BUREAU OF RECLAMATION

Post-2026 Integrated Technical Education Workgroup Session 4: Demands

Virtual Session – August 2, 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

- Welcome and introductions
- Review purpose of group
- Review of Decision Making under Deep Uncertainty (DMDU) and the Post-2026 Technical Framework
- General Overview of Demands & Terminology
- Overview of Colorado River Simulation System (CRSS) Demands with In-Depth Focus on Upper and Lower Basin Demands
- Approach to Demands in the Post-2026 Web Tool
- Follow up from ITEW Session 3: Hydrology
- Wrap up and future sessions

Welcome & Introductions

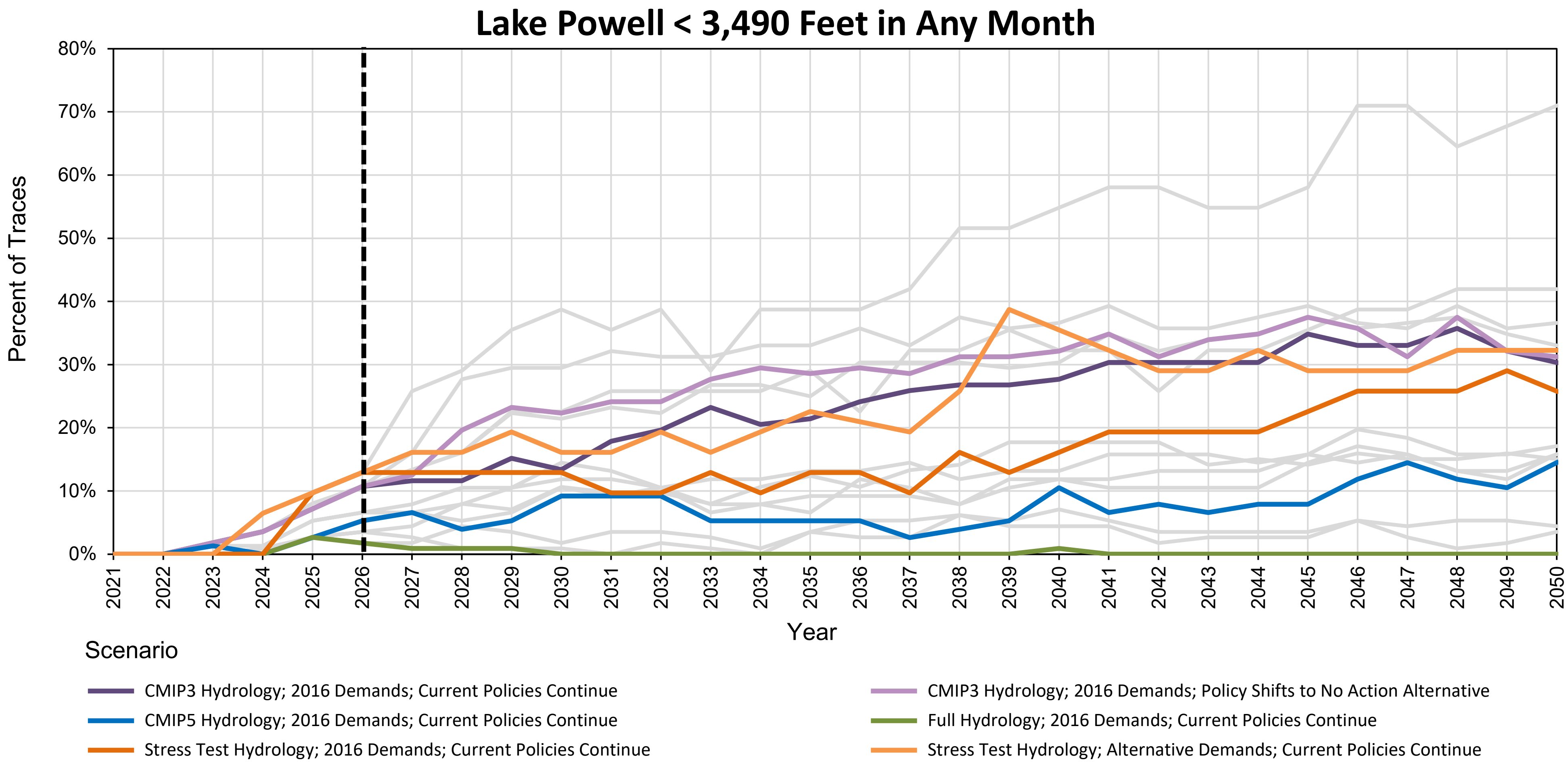
- This is the 4th session of Reclamation's Integrated Technical Education Workgroup (kickoff session was December 7, 2022)
- The Technical Workgroup has been formed for the purpose of assisting our partners and stakeholders to gain a better understanding of the technical tools and approaches to be used in the Post-2026 process and help our partners improve technical capacity
- Workgroup "ground rule": Please refrain from publishing/posting presentation material until posted to Reclamation website
- Thank you for your participation in this Workgroup

Purpose of Technical Workgroup

- The purpose of the Workgroup is for Reclamation to offer education about the technical approach, tools, and data frequently used in its long-term planning studies and to specifically share information about the technical framework that will support the Post-2026 Process
  - The Workgroup will be led through a set of technical education sessions throughout 2023
- The goal is to increase technical capacity and build a solid technical foundation to facilitate meaningful involvement in the Post-2026 Process
- The purpose of the Workgroup is NOT to develop operational alternatives for Post-2026 as a group or to discuss other non-technical aspects of the Process
  - There will be other opportunities to engage with Reclamation on those aspects in separate venues
- The Workgroup does not replace Reclamation's commitment to providing technical support to individual partners upon request

Review of Decision Making under Deep Uncertainty and the Post-2026 Technical Framework

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



Different combinations of inputs result in different views of risk, and no combination is "best"

*All projections are from August 2020 Colorado River Simulation System (CRSS) modeling with Lake Powell initial elevation of 3,592'. Lake Powell's current elevation is ~3,581'

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 important 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

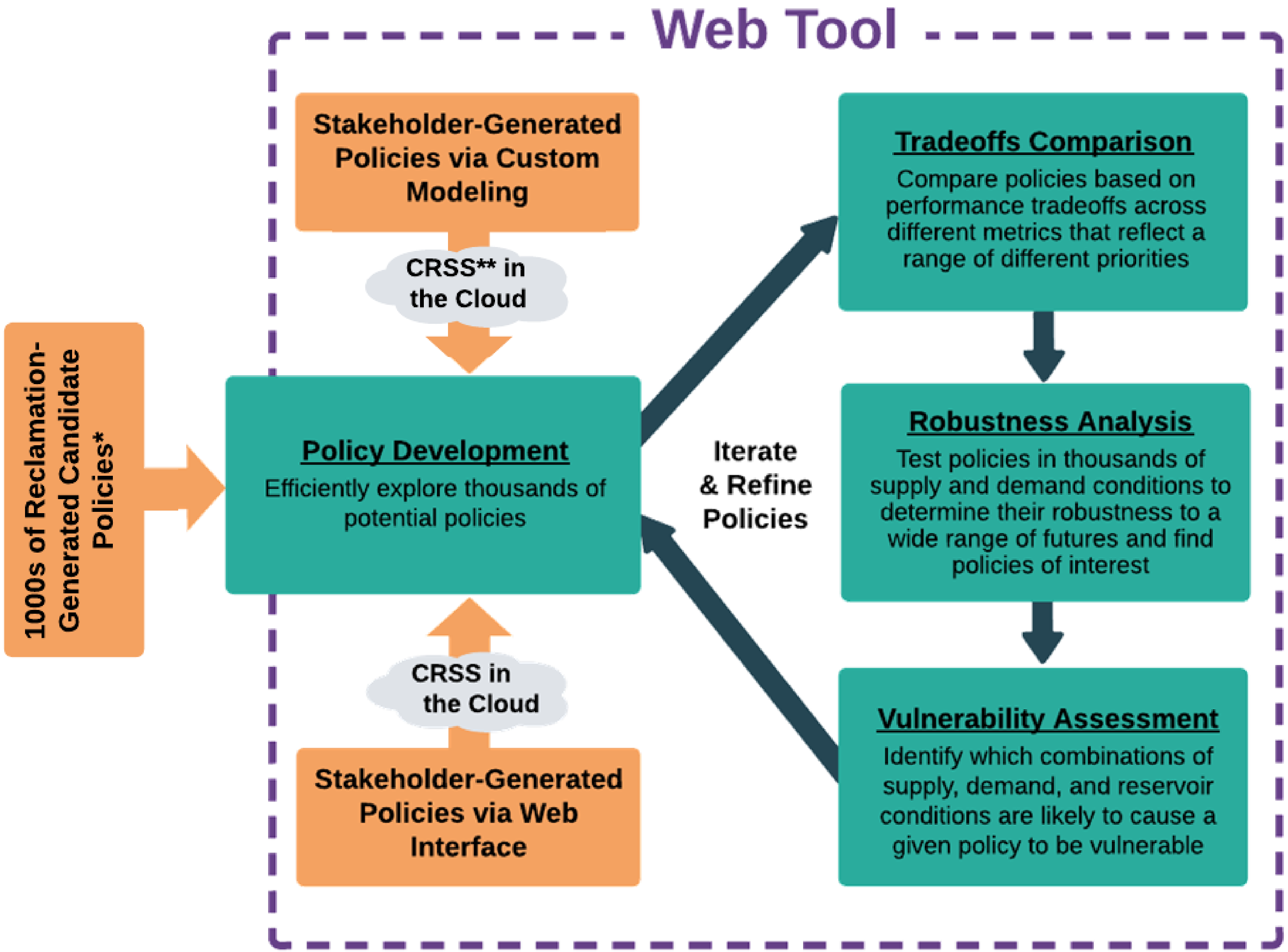
- Consider a *wide range* of future conditions without assigning likelihood beforehand
- Prioritize *robustness*, or the ability of a policy to perform acceptably well in a wide range of conditions
- Assess the *vulnerability* of a policy: what uncertain future conditions might cause it to perform poorly?

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 Web Tool

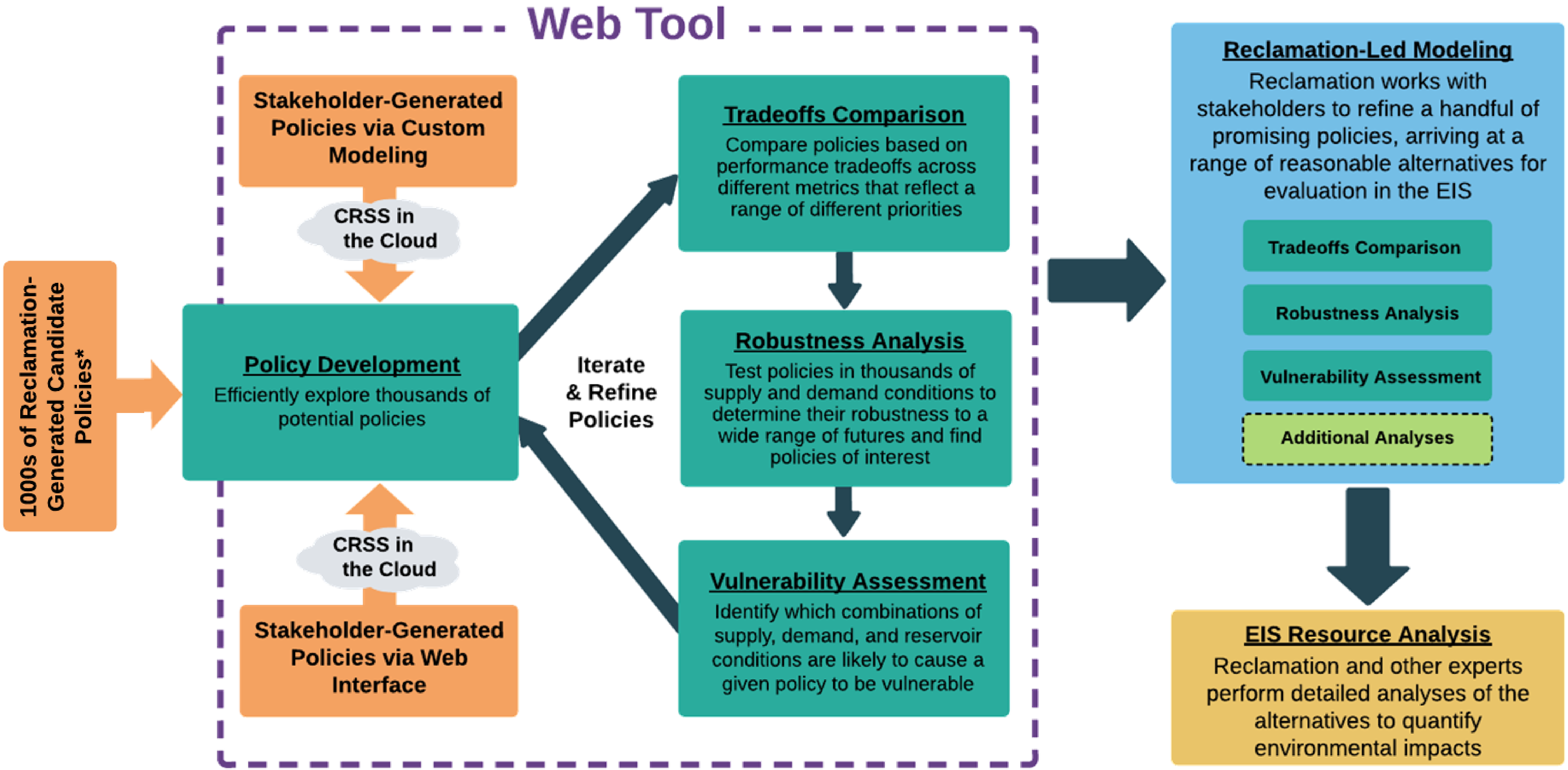


- User-friendly interface connected to CRSS
  - Create policies that are formatted and sent to CRSS
  - Interact with output from CRSS simulations
- Inclusive
  - No prior experience with CRSS required to create and explore policies
  - Compatible with stakeholders who perform advanced modeling
  - Facilitates 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

*Candidate policies will be generated for purposes of modeling analysis (more info on Notes slide)

MORDM & the Web Tool in the Post-2026 Process



*Candidate policies will be generated for purposes of modeling analysis (more info on Notes slide)

General Overview of Demands & Terminology

Demand Terminology

Terms used throughout the presentation defined in the context of CRSS & RiverWare

