BUREAU OF RECLAMATION

Long-Term Planning in the Colorado River Basin: The Challenge of Deep Uncertainty

Walter Orr Roberts Public Lecture, Aspen Global Change Institute

November 17, 2020

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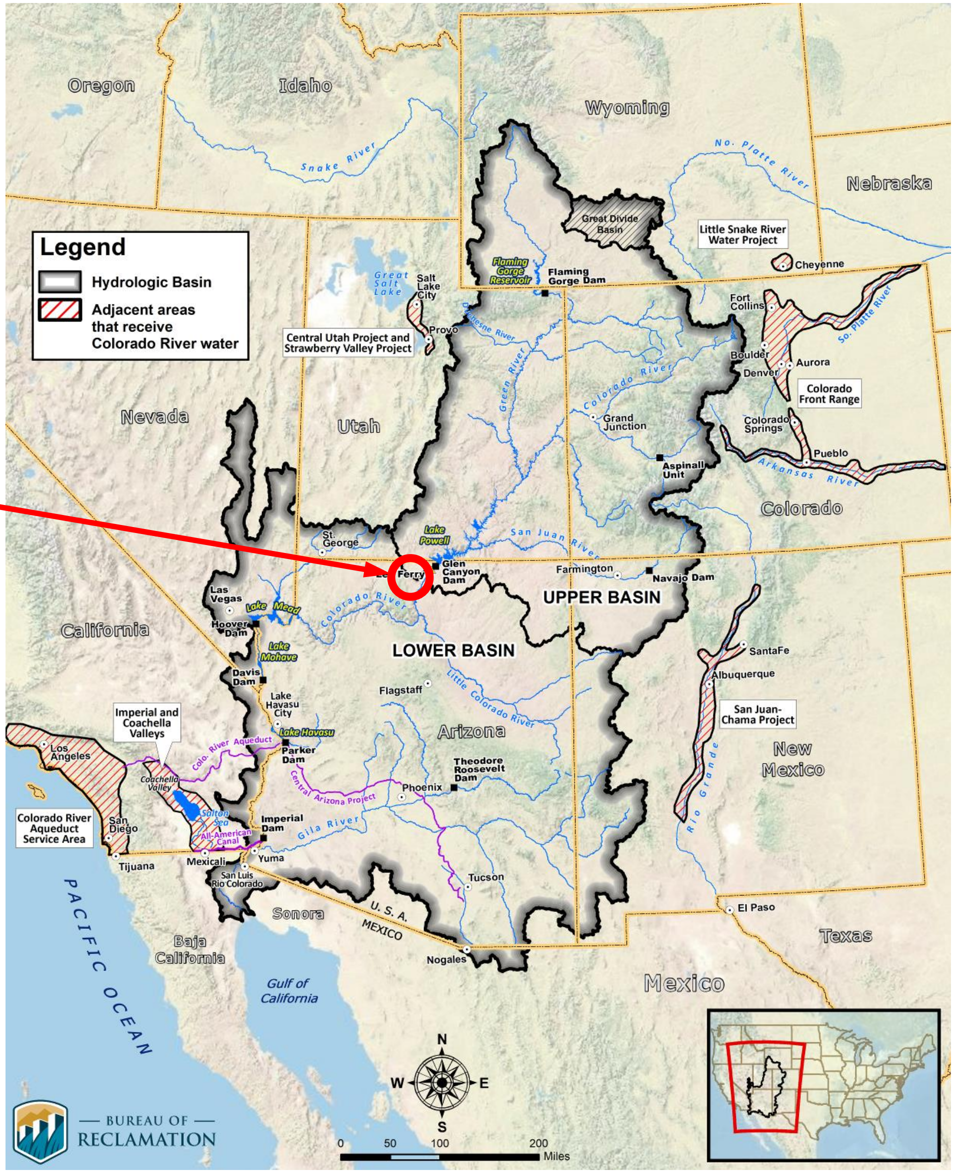
Outline

- Colorado River Basin Overview
- Define Deep Uncertainty and describe the implications for long-term Colorado River Basin planning
- Introduce concepts underlying Decision Making under Deep Uncertainty (DMDU) methods
- Describe recent Reclamation studies that employ DMDU techniques

Colorado River Basin Overview

- Vital resource for Western U.S.
  - Supplies water to ~40 million people
  - Irrigates >5 million acres of agriculture
  - Supports environment, recreation, hydropower, and culture

