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Moving toward probabilistic dam breach modeling and flood inundation mapping

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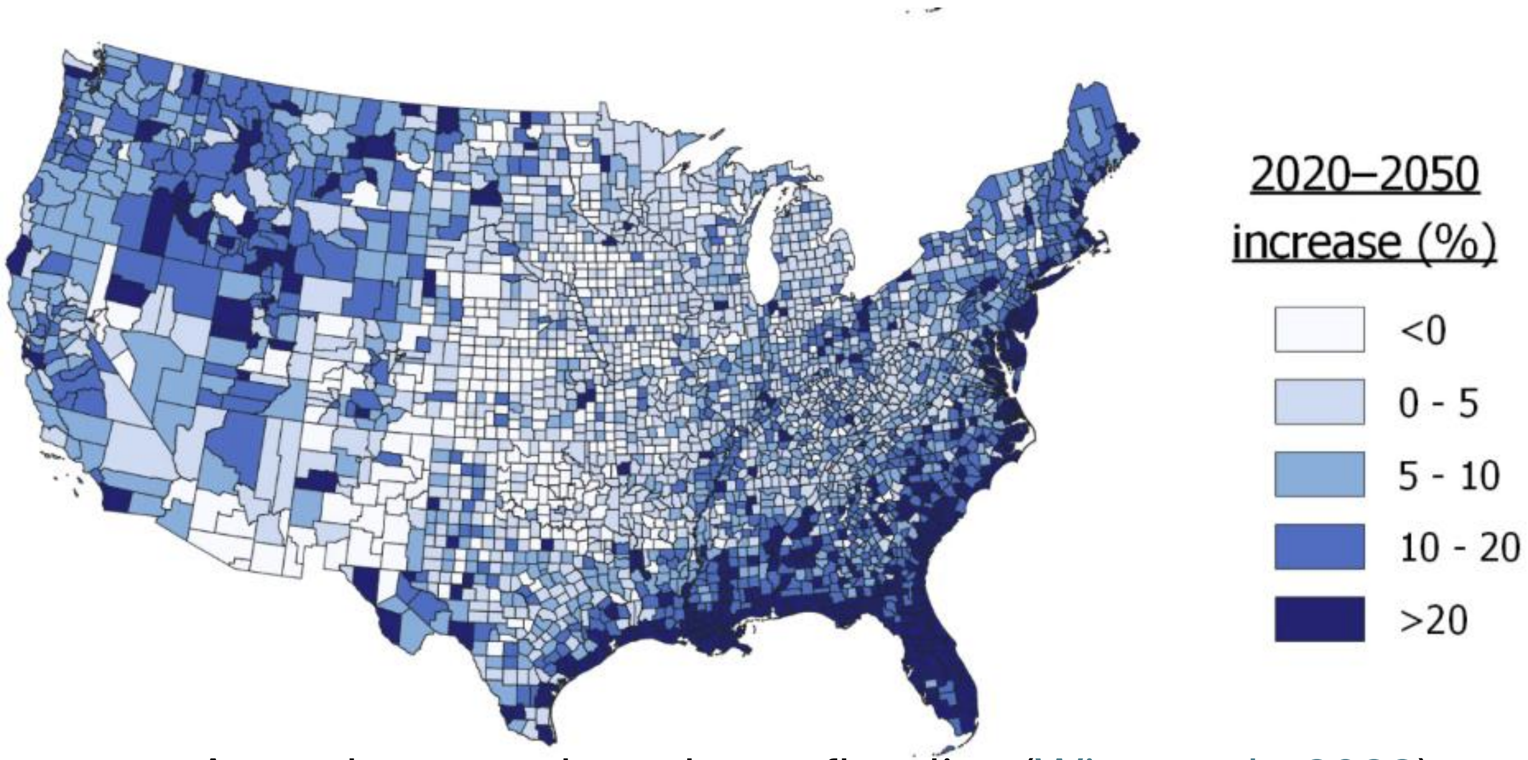
Outlines

- Introduction
- Model Development
- PMP and PMF Estimation
- Probabilistic Dam Breach Modeling

Introduction

- Flooding remains the most frequent and economically destructive natural hazard, resulting in more than $32 billion losses annually, and projected to surpass $40 billion by 2050.

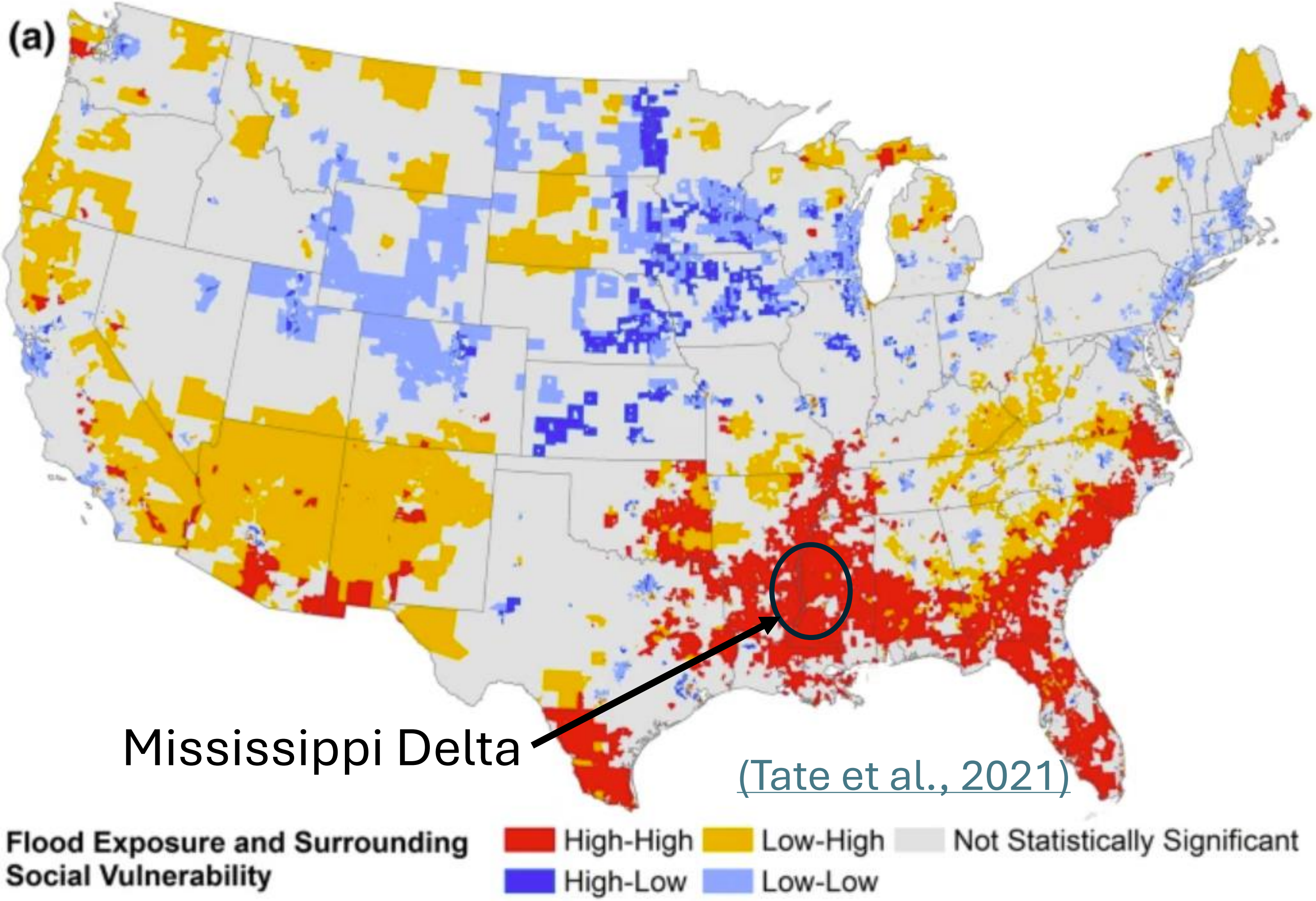


Annual average loss due to flooding (Wing et al., 2022)

Introduction

Flood risk are not uniform:

- Vulnerable communities are often concentrated in flood-prone areas, which amplifies their exposure and risk.

