RECLAMATION
Managing Water in the West

New DMI Development to Support Exploration of Many Objective Robust Decision Making Applications in the Colorado River Basin

RiverWare User Group Meeting

August 28, 2019

Overview

- Colorado River Basin hydrology ensembles and uncertainty
- Many Objective Robust Decision Making (MORDM)
- Lake Mead MORDM research project

Methods used to incorporate hydrologic uncertainty

- Ensemble-based planning

<table>
<tr><th>Ensemble Category</th><th colspan="2">Types of Ensembles</th></tr>
<tr><td rowspan="4">Resampled Historical Streamflow</td><td colspan="2">Full observed Record (Full Hydrology)</td></tr>
<tr><td colspan="2">Subset of Observed Record:</td></tr>
<tr><td>1988-2017 (Stress Test)</td><td>1931-2017 (Early Pluvial Removed)</td></tr>
<tr><td colspan="2">Paleo Record</td></tr>
<tr><td rowspan="2">GCM-based</td><td colspan="2">CMIP3 ensemble</td></tr>
<tr><td colspan="2">CMIP5 ensemble (under development)</td></tr>
<tr><td rowspan="2">Blended</td><td colspan="2">Paleo-conditioned</td></tr>
<tr><td colspan="2">GCM-conditioned (under development)</td></tr>
</table>

Methods used to incorporate hydrologic uncertainty

- Ensemble-based planning

2007 Interim Guidelines

Ensemble Category	Types of Ensembles	
Resampled Historical Streamflow	Full observed Record (*Full Hydrology*)	
	Subset of Observed Record:	
	1988-2017 (Stress Test)	*1931-2017 (Early Pluvial Removed)*
	Paleo Record	
GCM-based	CMIP3 ensemble	
	CMIP5 ensemble (under development)	
Blended	Paleo-conditioned	
	GCM-conditioned (under development)	

RECLAMATION
Managing Water in the West

Methods used to incorporate hydrologic uncertainty

- Ensemble-based planning

2012 Basin Study

Ensemble Category	Types of Ensembles	
Resampled Historical Streamflow	Full observed Record (*Full Hydrology*)	
	Subset of Observed Record:	
	1988-2017 (Stress Test)	*1931-2017 (Early Pluvial Removed)*
	Paleo Record	
GCM-based	CMIP3 ensemble	
	CMIP5 ensemble (under development)	
Blended	Paleo-conditioned	
	GCM-conditioned (under development)	

Methods used to incorporate hydrologic uncertainty

- Ensemble-based planning

2017 Minute 323

Ensemble Category	Types of Ensembles	
Resampled Historical Streamflow	Full observed Record (*Full Hydrology)*	
	Subset of Observed Record:	
	1988-2017 (Stress Test)	*1931-2017 (Early Pluvial Removed)*
	Paleo Record	
GCM-based	CMIP3 ensemble	
	CMIP5 ensemble (under development)	
Blended	Paleo-conditioned	
	GCM-conditioned (under development)	

Methods used to incorporate hydrologic uncertainty

- Ensemble-based planning

2018 Tribal Water Study

Ensemble Category	Types of Ensembles	
Resampled Historical Streamflow	Full observed Record (*Full Hydrology*)	
	Subset of Observed Record:	
	1988-2017 (Stress Test)	*1931-2017 (Early Pluvial Removed)*
	Paleo Record	
GCM-based	CMIP3 ensemble	
	CMIP5 ensemble (under development)	
Blended	Paleo-conditioned	
	GCM-conditioned (under development)	

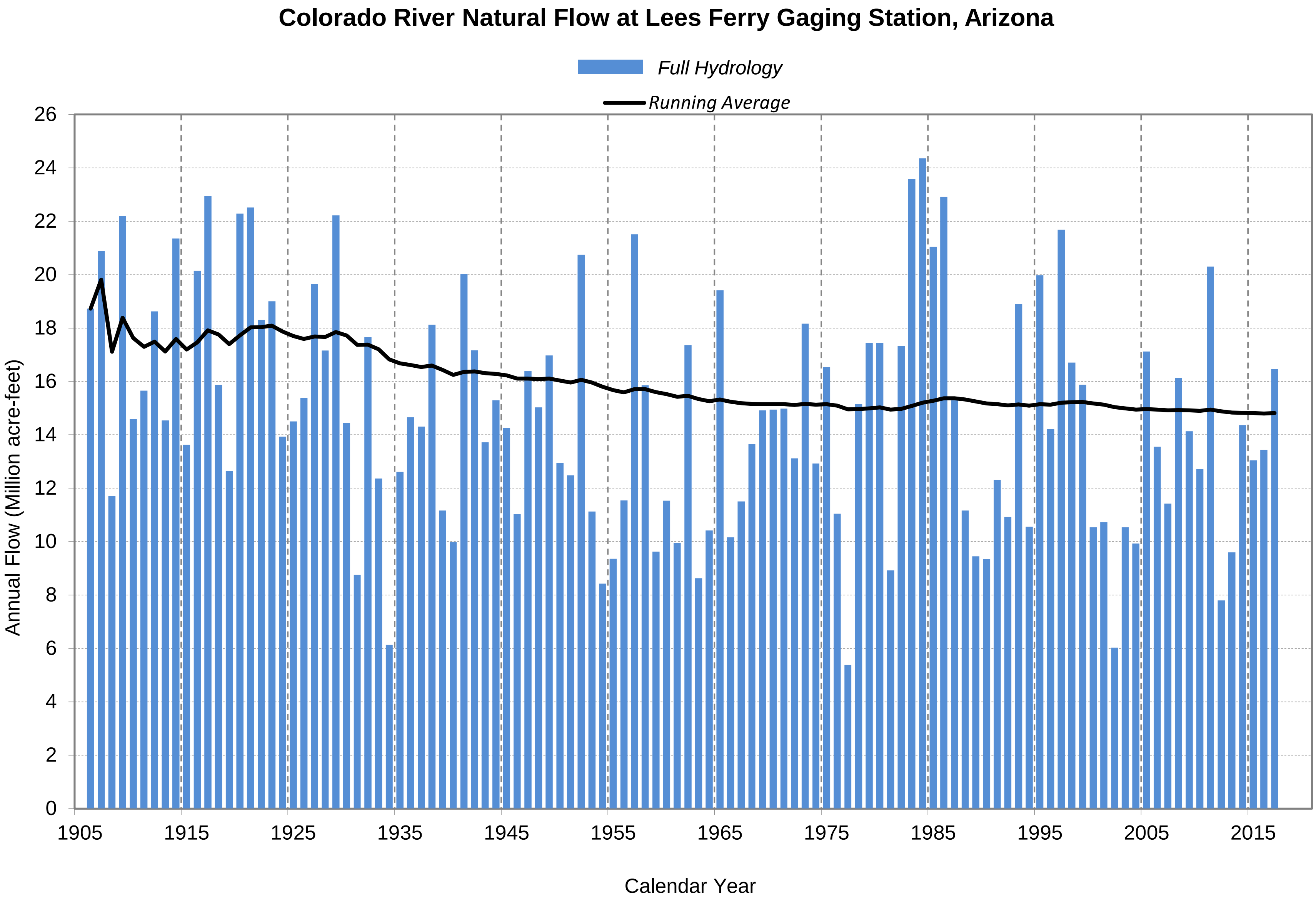
Methods used to incorporate hydrologic uncertainty

