BUREAU OF RECLAMATION

Post-2026 Integrated Technical Education Workgroup Session 5: Metrics, Tradeoffs, Robustness and Vulnerability

Virtual Session – September 20, 2023

The meeting will begin at 10:00 a.m., MDT

La interpretación en vivo será disponible en español. Live interpretation will be available in Spanish.

Dial In: (720) 928-9299 or (602) 753-0140; Meeting ID: 857 1121 4918

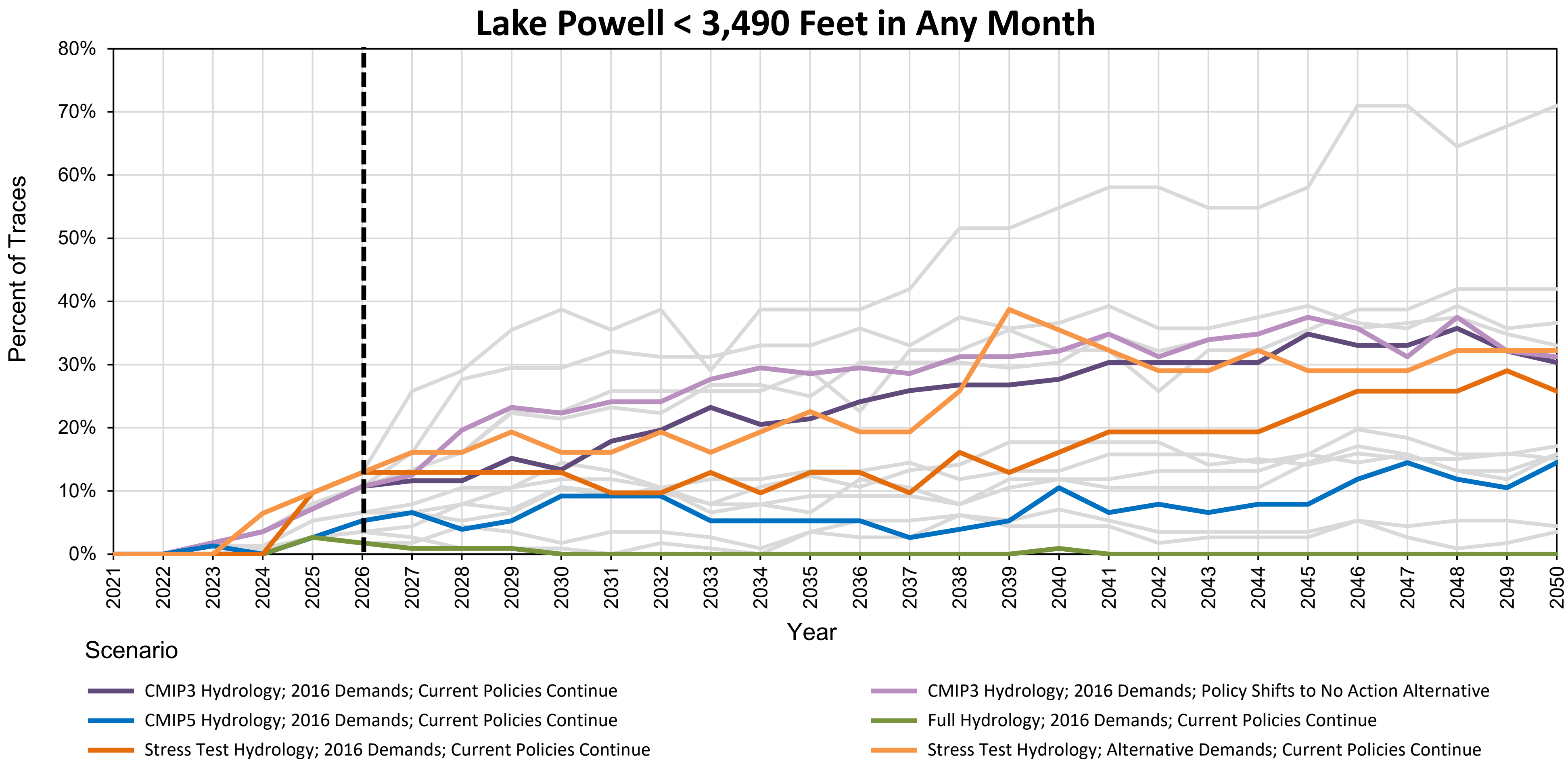
For technical support, please contact Megan Stone: megan.stone@empsi.com

Agenda

- Review of Decision Making under Deep Uncertainty (DMDU) and the Post-2026 Technical Framework
- Review of modeling and uncertainties discussed in previous ITEW sessions
- Overview of Many Objective Robust Decision Making (MORDM), the Post-2026 DMDU approach
- MORDM key concepts and the Post-2026 Web Tool
- Wrap up and future sessions

Review of DMDU and the Post-2026 Technical Framework

Long-term risk outlooks using different supply, demand, and operational assumptions*



*All projections are from August 2020 CRSS modeling with Lake Powell initial elevation of 3,592’. Lake Powell’s current elevation is ~3,574’
CMIP5 ensemble based on BCSD downscaling

Challenges of Planning under Deep Uncertainty

- Deep uncertainty (broadly defined) exists if
  1. It is impossible to determine the most appropriate planning assumptions;
  2. There is no universally agreed upon way to balance different system priorities; or
  3. Stakeholders disagree about how to best represent the system in a model.

- **In the Colorado River Basin**, 1 & 2 are major challenges[1]
  - Climate change is impacting hydrology and there is no scientific agreement on the best representation of supply
  - Future demands are uncertain
  - Water must be shared across many diverse Basin resources and interests

- Most previous planning efforts have relied primarily on achieving an acceptable level of "risk", i.e., percent of traces that have a bad outcome
  - Completely dependent on the chosen ensemble of hydrology traces and other assumptions
  - Changes over time as the system responds to new conditions
  - Can be particularly problematic when reservoirs are near critical thresholds

Decision Making under Deep Uncertainty

Decision Making under Deep Uncertainty (DMDU) methods incorporate concepts and tools that can help address the Basin's unprecedented planning challenges[1]

Key Elements

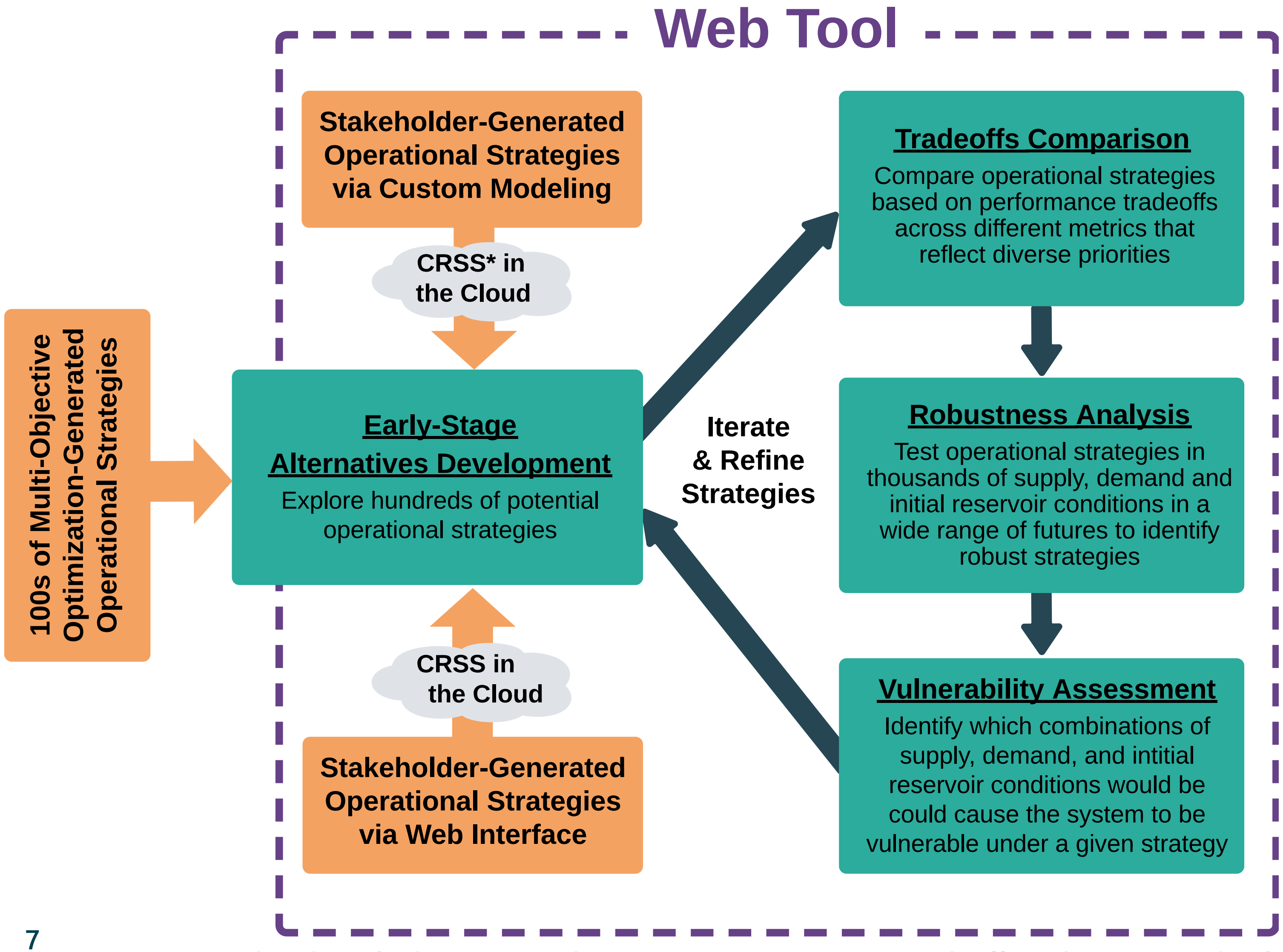
- Consider a *wide range* of future conditions without assigning likelihood beforehand
- Prioritize *robustness*, or the ability of an operational strategy to perform acceptably well in a wide range of conditions
- Assess the *vulnerability* of the system under an operational strategy: what uncertain future conditions might cause the system to have unacceptable performance?

Benefits

- Eliminates the need to choose specific hydrology and demand assumptions at the beginning of a planning process
- Helps prevent misperceptions of low risk that can accompany probabilistic analyses
- Encourages dialogue about balancing priorities and preferred vs. acceptable levels of performance
- Facilitates ability to adapt based on observable conditions as they unfold

Different frameworks can be used to apply DMDU methods. Post-2026 is using Many Objective Robust Decision Making (MORDM)[2]

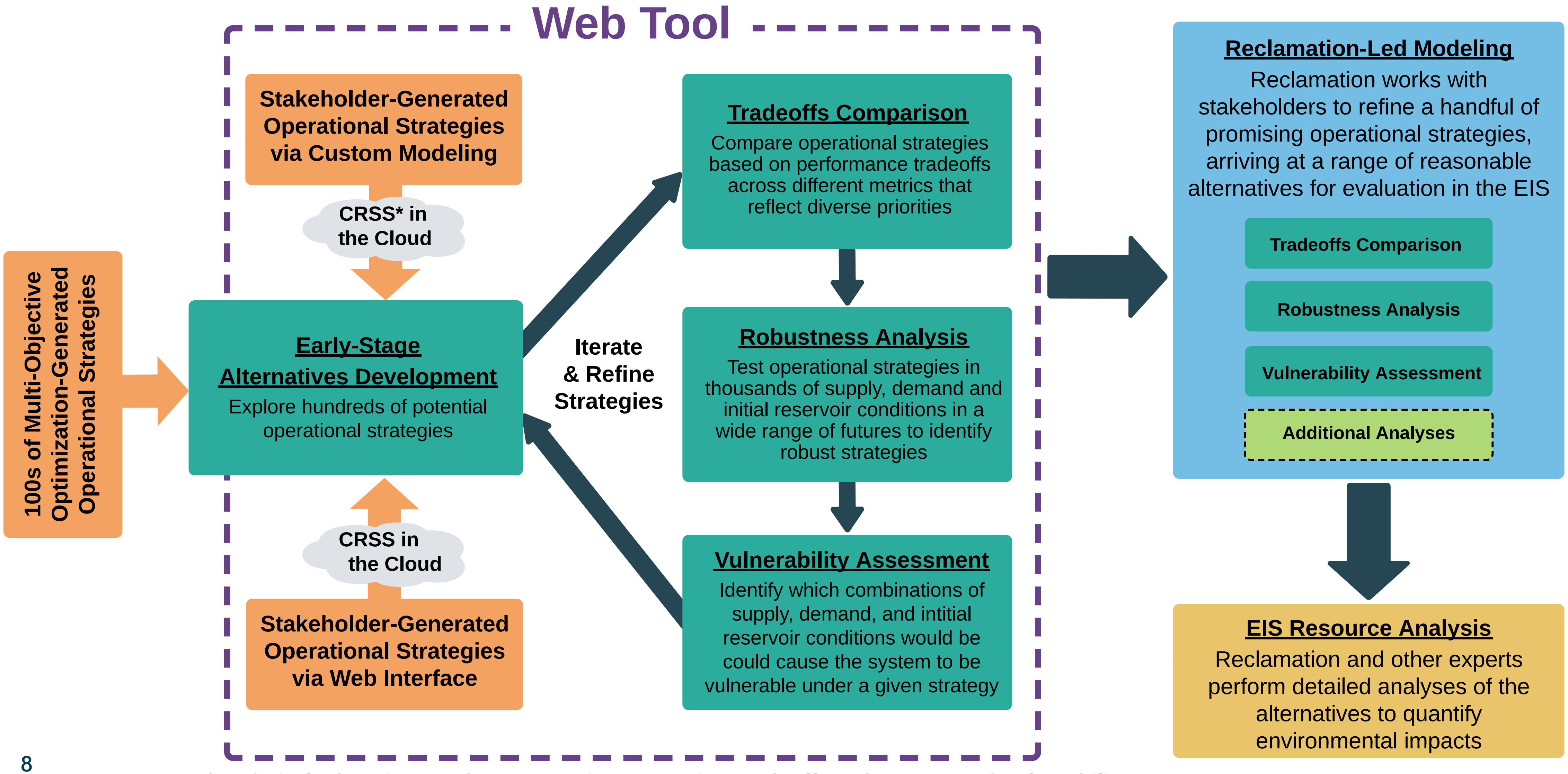
Many Objective Robust Decision Making (MORDM) in the Post-2026 Operations Exploration Web Tool



- **User-friendly interface connected to CRSS**
  - Create operational strategies that are formatted and sent to CRSS
  - Interact with output from CRSS simulations
- **Inclusive**
  - No prior experience with CRSS is required to create and explore operational strategies
  - Compatible with stakeholders who perform advanced modeling
  - Facilitates collaboration
- **Transparent**
  - Common technical platform
  - Consistent information
- **Best available science**
  - Provides in-depth DMDU information and education
- **Screening tool**
  - Important to present a variety of metrics to engage a diverse set of stakeholders and support analysis
  - Many implementation details of policies will be addressed in later stages of alternative development

*Colorado River Simulation System, Reclamation's long-term planning model

MORDM & the Web Tool in the Post-2026 Process



Review of Modeling and Uncertainty Approaches from Previous ITEW Sessions

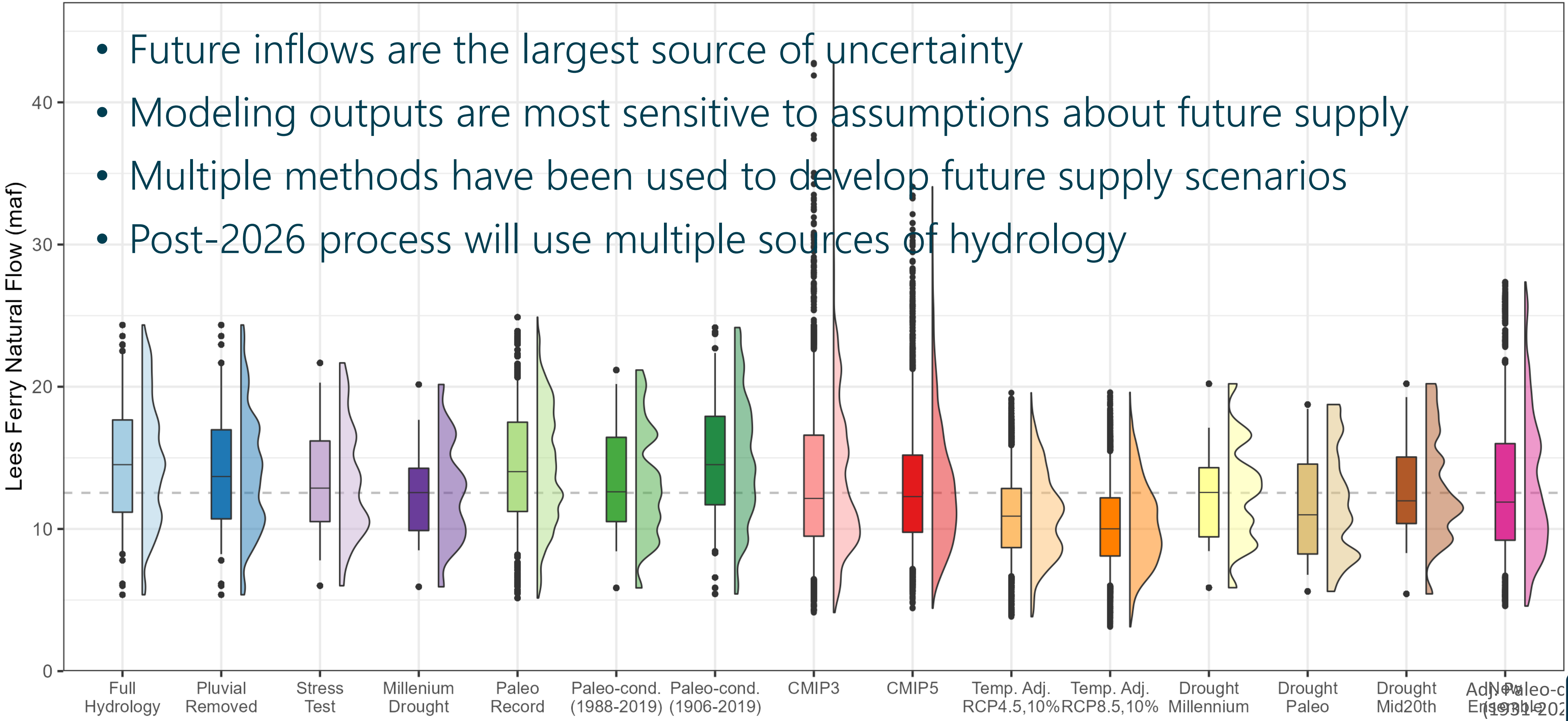
CRSS Modeling

- Colorado River Simulation System (CRSS) is Reclamation's long-term planning model that projects system conditions decades into the future
  - Upper Basin: Colorado, Green and San Juan Rivers and their major tributaries
  - Lower Basin: Mainstem Colorado and some tributaries
  - 15 major reservoirs
  - 500+ water users
- Inputs
  - Hydrology (supply)
  - Demands
  - Initial reservoir conditions
  - Model operating rules (policy/operational strategy)
- Outputs
  - Reservoir levels
  - Water use
  - River flow
  - Energy generation

Sourced from Groves, et. al. (2013) Adapting to a Changing Colorado River: Making Future Water Deliveries More Reliable Through Robust Management Strategies

Hydrology: Largest Uncertainty, Many Ensembles

- Future inflows are the largest source of uncertainty
- Modeling outputs are most sensitive to assumptions about future supply
- Multiple methods have been used to develop future supply scenarios
- Post-2026 process will use multiple sources of hydrology



Hydrologic Uncertainty and DMDU

Not Enough

Single ensemble using only summary statistics

- Familiar
- Only one story
- Every ensemble has limitations
- Risk calculations are unreliable
- Ranges of reservoir elevations are not very useful

→

Appropriate in some contexts

Multiple ensembles using only summary statistics

- Somewhat familiar
- Multiple stories provide more context but not enough under deep uncertainty
- Every ensemble has limitations
- Risk calculations are unreliable and now competing
- Ranges of reservoir elevations are not very useful

→

Good

Multiple ensembles analyzed as individual traces

- New
- Multiple ensembles provide more traces and more data
- Individual trace analysis provides more information
- Ensembles may not cover range of uncertainty completely or evenly

→

Great in DMDU analysis

Multiple carefully chosen ensembles analyzed as individual traces

- New
- Multiple ensembles provide more traces and more data
- Chosen and generated ensembles ensure individual traces provide range and coverage to support reliable analysis

Advantage/Drawback/Limitation

Demands: Sources and Representation in the Post-2026 Web Tool

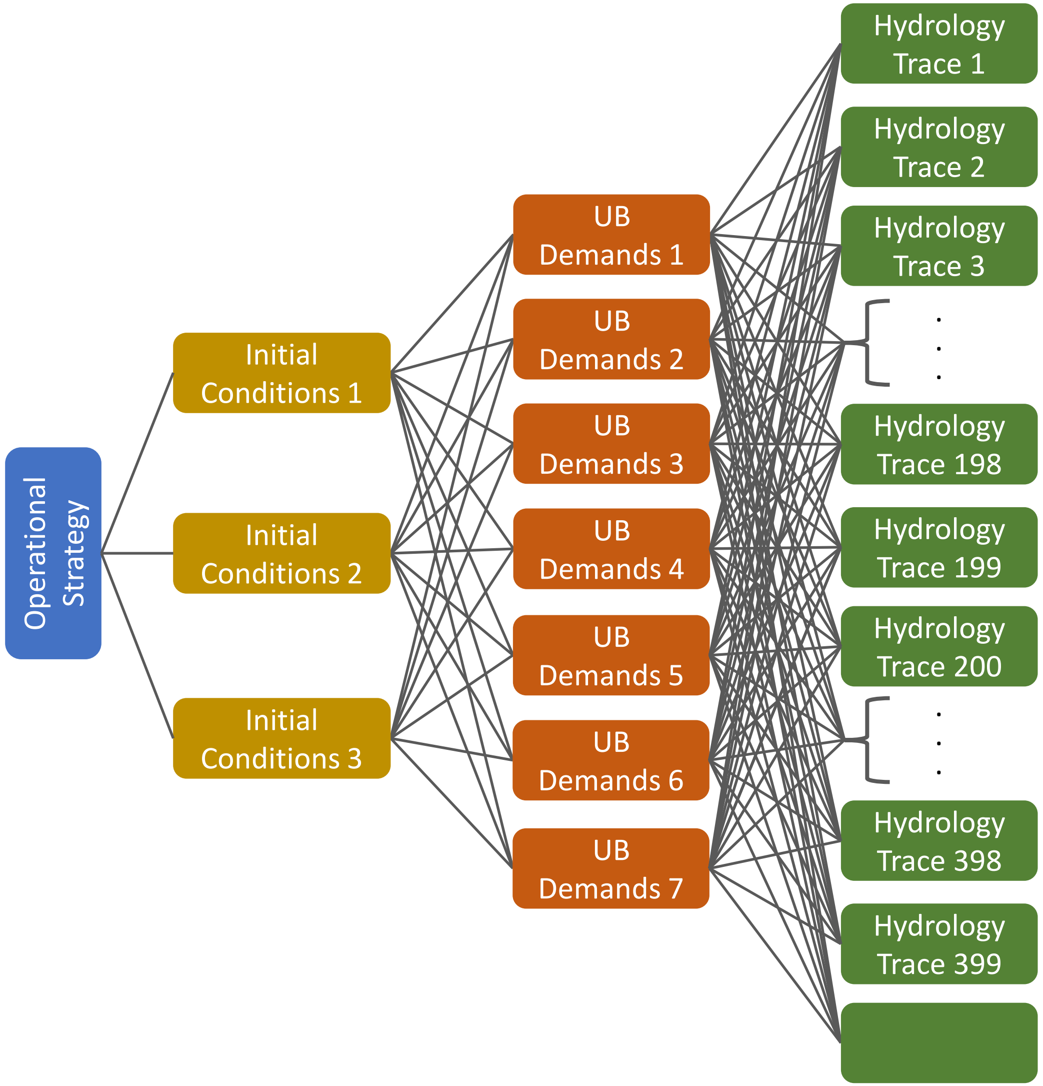
- Upper Basin Demands
  - Standard projections for Upper Basin demands are derived from decadal schedules developed by the Upper Colorado River Commission and the 2018 Tribal Water Study
  - Uncertainty in Upper Basin demands will be represented by using multiple inputs
    - Time-varying *scenarios*, or assumption-based stories projecting how demands may evolve in the future
    - Steady-state demand levels which do not represent any assumptions and are useful for filling in the range of potential future conditions
- Lower Basin Demands
  - Derived from the 2007 Interim Guidelines Final Environmental Impact Statement schedules with minimal updates made at the request of specific Lower Basin water users
  - Uncertainty in Lower Basin demands will be represented as different "levels" represented by modeling operational strategies with different structures and volumes of delivery reductions
  - Distribution of Lower Basin delivery reductions will not be represented in Web Tool modeling

Initial Conditions and Post-2026 Web Tool Futures

- Initial conditions have a large impact on the range of potential system conditions in the first 5-10 years of a simulation, especially at Lake Powell and Lake Mead

- 2027 system conditions are uncertain, so Post-2026 will use multiple sets of initial conditions during early stages of alternatives development

- Fully combining all sets of initial conditions, Upper Basin demands, and hydrology traces = 8,400 futures



Post-2026 Lake Powell and Lake Mead Operations

- Early stage of Post-2026 alternatives development is an opportunity to explore a range of operational strategies that are different from the current paradigm
- Many diverse interests and competing performance priorities
- Lake Powell and Lake Mead operations have complex interactions and impacts on different types of system performance
- More information on alternative operational paradigms will be provided at next the ITEW session

Lake Powell

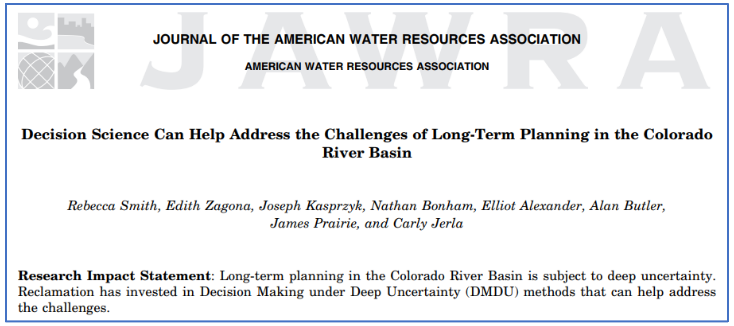
Elevation (feet)	Operation According to the Interim Guidelines	Live Storage (maf)[1]
3,700	**Equalization Tier** Equalize, avoid spills, or release 8.23 maf	24.3
3,636-3,666 (2008-2026)	**Upper Elevation Balancing Tier[3]** Release 8.23 maf; if Lake Mead < 1,075 feet, balance contents with a min/max release of 7.0 and 9.0 maf	15.5-19.3 (2008-2026)
3,575	**Mid-Elevation Release Tier** Release 7.48 maf; if Lake Mead < 1,025 feet, release 8.23 maf	9.5
3,525	**Lower Elevation Balancing Tier** Balance contents with a min/max release of 7.0 and 9.5 maf	5.9
3,490		4.0
3,370		0

Lake Mead

Elevation (feet)	Operation According to the Interim Guidelines	Live Storage (maf)[1]
1,220	**Flood Control Surplus or Quantified Surplus Condition** Deliver > 7.5 maf	25.9
1,200 (approx.)[2]	**Domestic Surplus or ICS Surplus Condition** Deliver > 7.5 maf	22.9 (approx.)[2]
1,145	**Normal or ICS Surplus Condition** Deliver ≥ 7.5 maf	15.9
1,075	**Shortage Condition** Deliver 7.167[4] maf	9.4
1,050	**Shortage Condition** Deliver 7.083[5] maf	7.5
1,025	**Shortage Condition** Deliver 7.0[6] maf Further measures may be undertaken[7]	5.8
1,000		4.3
895		0

Many Objective Robust Decision Making (MORDM) Overview and Key Concepts

Decision Making Under Deep Uncertainty (DMDU)



JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION

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Decision Science Can Help Address the Challenges of Long-Term Planning in the Colorado River Basin

Rebecca Smith, Edith Zagona, Joseph Kasprzyk, Nathan Bonham, Elliot Alexander, Alan Butler, James Prairie, and Carly Jerla

Research Impact Statement: Long-term planning in the Colorado River Basin is subject to deep uncertainty. Reclamation has invested in Decision Making under Deep Uncertainty (DMDU) methods that can help address the challenges.

