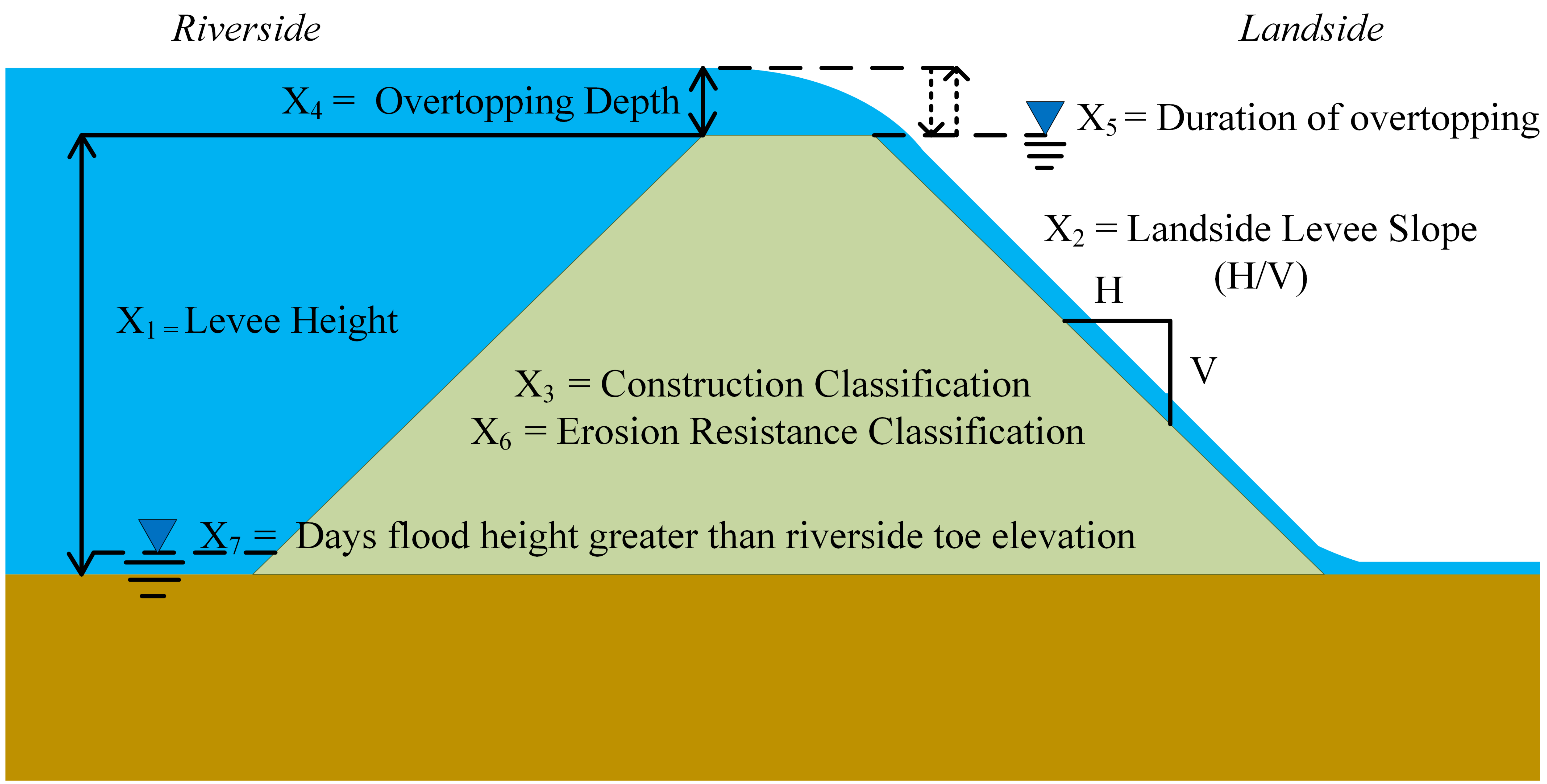




Proposed Modeling Framework: Levees under Climate-Adjusted Flooding

C) Data-Driven Modeling of Overtopping Failure

- Data for 230 levee overtopping events
- Logistic regression model