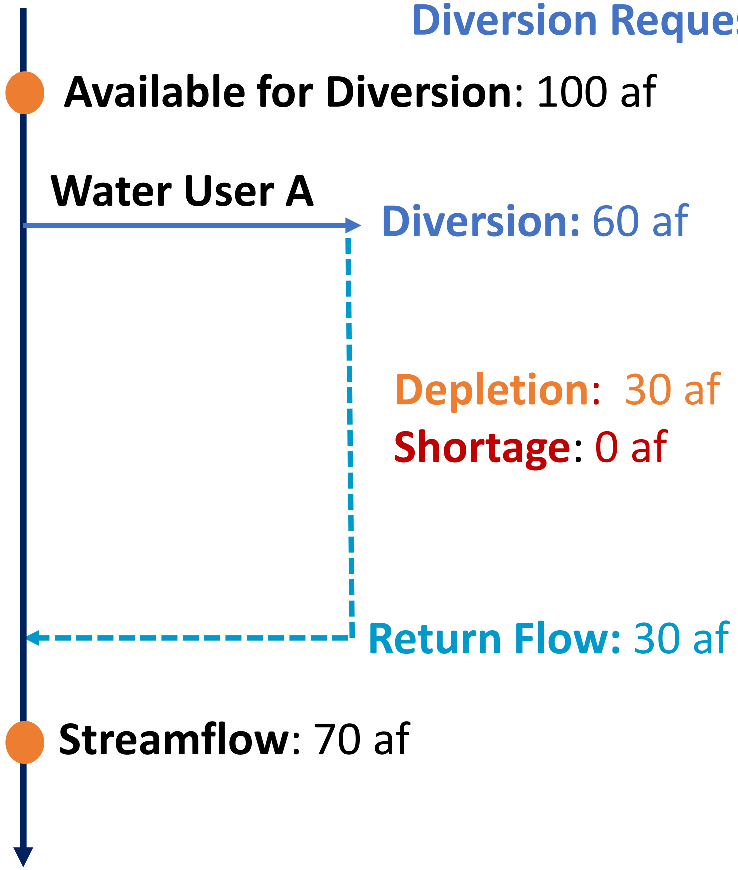
- Demand/Depletion Requested: volume of water needed to meet identified uses under ideal hydrologic and economic conditions
  - Represented in CRSS as “Depletion Requested”
  - Input to CRSS
- Diversion: volume of water diverted from the river system
- Depletion: volume of water diverted and not returned to the river system
  - Used interchangeably with “consumptive use”
  - Calculated by CRSS
- Shortage: unmet demand

Example of Water Use

- Demand/Depletion Requested: volume of water needed to meet identified uses under ideal hydrologic and economic conditions
- Water User Efficiency: portion of the diversion that is depleted
- Diversion: volume of water diverted from the river system
- Depletion: volume of water diverted and not returned to the river system (i.e., consumed)
- Shortage: unmet demand

Model Inputs

Depletion Requested: 30 af
Water User Efficiency: 50%
Diversion Requested: 60 af



Example of Hydrologic Shortage

- Demand/Depletion Requested: volume of water needed to meet identified uses under ideal hydrologic and economic conditions
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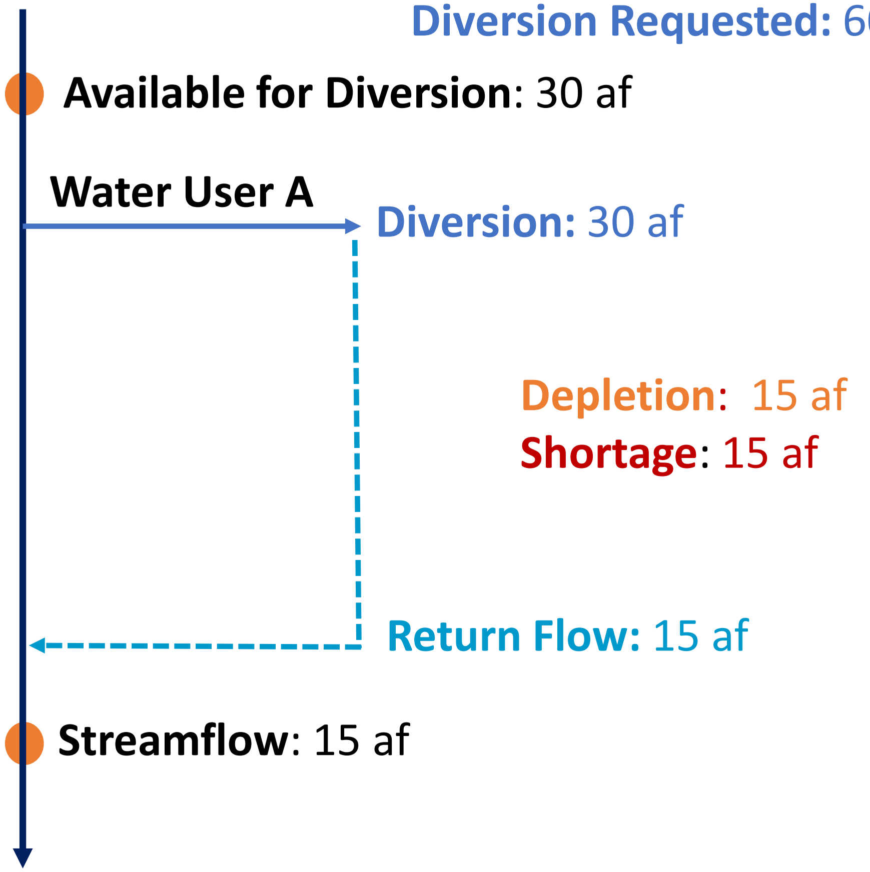


Overview of Colorado River Simulation System (CRSS) Demands

General Representation of CRSS Demands

- CRSS includes approx. 500 water users (i.e., demand nodes)
- Representation of modeled water users varies by Basin
  - Upper Basin includes aggregated water users delineated by sector, such as agricultural, municipal & industrial (M&I), transbasin exports, Tribal, additional losses etc.
  - Lower Basin includes all mainstream entitlement holders
- Monthly depletion and diversion projections are required as CRSS inputs for each water user

CRSS Input

- Monthly Diversion & Depletion Projected Schedules

→

Policy Adjustments

- Schedules are copied over to Diversion Requested & Depletion Requested slots
- Rules can modify these slots to adjust potential use

→

Modeled Depletion

- Model attempts to meet Diversion Requested & Depletion Requested with available water

Current Demands Used in Official CRSS Runs

- Upper Basin
  - Developed by the Upper Colorado River Commission (UCRC), which provides decadal depletion demand schedules by water use sector at a state level
  - 2016 Updated UCRC Demands: disaggregated with cooperation from the Upper Basin States
  - Tribal demands are based on the 2018 Tribal Water Study
- Lower Basin
  - Derived from 2007 Interim Guidelines Final Environmental Impact Statement (FEIS) schedules with minimal updates made at the request of specific Lower Basin water users

Colorado River Simulation System (CRSS) Demands: Upper Basin

Upper Basin Depletion Demand Schedule

- Developed by the UCRC for long-term planning
  - Decadal projected depletion demands by sector at the state level
- Currently using the updated [2016 Depletion Demand Schedule]
  - New schedules are periodically released (approx. every 5-8 yrs.)
- Tribal demands are based on the 2018 Tribal Water Study

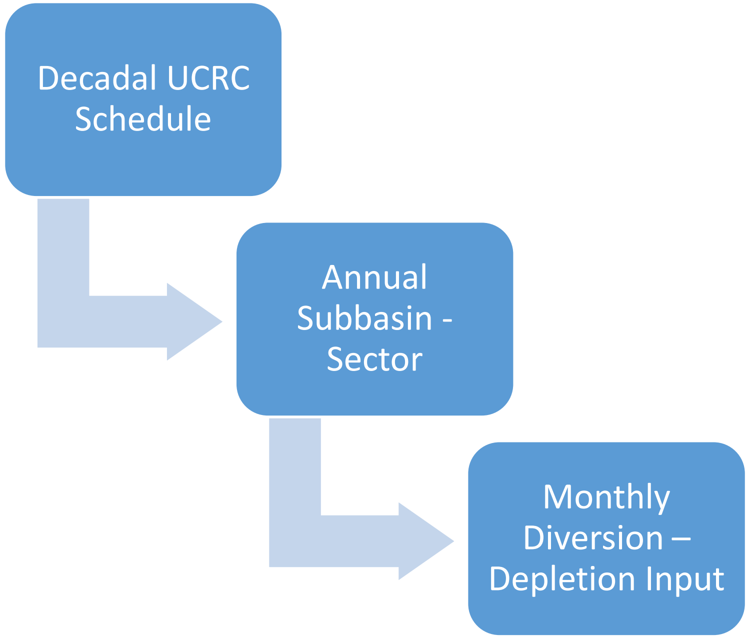
Upper Colorado River Division States Updated Current and Future Depletion Demand Schedule[1,2,5]
Total Upper Colorado River Division States
(1000 Acre-Feet)

ITEM	YEAR						
	Current/Historical	2020	2030	2040	2050	2060	2070
Agriculture – Irrigation & Stock	3,548	3,567	3,596	3,620	3,629	3,633	3,622
Potential Agriculture-Irrigation & Stock		*0*	*0*	*0*	*0*	*0*	*0*
Municipal/Industrial	106	115	132	144	158	167	172
Potential Municipal/Industrial		*2*	*4*	*12*	*14*	*16*	*16*
Self-Served Industrial	12	12	12	12	12	12	12
Potential Self-Served Industrial		*0*	*0*	*0*	*0*	*0*	*0*
Energy	148	151	158	163	168	173	178
Potential Energy		*5*	*10*	*10*	*15*	*10*	*0*
Minerals	53	57	65	73	81	94	103
Potential Minerals		*2*	*8*	*17*	*16*	*31*	*33*
Export	1,055	1,085	1,167	1,239	1,302	1,377	1,513
Potential Export		*50*	*75*	*100*	*125*	*100*	*0*
UT Tribal Water Settlements[3]	0	2	70	141	148	153	153
Reservoir Evaporation (in-state)	261	261	261	261	261	261	261
Potential Reservoir Evaporation		*0*	*0*	*0*	*0*	*0*	*0*
TOTAL Forecasted Depletions	5,183	5,309	5,558	5,792	5,939	6,027	6,063
Shared CRSP Evap (0.520maf)[4]	520	520	520	520	520	520	520
TOTAL	5,703	5,829	6,078	6,312	6,459	6,547	6,583

[1] This depletion schedule does not attempt to interpret the Colorado River Compact, the Upper Colorado River Basin Compact, or any other element of the "Law of the River." This schedule should not be construed as an acceptance of any assumption that limits the Upper Colorado River Basin's depletions.
[2]This depletion schedule is for planning purposes only. It is not a tabulation or determination of water rights or actual uses.
[3]Existing Tribal uses are captured by the Agricultural and M&I sectors, and future Tribal uses are represented in the Tribal Settlements category.
[4]"Shared CRSP Evap" refers to evaporation from the reservoirs constructed under the Colorado River Storage Project (CRSP) Act that are used to regulate compact deliveries at Lee Ferry and generate CRSP hydroelectric power. These include Lake Powell, Flaming Gorge Reservoir, and the Aspinall Unit. This evaporation amount is the anticipated long-term average. Evaporation will vary annually depending on reservoir storage and climatic conditions.
[5]To find more materials related to this Depletion Demand Schedule, please follow this link to the Upper Colorado River Commission's Depletion Demand Schedule webpage: http://www.ucrcommission.com/upper-colorado-river-division-states-depletion-demand-schedules/

Upper Basin Demand Disaggregation

- Reclamation assists each state with disaggregating their UCRC decadal demand schedule to CRSS's spatial distribution at an annual timestep
- Use monthly distribution coefficients to disaggregate annual demands to monthly demands
  - Coefficients derived from Consumptive Use & Loss (CU&L) average distributions*, varying by sector and sub-basin
  - Monthly distribution of demands can affect modeled depletions and shortages
- Calculate the CRSS Diversion Schedules using water user efficiency ratios and CRSS Depletion Schedules



Some distributions were provided by states

Incorporating 2016 UCRC Demands into CRSSv6

CRSSv6 model was developed to

- Further reduce model streamflow bias[1] during the historical verification[2], and
- Improve characterization of the variability and range of Upper Basin depletions

This was achieved by

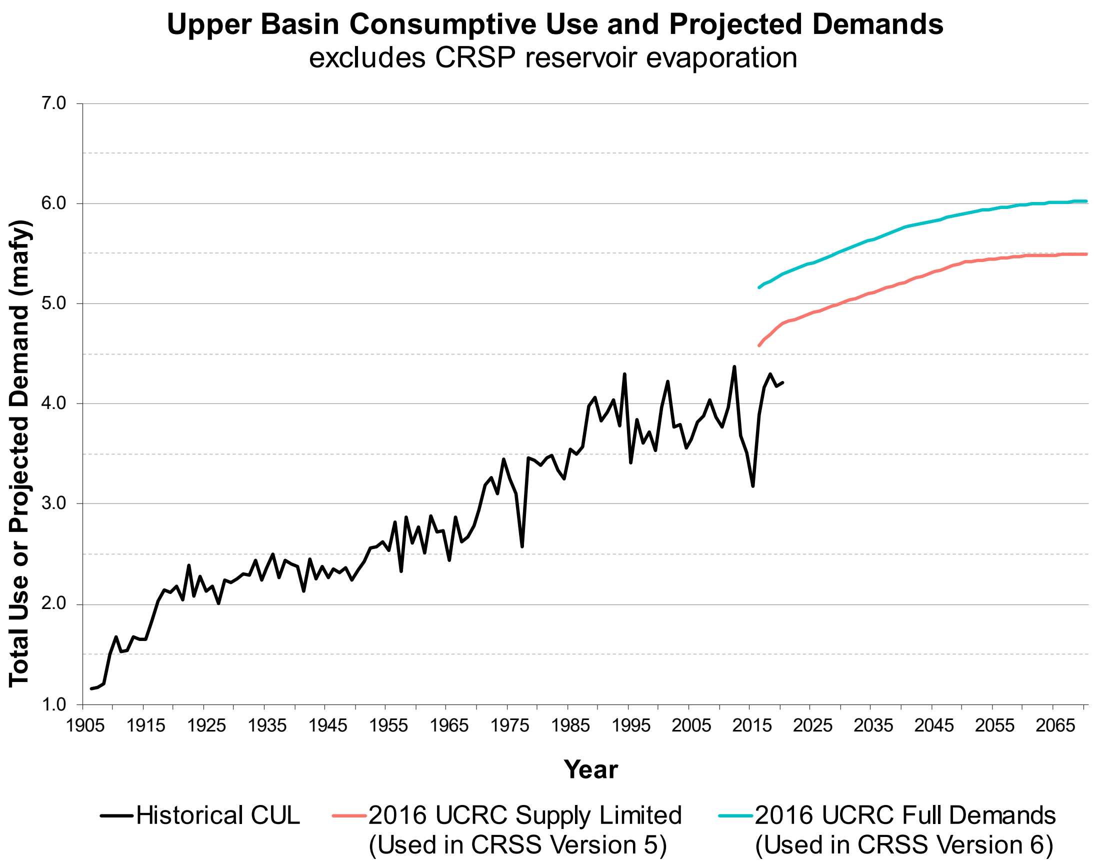
- Incorporating "full" Upper Basin demands; and
- Calibrating the model to reduce the bias in Upper Basin reaches