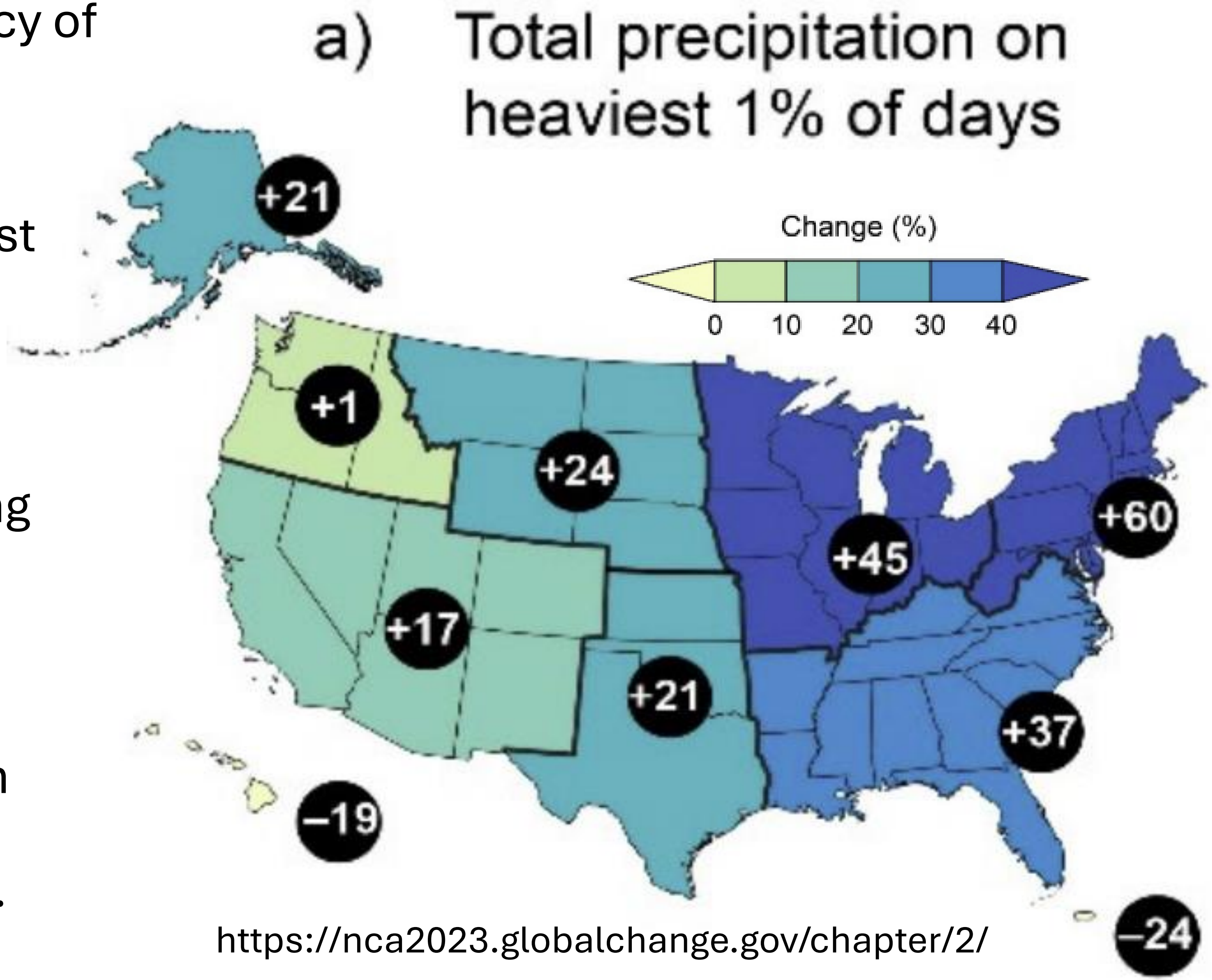


[(Tate et al., 2021)]

***High-High**: hotspots with higher-than-average exposure surrounded by higher-than-average social vulnerability.*

Introduction

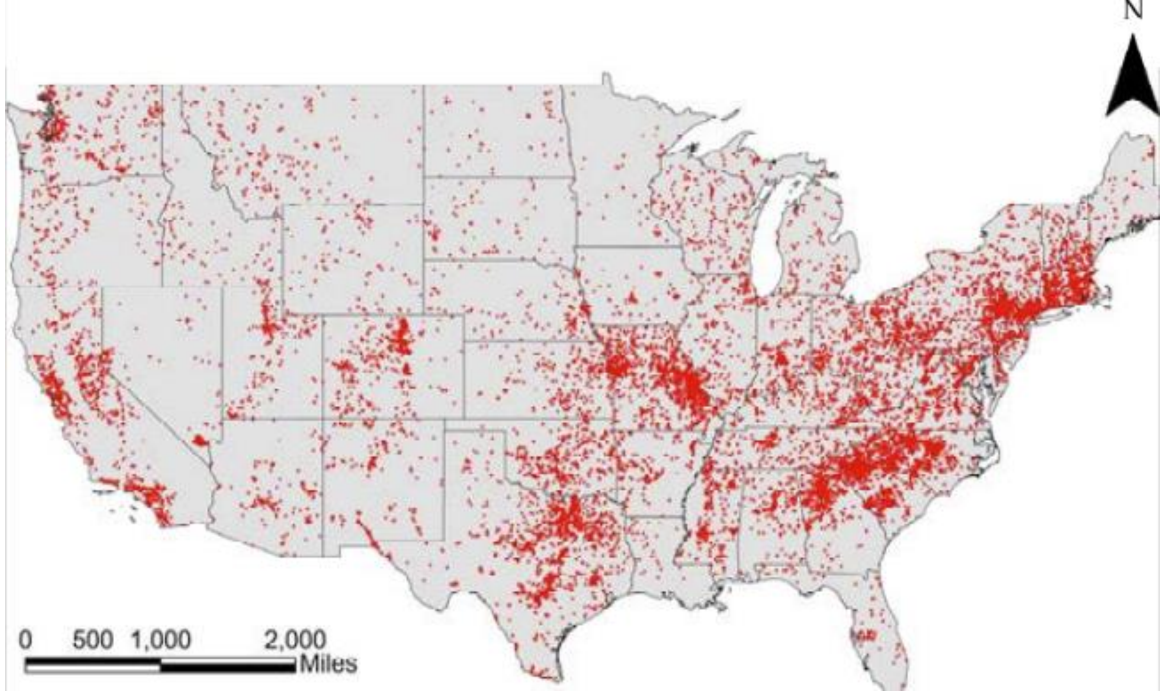
- Increasing intensity and frequency of heavy precipitation events.
- Total rainfall delivered by heaviest 1% rainfall days increased significantly (1958-2021).
- Extreme rainfall events, becoming more intense over time.
- Current maximum possible precipitation estimates based on historical climate already underestimate today's flood risk.



https://nca2023.globalchange.gov/chapter/2/

Introduction

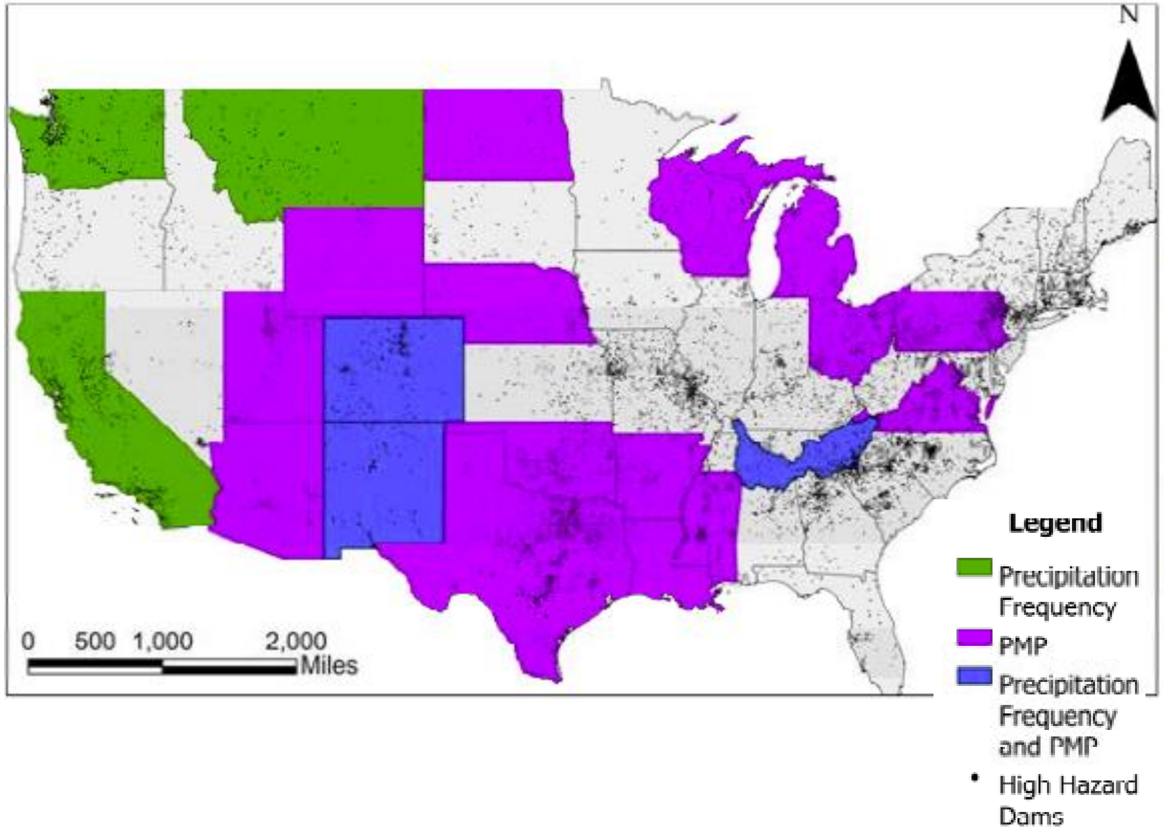
- Fore more than 75-years high-hazard structures designed against floods resulting from most possible precipitation, PMP.