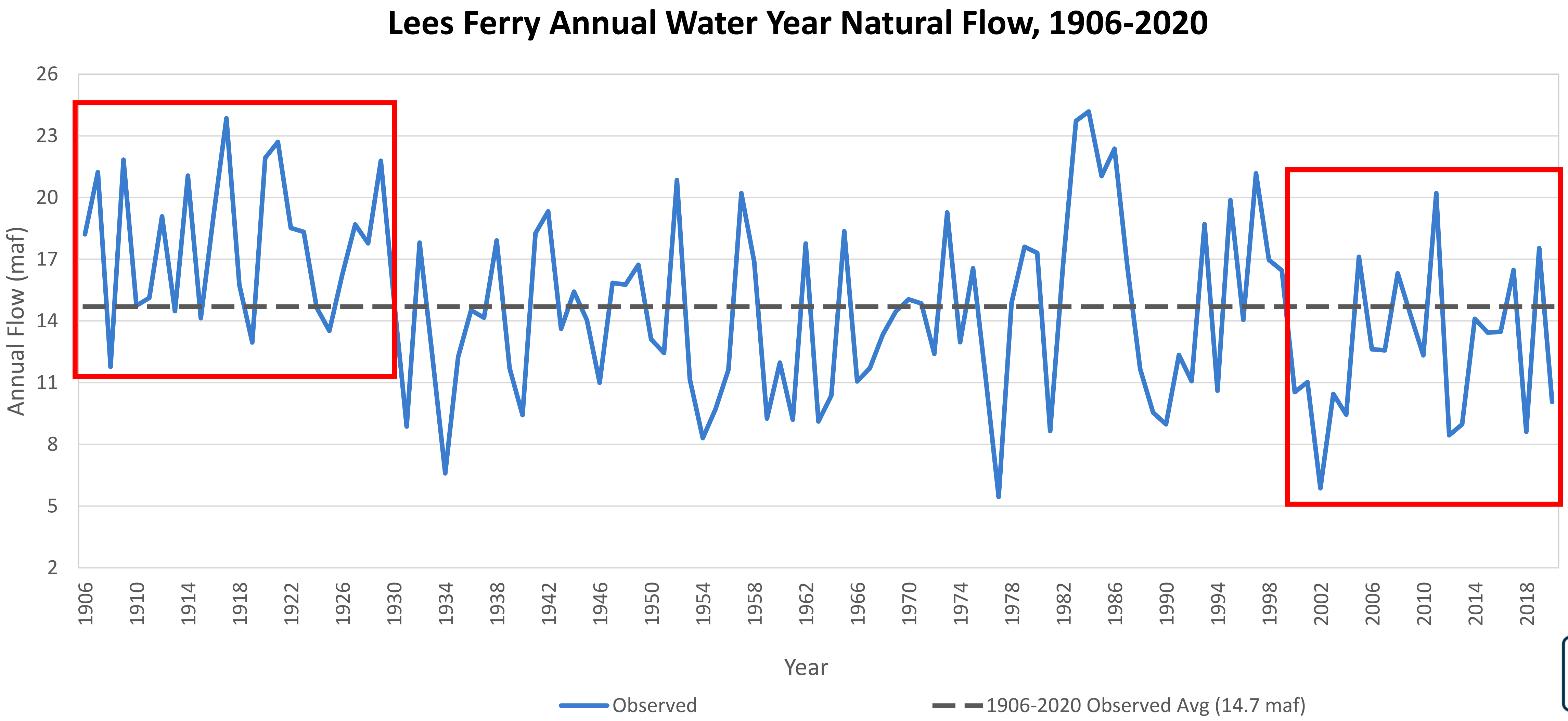
Lees Ferry, AZ



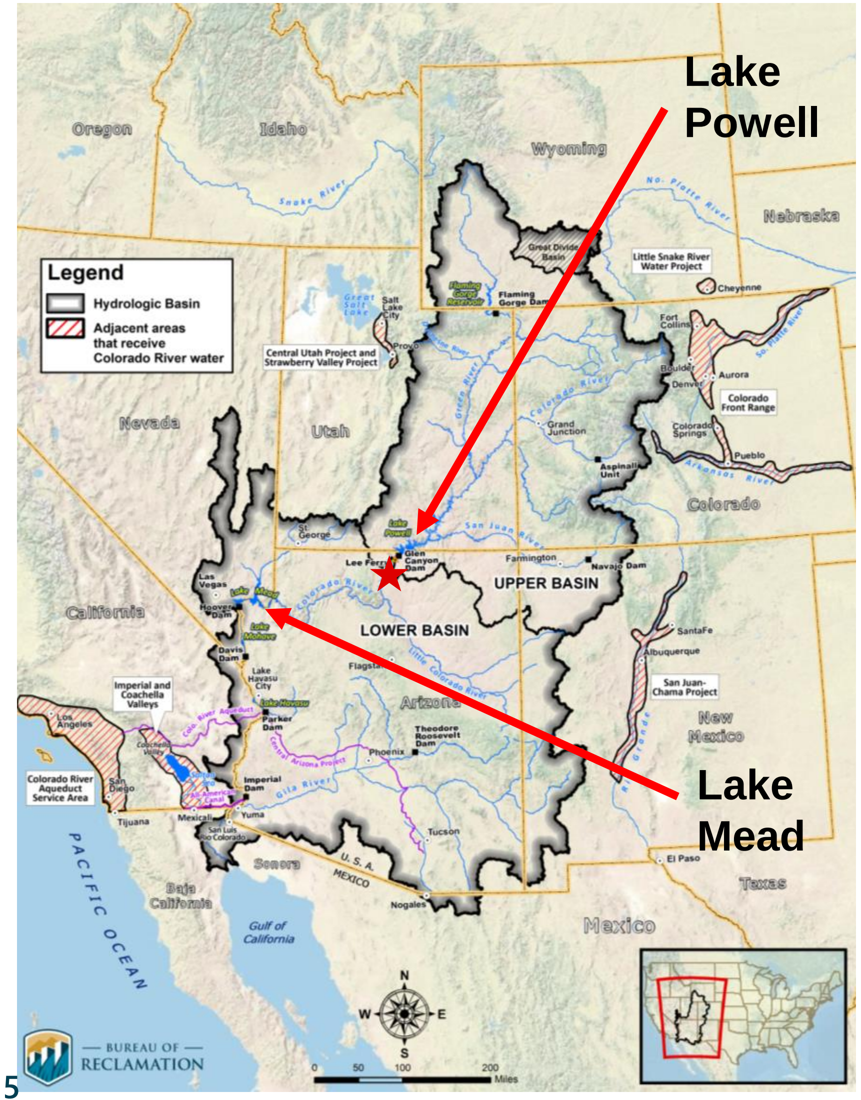
- Law of the River
  - 1922 Compact created Upper and Lower Basins and allocated 7.5 million acre-feet (maf) to each basin
  - 1944 Treaty allocated 1.5 maf to Mexico

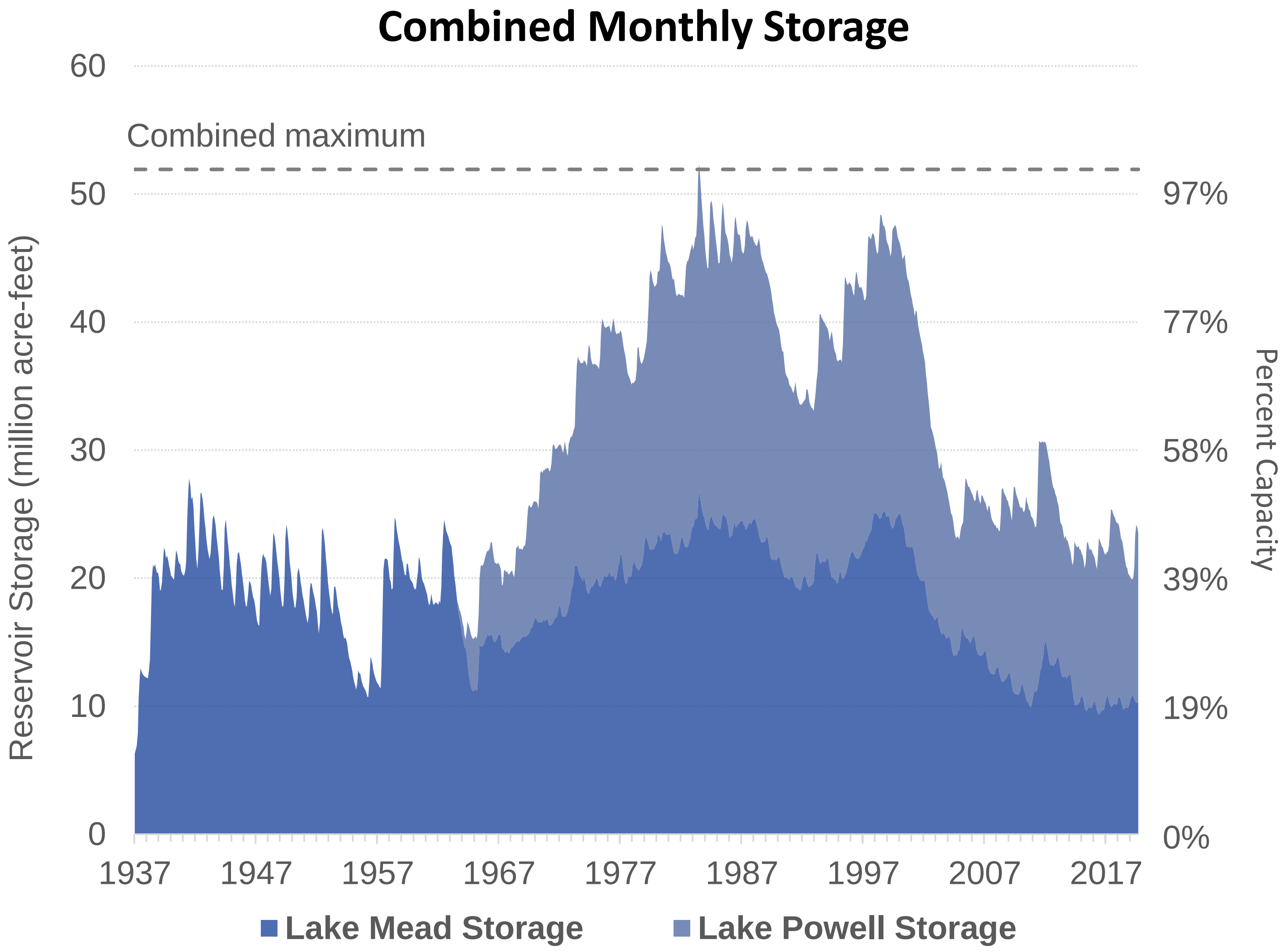
- 92% of flow originates in Upper Basin above Lees Ferry, AZ

Highly Variable Annual Flow



Colorado River Basin Storage





Recap of System and Planning Challenges

- Over-allocated
- Highly variable flow
- Extended drought
- Depleted storage
- Climate change