Model Version	Lake Powell Inflow Bias (kaf)	Lake Powell Inflow Bias (%)
April 2020 CRSS + 2007 UCRC Demands	-535	-6
January 2022 CRSS + 2016 "Supply Limited" UCRC Demands	-145	-2

1) Bias: average difference between modeled and observed streamflow at each location
2) Verification run: 2000-2020 simulation run with observed natural flow hydrology, 2016 demands extended back to 2000, and current ruleset

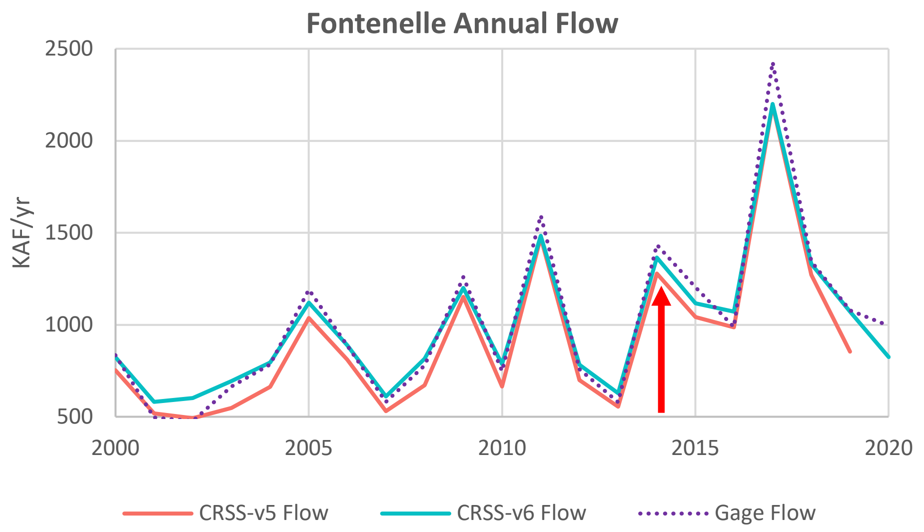
Moving to Full Upper Basin Demands

- Previous UCRC Depletion Demand Schedules represented "supply limited" demands
  - Reflected anticipated Upper Basin shortages in high elevation and/or supply limited tributaries
- The Updated 2016 UCRC Depletion Demand Schedule represents "full" demands
  - More accurately simulate range and variability in Upper Basin depletions under different water supply conditions in conjunction with new calibration method



CRSS Calibration

- Calibrate to reduce model streamflow bias[1] during the historical verification period[2]
- Calibrate by adjusting percent of streamflow available to Upper Basin agricultural water users on each reach
  - Performed in CRSS by iteratively adjusting percent and re-running to reduce bias further
- *Example: Green River above Fontenelle Reservoir*
  - *CRSSv5 under-estimated gage flow, average annual bias is -96 KAF*
  - *Calibrated water available to agricultural users to 31%*
  - *CRSSv6 average annual bias is -15 KAF*



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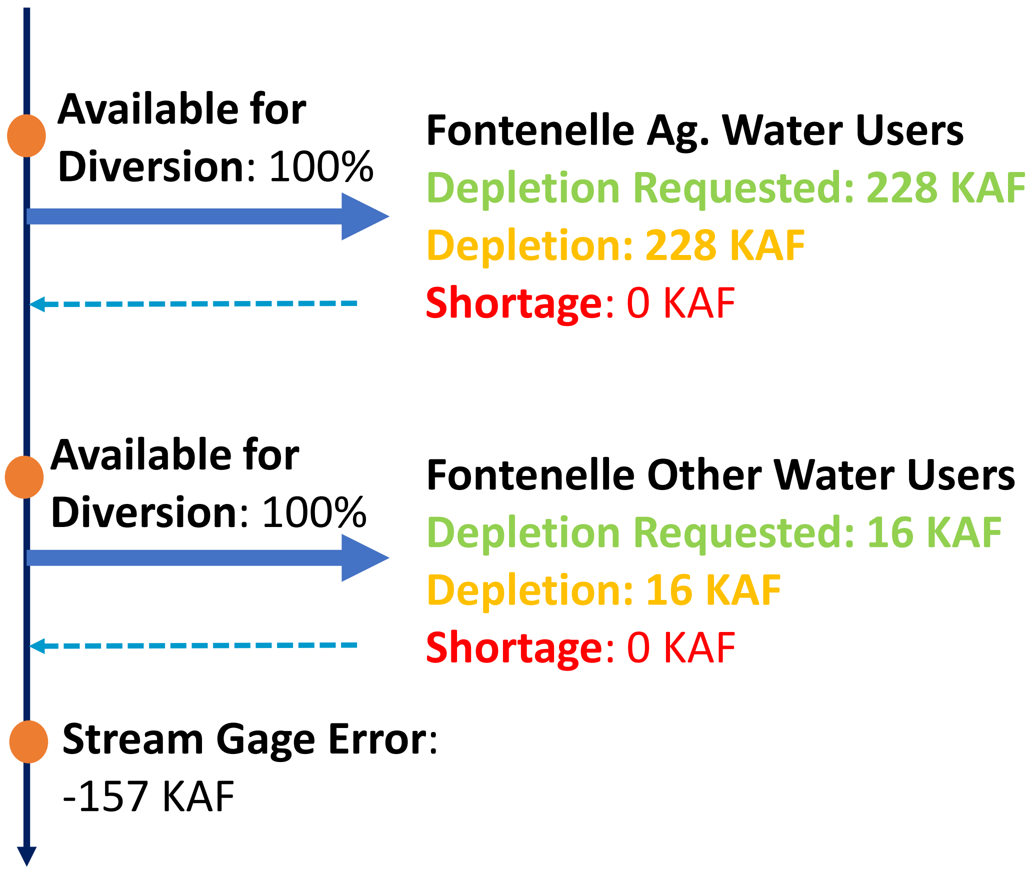
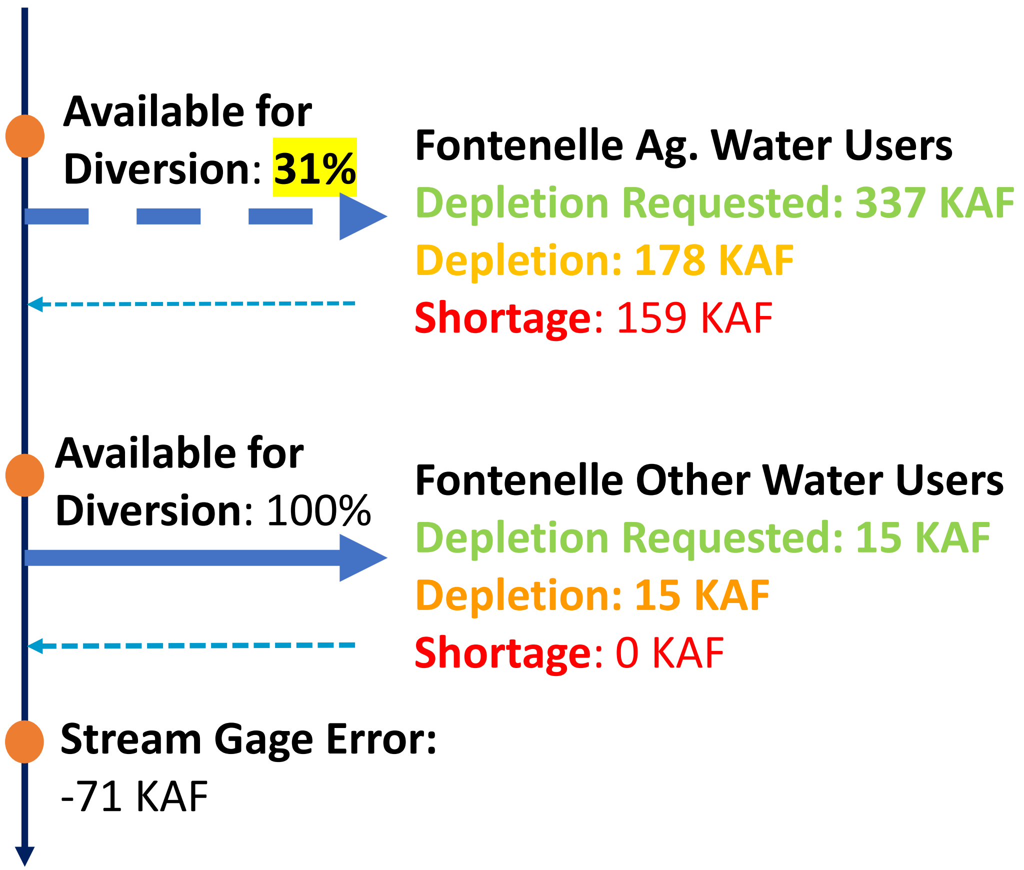
CRSSv5 Example



- Green River above Fontenelle in 2014
  - CRSSv5 underestimated streamflow at gage
  - 100% of water available to agricultural users

CRSSv6 Example

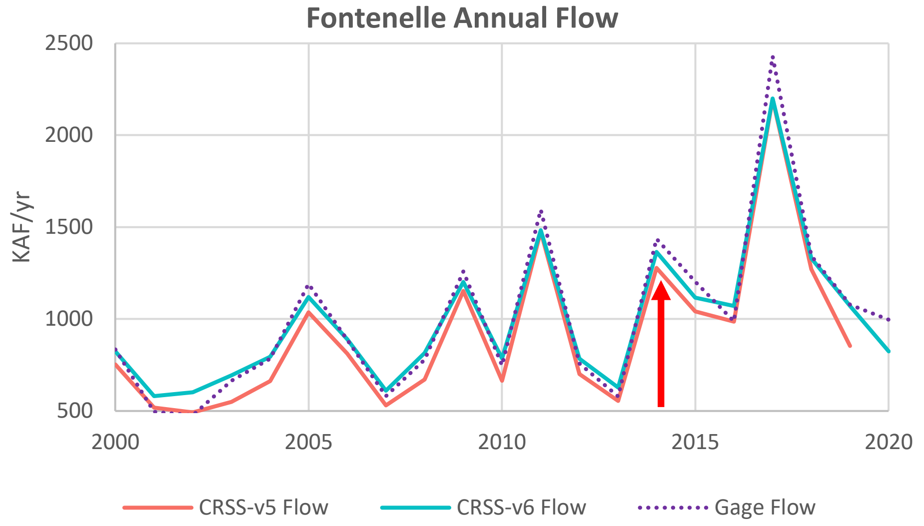


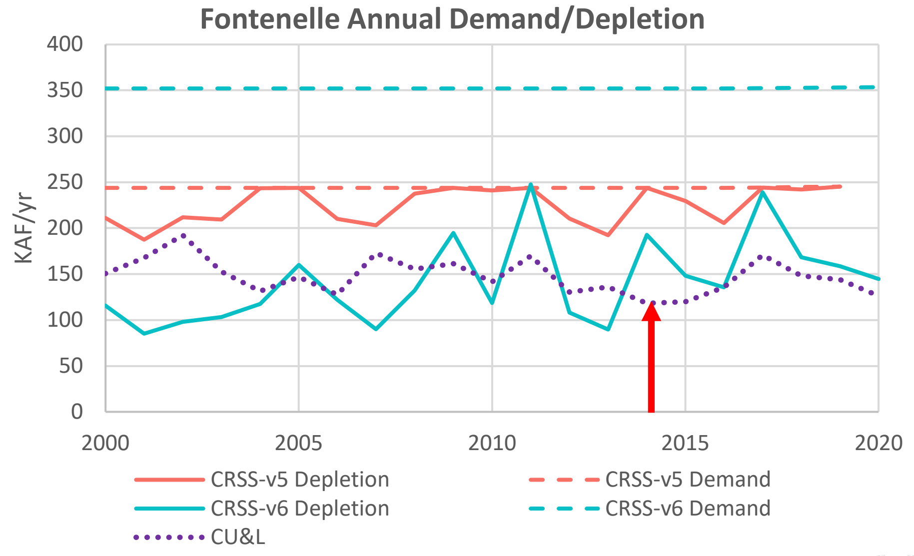
- Green River above Fontenelle in 2014
  - Agricultural depletion requested increased from 228 to 337 KAF moving from Supply Limited to Full Demands Schedule
  - Calibrated percent of water available to agricultural users to 31%
  - Calculated agricultural depletions reduced 228 to 178 KAF
  - Reduced 2014 stream gage error by 86 KAF
- Note: CRSS modeled agricultural use is a function of calibration and does not represent actual agricultural depletions and shortages.