Smith et al. (2022)

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https://www.deepuncertainty.org/

Our DMDU research program includes:

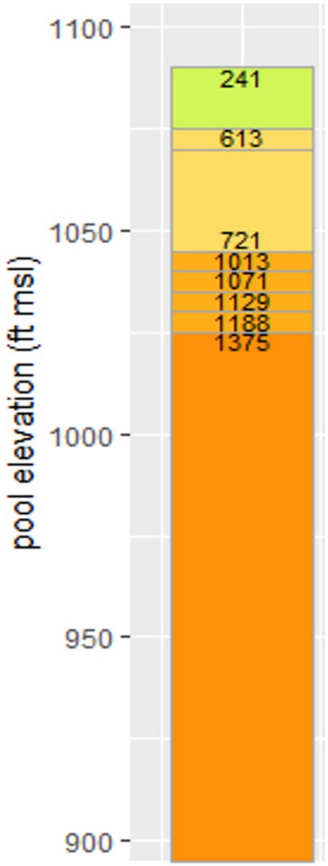
- Combating **deep uncertainty** by sampling (rather than assuming) plausible futures
- Collaborative, **multi-objective** optimization frameworks with trusted simulation models
- Reporting interactive estimates of **robustness** across a wide range of futures
- Statistical learning for characterizing **vulnerabilities** and failure states

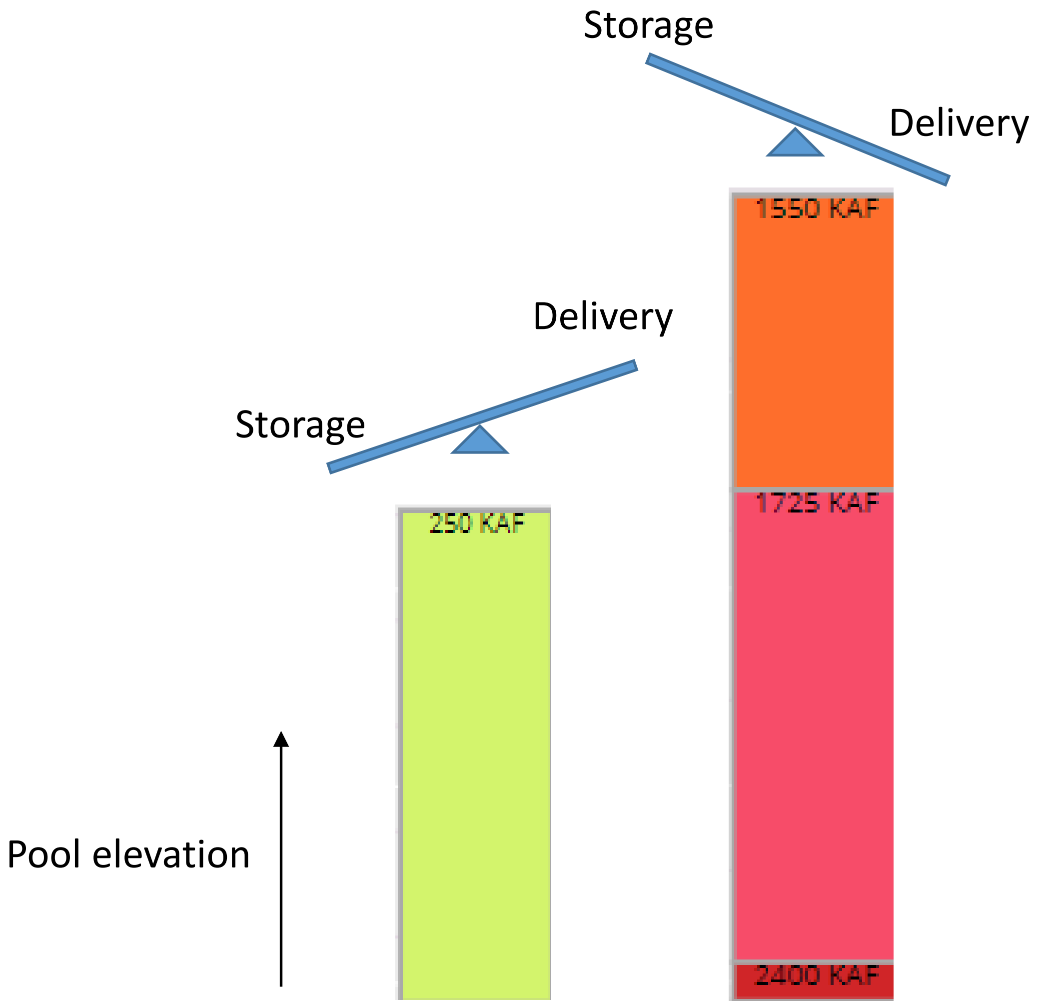
In a collaboration with Reclamation for more than 6 years, we:

- Survey multiple methods and compare them
- Develop improvements to the methods that are relevant to the CRB

Existing DMDU methods are appropriate for looking at a small number of strategies

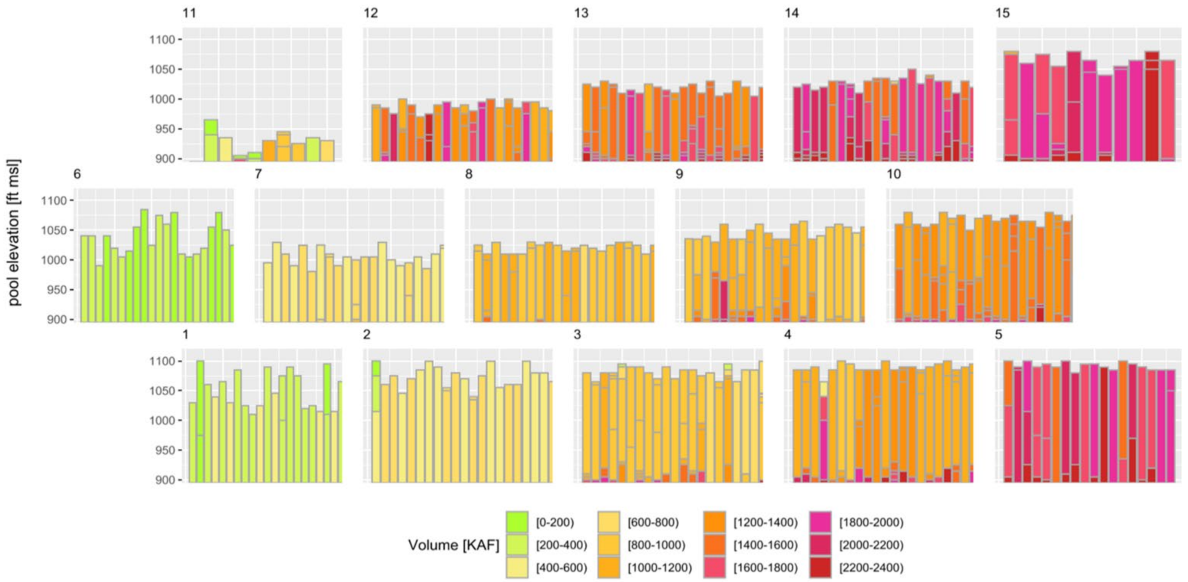
Lake Mead Tiers under
2007 Interim Guidelines and DCP





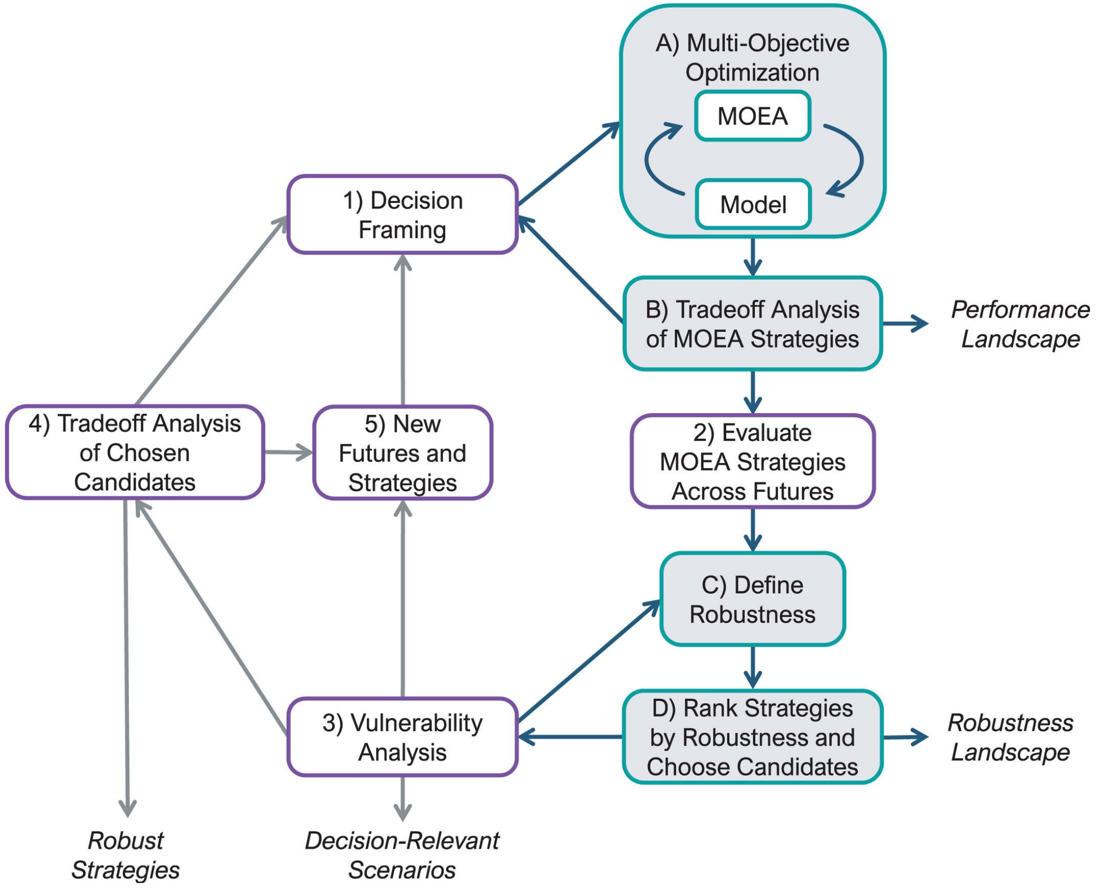
Expanding to a larger number of strategies, additional methods were needed

Considering multiple goals



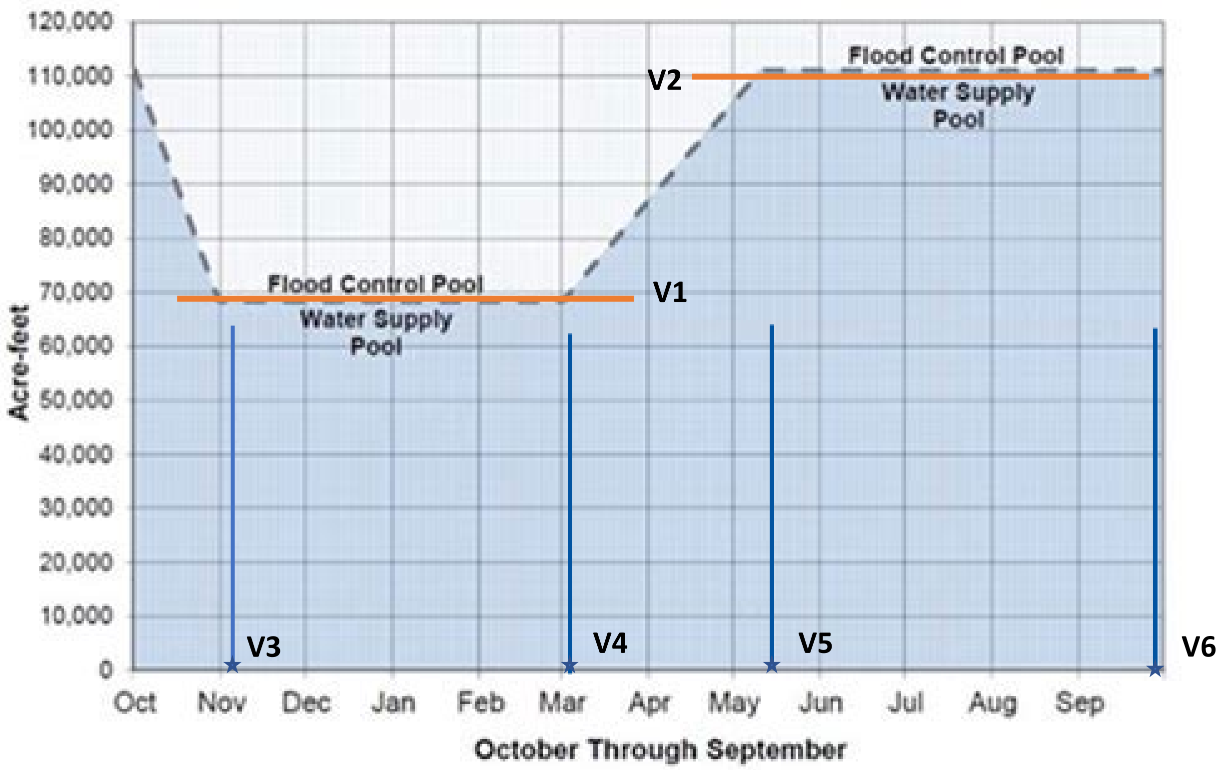
Generating many new strategies that balance performance goals differently

From a literature review of DMDU methods, Many Objective Robust Decision Making (MORDM) was chosen for the Colorado River Basin



- MORDM is built on RDM methods that broadly sample uncertainties.
- Uses a Multi-Objective Evolutionary Algorithm (MOEA) to optimally balance the conflicting goals (see next slide)
  - Objectives are chosen from a larger set of metrics to best enable the algorithm to find diverse strategies
  - MOEA discovers many strategies that demonstrate diverse compromises between the metrics. These strategies help demonstrate what types of decisions and outcomes are possible.

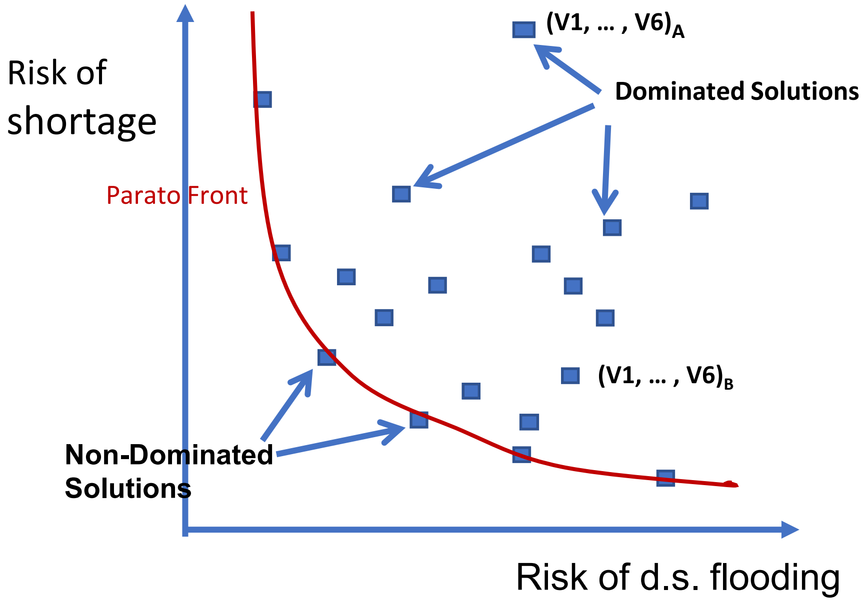
Example: multi-objective optimization of a flood control strategy



Problem: Find the best set of values of these 5 variables

Criteria (objectives):
Minimize risk of flooding downstream
Minimize risk of water supply shortage

How to solve: run many simulations, e.g. POR, with combinations of values of the variables.
Compute the values of the objectives for each.



1. Eliminate dominated solutions
2. Identify non-dominated solutions to consider for the policy
3. Decision-making: what tradeoff to accept between the objectives?

Automate by using MOEA
Multi-Objective Evolutionary Algorithm

A search algorithm that generates many sets of variables and identifies the pareto optimal solutions

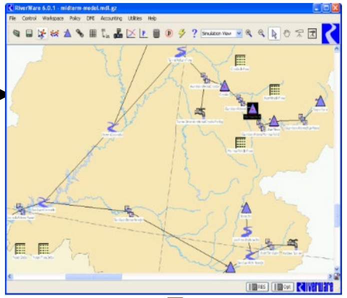
Borg-RiverWare Wrapper

Software that exchanges information between simulator RiverWare and the MOEA Borg to find a non-dominated (pareto optimal) set of solutions

Borg is an MOEA developed by David Hadka and Patrick Reed at Pennsylvania State University and licensed by The Pennsylvania State University. See borgmoea.org

Hydrology and Demand Scenarios for probabilistic or risk based objectives

RiverWare Simulation



Model Outputs

Results of single runs or multiple runs

Values of Decision Variables
Operations, policy, infrastructure options

V1, V2, ……Vn

Borg-RiverWare

Objectives
Measurements of system performance

f_1 f_2 f_3

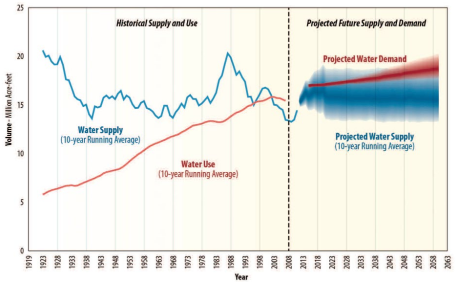
Constraints
limits of acceptable performance

$f_1 < n_1$, $f_2 < n_2$, $f_3 > n_3$

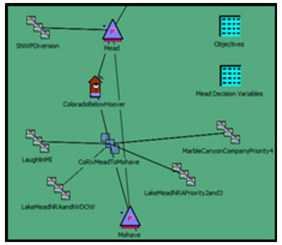
Borg
Evaluates solution; searches for better solution

Coupling Colorado River Simulation System (CRSS) with Borg-MOEA

Supply & Demand Scenarios



CRSS Model



Model Outputs

Results of single runs or multiple runs

Values of decision Variables
Operations, policy, infrastructure options

V1, V2, ……Vn

Borg-RiverWare

Objectives
Measurements of system performance

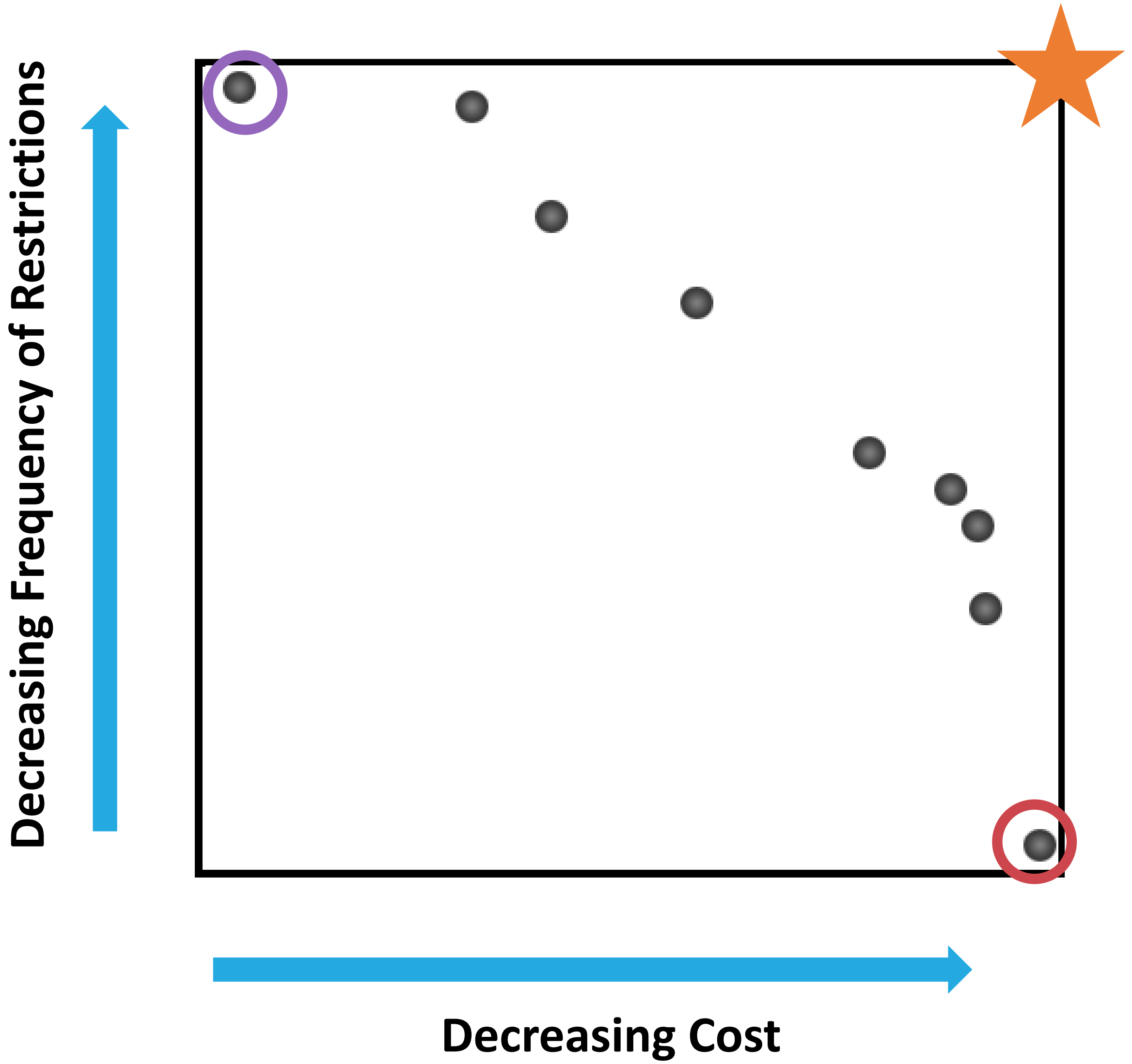
$f_1 \quad f_2 \quad f_3$

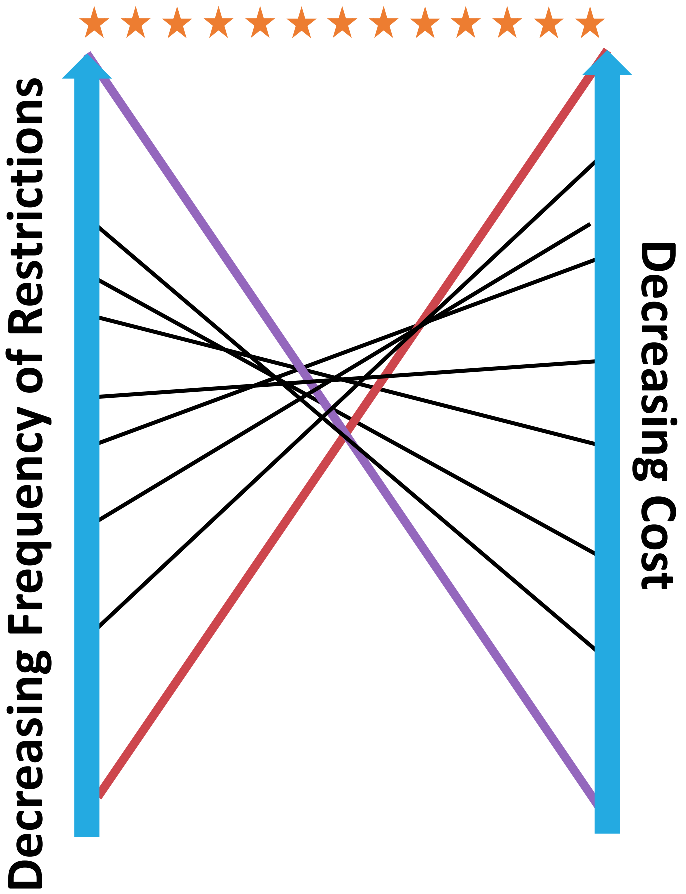
Constraints
limits of acceptable performance

$f_1 < n_1 , \; f_2 < n_2 , \; f_3 > n_3$

Borg
Evaluates solution; searches for better solution

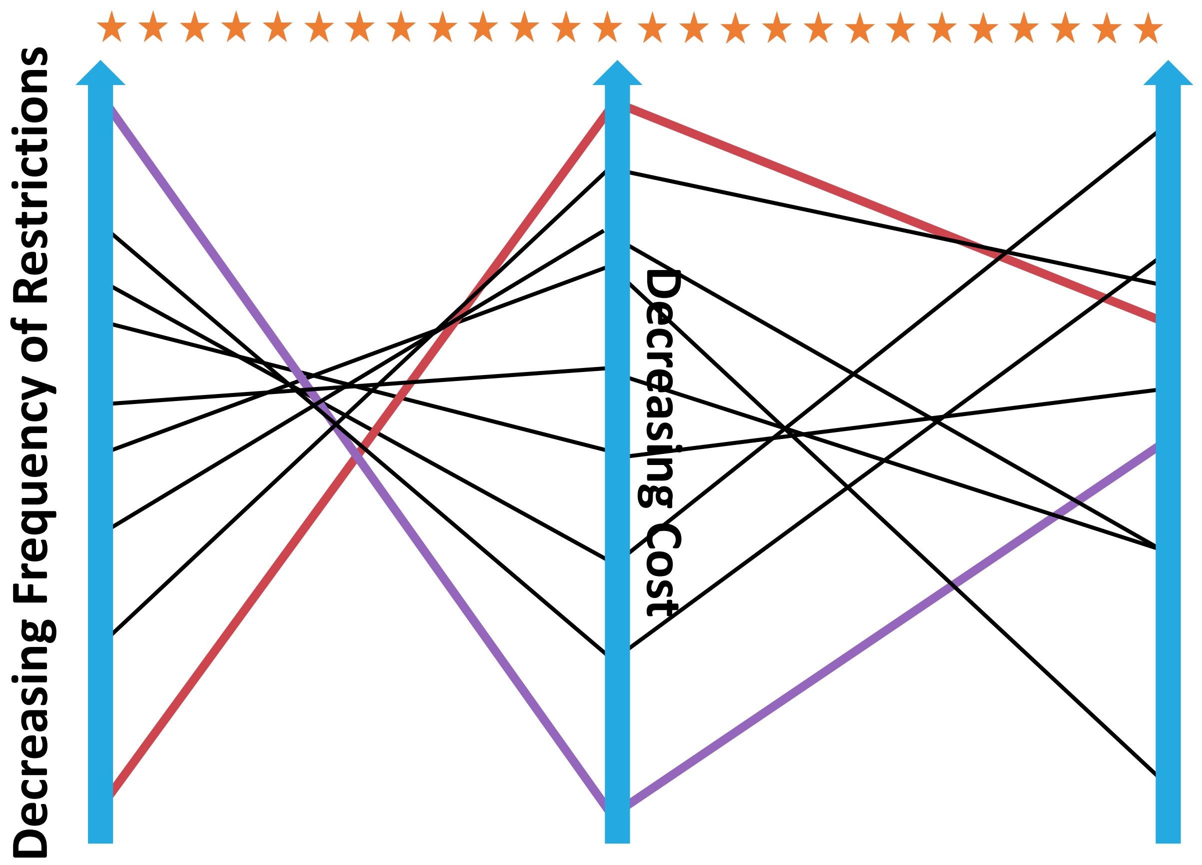
Tradeoff analysis with parallel coordinates