Departure of Annual CRB Temperature from 1970-1999 Average

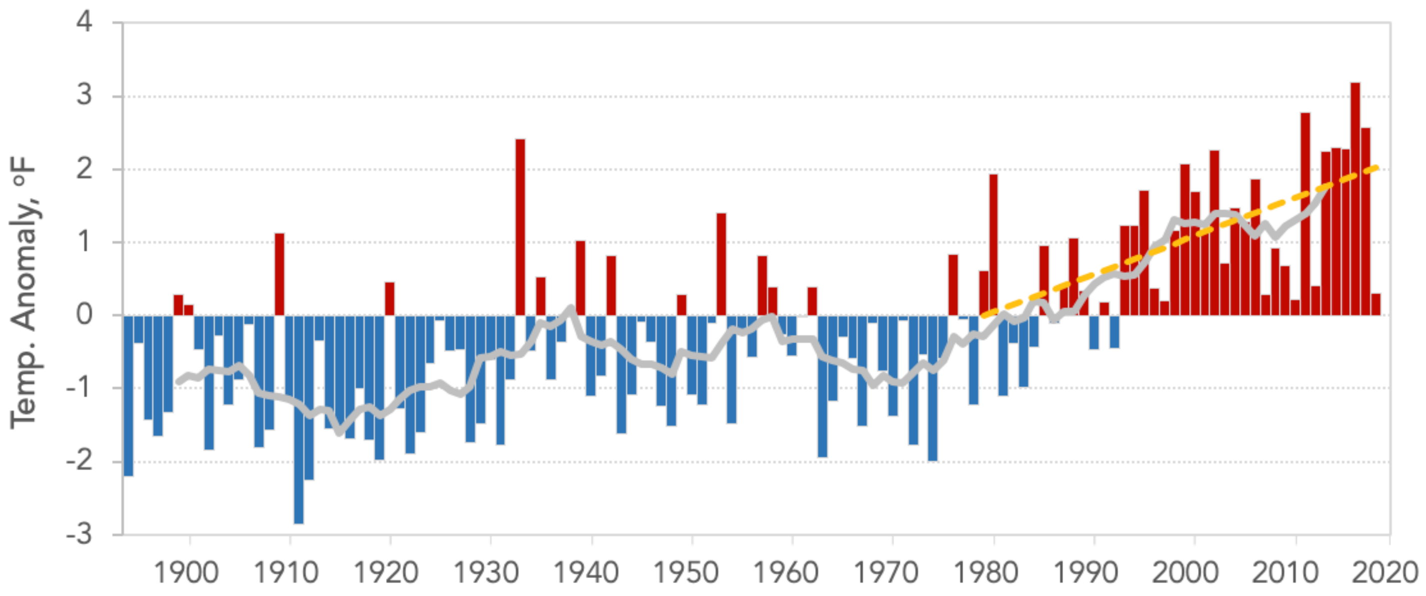


Figure 2.16 from CRB State of the Science Report

Deep Uncertainty

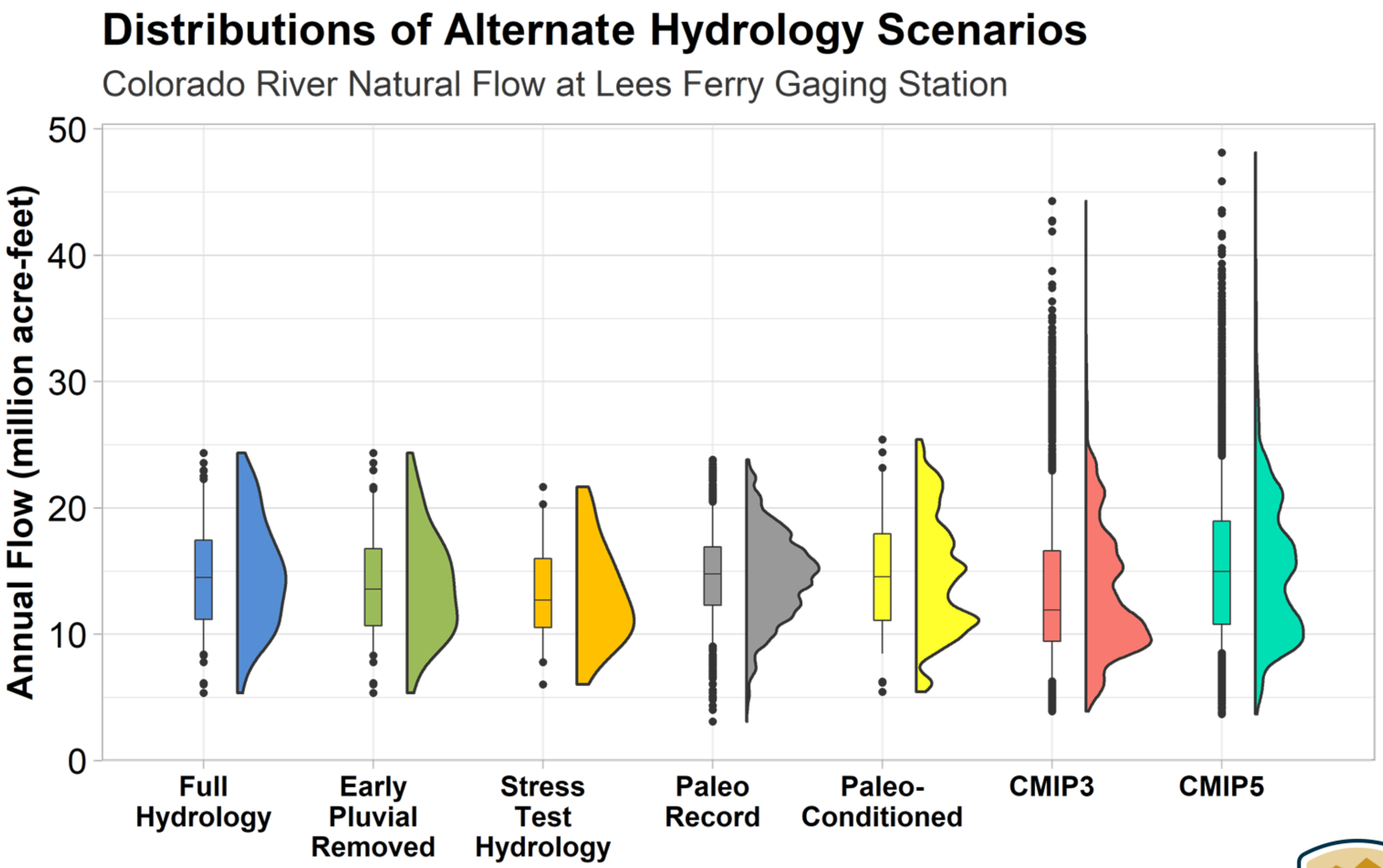
- Deep Uncertainty[1]: when parties do not know or cannot agree on
  - the most appropriate system model(s) and/or
  - probability distributions of key external conditions and/or
  - how to value different measures of system performance

- Deep Uncertainty in the Colorado River Basin
  - Many sources of projections of future hydrology and demand
  - Multiple management objectives

[1]Lempert, R. J., et al. (2006). "A General, Analytic Method for Generating Robust Strategies and Narrative Scenarios." *Management Science* 52 (4): 514–28

Deep Uncertainty: Many Sources of Hydrology

- Observations
  - Full Hydrology: 1906-present*
  - Pluvial Removed: 1931-present
  - Stress Test: 1988-present
- Tree rings
  - Paleo Record[2]: 762-2005
  - Paleo-Conditioned Ensemble[3]
- Climate projections
  - CMIP3* ensemble
  - CMIP5 ensemble