Overall Impacts of Calibration

- Reduces streamflow bias
  - Generally, decreases agricultural depletions which increases streamflow
- More accurately characterizes Upper Basin depletions under a broad range of water supply conditions

Model Version	Lake Powell Inflow Bias (kaf)	Lake Powell Inflow Bias (%)
April 2020 CRSS + 2007 UCRC Demands	-535	-6
January 2022 CRSS + 2016 "Supply Limited" UCRC Demands	-145	-2
March 2023 CRSS + 2016 "Full" UCRC Demands	0	0





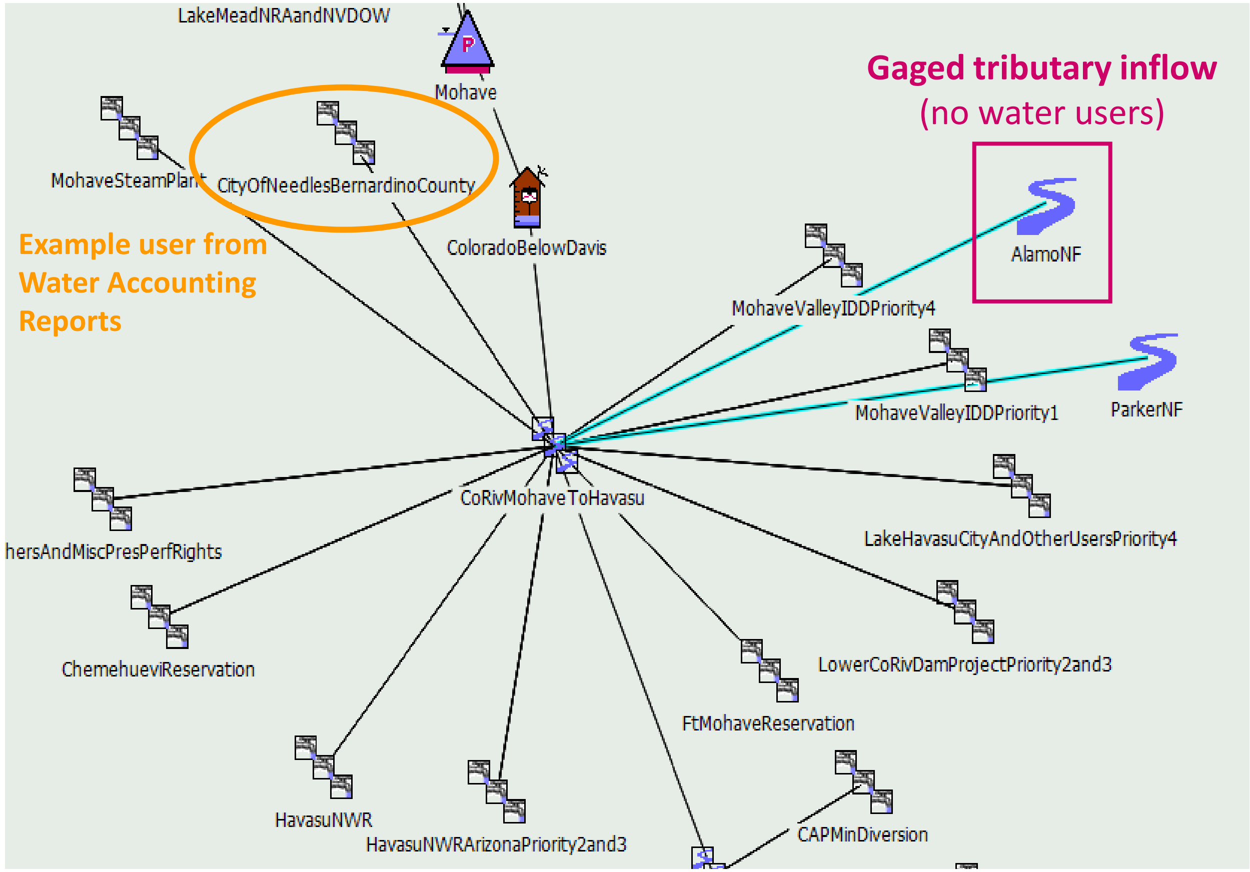
Colorado River Simulation System (CRSS) Demands: Lower Basin

Lower Basin Demands

- Derived from 2007 Interim Guidelines Final Environmental Impact Statement (FEIS) schedules with minimal updates made at the request of specific Lower Basin water users
- Annual demands reflect Lower Basin state apportionments and Mexico's allocation
  - 7.5 maf for the Lower Basin States (4.4 maf CA, 2.8 maf AZ, 0.3 maf NV)
  - 1.5 maf for Mexico
- CRSS logic is used to make additional adjustments to demands to account for policy operations—such as the 2007 Interim Guidelines Surplus, Shortage, and Intentionally Created Surplus (ICS); Drought Contingency Plan (DCP) contributions; and Minute 323

Lower Basin Demands in CRSS

- Only model use from mainstream entitlement holders
  - Do not model tributary use
- Modeled water users are consistent with those in Reclamation's Water Accounting Reports
- Water users demands are adjusted in CRSS according to existing operational policies (i.e., the 2007 Interim Guidelines, DCP and Minute 323)



Water Accounting Reports available at https://www.usbr.gov/lc/region/g4000/wtracct.html

Reservoir Evaporation & Other Losses

- Reservoir Evaporation
  - CRSS calculates evaporation for the larger Basin reservoirs
    - Powell, Flaming Gorge, Navajo Blue Mesa, Morrow Point, Crystal, Fontenelle
    - Mead, Mohave, Havasu
  - Other reservoirs estimated from historical losses
- Phreatophyte Losses
  - Losses due to evapotranspiration by riparian vegetation are implicitly included in the water budget through natural flow computations
- Other Losses
  - Flows to Mexico in excess of Treaty requirement
  - Water bypassed pursuant to IBWC Minute 242

Next Steps

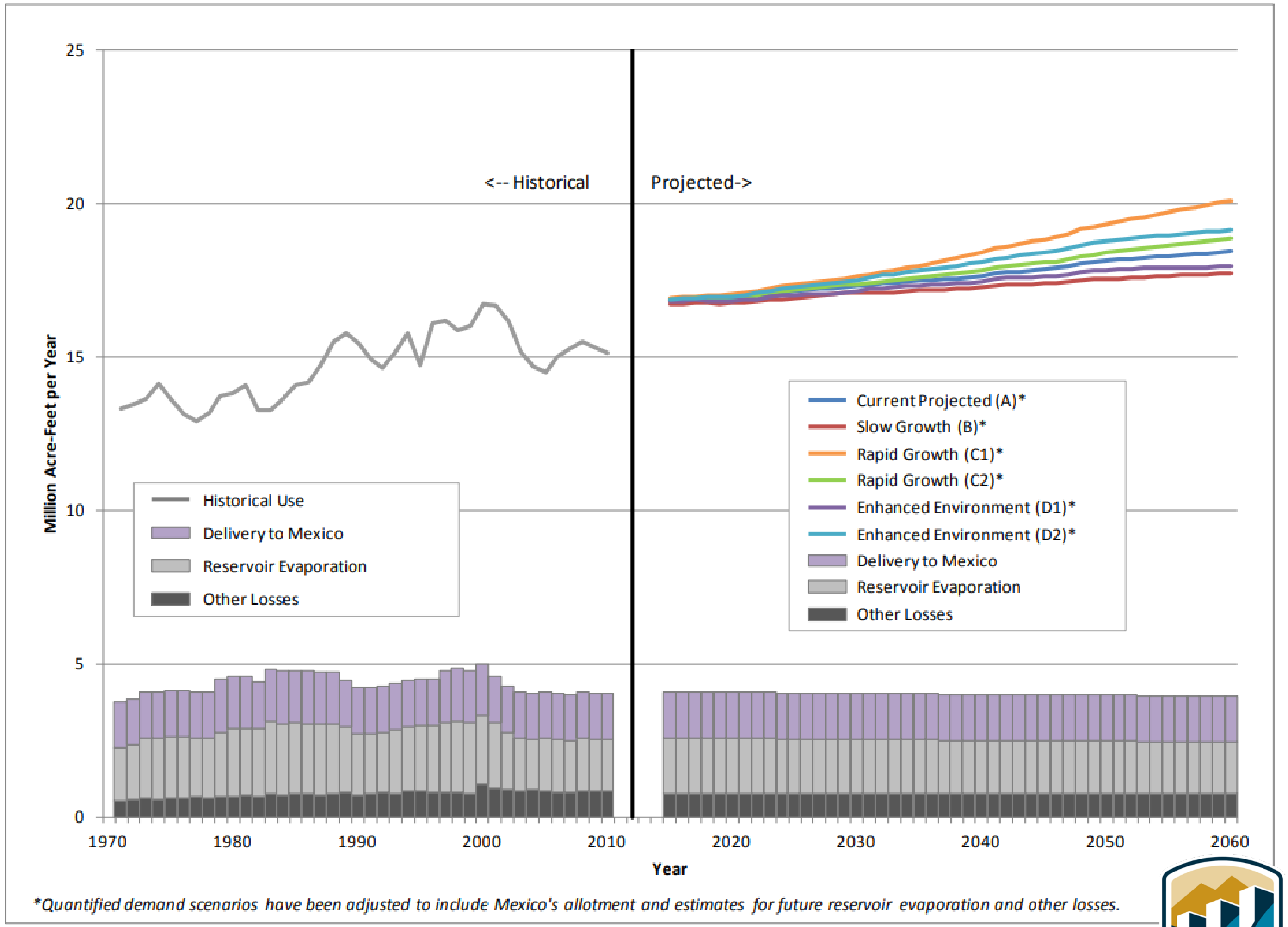
As needed, for alternative development and analysis beyond the Web Tool, the Upper and Lower Basin demands will be updated in coordination with the States, Tribes, and other key water users.

Approach to Demands and Other Model Inputs in the Post-2026 Web Tool

Previous Studies Explored Alternative Demand Scenarios

- Future demands are complex and uncertain
- Demands impact reservoir elevations and performance of potential policies
- Scenario planning approach
  - Brainstorm factors that could influence water use and rank factors on importance and uncertainty
  - Determine what changes in each factor would cause water use to grow or decline for the most important and uncertain factors
  - Use this information to define different potential future: called "storylines"
  - Quantify water use under each storyline
- Resulting scenarios
  - Basin Study developed 4 storylines and 6 future demand scenarios
  - Tribal Water Study developed 3 storylines and 4 future demand scenarios
  - Paired with projected future hydrology scenarios and different policies to explore vulnerabilities under a wide range of potential future conditions

Basin-Wide Historical Use and Projected Future Demands, etc.



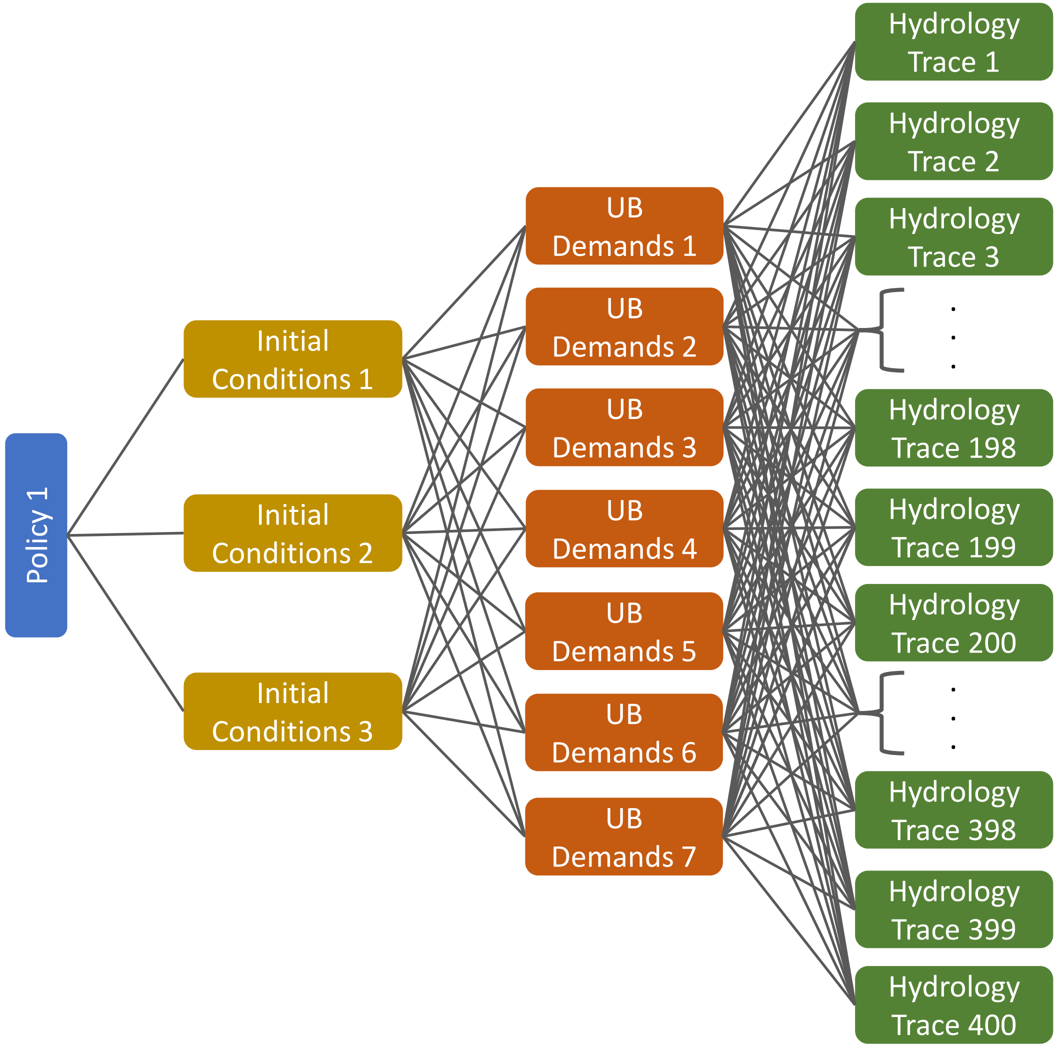
Source: 2012 Basin Study Technical Report C

Approach to Upper Basin Demands in Post-2026 Web Tool

- Previous long-term planning studies have used demand *scenarios*, or stories projecting how demands may evolve in the future
  - Valuable for considering how complex forces impact future water use
  - Embed assumptions about timing and magnitude of changes
  - Can obscure relationships between model inputs, reducing ability to identify conditions that drive system vulnerability
- Steady-state demand levels are appropriate for DMDU analysis
  - Need to span and fill in a range of potential future conditions, not create new stories about how water use will evolve
  - Want to avoid the layers of assumptions embedded in time-varying scenarios
  - DMDU is not seeking to identify system conditions at a specific point in time, just under a specific intersection of inputs; impacts of high or low steady-state demands are relevant at any point in the future
- Web Tool will use multiple demand scenarios along with different steady-state demand levels to help distinguish how combinations of inputs interact to cause system vulnerability

Structuring Data to Support DMDU Analysis

- The Post-2026 Web Tool is designed to support DMDU analysis, which emphasizes the identification of specific combinations of uncertain future conditions that can lead to system vulnerability
- Projected system conditions are affected by complex interactions between modeling inputs: supply, demand, initial conditions, and policy
- To generate data that is useful for analyzing vulnerability we are
  - Structuring the variability of inputs to span and fill in a wide range of values
  - modeling all combinations of inputs
  - framing analysis in terms of generic timespans, not tying to specific years (2027, 2028, etc.)
    - reduces focus on the likelihood of conditions occurring at any given time (probabilistic thinking)
    - clarifies that we are seeking combinations of conditions, not predicting how conditions will evolve
- All policies in the Web Tool will be modeled in all combinations of inputs and certain dashboards will allow users to filter to specific combinations