- Ensemble-based planning

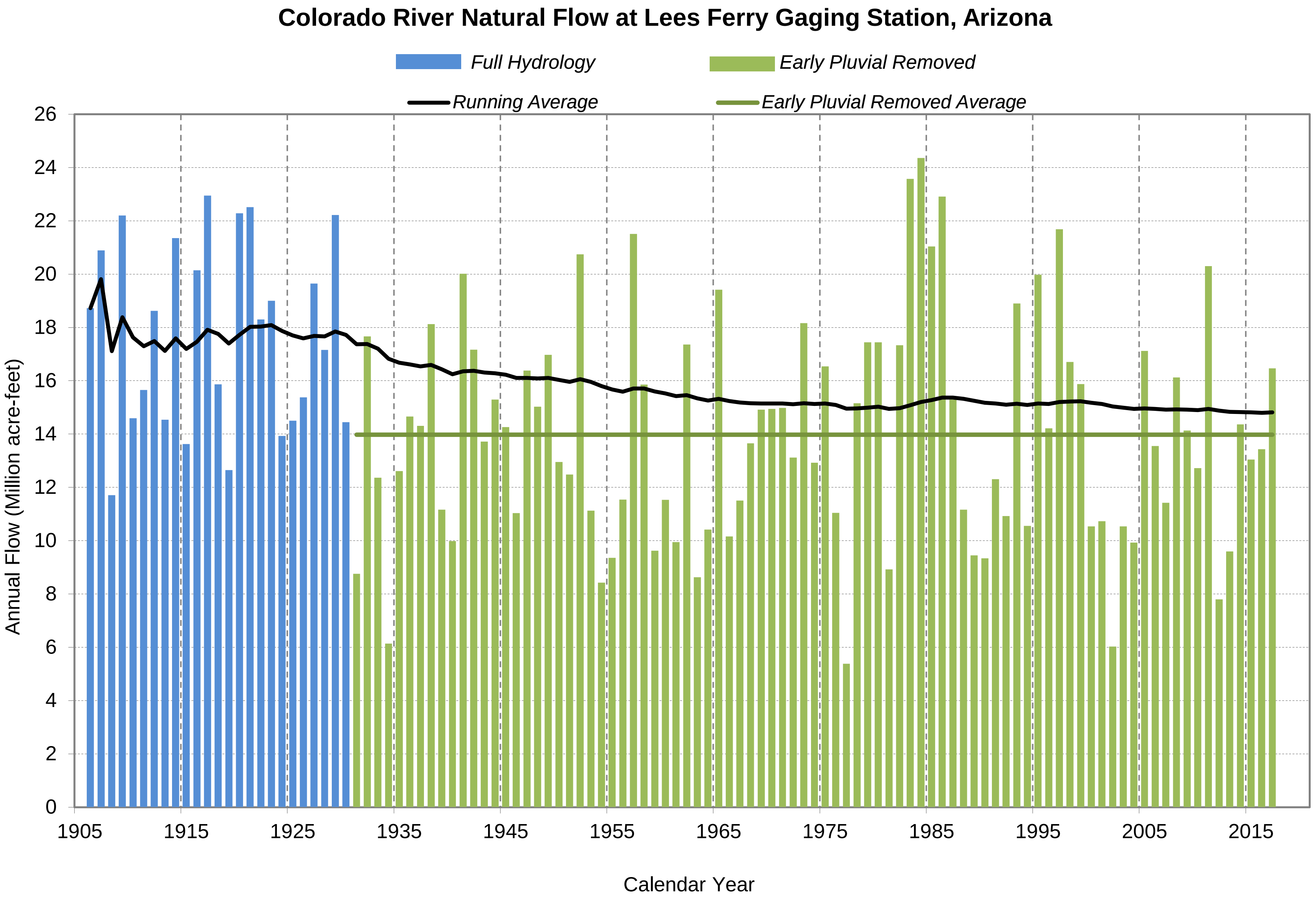
2019 DCP

Ensemble Category	Types of Ensembles
Resampled Historical Streamflow	Full observed Record (*Full Hydrology)*
	Subset of Observed Record: *1988-2017 (Stress Test)* / *1931-2017 (Early Pluvial Removed)*
	Paleo Record
GCM-based	CMIP3 ensemble
	CMIP5 ensemble (under development)
Blended	Paleo-conditioned
	GCM-conditioned (under development)

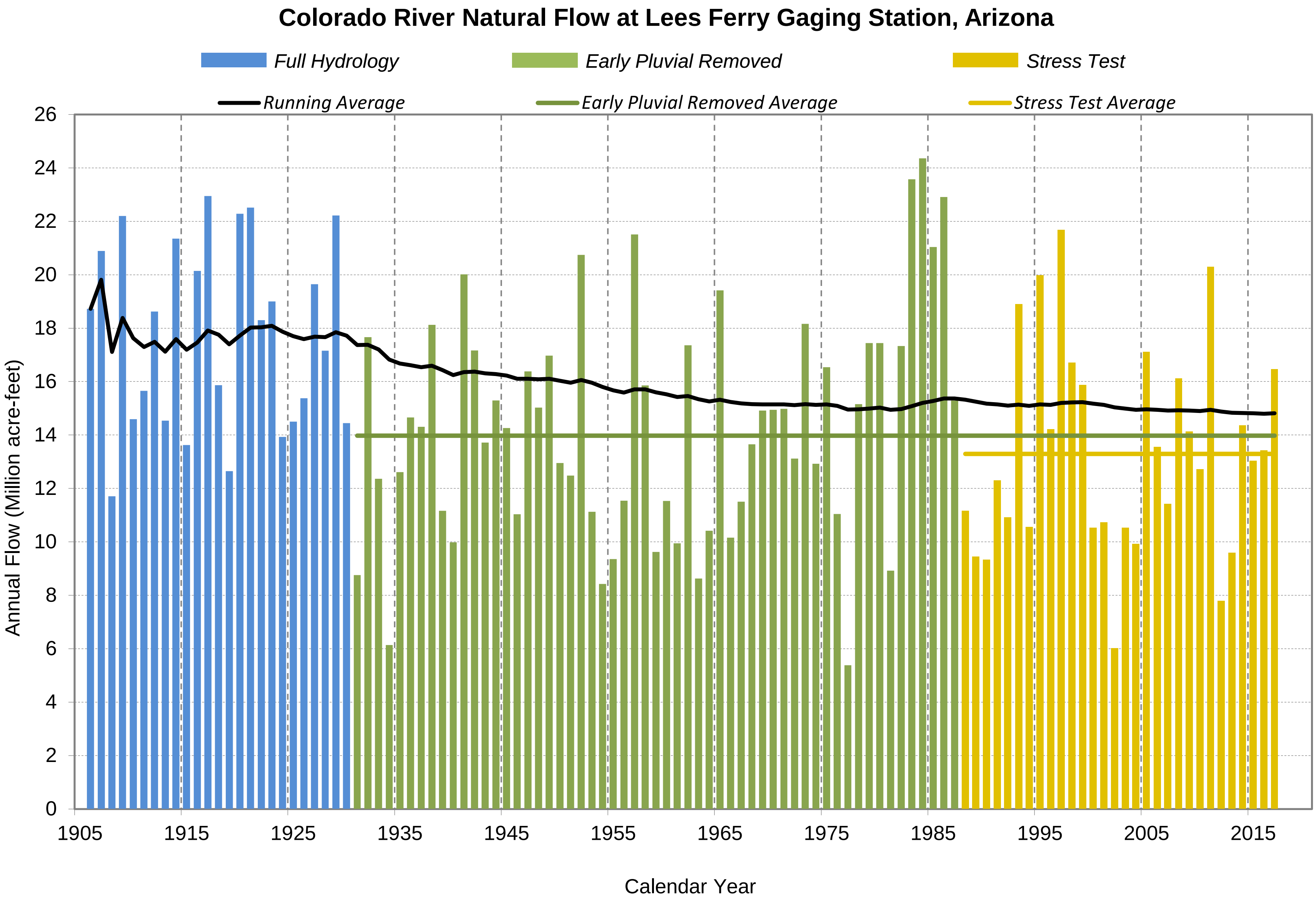
Hydrologic ensembles and how they compare



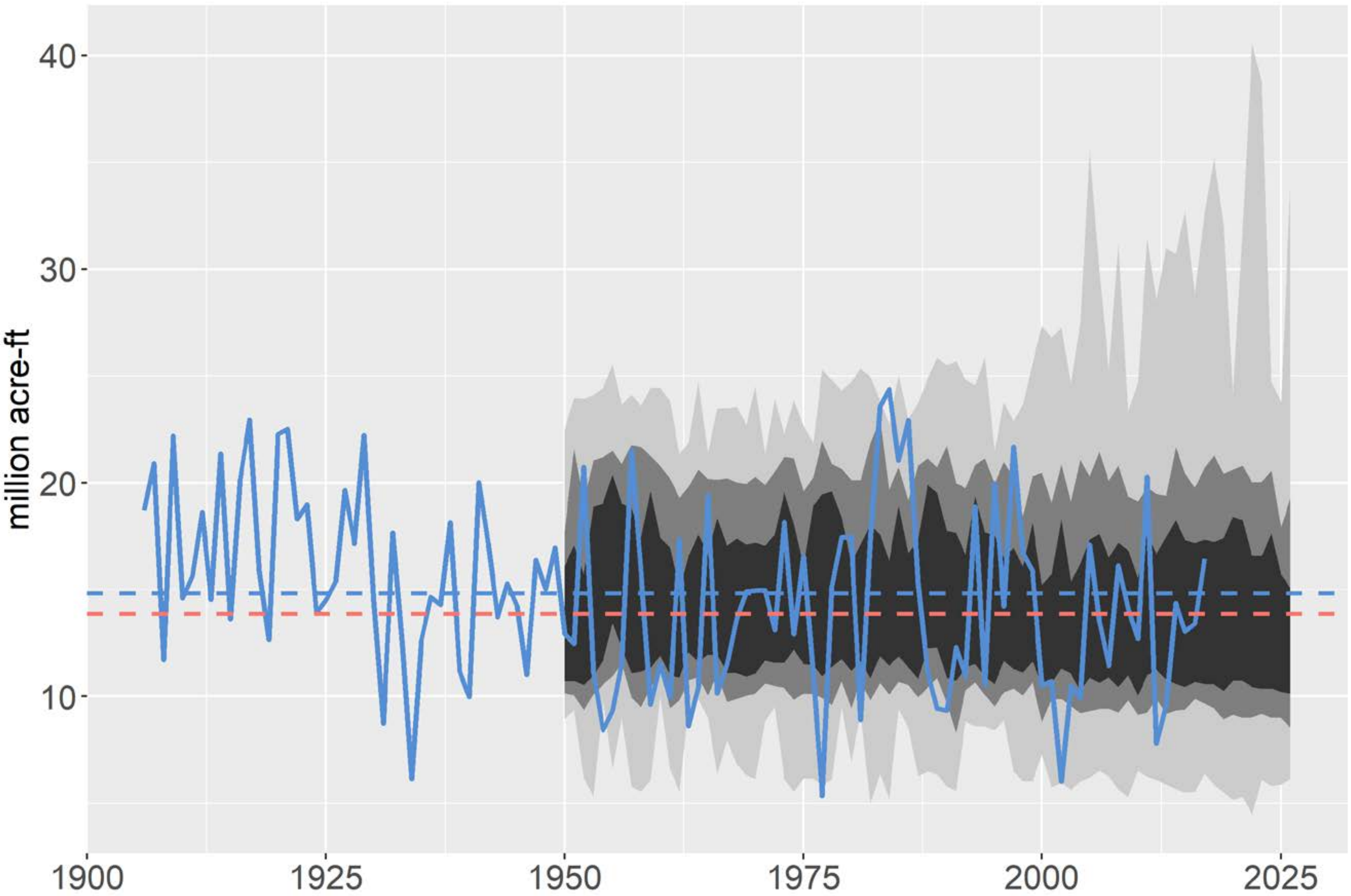
Hydrologic ensembles and how they compare