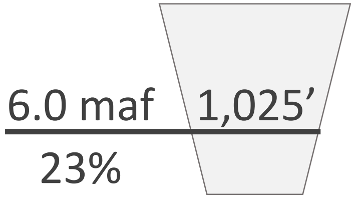


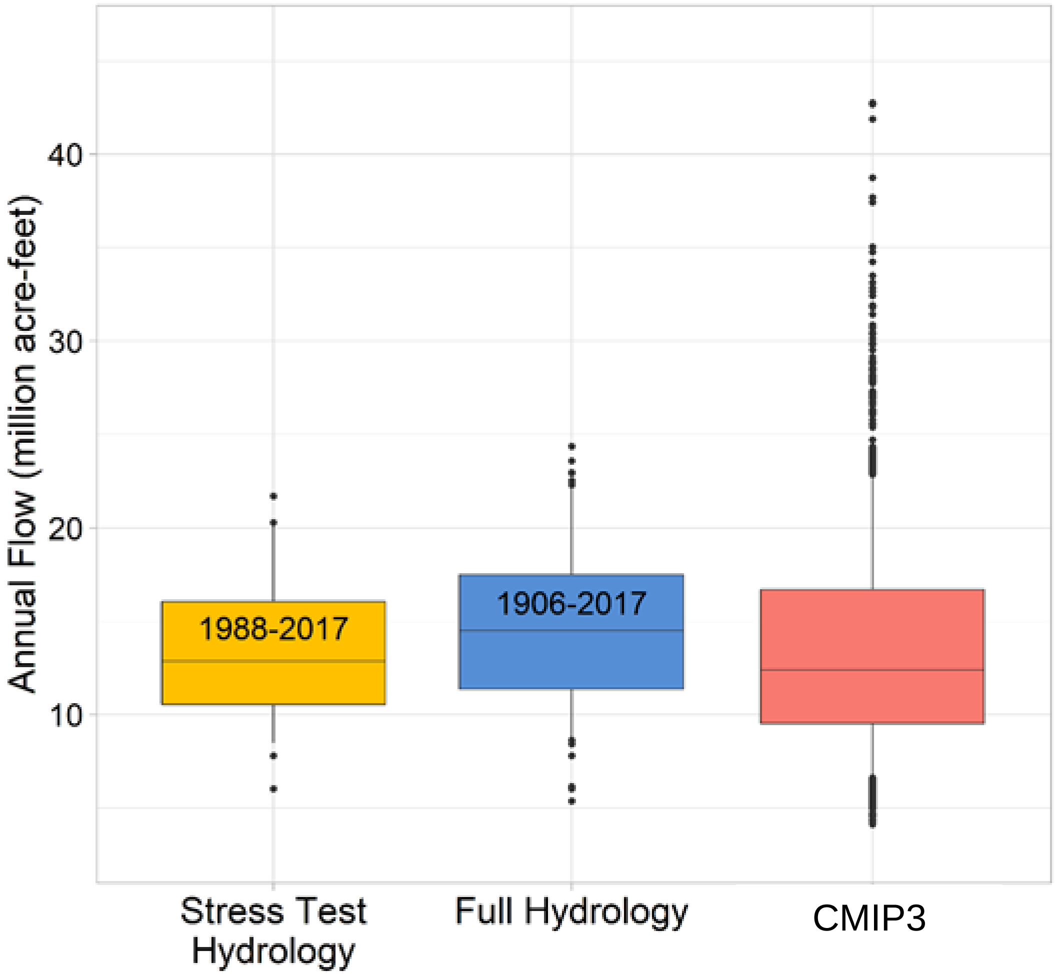
*conceptually these scenarios get updated annually but the distributions shown here capture observations through 2017

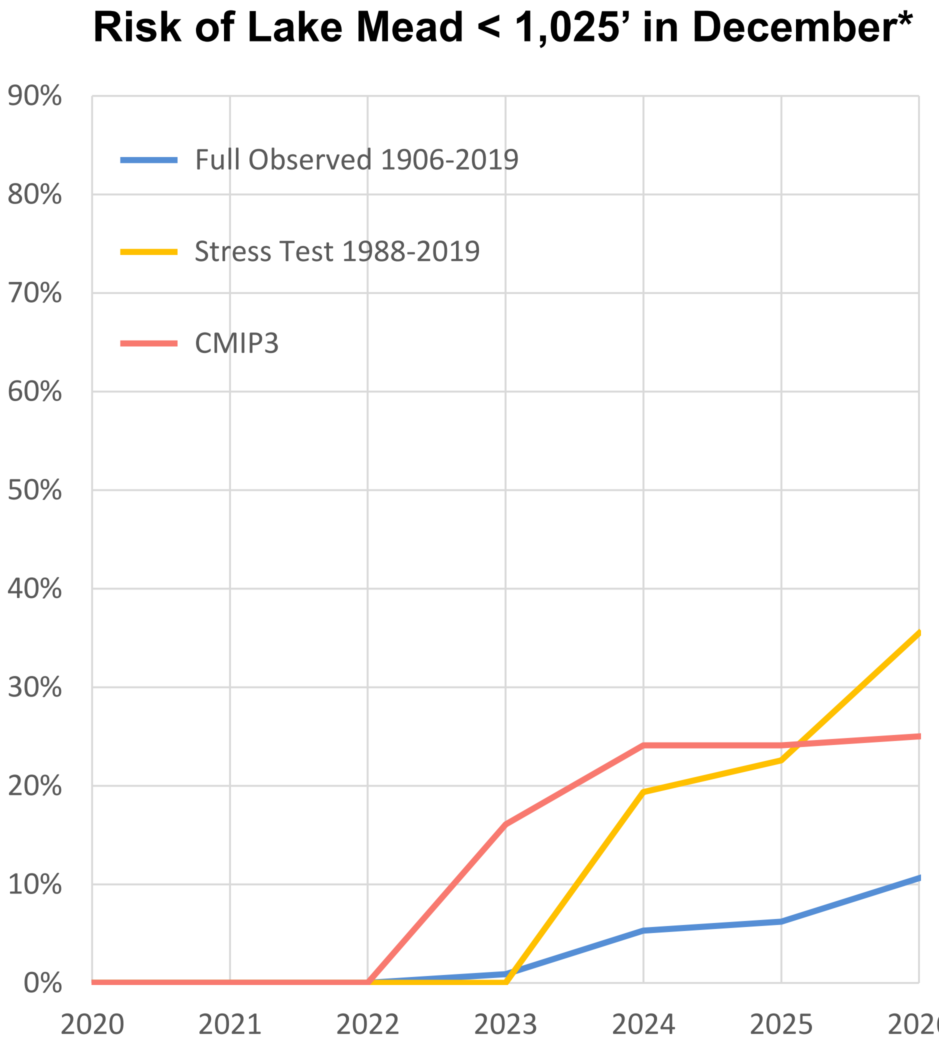
[2]Meko DM, et al. (2007) Medieval drought in the Upper Colorado River Basin. Geophys Res Lett 34, doi:10.1029/2007GL029988

[3]Prairie, J, et al. (2008) A stochastic nonparametric approach for streamflow generation combining observational and paleoreconstructed data, Water Resour. Res., 44, W06423, doi:10.1029/2007WR006684