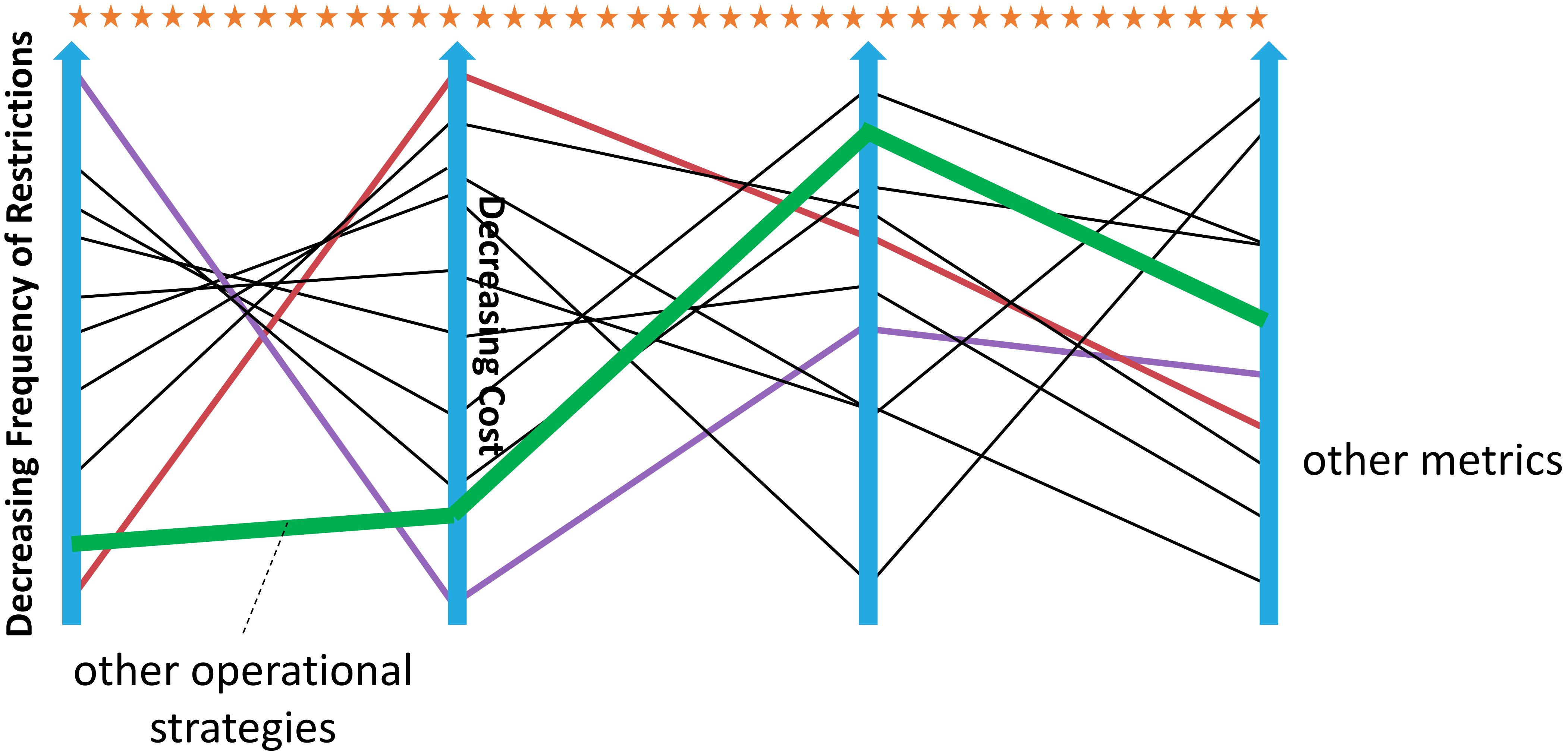


Each operational strategy captures a different set of compromises

Expanding the number of dimensions considered…



Parallel coordinates can visualize other metrics and operational strategies, not only those considered by MOEA

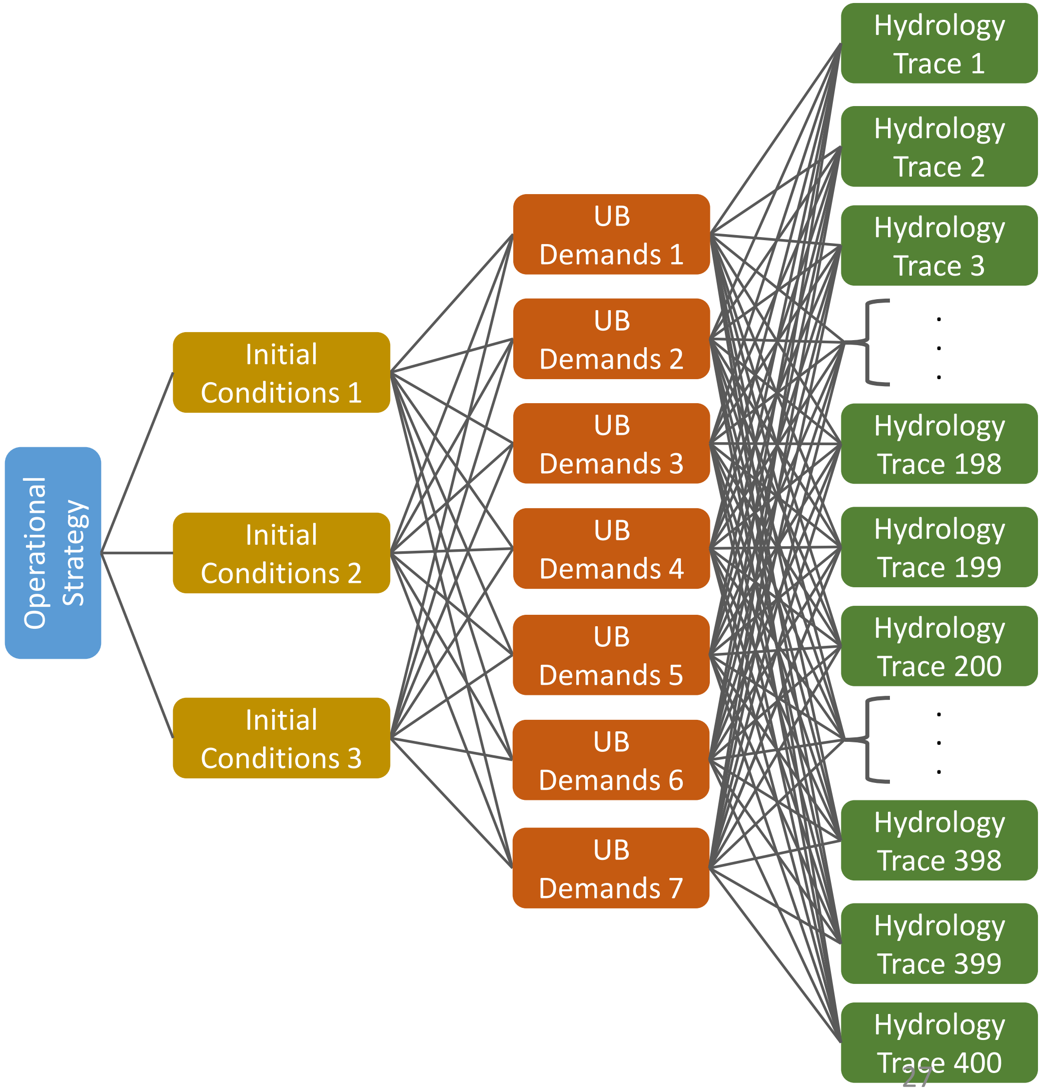


Because of deep uncertainty, it is important to evaluate performance of operational strategies over many possible futures

- There is no “correct” or broadly agreed-upon set of assumptions for hydrology, demands and initial conditions for long-term planning in the Colorado River Basin, and climate change projections show a wide range of potential hydrologic futures

- It is necessary to test an operational strategy in a wide range of plausible futures (e.g., 8,400 in the Post-2026 Web Tool)
    - Different data structure and meaning compared to ensemble-based modeling
    - Probability-based statistics are not appropriate

- Need to provide specific definitions for DMDU analytical methods (robustness)



Robustness is a property of how well an operational strategy performs over many possible futures

Example:

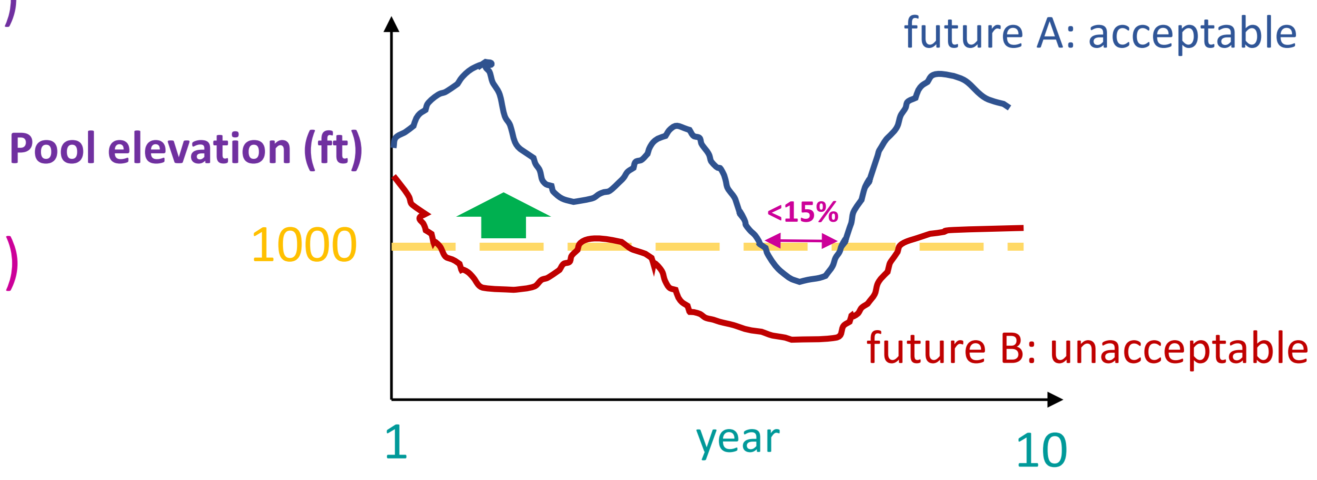
- Strategy A has acceptable performance in 60% of futures
- Strategy B has acceptable performance in 80% of futures
- Strategy B is more robust than policy A

But, how is acceptability defined?

Helpful to use a handful of futures to demonstrate

The definition of acceptability has multiple parts

- Measure (e.g., Lake Mead pool elevation)
- Preferred Direction (stays above)
- Threshold (1000 feet)
- Frequency (greater than 85% of the time)
- Time Horizon (over a 10 year period)



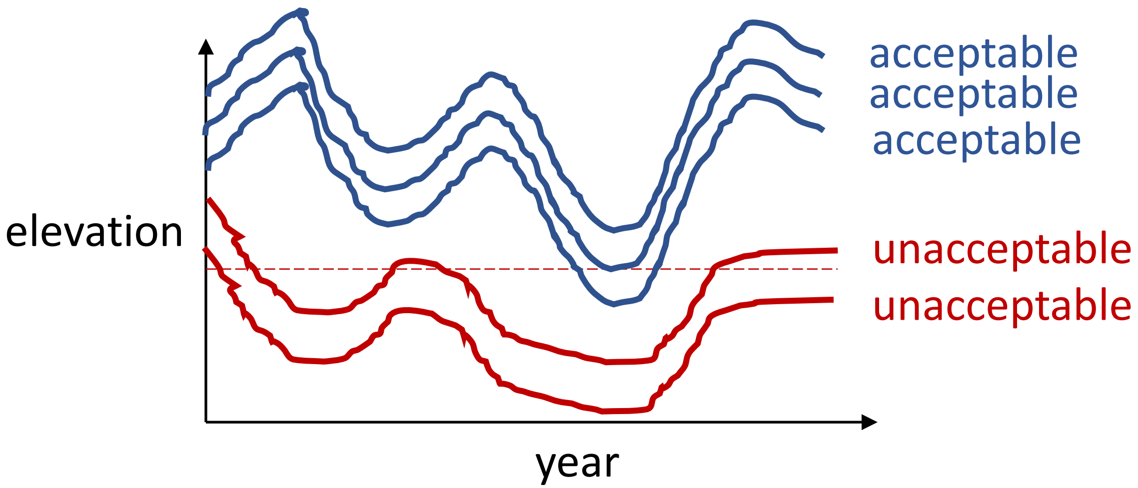
i.e., A strategy is acceptable in a future if
Mead Pool Elevation stays above 1000 feet
greater than 85% of the next 10 years.

If not, unacceptable.

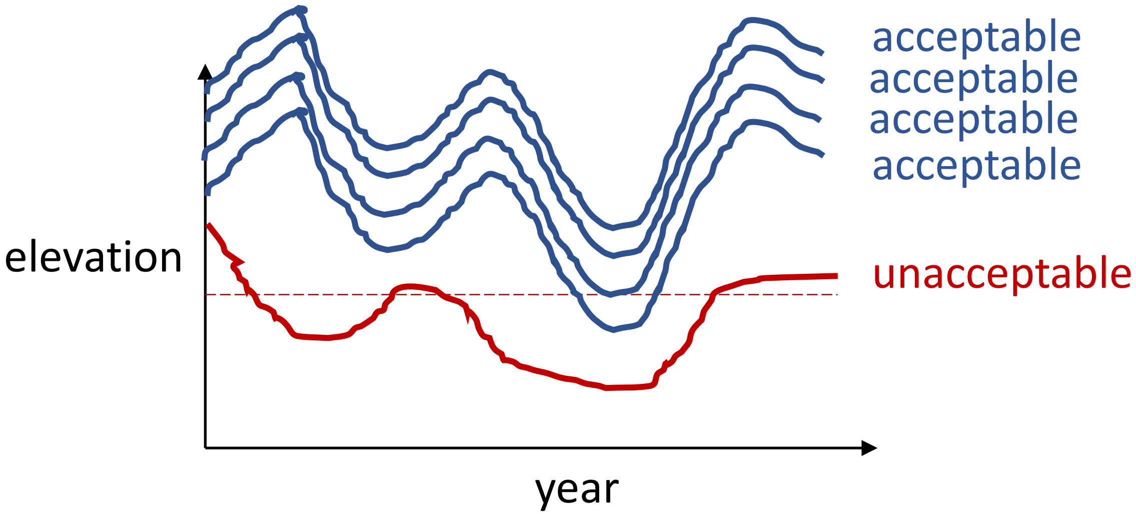
Robustness is the percentage of futures where the strategy is considered acceptable

(note: robustness considers hundreds-to-thousands of futures. Here, we use 5 for demonstration.)

Strategy A robustness: 60%



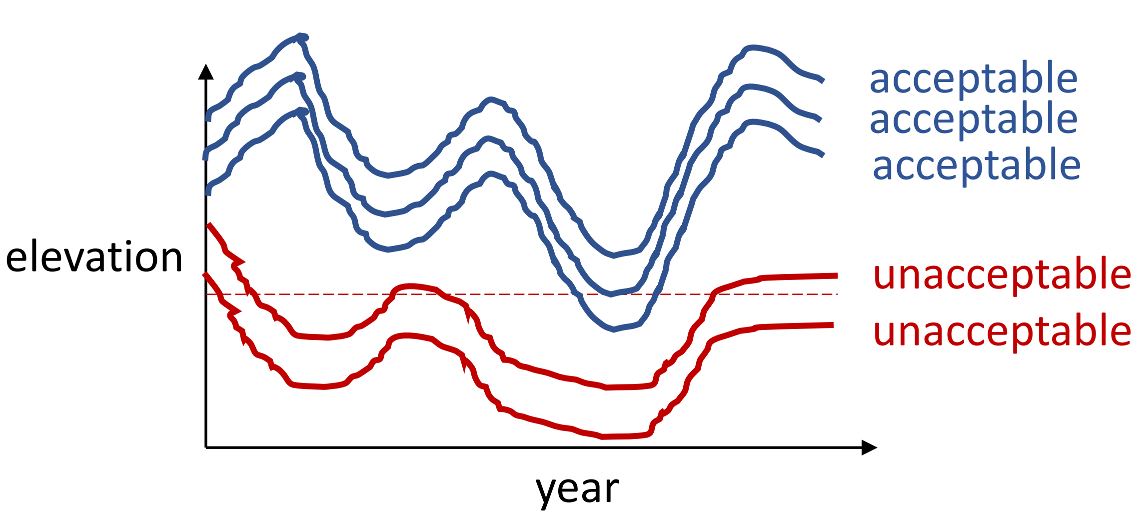
Strategy B robustness: 80%



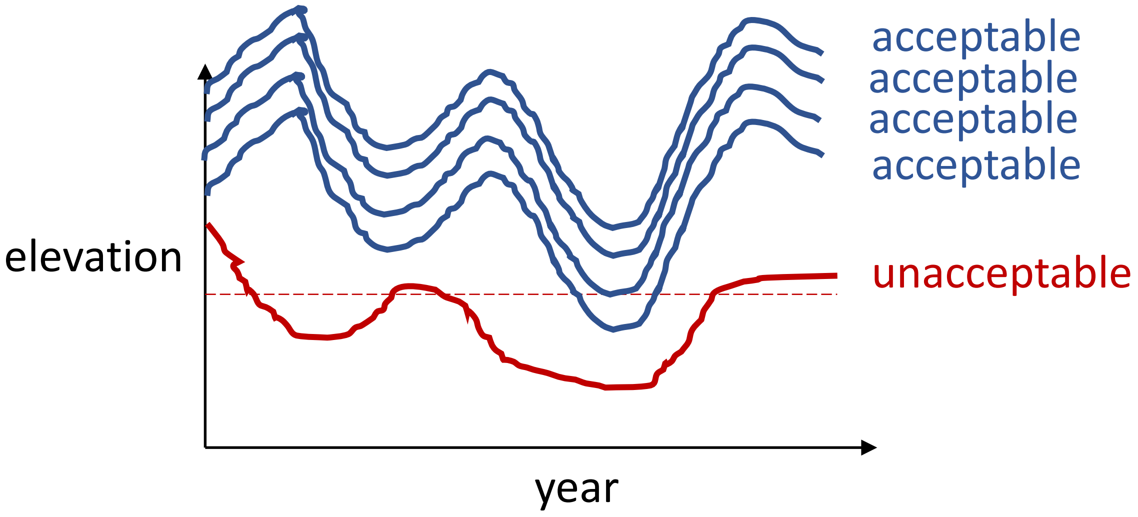
Strategy B is more robust than strategy A

But, *why* do these strategies have unacceptable performance in some futures?

Strategy A robustness: 60%



Strategy B robustness: 80%

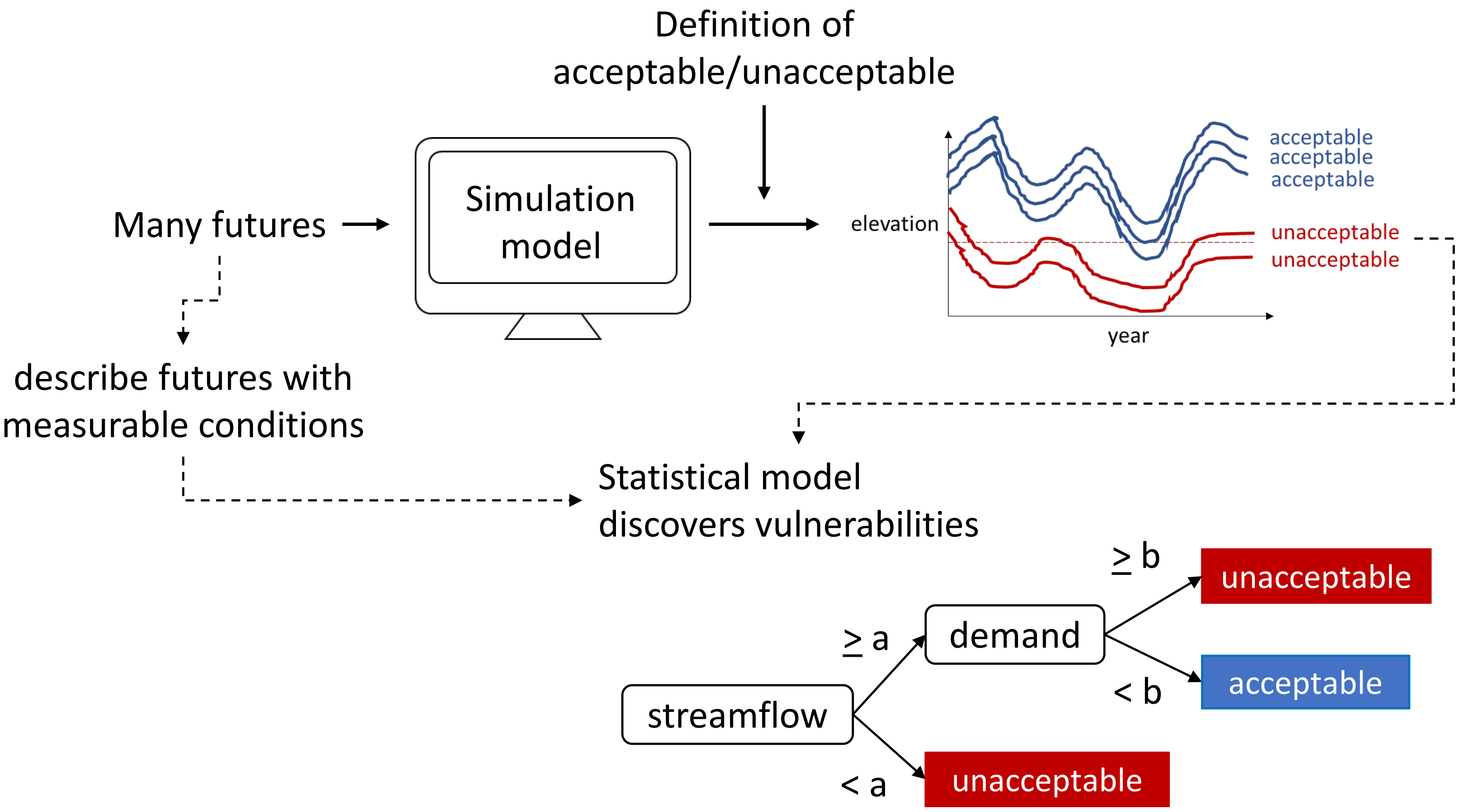


i.e., what are the streamflow, demand, and other conditions driving poor performance?

Vulnerability analysis discovers the conditions that cause a strategy to have unacceptable performance

- At any point, under a given operational strategy, a system is vulnerable to some future conditions but not others
- When there is an opportunity to adopt a new operational strategy, it is valuable to discover relationships between the system, different strategies and specific conditions
- Conditions: features describing plausible futures, such as average flow at Lees Ferry, duration/intensity of low-flow years, demand
- Unacceptable performance: can be same definition used for robustness, or a different definition
- Purposes of vulnerability analysis include:
  - Motivating changes to an existing or proposed strategy
  - Comparing two or more strategies
  - Designing a monitoring and adaptation strategy

Vulnerability analysis uses statistical methods to discover concise descriptions of vulnerability



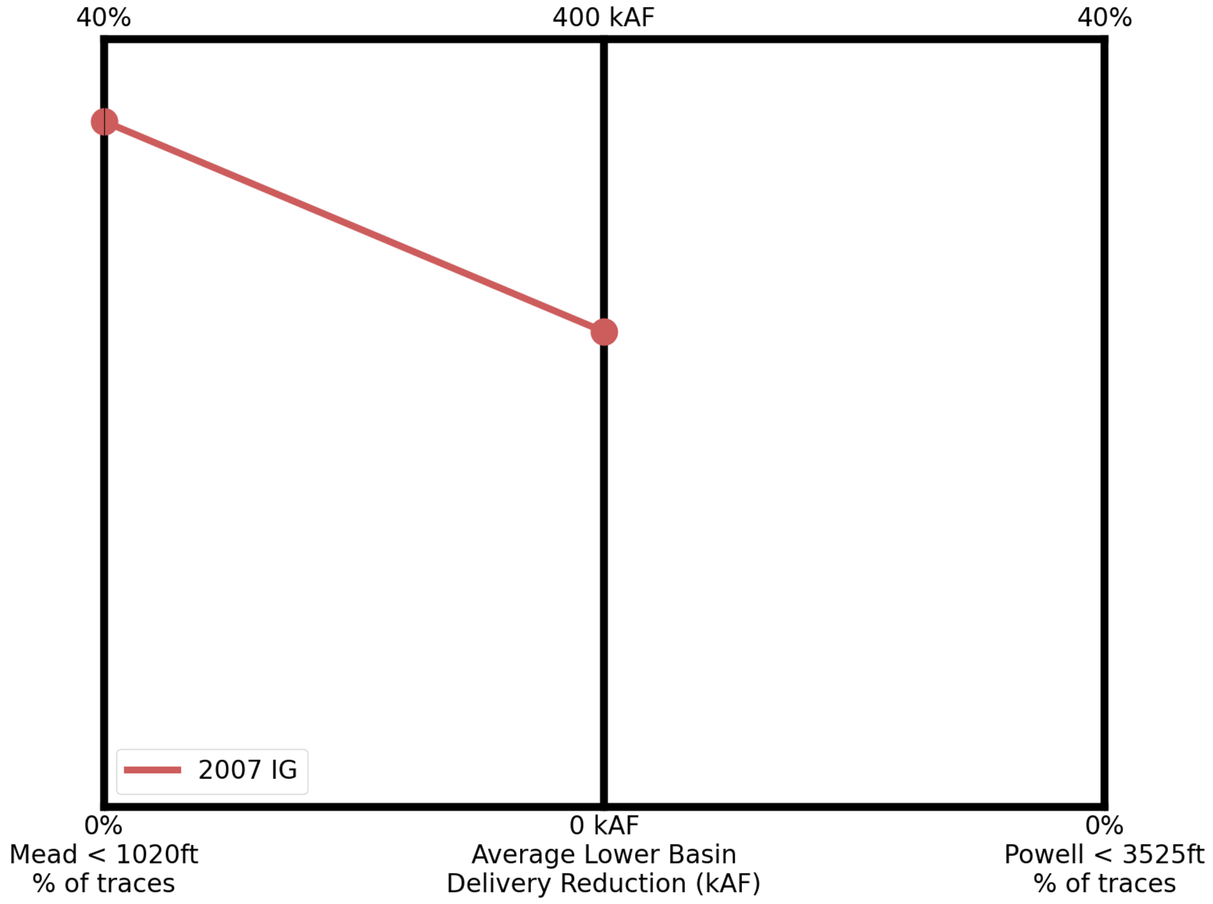
MORDM Key Concepts and the Post-2026 Web Tool