Hydrologic ensembles and how they compare



Hydrologic ensembles and how they compare



CMIP3

25th – 75th percentile

10th – 90th percentile

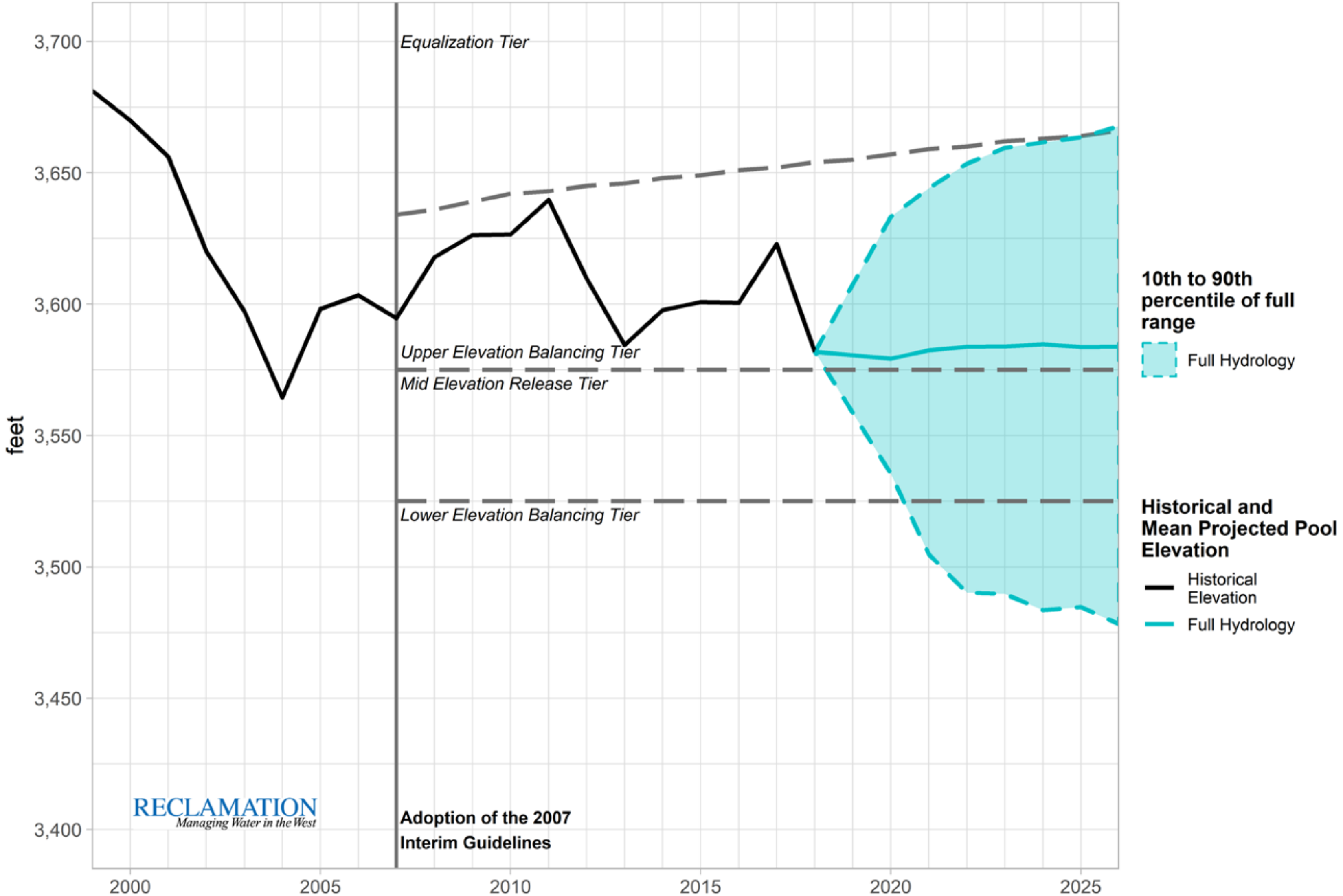
Min - max

2020-2026 average of 112 sequences

Full Hydrology

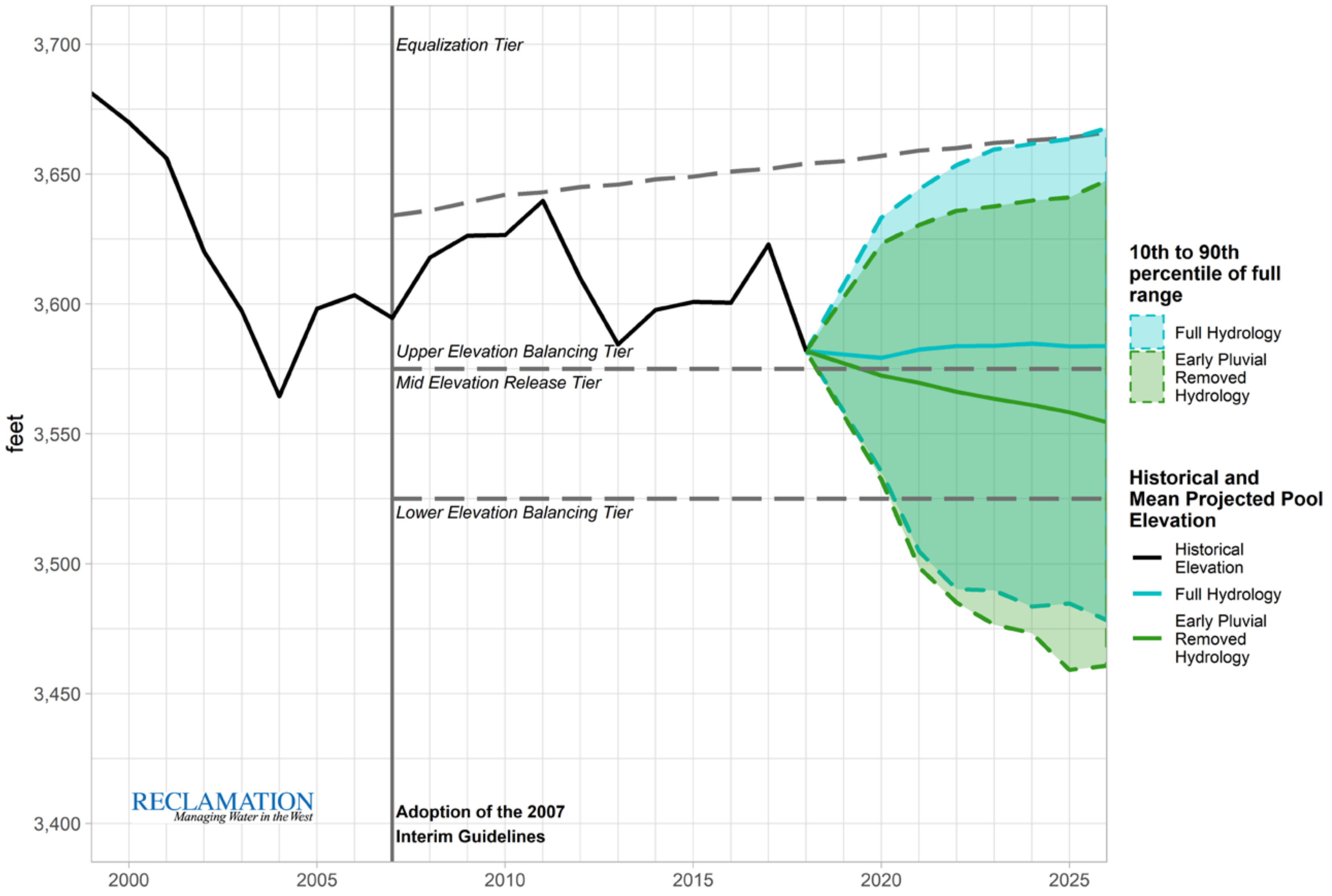
1906-2016 average

Hydrologic ensembles and how they compare



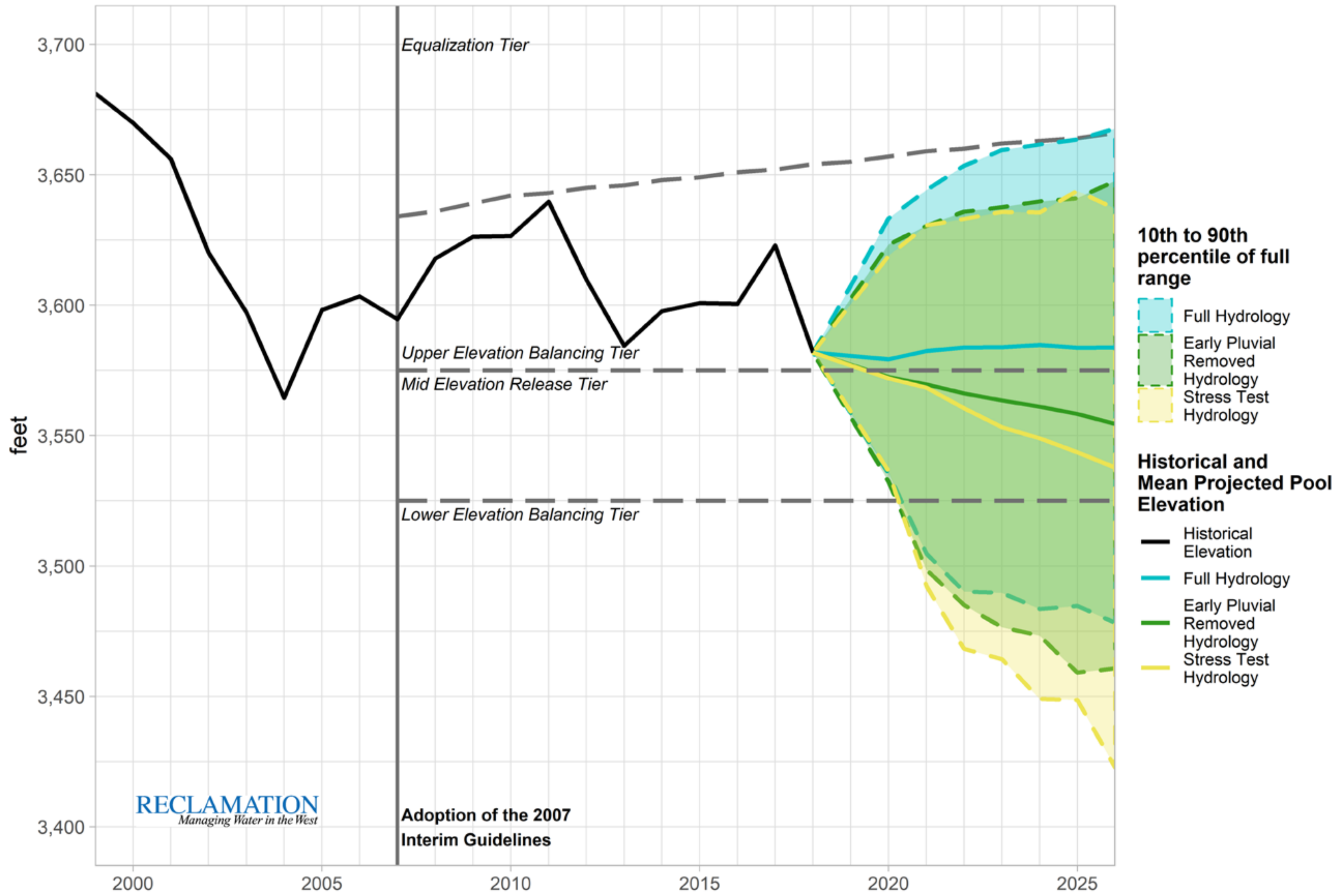
All projections are from January 2019 CRSS modeling, which **do not include the DCP**.
Full Hydrology uses 111 hydrologic inflow sequences based on resampling of the observed natural flow record from 1906-2016.

Hydrologic ensembles and how they compare



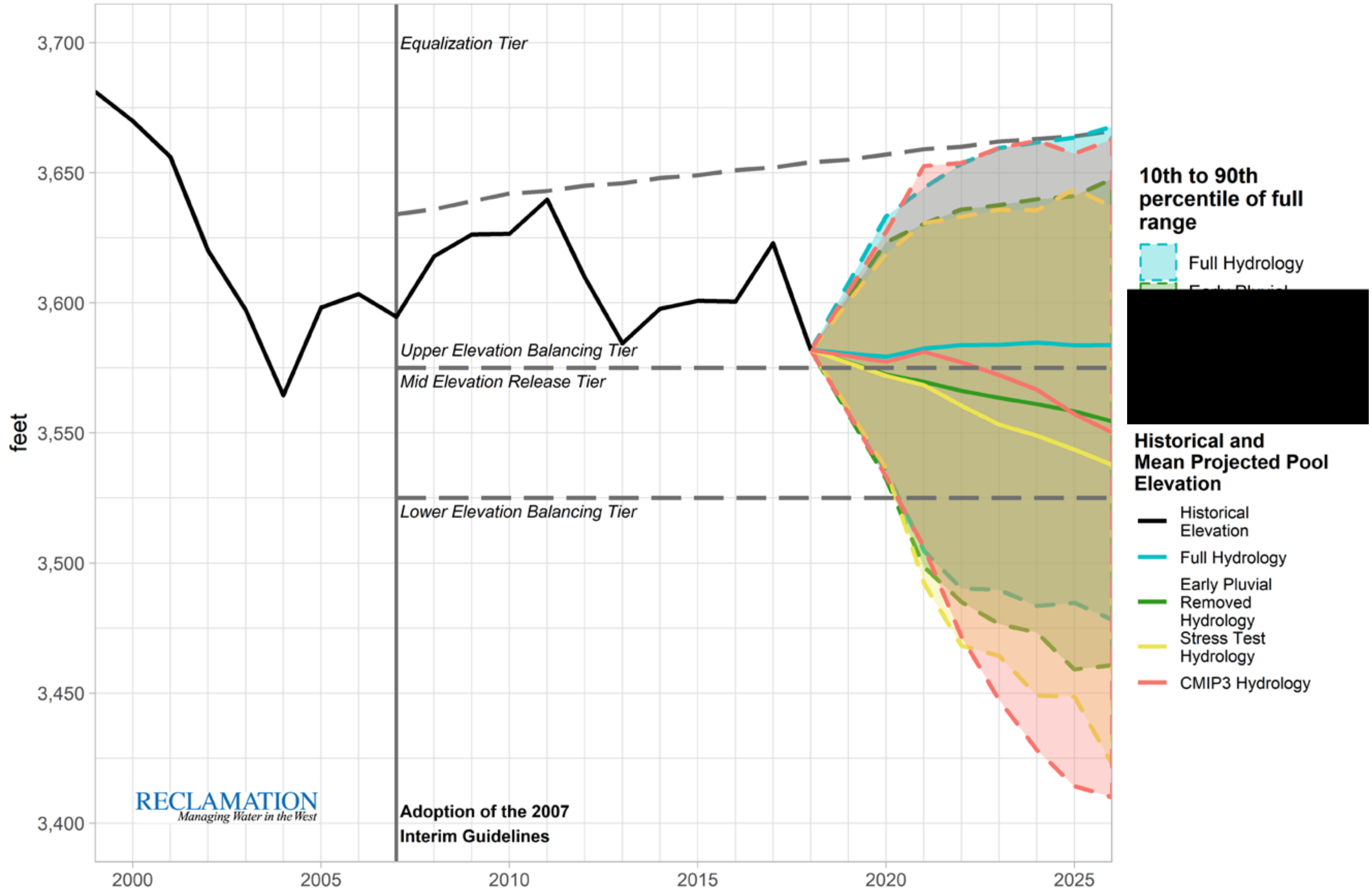
All projections are from January 2019 CRSS modeling, which **do not include the DCP**.
Full Hydrology uses 111 hydrologic inflow sequences based on resampling of the observed natural flow record from 1906-2016.
Early Pluvial Removed Hydrology uses 86 hydrologic inflow sequences based on resampling of the observed natural flow record from 1931-2016.

Hydrologic ensembles and how they compare



All projections are from January 2019 CRSS modeling, which **do not include the DCP**.
Full Hydrology uses 111 hydrologic inflow sequences based on resampling of the observed natural flow record from 1906-2016.
Early Pluvial Removed Hydrology uses 86 hydrologic inflow sequences based on resampling of the observed natural flow record from 1931-2016.
Stress Test Hydrology uses 29 hydrologic inflow sequences based on resampling of the observed natural flow record from 1988-2016.