- Nuclear facilities must be resilient to both pluvial flooding driven by localized PMP-magnitude precipitation events and to fluvial inundation arising from flooding from nearby rivers or coasts.

Probable Maximum Precipitation (PMP) Estimation

PMP (Current definition): *"Theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of year (AMS, 2022, Hansen et al. 1982)".*



- US Weather Bureau produced series of national PMP documents: **Hydrometeorological Reports (HMRs: 1-22** in 1940s-1960s to **59** in 1999**).**

- As of 2023 PMP estimates have been updated in 16 states, based on regionalization/spatial homogeneity and stationary climate.

Probable Maximum Precipitation (PMP) Estimation

PMP (Current): *Parameters*

- Storm catalogs: measurements developed form old non-standard instruments and incomplete spatial and temporal sampling of storm.
- Storm transposition: most sensitive yet most subjective.
- Moisture maximization: assume rainfall scales linearly with precipitable water

$$PMP = R_{observed} * MMF * OTF * BAF$$

$$R_{obs} = observed\ rainfall\ depth$$

$$MMF = Moisture\ maximazation\ factor$$

$$OTF = Orographic\ transposition\ factor$$

$$BAF = Barrier\ adjustment\ factor$$

$$PMP_{final} = \underbrace{(PMP_{storm1}, PMP_{storm2}, PMP_{storm3})}$$

Envelopment: take upper bound across all storms

Probable Maximum Precipitation (PMP) Estimation

PMP (New definition): "The depth of precipitation for a particular duration, location and areal extent, such as drainage basin, with an extremely low annual probability of being exceeded (AEP), for a specified climate period".

Two fundamental changes:

- "Upper bound" → "extremely low AEP"
- "A certain time of year" → "a specified climate period"

New definition carry formal statistical uncertainty bounds, essential for integrating PMP into modern **Risk-Informed Decision Making (RIDM).**

Probable Maximum Precipitation (PMP) Estimation

Proposed probabilistic AEP-based PMP:

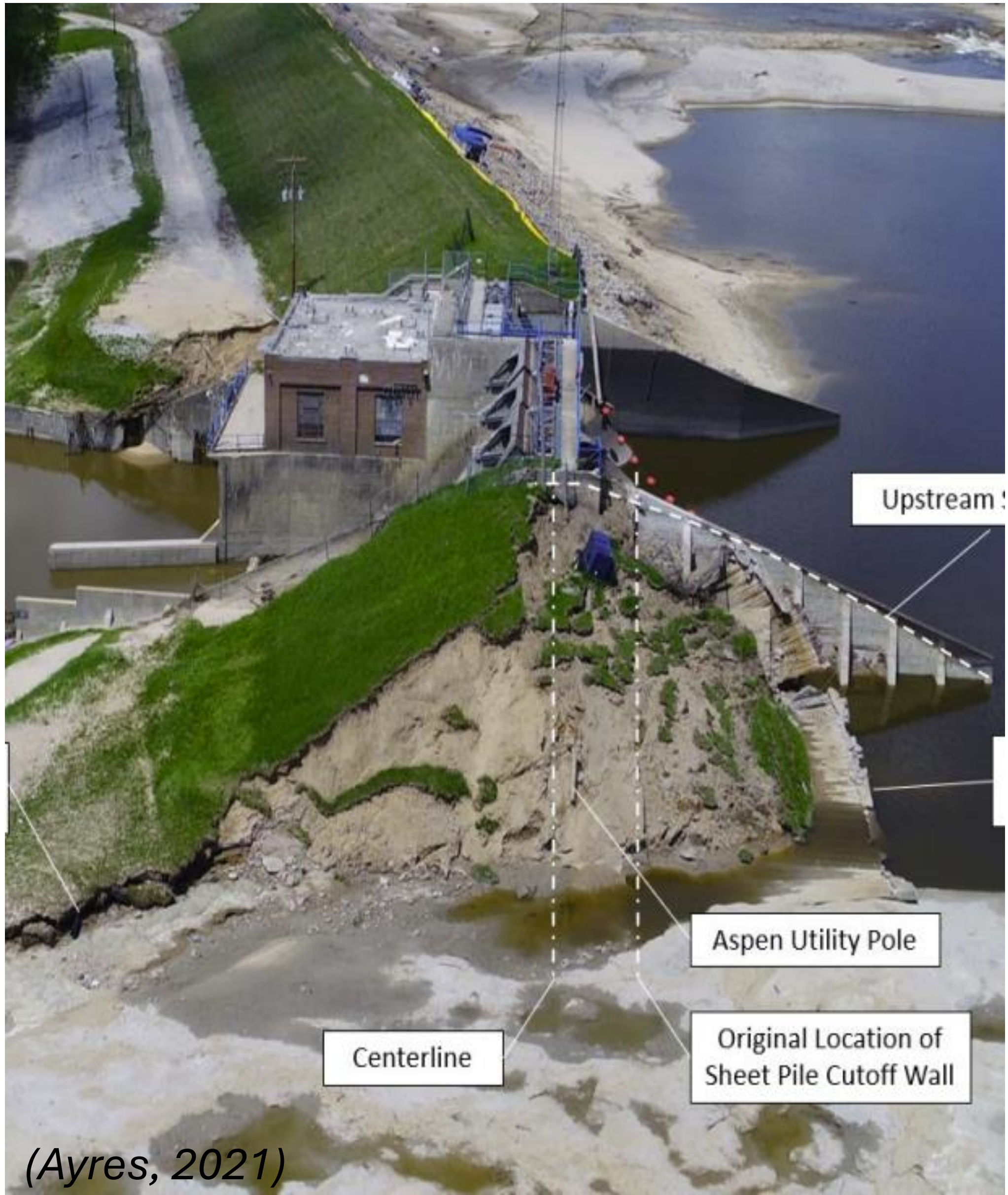
$$PMP_p = Z_p = u + \frac{\sigma_u}{\xi}\left[\left(\frac{\lambda}{p}\right)^{-\xi} - 1\right]$$

$where$
$u = threshold,$
λ =*mean number of exceedance per year above threshold* u,
$p = chosen\ Annaul\ Exceedance\ Probability\ (AEP)$
$\xi\ and\ \sigma_u$ *fitted Generalized Pareto Distribution (GPD) parameters*

- Shift from multiplying empirical ratios to estimating quantiles of a statistically fitted extreme value distribution from climate model ensemble.

Case study: Edenville-Sanford Cascading Dam Failure

- On May 19, 2020 Edenville-Sanford Dams in Michigan failed sequentially, resulting 10,000 evacuation and over $200 million damage.
- May 17-19, watershed received significant rainfall (175 – 200 mm, NWS, 2020), however not extreme (PMP: 437 mm, AWA 2021).
- Resulted inflow of 694 m^3/s, despite spillway gates opened to 70% capacity, yet both dams still failed.
- Current dam safety frameworks focus on individual dam assessment based on deterministic approach.



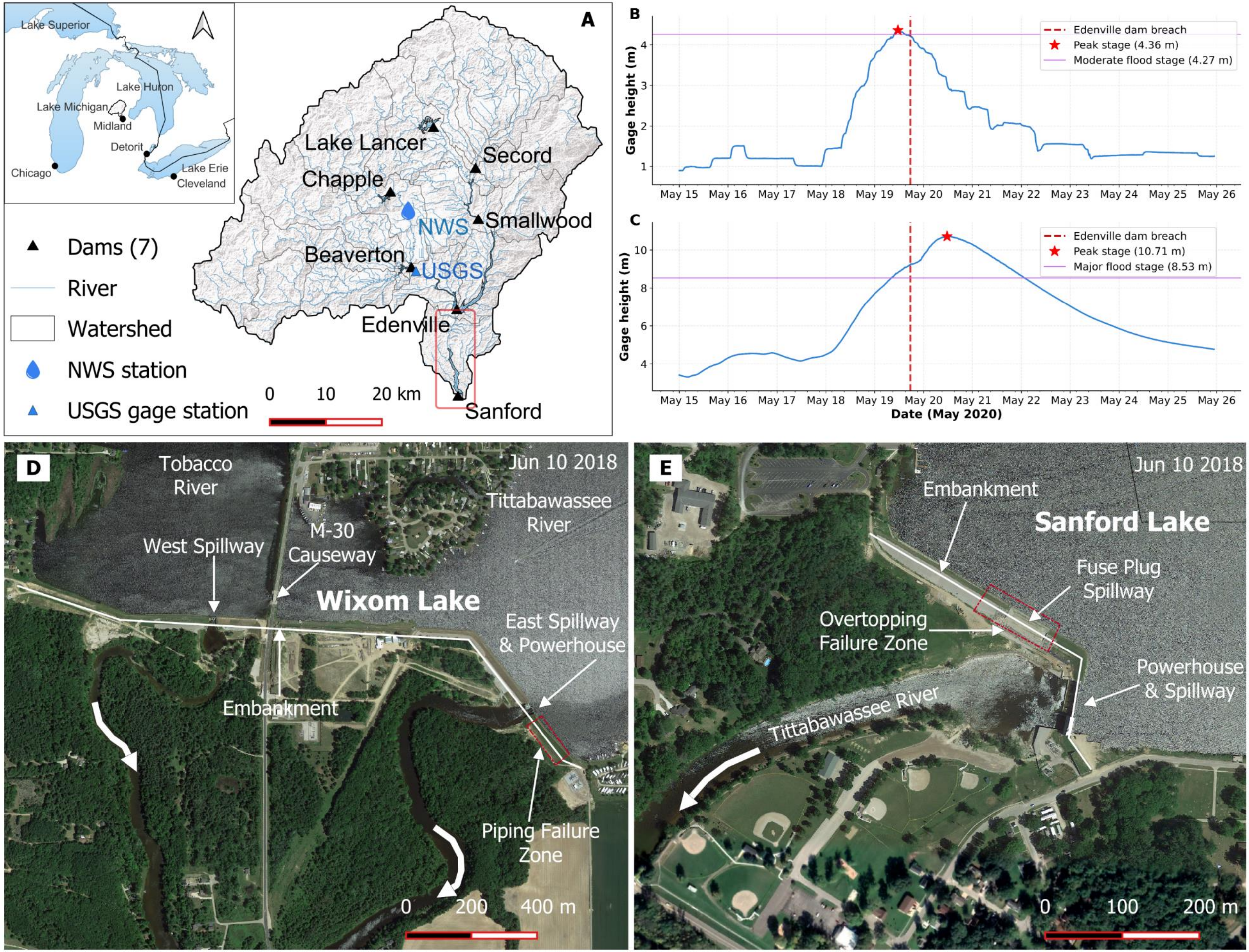
(Ayres, 2021)