Resource Categories Supported in the Post-2026 Web Tool

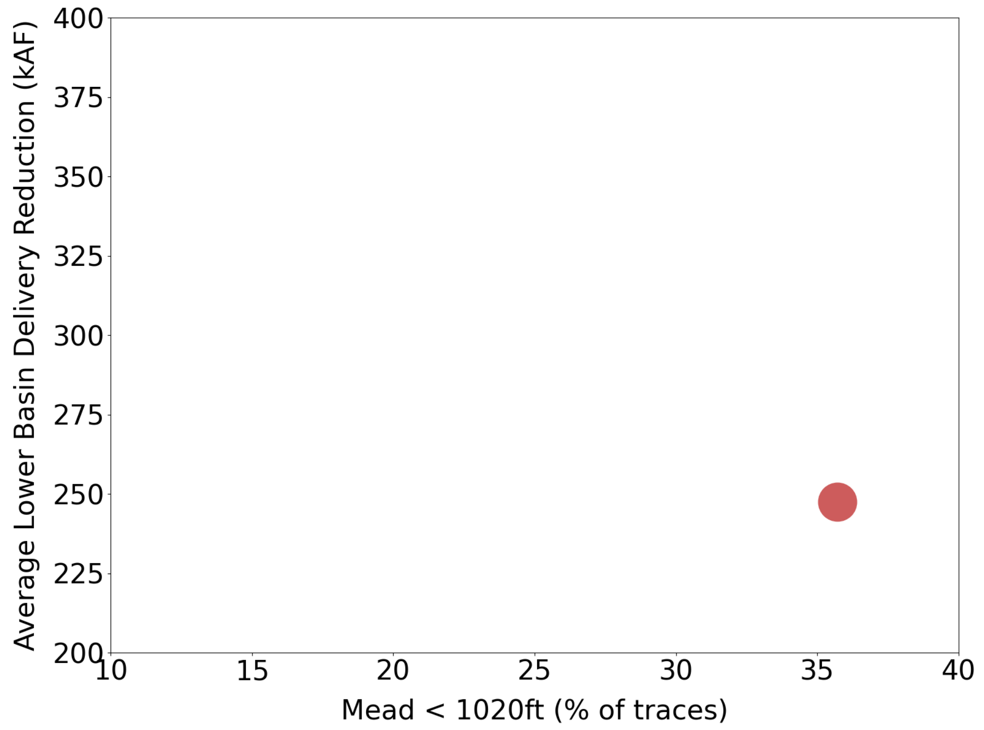
- Post-2026 Web Tool analysis is driven by CRSS outputs
  - Reservoir levels
  - Water use
  - River flow
  - Energy generation
- Timeseries outputs from CRSS are used in different ways to support DMDU analytical components
- The Web Tool will enable users to explore effects of different operational strategies on many types of resources

- Water Supply
- Hydropower
- Recreation
- Water Quality
- Cultural/Paleo
- Air Quality
- Fish
- Vegetation
- Sediment

Performance Metrics Enable Analysis of Tradeoffs

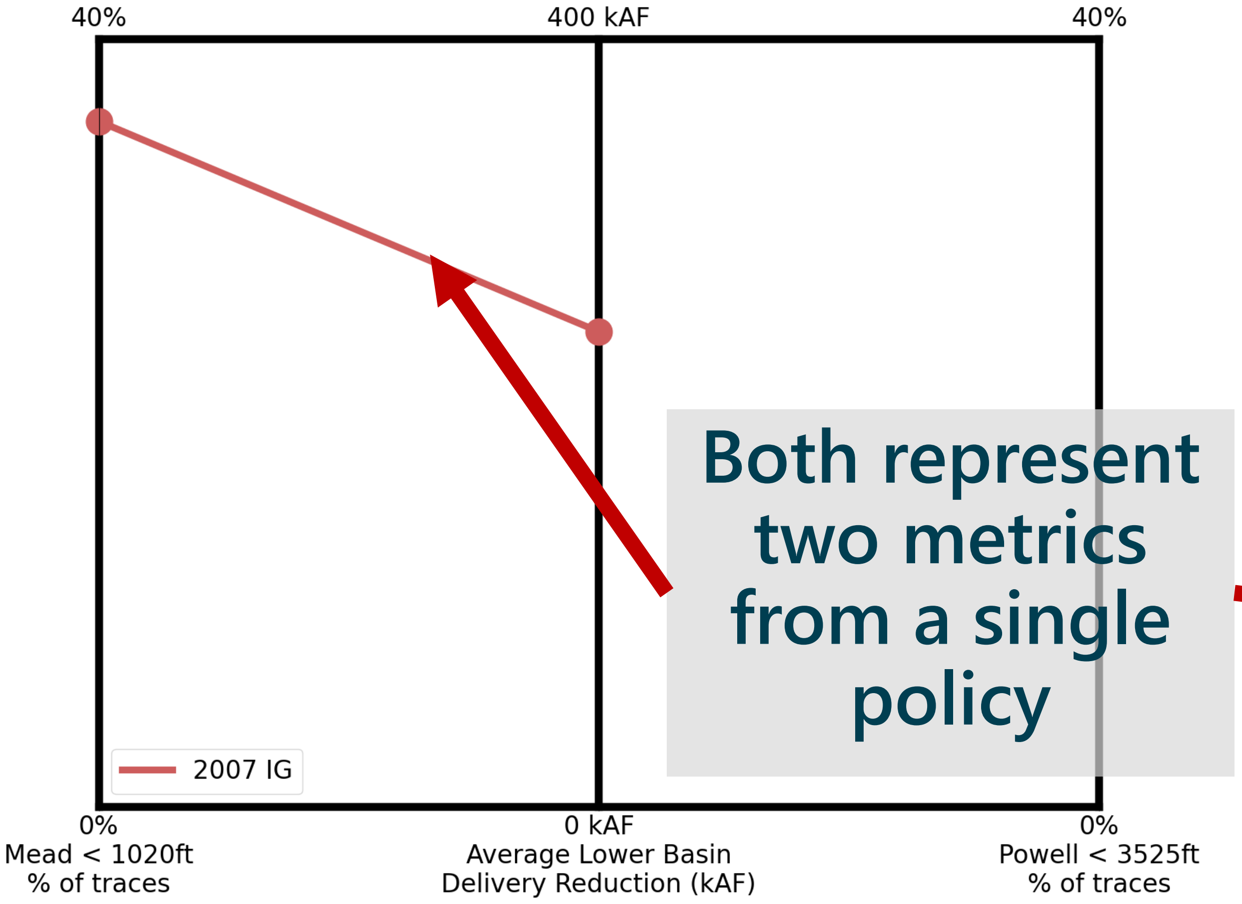


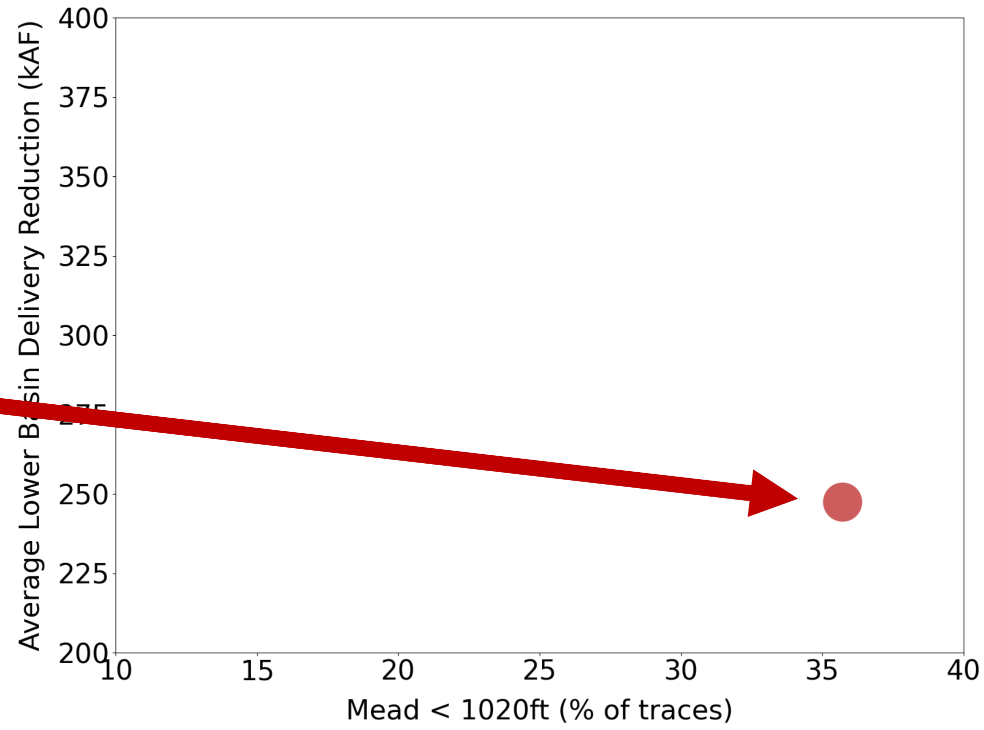
Tradeoffs occur when comparing policies – often improvement requires something else to get worse



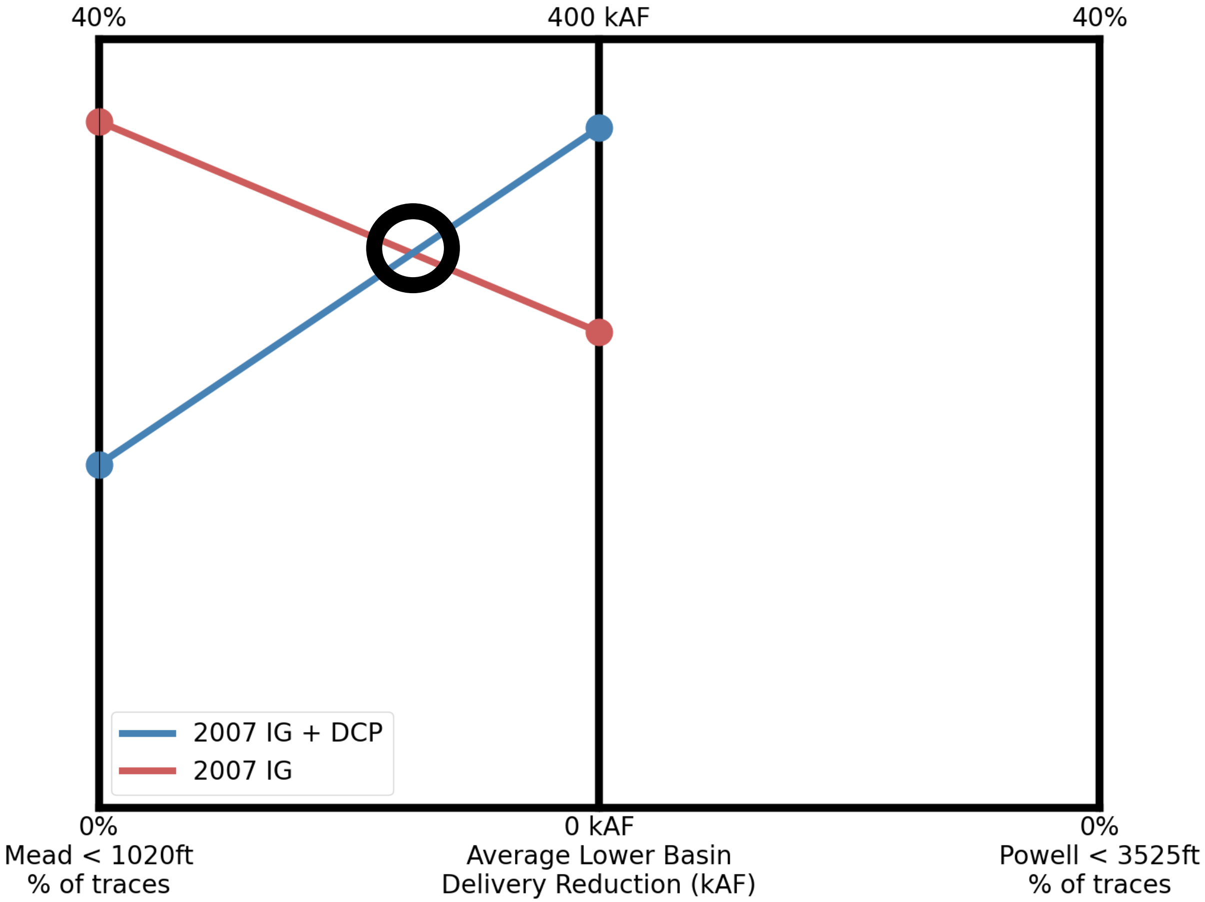
Performance Metrics Enable Analysis of Tradeoffs

Tradeoffs occur when comparing policies – often improvement requires something else to get worse

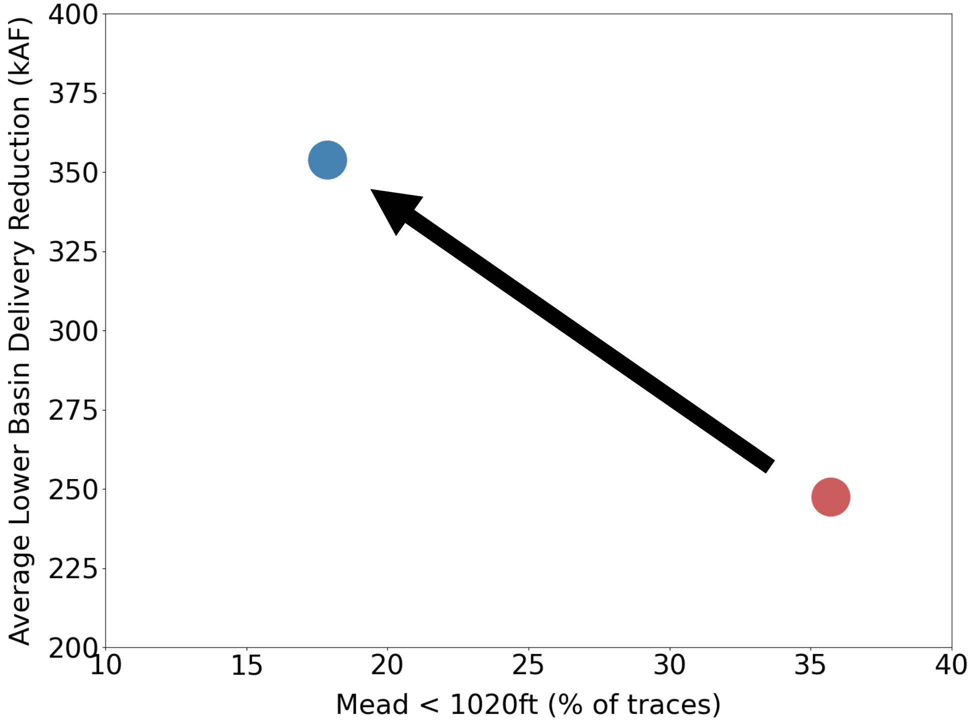




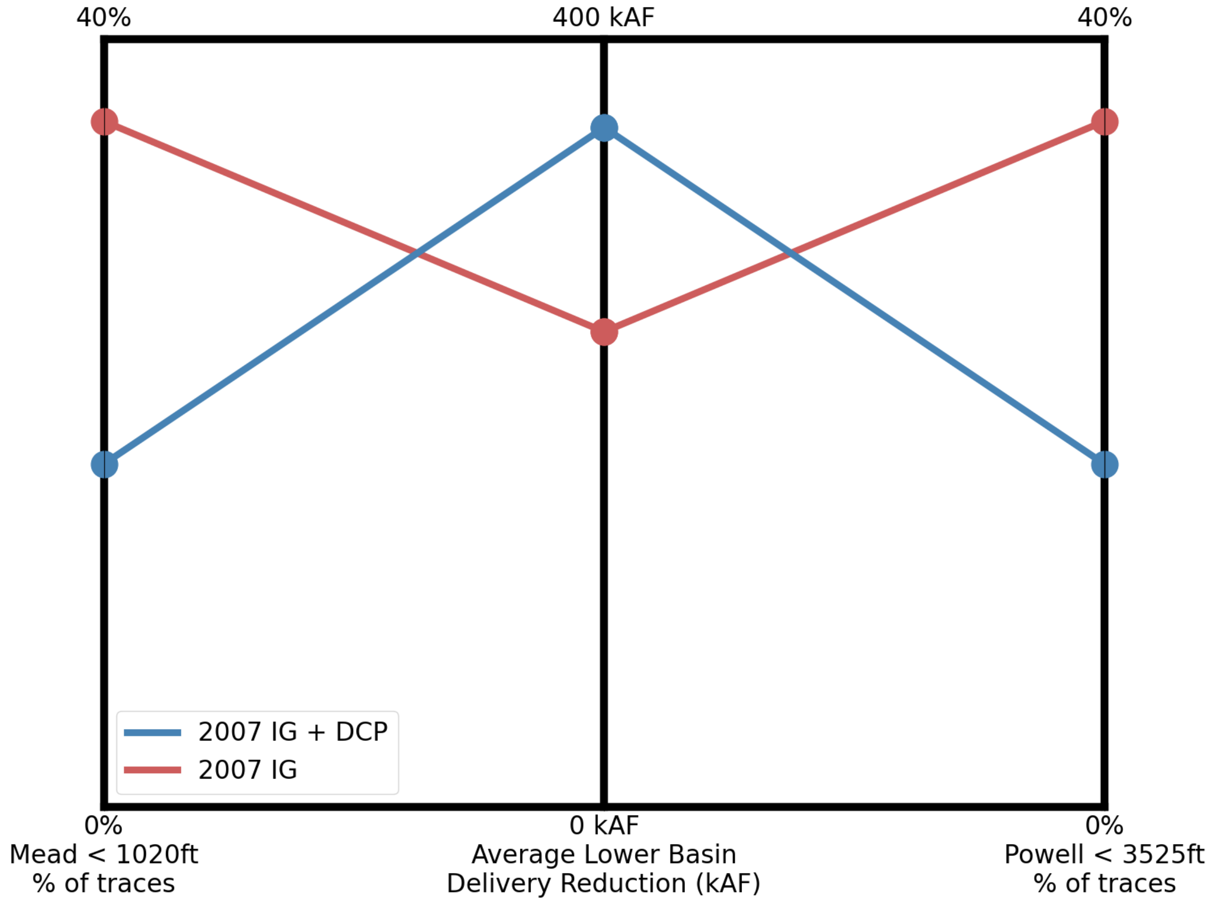
Performance Metrics Enable Analysis of Tradeoffs



A second policy represents an improvement in one metric, and a setback in the other



Performance Metrics Enable Analysis of Tradeoffs

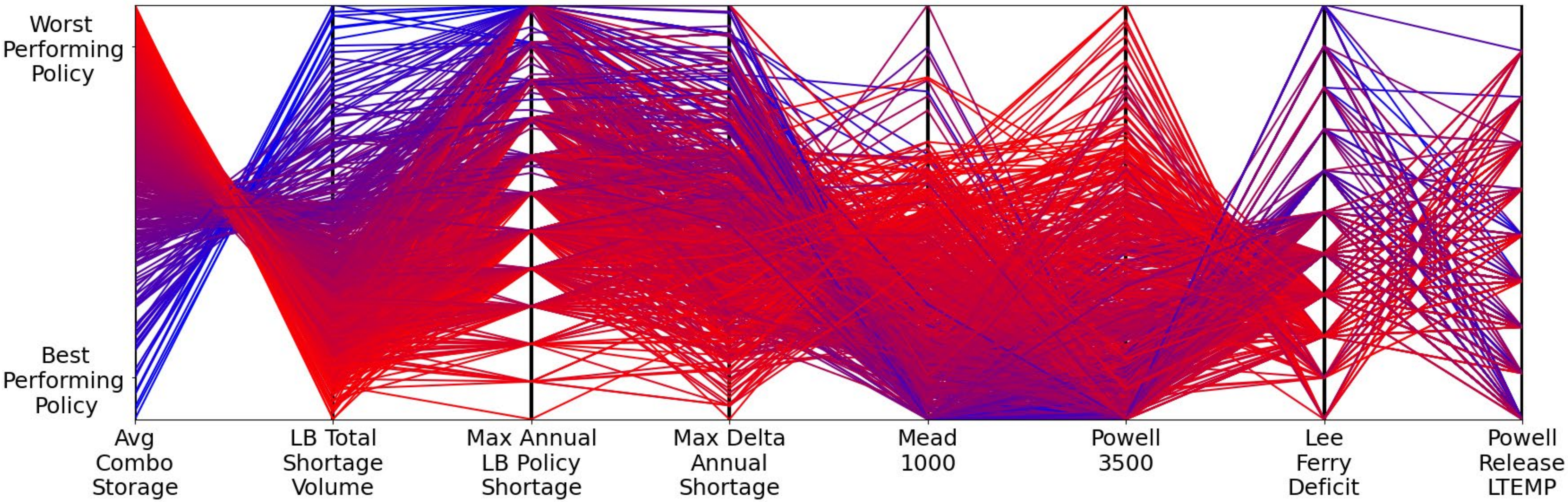


A second policy represents an improvement in one metric, and a setback in the other

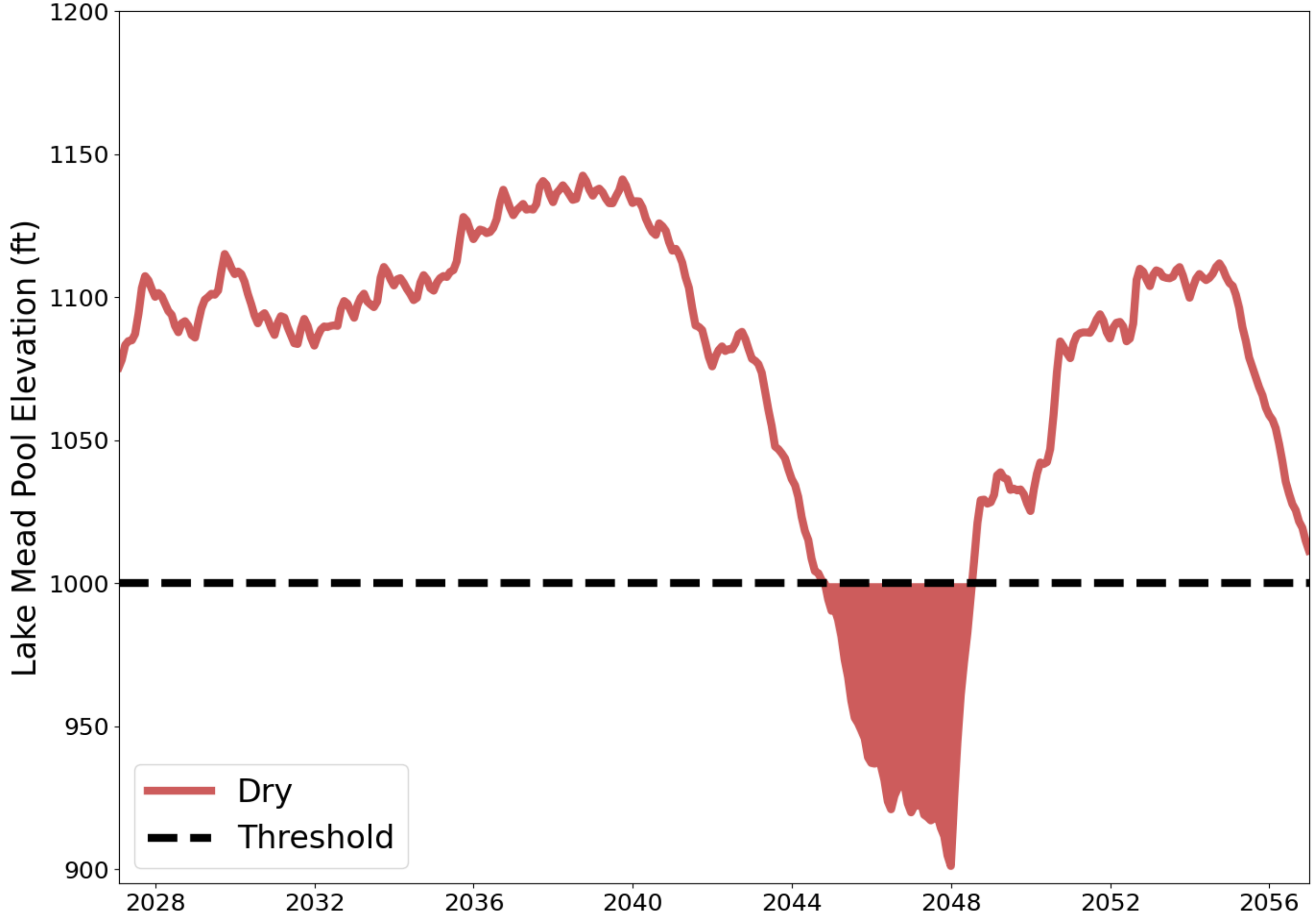
Additional metrics can tradeoff with existing metrics (Powell < 3525 ft and Average Lower Basin Shortage) or be correlated with them (Powell < 3525 ft and Mead < 1020 ft)

Performance Metrics Enable Analysis of Tradeoffs

With many objectives + policies we can begin to understand what we have to 'give up' in one (or more) objectives to improve in another



Performance Metrics are Averages of a Small Number of Traces



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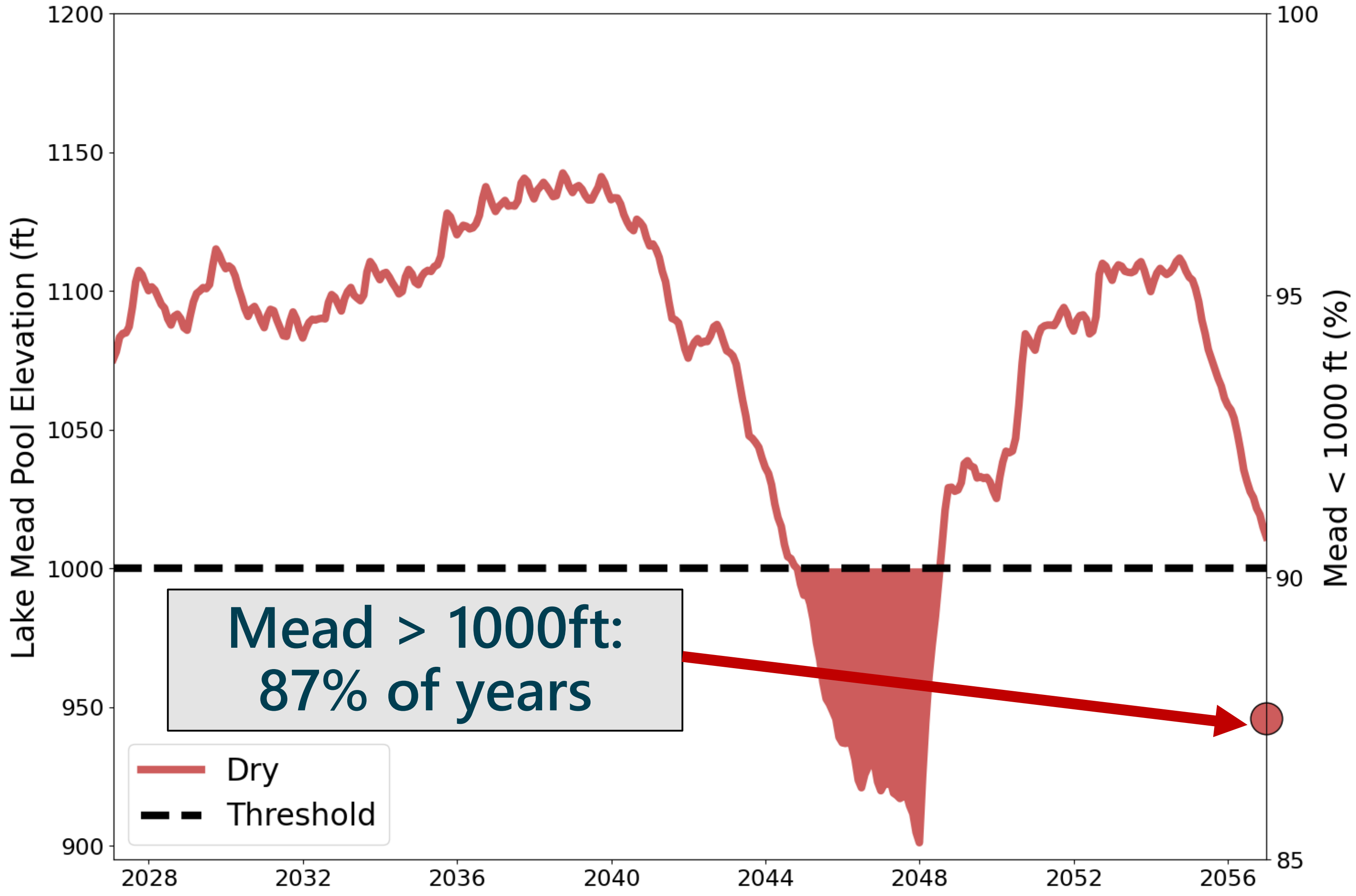