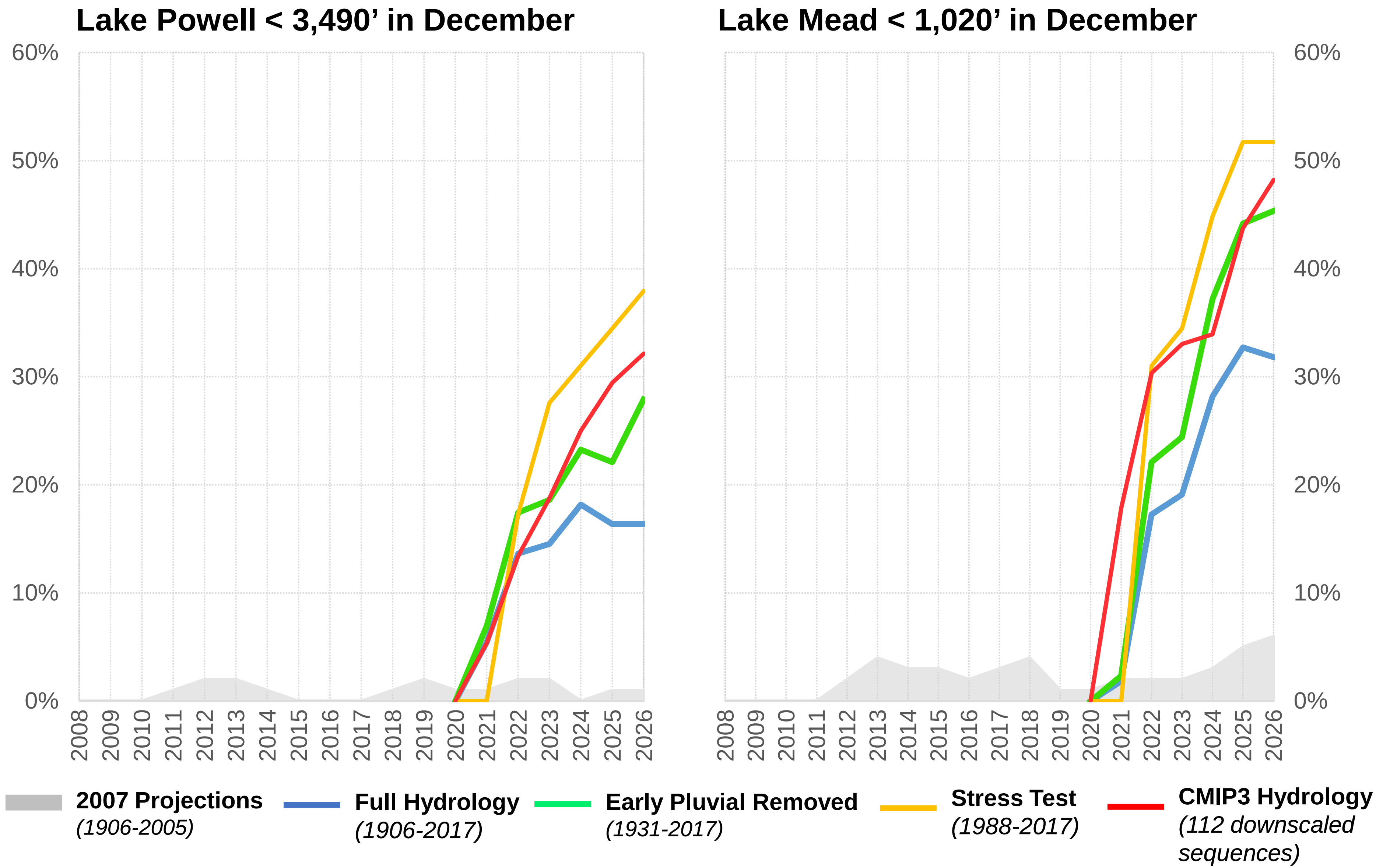
Hydrologic ensembles and how they compare



All projections are from January 2019 CRSS modeling, which **do not include the DCP**.
Full Hydrology uses 111 hydrologic inflow sequences based on resampling of the observed natural flow record from 1906-2016.
Early Pluvial Removed Hydrology uses 86 hydrologic inflow sequences based on resampling of the observed natural flow record from 1931-2016.
Stress Test Hydrology uses 29 hydrologic inflow sequences based on resampling of the observed natural flow record from 1988-2016.
CMIP3 Hydrology uses 112 hydrologic inflow sequences based on downscaled CMIP3 GCM projections.

RECLAMATION
Managing Water in the West

Shifting Risk



*All projections are from January 2019 CRSS modeling, which **do not include the DCP**.

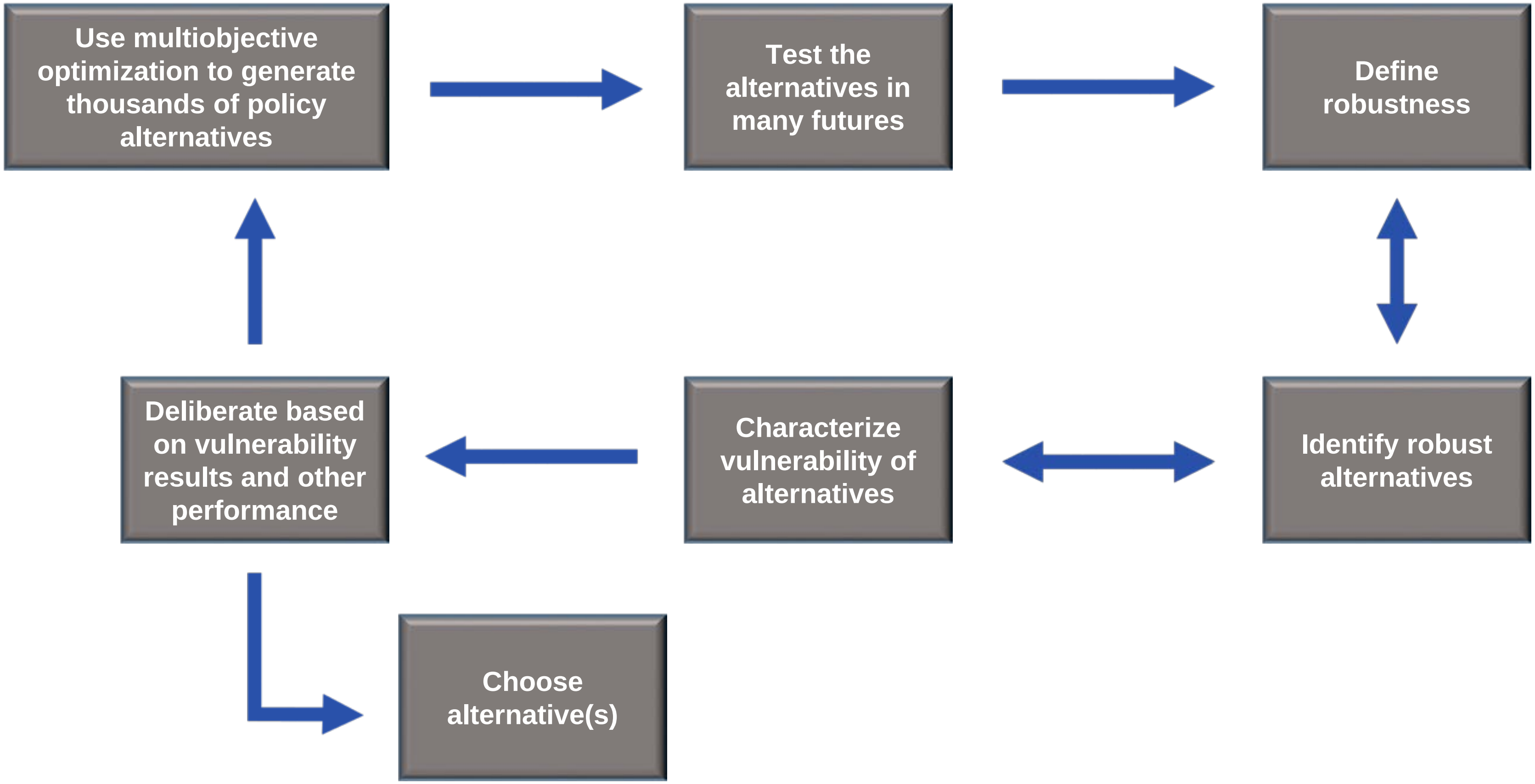
RECLAMATION
Managing Water in the West

Motivation for exploring Decision Making under Deep Uncertainty (DMDU) techniques

- Deep uncertainty[1]: when parties do not know or cannot agree on
  - the most appropriate system model(s)
  - probability distributions of key external conditions
  - how to value different measures of system performance
- Decision Making under Deep Uncertainty (DMDU) techniques are designed to mitigate the planning challenges posed by deep uncertainty
  - Focus on system response and vulnerability
  - Goal is to find a **robust** solution- one that has acceptable performance in a wide range of futures
- The DMDU technique Robust Decision Making was used in the 2012 Basin Study
- Many Objective Robust Decision Making (MORDM) has three important strengths:
  1. Efficient way to test thousands of operating policies
  2. Quantitative mechanism for expressing conflicting performance priorities
  3. Reduces the importance of choosing ensembles of future conditions

[1] Lempert, R. J., D. G. Groves, S. W. Popper, and S. C. Bankes. (2006). "A General, Analytic Method for Generating Robust Strategies and Narrative Scenarios." *Management Science* 52 (4): 514–28