Approach to Lower Basin Demands in Post-2026 Web Tool

- Different "levels" of Lower Basin demands will be represented by modeling policies that specify different shortage volumes
- Policies can have many different structures and a wide range of shortage volumes to explore how Lower Basin water use interacts with combinations of supply, demand, and initial conditions to cause vulnerabilities
- Distribution of Lower Basin shortages will not be represented in Web Tool modeling
  - Lake Mead releases will be reduced as specified by a given policy, enabling analysis of reservoir levels
  - Lower Basin demand schedules will not affect Web Tool modeling

Demands Summary

- Demands are an important input to CRSS and are handled differently depending on basin. In the current "official" model:
  - Upper Basin demand inputs are derived from state- and tribe-generated projections and represent the amount of water that would be used under ideal future hydrologic and economic conditions. CRSS simulations using different hydrologic inputs affect deliveries to water users
  - Lower Basin demands reflect legal apportionments and schedules developed during the 2007 Interim Guidelines FEIS, and CRSS logic is used to adjust the demands to account for policy operations (e.g., 2007 Interim Guidelines)
- CRSS simulates potential futures by using multiple different combinations of uncertain inputs – supply, demand, initial conditions, and policy – that interact in complex ways to impact system conditions
- In order to understand how specific combinations of CRSS inputs drive system vulnerability in the Web Tool, we are structuring inputs from each category to span and fill in a wide range of potential future values
- The approach to representing demand uncertainty for Web Tool modeling to be able to identify how demands interact with other inputs is handled differently depending on basin:
  - Upper Basin demands will be represented by multiple scenarios and multiple steady state demand levels
  - Lower Basin demand variability will be represented by adjusting shortage volumes in different policies
- The approach to and representation of demands in CRSS will be revisited and updated or revised where appropriate to support analysis beyond the Web Tool

Additional Information about Hydrology Ensembles

Outline

- Review of approach to choosing hydrology for the Post-2026 Web Tool
- Review of feedback from ITEW Session 3: Hydrology
- Nonparametric Paleo Conditioned hydrology generation method
- Newly developed hydrology ensemble from Utah State University

Going from Individual Ensembles to a Wide Range of Individual Futures

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

Approach to Choosing Ensembles for the Post-2026 Web Tool

- Ensembles have many characteristics that inform whether they are appropriate or useful for our analysis
  - Data source
  - Previous applications
  - Range, distribution, trends, etc. (violin plots)
  - Static characteristics (5-yr avg, long-term avg)
  - Patterns

- Reclamation will use a combination of all characteristics to identify the ensembles that will be used in the Post-2026 Web Tool and throughout alternatives development

- To ensure that the overall **group of traces** fully captures characteristics and patterns needed for sound analysis, additional ensembles may be developed

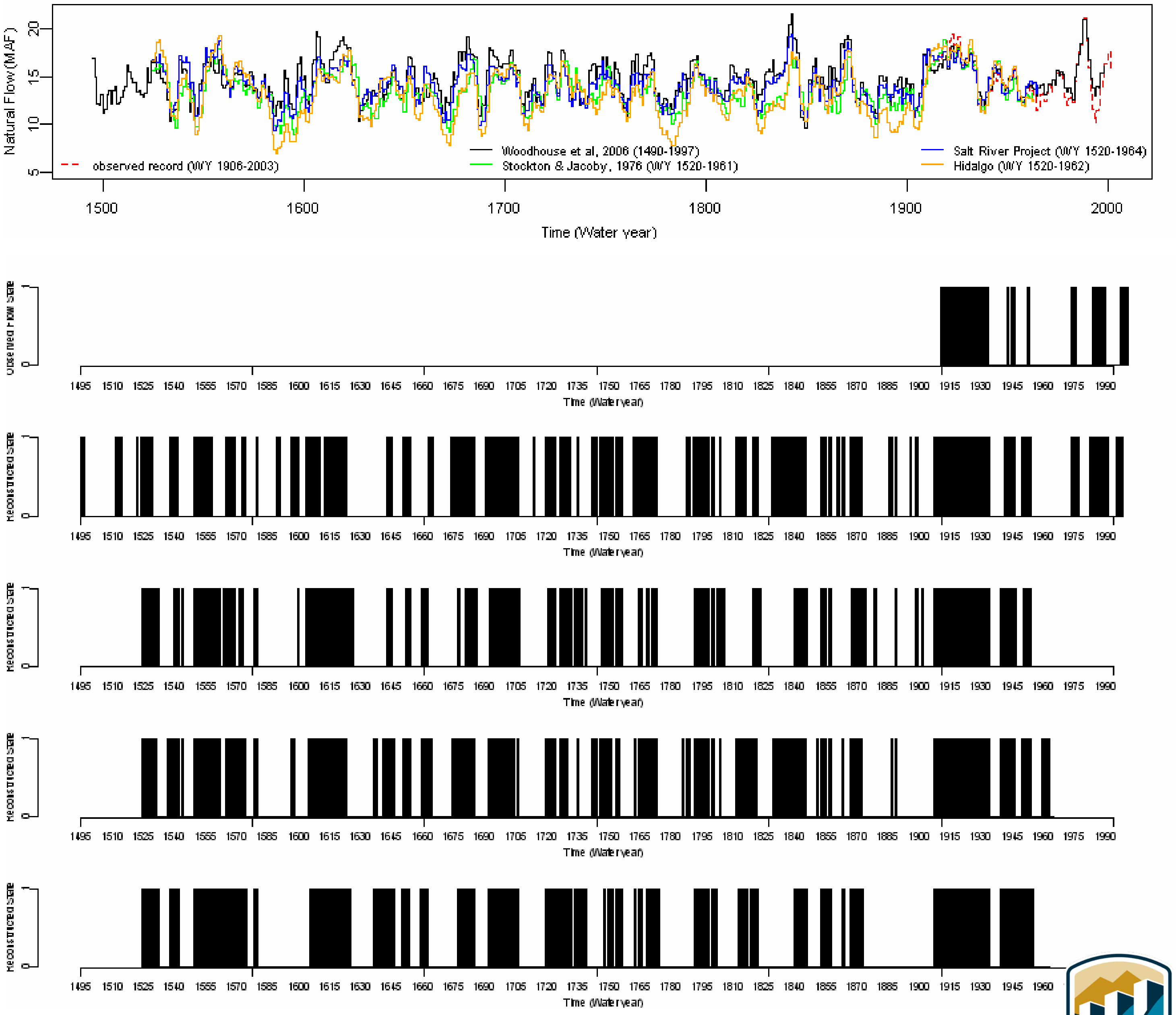
Follow-up from ITEW Session 3

- Respondents requested inclusion of hydrology ensembles that exhibit:
  - flows lower than those in the observed record
  - a downward trend that reflects the potential for continued warming and drying in the Basin
  - drier conditions while maintaining interannual variability
  - several years of dry conditions followed by one or more years of unprecedented high flows

- Data related to hydrology ensembles presented in ITEW sessions is available upon request

Paleohydrology Records

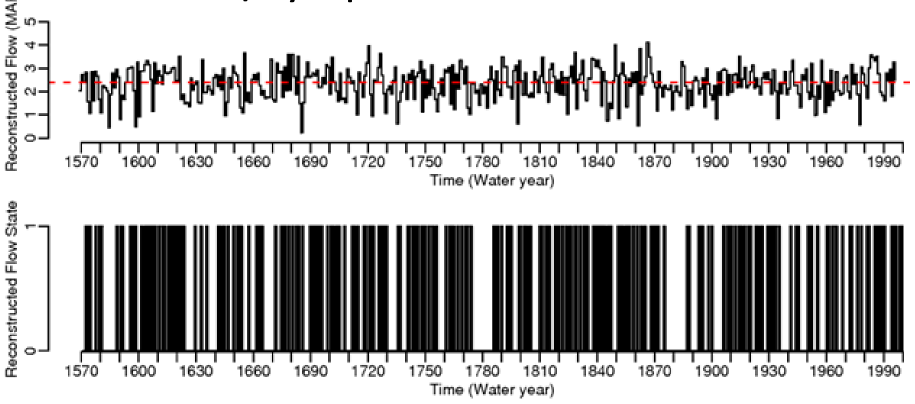
- Tree ring widths are used to reconstruct annual water availability before gaged observations
- Reconstructions are highly skillful but only capture a portion of the variability in their respective time periods
- Paleo magnitudes differ by reconstruction approach
- Reconstructions capture wet and dry cycles similarly



Nonparametric Paleo Conditioning (NPC)

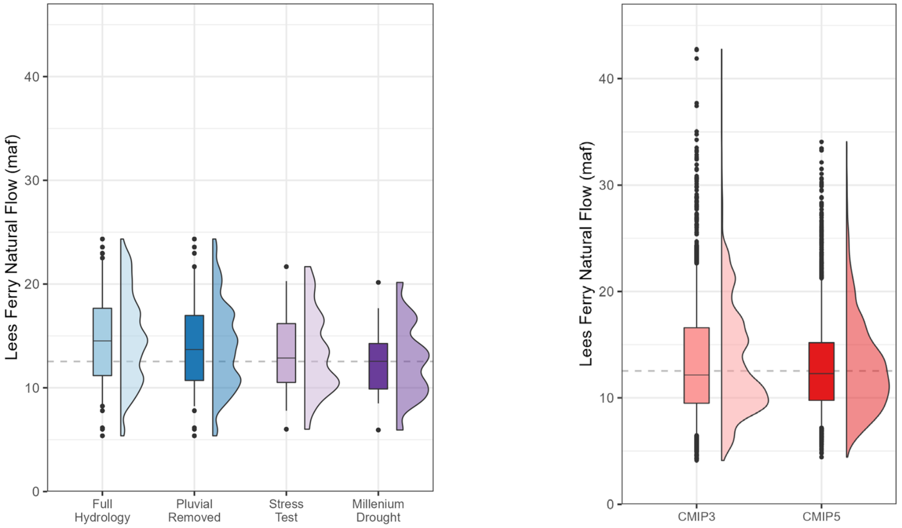
- Combines multiple data sources
  - Paleo-based flow sequences
    - Paleo median flow used to split wet versus dry years
    - Sequences of wet and dry states capture longer dry spells than 1906-2020 observed record
  - Flow magnitudes from different ensembles (observed or projected)
    - Provide range of flow magnitudes
    - Observed or projected median flow used to bin wet and dry flows for resampling
- Can generate any number of unique sequences (patterns)
- Previously used NPC + observed natural flow record
  - 2007 Interim Guidelines FEIS (Appendix N)
  - 2012 Basin Study

Wet/dry sequences taken from Paleo record



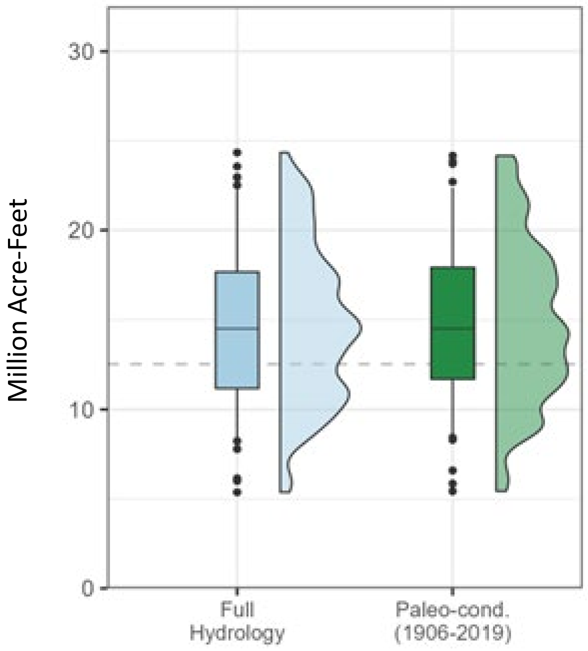
Magnitudes taken from different ensembles

Observed Record **Projections**



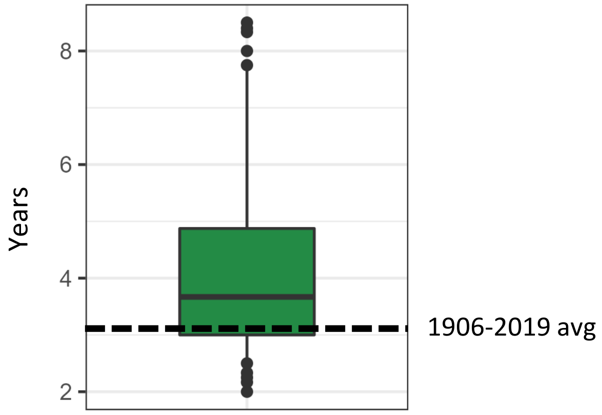
Nonparametric Paleo Conditioning using Full Observed Record (1906-2019)

Distributions of Annual Natural Flow
Lees Ferry, AZ



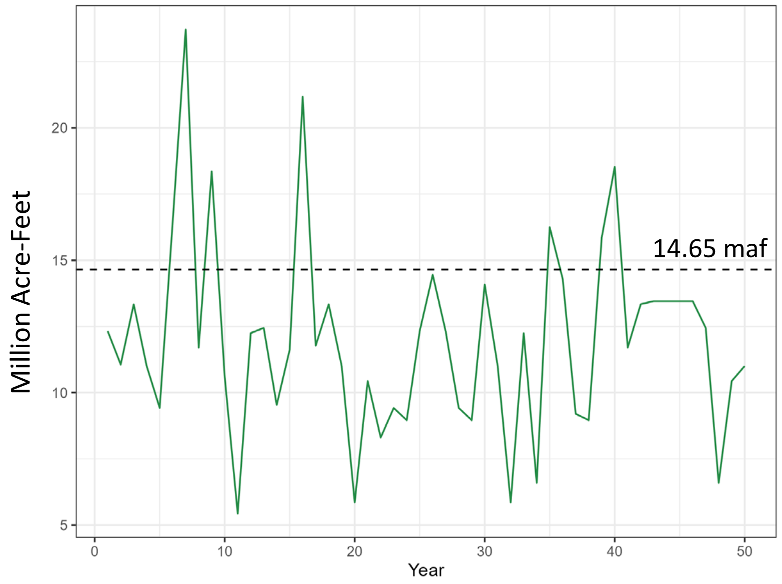
- Minimum annual flow, maximum annual flow, and distribution are the same in the Full Observed Record and NPC+ Full Observed

