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Reservoir Operational Strategies for Sustainable Sand Management in the Colorado River

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U.S. Department of the Interior
U.S. Geological Survey

Sandbar Erosion in Grand Canyon

- Glen Canyon Dam cuts off all upstream sand supply to Grand Canyon
- Led to massive sand evacuation in downstream channel
- Accompanied by decrease in number and size of sandbars due to erosion
- Sandbars are valued for recreation, habitat, and for archaeological sites

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High Flow Experiments: A strategy to rebuild/maintain sandbars

- Modern sand supply only from tributaries downstream of dam
- High Flow Experiments (HFEs) are short-duration controlled floods
- Transfer sand from the channel bottom onto sandbars
- Cause sand evacuation, so must be designed to avoid exhausting the limited sand supply

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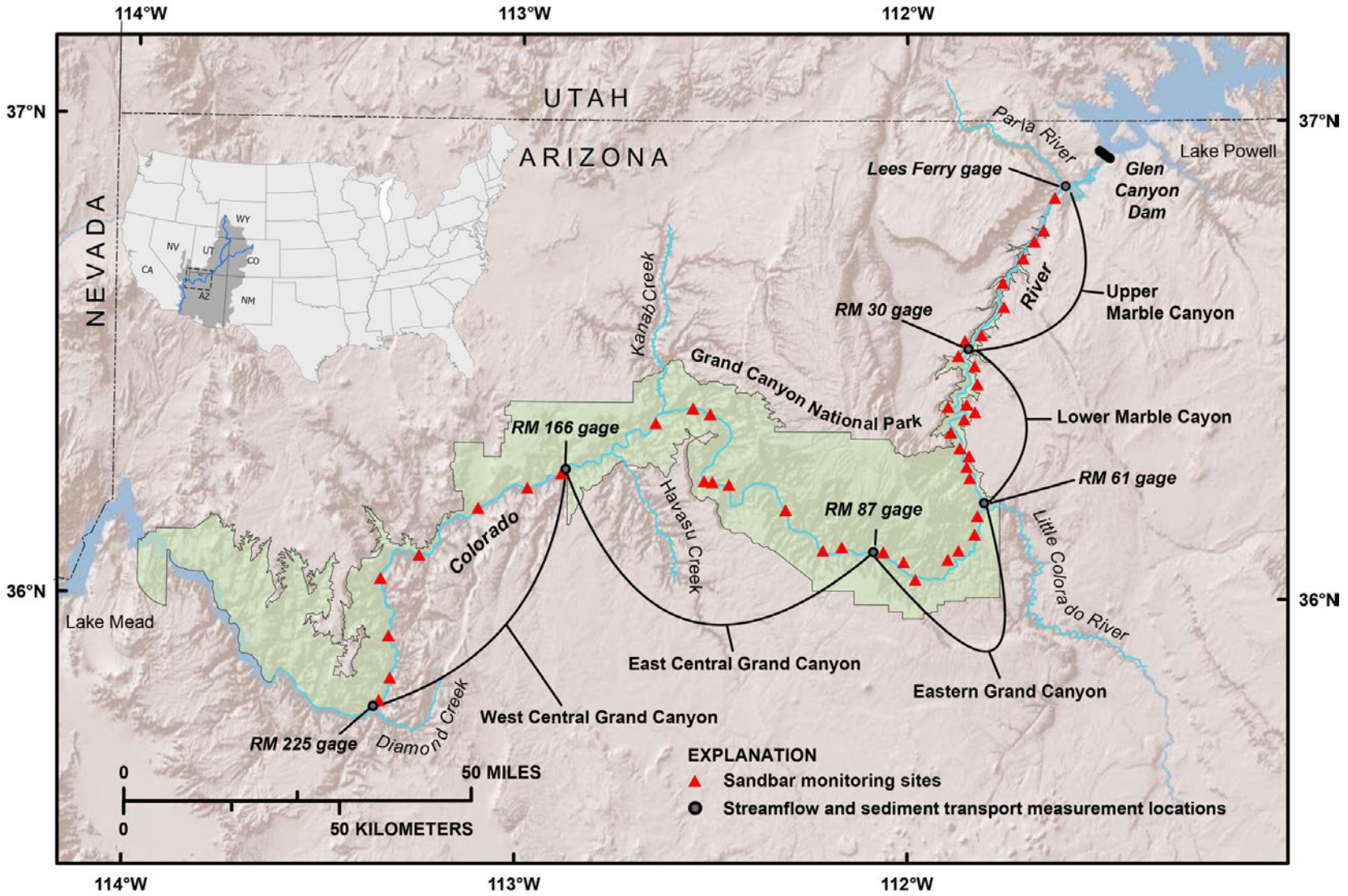
Study Region



- Water released from Lake Powell to Lake Mead flows through the Colorado River in Grand Canyon
- Paria and Little Colorado Rivers are main tributary suppliers of sand
- Sand mass balance is tracked for river segments between gages
- Sandbar volumes are measured throughout the canyon (45 sites)

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Grams et al., 2024

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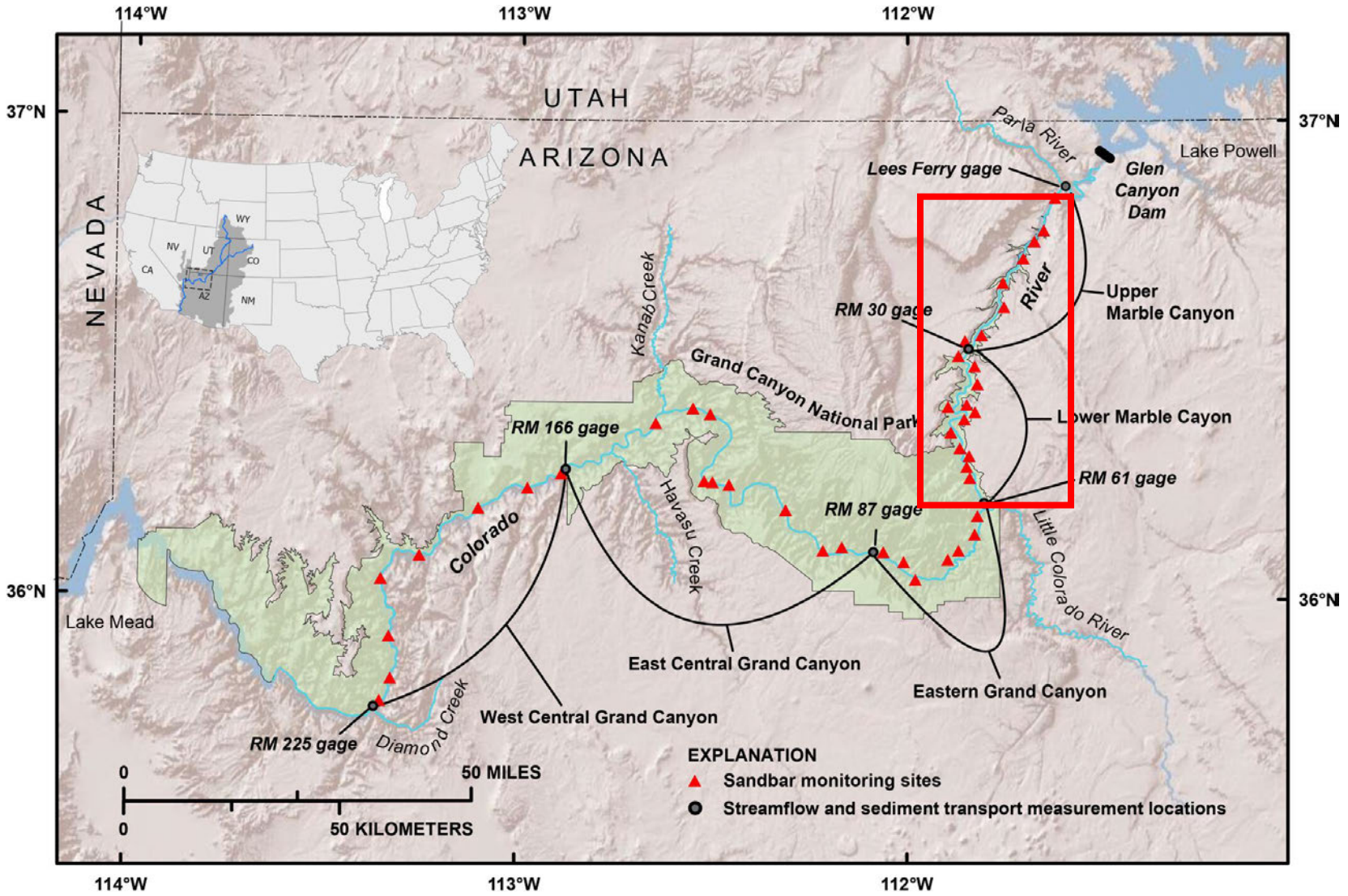

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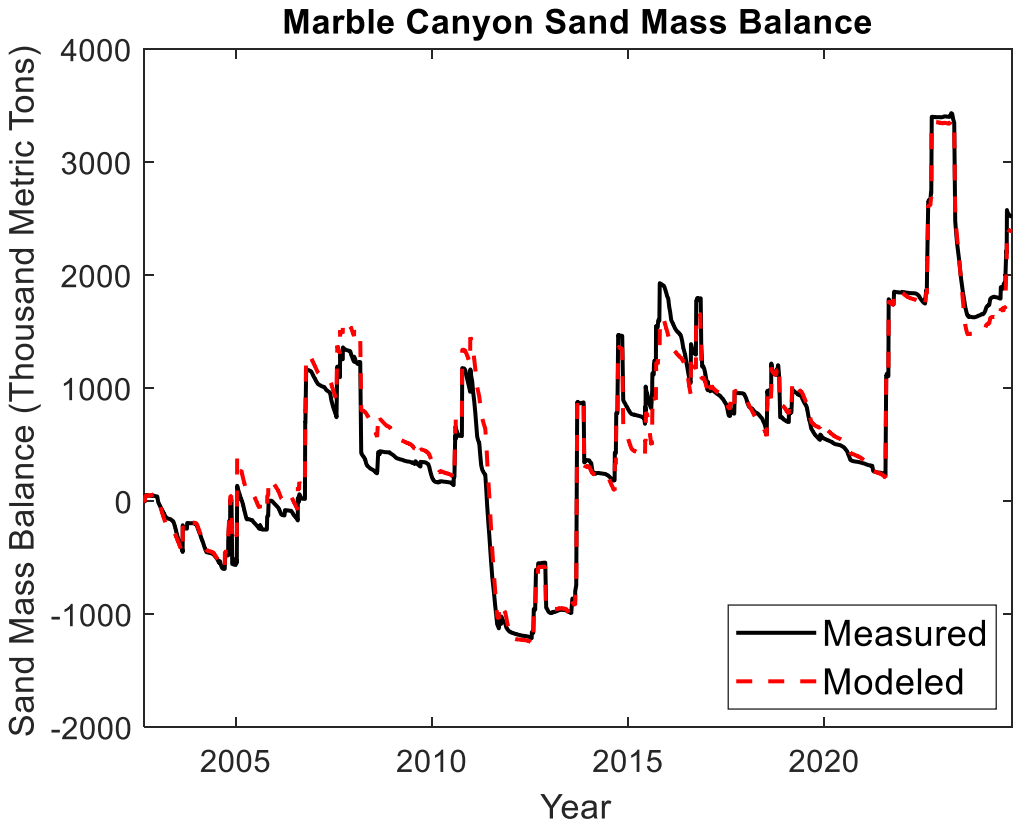
Numerical Models to Support Sand Management

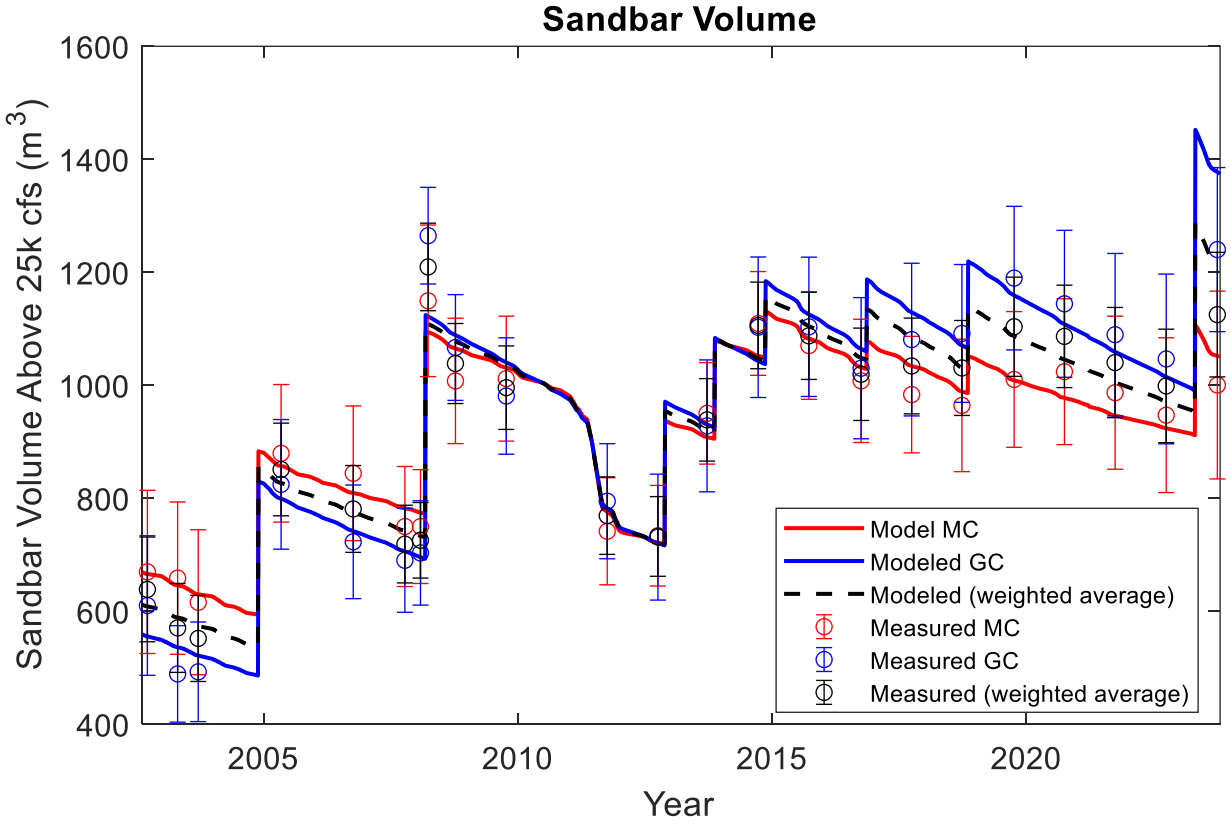
Sand Routing Model



Used to determine sand availability for HFEs and predict sand erosion from dam operations

Wright et al., 2010; Salter et al., 2025

Sandbar Model



Used to predict sandbar size in response to HFEs and dam operations

Mueller and Grams 2021; Salter et al., 2025

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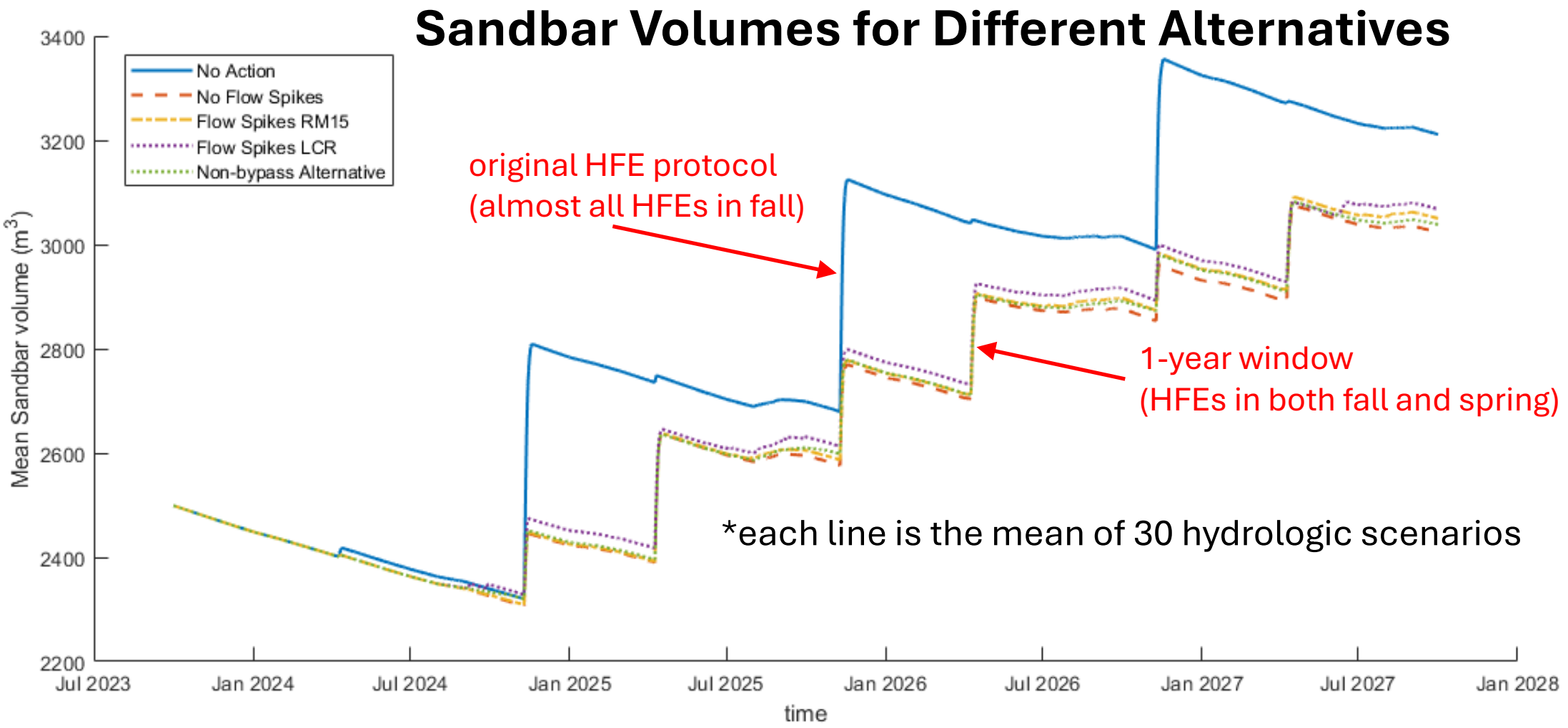
Modifying the HFE Protocol for Management under Aridification



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Salter and Grams, 2024

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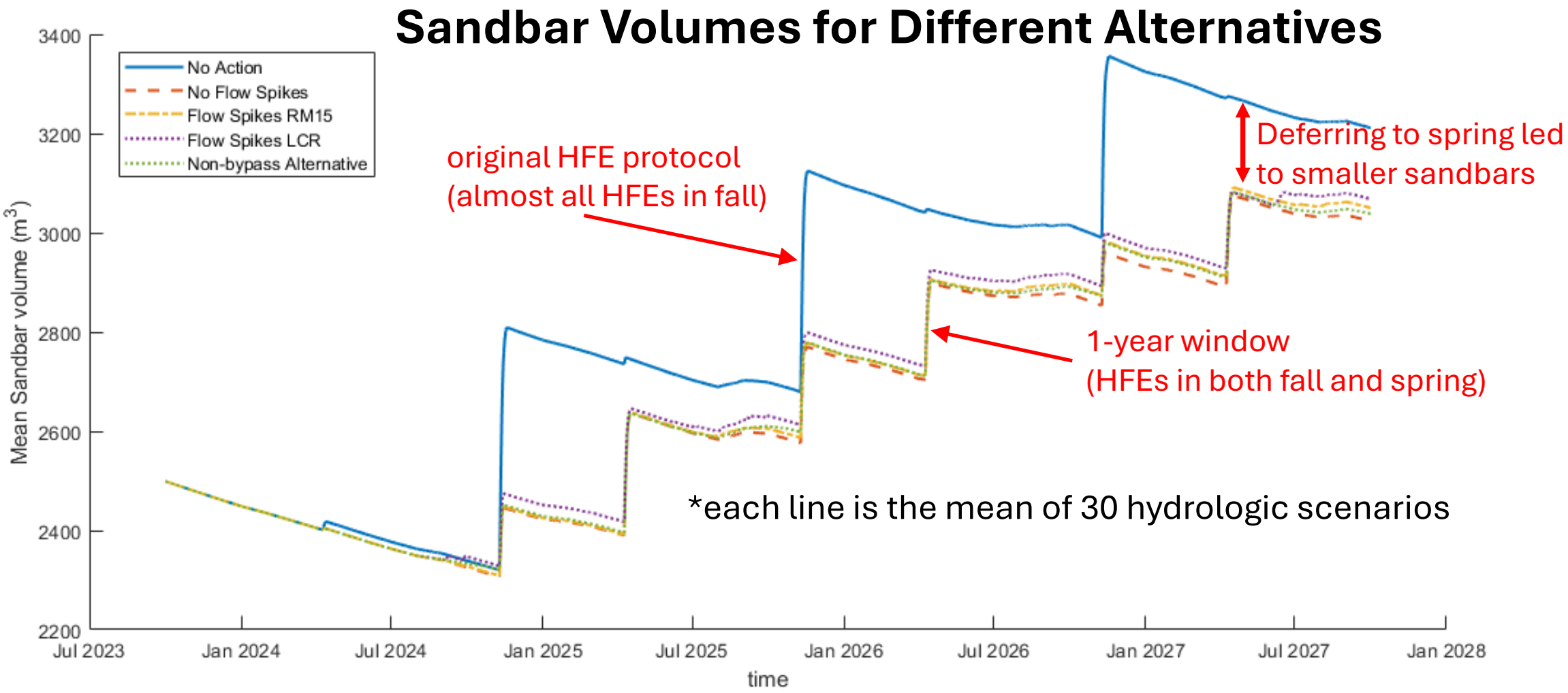