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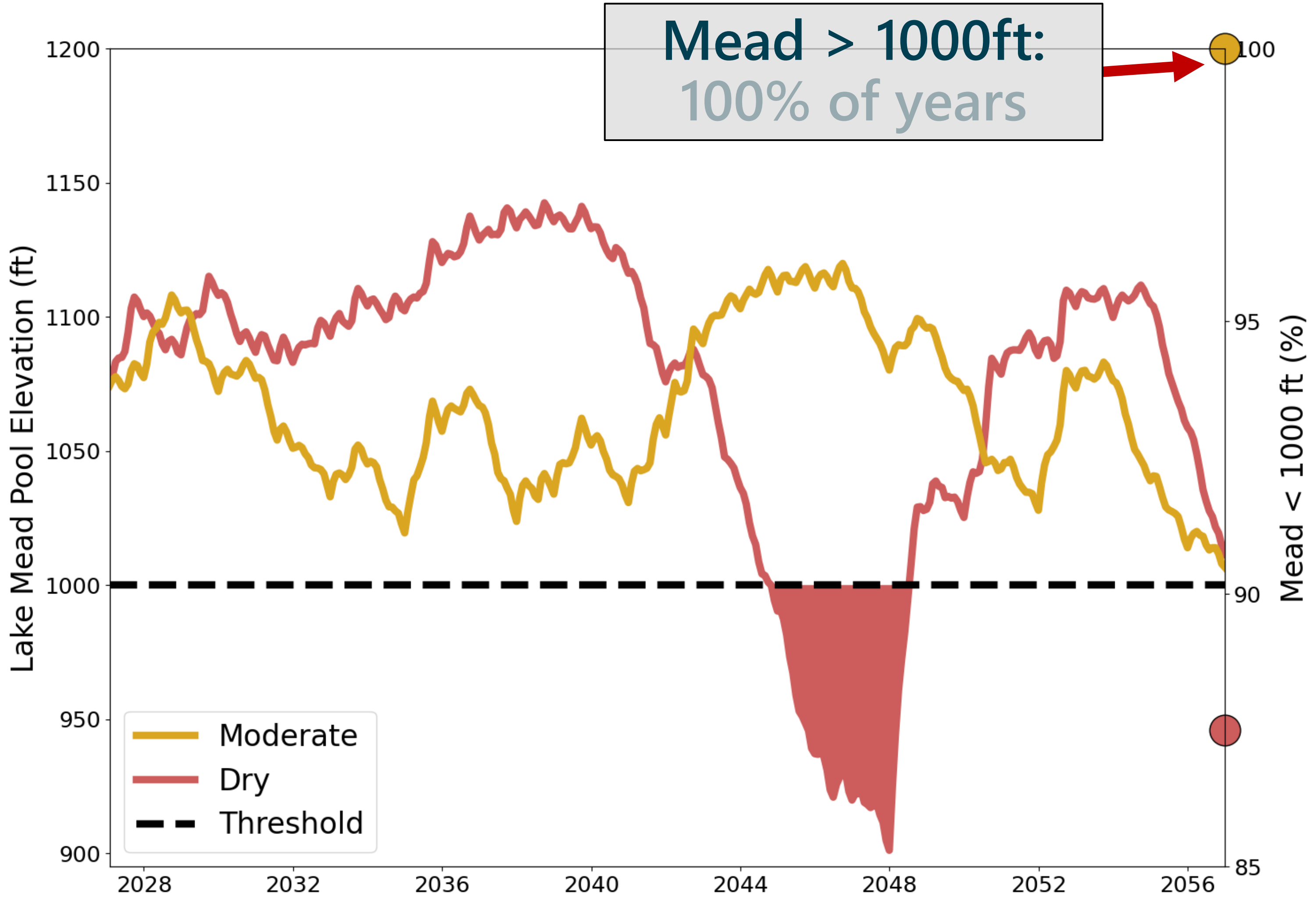

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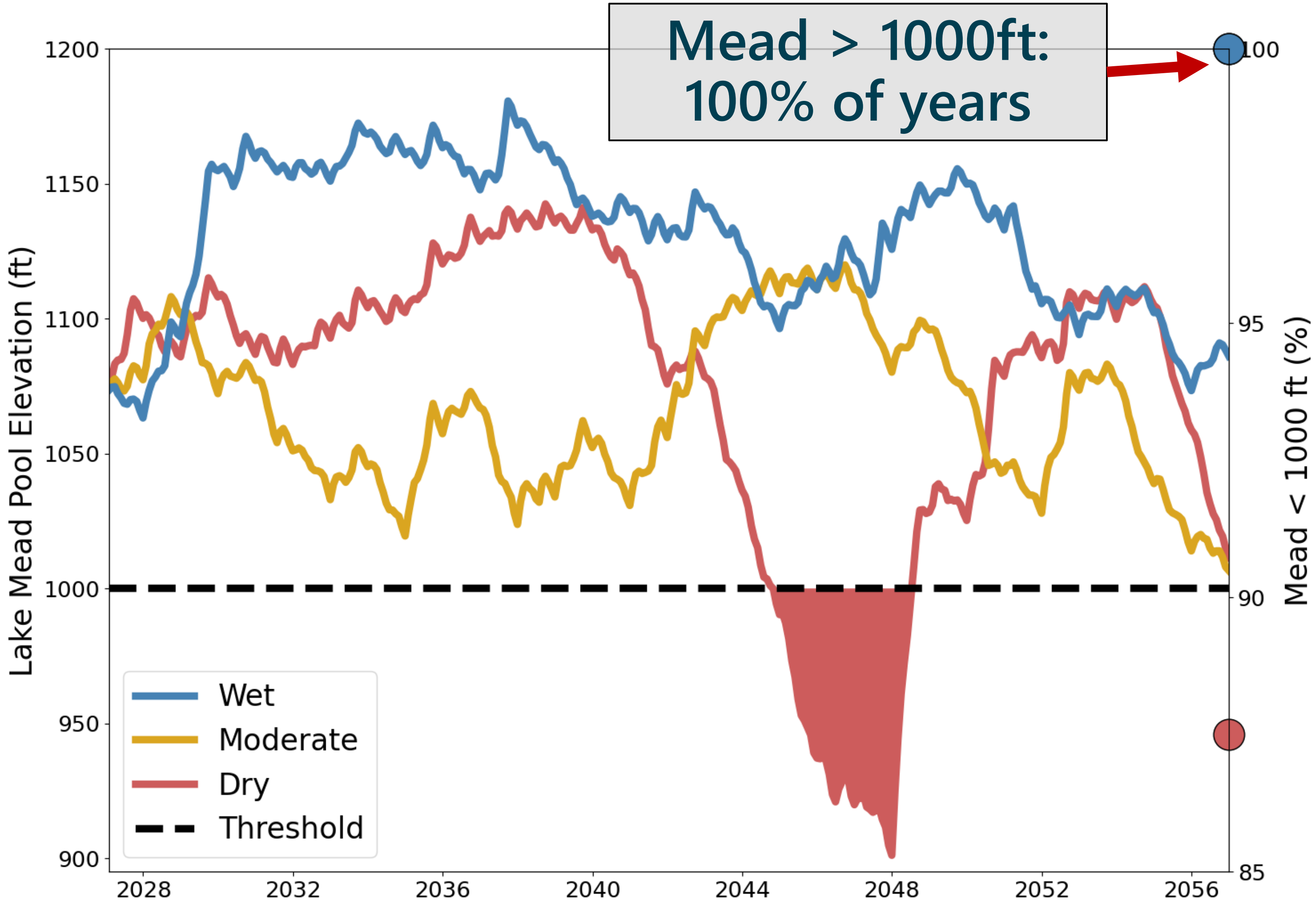

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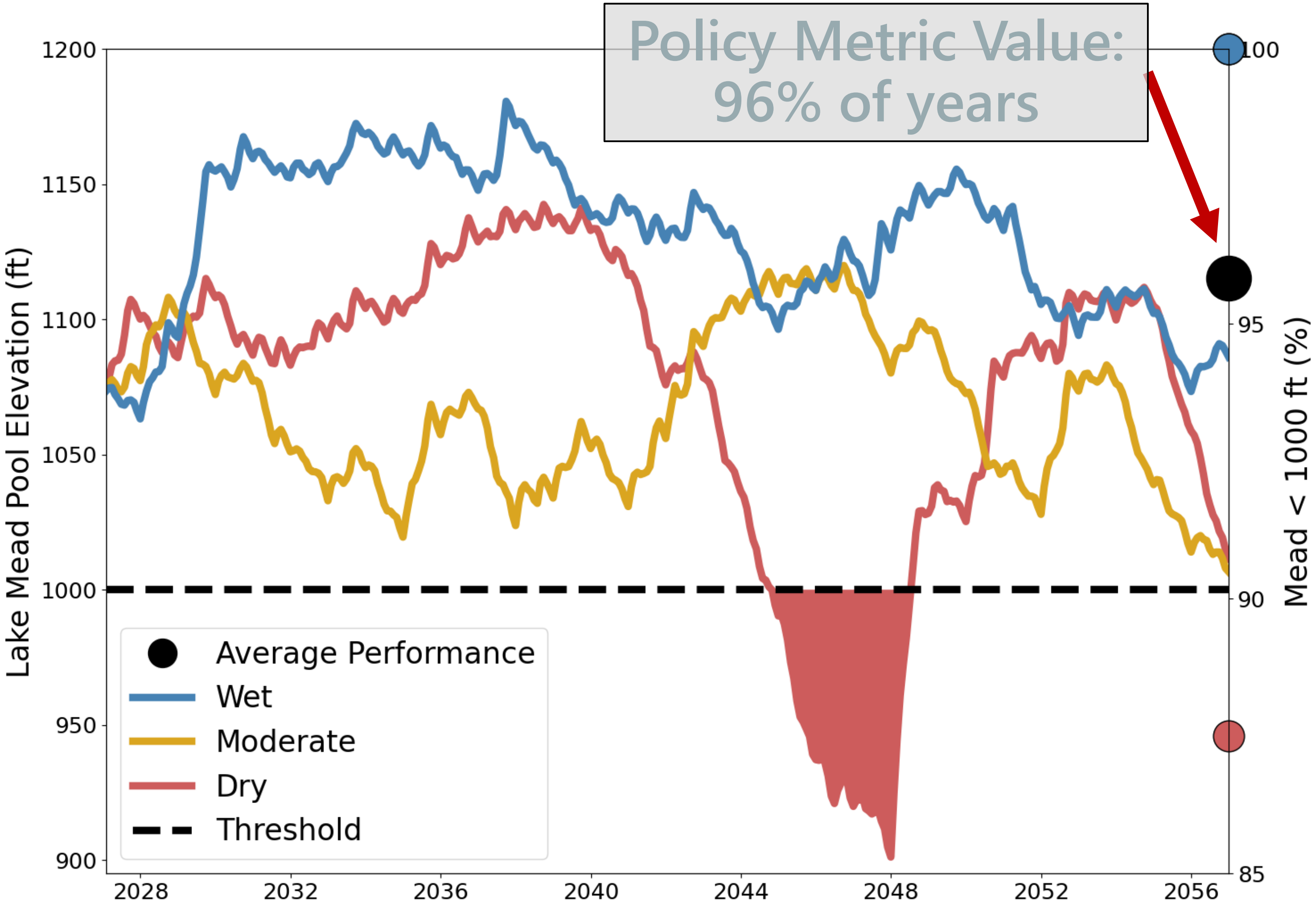

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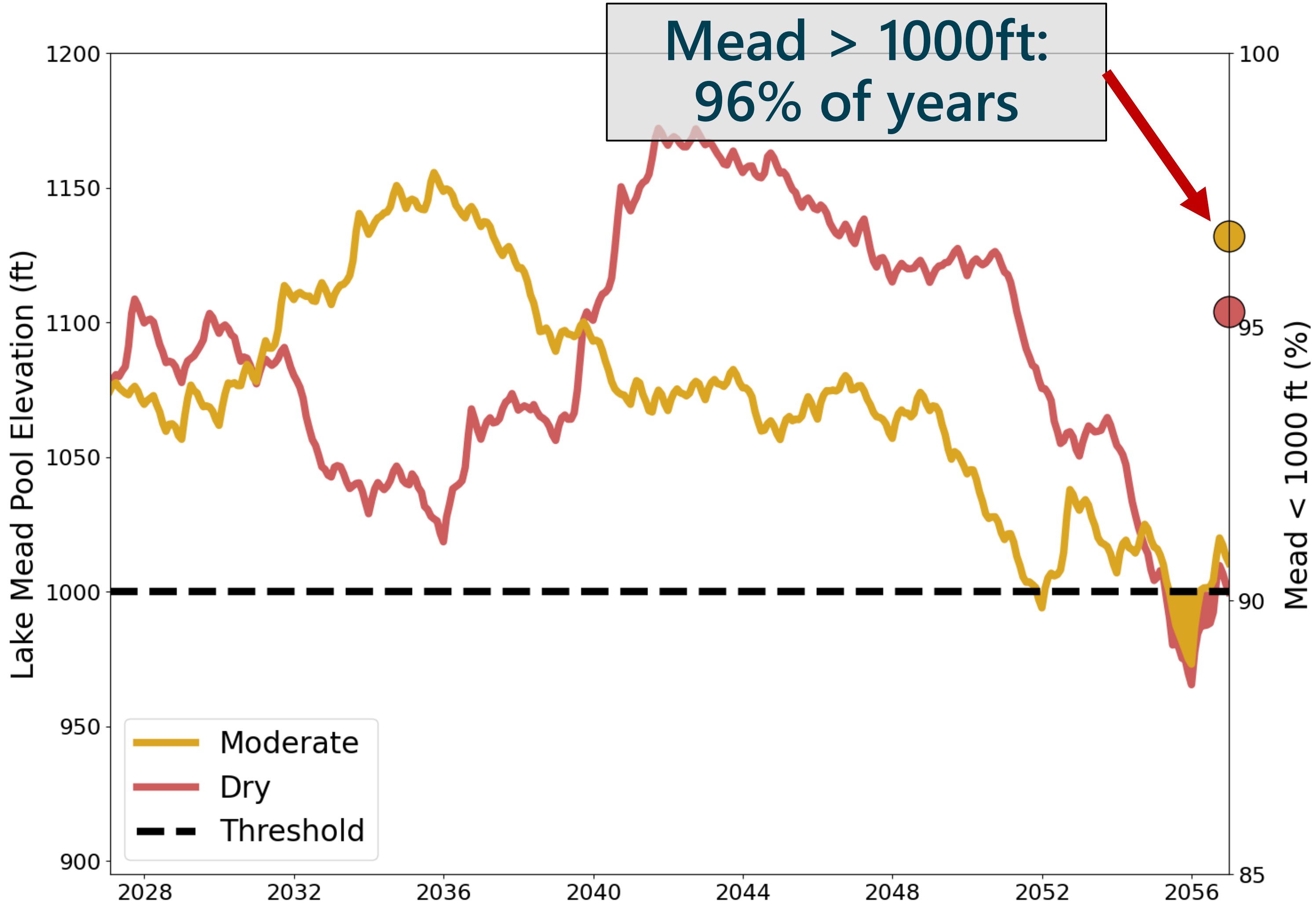

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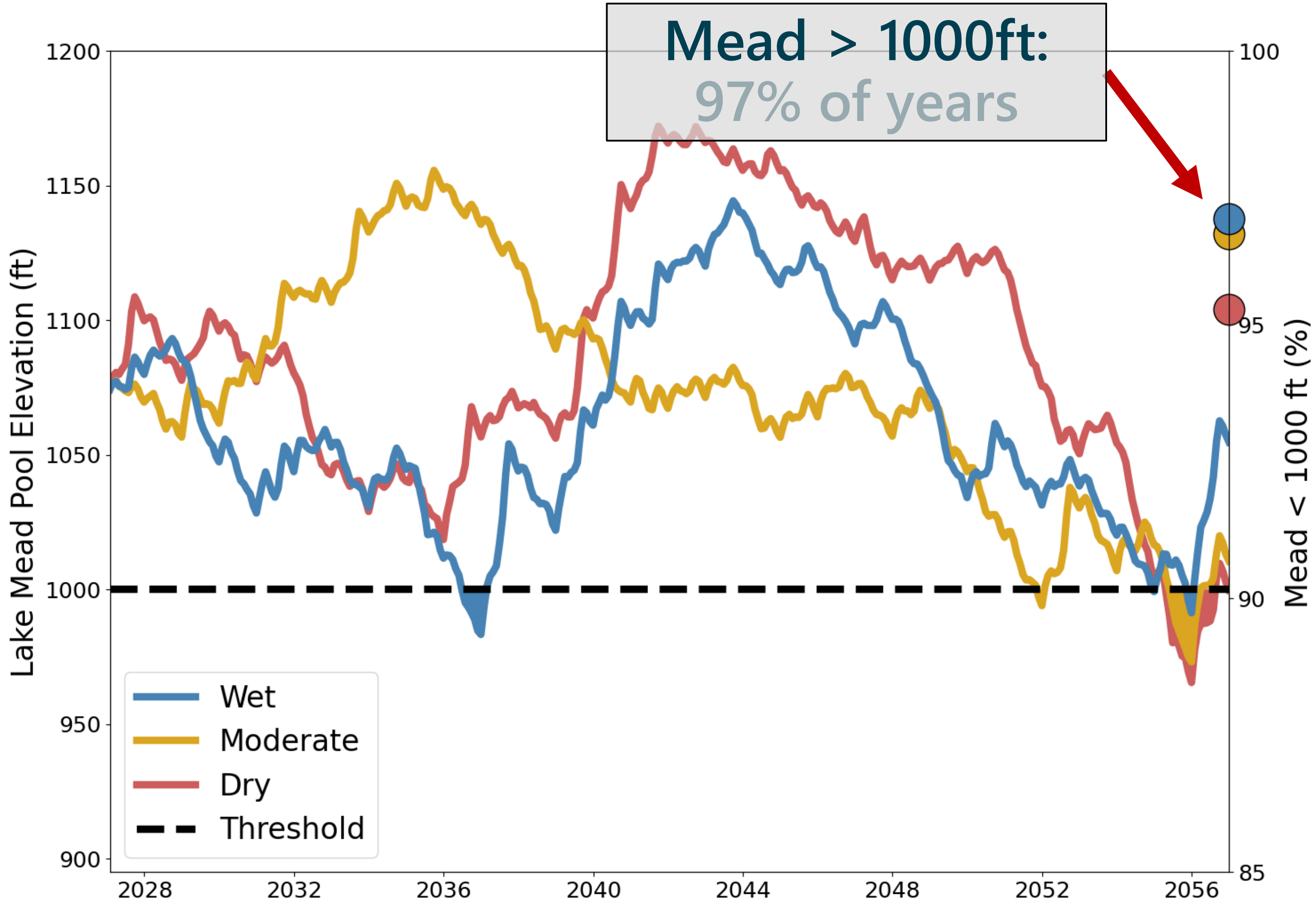

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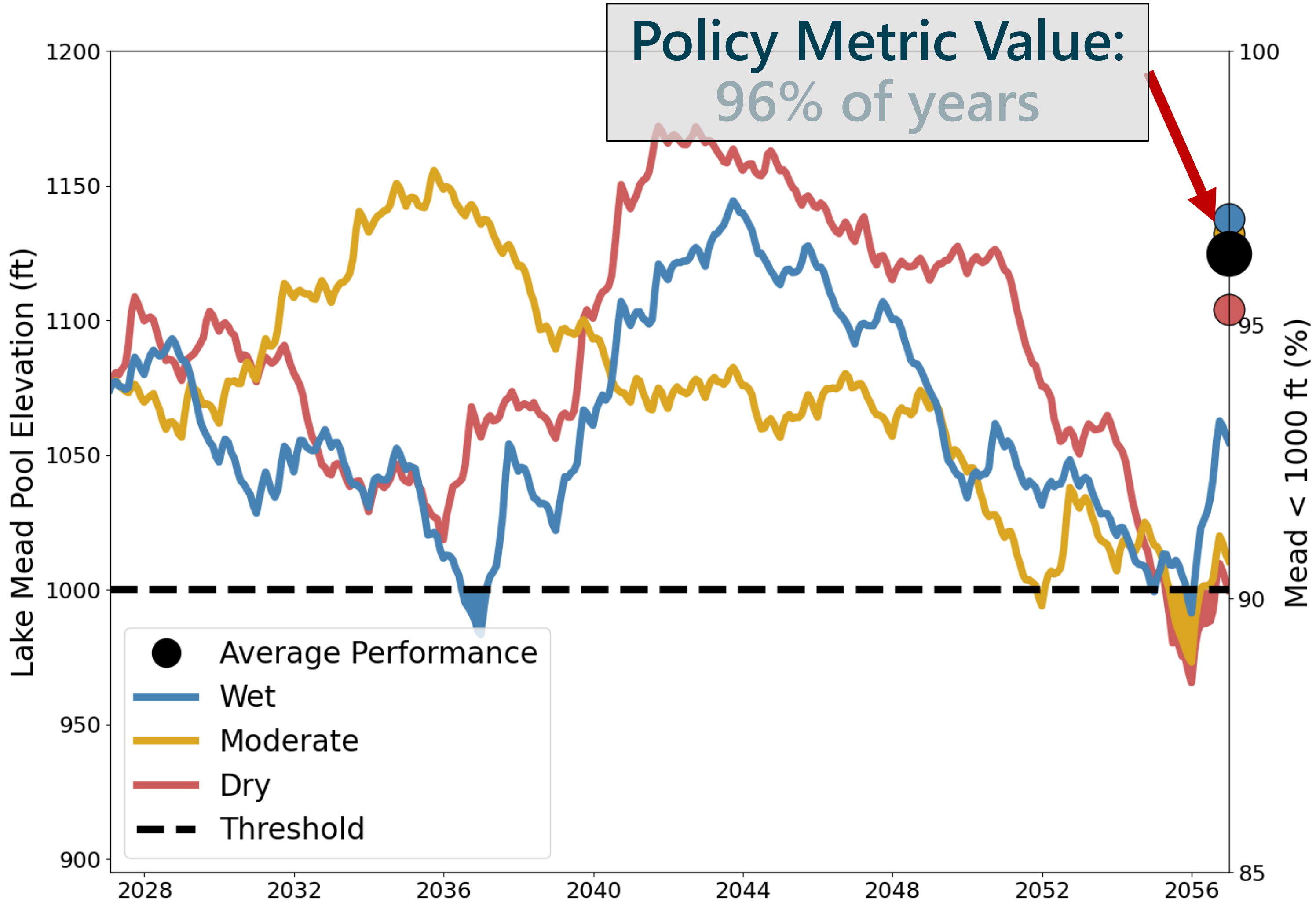

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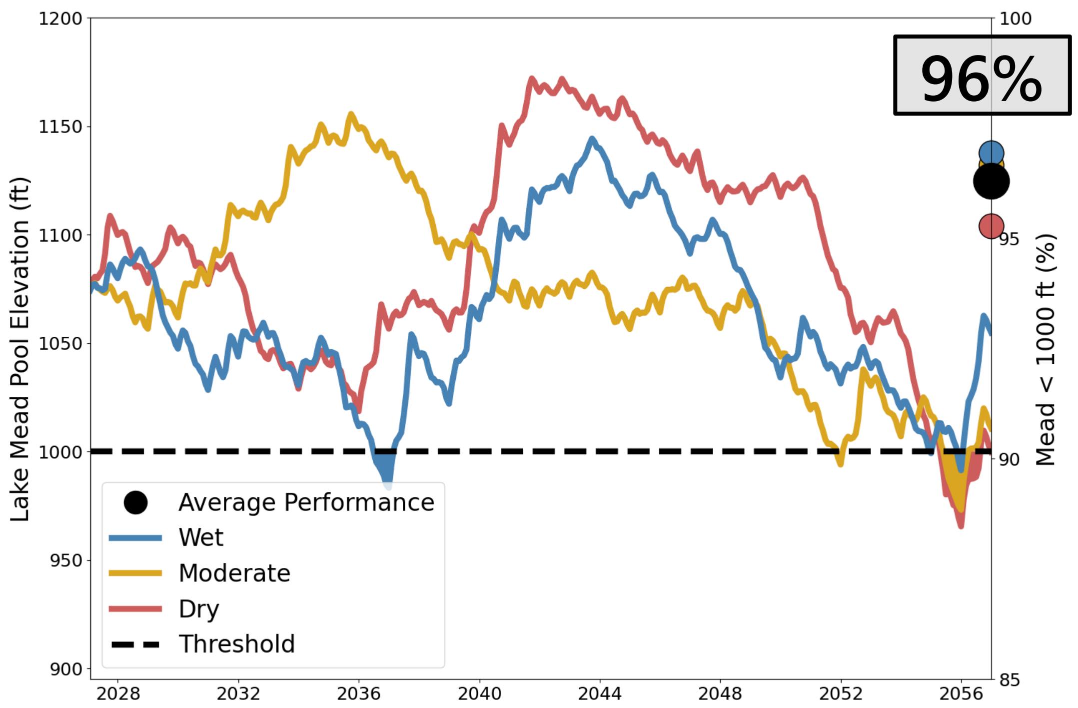
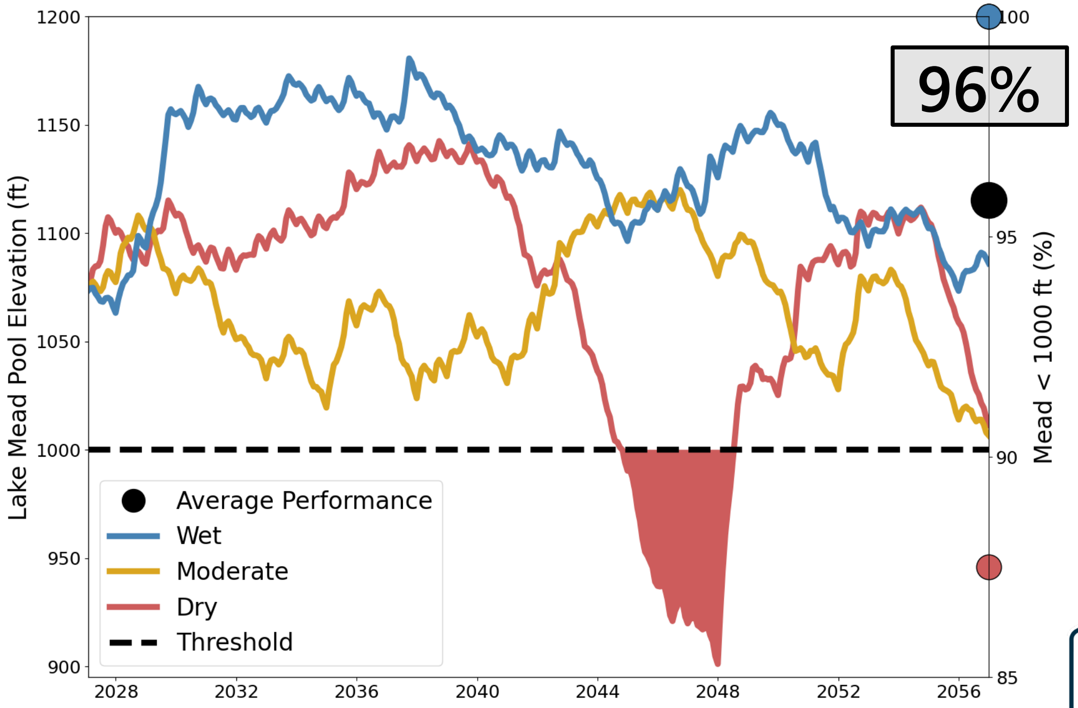
Robustness Provides Information about Outcomes across Large Ensembles