Model development: Edenville-Sanford Cascading Dam Failure

Key questions?

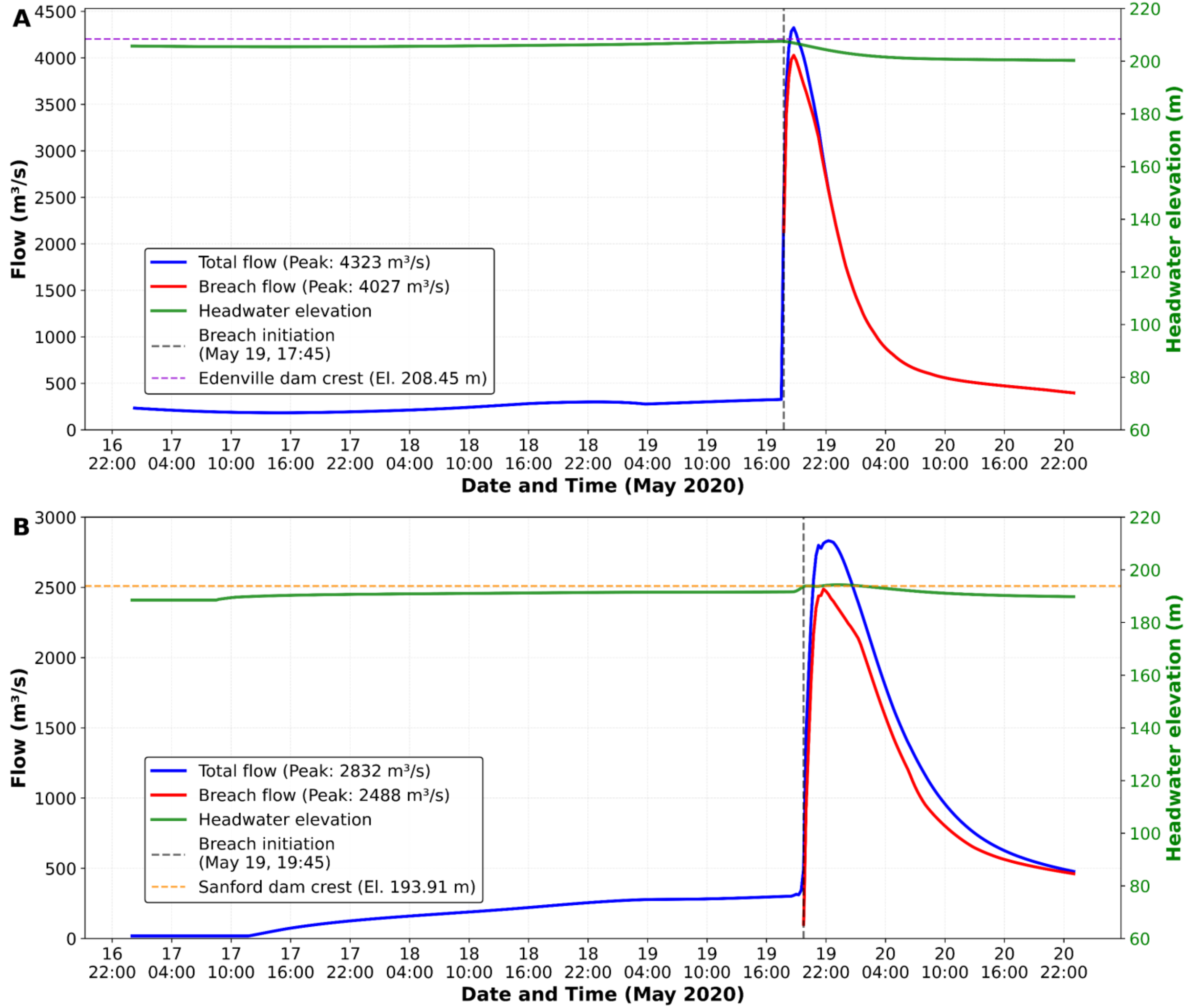
1. What hydraulic mechanisms governed the cascade failure sequence?
2. Could alternative spillway gate operations have prevented the breach?

Case study: Edenville-Sanford Cascading Dam Failure



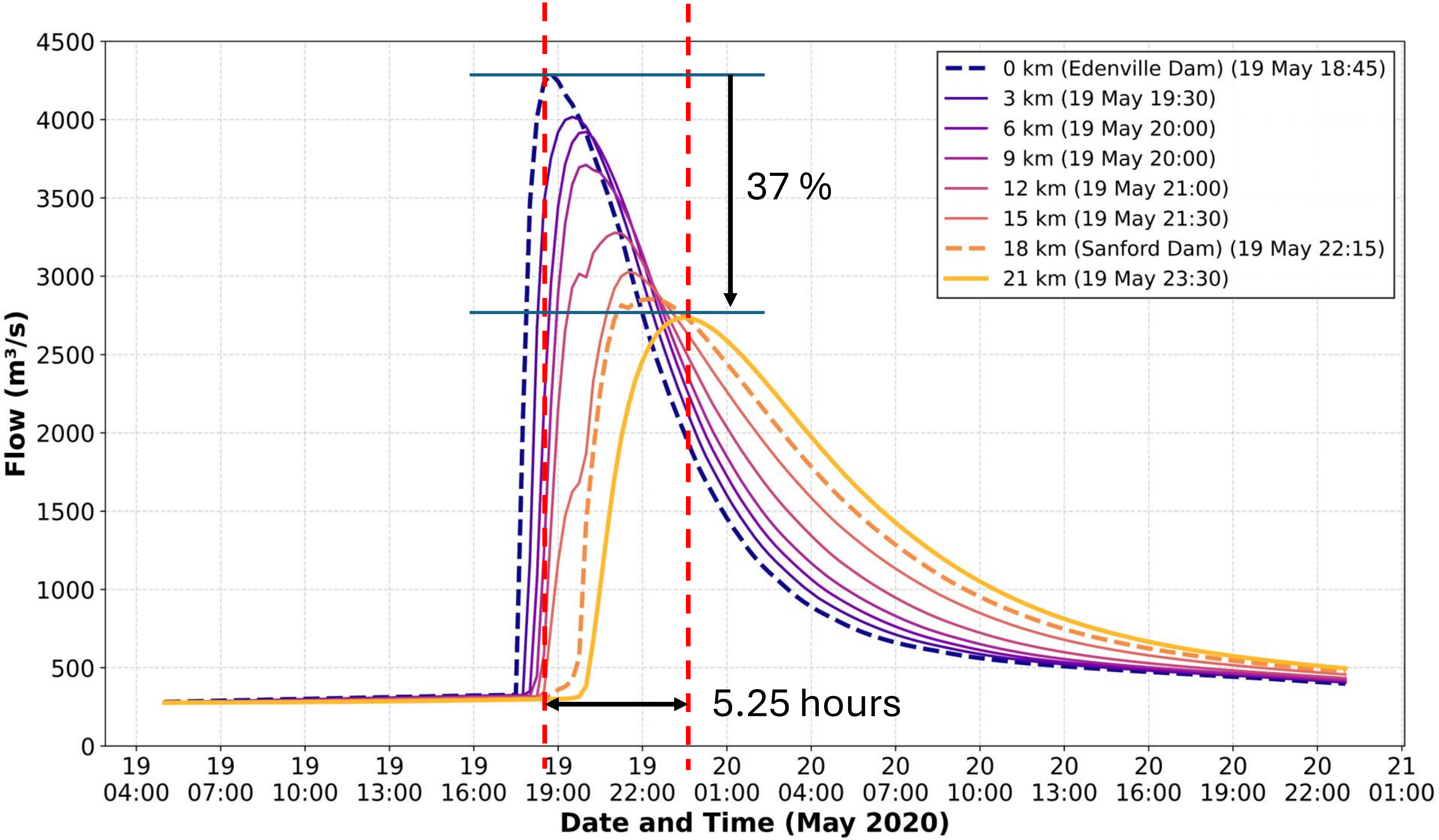
Case study: Edenville-Sanford Cascading Dam Failure