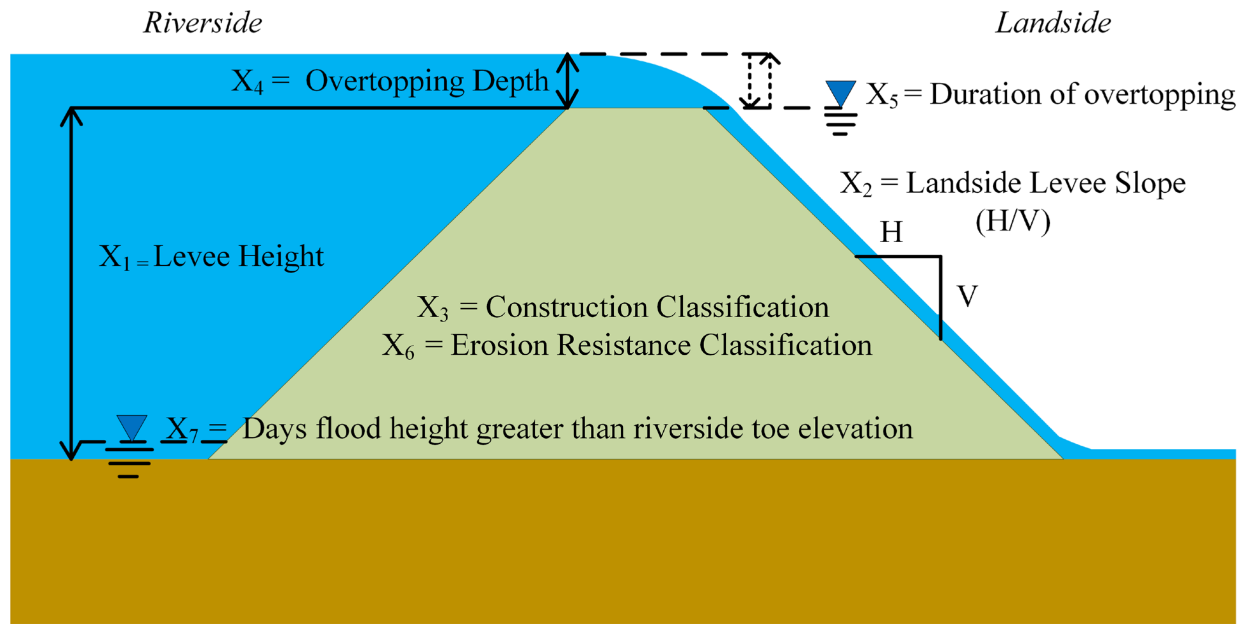


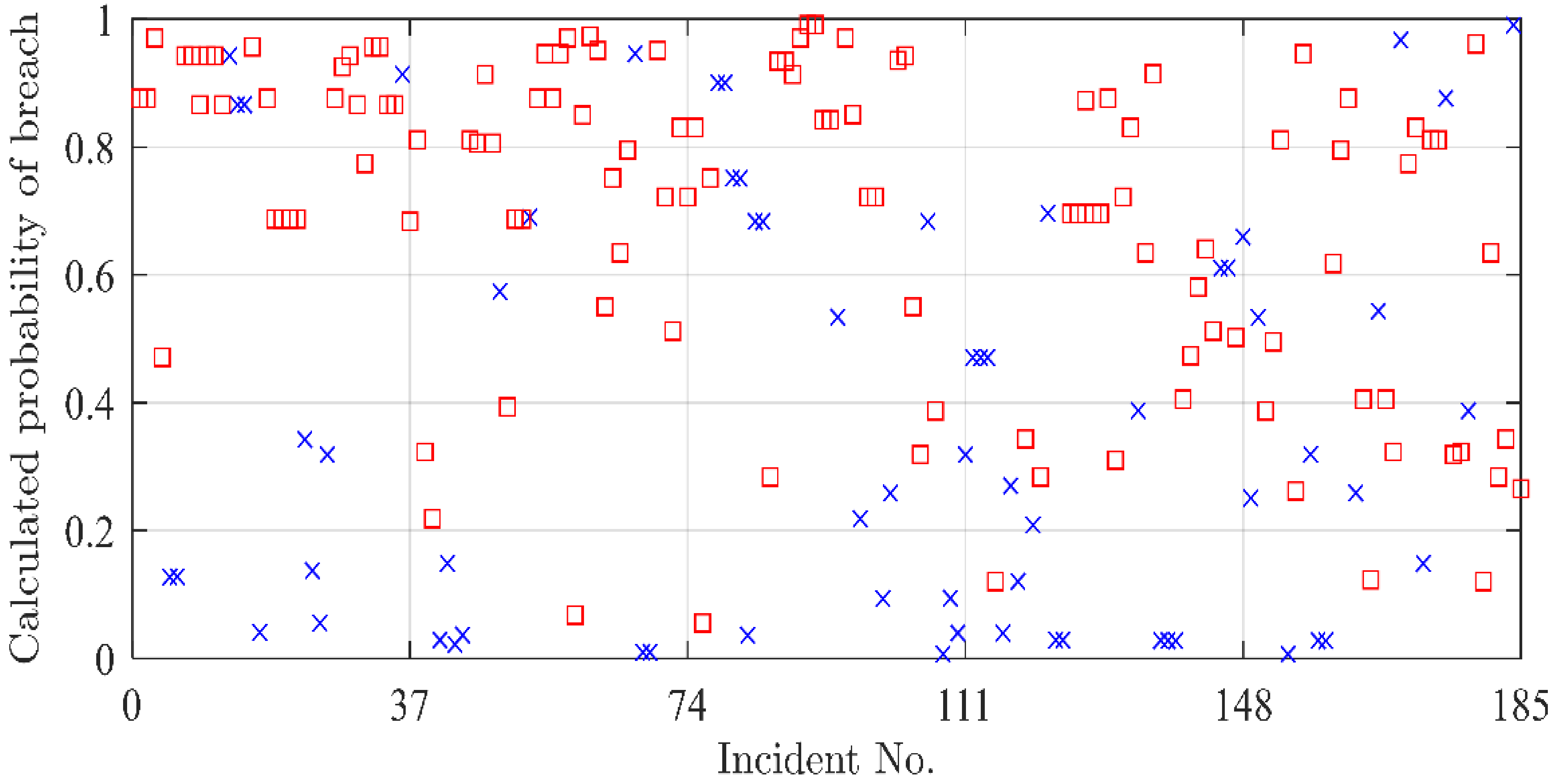
Flynn et al. 2021

Proposed Modeling Framework: Levees under Climate-Adjusted Flooding

C) Data-Driven Modeling of Overtopping Failure

- Data for 230 levee overtopping events