Comparing System Risk

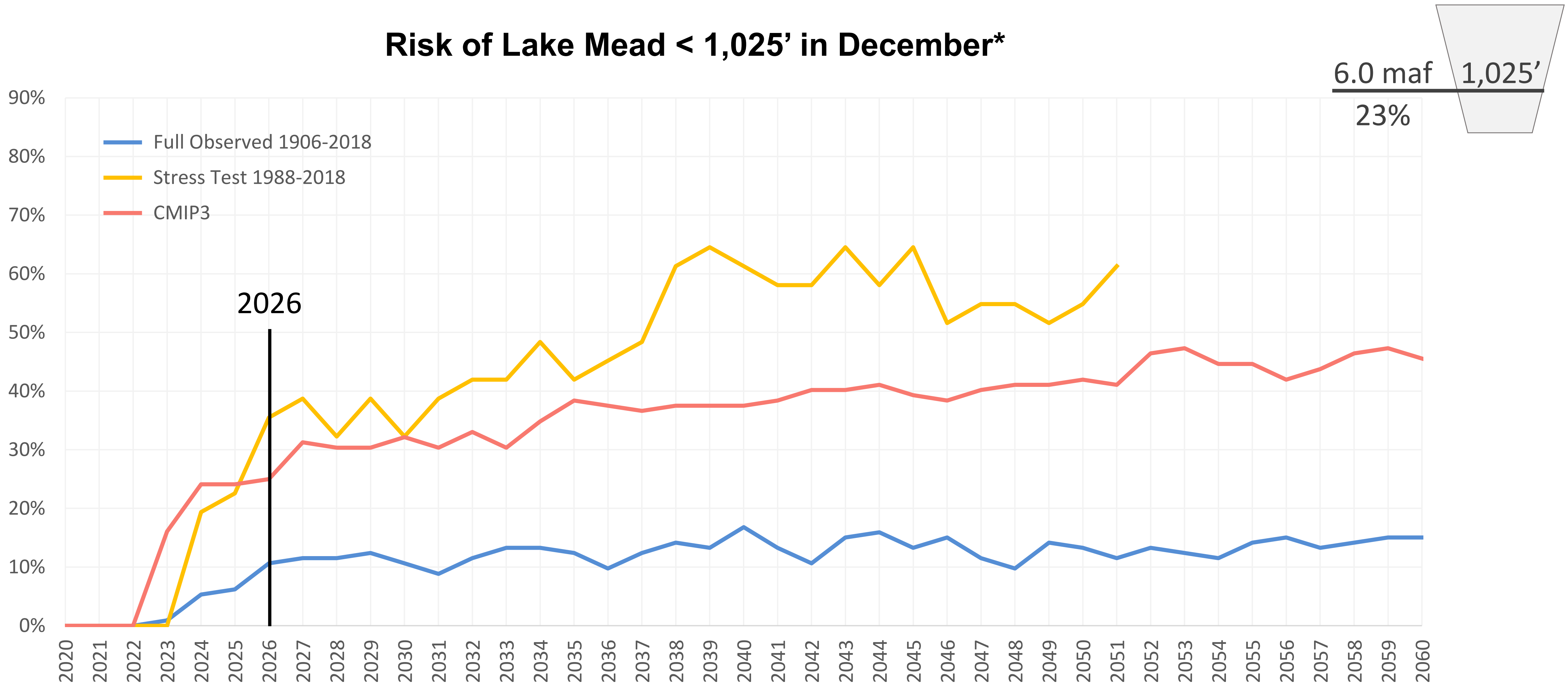






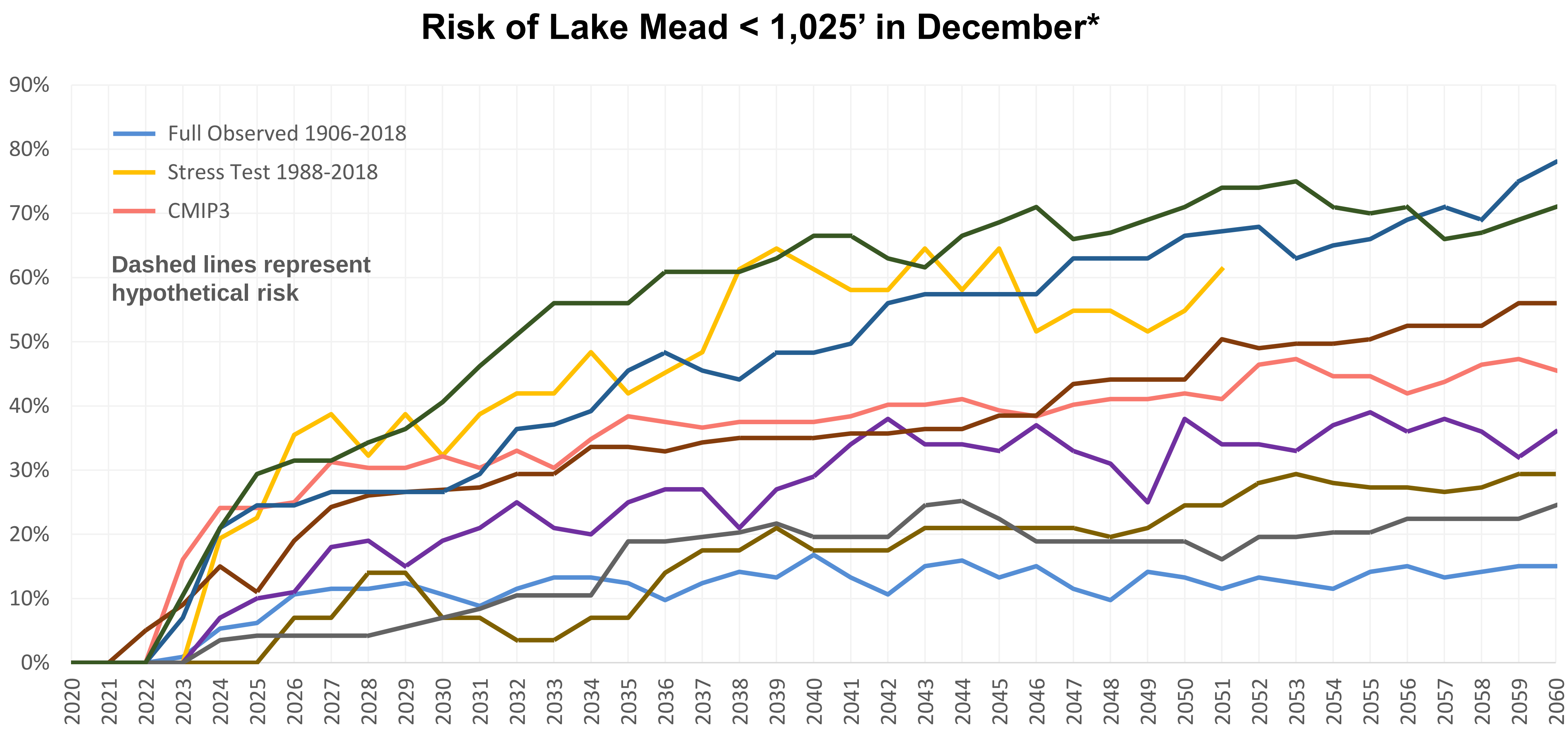
*Projections from August 2020 CRSS run

Risk of Lake Mead < 1,025' in December*



*Projections from August 2020 CRSS run

- Each line represents a set of assumptions about future hydrology, demand, and policy



*Projections from August 2020 CRSS run

- Each line represents a set of assumptions about future hydrology, demand, and policy
- There are essentially infinite lines
- There is no way to determine which set of assumptions is best

Decision Making under Deep Uncertainty

- Decision Making under Deep Uncertainty (DMDU) methods incorporate concepts and techniques that help address the problem of choosing a subset of future conditions

- Robustness
  - Test a plan or policy in a wide range of futures, treating all futures as equally likely
  - A *robust* policy will perform *acceptably well* across the range

- Vulnerability-based analysis
  - Identify observable external conditions that cause the system to be vulnerable
  - Create signposts that provide early warning that action may be required

DMDU in the 2012 Colorado River Basin Water Supply and Demand Study

- Used Robust Decision Making (RDM) to analyze:
  - 4 supply scenarios
  - 6 demand scenarios
  - 6 resource categories
  - 160 options and strategies to address future supply-demand imbalance
- Wide range of uncertainty: 23,508 equally likely futures
- Vulnerability analysis of baseline system
  - Defined reliability metrics, e.g. keeping Lake Mead pool elevation >1,000 ft
  - Chose vulnerability thresholds, e.g. if Lake Mead <1,000 ft in any month, the system is vulnerable
  - Simulated the system in all futures to identify what *conditions* cause vulnerability
- Used signposts to dynamically develop thousands of long-term plans to try to reduce vulnerability

Robust Decision Making (RDM)