Breach flow estimation:



Case study: Edenville-Sanford Cascading Dam Failure

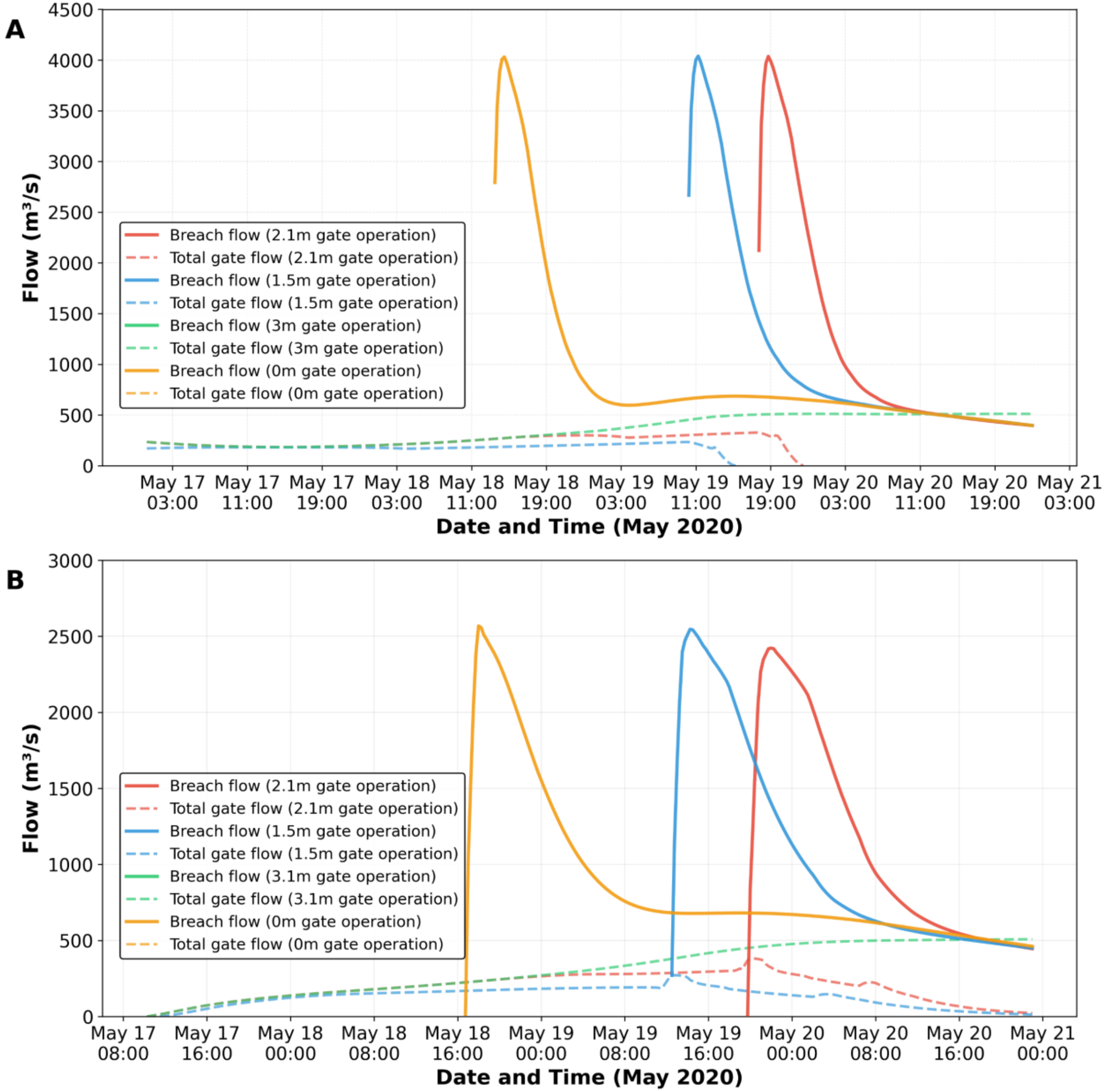
Flood hydrograph propagation:



Case study: Edenville-Sanford Cascading Dam Failure

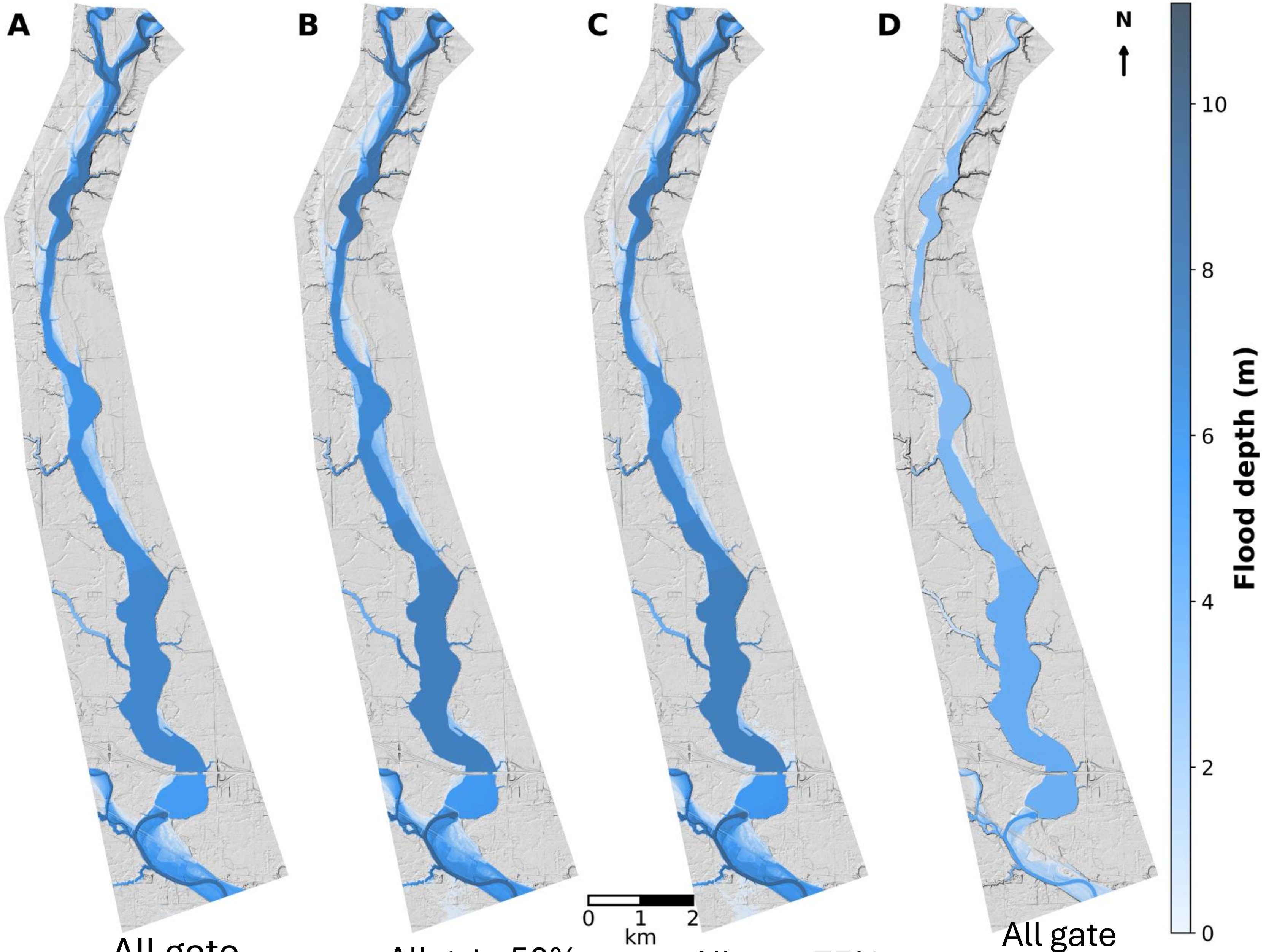
Spillway gate operation:

- when all gates fully opened, prevent the breaching at both dams, with headwater elevation below the breach initiation thresholds (plot with green hydrograph).