- Logistic regression model





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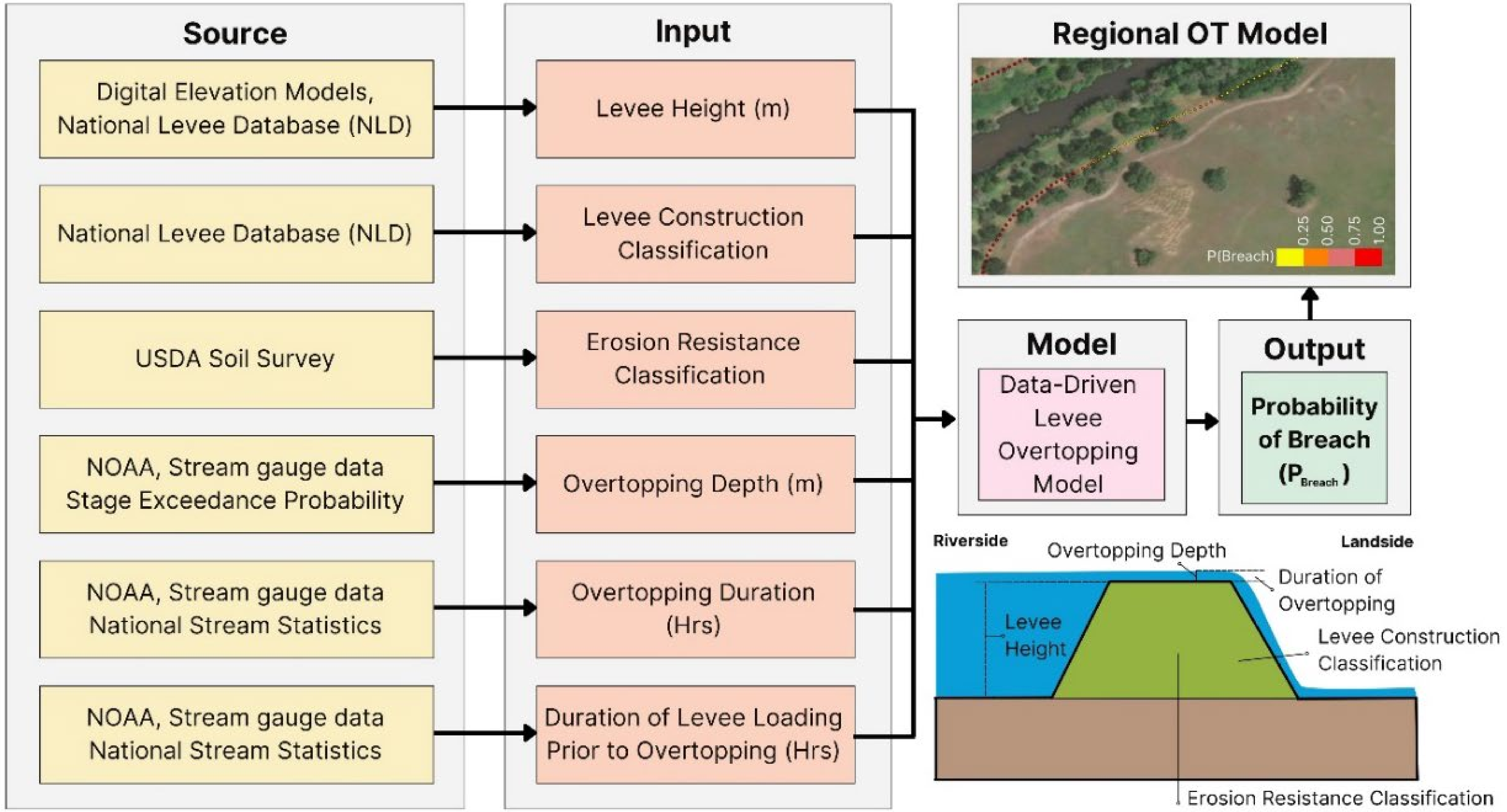
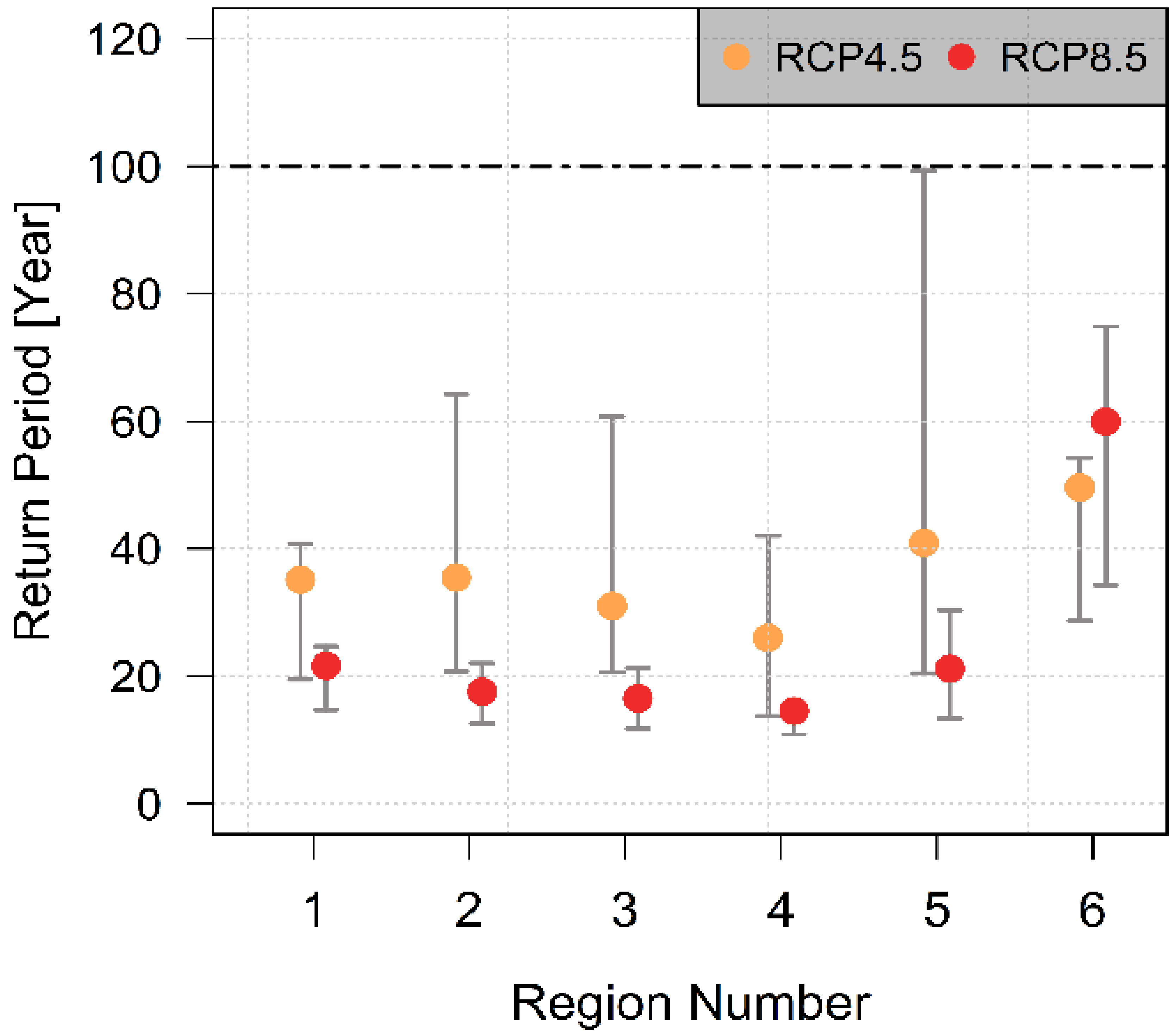
Proposed Modeling Framework: Levees under Climate-Adjusted Flooding