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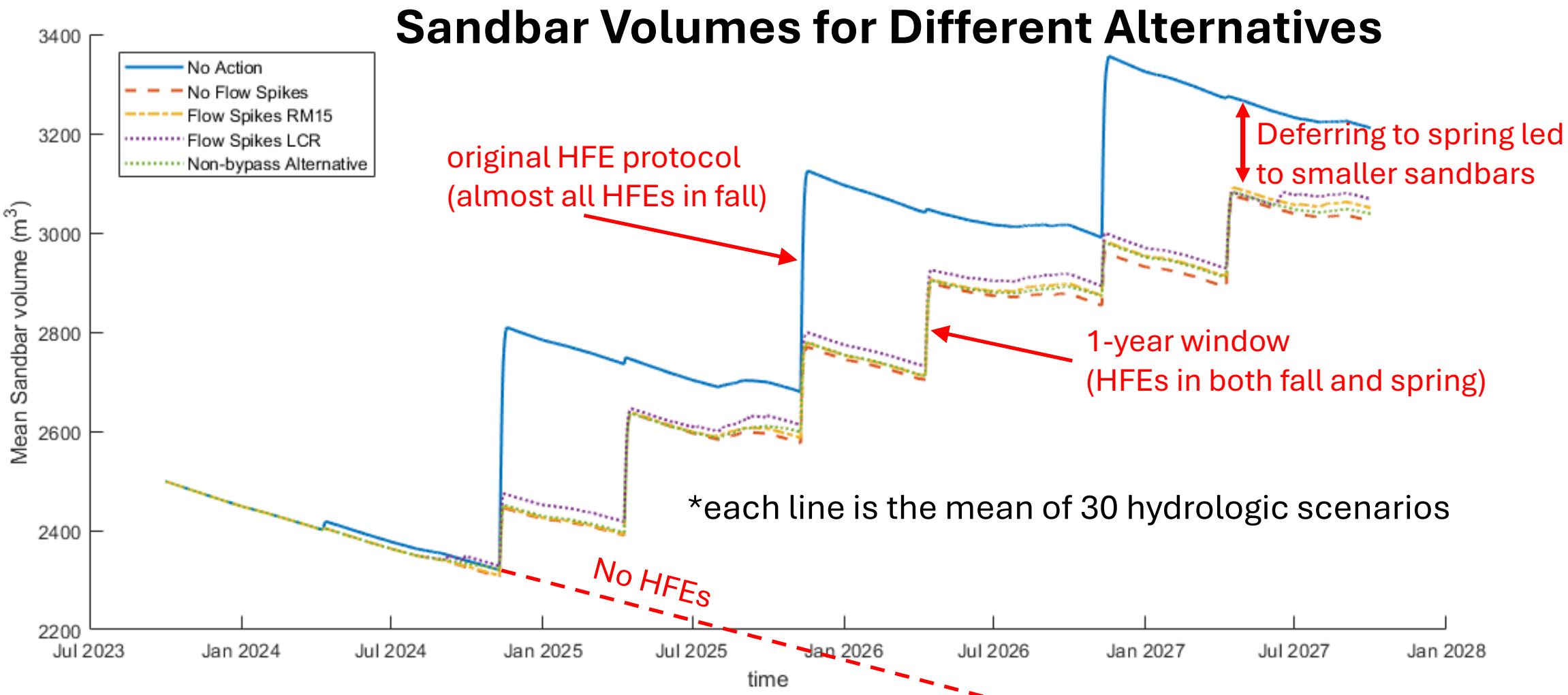

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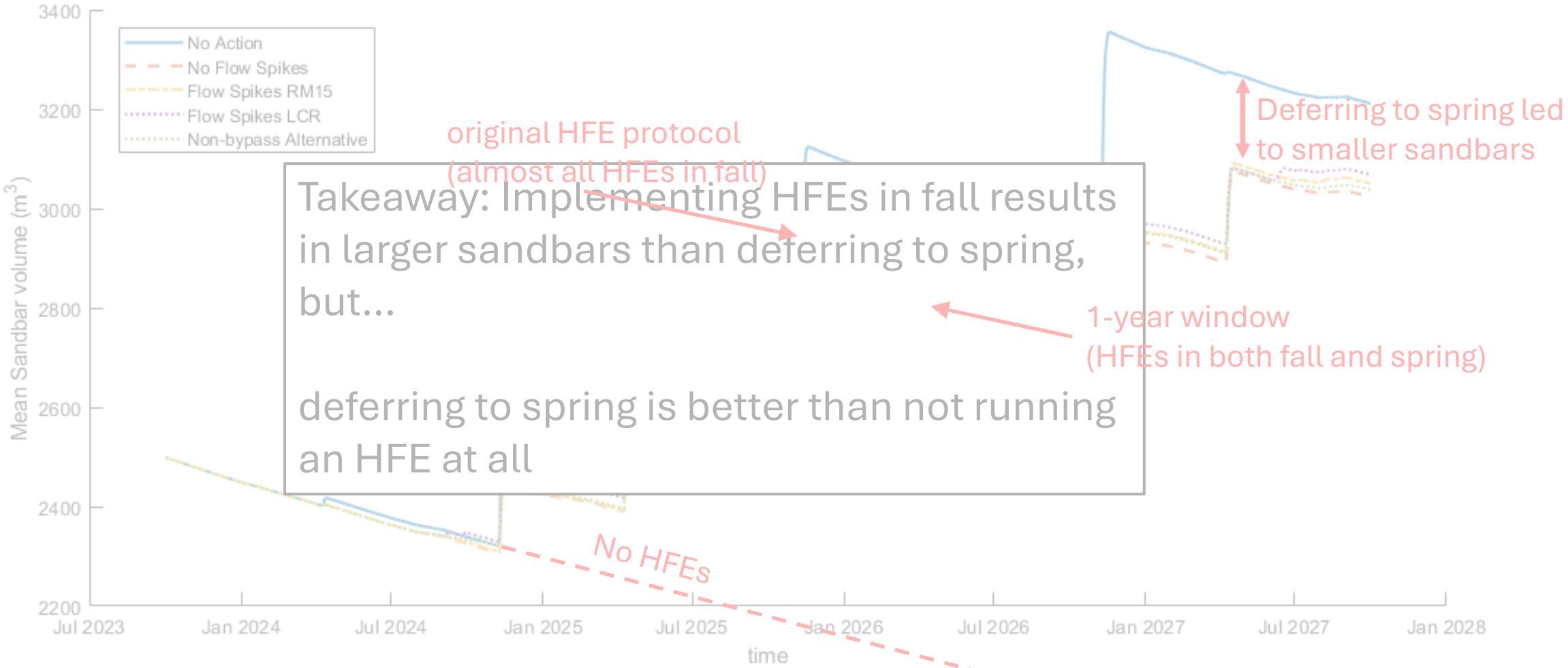

Salter and Grams, 2024

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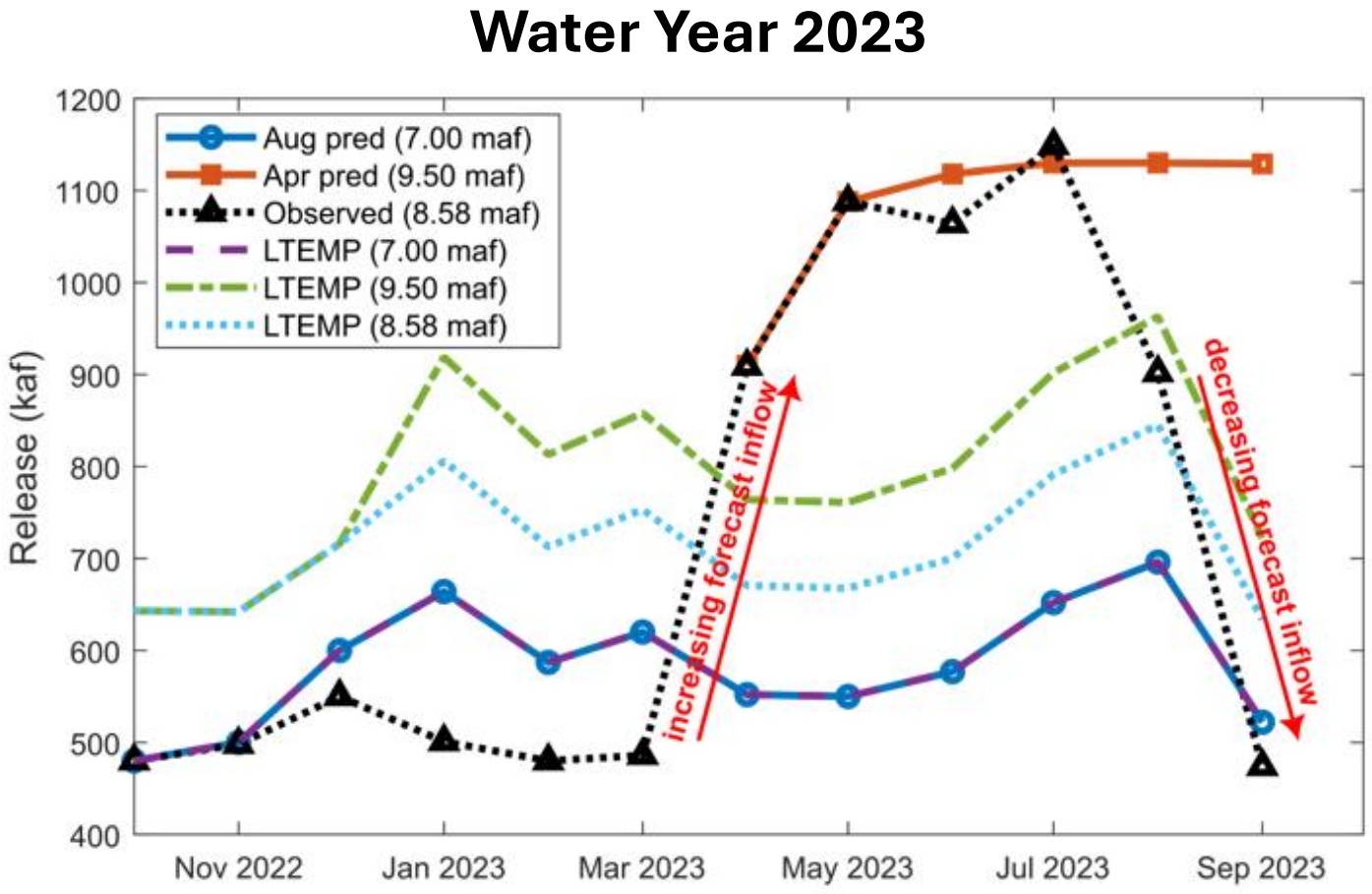
Annual release policies can affect monthly release patterns



- Even amidst ongoing drought, high-inflow years can occur
- Water Year (WY) 2023 illustrates that policies for determining annual releases can affect monthly releases
- High snowmelt runoff led to a higher annual release than originally expected, which was compressed into half of the year
- These high releases led to large amounts of sand erosion

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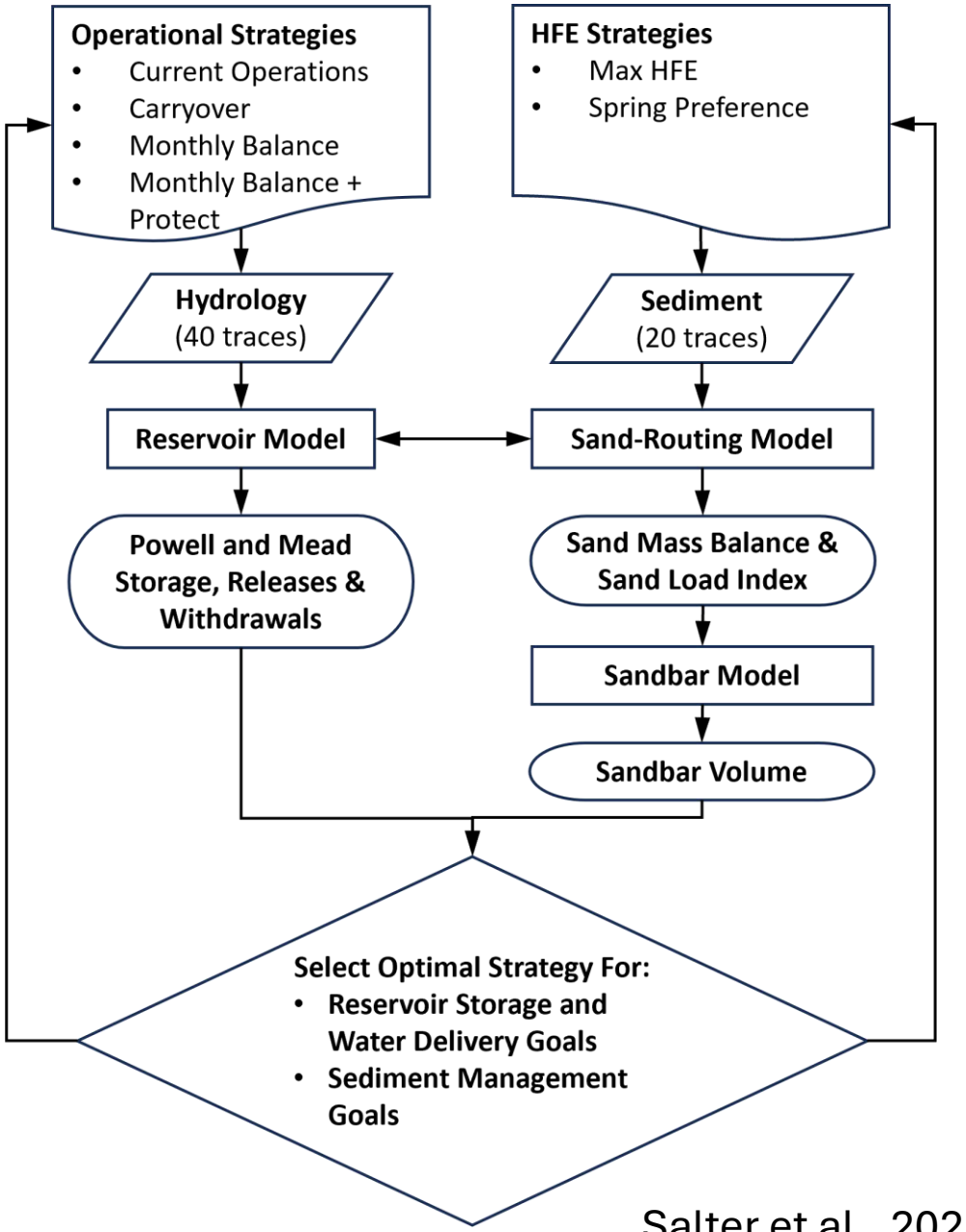
Salter et al., 2025

A modeling framework for selecting optimal strategies to meet management goals for both water and sediment

- We modeled the Lake Powell/Lake Mead system under different hypothetical reservoir operational and HFE strategies
- Included effects of inflow forecast uncertainty on sub-annual releases
- 40 hydrologic scenarios combined with 20 sediment input scenarios
- We obtained sand mass balance and sandbar volume for all scenarios and operational strategies
- **“Sustainable”** = rebuild/maintain sandbars with increasing or stable sand mass balance



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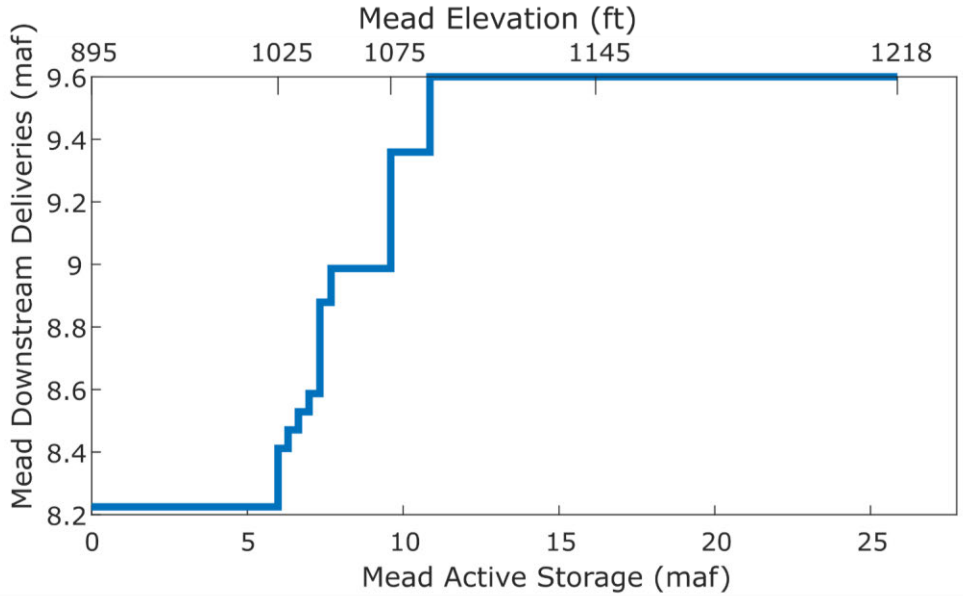
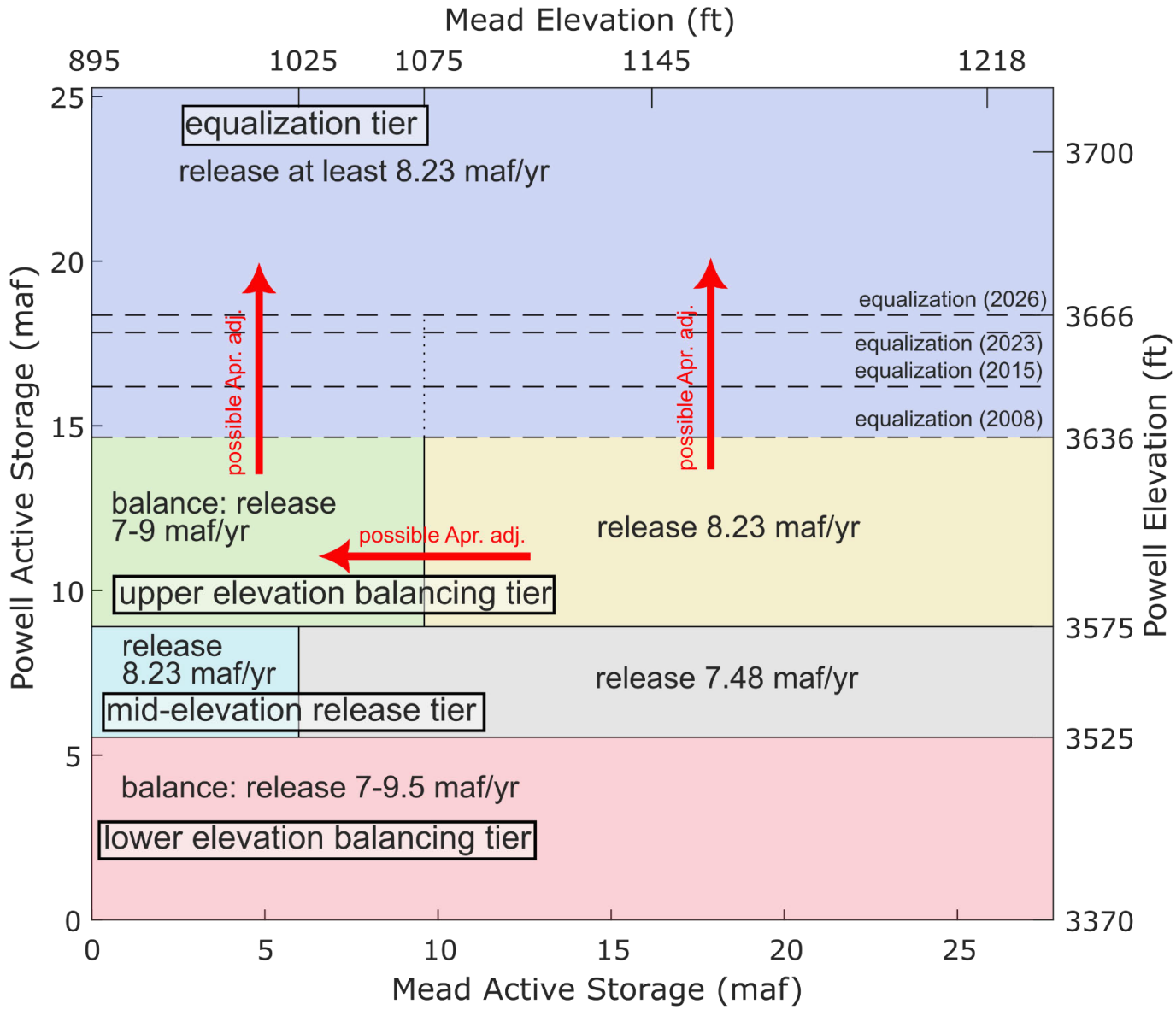
Flexibility of operational strategies

- We used “Current Operations” as our starting point, and selected strategies that maintained similar ranges of reservoir elevations and releases
- Parameters within each operational strategy can be adjusted to meet different water management goals (what those should be is beyond the scope of our work).
  - One exception: if goals are adjusted to avoid critically low Powell elevations, more HFEs could be implemented (given existing dam infrastructure limitations)
- Can we create better conditions for sandbars while maintaining similar water delivery and reservoir management goals?