MORDM framework



MORDM framework

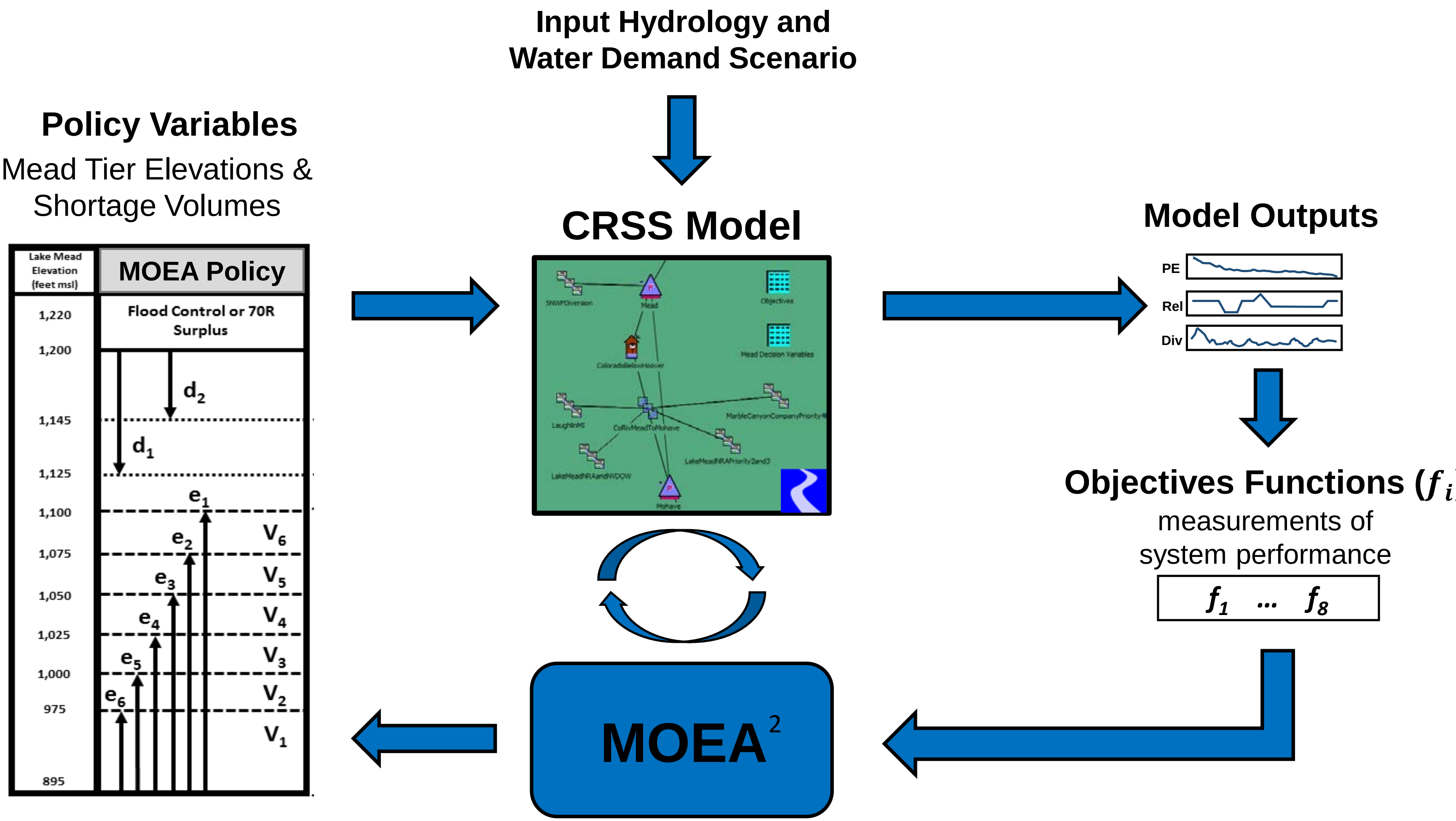
Use multiobjective optimization to generate thousands of policy alternatives → Test the alternatives in many futures → Define robustness ↔ Identify robust alternatives

Searching for a Robust Operation of Lake Mead

Elliot Alexander M.S. Thesis

https://www.usbr.gov/lc/region/programs/recently-completed-research.html

Generating new operating policies for Lake Mead



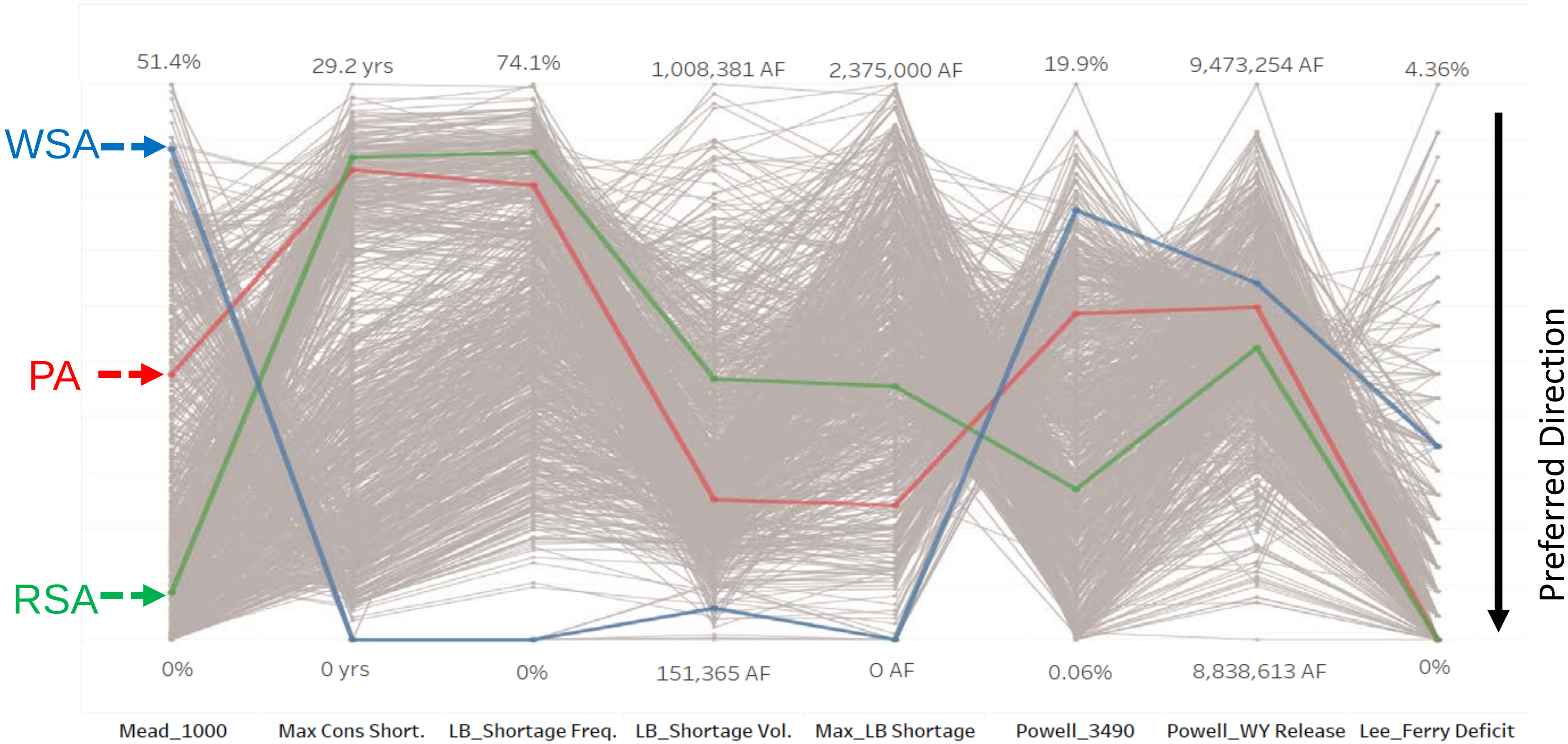
[2] Multi Objective Evolutionary Algorithm

Evaluating performance: 8 objectives

Lower Basin Objectives		
Mead 1000	**1**	**Minimize % of time that monthly Lake Mead Pool Elevation is < 1,000'**
LB Max Consecutive Shortage Duration	2	Minimize the maximum amount of consecutive years in shortage operation
LB Shortage Frequency	3	Minimize % of time that the system is in an annual shortage operation
LB Shortage Volume	**4**	**Minimize the cumulative average annual Lower Basin total shortage volume**
Max Annual LB Shortage	5	Minimize the maximum annual Lower Basin policy shortage volume
Upper Basin Objectives		
Powell 3490	**6**	**Minimize % of time that monthly Lake Powell Pool Elevation is < 3,490'**
Powell WY Release	7	Minimize cumulative average annual Water Year release from Lake Powell
Lee Ferry Deficit	8	Minimize % of time that annual 10 year compact volume falls below 75 maf

* All objectives are minimized, meaning lower values indicate superior performance.

Results: MOEA-generated operating policies



* The MOEA evaluated 7,500 policies and 463 of those policies were considered to be high performing.