D) Regional Modeling of Breach due to Overtopping



Azhar et al. 2025

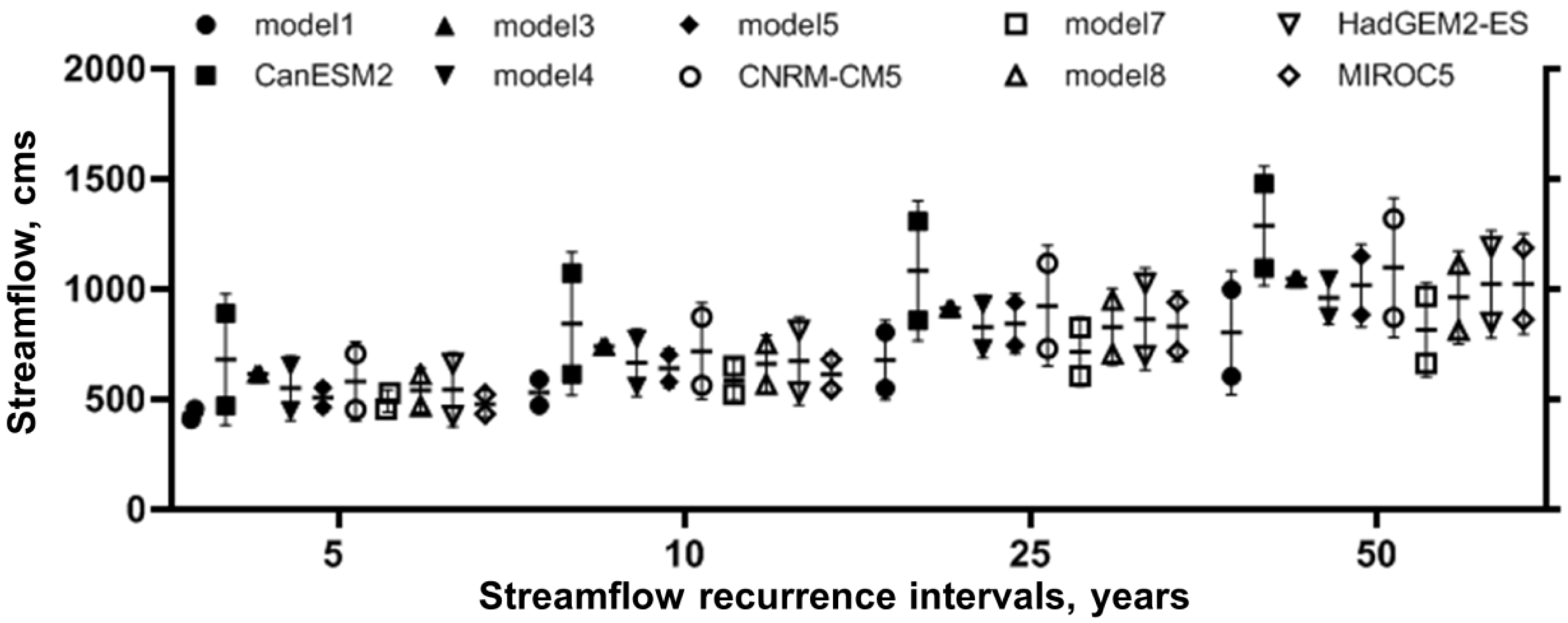
Results: Changes in Flooding Probability