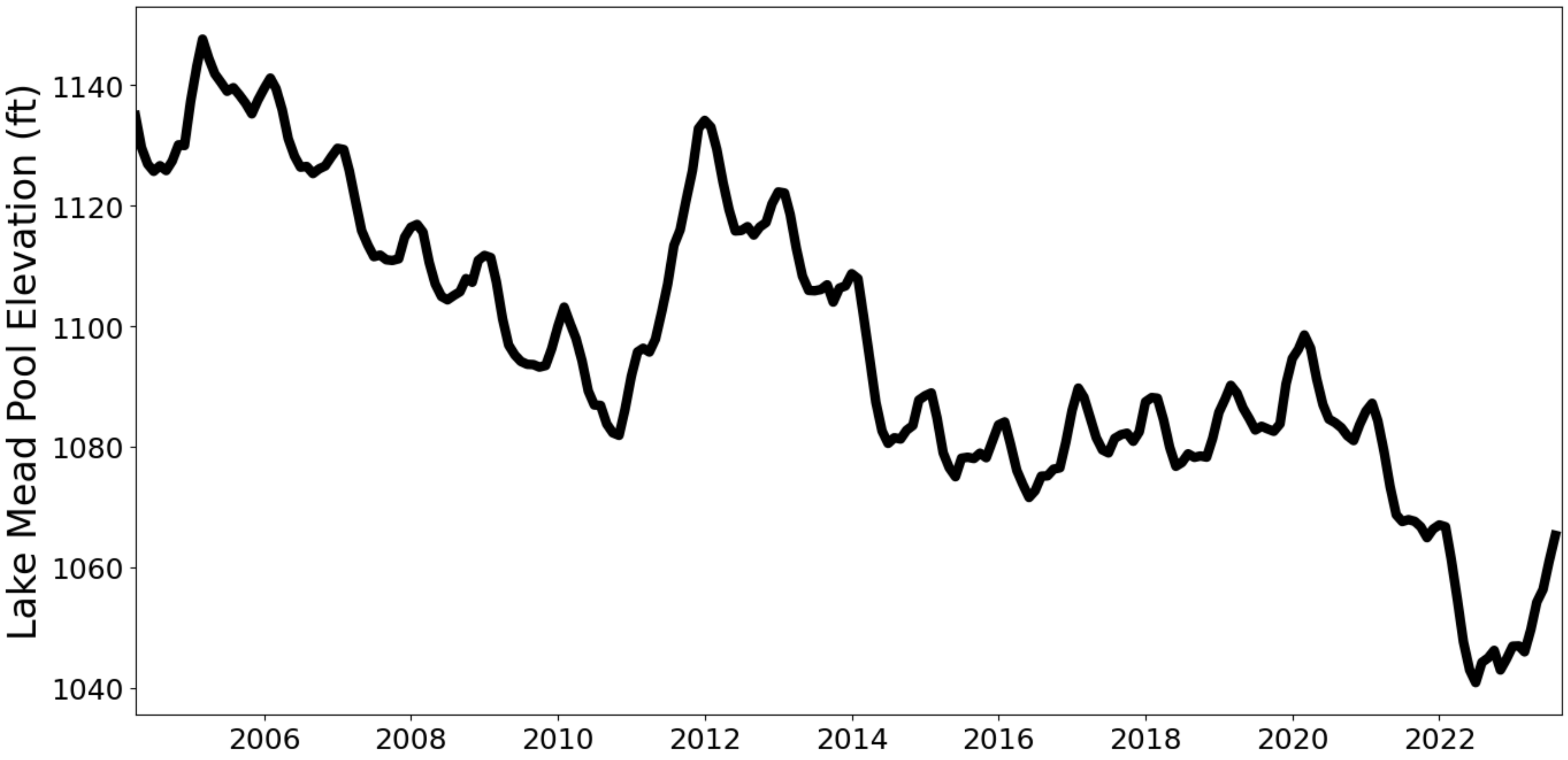
- A 'robustness definition' specifies some *desirable* outcome for a policy where a measure stays on the good side of some threshold in greater than some fraction of a future period of time.





Robustness Thresholds Should Represent a Desirable Outcome – Not a 'Failure Point'

A policy has a desirable outcome in a future if…….



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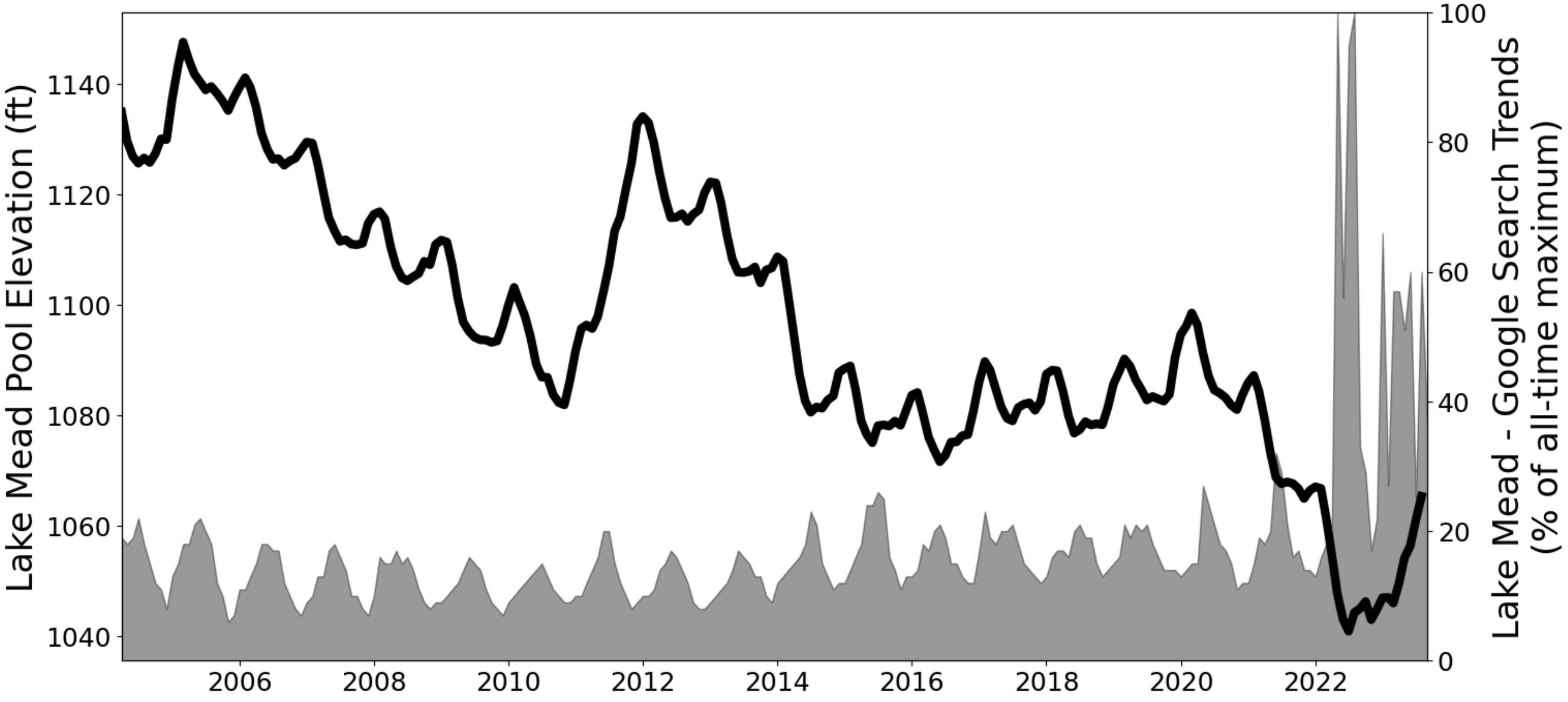
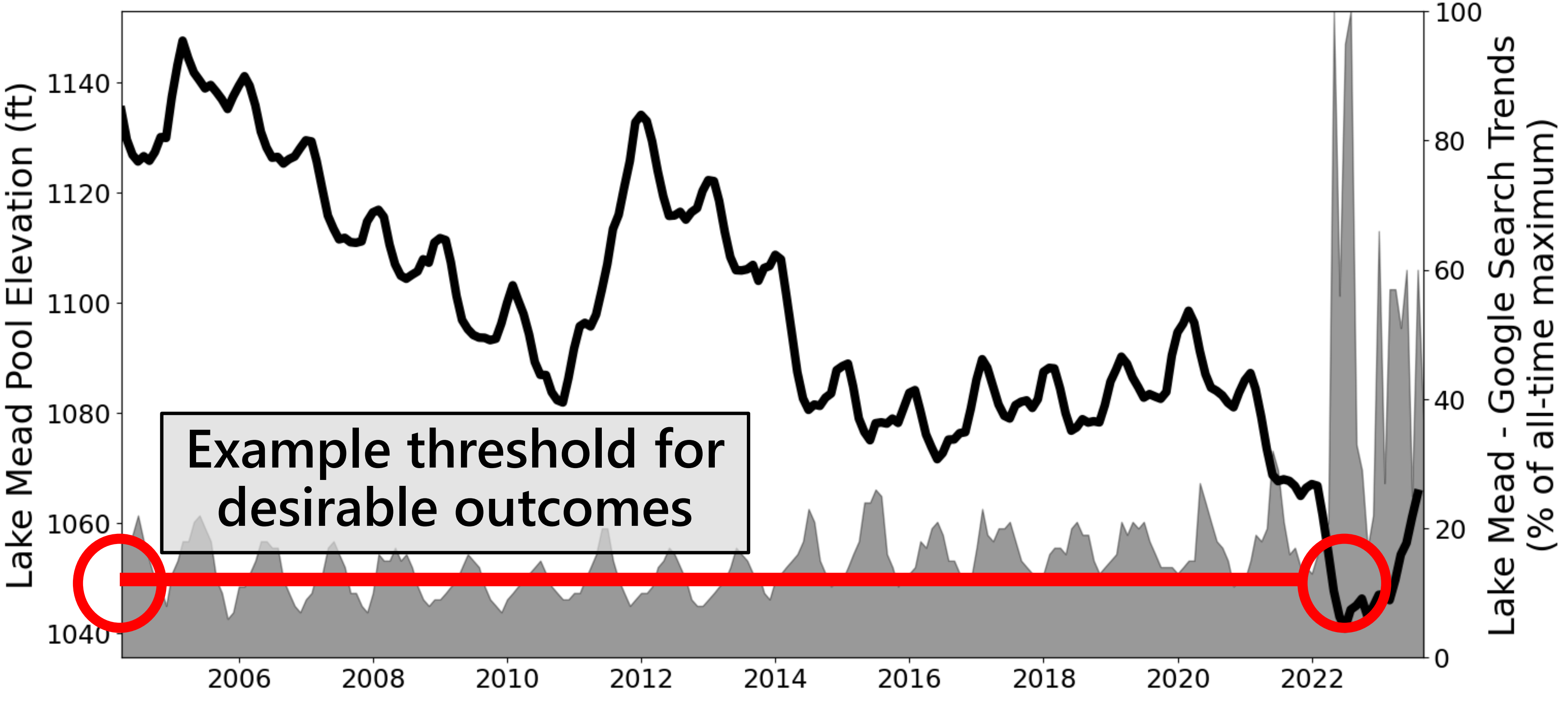


Robustness Thresholds Should Represent a Desirable Outcome – Not a 'Failure Point'

A policy has a desirable outcome in a future if Mead Pool Elevation stays above 1050 feet in greater than 80% of the next 30 years.



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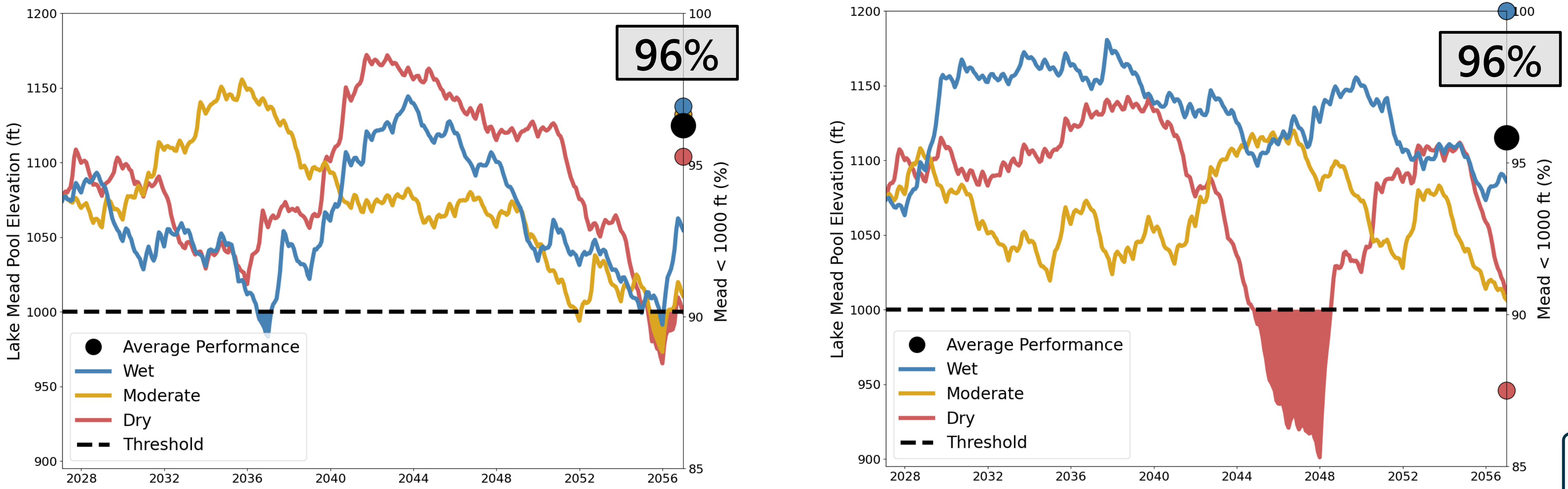

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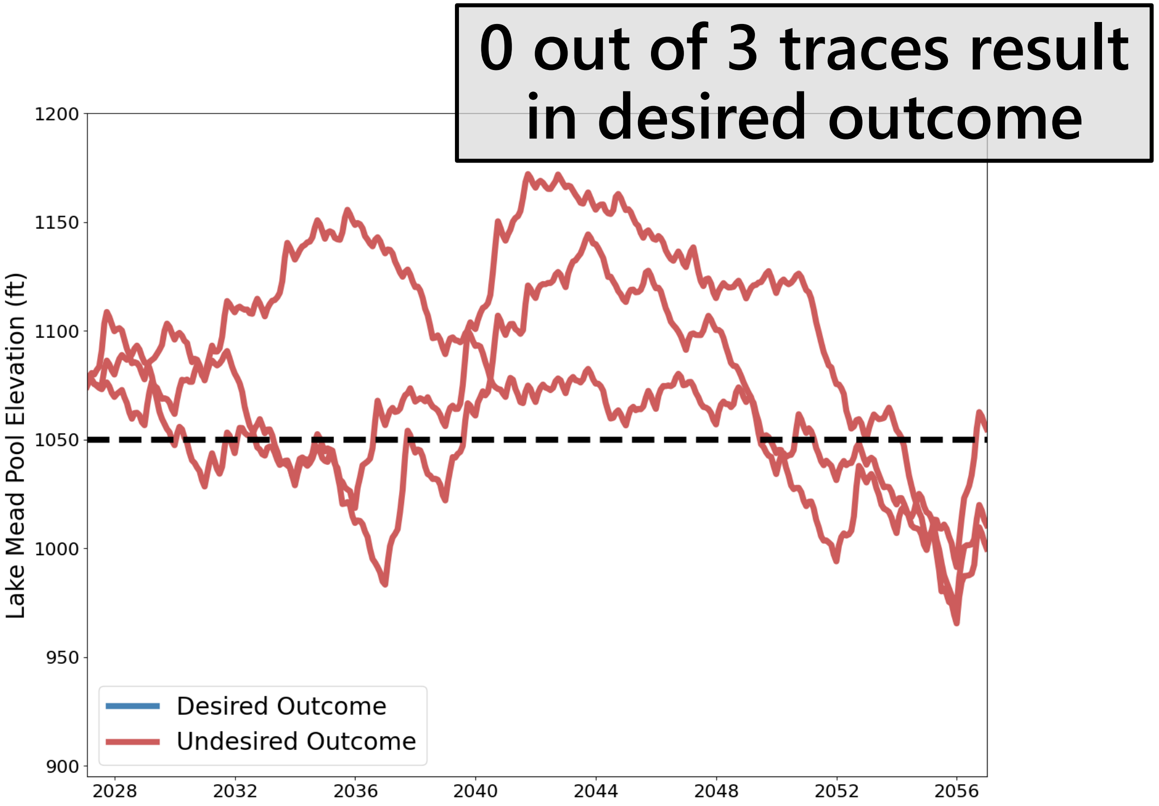

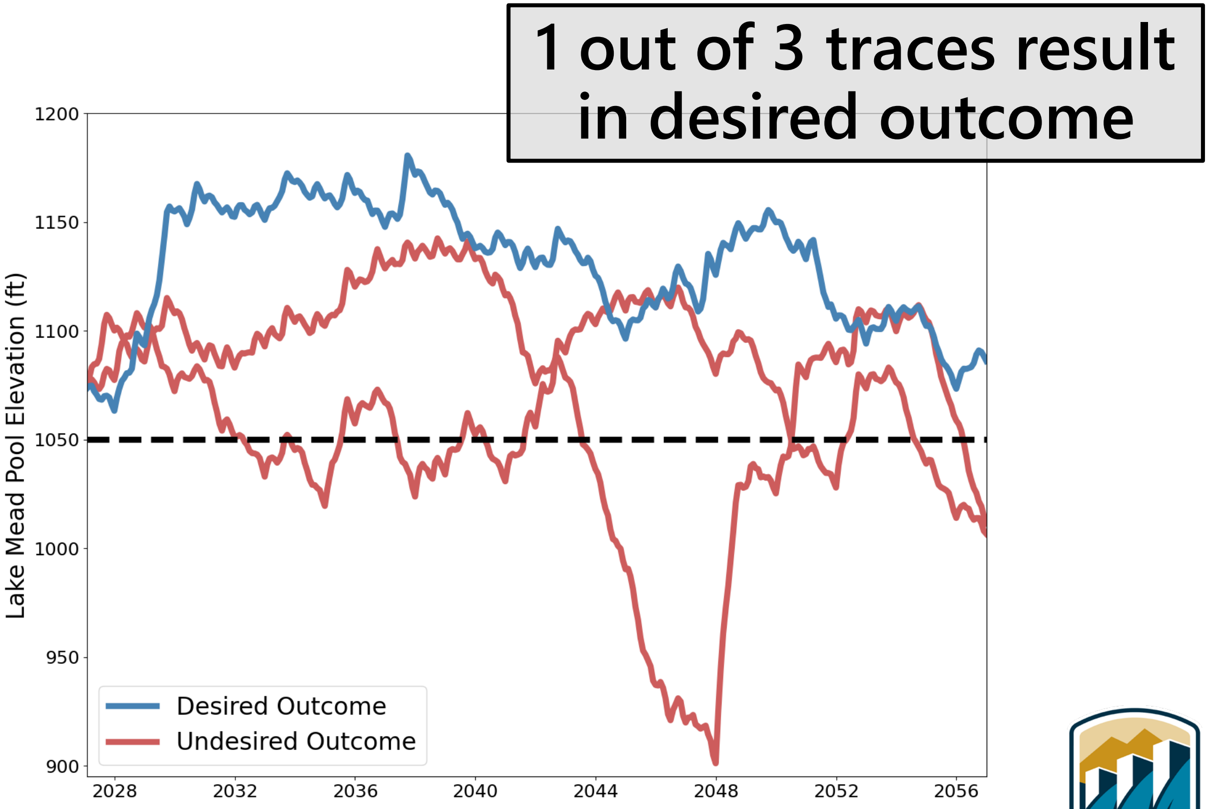

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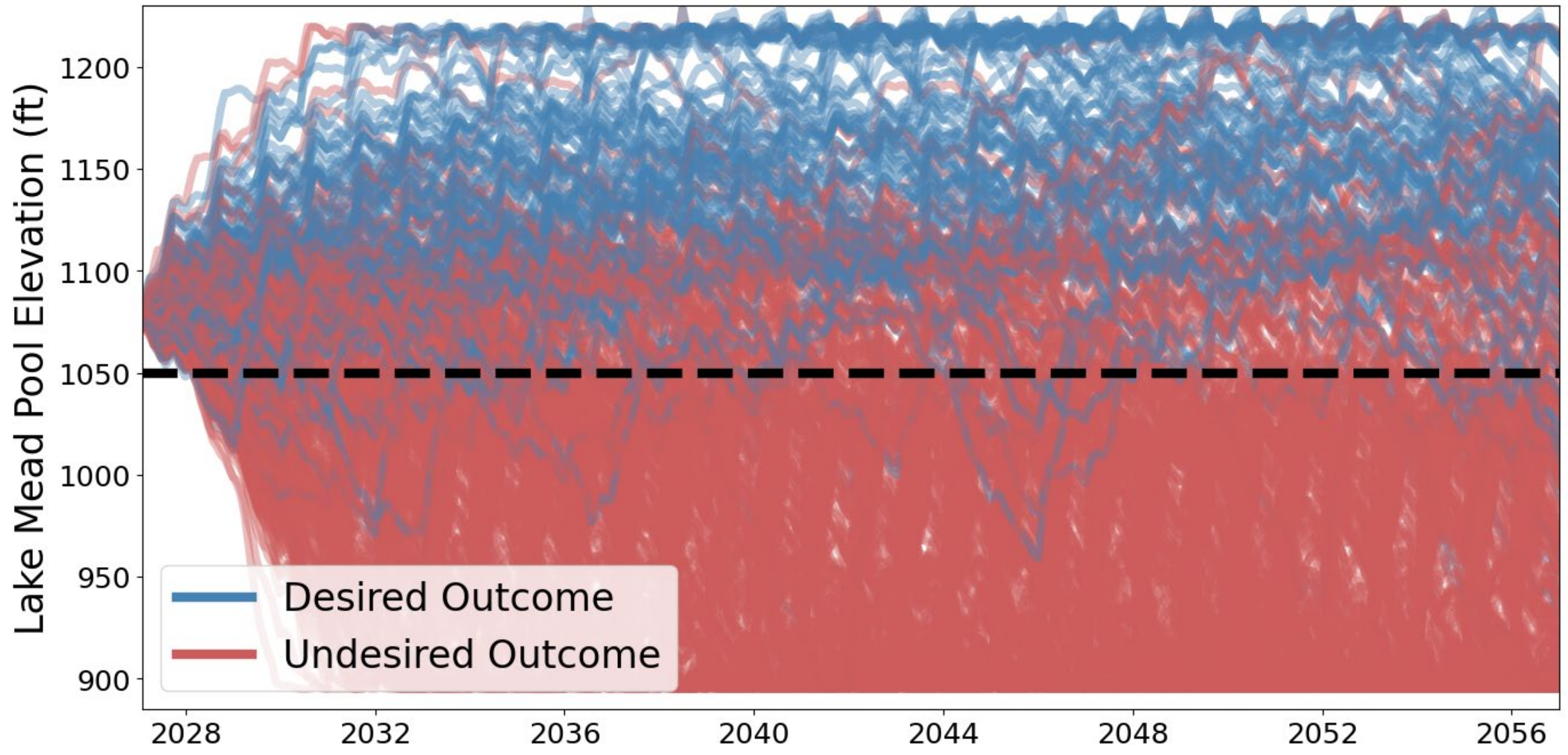
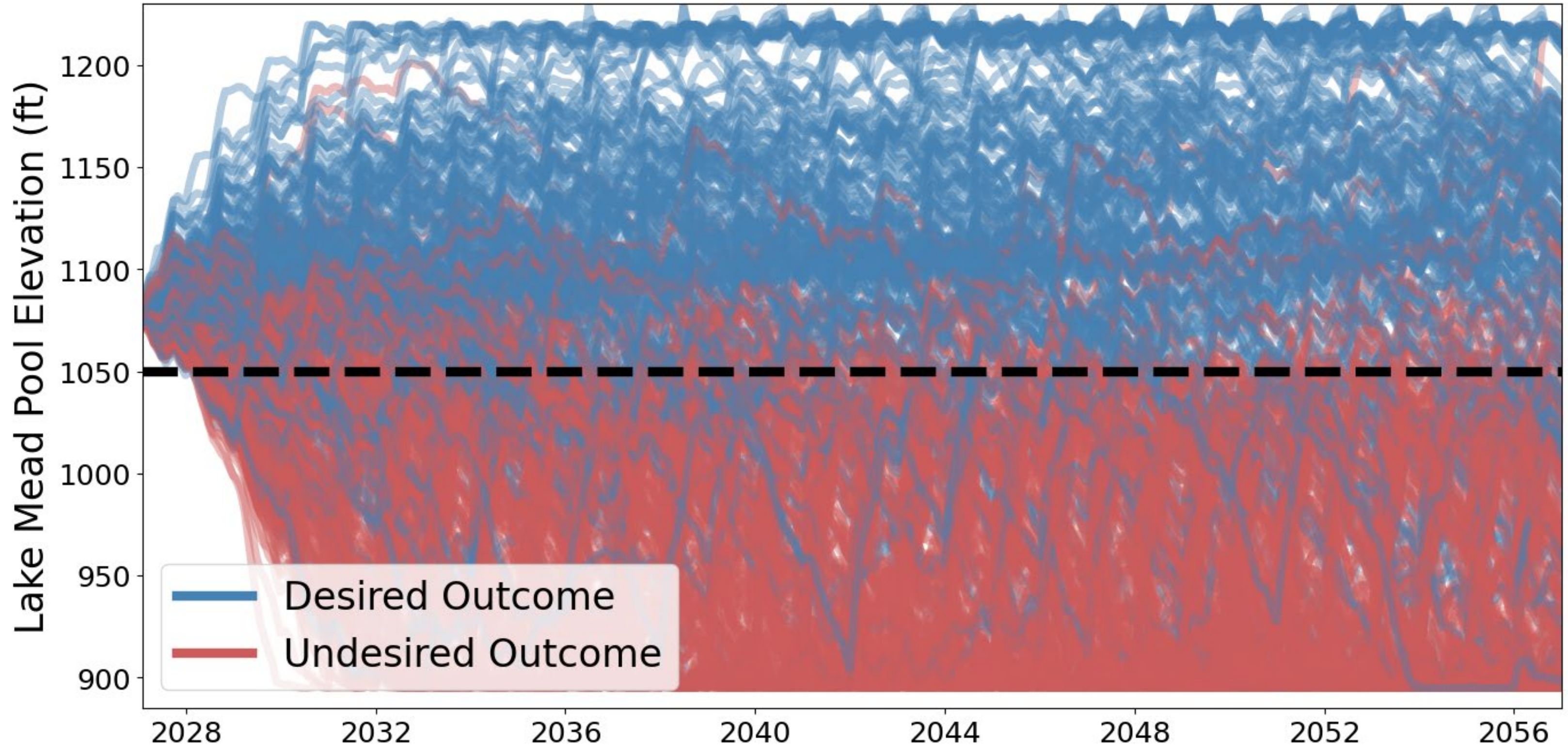


90 out of 400 traces (22.5%) result in desired outcome

Robustness Provides Better Information about Outcomes across Large Ensembles

A policy has a desirable outcome in a future if Mead Pool Elevation stays above 1050 feet in greater than 50% of the next 30 years.