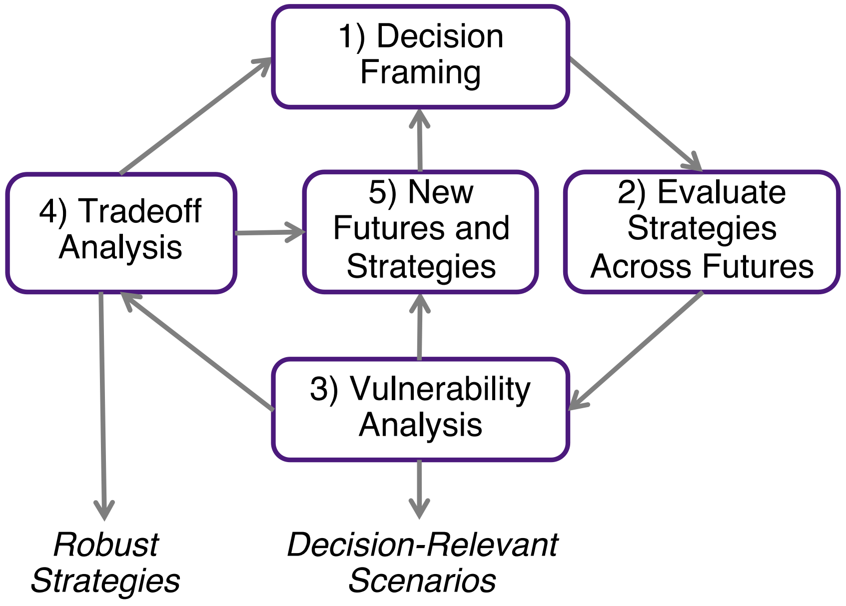
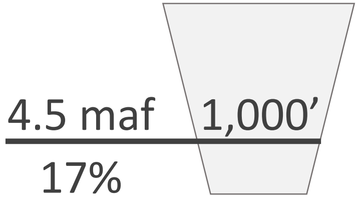


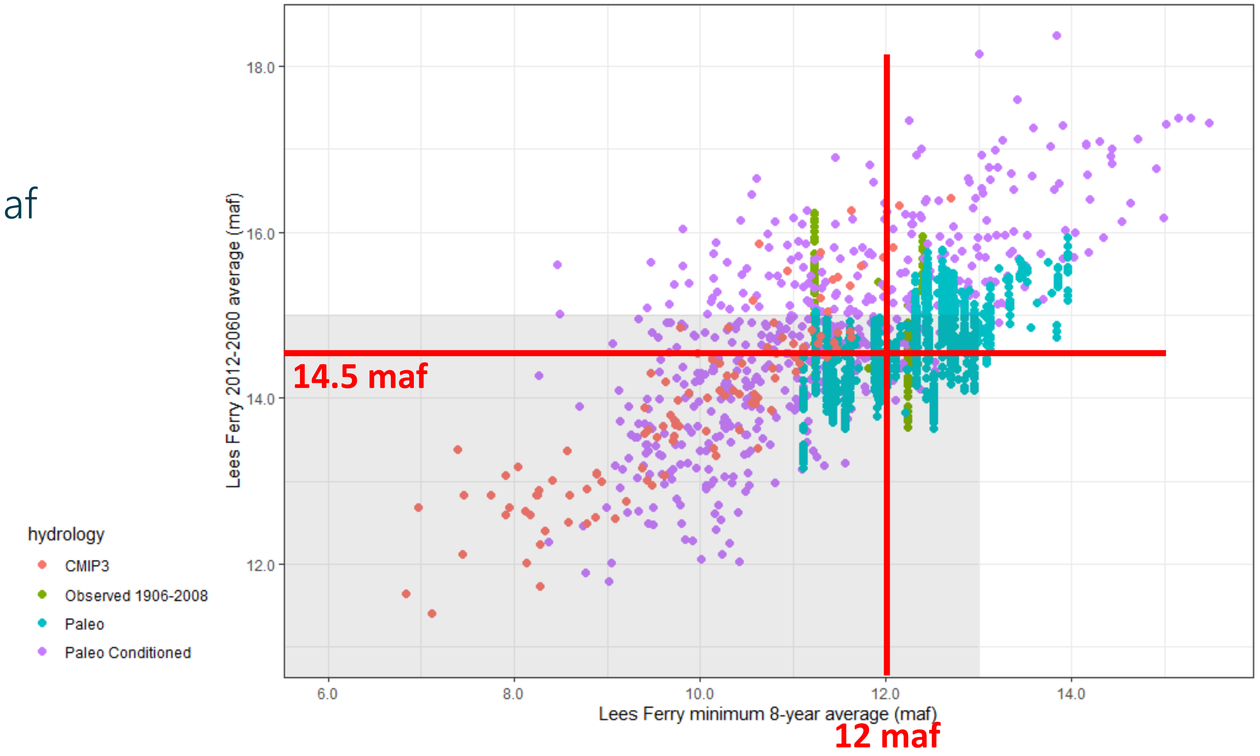
Figure courtesy David Groves
RDM initially developed at RAND:
See www.rand.org/rdmlab

Vulnerability Analysis: Lake Mead Pool Elevation



- **Reliability Metric**: Lake Mead Pool Elevation >1,000 ft
- **Threshold**: Elevation <1,000 ft in any month
- **Vulnerable conditions**:
  - Long term avg annual Lees Ferry flow < 15 maf *and*
  - 8-year drought where avg annual Lees Ferry flow < 13 maf
- **Signposts**:
  - Lake Mead elevation = 1,040 ft
  - 8-year avg annual Lees Ferry flow = 13.35 maf
- **Vulnerable conditions with portfolio A in place**:
  - Long term avg annual Lees Ferry flow < 14.5 maf *and*
  - 8-year drought where avg annual Lees Ferry flow < 12 maf

Vulnerable Conditions for Lake Mead <1,000 ft*



* Based on Figure G3-75 and Table G3-4 from Basin Study; See Technical Report G: https://www.usbr.gov/lc/region/programs/crbstudy/finalreport/techrptG.html

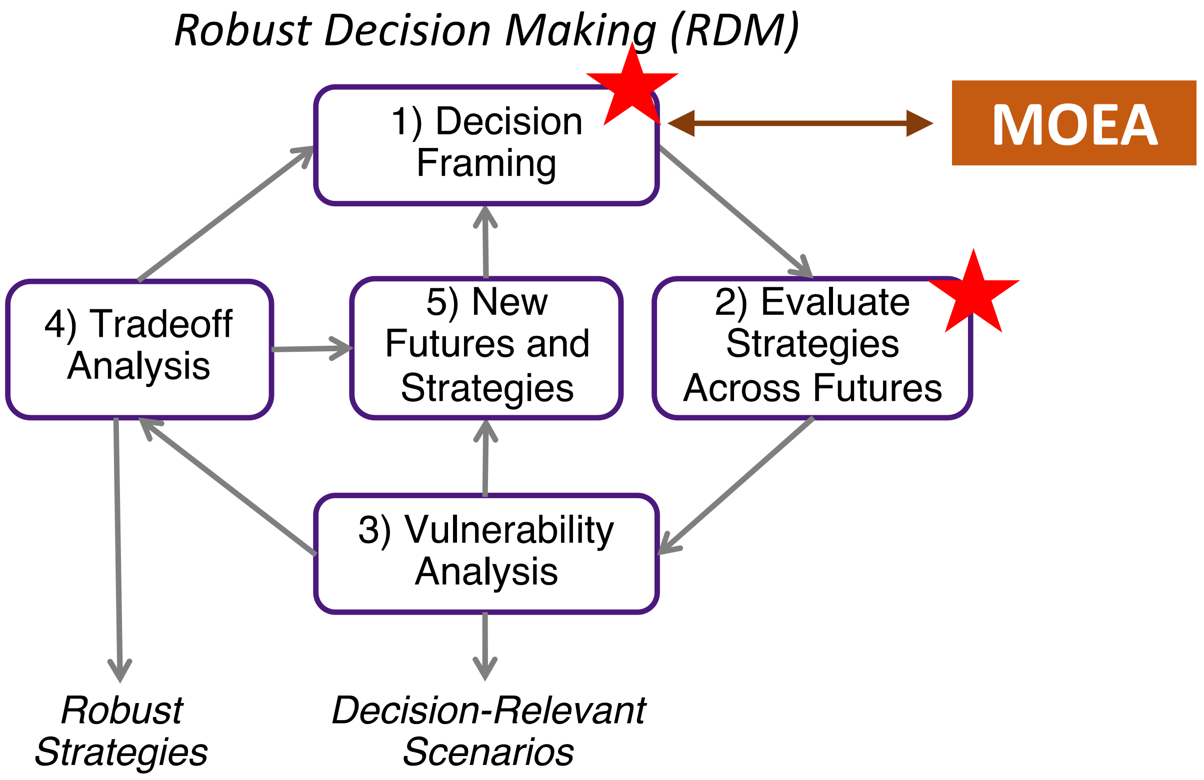
Deep Uncertainty: Multiple Management Objectives