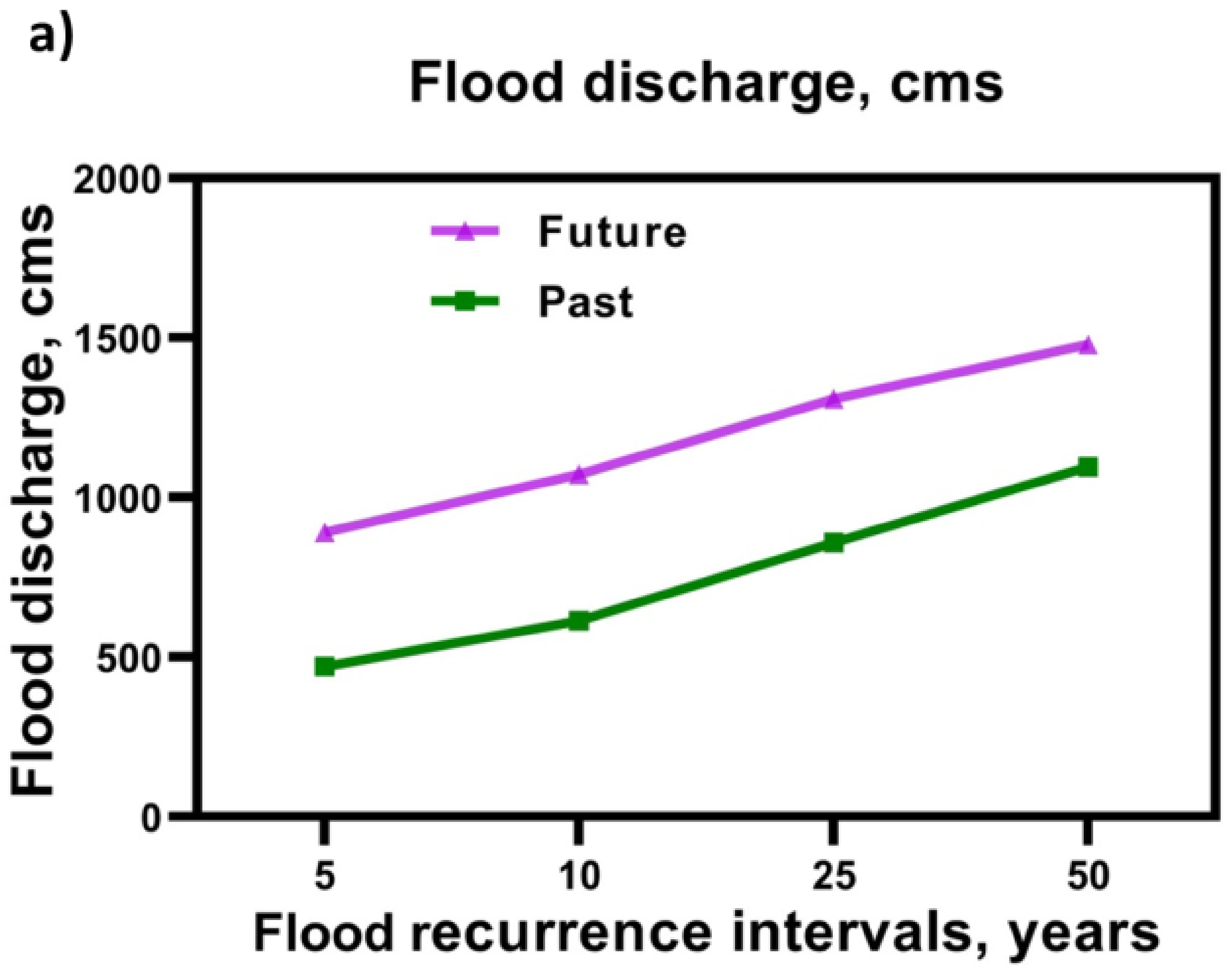


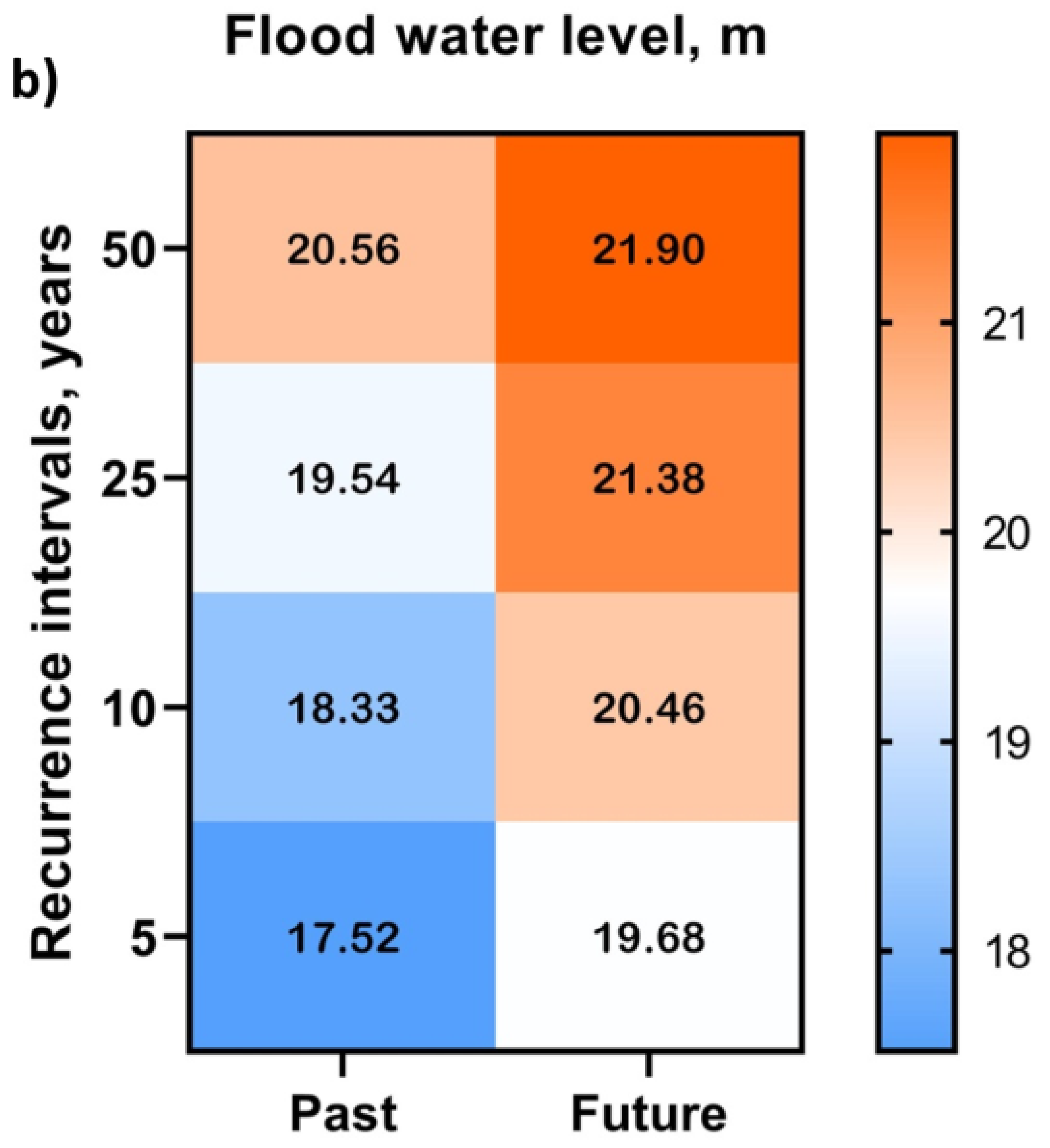
Region No.	Levee System ID	RCP 4.5		RCP 8.5	
		RP_{future} (yrs)	$\Delta P_{\text{flood}}(\%)$	RP_{future} (yrs)	$\Delta P_{\text{flood}}(\%)$
1	5205000441	35.2	184.1	21.6	363.0
2	5205000521	35.5	181.7	17.6	468.2
3	5205000561	31.0	222.6	16.5	506.1
4	5205000922	26.0	284.6	14.5	589.7
5	5205001151	40.9	144.5	21.2	371.7
6	5205000923	49.6	101.6	59.9	66.9
RP_{future}	= projected future return period of a flood currently associated with return period of 100-years				
ΔP_{flood}	=Relative change in hazard level of the currently known 100-year flood				