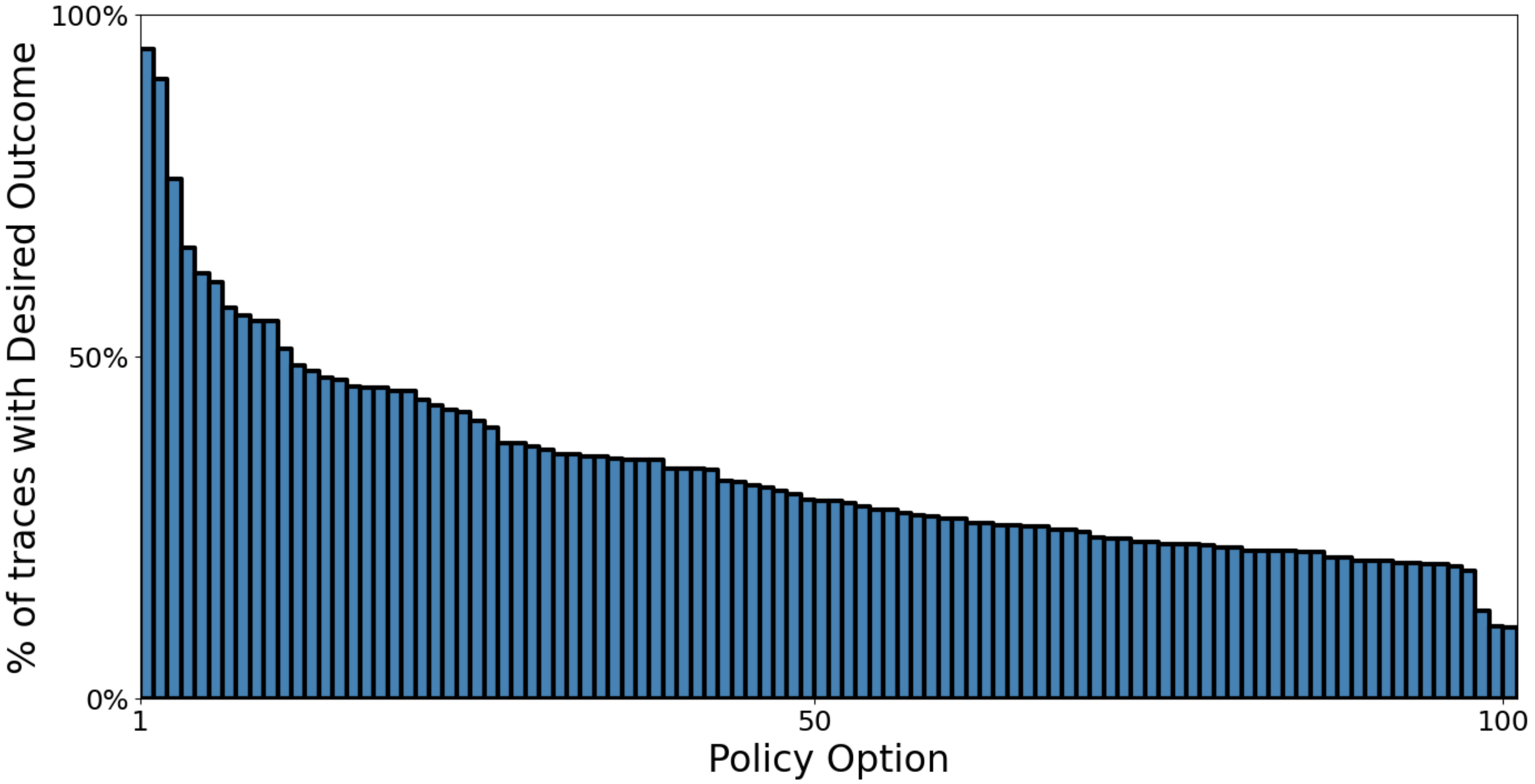


175 out of 400 traces

(43.75%)

result in desired outcome

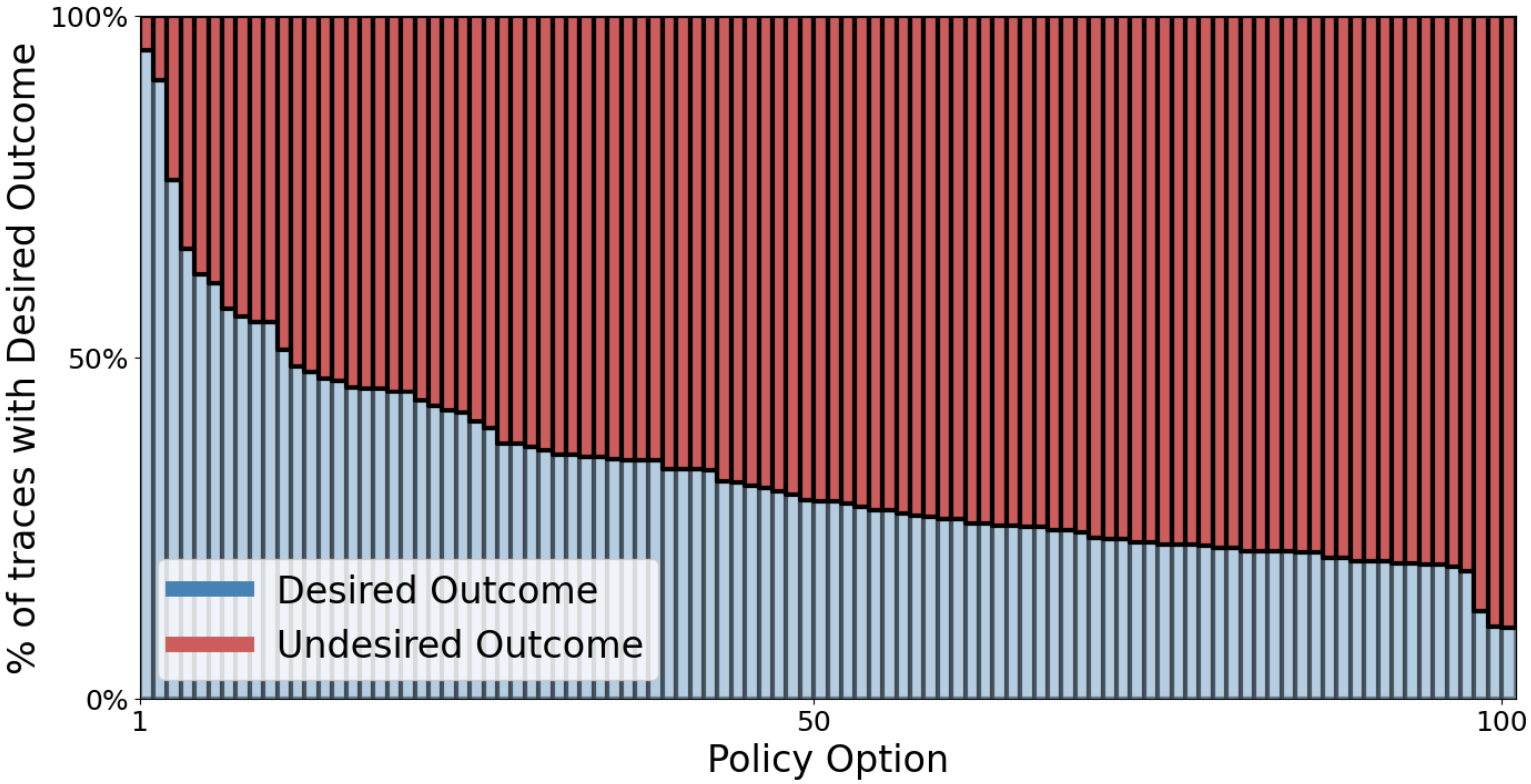
Robustness Provides Better Information about Outcomes across Large Ensembles



Widest range of desirable performance ⟷ Narrowest range of desirable performance

Robustness determines which policies perform broadly well

Robustness Provides Better Information about Outcomes across Large Ensembles



Robustness determines which policies perform broadly well but it doesn't tell us anything about poor performance when they fall short

Widest range of desirable performance ⟷ Narrowest range of desirable performance

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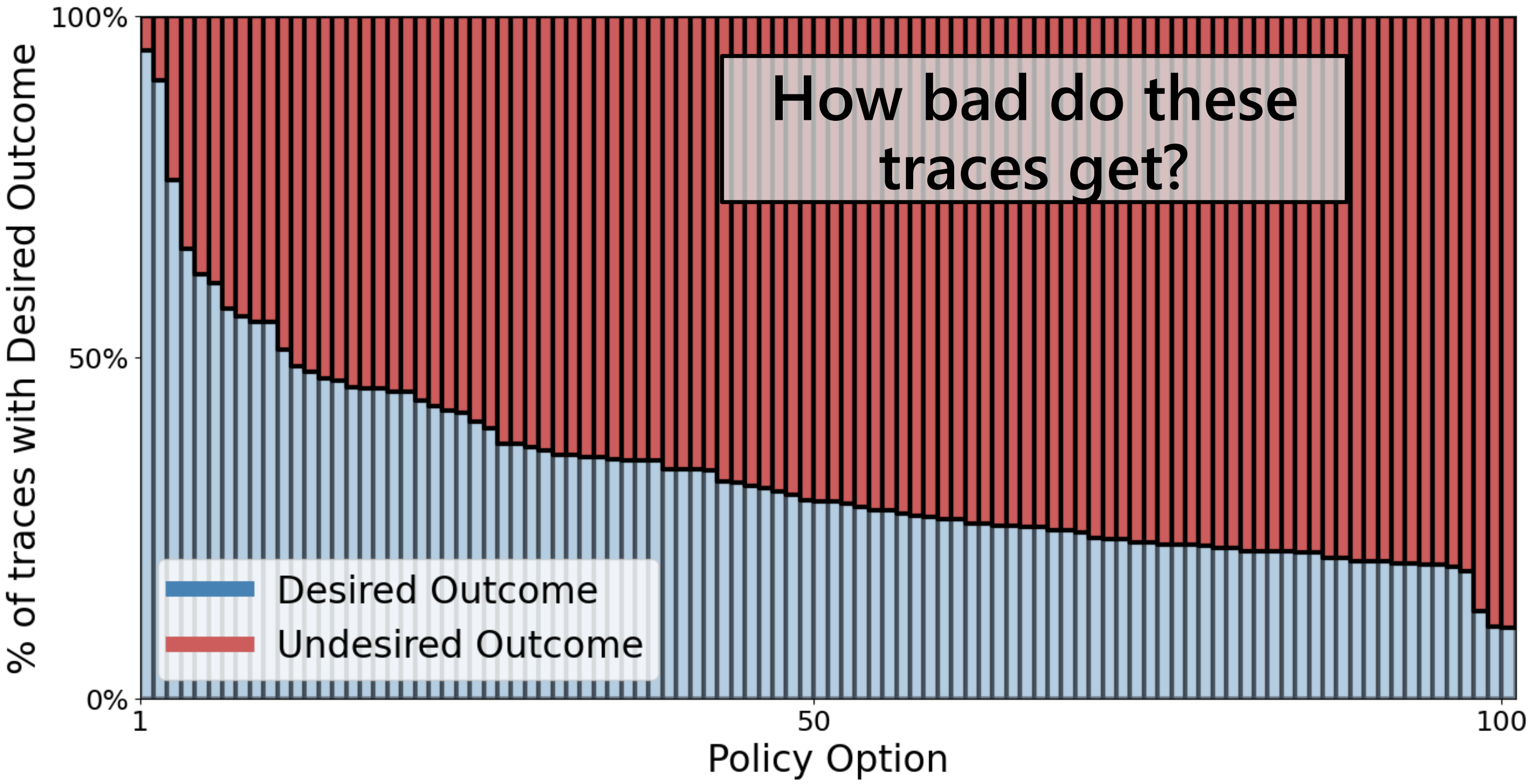

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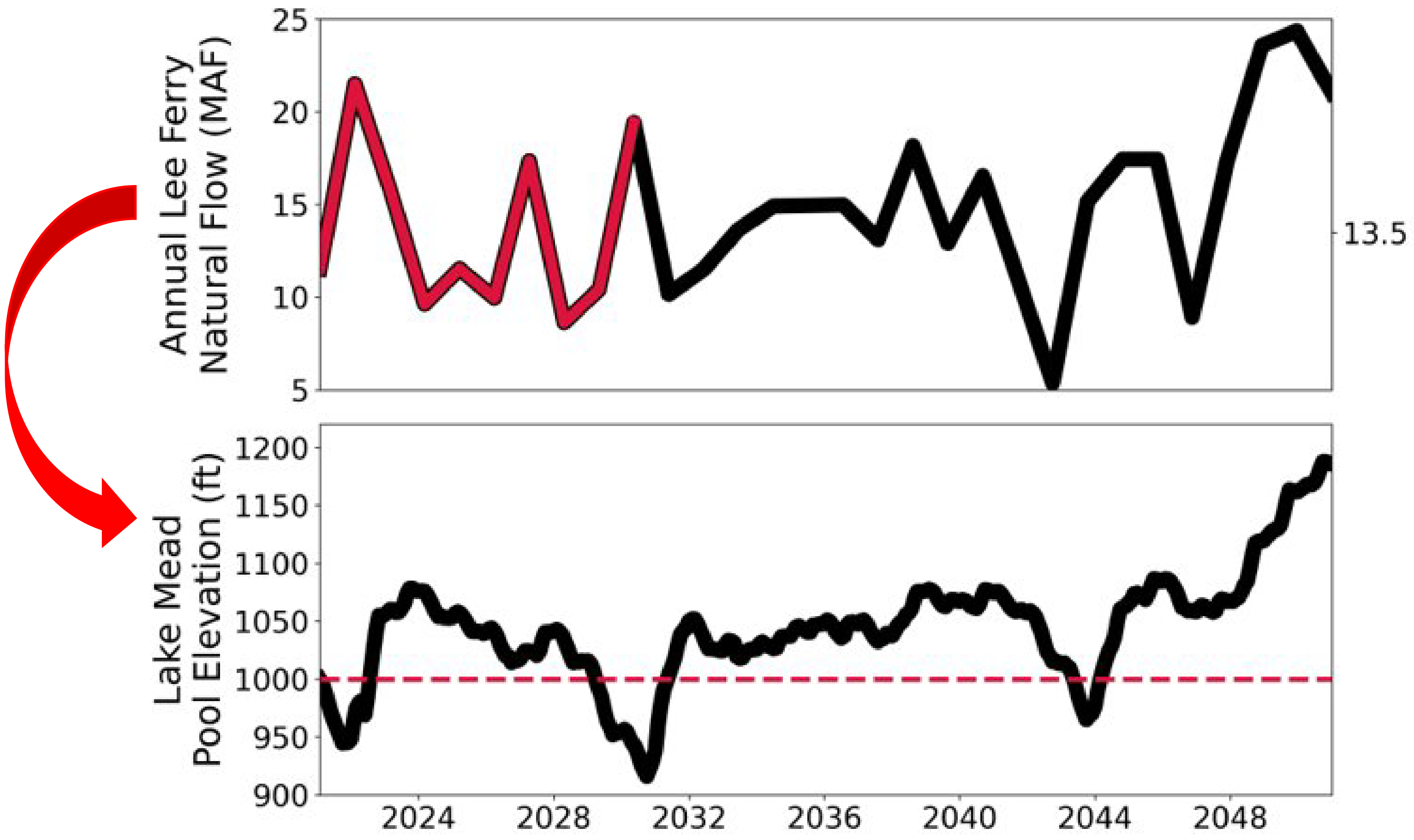
Vulnerability Finds the Conditions that Cause Unacceptable Outcomes

Each trace represents certain conditions that could occur in the future – determining which conditions cause *unacceptable* outcomes creates a map to evaluate a policy's vulnerabilities



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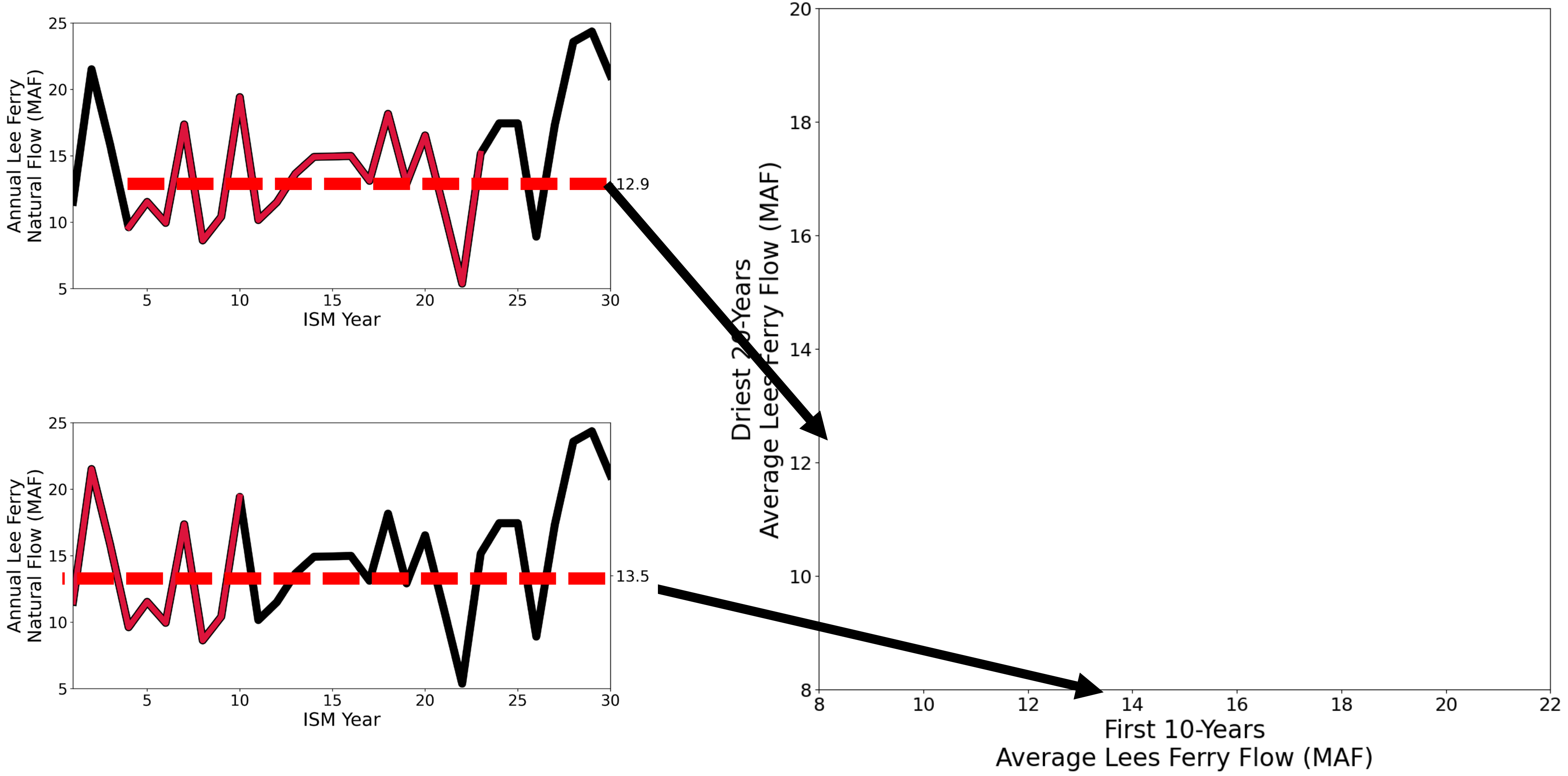

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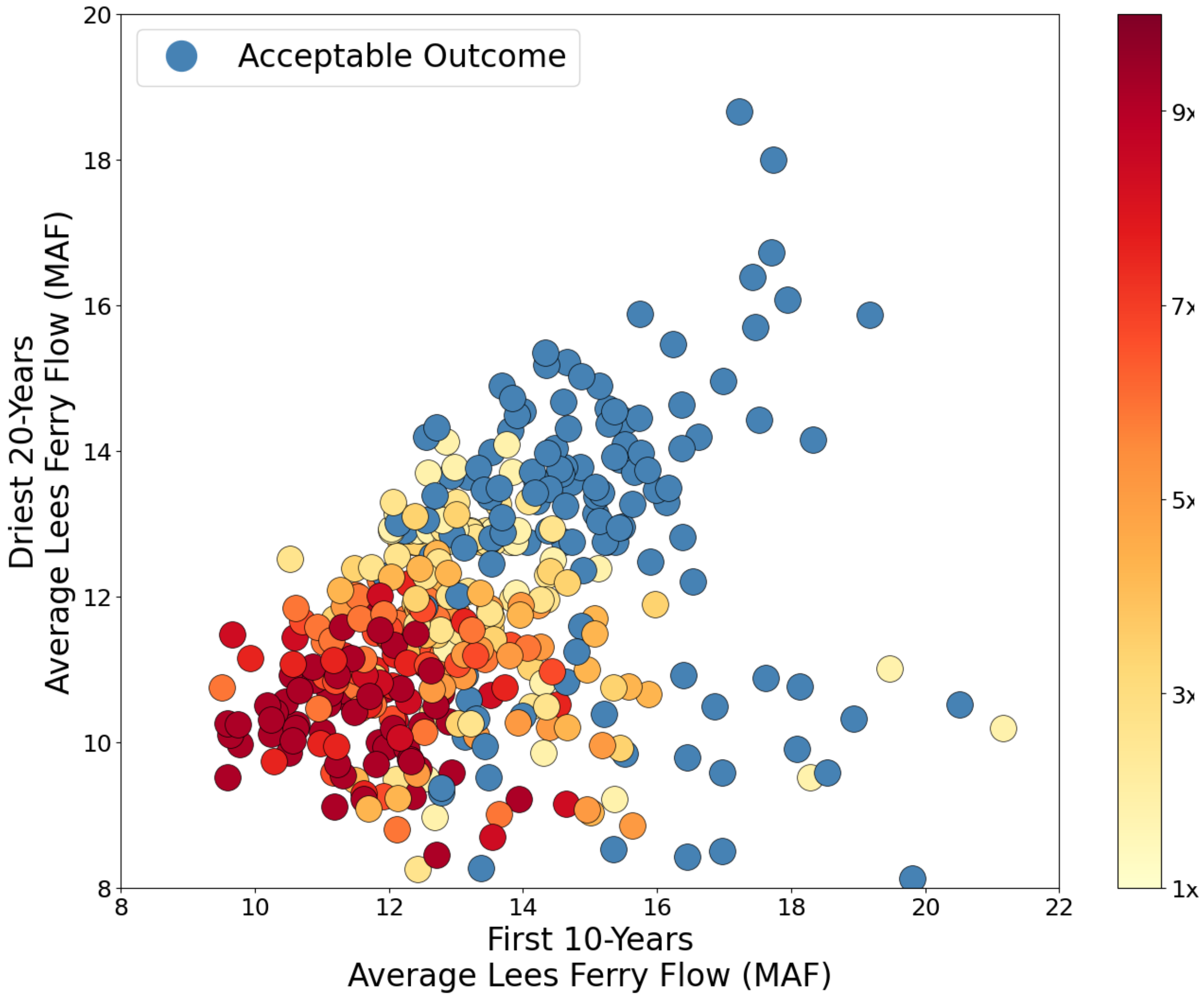

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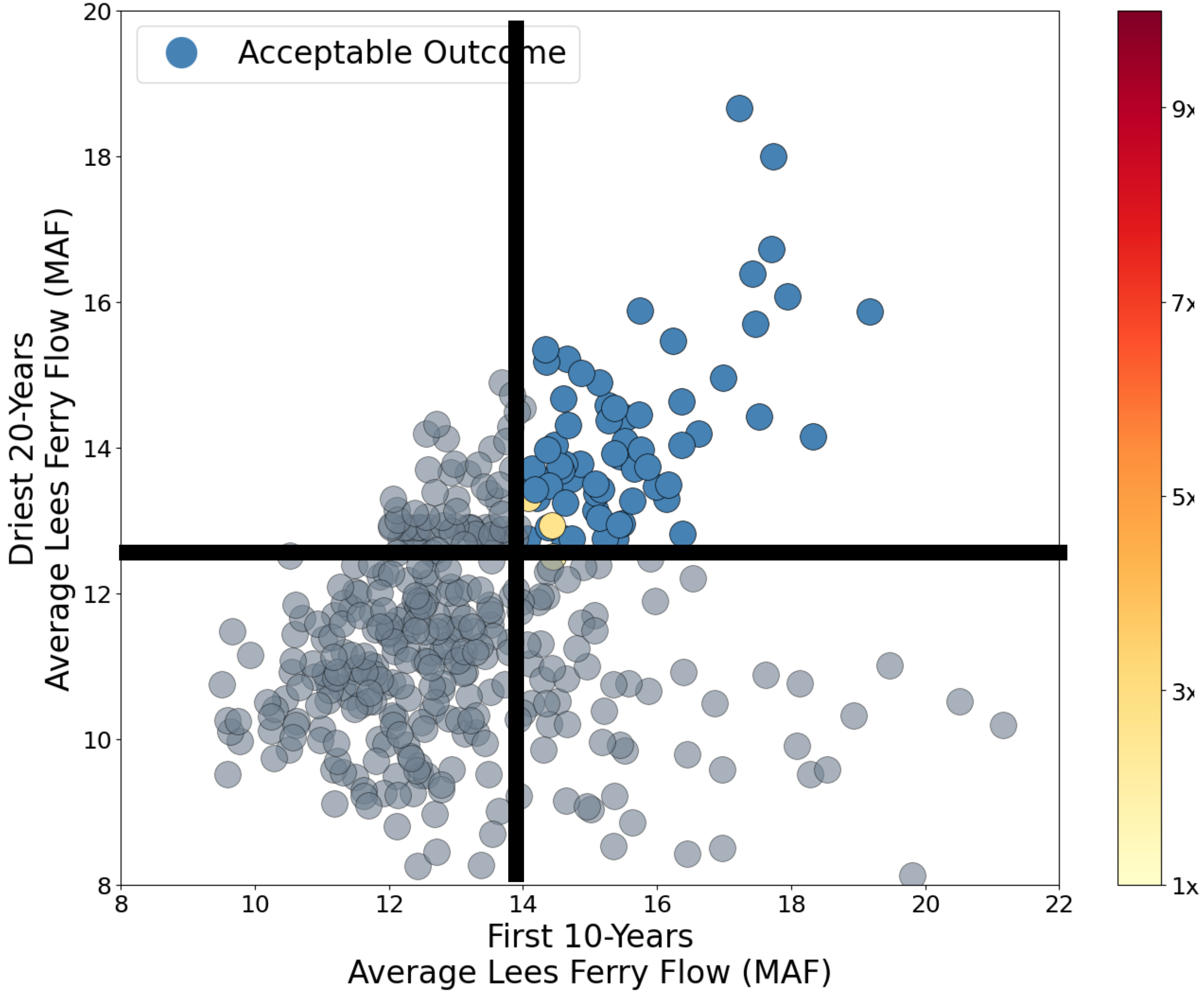