1. Current Operations (Interim Guidelines+DCP)





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2. Carryover

- Same as “Current Operations”, except…
- Any monthly releases exceeding an average release of 15,100 cfs (900 kaf in a 30-day month, or 11 maf/yr) are “carried over” to the next month
- Carry-over volume is added to subsequent months so that each month has a ~900 kaf release until the carry-over volume is exhausted.
- **Release volumes may be carried over across water years.**
- Once the carry-over period is complete, the total volume released from Powell is identical to what it would have been under “Current Operations”

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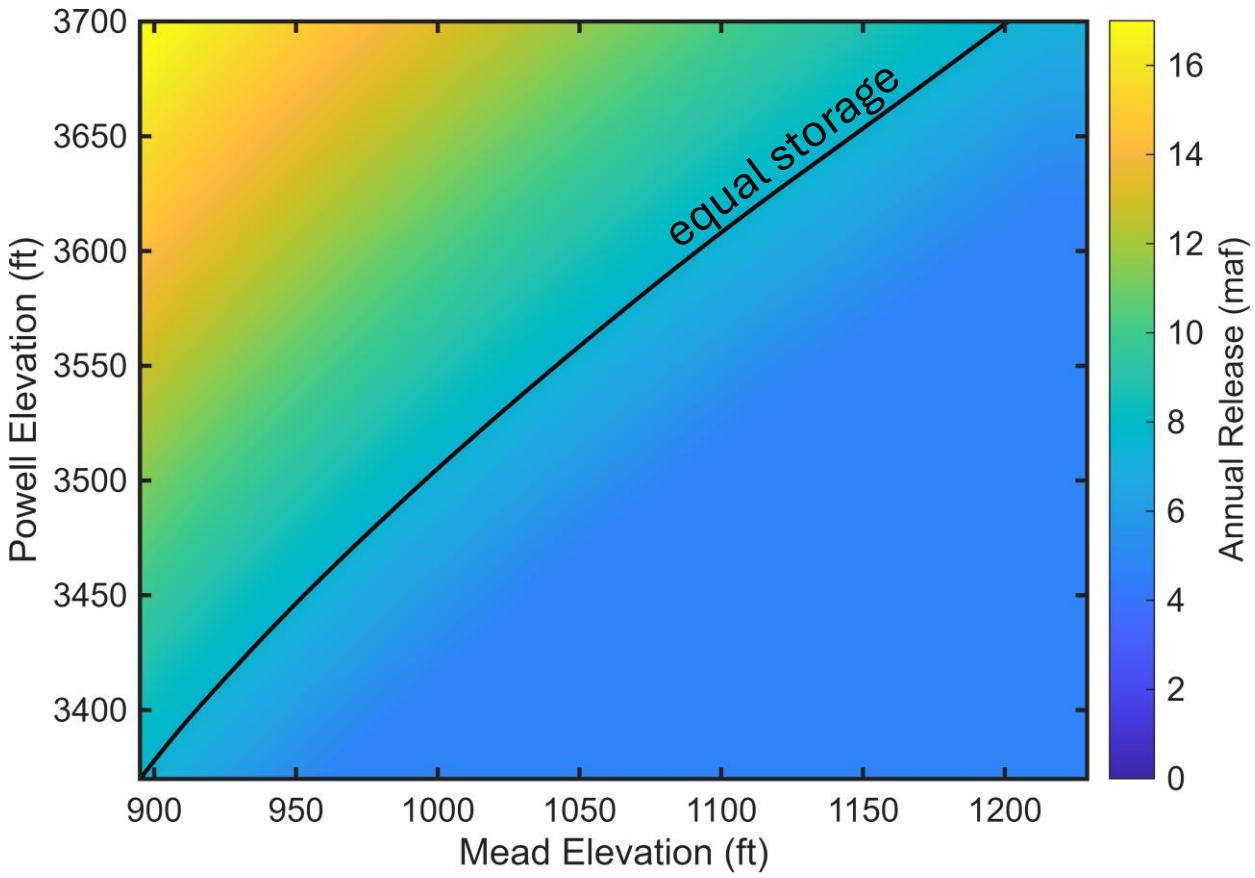
3. Monthly Balance

- Releases are determined monthly based on Powell and Mead elevation.
- Releases are adjusted to meet prescribed sub-annual pattern (e.g. higher summer releases)
- Like balancing/equalization, water-year release is a moving target, except monthly adjustments are relatively small and predictable
- Mead deliveries based on combined storage



$$Annual\ Release(maf) = 7.5\ maf + \frac{0.03\ maf}{ft}\left(Powell\ (ft) - Powell\ Target\ (ft)\right)$$

*where the Powell target elevation is the Powell elevation if its storage volume were the same as Mead's
*converted to monthly release by multiplying by [days in month]/365.25

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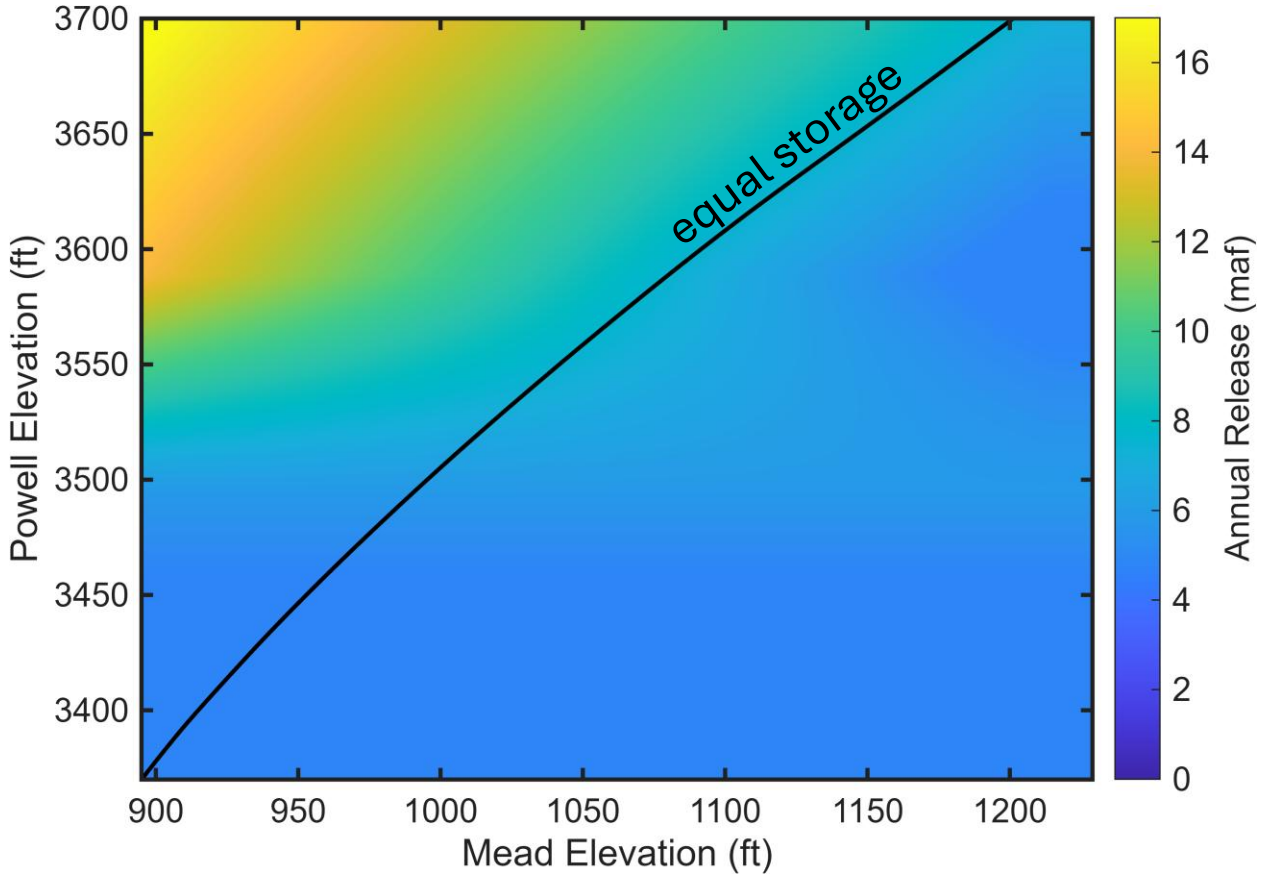
4. Monthly Balance + Protect

- Same as “Monthly Balance” when Powell storage exceeds 10 maf (3589 ft)
- When Powell storage is below 4 maf (3496 ft), release is based on Powell elevation alone.
- In between 4 maf and 10 maf, release smoothly transitions between the balancing and elevation-based target



$$Annual\ Release(maf) = 7.5\ maf + \frac{0.03\ maf}{ft}\left(Powell\ (ft) - Powell\ Target\ (ft)\right)$$

*Above 10 maf, Powell target elevation is the Powell elevation if its storage volume were the same as Mead’s
*Below 4 maf, Powell target elevation is 3550 ft
*Between 4-10 maf, Powell target elevation is the linear interpolation of the elevation and balancing targets
*converted to monthly release by multiplying by [days in month]/365.25

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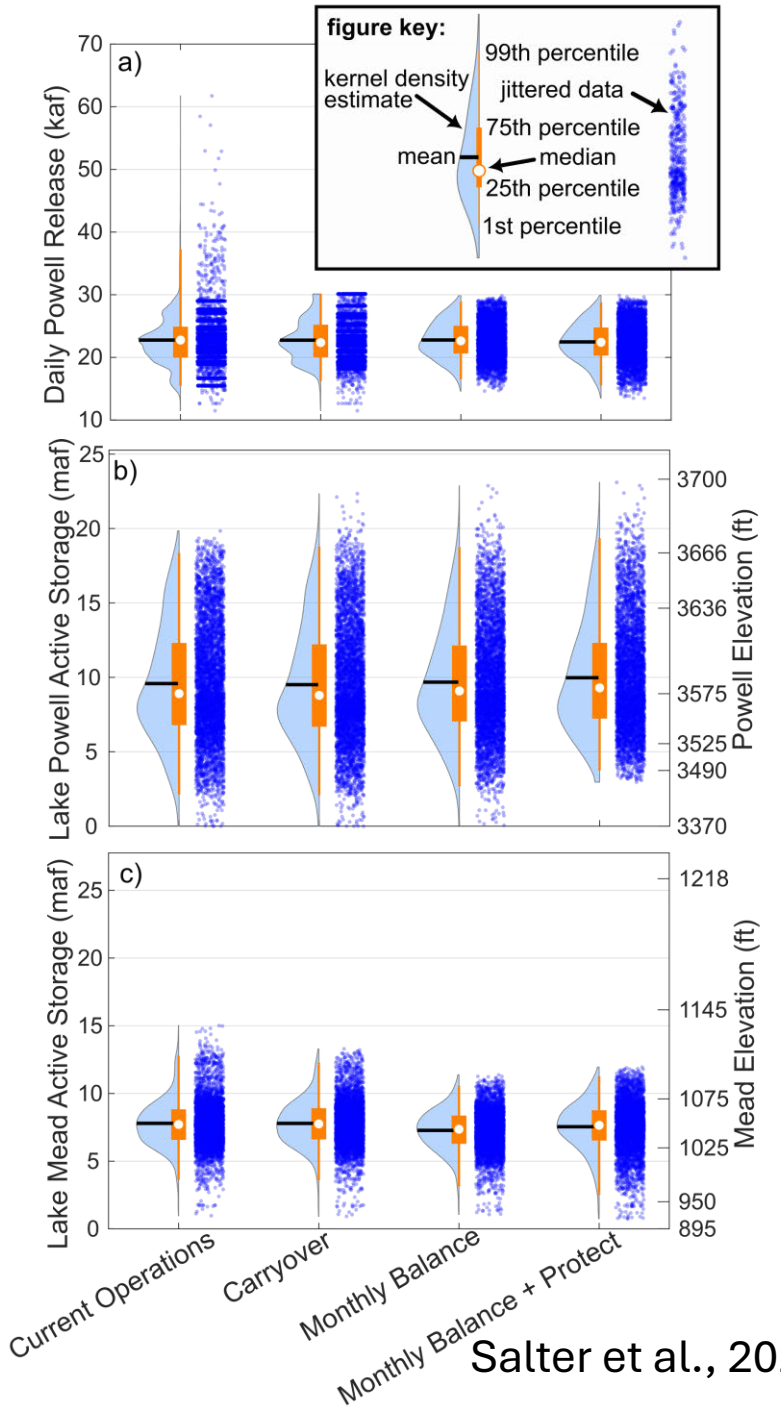
Operational strategies for avoiding high monthly releases

- High monthly releases decrease sandbar volume through direct erosion and by decreasing sand availability for HFEs
- We found that flexibility in annual release can help avoid high monthly releases
- Strategies maintained similar reservoir elevations and delivery as current operations
- “Monthly Balance + Protect” better avoided low Powell elevations that could preclude HFEs, but at the expense of water delivery (but within the range explored under Post-2026 operations)
- These operational strategies give flexibility in monthly and annual release volumes while still meeting the agreed upon water delivery targets. They don't address the critical post-2026 issue of how shortages are distributed, but could be adapted to be consistent with whatever solution on that problem is reached.



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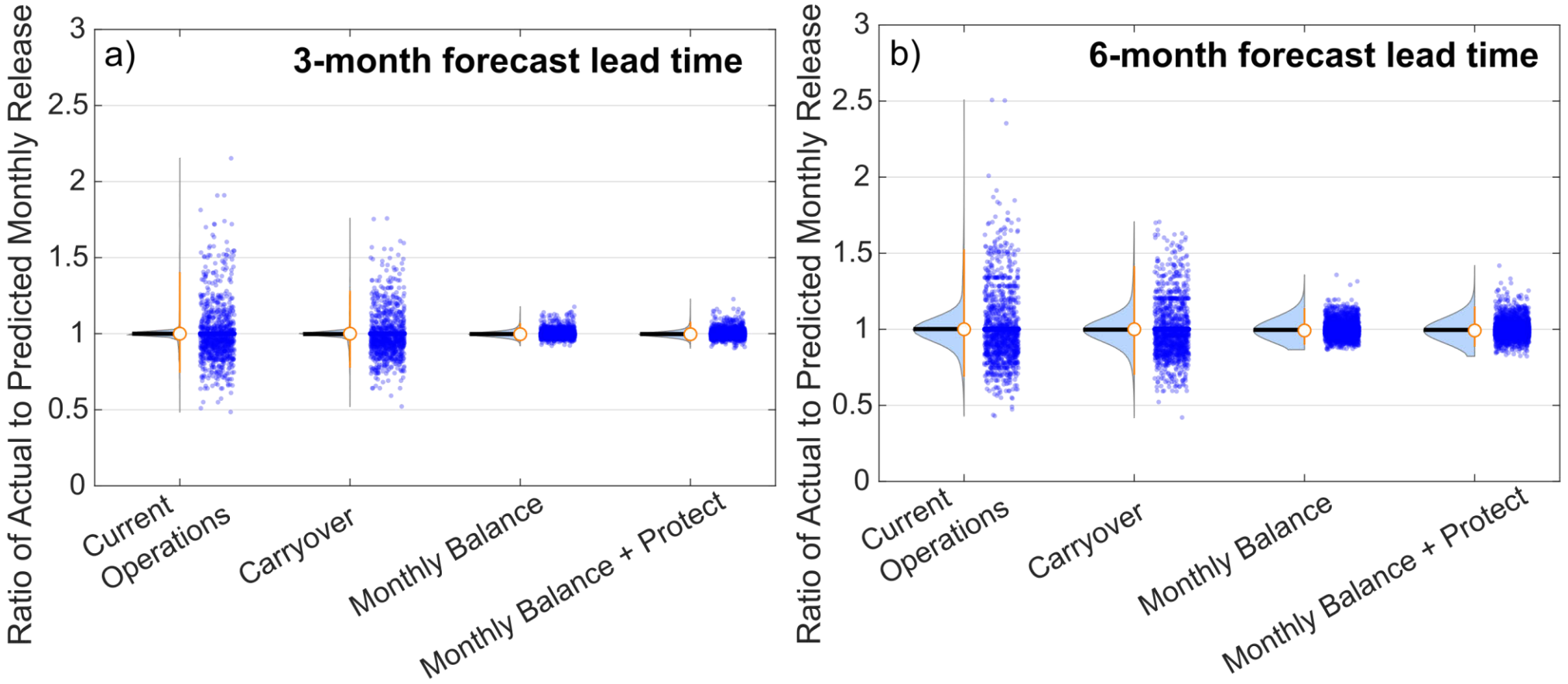
Improved ability to predict monthly releases



Improved predictability not only beneficial for sand resources, but could increase hydropower revenue by allowing for better forecasts of power generation

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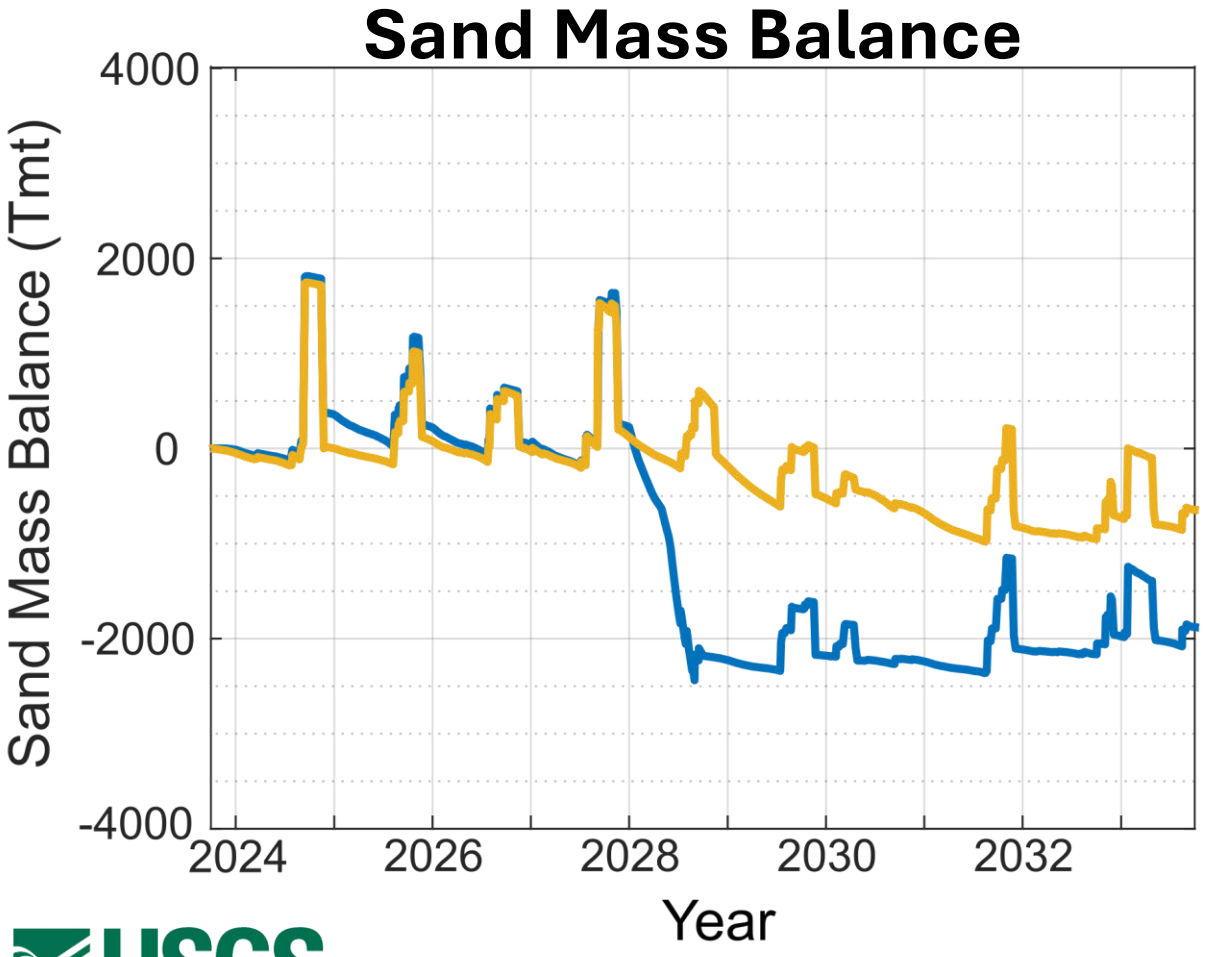
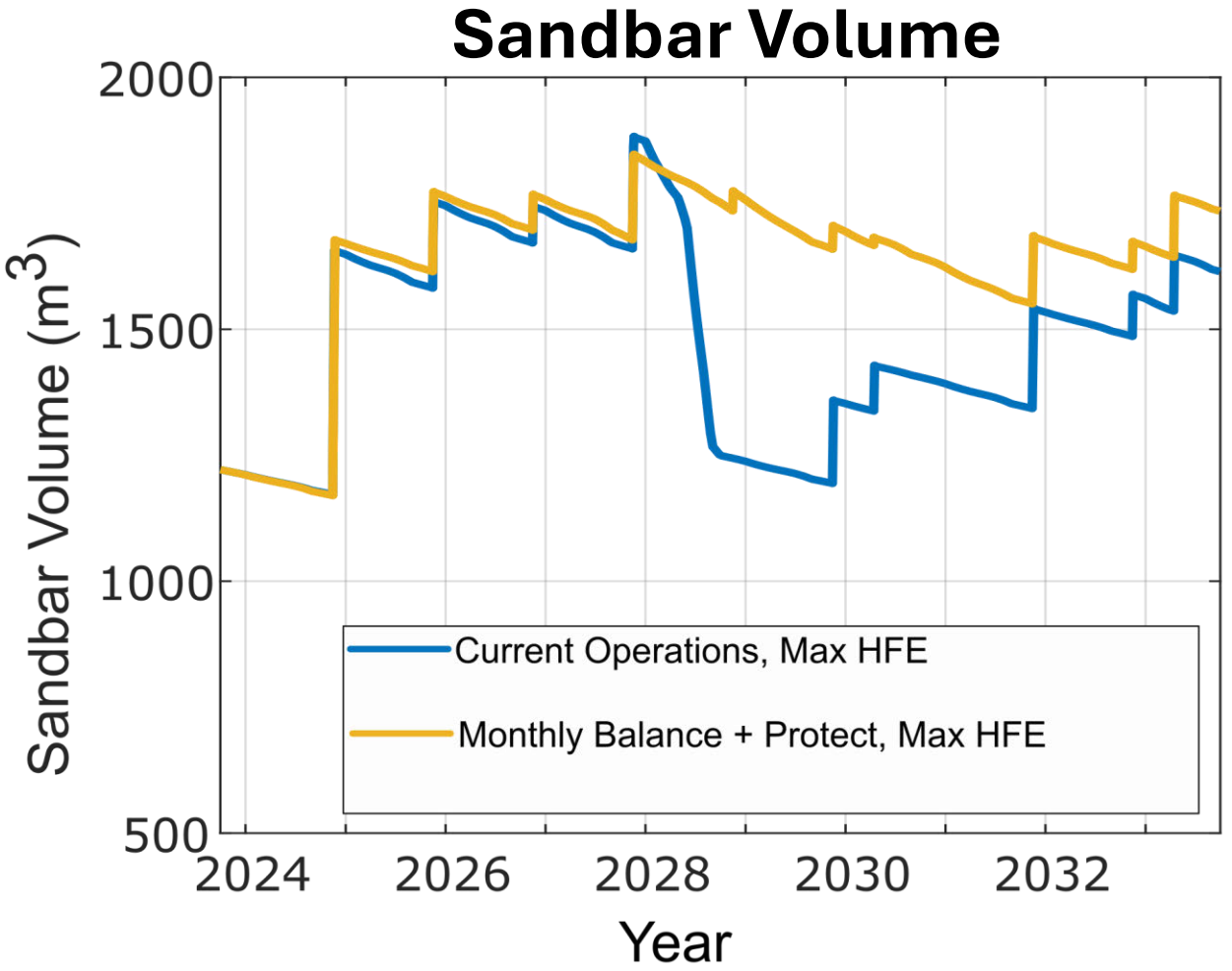
Effect of reservoir operational and HFE strategies for an example scenario