Miraee-Ashtiani et al. (2022)

Results: Changes in Flooding Return Period

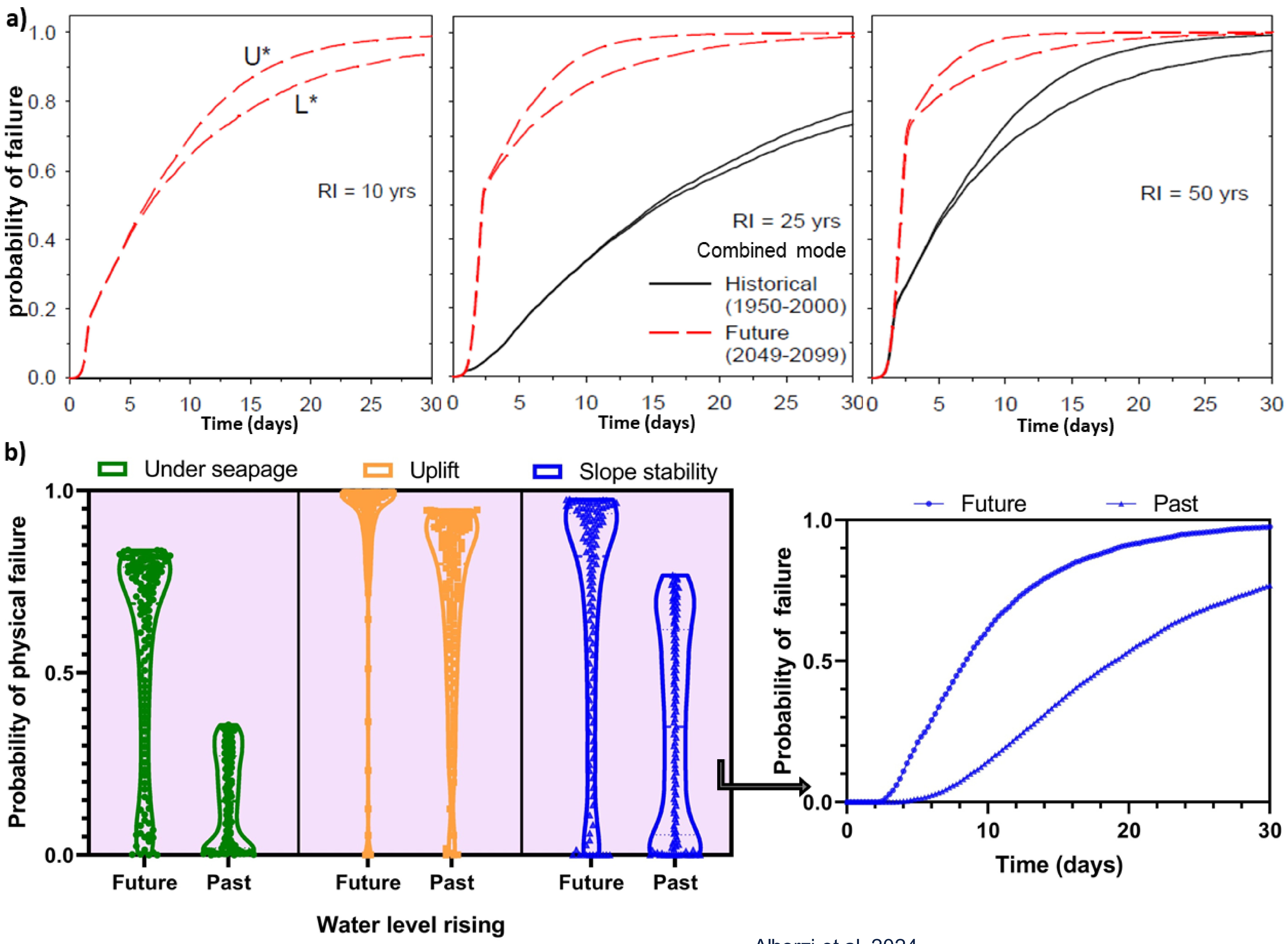