- Many resources supported by the Colorado River

- Multiple management objectives
  - Deliver water
  - Store water
  - Release water
  - Increase flows
  - Reduce flows
  - Save space in reservoir

- Conflicting objectives = impossible to define optimal performance

Many Objective Robust Decision Making[4] (MORDM)



- Use a Multi Objective Evolutionary Algorithm (MOEA) to efficiently search for policies that strike different balances between conflicting management objectives
- Enhances the traditional by-hand, ad hoc process of exploring potential future policies
- Generates a set of policies that illuminate how well the system can perform from multiple perspectives

[4]Kasprzyk, J. R., et al. (2013). Many objective robust decision making for complex environmental systems undergoing change. Environmental Modelling & Software, 42. https://doi.org/10.1016/j.envsoft.2012.12.007

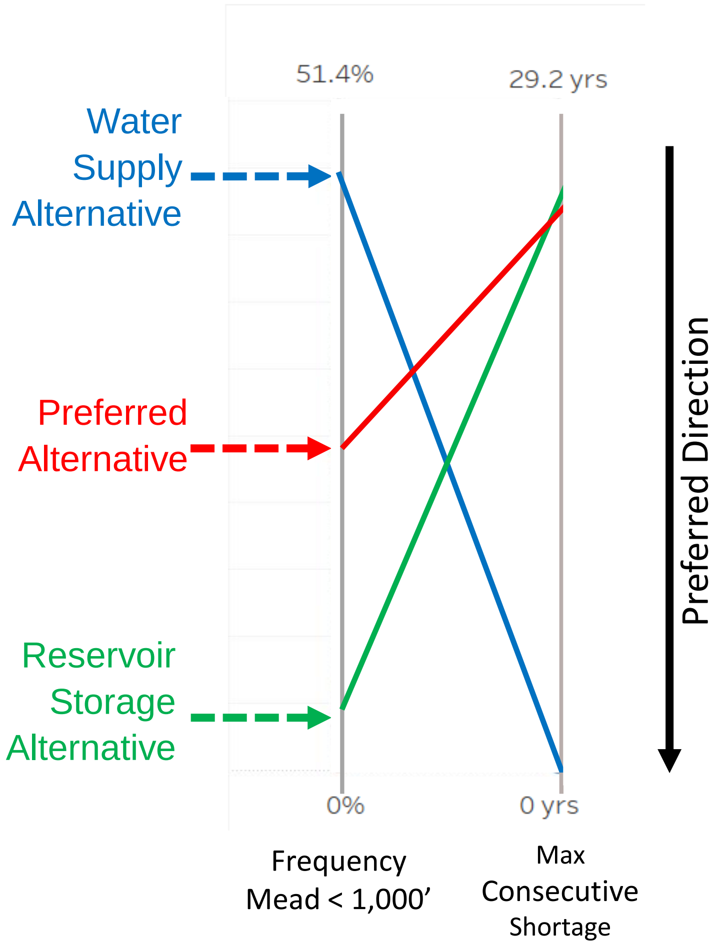
2018 Research Study: *Searching for a Robust Operation of Lake Mead*[5]

- Linked an MOEA to our trusted system model to generate and test thousands of alternative Lake Mead operating policies
  - Elevation thresholds that define tiers
  - Shortage volumes associated with tiers
- Defined eight mgmt. objectives based on analysis from Basin Study
- Simulated 751 MOEA policies in 657 futures
- Compared MOEA policies to alternatives from the Environmental Impact Study (EIS) used to develop the current policy (2007 Interim Guidelines)

Lake Mead Elevation (feet msl)	Water Supply Alternative	Reservoir Storage Alternative	Preferred Alternative	Lake Mead Storage (maf)
1,220	Flood Control or 70R Surplus	Flood Control or 70R Surplus	Flood Control or 70R Surplus	25.9
1,200	Full Domestic Surplus	Normal Operations	Domestic Surplus	22.9
1,145	Partial Domestic Surplus		Normal Operations	15.9
1,125	Normal Operations			13.9
1,100		Shortage 500[1] kaf		11.5
1,075		Shortage 667[1] kaf	Shortage 333 kaf[1]	9.4
1,050		Shortage 833[1] kaf	Shortage 417 kaf[1]	7.5
1,025		Shortage 1,000[1] kaf	Shortage 500 kaf[1] and Consultation[2]	5.8
1,000				4.3
895				0

[5]Alexander, E. (2018) "Searching for a Robust Operation of Lake Mead", M.S. Thesis, University of Colorado.

Introduction to Tradeoffs

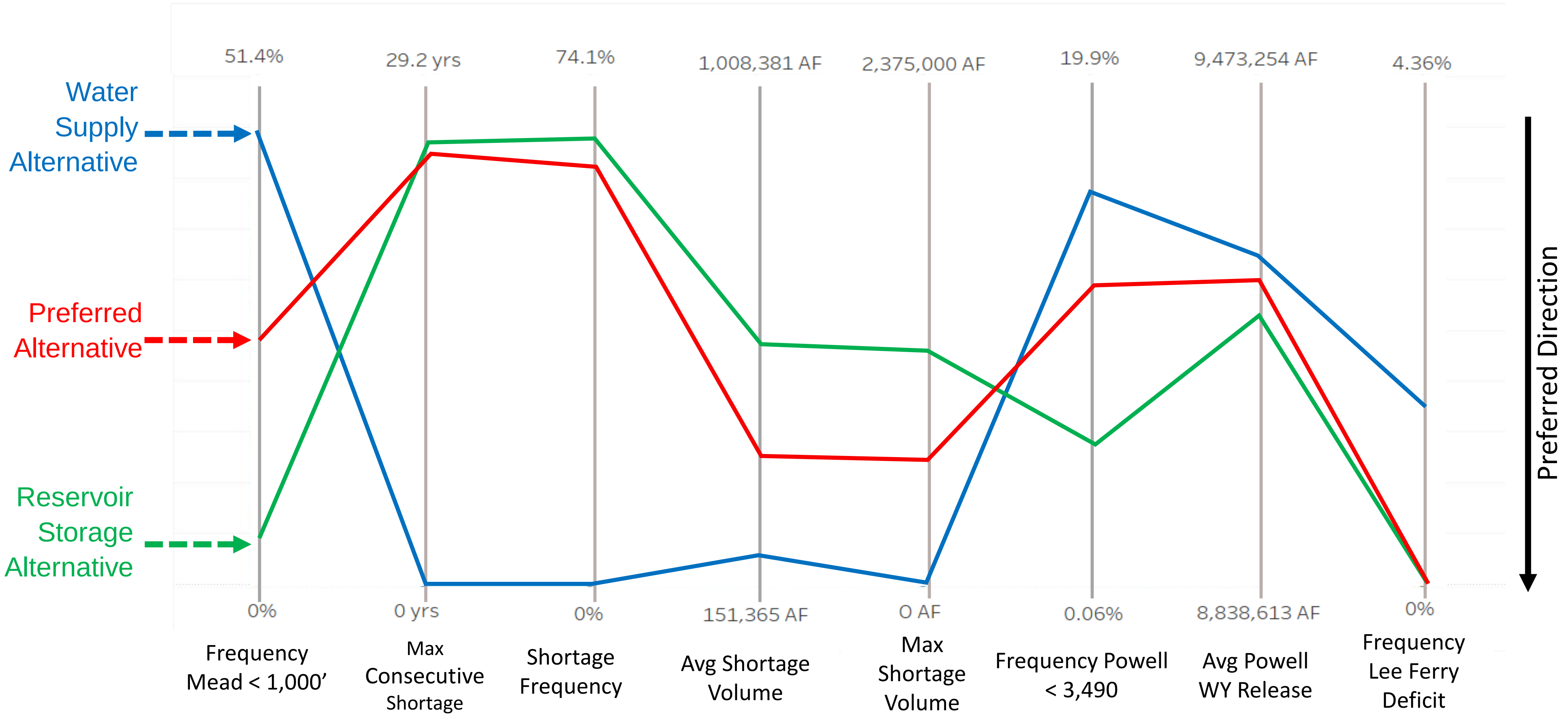


Water Supply Alternative (WSA) - policy that maximizes water deliveries at the expense of retaining water in storage in Mead and Powell