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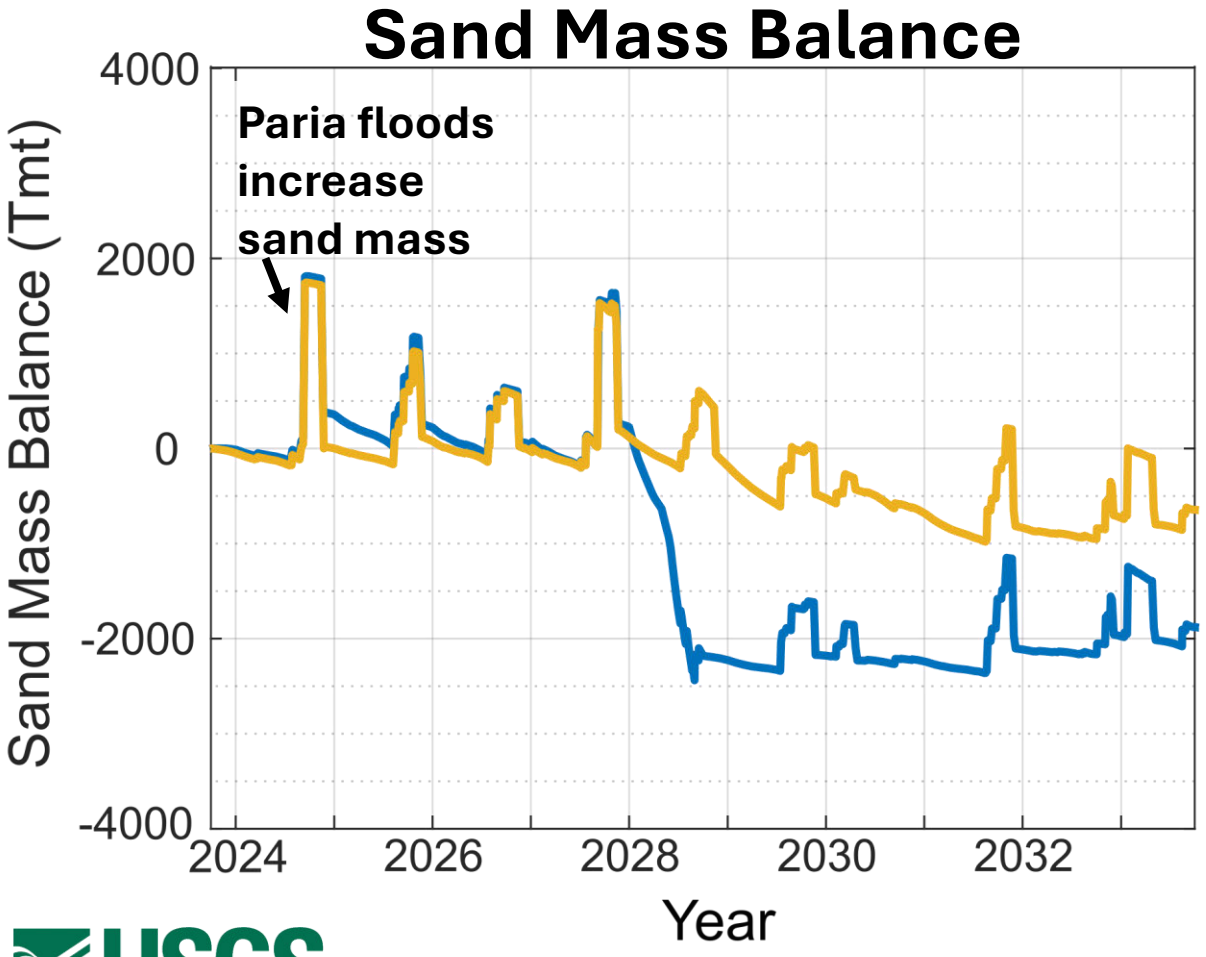

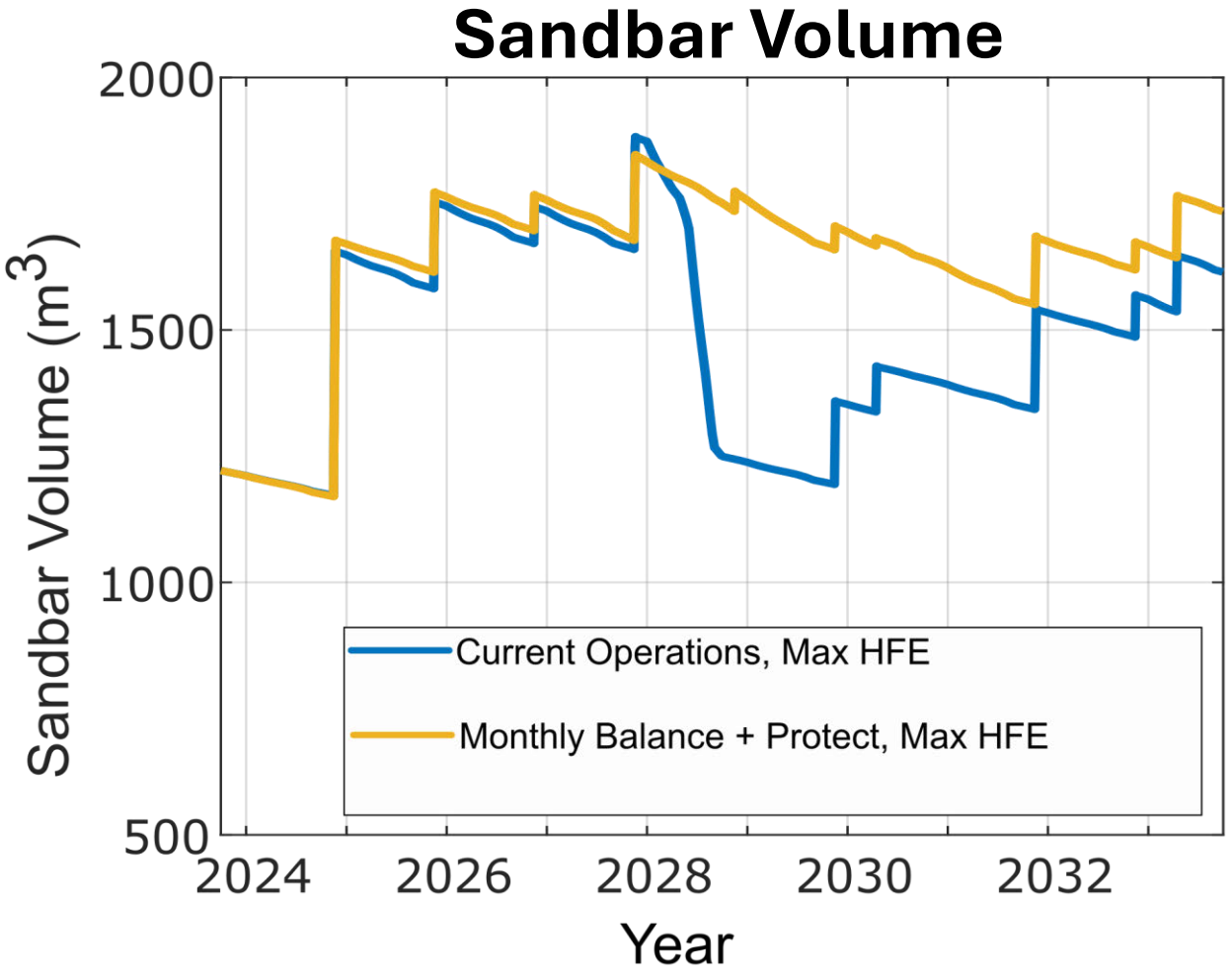

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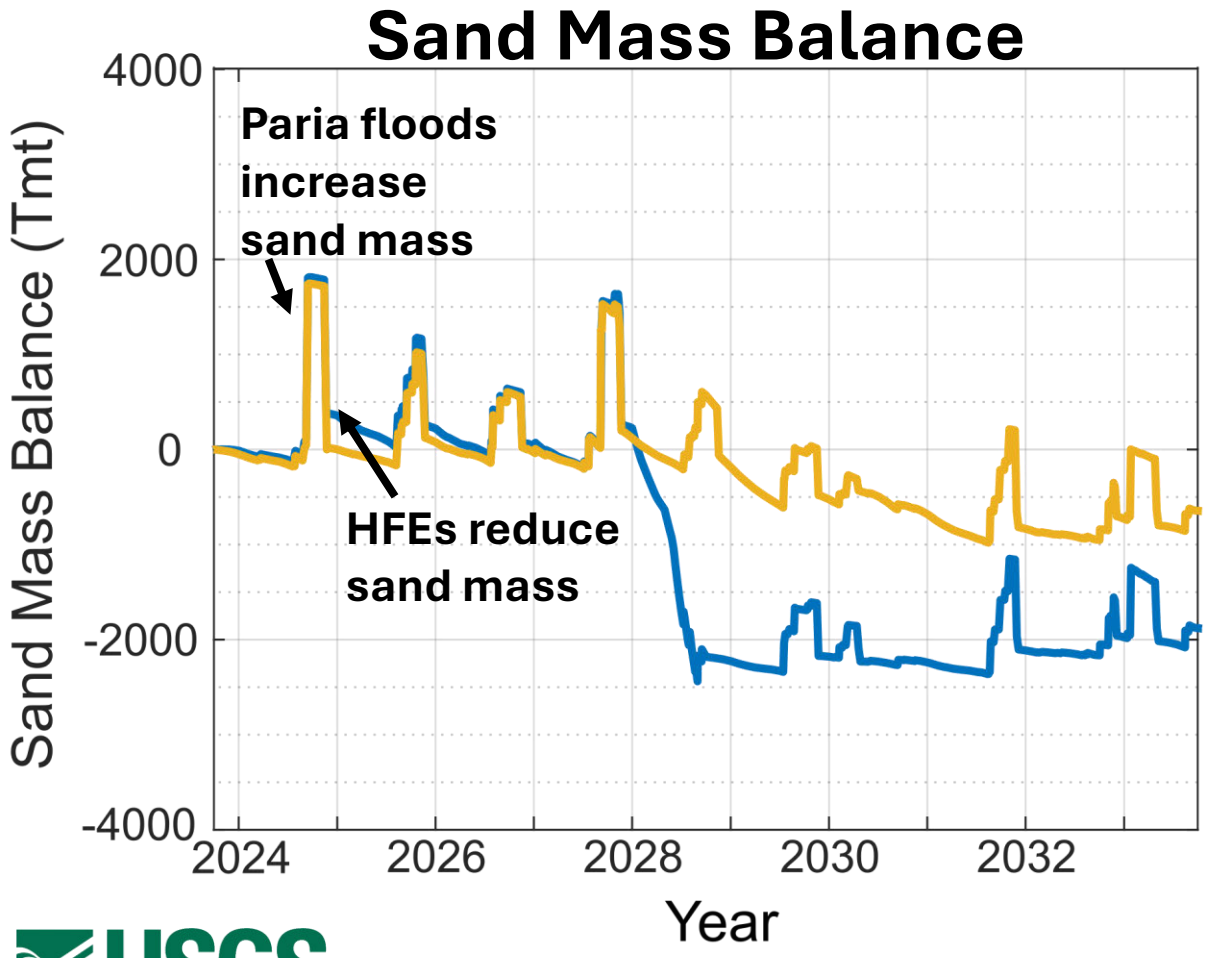

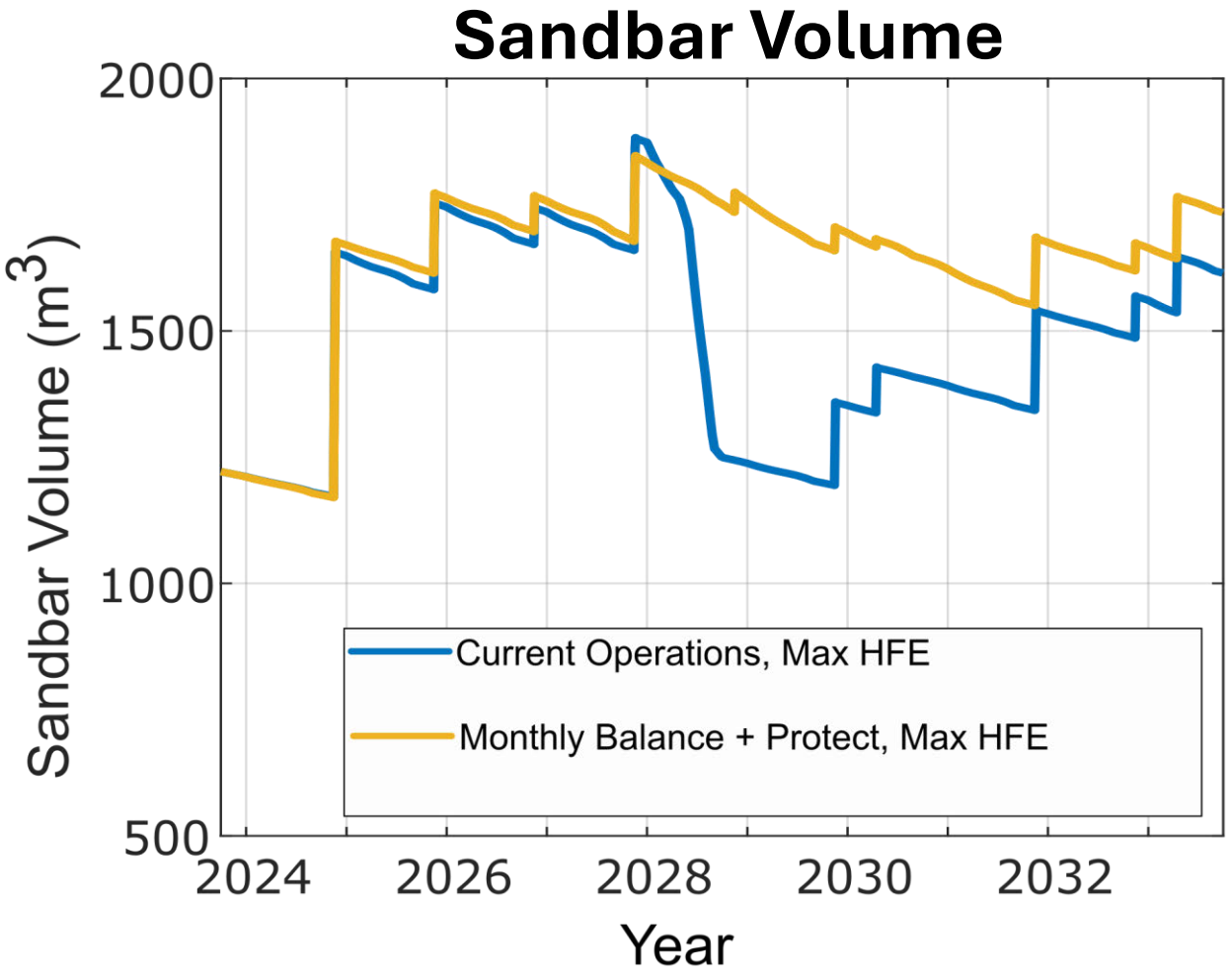

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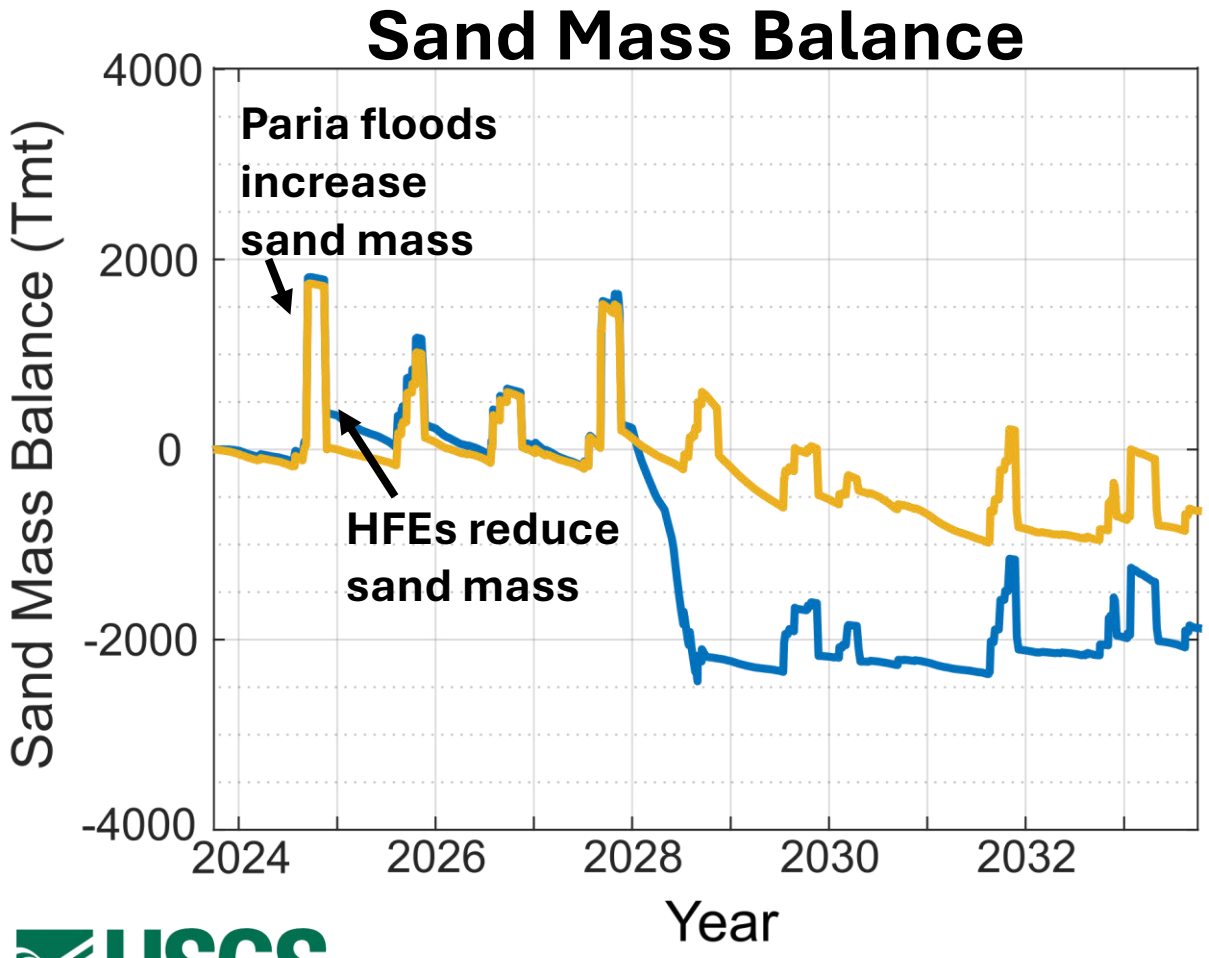