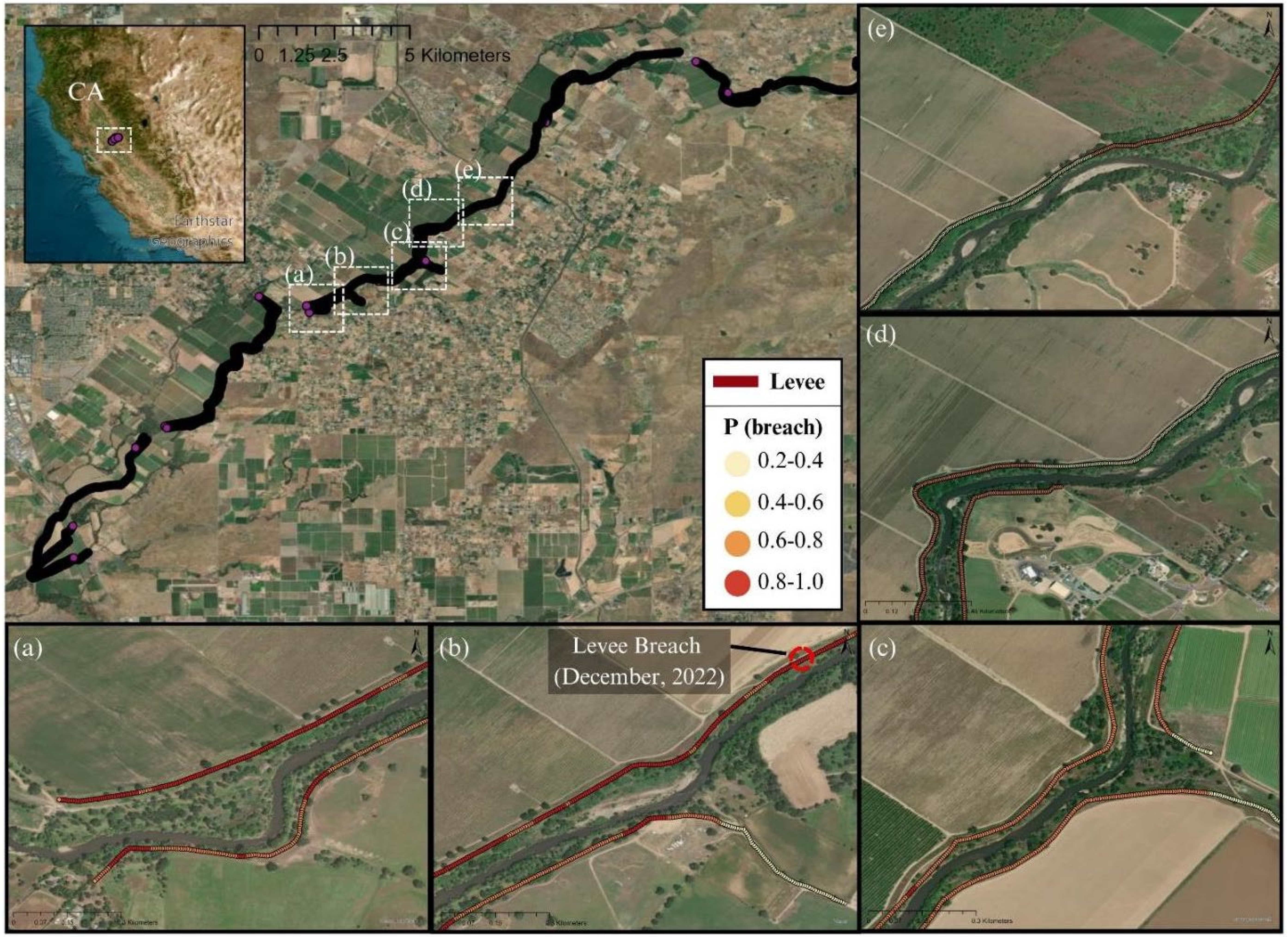
Alborzi et al. 2024

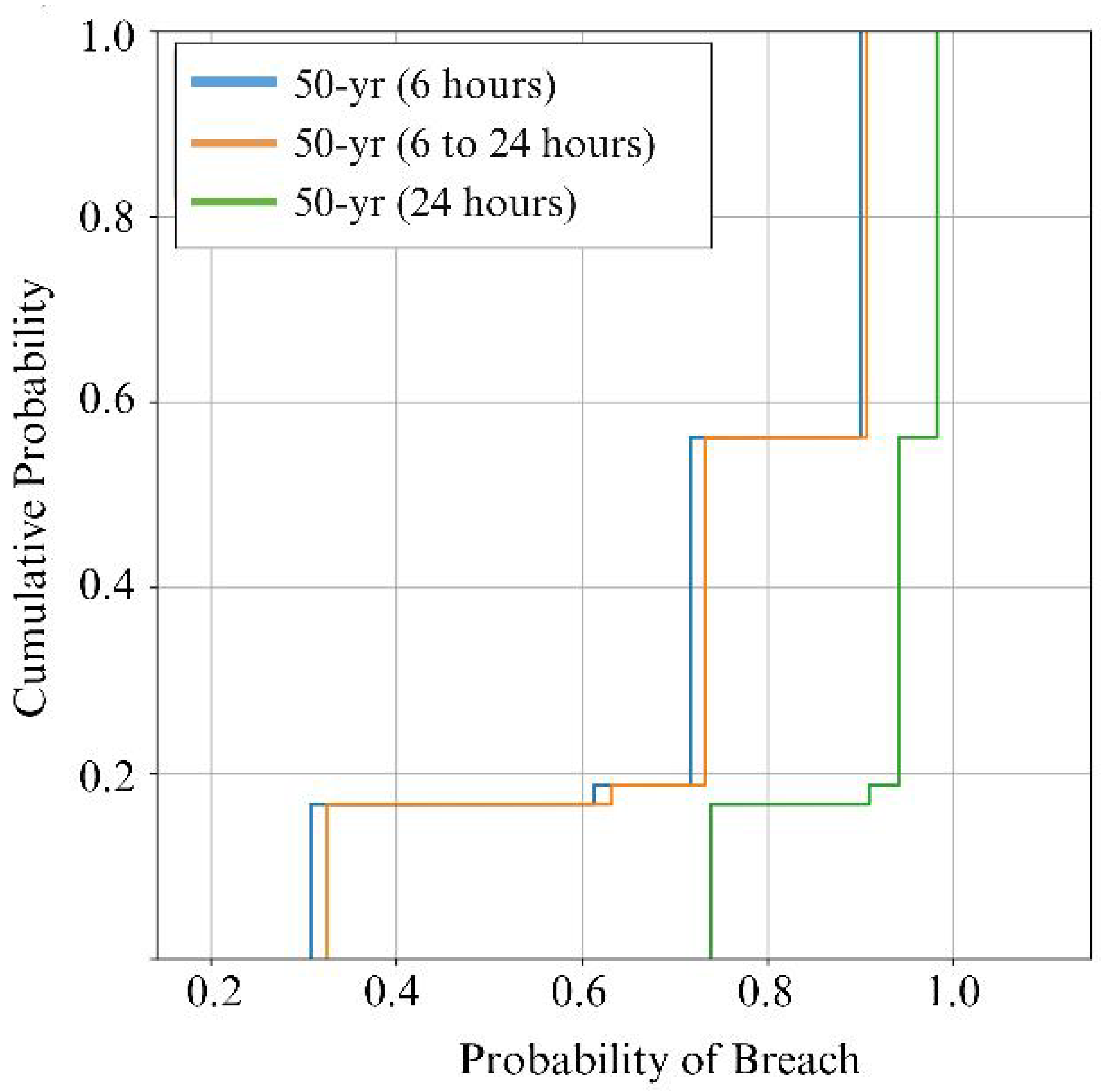
Results: Structural-Scale Changes in Fragility of Levees