Case study: Edenville-Sanford Cascading Dam Failure

Flood hazard mapping:



All gate closed (11.47 km^2)

All gate 50% opened (12.25 km^2)

All gate 75% opened (12.41 km^2)

All gate 100% opened (8.56 km^2)

Case study: Edenville-Sanford Cascading Dam Failure

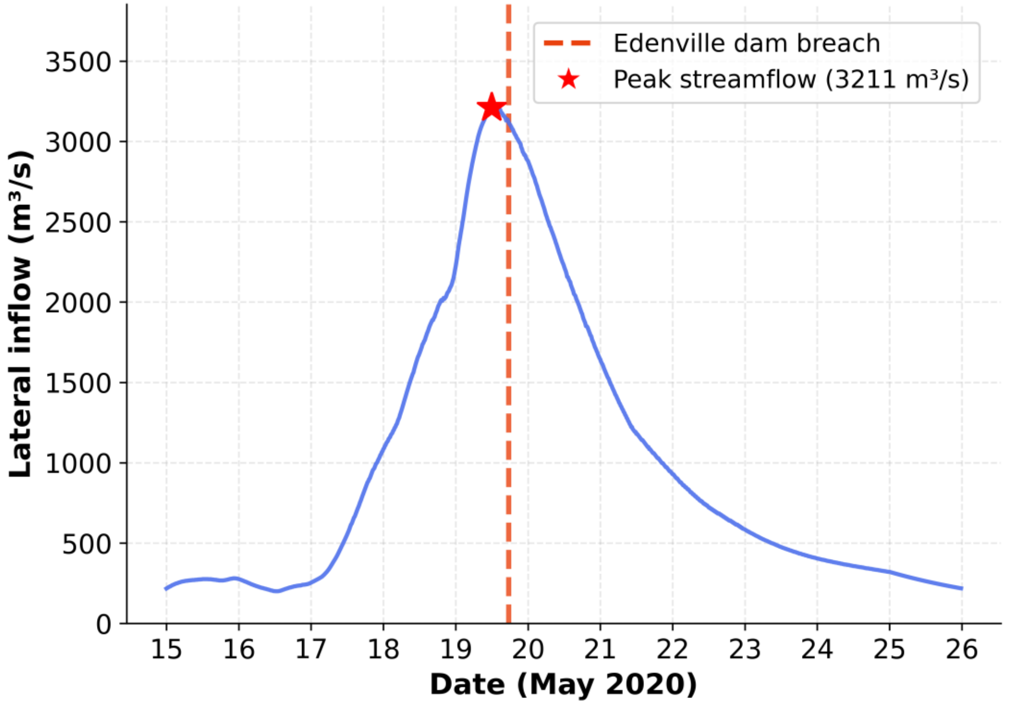
Way forward:

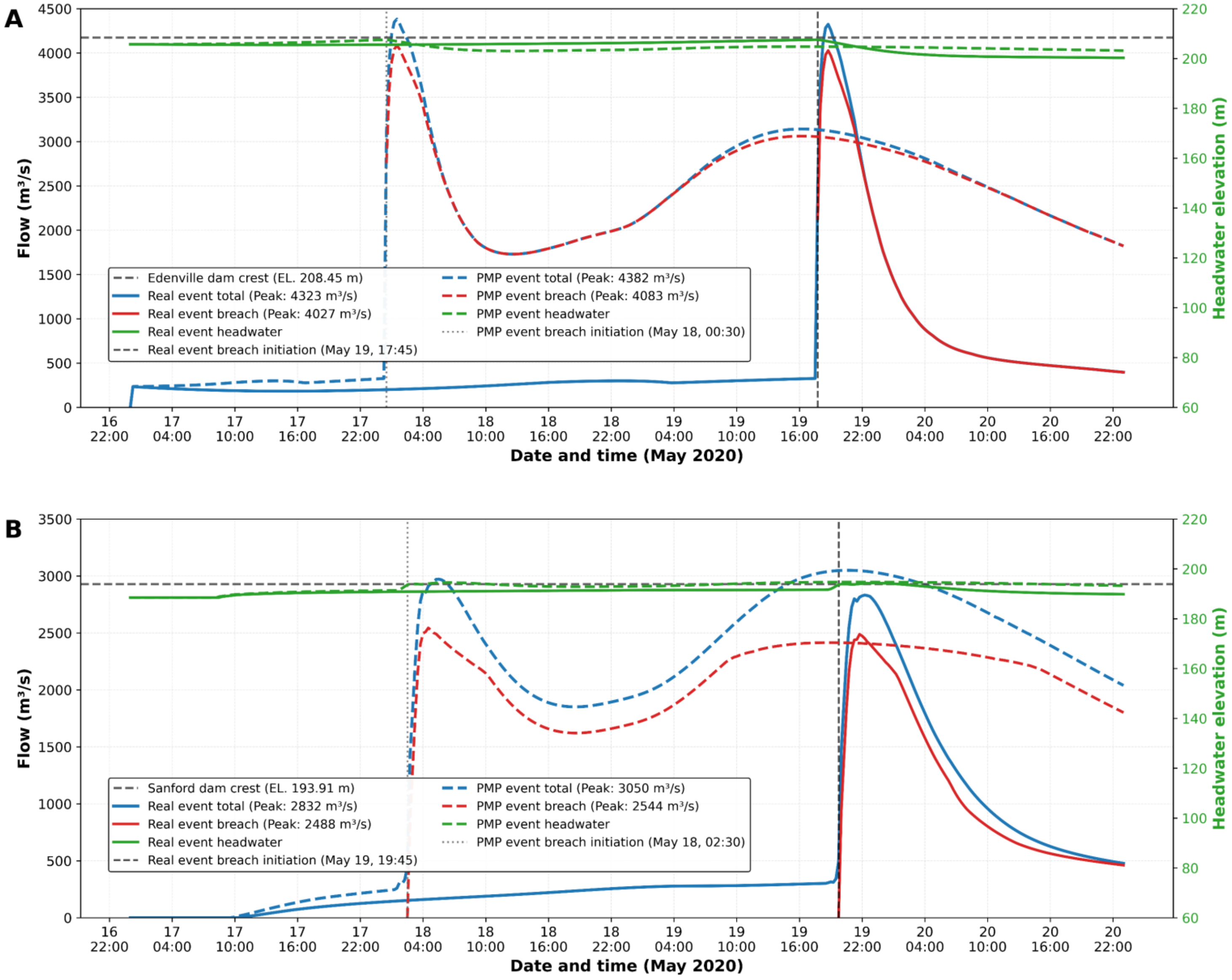
- This approach triggered dam failure when headwater elevation reached critical thresholds, explicit simulation of geotechnical failure mechanism, including static liquefication, internal erosion, and piping processes observed at similar embankment dams (Nemnem et al., 2025) represents an avenue for future refinement.

- Future extensions could assess cascade failure dynamics under climate-adjusted Probable Maximum Flood (Ho et al., 2025b).

Case study: Edenville-Sanford Cascading Dam Failure

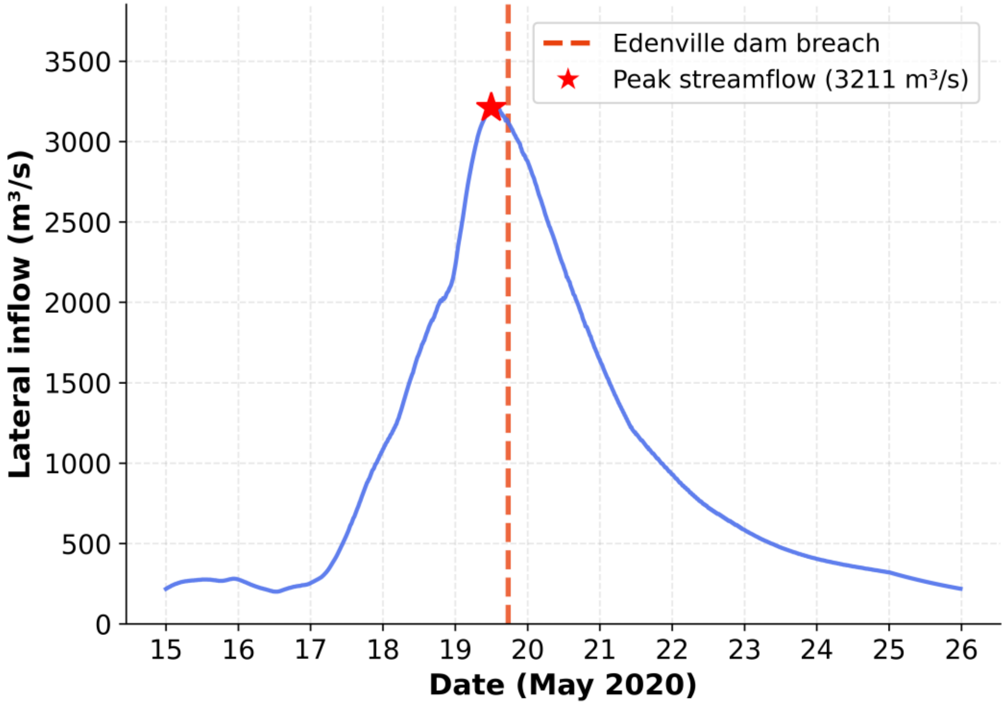
Deterministic approach: PMP is estimated as 437 mm over 72 hours