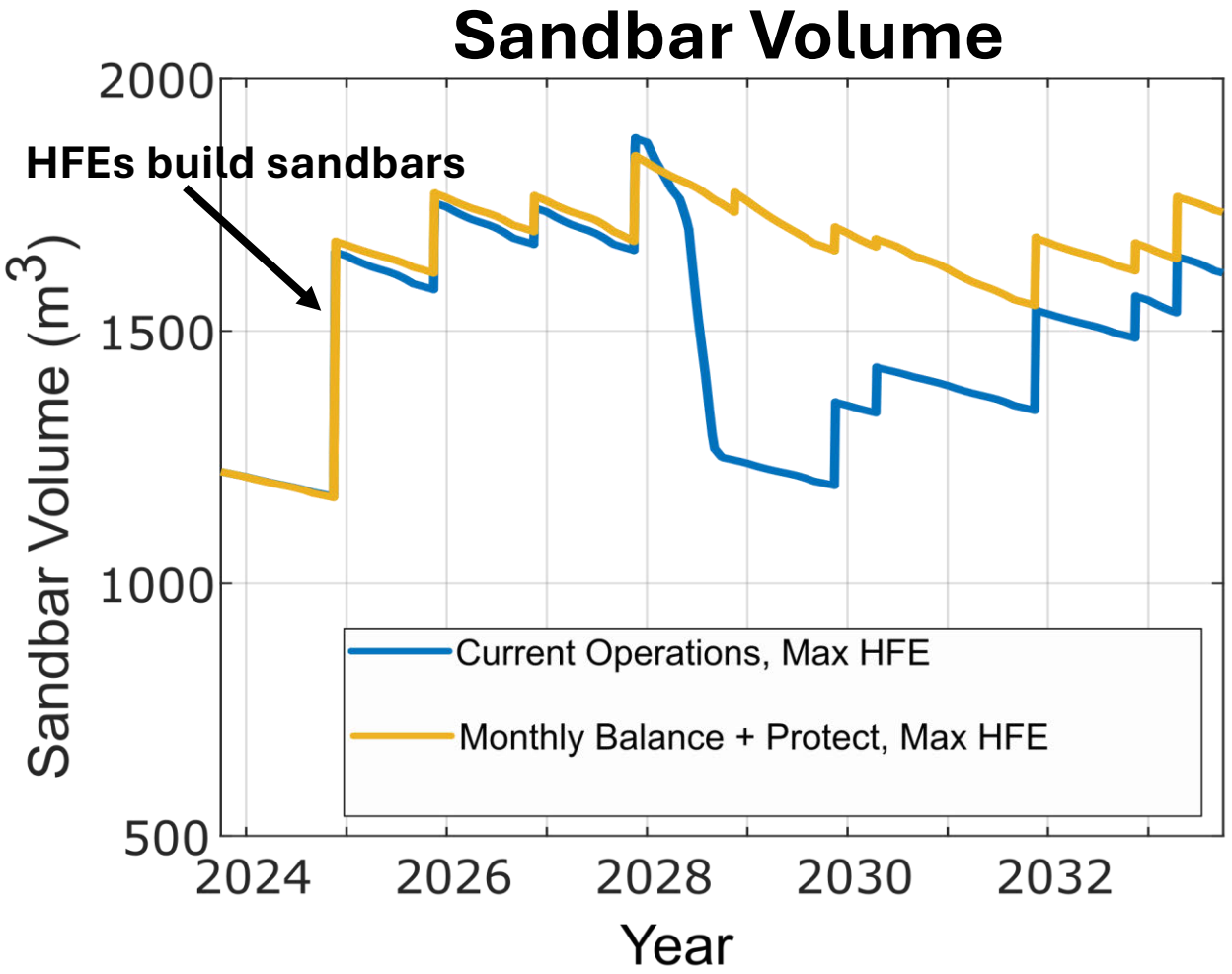

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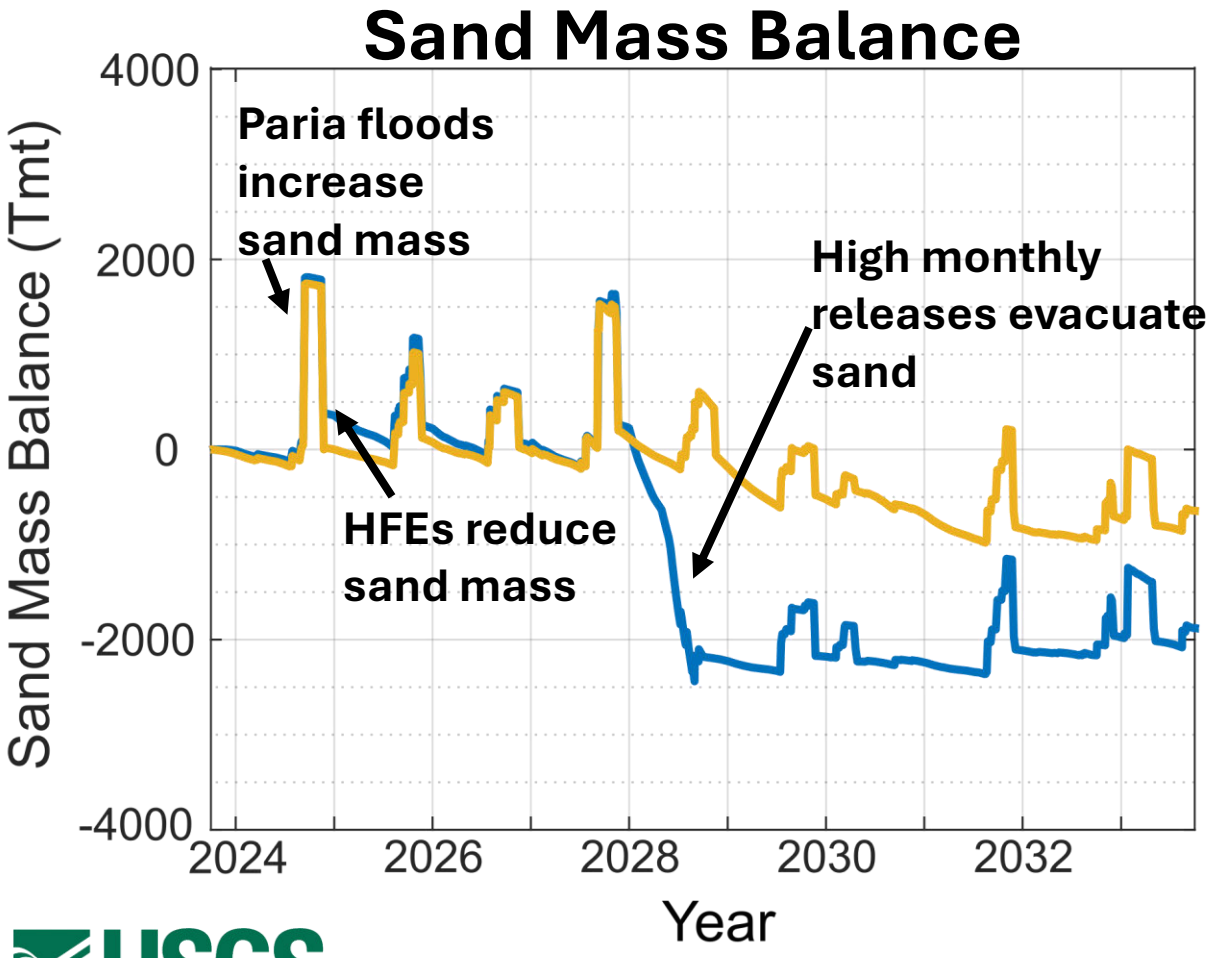

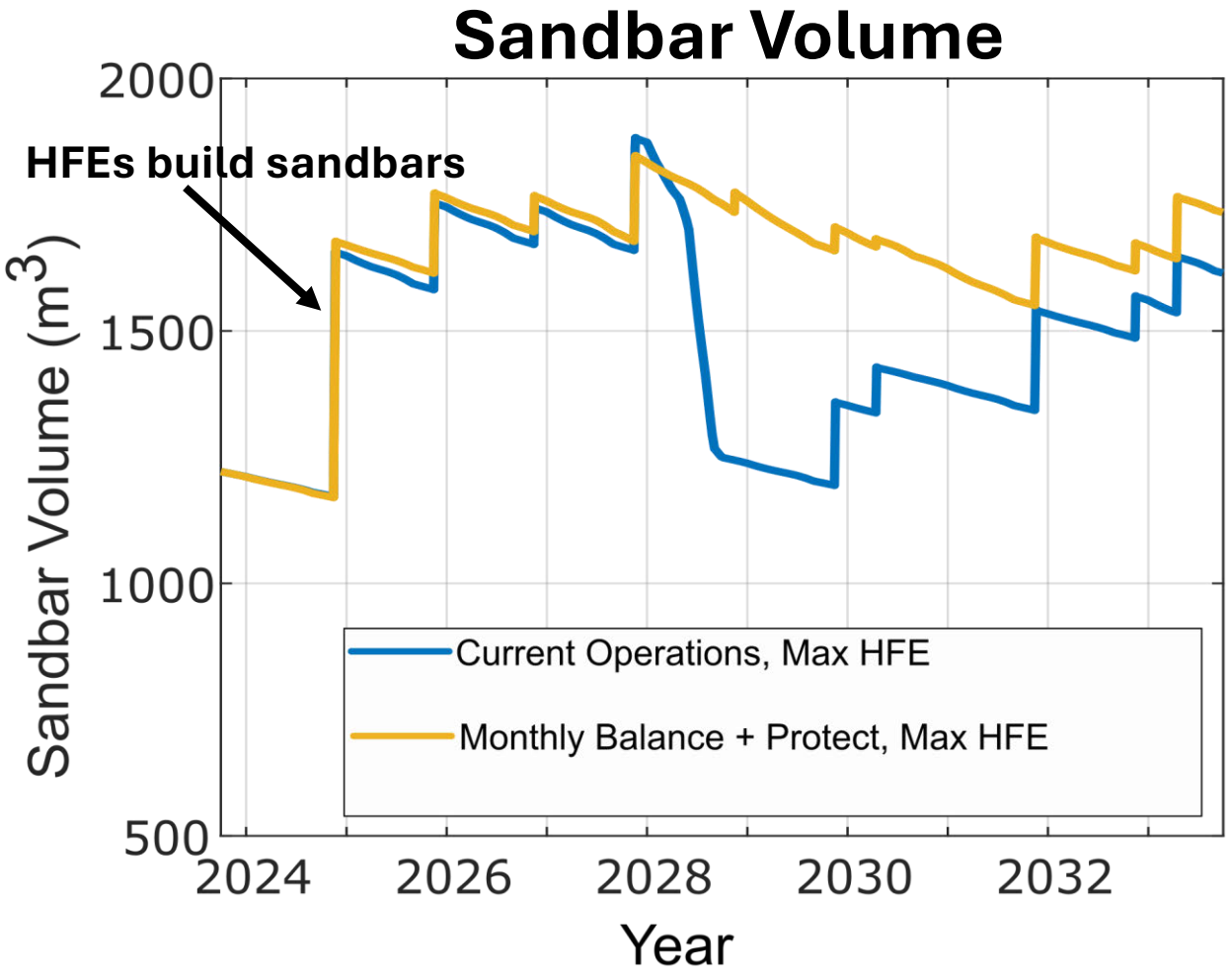

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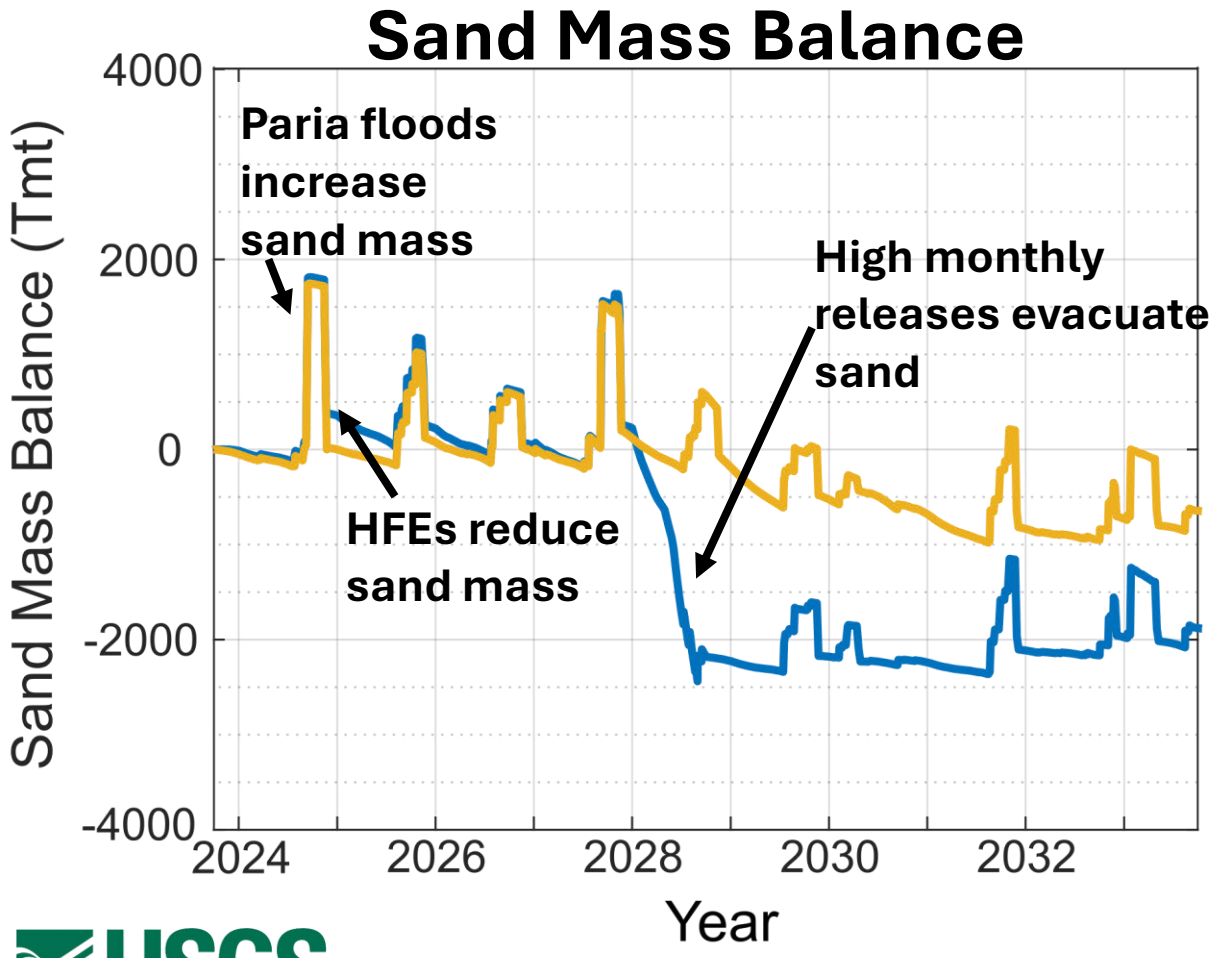

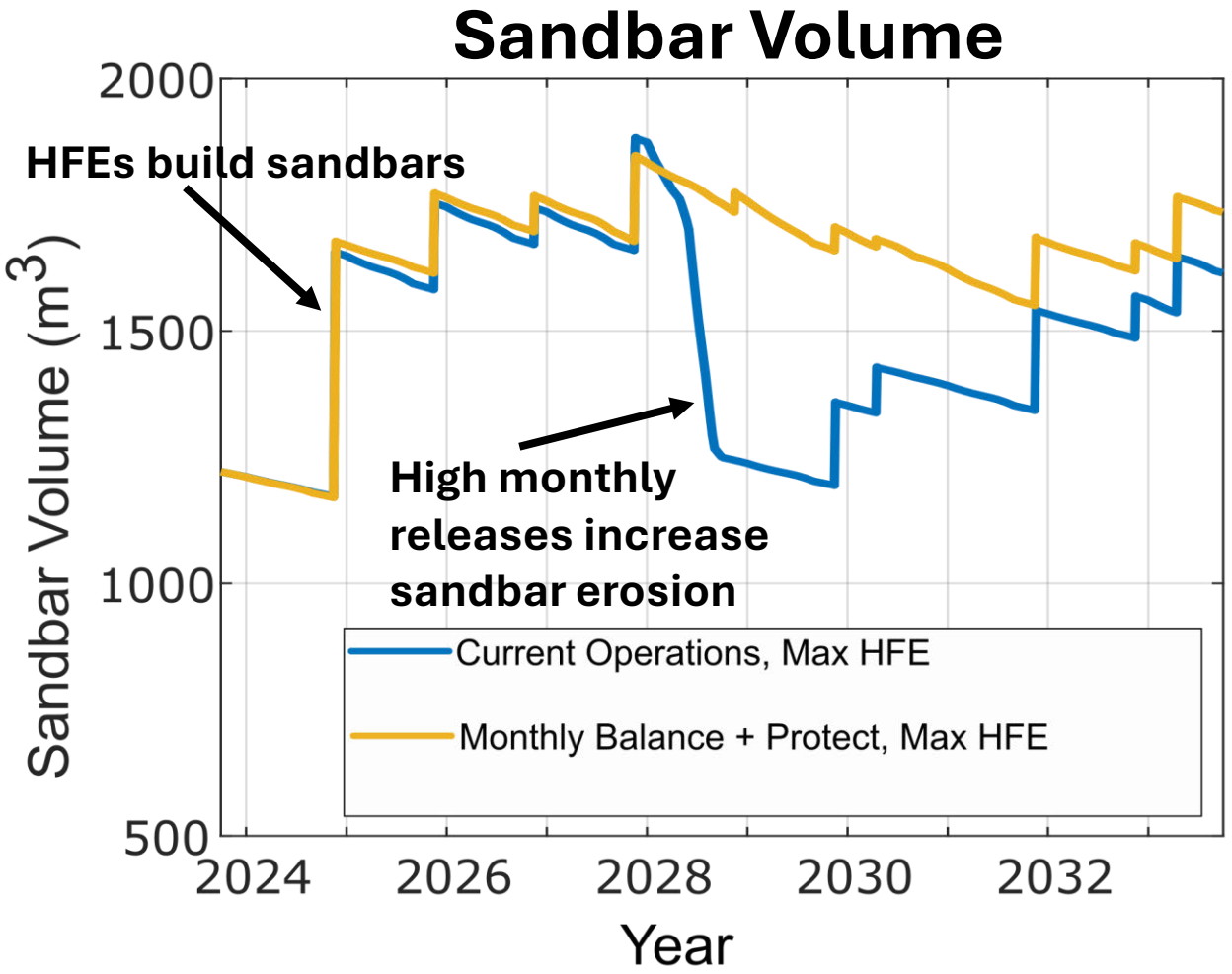

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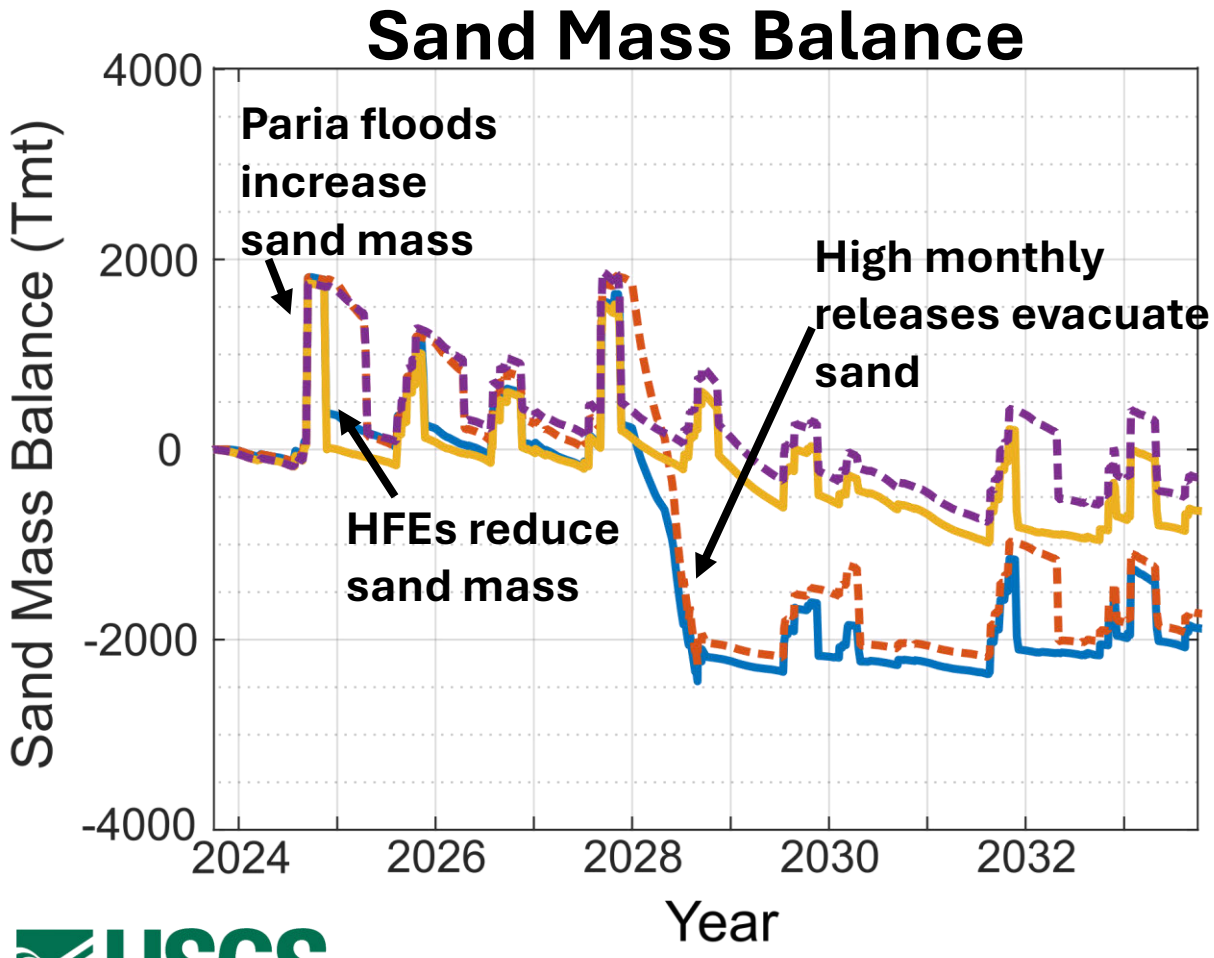