Alborzi et al. 2024

Results: Regional-Scale Probability of Breach due to Overtopping





Azhar et al. (2025)

Results: Changes in Grid Network Resiliency

Calculated System Resilience Index and Expected Energy Not Supplied (EENS) for the Study Area Under Different Climate Scenarios Using IEEE 118-Bus Standard Test System with Total Load of 4242 MW.

	Resilience index	$\Delta R(\%)$	EENS (MWh)	EENS (MWh/d)	EENS (MWh/m)
Pre-Flooding	0.011921	-	-	-	-
Current Climate	0.012264	-2.9	52.02	1249	37458
Projected Future RCP 4.5	0.012939	-8.5	54.89	1317	39520
Projected Future RCP 8.5	0.013558	-13.7	57.51	1380	41410

Miraee-Ashtiani et al. (2022)

Results: Changes in Grid Network Resiliency

Calculated expected value (resiliency) Index of percentage of in-service power (customers).

	Power Grid Link ID	Average Vulnerability Index of each link % (Calculated by DC Power Flow Model)	Predicted Total Power Loss (%)	Probability of Levee Failure		Expected Value out of Service Power (EENS%)		Total in Service Power (Resiliency Index %)	
				RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Links on protected area of Levee (sys. ID 5205000441)	16	13.5	35.8	0.70	0.95	25.0	34.0	66.5%	59.2%
	21	11.9							
	25	10.4							
Links on protected area of Levee (sys. ID 5205000293)	2	10.5	34.0	0.25	0.20	8.5	6.8		
	14	10.9							
	19	12.6							

Miraee-Ashtiani, 2022

Concluding Remarks

- Levees play a critical role in protecting populations and critical infrastructure across the country.
- Climate change has increased the frequency and severity of flooding in several regions. More frequent, severe floods can significantly raise the probability of levee failure. Further, there has been a surge in power outages due to extreme weather events including flooding.
- A new framework is proposed to quantify the effects of climate change on flooding, translate these impacts into levee failure probabilities, and assess the cascading effects on the resilience of levee-protected power grid.
- The framework was applied to a study area in Northern California, focusing on levees and the levee-protected power grid.
- Further research is needed to conduct regional-scale assessments of levee breaches and the resulting impacts on infrastructure systems and communities behind levees. This approach will provide a comprehensive view of risk, supporting resilience planning across broader areas.

As climate change escalates flood risks, understanding the vulnerabilities of interconnected systems—such as levees, power grids, and communication networks—becomes vital to safeguarding the nation's resilience.

Thanks!

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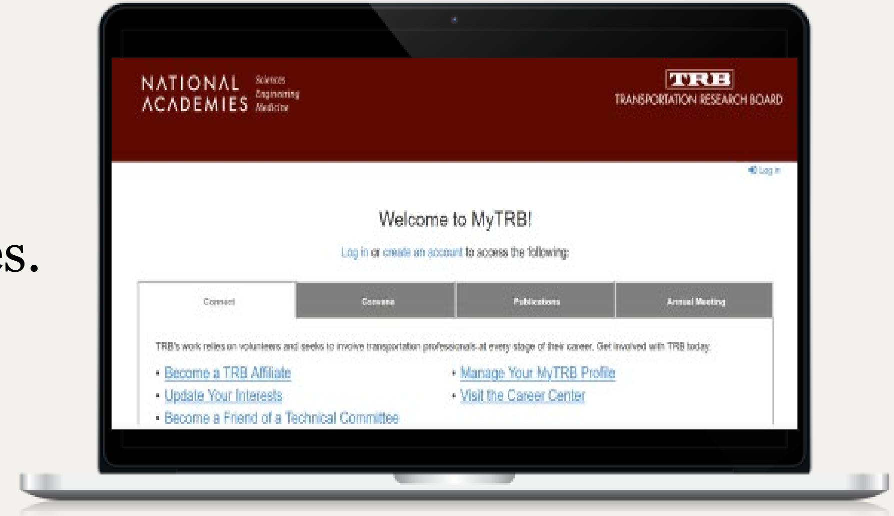

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