Testing the MOEA-generated policies in many futures

- 107 Observed traces
- 112 CMIP3 traces

- Official 2007 Demand
- Slow Growth
- Rapid Growth

Many Futures

Water Supply Scenarios (Q)

Observed Flow Ensemble

Q_{107}

Future Climate Ensemble

Q_{112}

Water Demand Scenarios

Baseline Demand

D_1

Slow Growth Demand

D_2

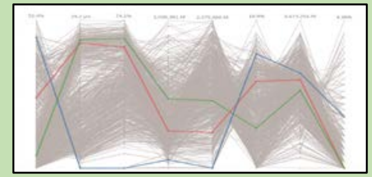
Rapid Growth Demand

D_3

219

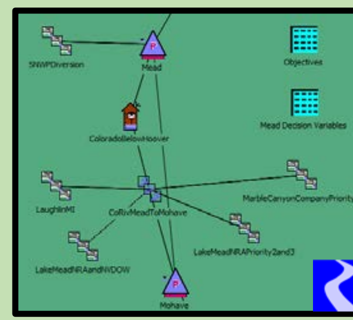
3

MOEA-generated Operating Policies



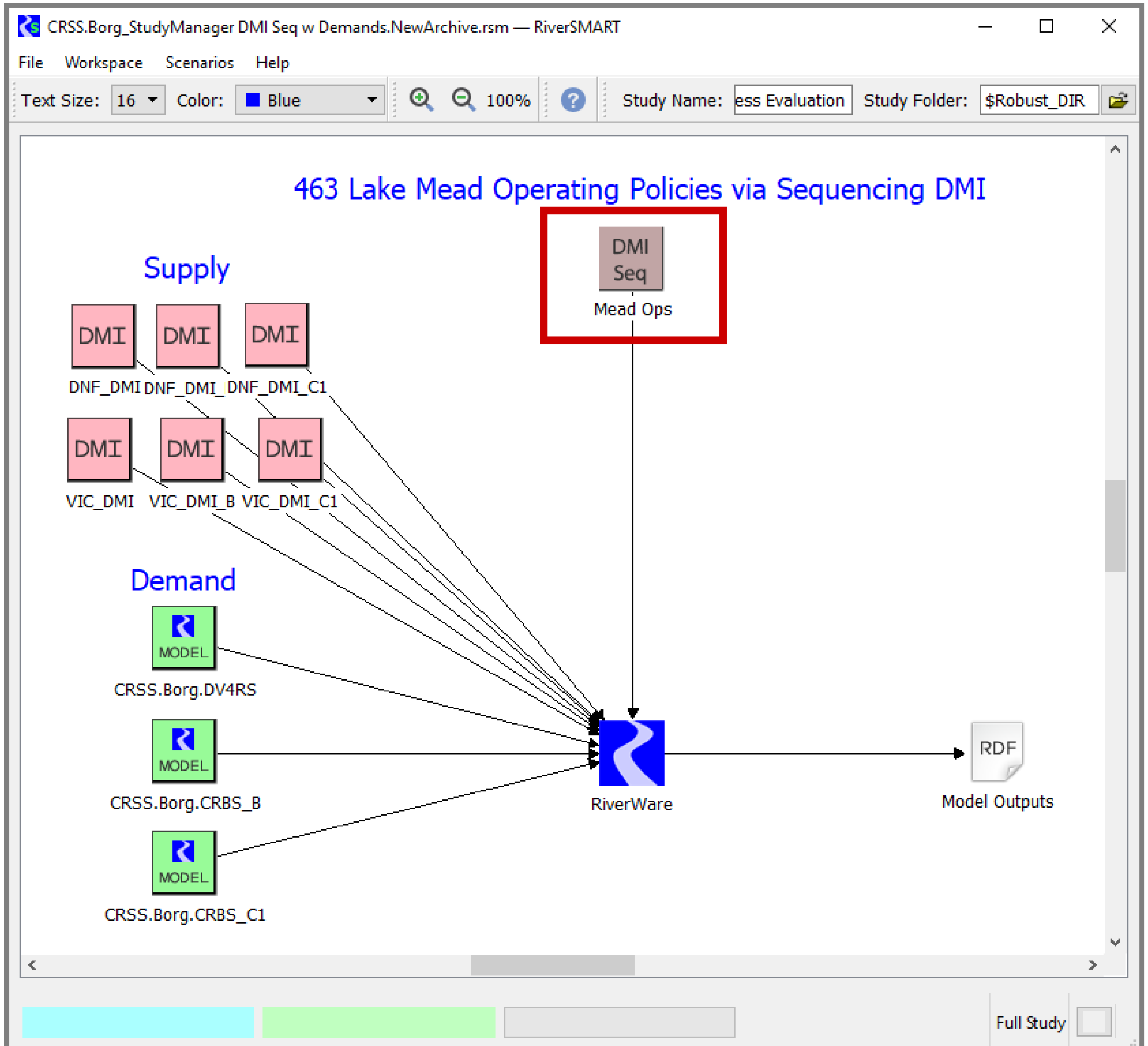
463

Simulation Model



(219 Supply Traces) x (3 Demand Scenarios) x (463 Policies) =
304,191 Simulations

New RiverSMART DMI supports policy dimension



Defining robustness

$$\boldsymbol{Satisficing} = \frac{1}{N}\sum_{j=1}^{N} S_{i\epsilon I}\{F(\boldsymbol{x_m})_{i,j}\}$$

→

How Should Robustness Be Defined for Water Systems Planning under Change?

Jonathan D. Herman, S.M.ASCE[1]; Patrick M. Reed, Ph.D., A.M.ASCE[2]; Harrison B. Zeff[3]; and Gregory W. Characklis, Ph.D., M.ASCE[4]

Herman, J. D., Reed, P. M., Zeff, H. B. & Characklis, G. W., 2015. How Should Robustness Be Defined for Water Systems Planning under Change? *Journal of Water Resources Planning and Management*, pp. 1 - 14.

N = is the total number of states of the world (SOW) within set of J.

$\boldsymbol{x_m}$ = operating policy, m

i = objective counter in set of *I* objectives considered in performance requirements

$F(x_m)_{i,j}$ = the value of the ith objective in SOW *j*

$S_{i\epsilon I}$= indicator function that returns 1 if policy x_m meets ith objective performance requirement in state of the world *j and* I_s = 0 otherwise.

Robustness criteria used in this research:

If a policy:

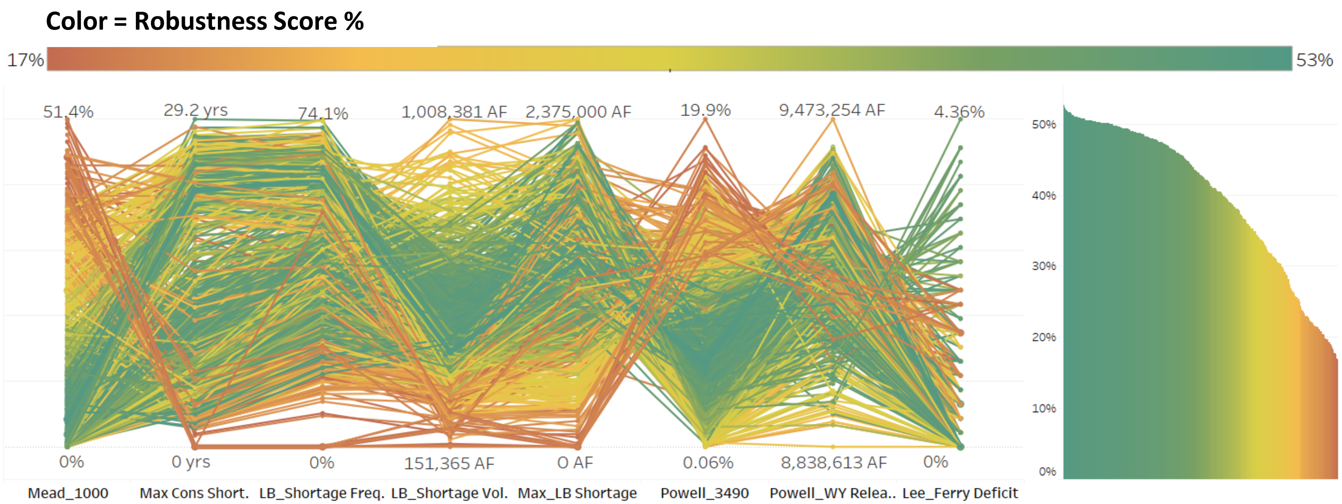
- keeps Lake Mead above 1,000’ greater than 90% of the time,
- results in an average annual shortage volume less than or equal to 600 kaf, and
- keeps Lake Powell above 3,490’ greater than 95% of the time

then it is robust in a given supply and demand future.