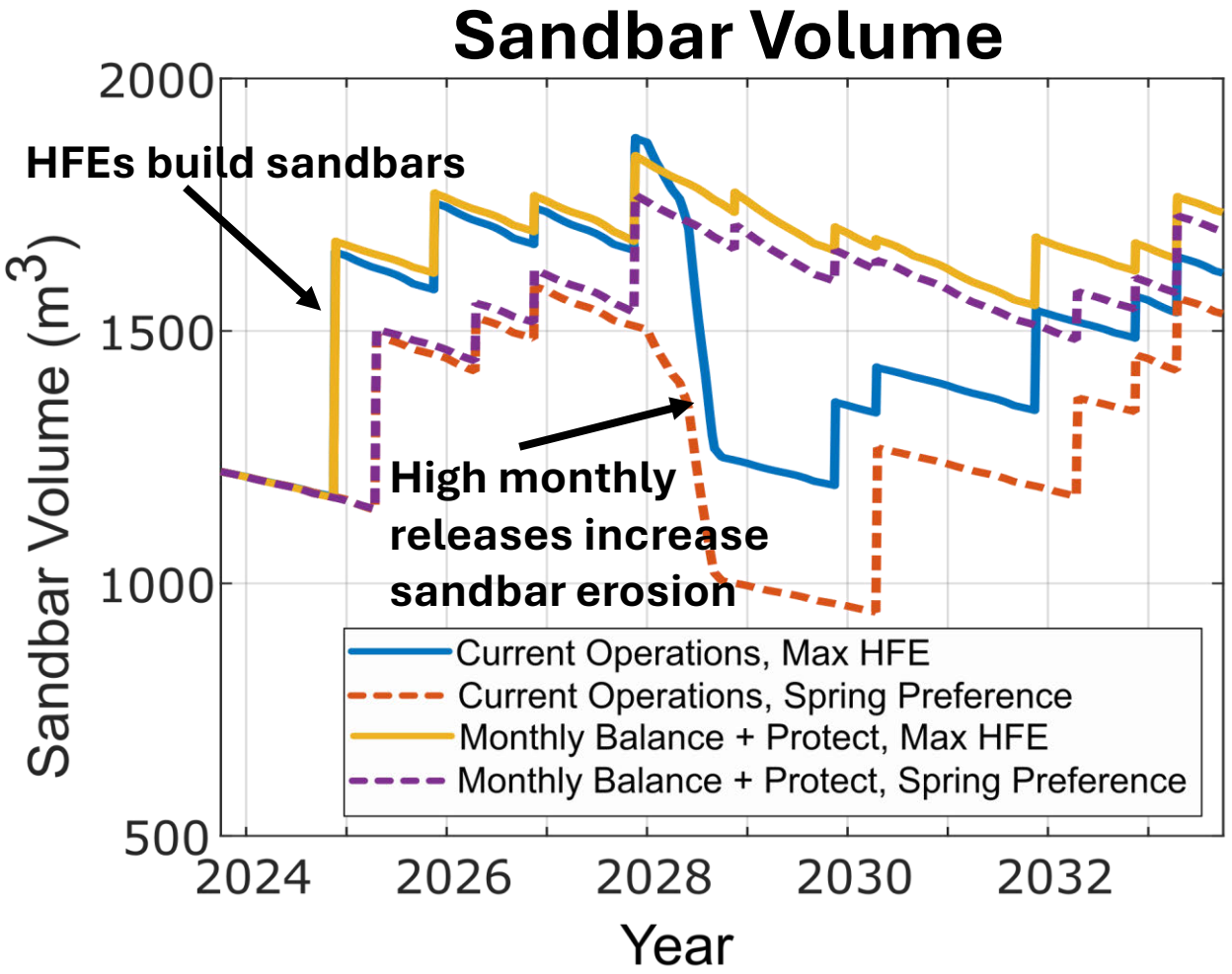

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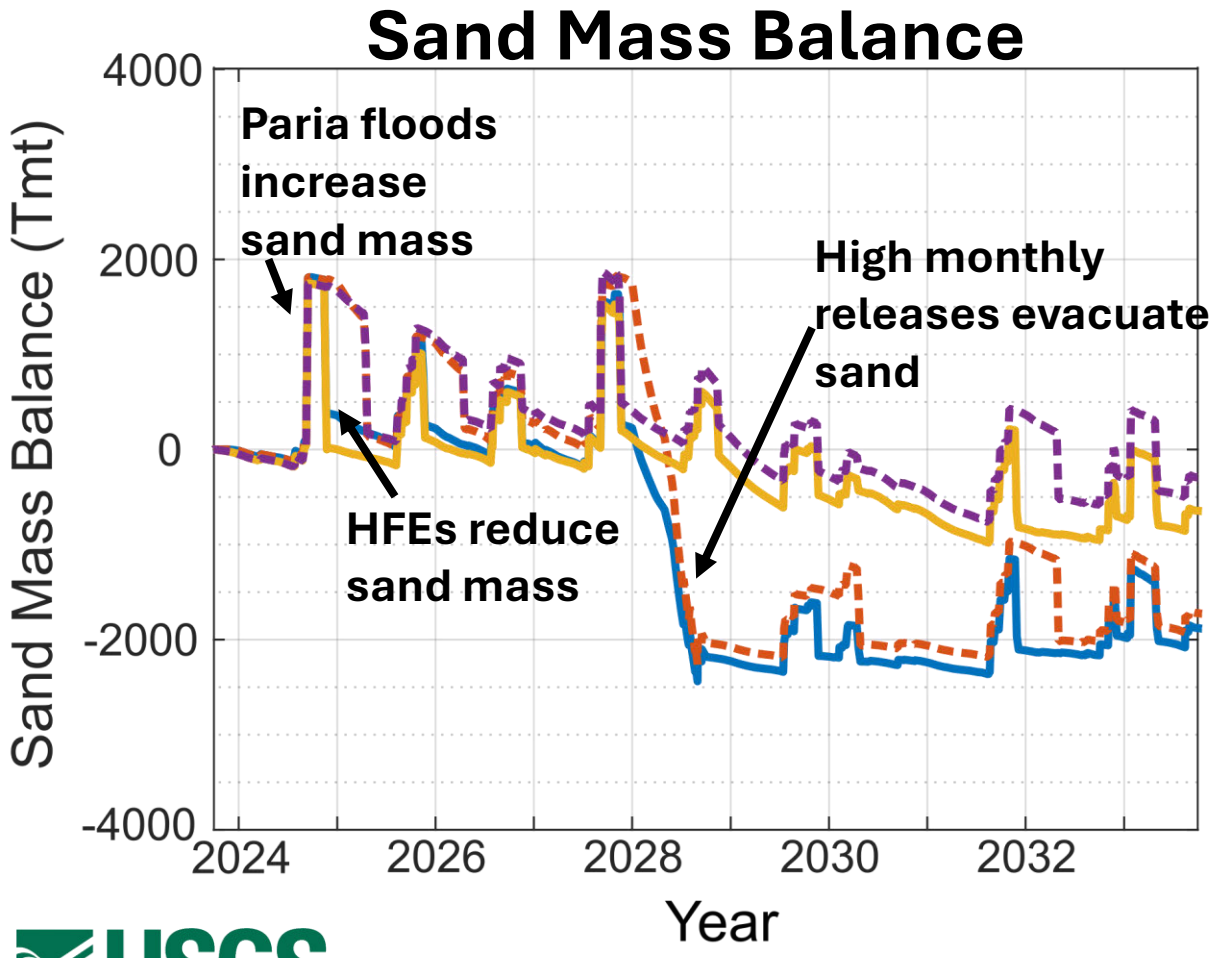

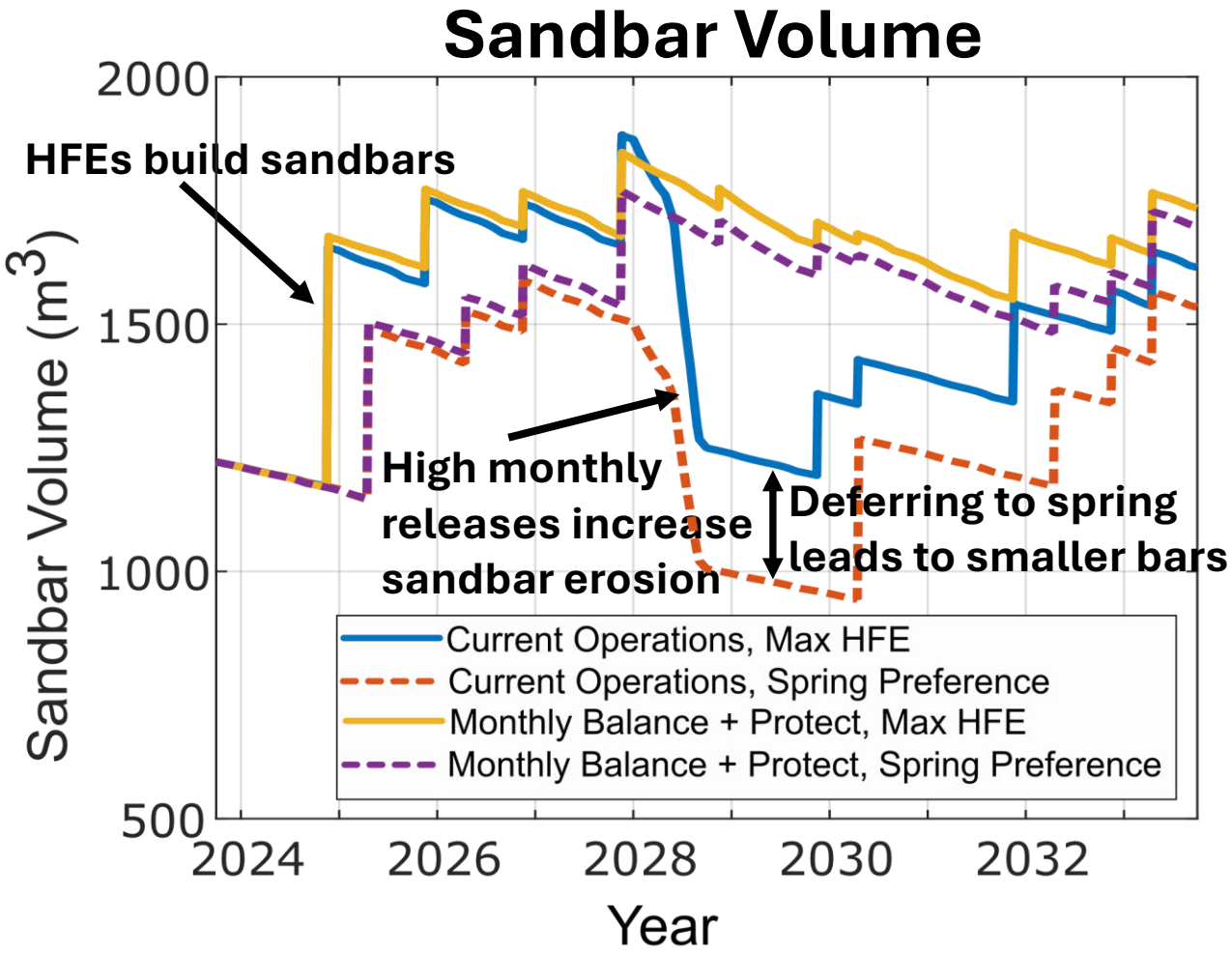

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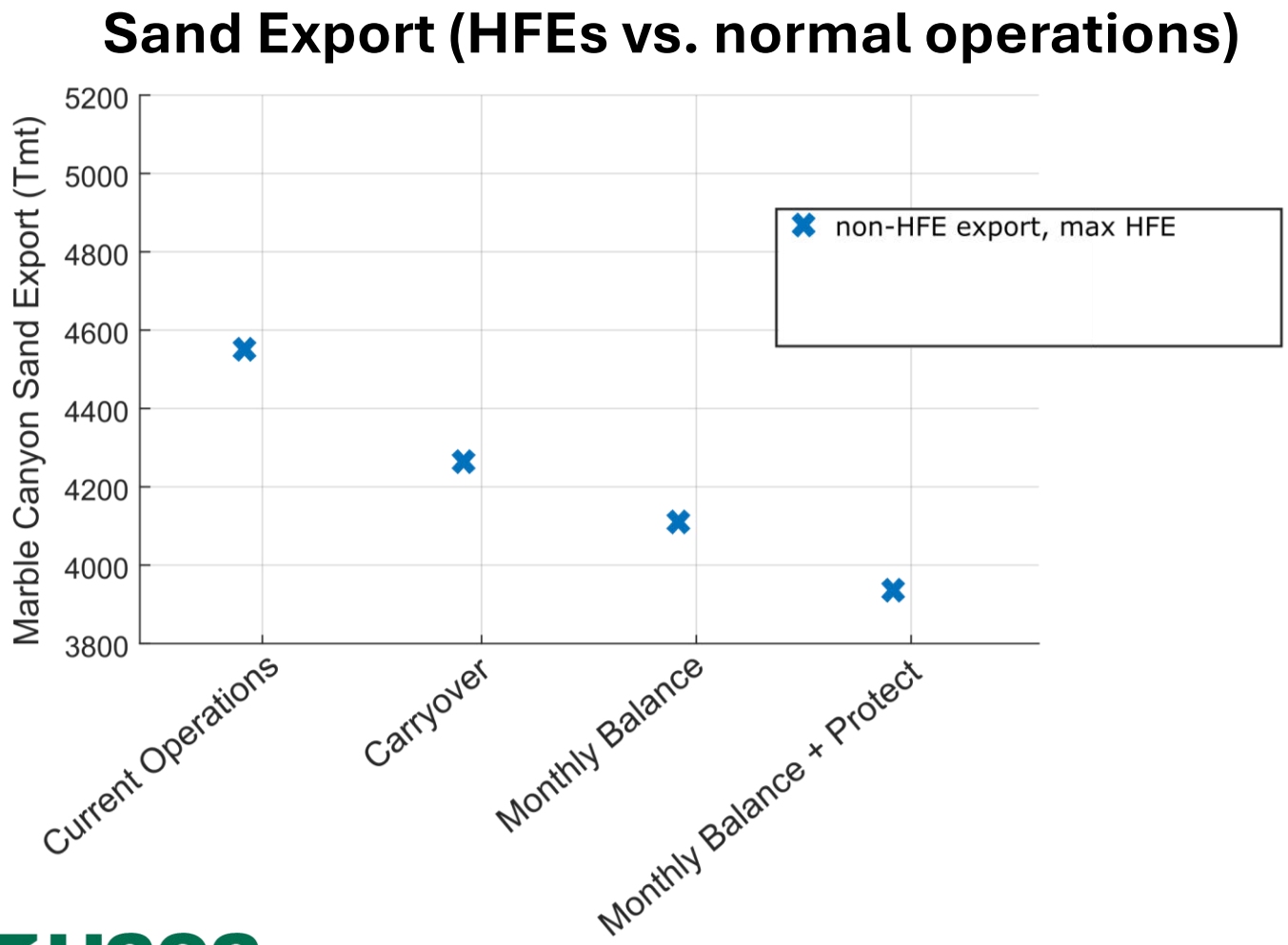
Testing strategies across 800 scenarios



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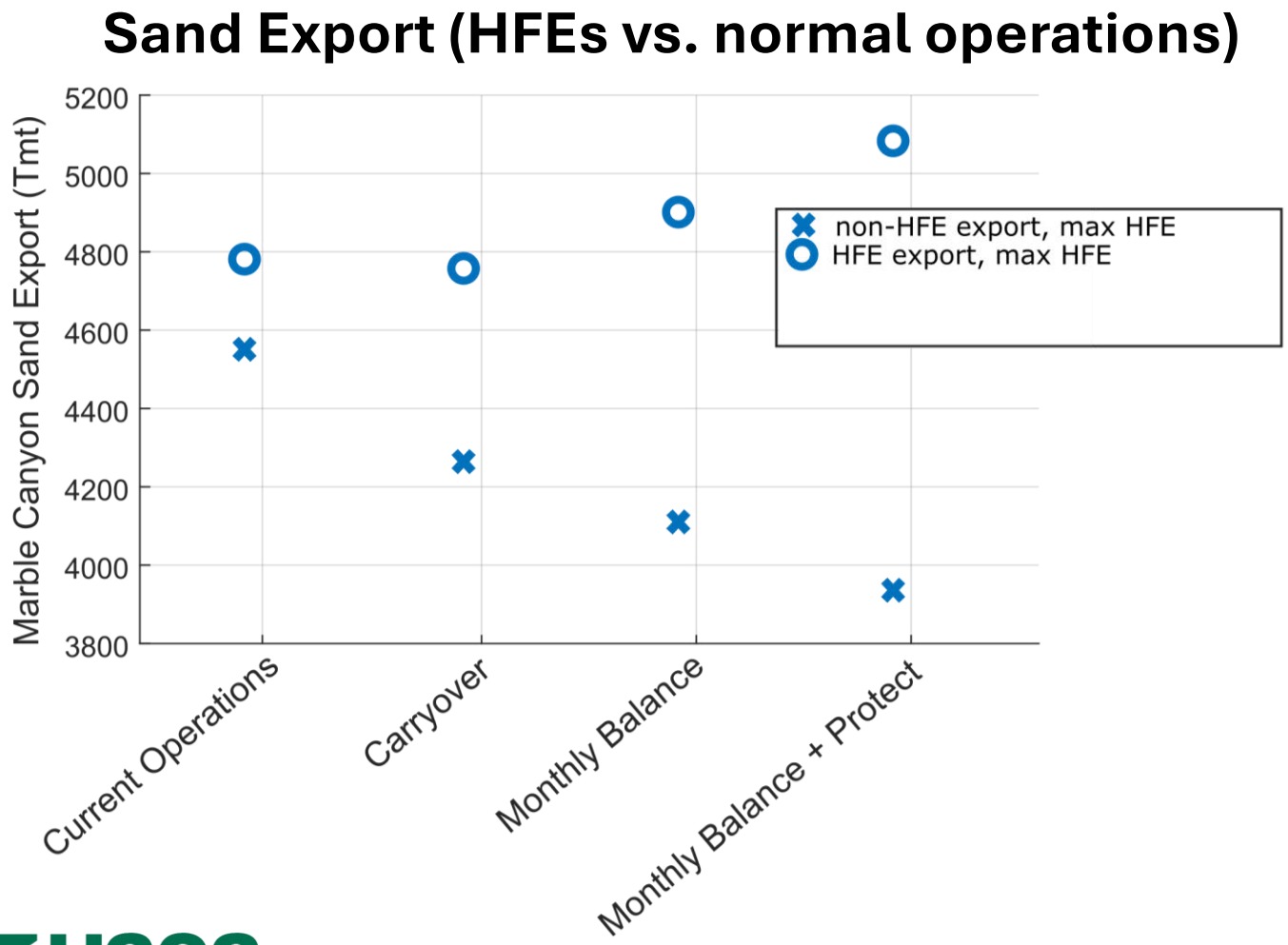