Average Drought* Lengths
NPC + Full Observed (100 Traces)



- 1906-2019 average drought length = 3.06 years

Annual Lees Ferry Flow
NPC + Full Observed (Representative Trace)



- Representative trace average drought length = 8.4 years

*Drought is defined as two or more consecutive years below 14.65 million acre-feet (maf)

Opportunities to Blend Hydrologic Knowledge, Methods, and Datasets

Motivation for Developing a New Ensemble

- What we have learned from climate change projections
  - Warming will continue in the future
  - Future precipitation is highly uncertain
    - Physical mechanisms for increased precipitation are credible: a warm, chaotic atmosphere can lead to more extreme precipitation
    - Extreme-high annual flows that result from climate projections and data processing steps may not be credible
- Warming reduces the amount of streamflow that can be expected from a given amount of precipitation
  - Increasing temperatures increase the amount of water that is used by plants and evaporated from the soil, and consecutive warm years can compound soil moisture deficits that must be "repaid"
  - Milly and Dunne (2020)[3] estimated that the amount of precipitation that becomes streamflow decreases 7.8% to 12.2% per 1°C of warming (mean decrease of 9.3%)
- The variability represented in paleohydrology can happen again
- Storyline: "What if future flows had a lower and declining average, but the Basin still experienced infrequent high flows?"
- Blending data from observations, reconstructions and projections

> "... the main value of the tree-ring reconstructions is in their broader and richer sequences of wet and dry years, compared to the instrumental record. This information can be combined with the most robust aspects of climate projections from GCMs (i.e., future warming) to develop plausible scenarios for future hydrology."
>
> *- Colorado River Basin Climate and Hydrology: State of the Science p. 381*[4]

New Ensemble Developed to Model Potential Warming-Driven Declining Streamflow

Homa Salehabadi (Utah State University)
David Tarboton (Utah State University)
Kevin Wheeler (Water Balance Consulting)

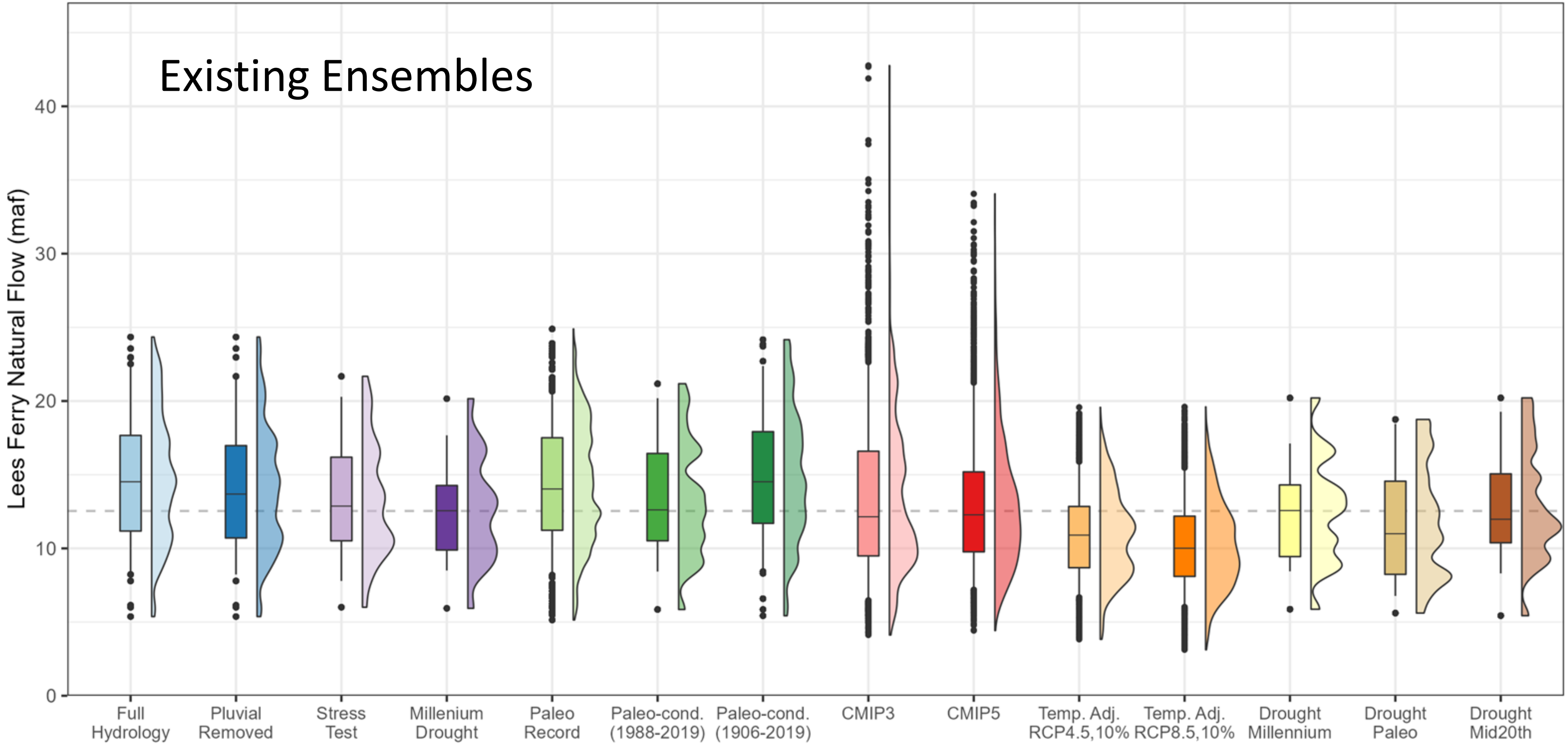
In collaboration with Bureau of Reclamation

Outline

- Why a new ensemble?
- Metrics to characterize ensembles
- Gaps in the existing ensembles
- Method used to create the new ensemble
- Characteristics of the new ensemble

Why is a new Ensemble Needed?

- There are multiple hydrology ensembles available for Post-2026 planning



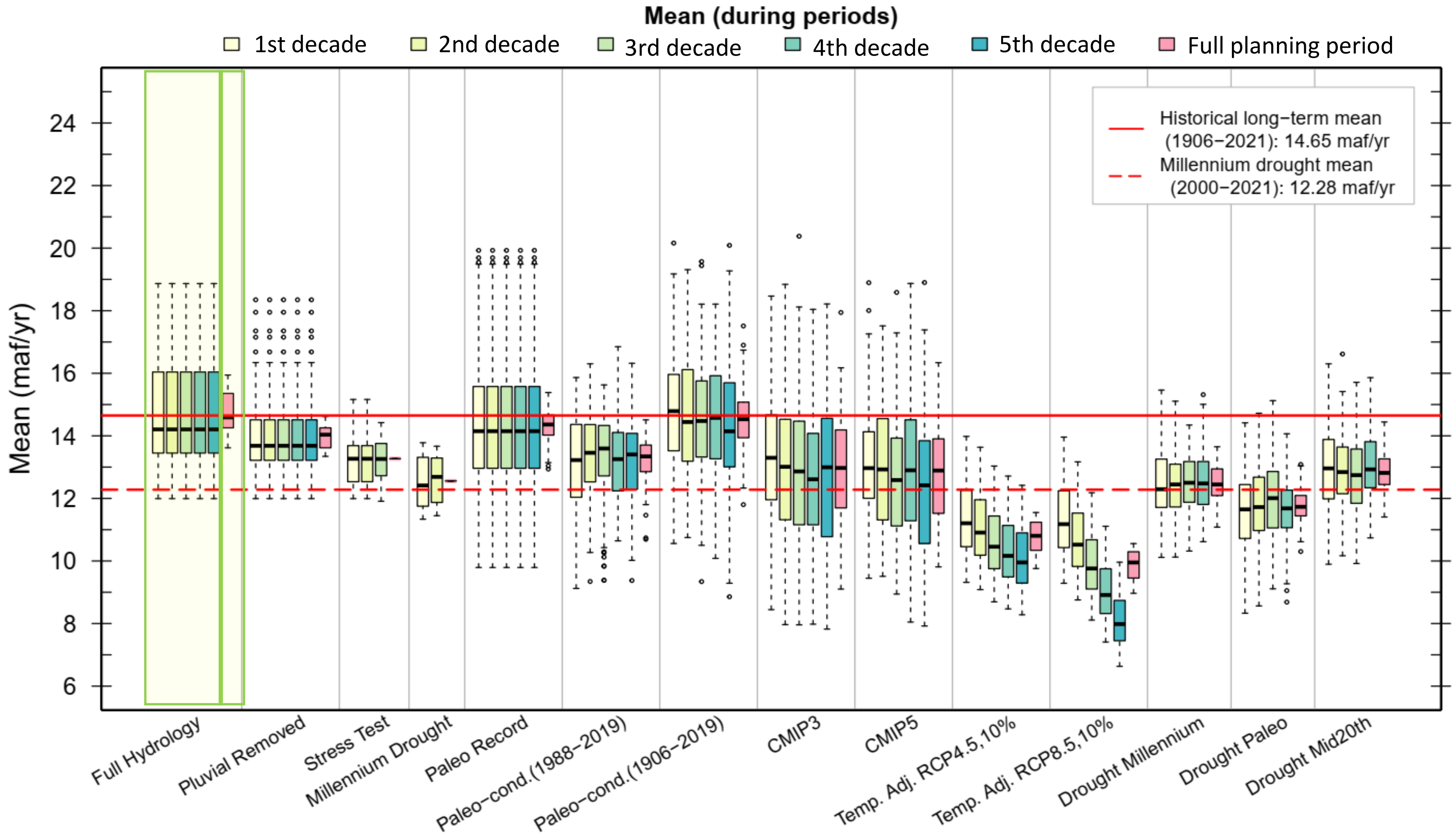
Why is a new Ensemble Needed?

- We developed **a comprehensive set of metrics** to characterize each ensemble.
- Using these metrics,
  - We identified similarities and differences between ensembles.
  - Each ensemble was associated with a plausible storyline for decision-making under deep uncertainty.
  - Gap found: None of the available ensembles sufficiently characterize the plausible condition of warming-driven declining streamflow with modestly increasing variability and high-flow year frequency similar to the past.

Developed a new ensemble to fill the gaps.

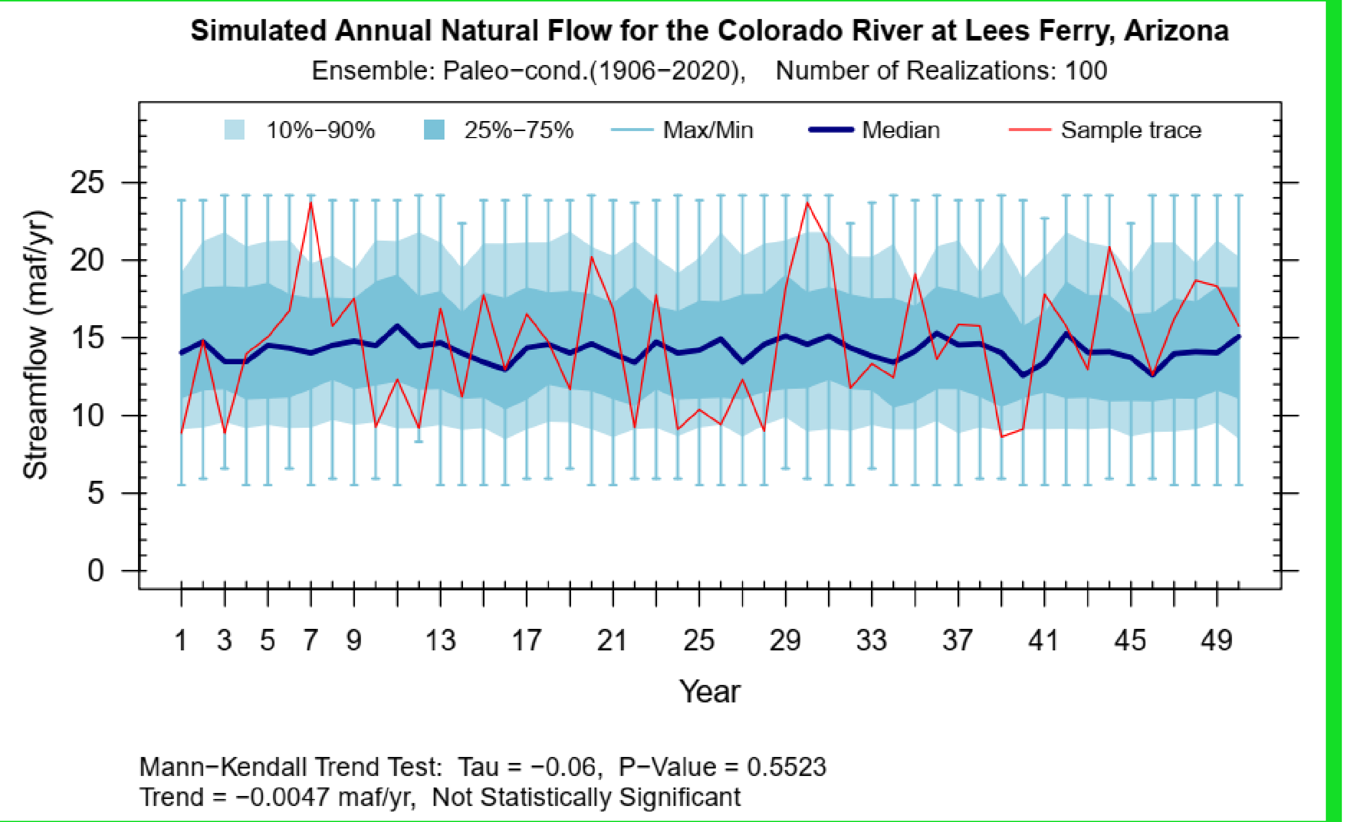
An extensive set of metrics developed to characterize ensembles