If a policy meets these three performance requirements in all futures tested, then that policy would have a 100% **robustness score**

RECLAMATION
Managing Water in the West

Evaluating the robustness of the MOEA-generated policies

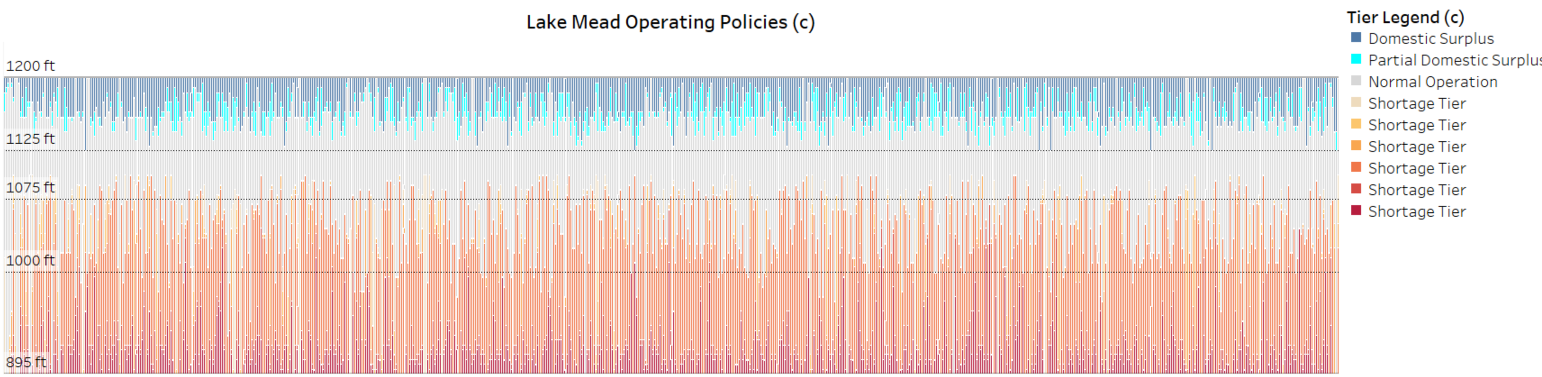


Robustness Criteria:

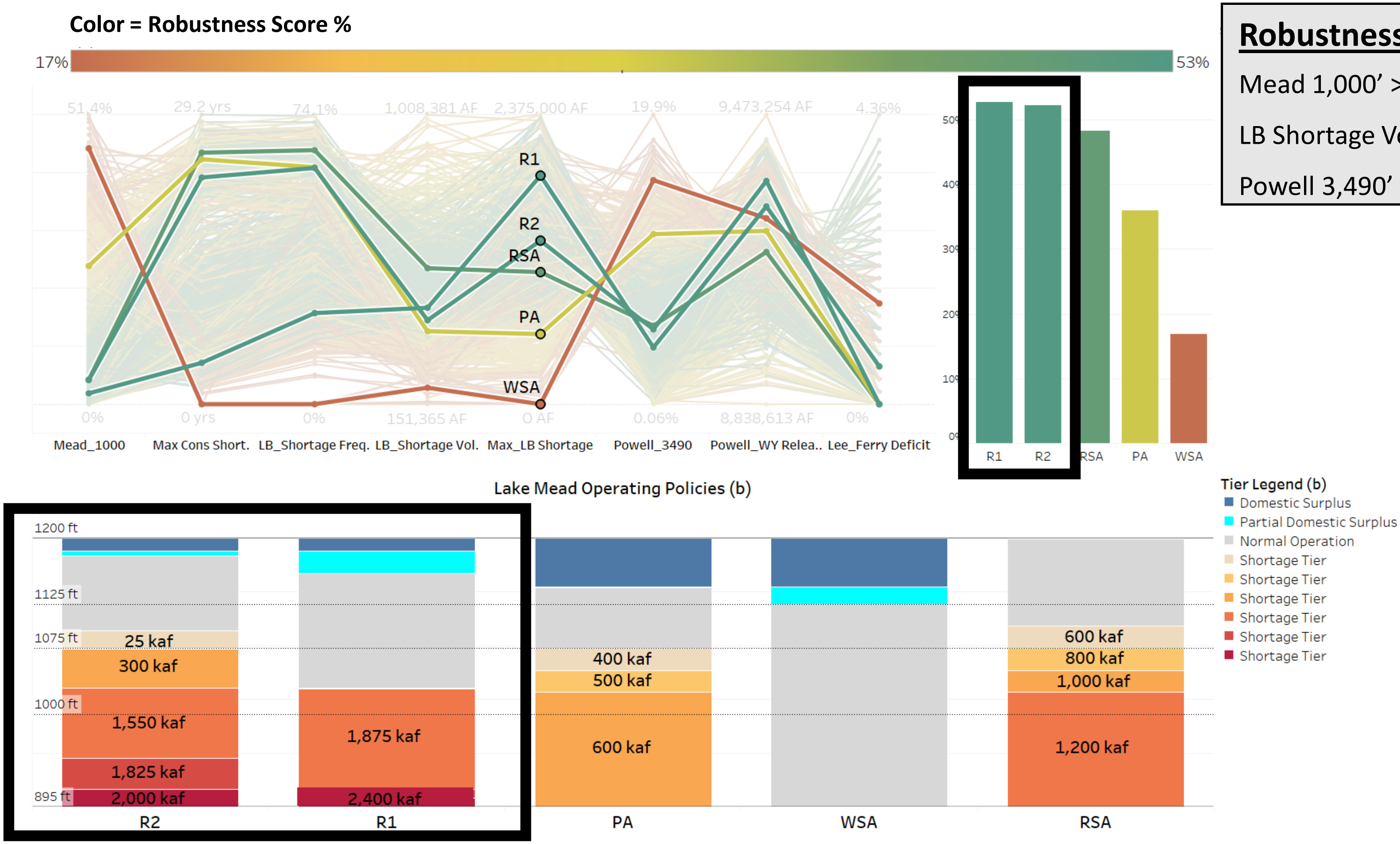
Mead 1,000’ > 90%

LB Shortage Volume ≤ 600 kaf

Powell 3,490’ > 95%



Evaluating the robustness of the MOEA-generated policies



Robustness Criteria:

Mead 1,000’ > 90%

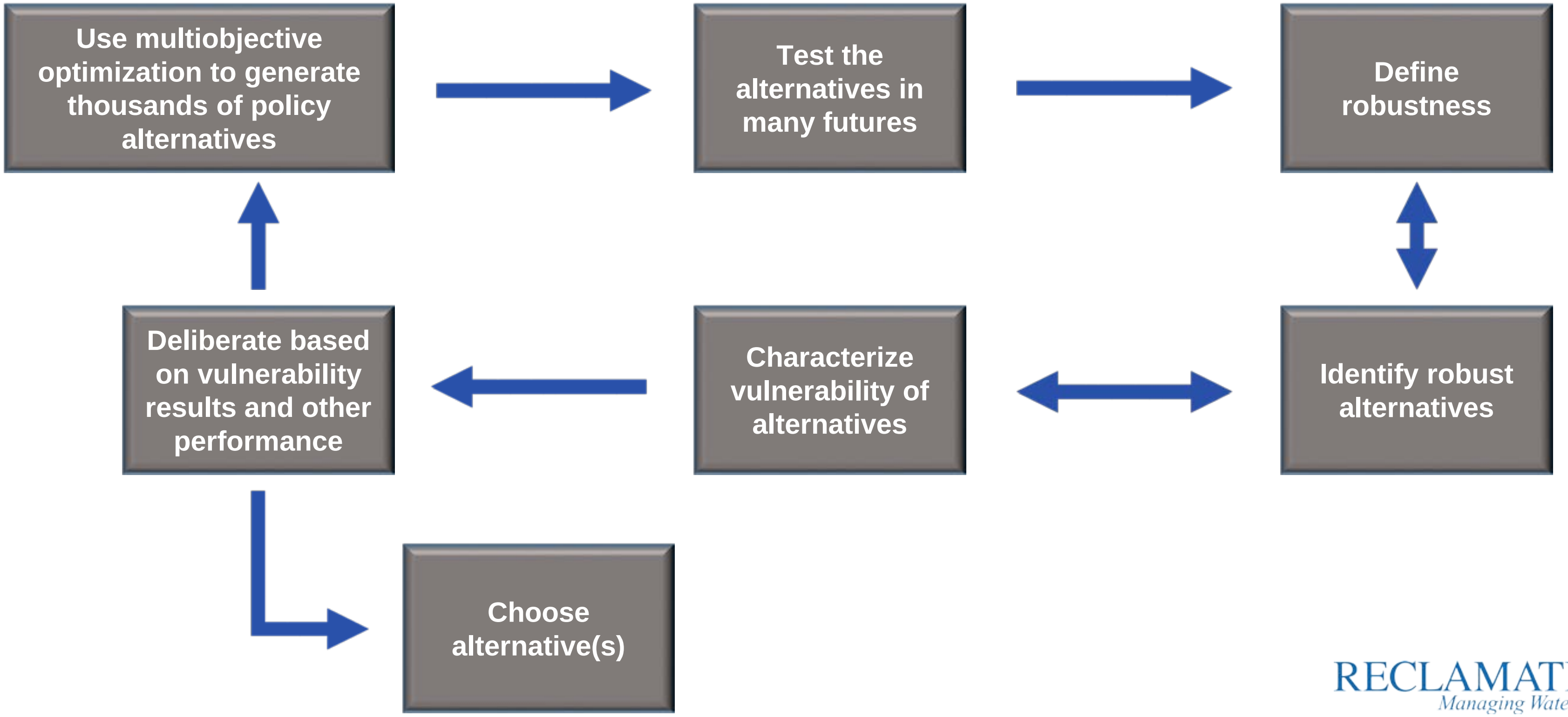
LB Shortage Volume ≤ 600 kaf

Powell 3,490’ > 95%

RECLAMATION
Managing Water in the West

Ongoing and future work

- Expand MOEA search to include coordinated operations between Lakes Powell and Mead
- Quantitative analyses to identify conditions that result in system vulnerability under different policies
- Developing structured approach to combine performance, robustness, and vulnerability information to aid planning process.



RECLAMATION
Managing Water in the West

Conclusions

- Choosing an ensemble to represent future hydrology has a significant impact on planning studies and the uncertainty is not reducible.

- MORDM offers a promising way to de-emphasize ensemble choice while efficiently identifying new policies and quantitatively incorporating different performance priorities.

- Recent RiverWare developments have been critical to Reclamation's exploration of MORDM and future work with CADSWES will continue to enhance these new capabilities.