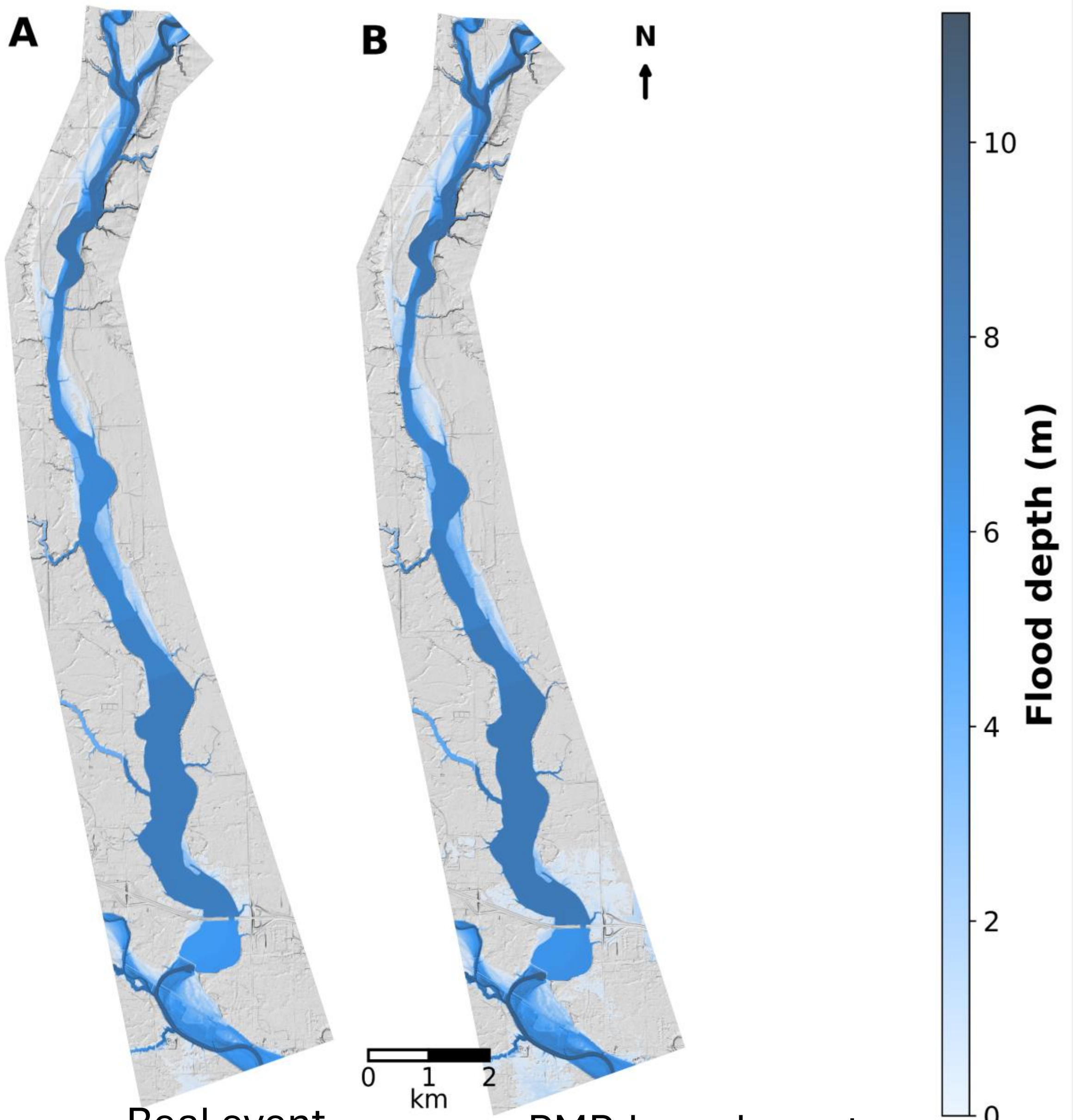




Case study: Edenville-Sanford Cascading Dam Failure

Deterministic approach:





Real event
(12.41 km^2)

PMP-based event
(14.24 km^2)

Part 1: Accepted for publication in ASCE Journal of Hydrologic Engineering

Hydrodynamics of Cascading Dam Failures: Flood Wave Propagation and Spillway Gate Operations in the Edenville-Sanford Sequential Breach

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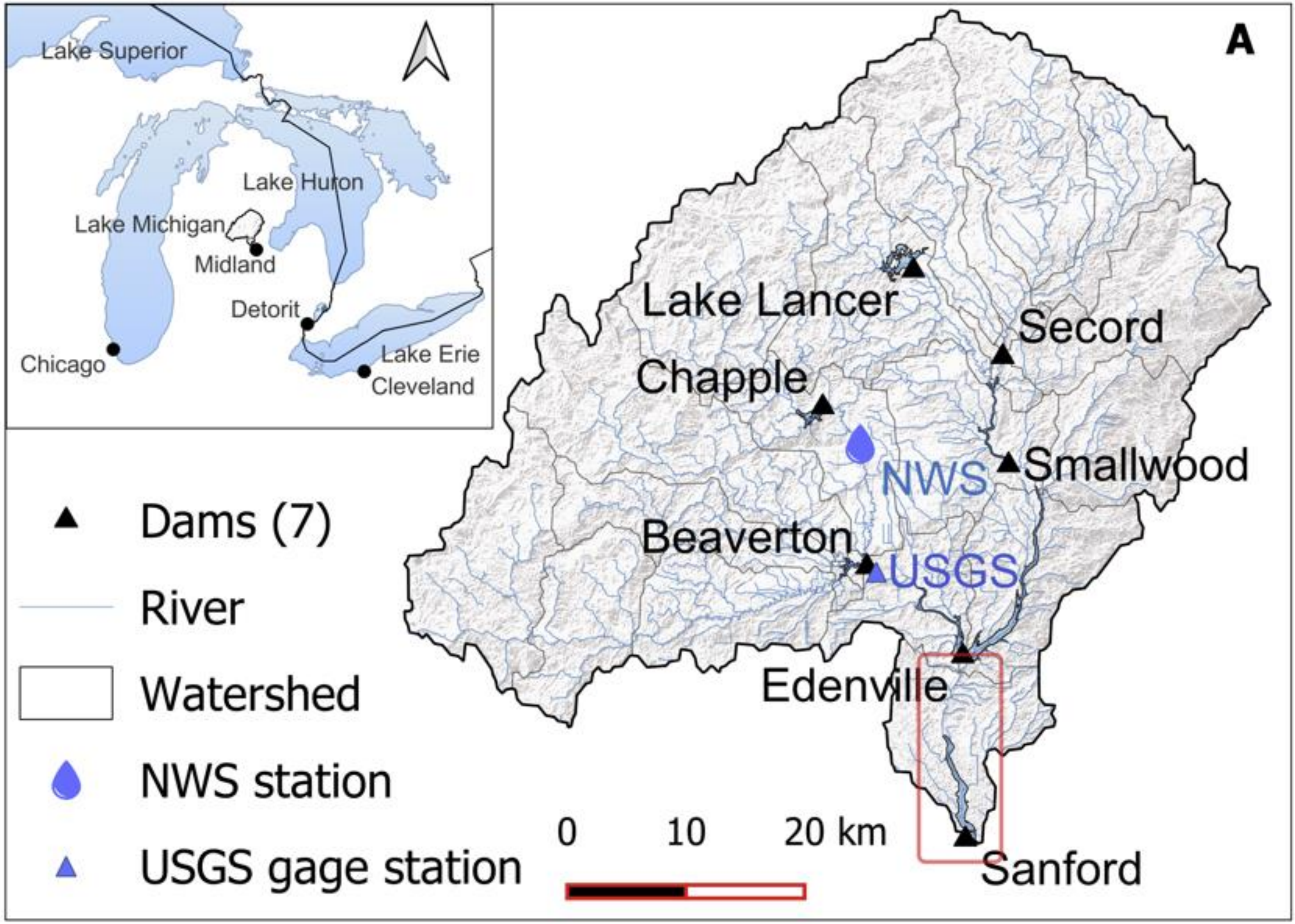
Abstract: Aging high-hazard dams with limited spillway capacity face increasing risk from extreme hydrologic events. The May 2020 Edenville-Sanford cascading dam failure in Michigan exemplifies these vulnerabilities. In this study, we conducted a forensic and counterfactual hydraulic analysis using a calibrated two-dimensional hydrodynamic model to reconstruct the breach sequence and evaluate how alternative spillway gate operations influenced hydraulic conditions related to breach initiation and downstream flood hazard. Our study examines four spillway gate operation scenarios: (1) all gates closed, (2) gates open to 1.5 m, (3) gates open to 2.1 m, and (4) gates fully opened in advance of flood peak. The model was calibrated against the satellite-derived flood extent and validated with high-water mark evidence. The model achieved an F1 score of 0.66, demonstrating moderate spatial agreement in inundation extents. Although some overprediction occurred in marginal floodplains, close agreement of inundation extent and water surface elevation confirmed the model's reliability for scenario analysis. Modeling results show that the Edenville Dam breach could generated 4,323 m^3/s total peak flow, attenuated by 35%, with peak arrival delayed approximately 3.5 hours before reaching Sanford Dam, located about 18 km downstream. Results inform that all gates closed and partially open scenarios produce water surface elevation exceeding the breach-initiating thresholds at both dams, whereas full gates opening could maintained safety margins and prevented breach entirely. The fully open scenario can reduced downstream flood area by 31% and maximum depths from over 10 m to

Way Forward: Probabilistic dam breach modeling and flood inundation mapping

- PMP serves as a critical input to estimate Probable Maximum Flood (PMF), a operative flood metric.