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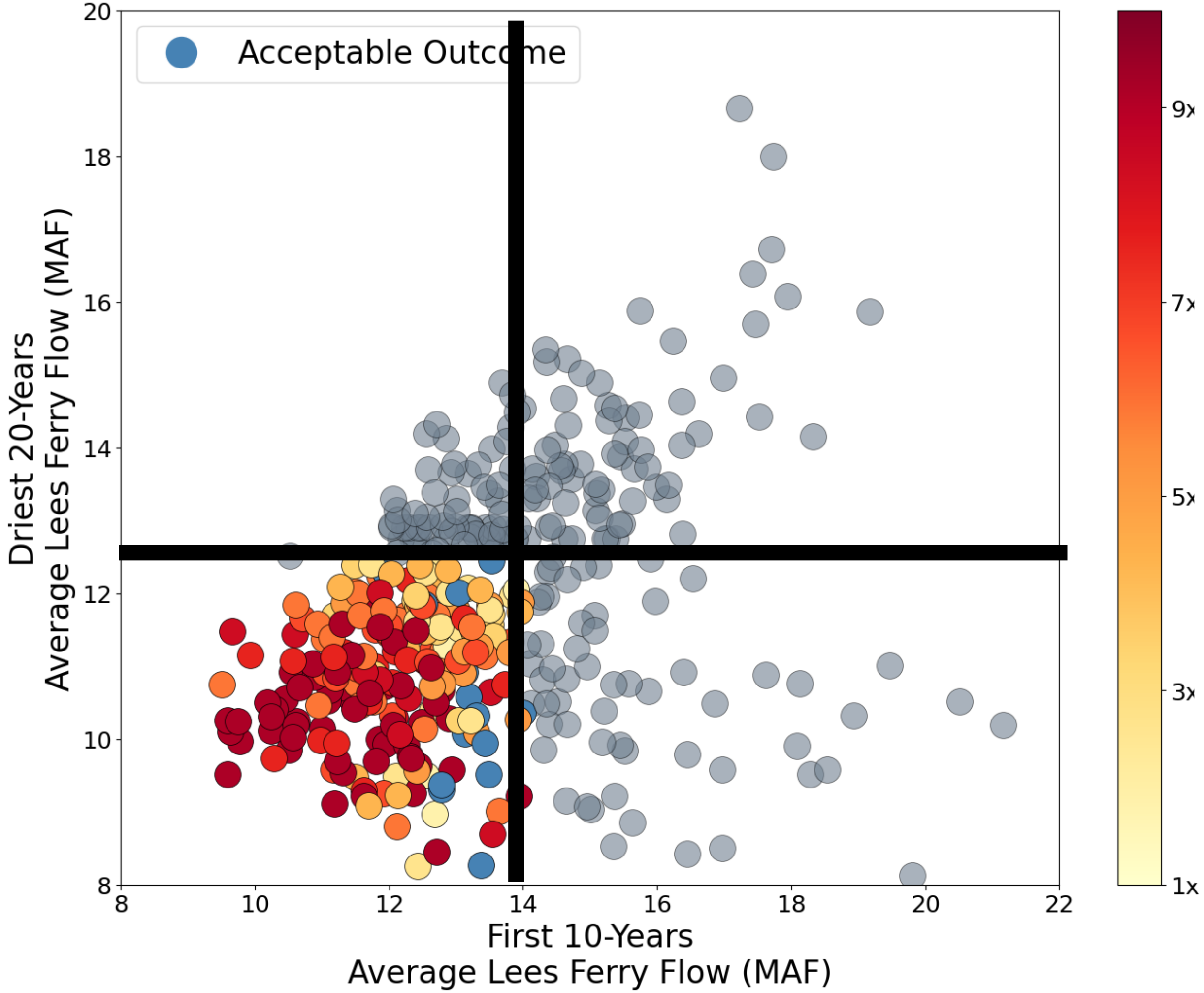

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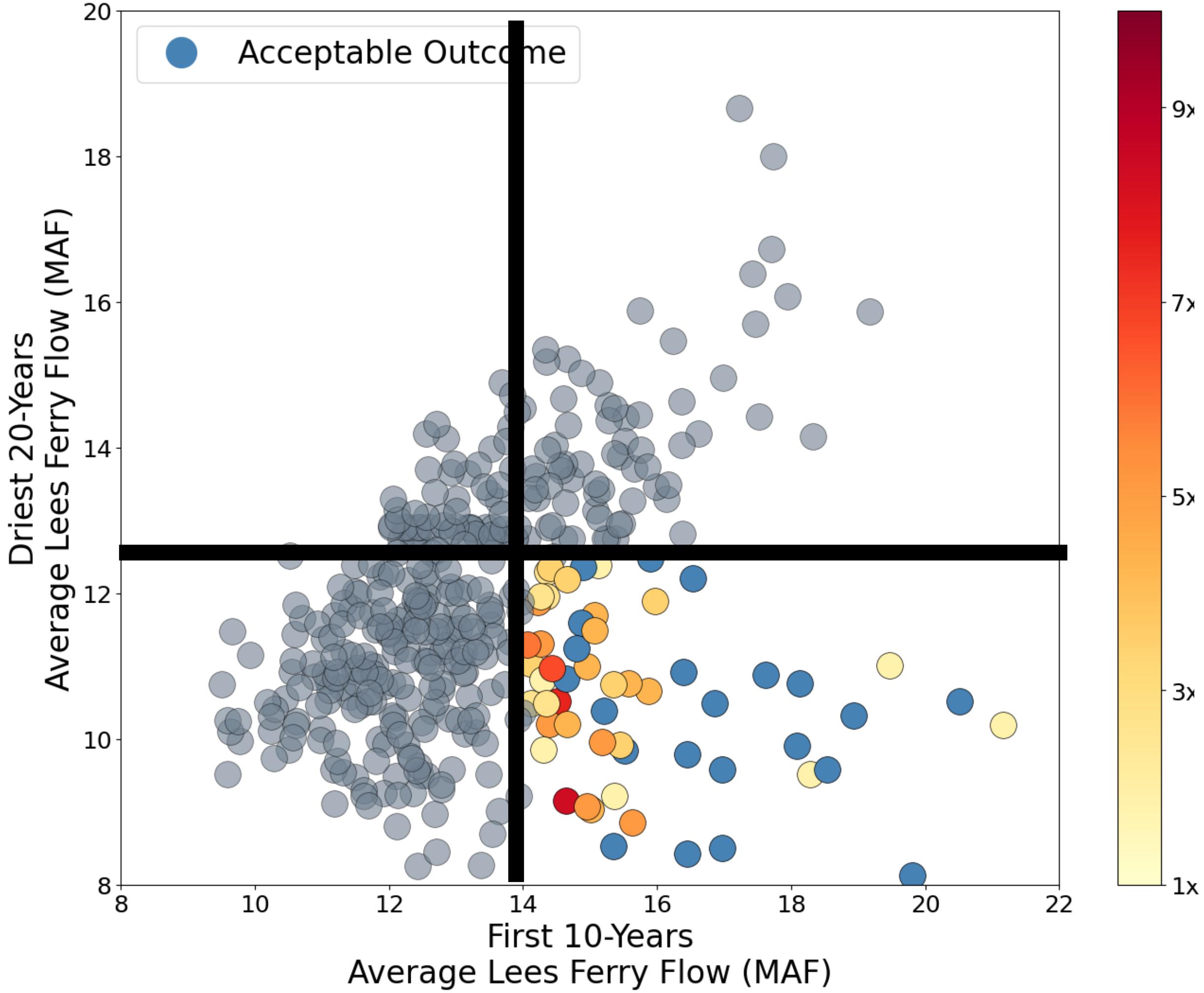

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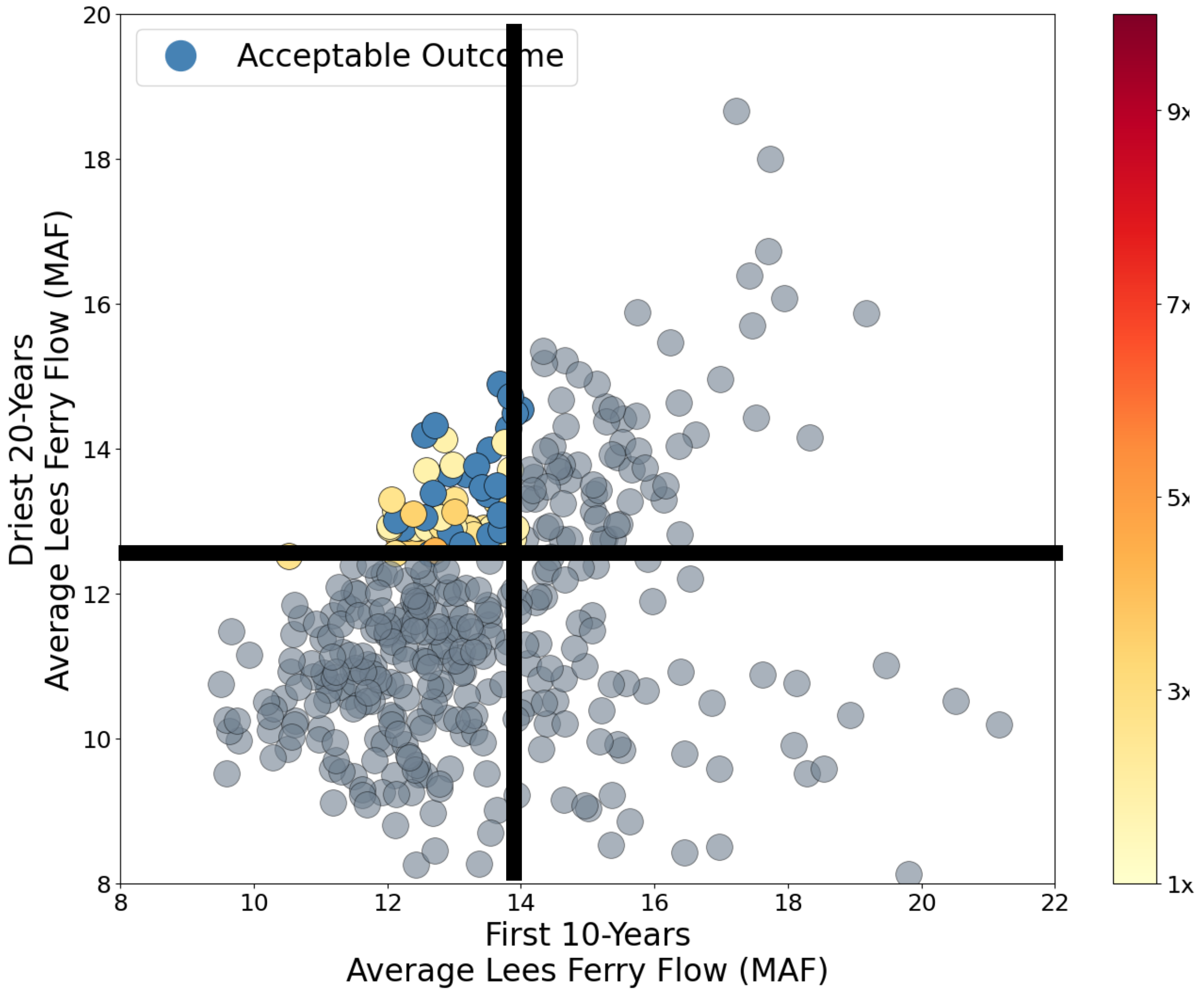
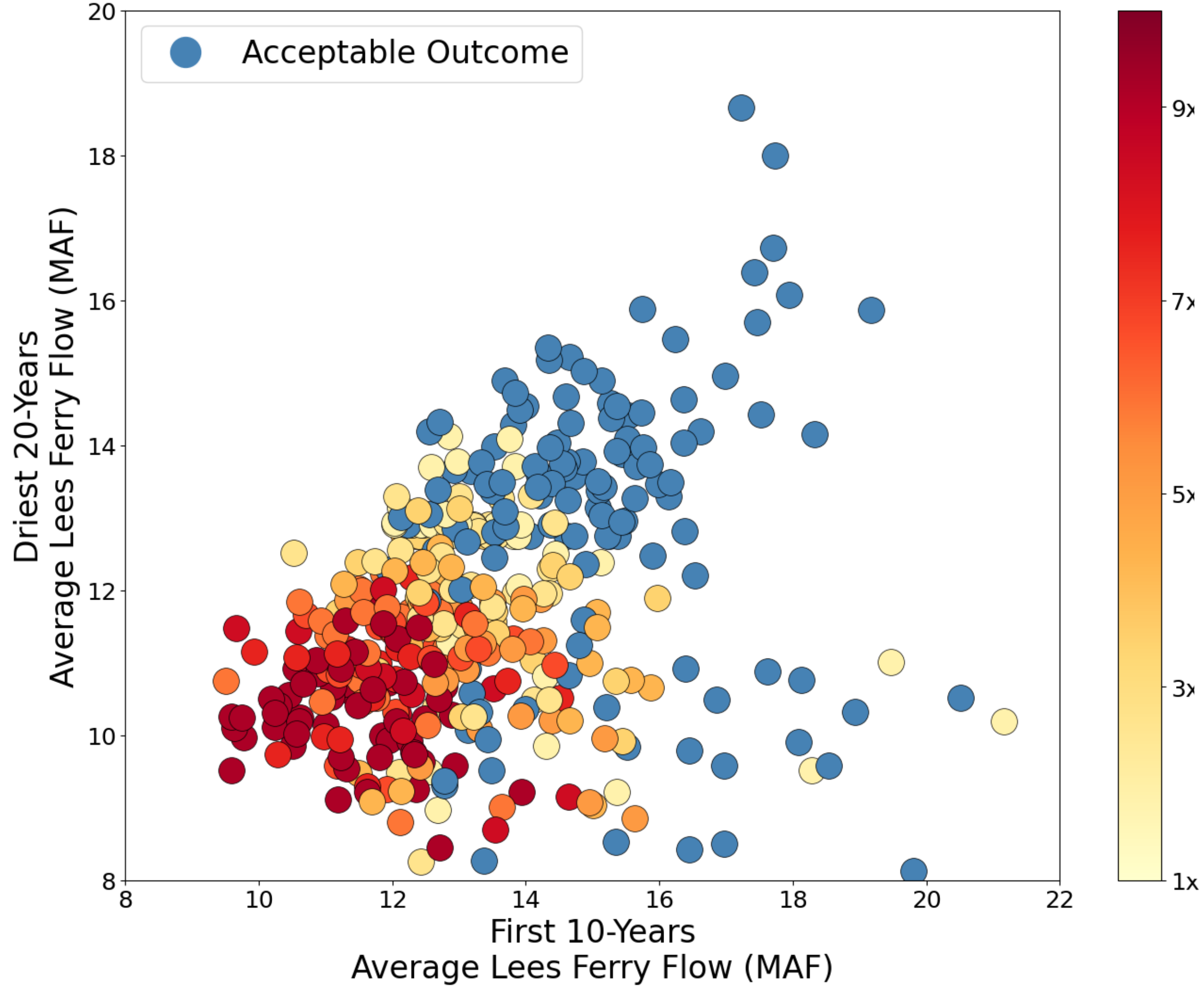


Vulnerability Finds the Conditions that Cause Unacceptable Outcomes

Identifying policy vulnerabilities can also be a way to compare two policies in more detail



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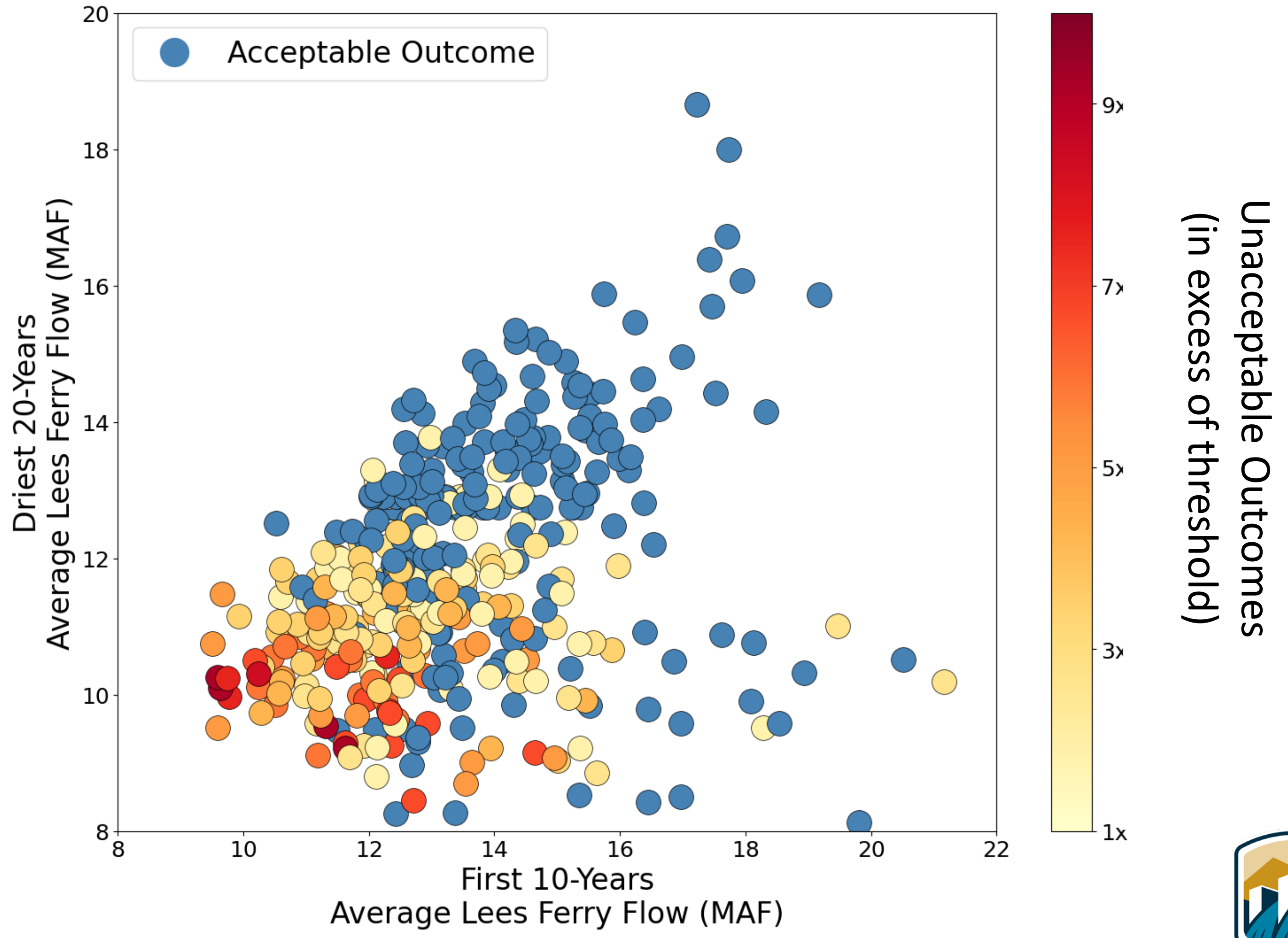
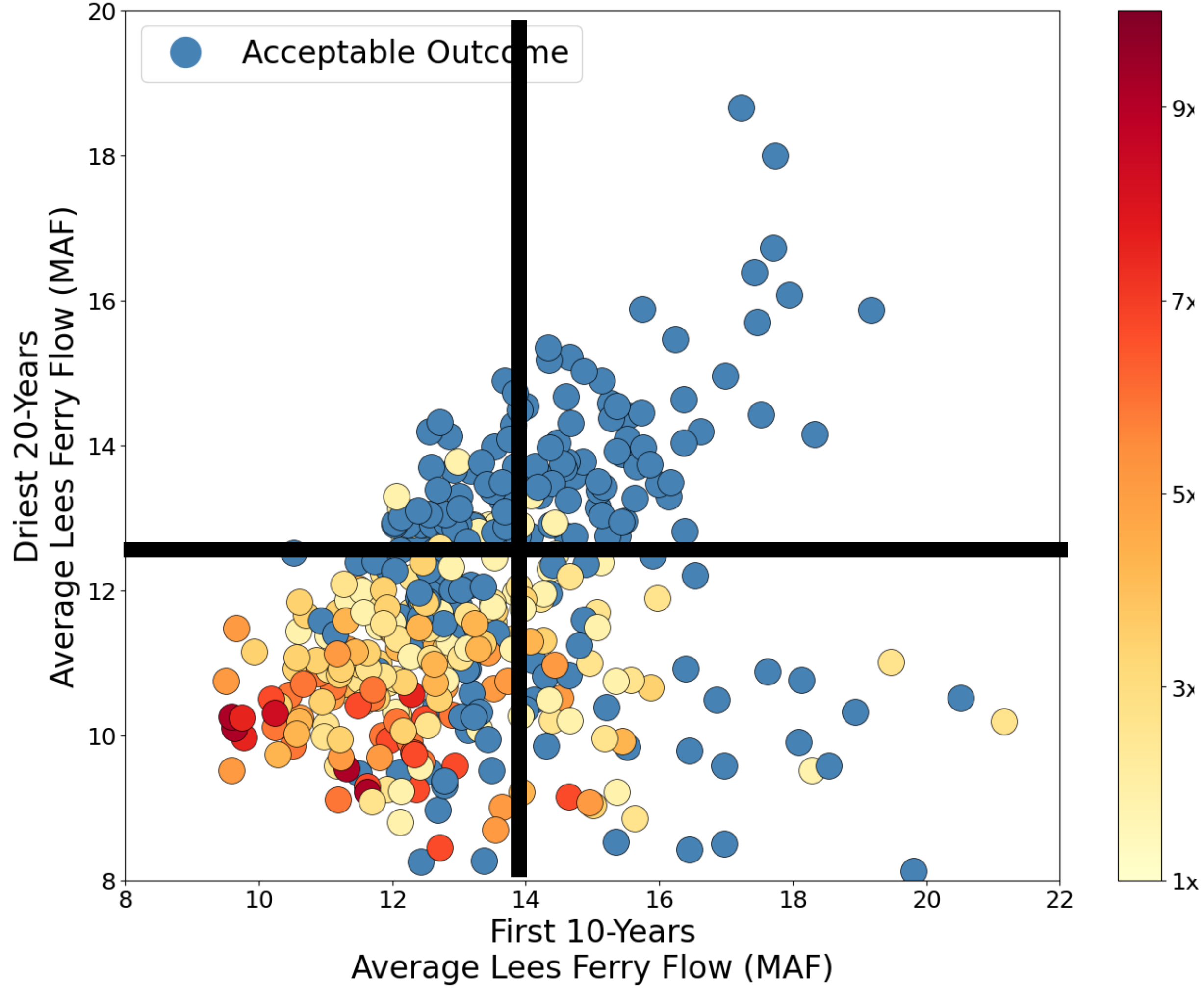
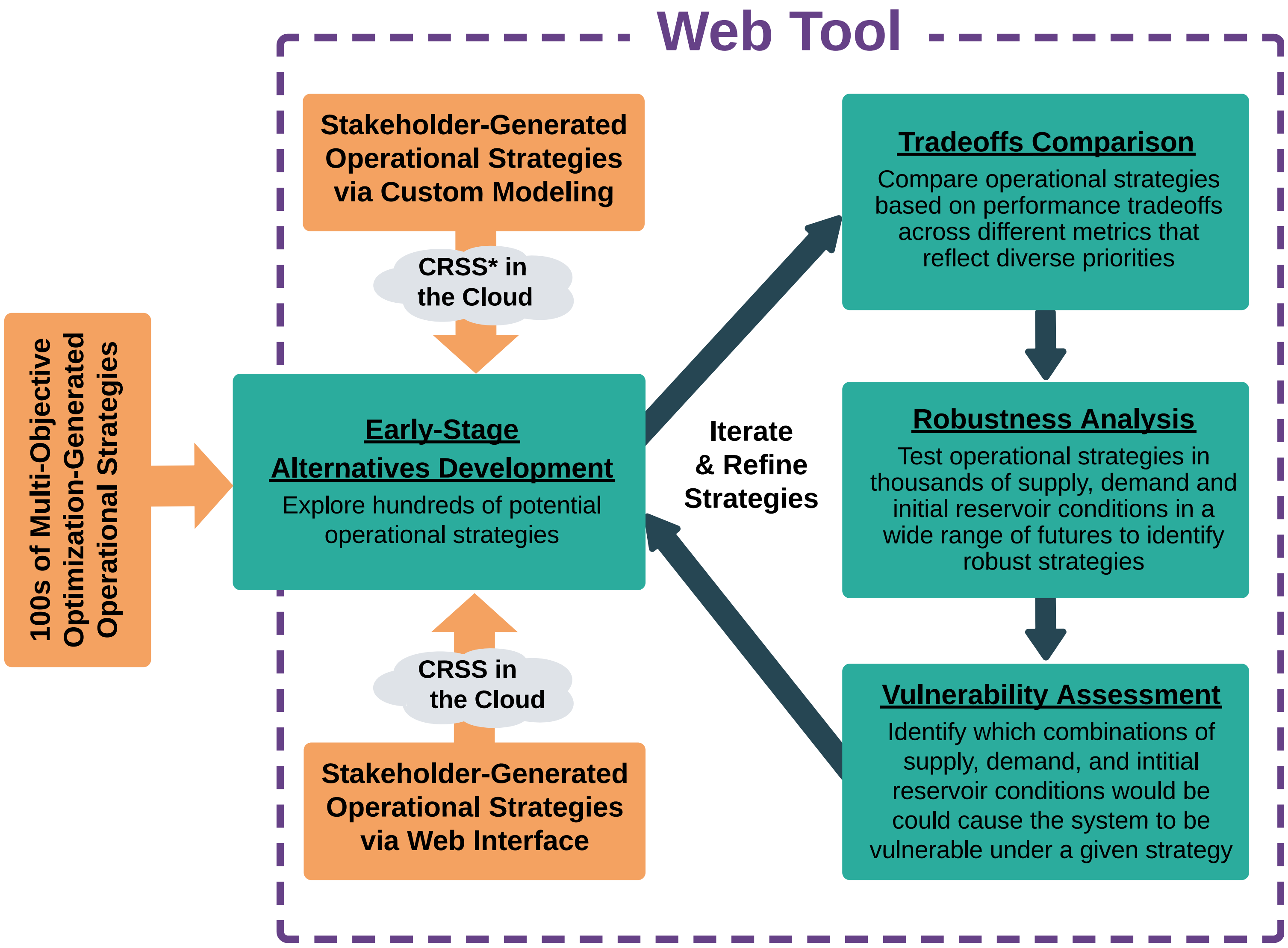


Vulnerability Finds the Conditions that Cause Unacceptable Outcomes

More 'acceptable' outcomes in the drier quadrants means this policy is less vulnerable than the first



MORDM Components and the Post-2026 Web Tool



Dozens of **performance metrics** have been developed across many resource categories; users can dynamically choose different combinations of metrics to use for comparing performance tradeoffs across different operational strategies

Users can dynamically develop criteria for **robustness**, i.e., create a custom definition of what it means for the system to perform acceptably well, and analyze the robustness of all operational strategies across a wide range of futures

Users can dynamically develop criteria for **vulnerability**, i.e., create a custom definition of unacceptable performance, to identify conditions that cause the system to be vulnerable under different operational strategies

*Colorado River Simulation System, Reclamation's long-term planning model

Session Summary

- Development of Post-2026 operational strategies is taking place under deep uncertainty and significant complexity
- We have technical tools established through decades of applications and research that are ready to support the process, including an MORDM approach uniquely suited to Colorado River Basin planning needs
- The Post-2026 Web Tool will support exploration of performance tradeoffs, robustness, and vulnerability in a customizable way across many resource categories

Future Sessions and Request for Input

- Future ITEW session topics include
  - Alternative operational strategies (what is available in Web Tool, how to explore strategies that are not)
  - Web tool intro and training
- Content will include general education and information related to the Post-2026 Technical Framework
- Future sessions
  - November 2: Alternative Paradigms
  - Mid November: two Web Tool training sessions
- Please send questions, feedback, and requests for topics to bor-sha-crbpost2026@usbr.gov


Thank You
BUREAU OF
RECLAMATION

References & Resources

1. *Decision Science Can Help Address the Challenges of Long-Term Planning in the Colorado River Basin* (JAWRA, 2022) https://onlinelibrary.wiley.com/doi/10.1111/1752-1688.12985
2. *Many objective robust decision making for complex environmental systems undergoing change* (Environmental Modeling & Software, 2013) https://www.sciencedirect.com/science/article/pii/S1364815212003131