Preferred Alternative (PA) – recommended operating policy of Lake Mead and has less shortage reductions than RSA

Reservoir Storage Alternative (RSA) - policy that keeps more water in storage through increasing shortages volumes

Performance of Other Alternatives from the 2007 Interim Guidelines EIS



Thousands of New Lake Mead Operating Policies Tested

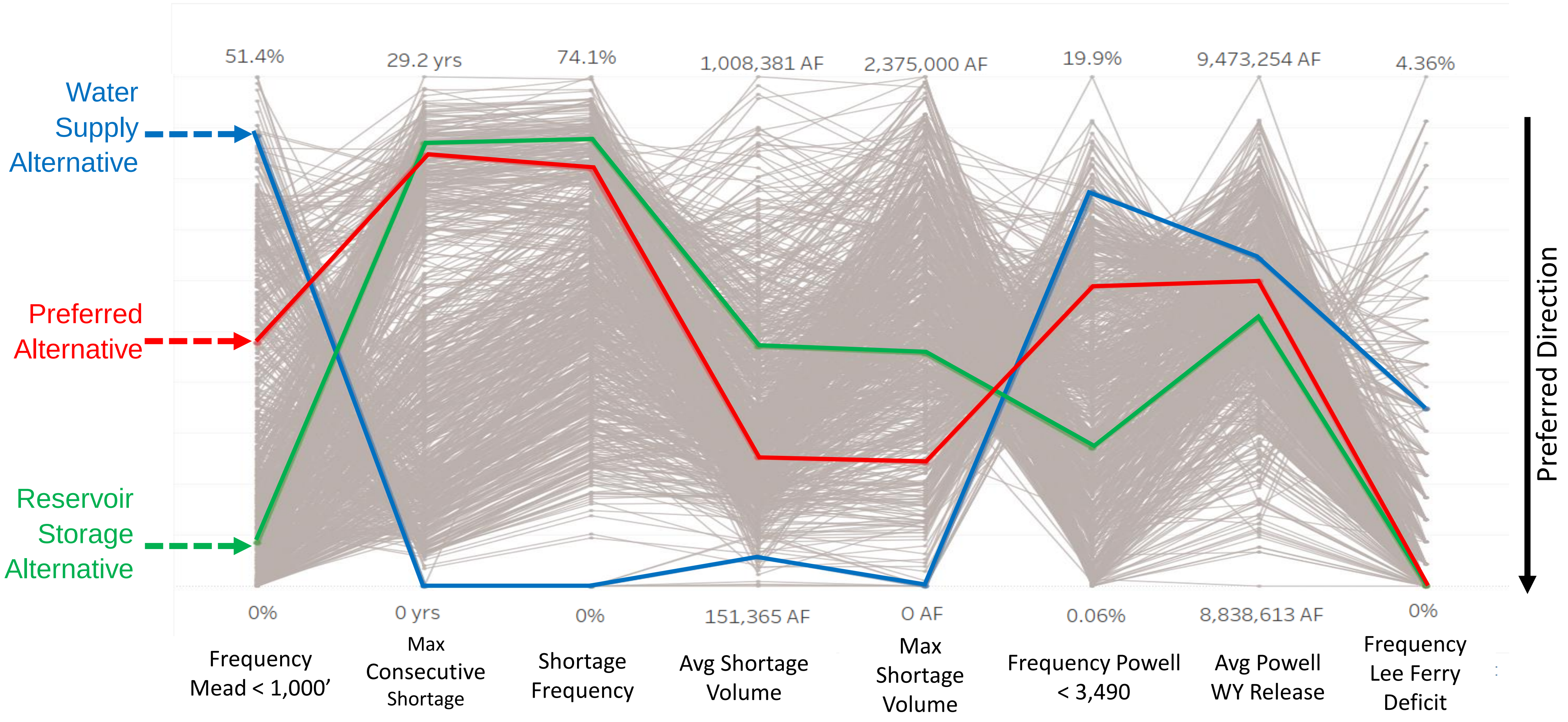
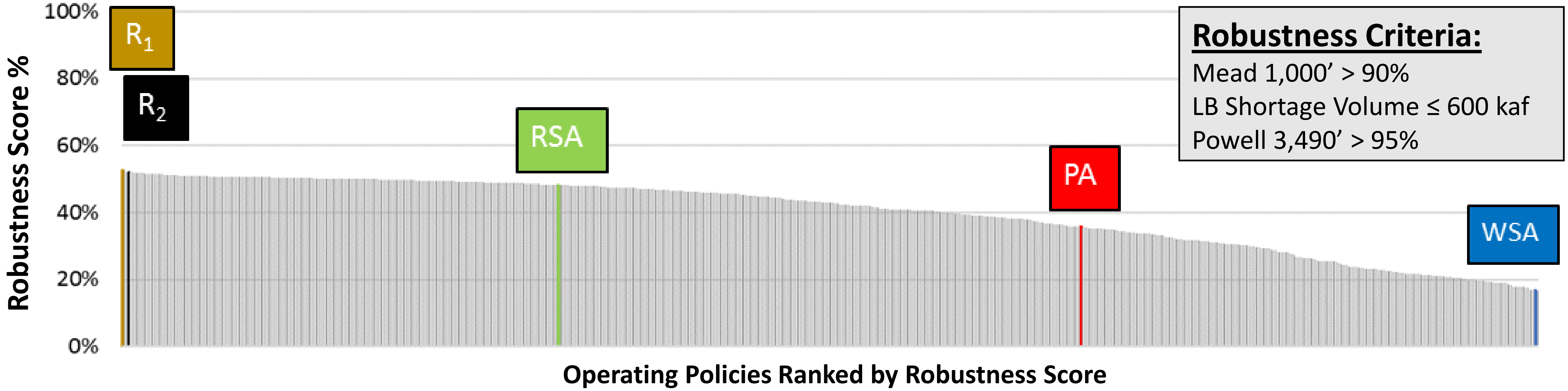


Figure from E. Alexander’s MS Thesis “Searching for a Robust Operation of Lake Mead”

Comparing Robustness of MOEA Policies to Alternatives from the 2007 Interim Guidelines EIS



LEGEND	PA = Lake Mead's Preferred Alternative
R1 = Policy with the highest robustness value	**WSA** = Water Supply Alternative
R2 = high robustness with different operational structure than R1	**RSA** = Reservoir Storage Alternative

Ongoing research to complete the remaining MORDM steps

Summary

- Long-term planning in the Colorado River Basin requires grappling with deep uncertainty
  - We cannot identify the best set of future assumptions to use in planning
  - There are different perspectives on performance priorities

- DMDU methods incorporate concepts and tools that help address the challenges of planning under deep uncertainty

- Reclamation has used DMDU methods in multiple past studies and is continuing to explore this field

Resources

- Basin Study https://www.usbr.gov/lc/region/programs/crbstudy/finalreport/index.html
  - Technical Report B: Supply Scenarios
  - Technical Report G: System Analysis

- Reclamation's Colorado River Basin Research-to-Operations website https://www.usbr.gov/lc/region/programs/CRB-R2O-homepage.html

- Society for Decision Making under Deep Uncertainty http://www.deepuncertainty.org/

- CRB State of the Science Report https://wwa.colorado.edu/publications/reports/CRBreport/
  - Chapter 2: Current Understanding of CRB Climate and Hydrology
  - Chapter 11: Climate Change-Informed Hydrology

Thank you

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