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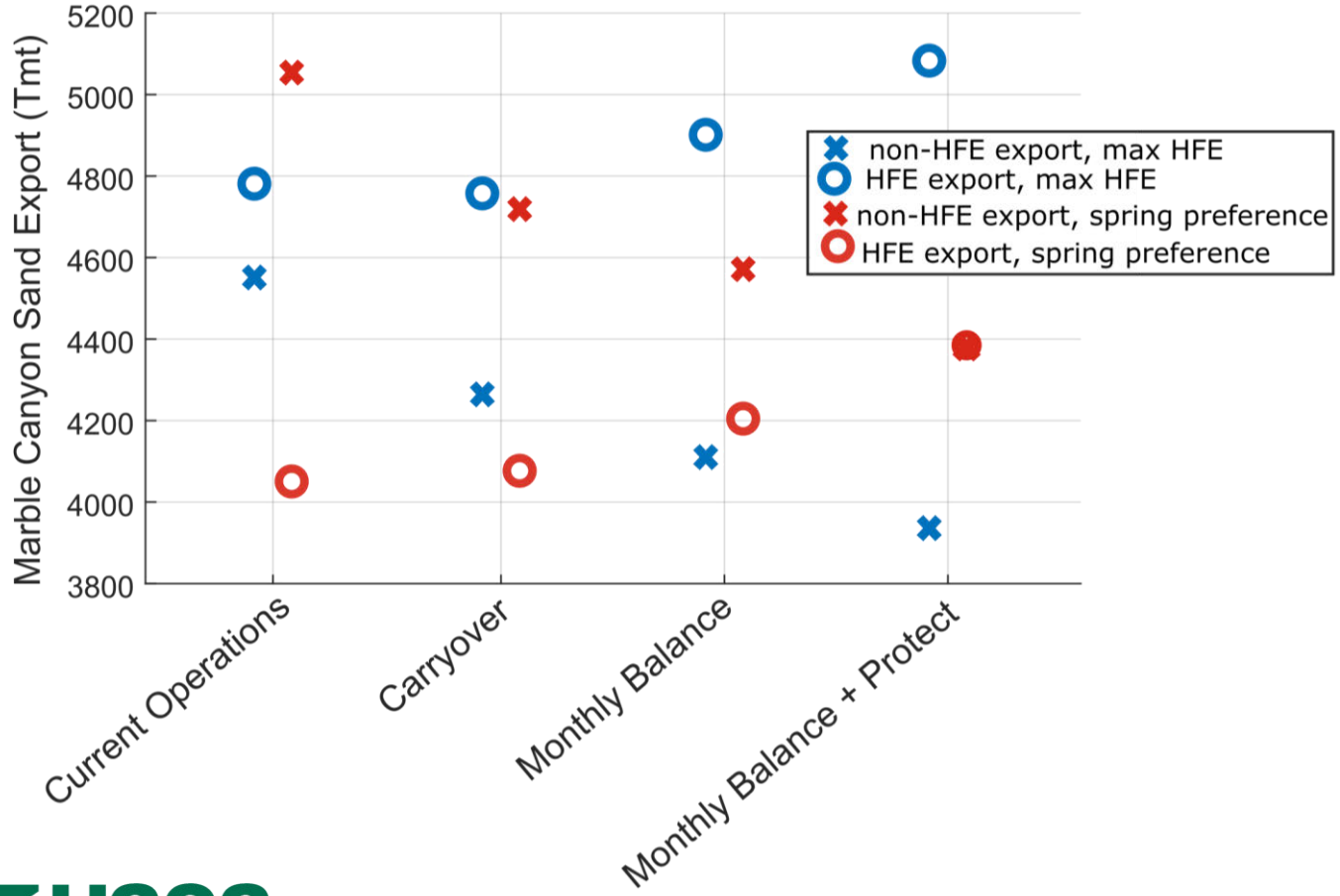
Sand Export (HFEs vs. normal operations)



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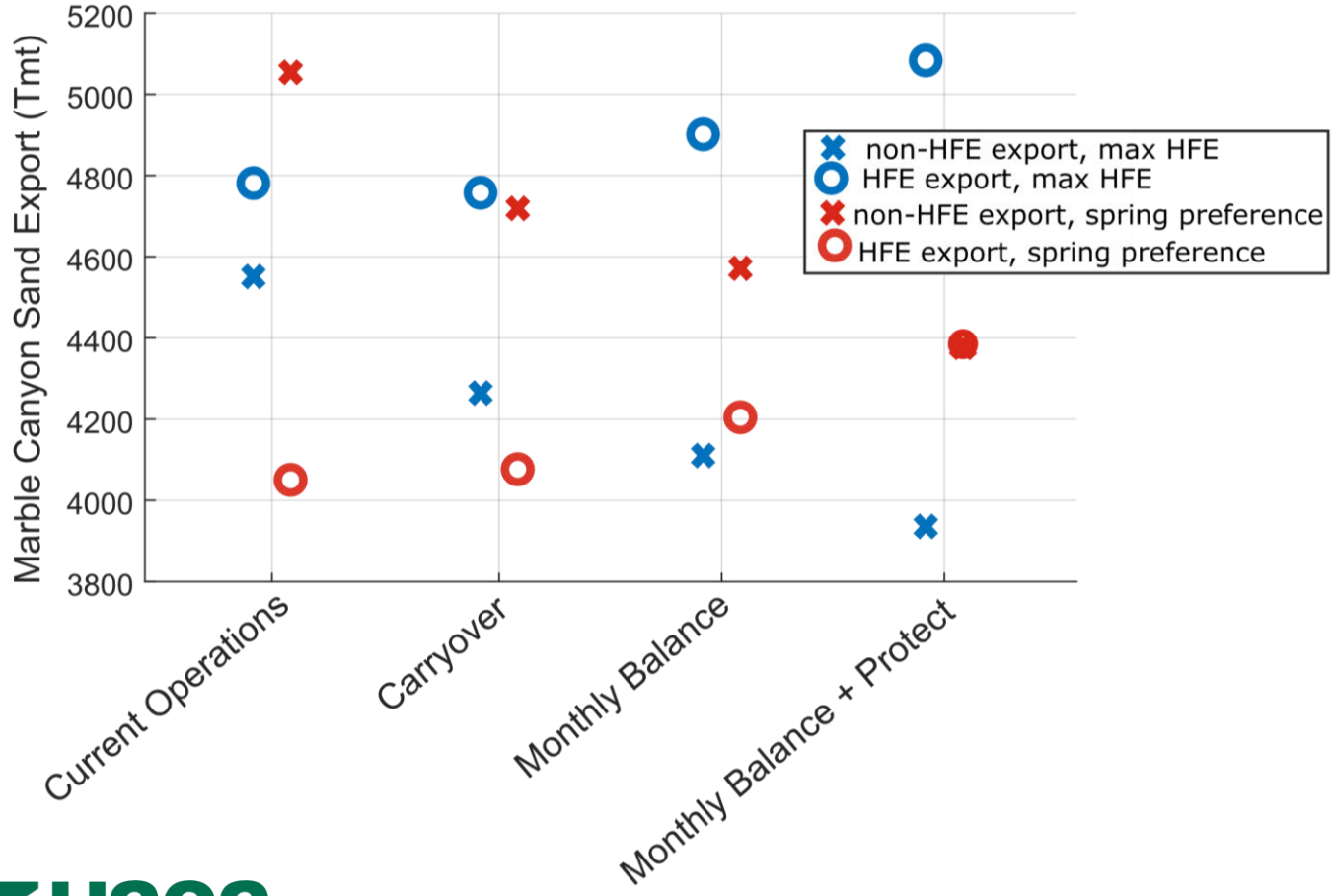
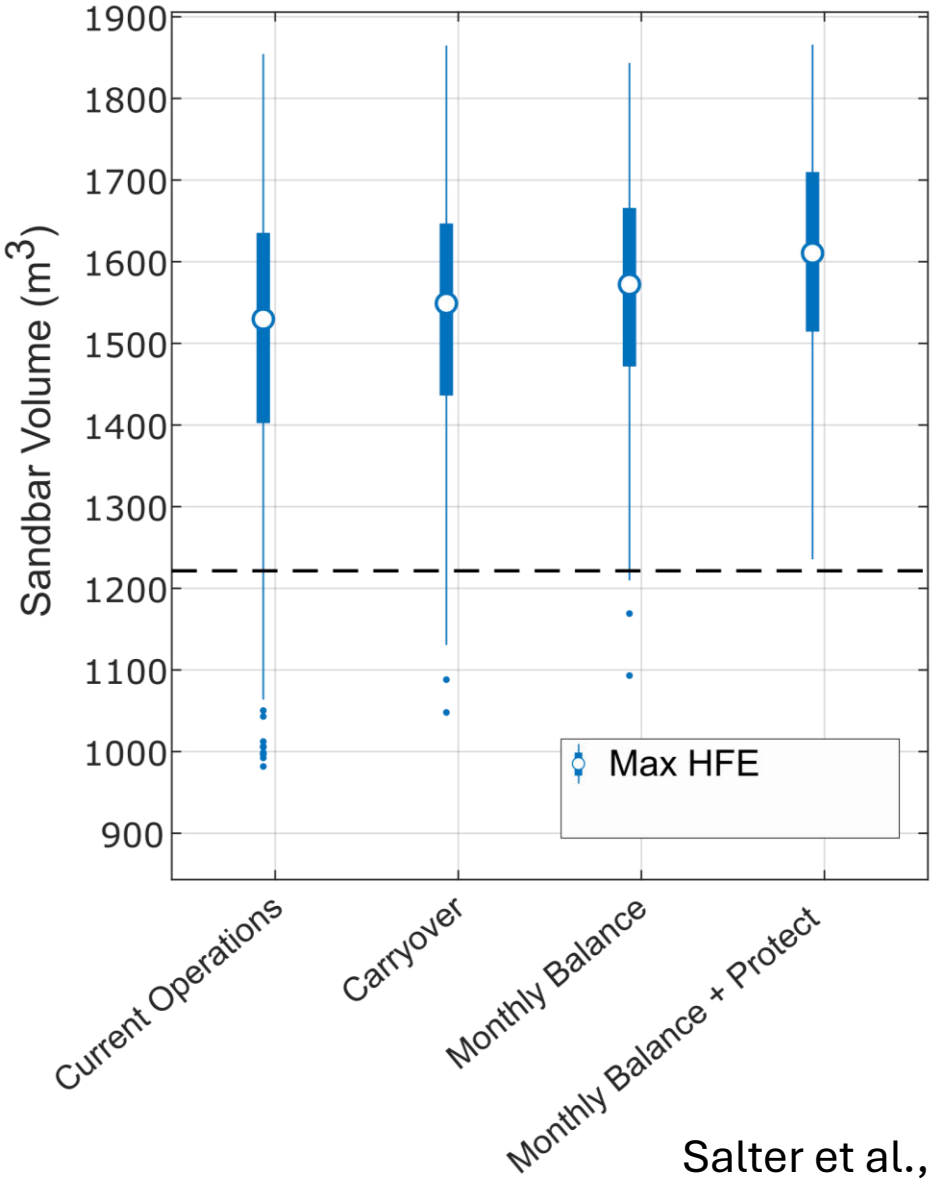


Sandbar Volume



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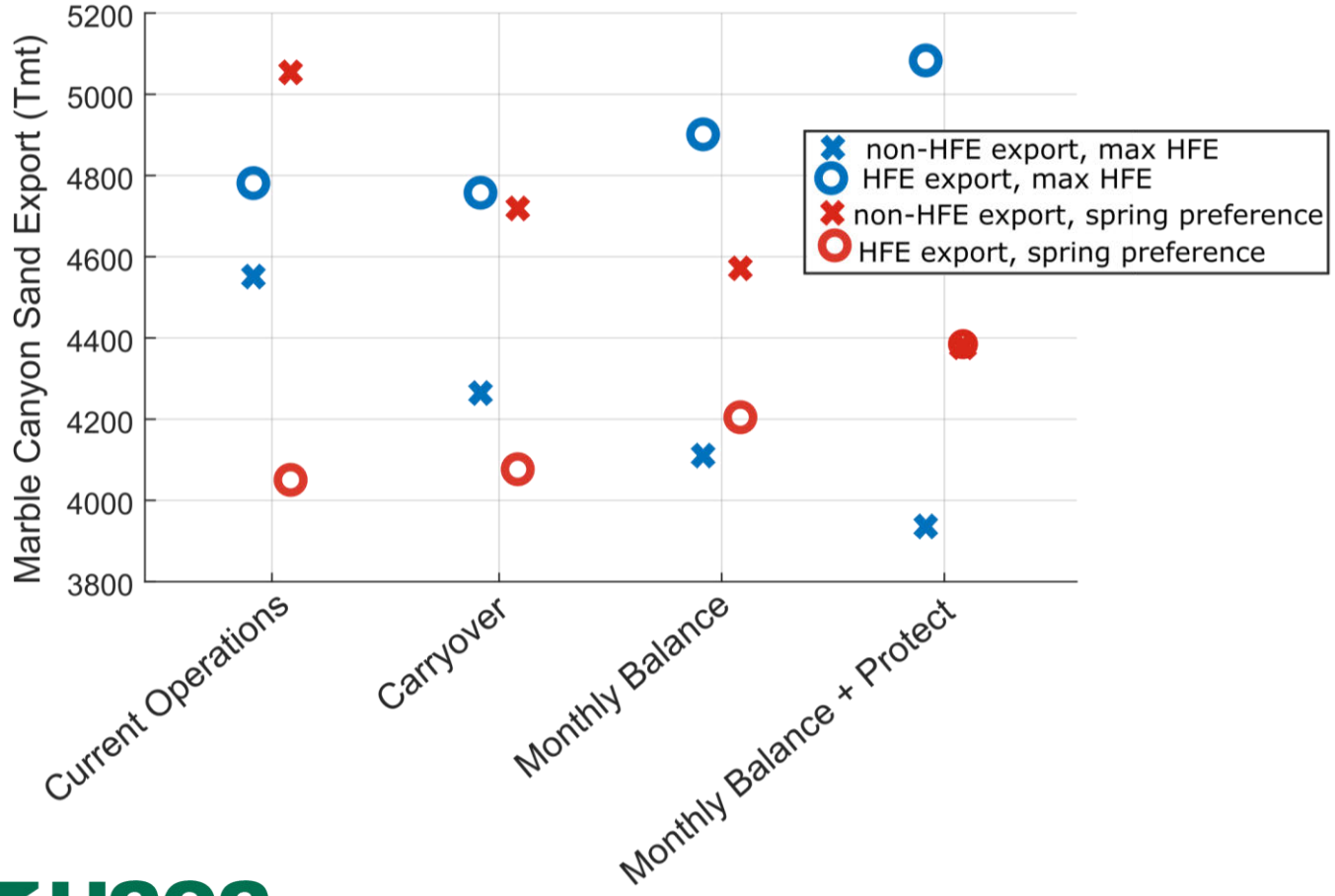

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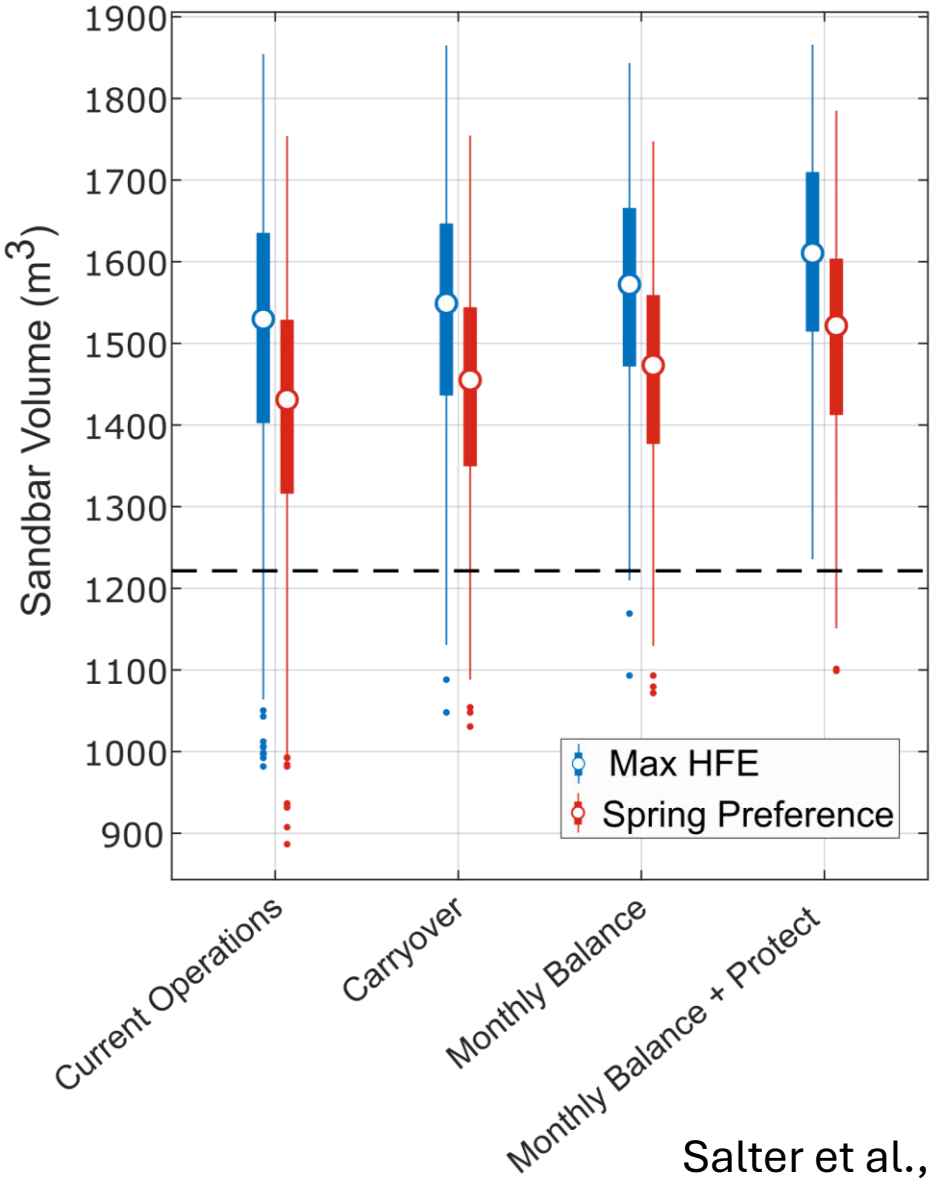

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Ongoing work for Colorado River Post-2026 Operations

1. Reclamation models reservoir elevations and releases under various alternatives. Each alternative has 400 hydrologic scenarios x 3 initial conditions.
2. We determine when HFEs can be implemented and their duration. We modify monthly volumes to accommodate HFEs and recalculate Powell elevations
3. Hourly flows (including HFEs) are produced by Western Area Power Administration
4. We model sand mass balance and sandbar volume for all alternatives and scenarios.
5. We collaborate with Reclamation to analyze alternatives (Decision Making under Deep Uncertainty framework)