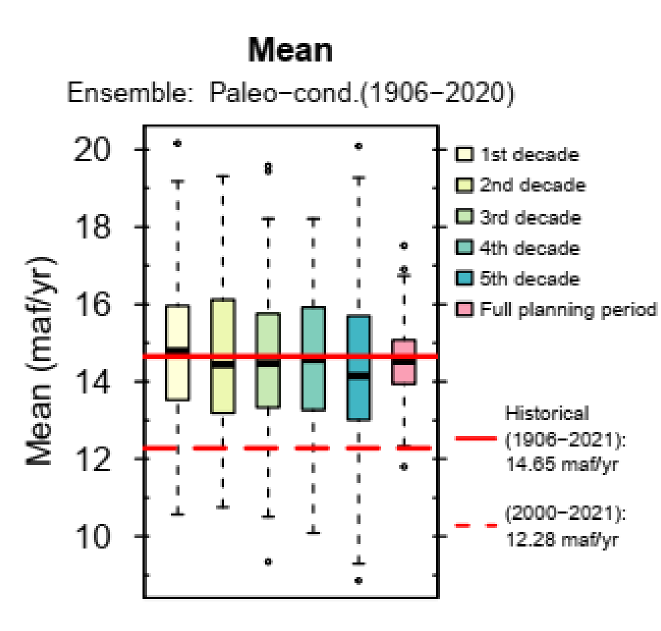
- Mean
- Minimum
- Maximum
- Standard Deviation
- Skewness
- Correlation
- Trend
- Drought Length
- Drought Cumulative Deficit
- Drought Intensity
- Drought Interarrival Time
- Duration-Severity
- Count Below Threshold
- Count Above Threshold
- Hurst Coefficient
- Reservoir Storage Yield and Reliability

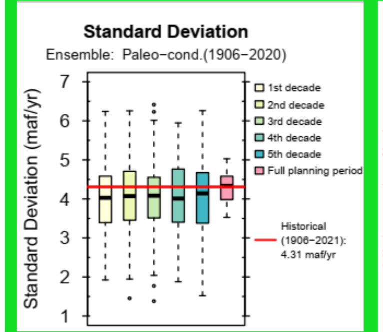


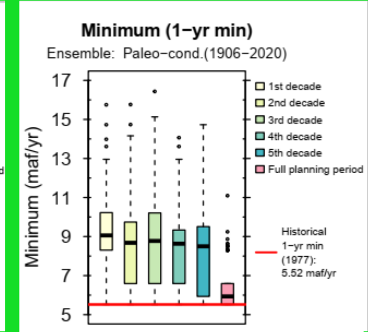
Some ensemble specific metrics

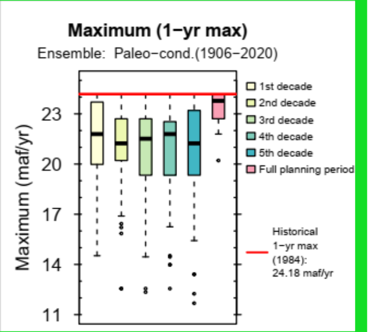
For Paleo-Conditioned ensemble produced using Prairie et al., 2008 method

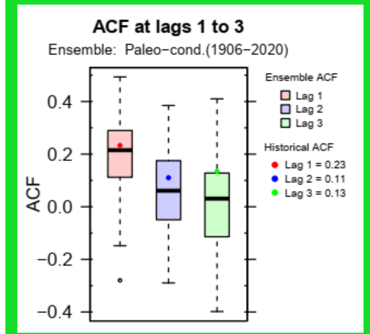


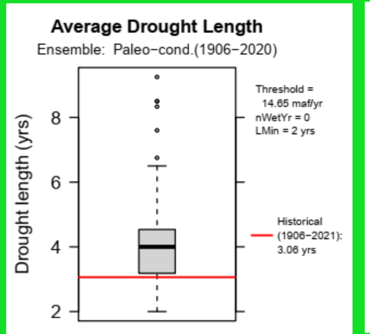


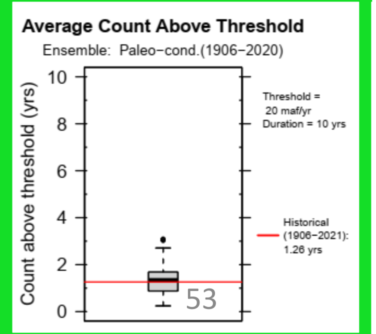












Limitations and Gaps in Existing Ensembles

- Ongoing millennium drought and climate literature suggests that warming-driven declining streamflow is a plausible hydrology future (storyline for planning).
- Previous USU work used resampling from past droughts, but it has its limitations. The resampling approach does not account for occasional high flow years, and it lacks the ability to capture declining trends and persistence (autocorrelation) well.
- Temperature-adjusted ensembles have declining trends, but they have limited high flows and variability is dampened.
- Paleo-conditioned ensemble captures persistence but does not have declining trend.
- CMIP-based ensembles have high flows significantly greater than observed and increased variability, neither of which has been observed in the Millennium period.
- **Thus, none of the available ensembles sufficiently characterize the plausible condition of warming-driven declining streamflow with modestly increasing variability and high flow year frequency similar to the past.**

New Ensemble

- Considering the gaps in the existing ensembles, we need an ensemble with the following characteristics:
  - Long-term mean lower than observed record
  - Downward Trend
  - Maintain variability
  - High-flows that occur infrequently
- We developed a new ensemble that has these characteristics by transforming the probability distribution of a Paleo-conditioned ensemble.
- This is an empirically derived ensemble constructed to have these characteristics
- As with all ensembles, rigorous quantification of the probability of this as an outcome is not possible, but it is a plausible representation of warming-driven declining streamflow.

New Ensemble

Steps to create the new Adjusted Paleo-Conditioned Ensemble:

1. Creating a base ensemble using the paleo-conditioning method developed by Prairie et al., 2008.
   - Hydrologic states (i.e. wet or dry) are modeled using **paleo flow data from 1416 to 2015** (data from Meko et al., 2017)
   - Flow magnitudes are derived from the **post-pluvial (1931-2020) observed flow data**.

High flows (>20 maf/yr) in the observed and paleo data

	Years	Count >20 maf	Frequency
Observed (Full record)	1906-2020	15	0.1304
Observed (Post-Pluvial)	1931-2020	8	0.0889
Paleo (Meko2017)	1416-2015	49	0.0817

Retain high flow frequency similar to post-pluvial observed and paleo data.

Prairie, J., K. Nowak, B. Rajagopalan, U. Lall and T. Fulp, (2008), "A stochastic nonparametric approach for streamflow generation combining observational and paleoreconstructed data," Water Resour. Res., 44(6): W06423, http://dx.doi.org/10.1029/2007WR006684

New Ensemble

Steps to create the new Adjusted Paleo-Conditioned Ensemble:

2. Adjusting the probability distribution (the marginal distribution) for each year of the base ensemble to incorporate estimated decline in future flow and impose desired declining trend, while retaining other properties.
    - Estimating the warming-driven declining streamflow trend
    - Transforming the distribution

New Ensemble

Estimating the Warming-Driven Declining Streamflow Trend:

- Temperature Trend starting ~1980:
  $2.4\ °\text{F}\ per\ 40\ years = 0.06\ °\text{F}\ per\ year$
  $= 0.0333\ °\text{C}\ per\ year$

- Sensitivity of streamflow to temperature (Milly and Dunne, 2020):
  $-9.3\%\ per\ °\text{C}$

- Streamflow declining trend for a mean of 13 maf/yr :
  $0.0333 \times 0.093 \times 13\ maf/yr$
  $= 0.04\ maf/yr$

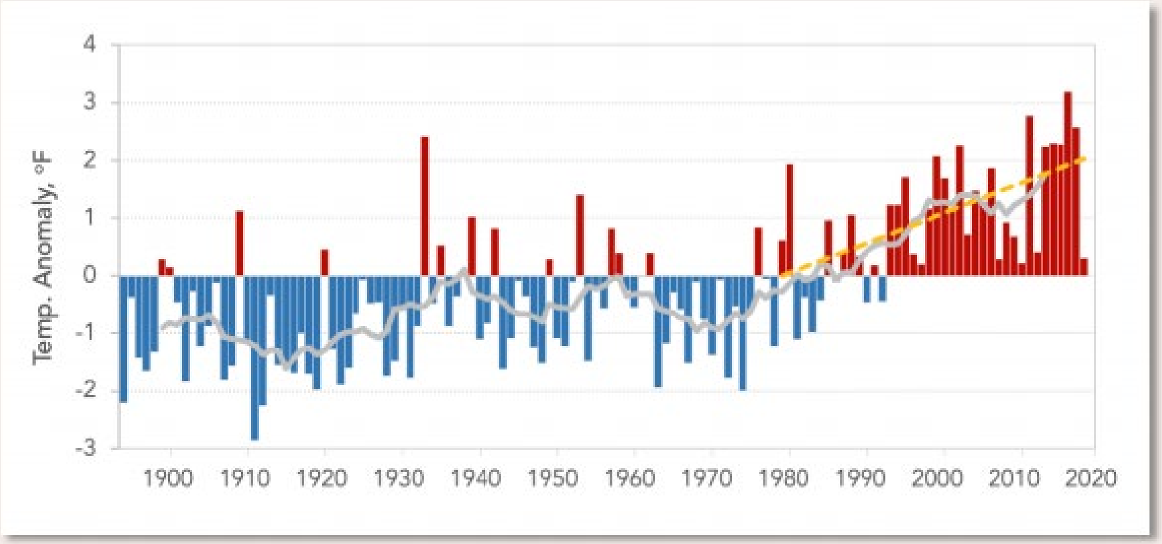


Figure 2.16

Annually averaged temperature for the Colorado River Basin, 1895–2019, shown as departures from a 1970–1999 average. The gray line is a 10-year running average plotted on the 6th year. A 40-year linear trend (dashed yellow line) shows 2.4°F of warming from 1980–2019. (Data: NOAA NCEI)

Milly, P. C. and K. A. Dunne, (2020), "Colorado River flow dwindles as warming-driven loss of reflective snow energizes evaporation," Science, 367(6483): 1252-1255, https://doi.org/10.1126/science.aay9187.

Lukas, J. and E. Payton, (2020), Colorado River Basin Climate and Hydrology: State of the Science, Western Water Assessment, University of Colorado Boulder, https://doi.org/10.25810/3hcv-w477.

New Ensemble

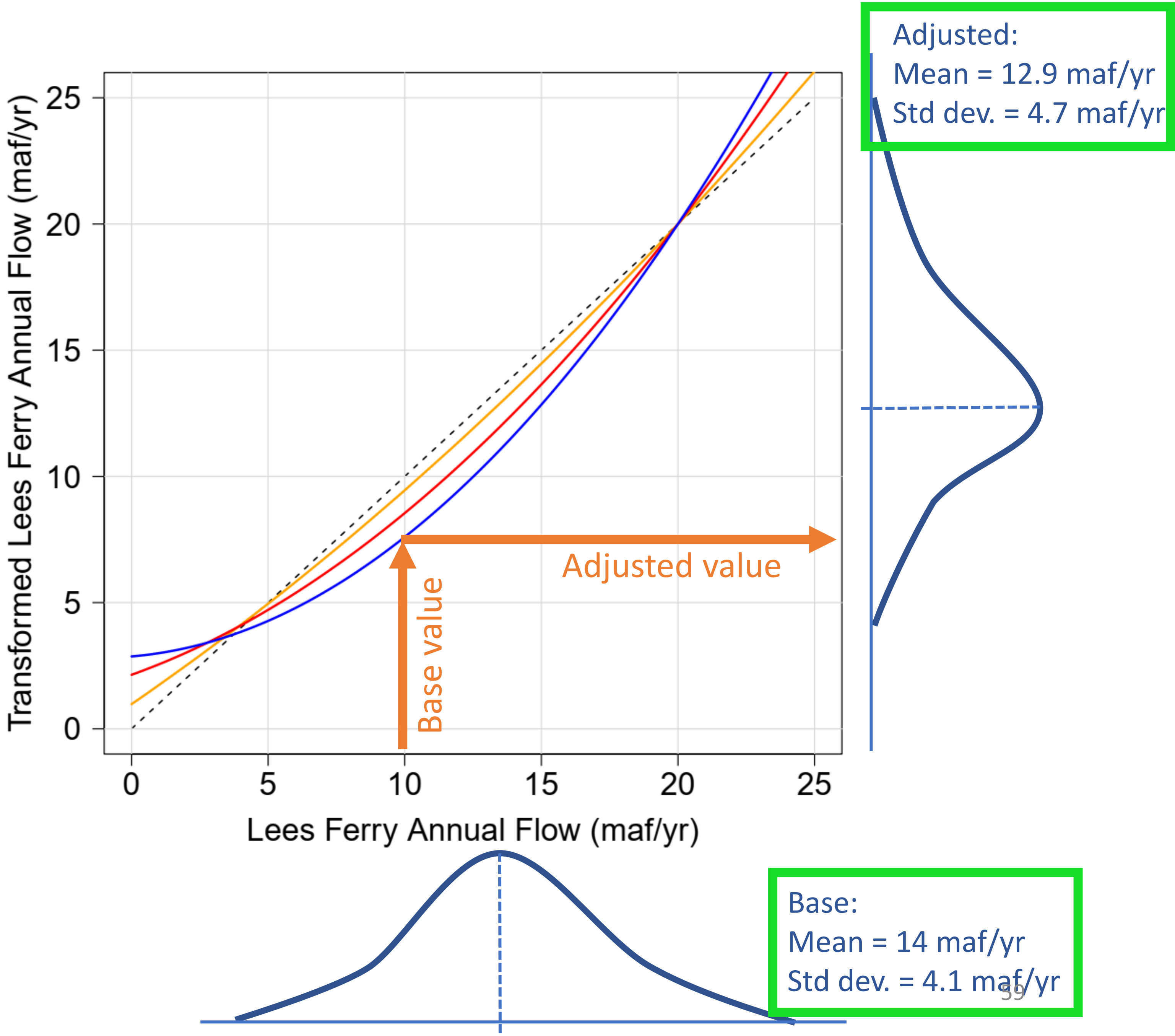
Parabola Family used to transform the marginal distribution

Parameters of the parabola used each year are selected to shift the mean from its value in the base ensemble to the value targeted for the adjusted ensemble.