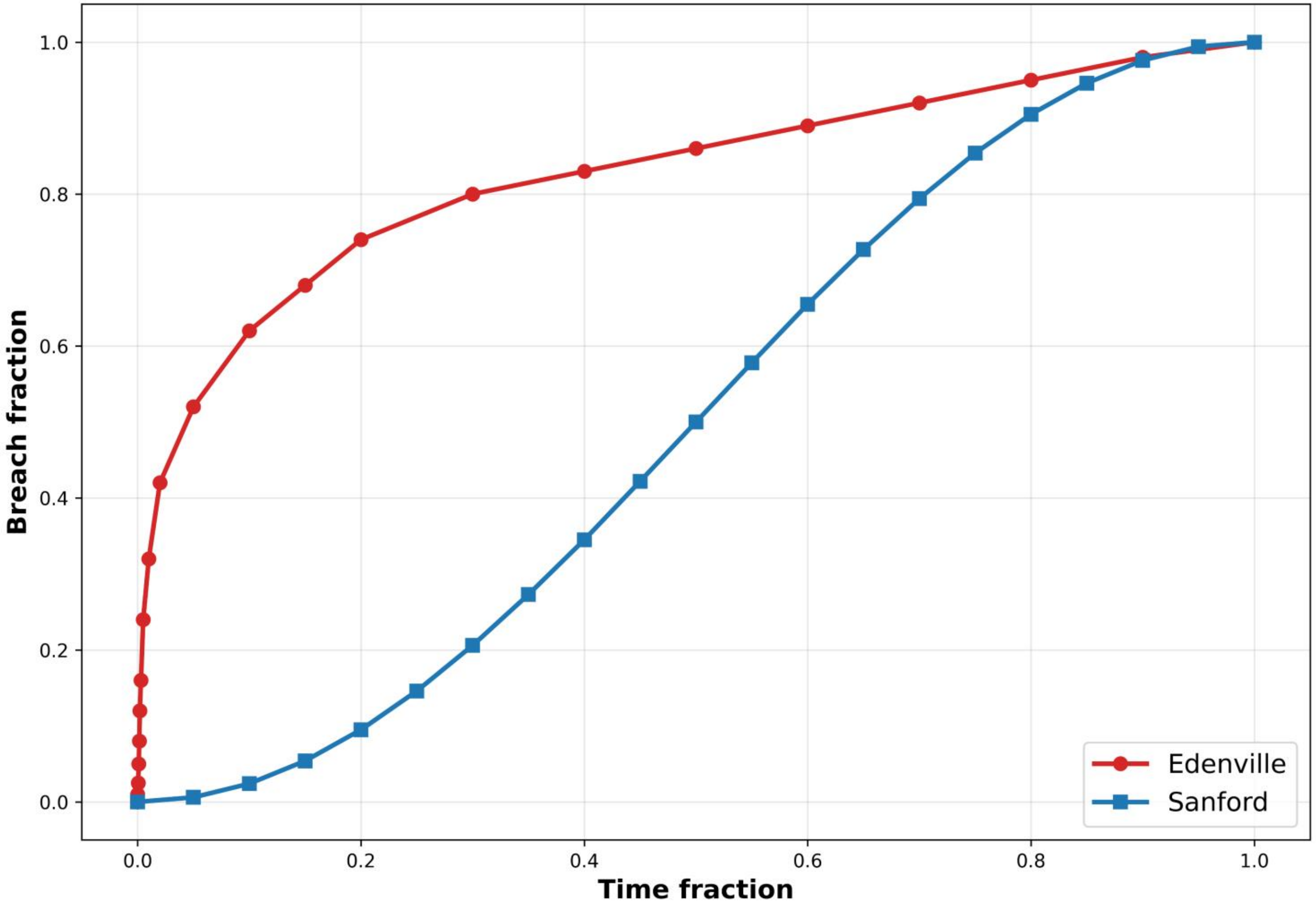
Way Forward: Probabilistic dam breach modeling and flood inundation mapping

Key questions:

1. How does uncertainties form empirical breach parameters estimation propagate to downstream?

2. How effective is the probabilistic framework compared to deterministic approaches?

3. How does climate change alter dam failure and downstream flood risk?



Way Forward: Moving toward probabilistic dam breach modeling and flood inundation mapping

$$\mathbf{Risk} = P(Flood\ loading) * P(Dam\ failure|flood) * Consequences$$

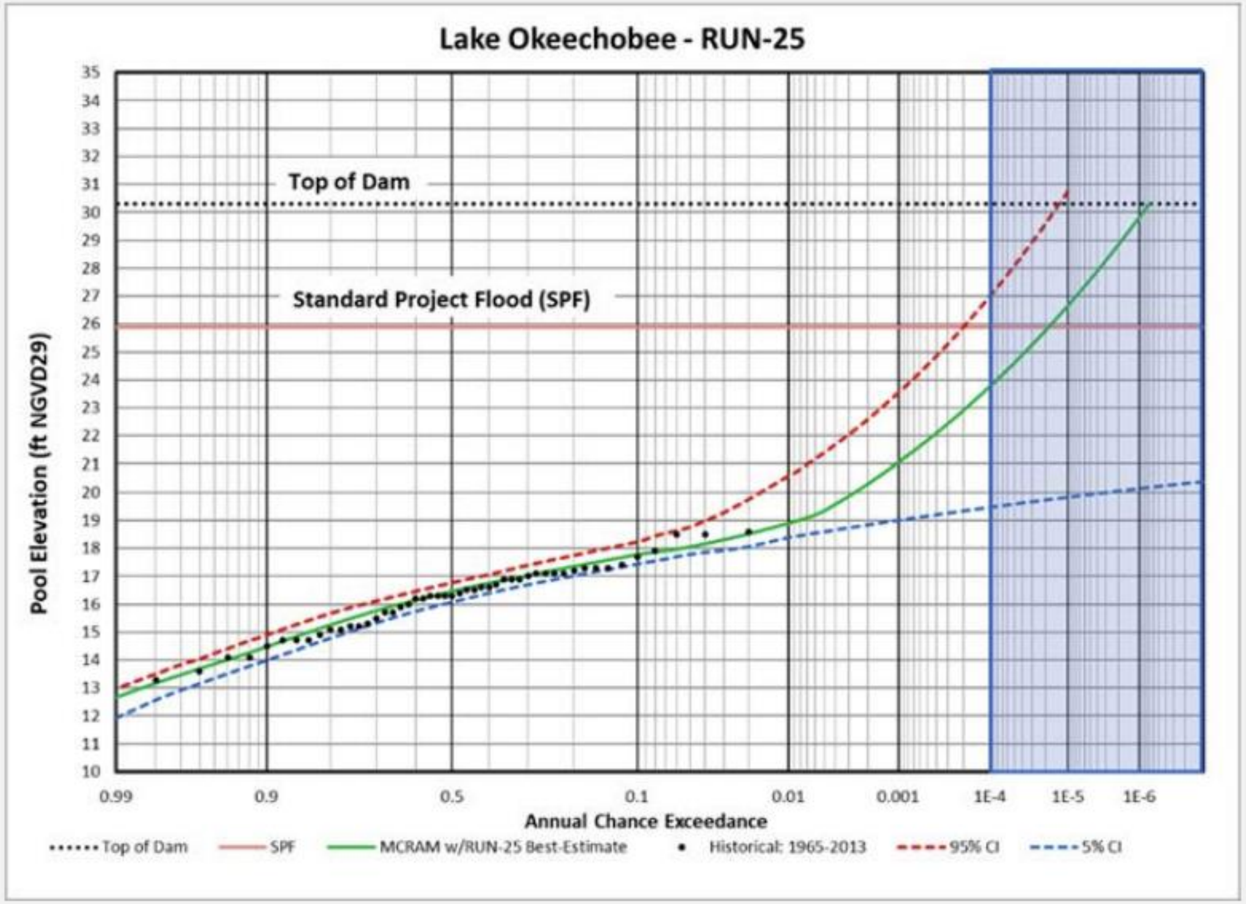


FIGURE 2-8 Example flood hazard curve (maximum reservoir stages) for Lake Okeechobee, Florida.
NOTES: The curve is estimated from observed data (black dots) and a rainfall-runoff model with stochastic weather generation of extreme rainfalls. Green solid line shows the best estimate stage-frequency curve; confidence limits are shown as red (95%) and blue (5%) dashed lines.
SOURCE: H. Smith et al. (2015).

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Thank You!

We highly appreciate your valuable comments, feedback, and suggestions.

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