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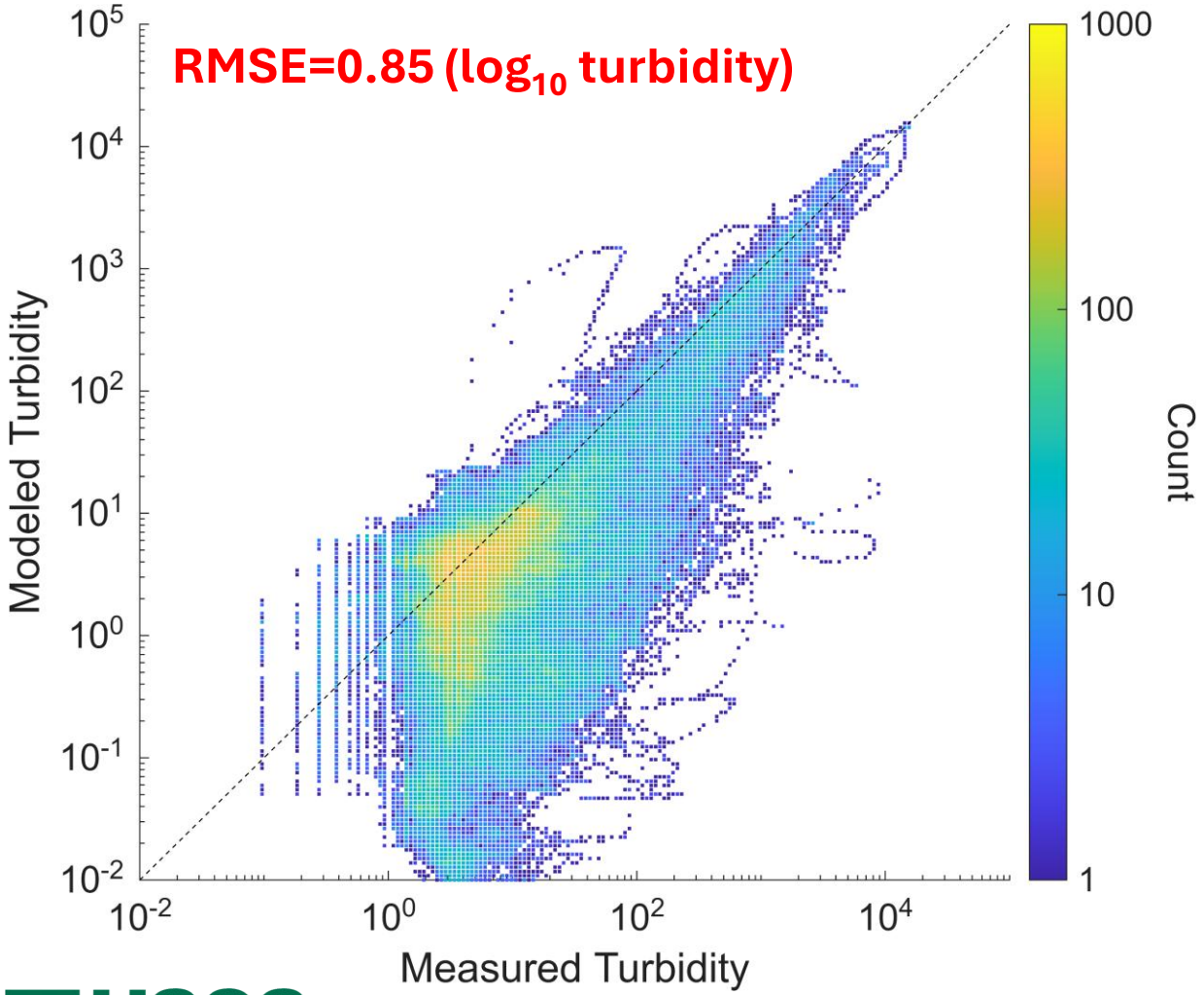
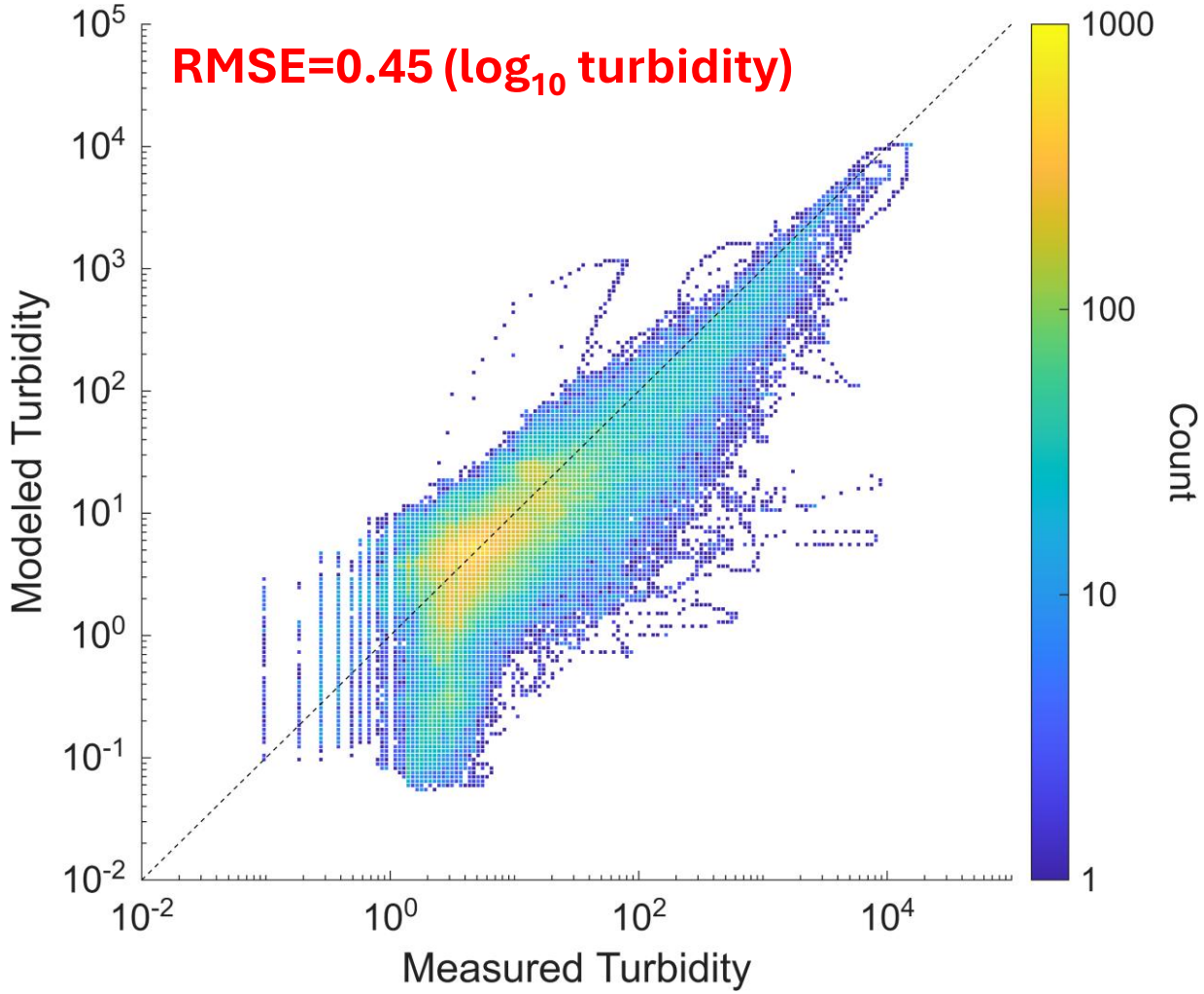
Ongoing work: Turbidity Modeling

No Settling Model



Mud as a passive tracer

Continuous Exchange Model



Settling and re-entrainment of mud depends on dam operations

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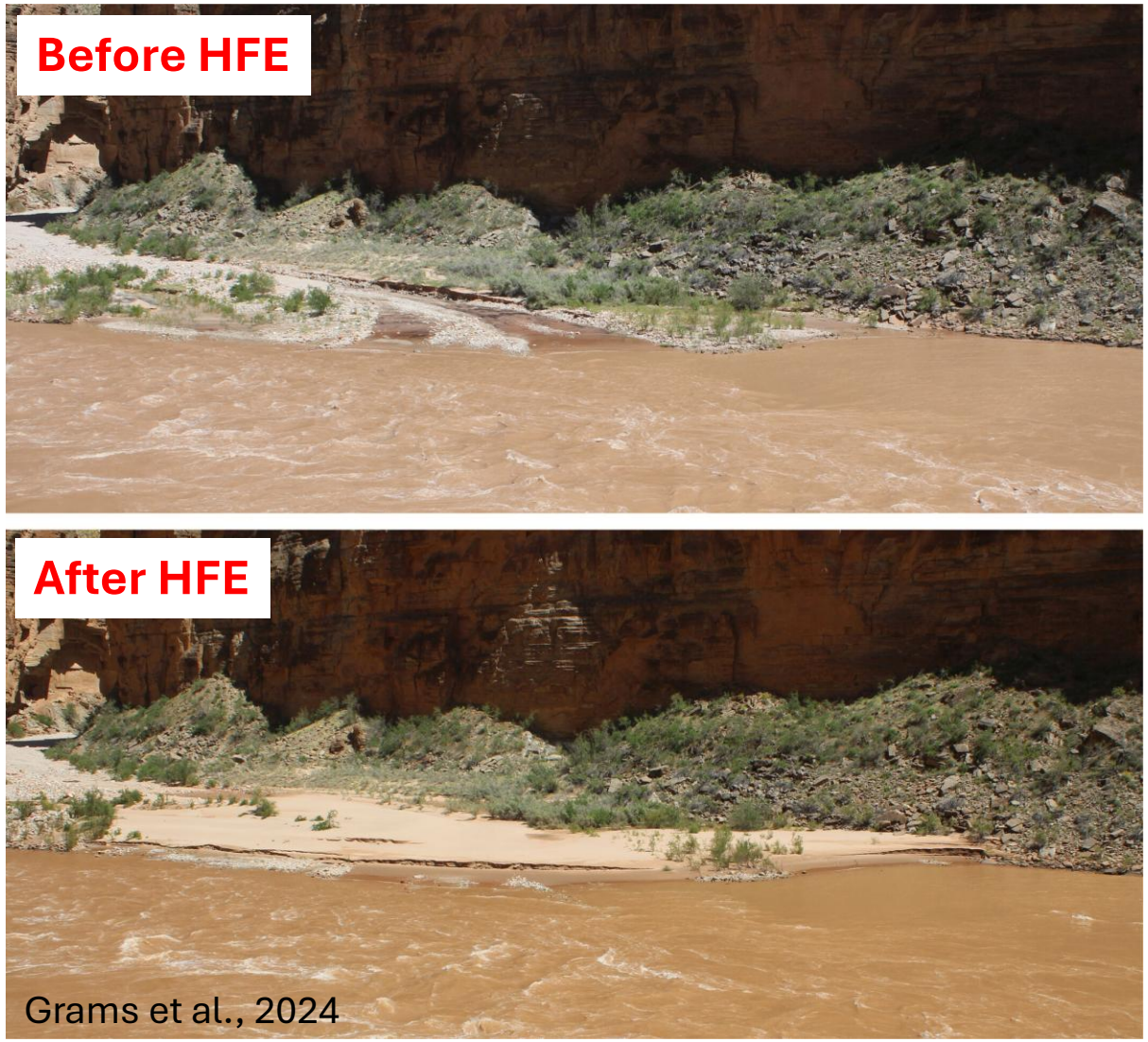
Conclusions

- We integrated sand mass balance, sandbar, and reservoir models to test reservoir operational strategies
- HFE implementation in fall leads to larger sandbars than implementation in spring, but a spring HFE is better than no HFE
- Given existing infrastructure, HFEs can be implemented more frequently if adequate Powell elevations are maintained
- Flexibility in annual releases can help avoid erosive high monthly releases, allowing for more sustainable sand management.
- Combining resource models with reservoir modeling can help develop and assess new strategies to benefit the environment, while balancing water management and societal needs



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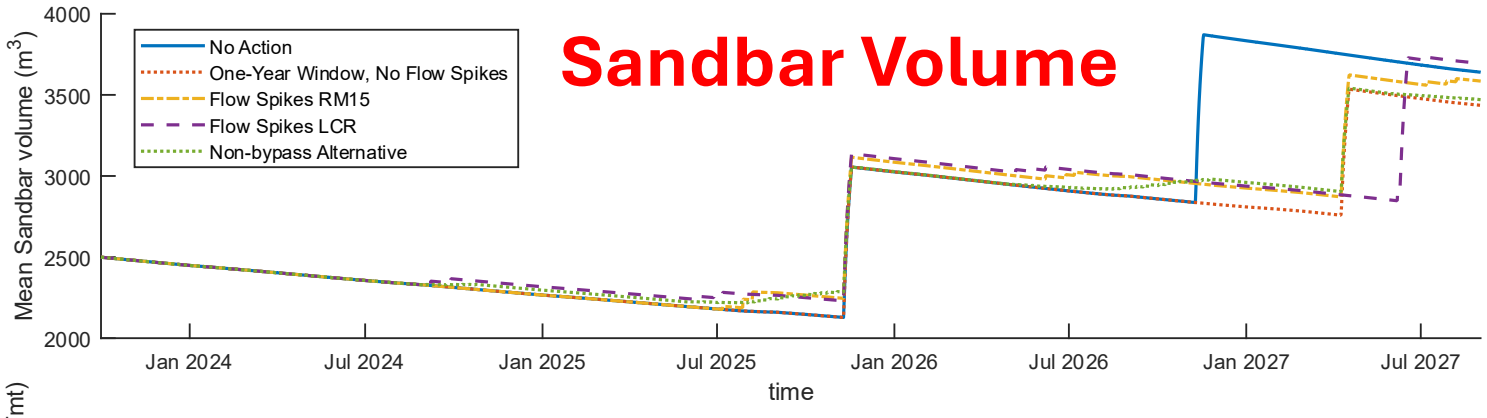
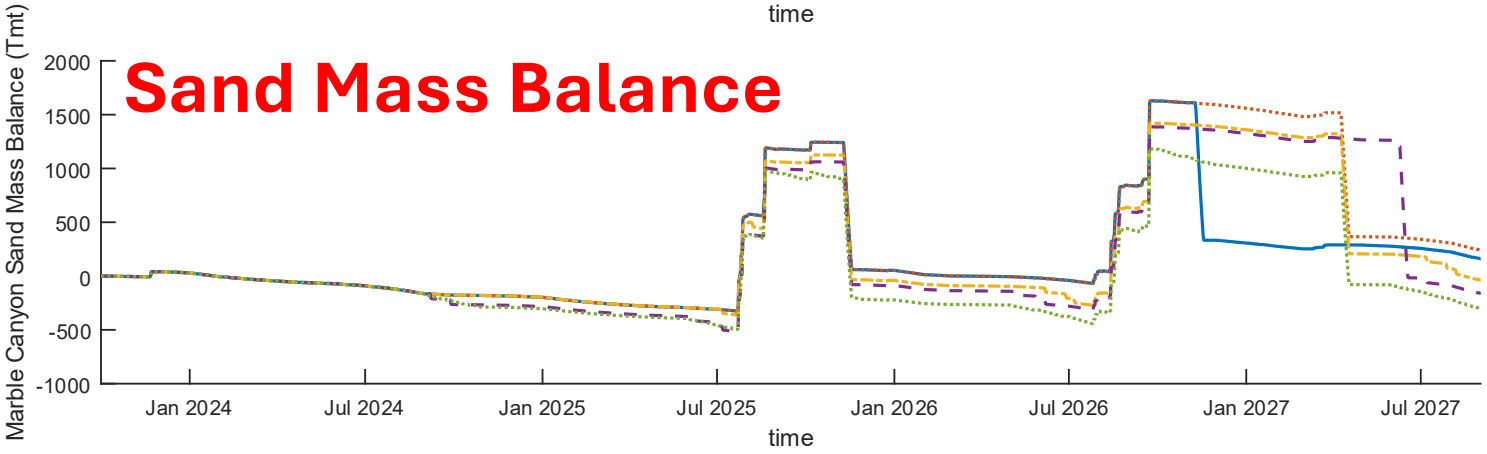
Extra Slides

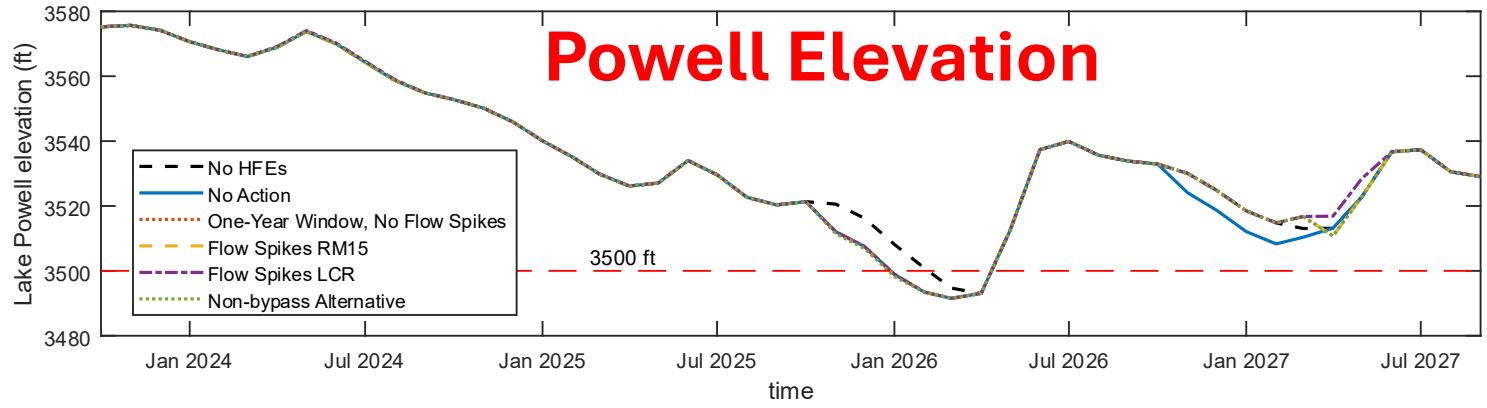
Modeling the Effect of a Change to the HFE Protocol

- The original HFE protocol allowed HFEs to be implemented in fall or spring, based on sand accumulated during the fall and spring "accounting periods"
- Despite sufficient sand, HFEs were not implemented in 2021 or 2022, in part due to low Powell elevations
- In the LTEMP SEIS (U.S. Bureau of Reclamation, 2024), we used our models to test a change to a 1-year accounting window, allowing managers flexibility for implementing HFEs
- We modeled 30 scenarios of hydrologic and sediment inputs for the original and modified HFE protocol, and interaction with smallmouth bass flows
- We determined HFE timing and duration, and effect on Lake Powell elevations

Example scenario of HFE implementation under different alternatives







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Operational Strategies: Summary

Strategy	Release Paradigm	Implementation Method	What happens?
Current operations	Annual volume set by tiers based on Powell and Mead elevations.	Monthly adjustment to meet annual volume by end of WY.	High monthly releases in balancing/equalization years cause rapid sand evacuation.
Carryover	Same as current operations.	Monthly adjustment with max flow cap. Volume above cap carried over for release in next WY.	High monthly releases avoided, better preserving sand availability.
Monthly Balance	Monthly volume set to gradually equalize storage volumes.	Gradual monthly adjustments with no rigid WY annual volume requirement.	High monthly releases avoided, better preserving sand availability.
Monthly Balance + Protect	Same as Monthly Balance adding goal to protect a selected minimum Powell target elevation.	Same as Monthly Balance, but additional release reductions when Powell elevation is very low.	High monthly releases avoided, and HFEs are implemented more frequently because adequate Powell elevations maintained, resulting in larger sandbars.

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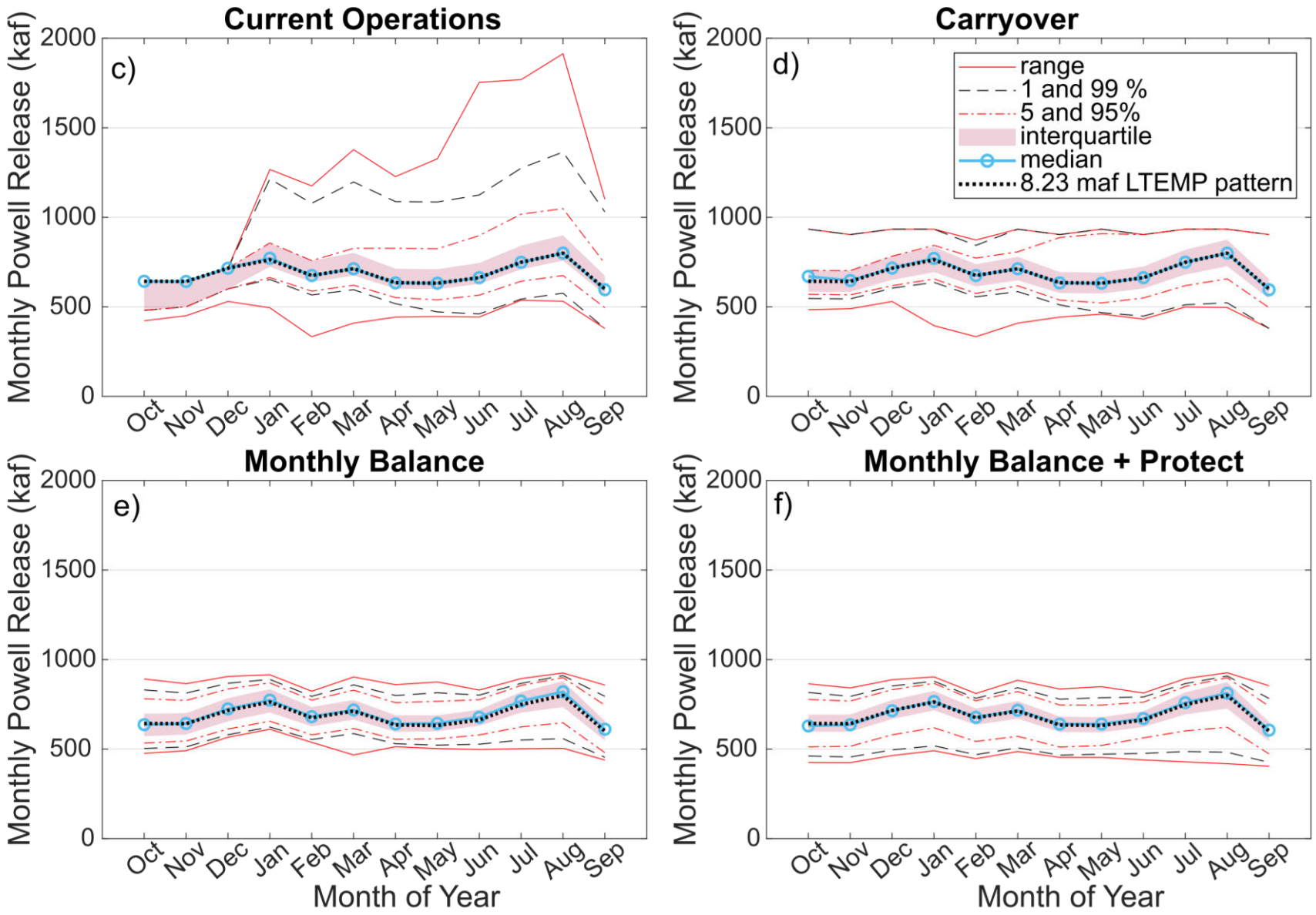
Improved ability to follow prescribed sub-annual patterns



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