Example annual flow value adjustments for a particular parabola

- 21 → 21.3 (high flows increase)
- 5 → 4.9 (avoid over-reducing)
- 10 → 8 (internal values move down)

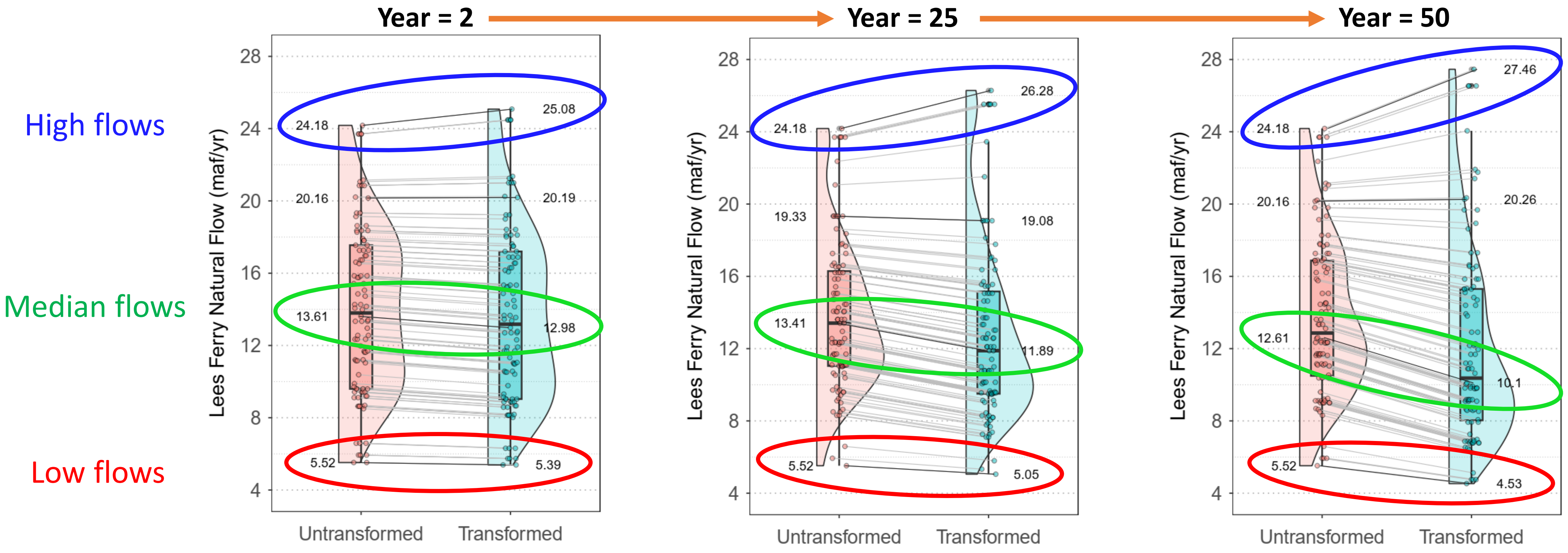
Illustrative maf/yr values



New Ensemble

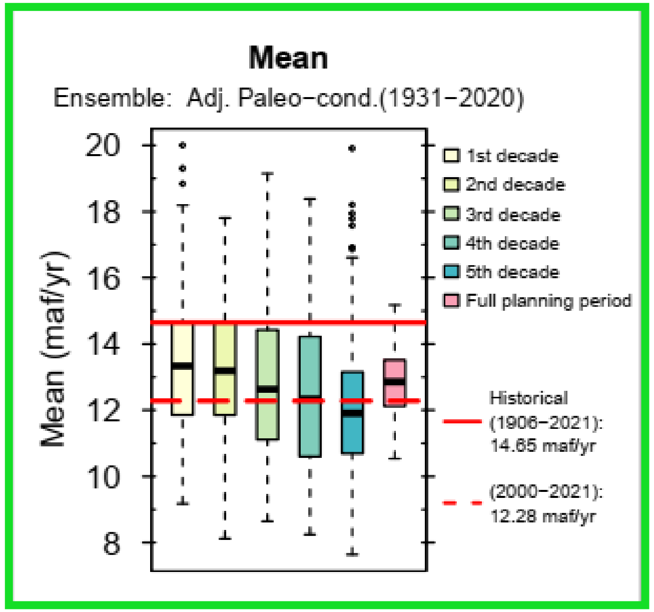
The marginal distribution of the base ensemble was adjusted to

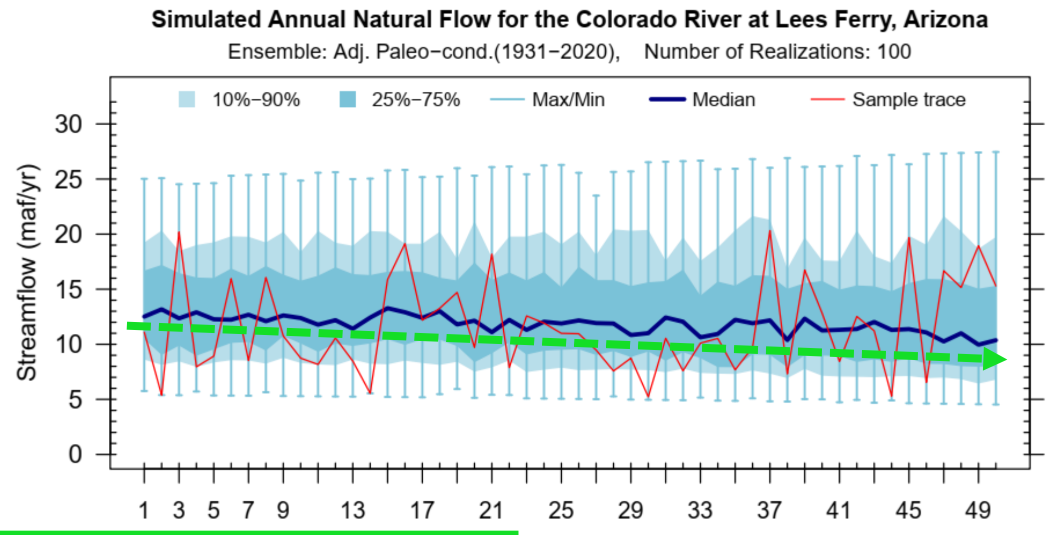
- Shift and stretch the marginal distribution at each future year
- Decrease the mean
- Retain the same frequency of higher flows
- Avoid over reducing the lower flows



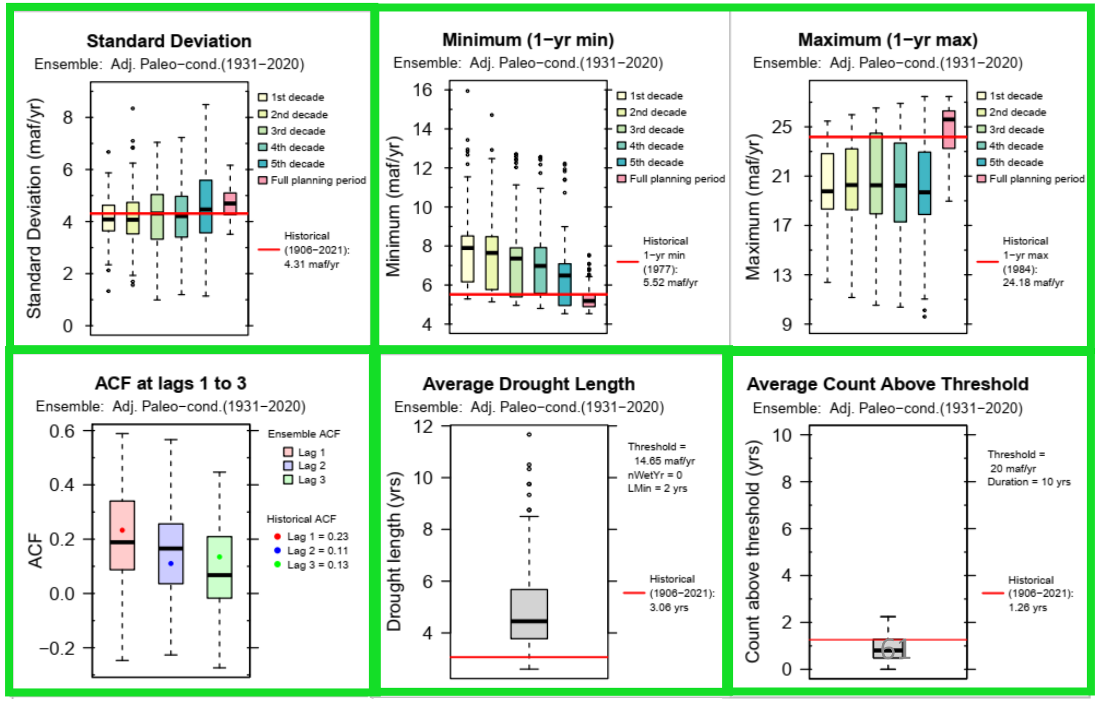
New Adjusted Paleo-Conditioned Ensemble

- It provides the estimated future downward trend (according to the historical temperature trend and the sensitivity of streamflow to changes in temperature)
- It provides a lower mean than the full observed record, and decadal mean is decreasing over time.
- It increases variability slightly.
- Low and high flows are not limited to what occurred in the historical record.
- Using the Paleo-conditioned method, it preserves historical correlation and long memory (from observed and tree-ring data)
- It provides droughts that are more severe than the historical record (in addition to droughts that are similar to the historical record)
- It includes infrequent high flows (same frequency as sampling period)

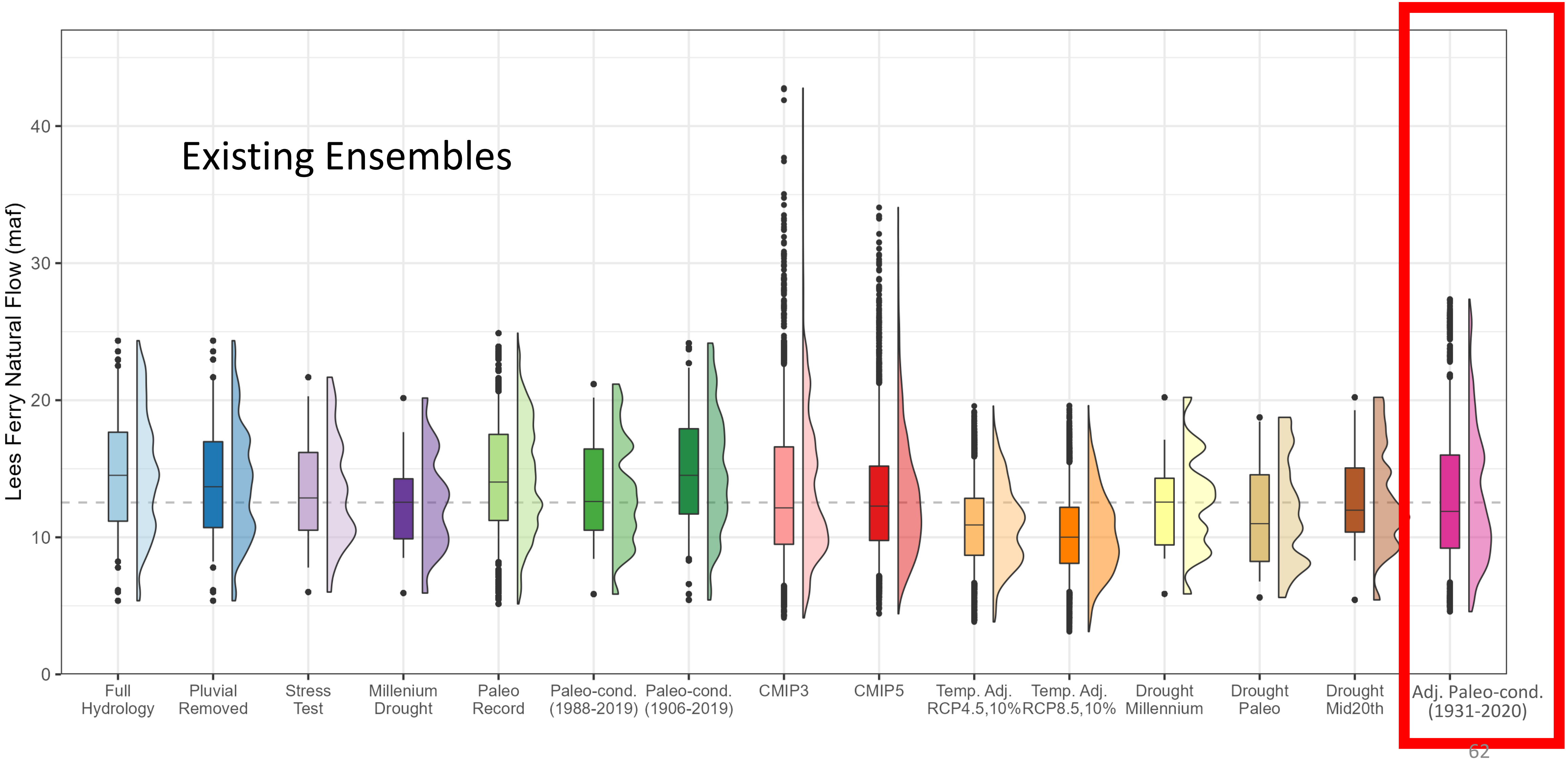




Mann–Kendall Trend Test: Tau = −0.51, P-Value = 0
Trend = −0.0378 maf/yr, Statistically Significant



New ensemble added brings in warming-driven declining streamflow as one additional plausible planning option for DMDU



Summary

- A comprehensive set of metrics were developed to characterize ensembles.
- Metrics indicated gaps in the ensembles.
- A new ensemble was created by adjusting a post-pluvial paleo-conditioned ensemble to incorporate estimated decline in future flow and impose declining trend, while retaining other properties.
- The new ensemble brings in warming-driven declining streamflow as one additional plausible planning option for DMDU

Future Sessions and Request for Input

- Future ITEW session topics include (order TBD)
  - Metrics, tradeoffs, robustness and vulnerability
  - Alternative operational strategies (what is available in web tool, how to explore those that are not)
  - Web tool intro and training
- Content will include general education and information related to the Post-2026 Technical Framework
- Future sessions
  - September 20th
  - Mid October
  - Early November
- Please send questions, feedback, and requests for topics to bor-sha-crbpost2026@usbr.gov

BUREAU OF RECLAMATION

Thank you for joining us

For more information visit:
https://www.usbr.gov/ColoradoRiverBasin/post2026/itew.html

Notes & References

*Candidate policies are comprised of combinations of operational actions, e.g., configurations of releases from Lake Powell and Lake Mead

[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

[3] Milly, P.C., and K.A. Dunne. 2020. "Colorado River Flow Dwindles as Warming-Driven Loss of Reflective Snow Energizes Evapora-tion. "Science367 (6483): 1252-55. https://doi.org/10.1126/science.aay9187

[4] Lukas, Jeff, and Elizabeth Payton, eds. 2020. Colorado River Basin Climate and Hydrology: State of the Science. Western Water Assessment, University of Colorado Boulder.

DOI: https://doi.org/10.25810/3hcv-w477