BUREAU OF RECLAMATION

Post-2026 Integrated Technical Education Workgroup Session 3: Hydrology

Virtual Session

June 28, 2023

BUREAU OF RECLAMATION

Agenda, Welcome and Introductions

Carly Jerla
Bureau of Reclamation

Agenda

- Welcome and introductions
- Review purpose of group
- Review of Decision Making under Deep Uncertainty (DMDU) and the Post-2026 Technical Framework
- Overview of historical hydrology
- Calculating historical natural flow
- Future hydrology ensembles
- Approach to hydrology in the Post-2026 Web Tool
- Using advanced characteristics to inform selection of hydrology ensembles
- Wrap up and future sessions

Welcome & Introductions

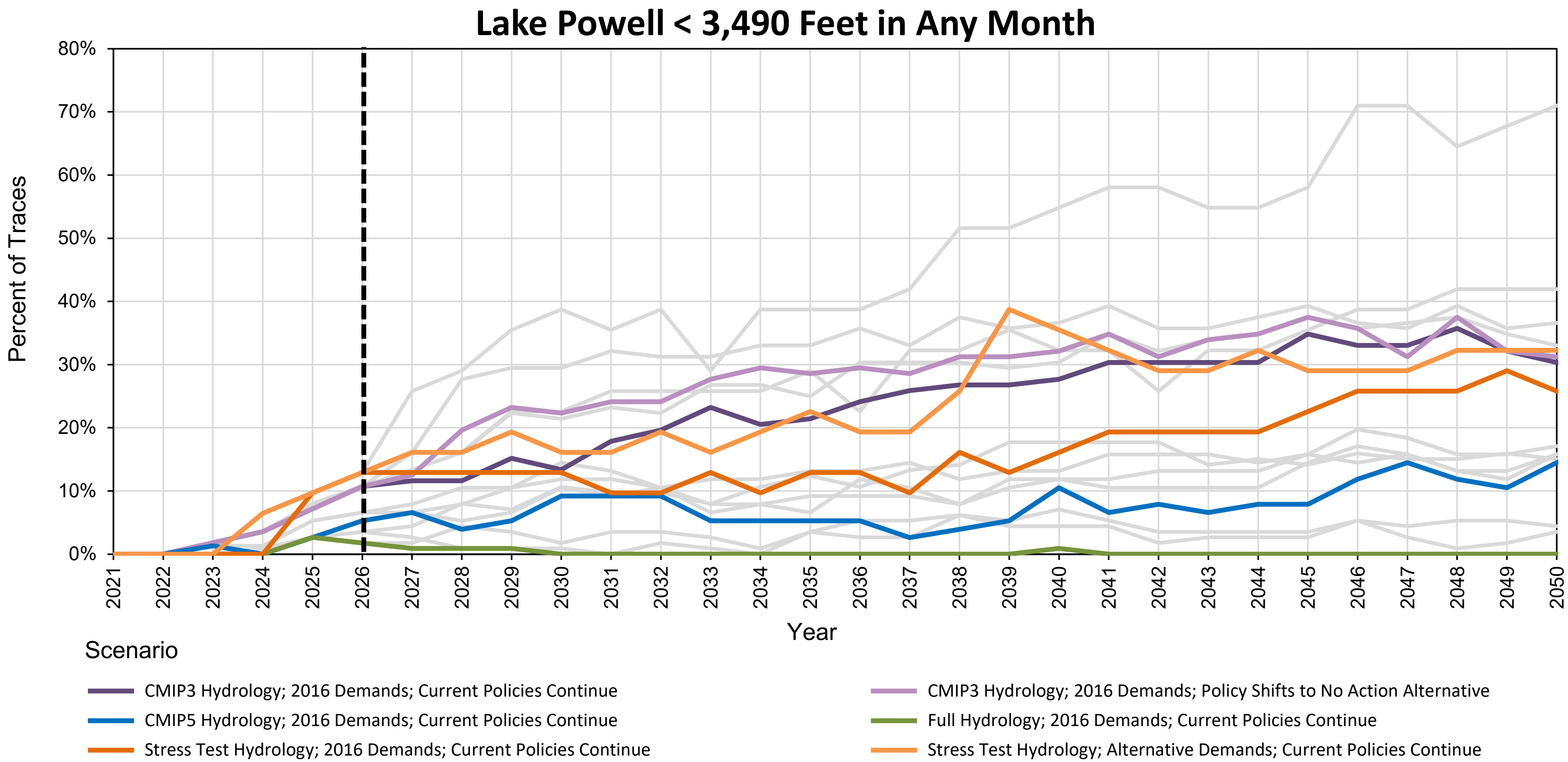
- This is the 3rd session of Reclamation's Integrated Technical Education Workgroup (kickoff session was December 7, 2022)
- The Technical Workgroup has been formed for the purpose of assisting our partners and stakeholders to gain a better understanding of the technical tools and approaches to be used 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 DMDU and the Post-2026 Technical Framework

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



*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

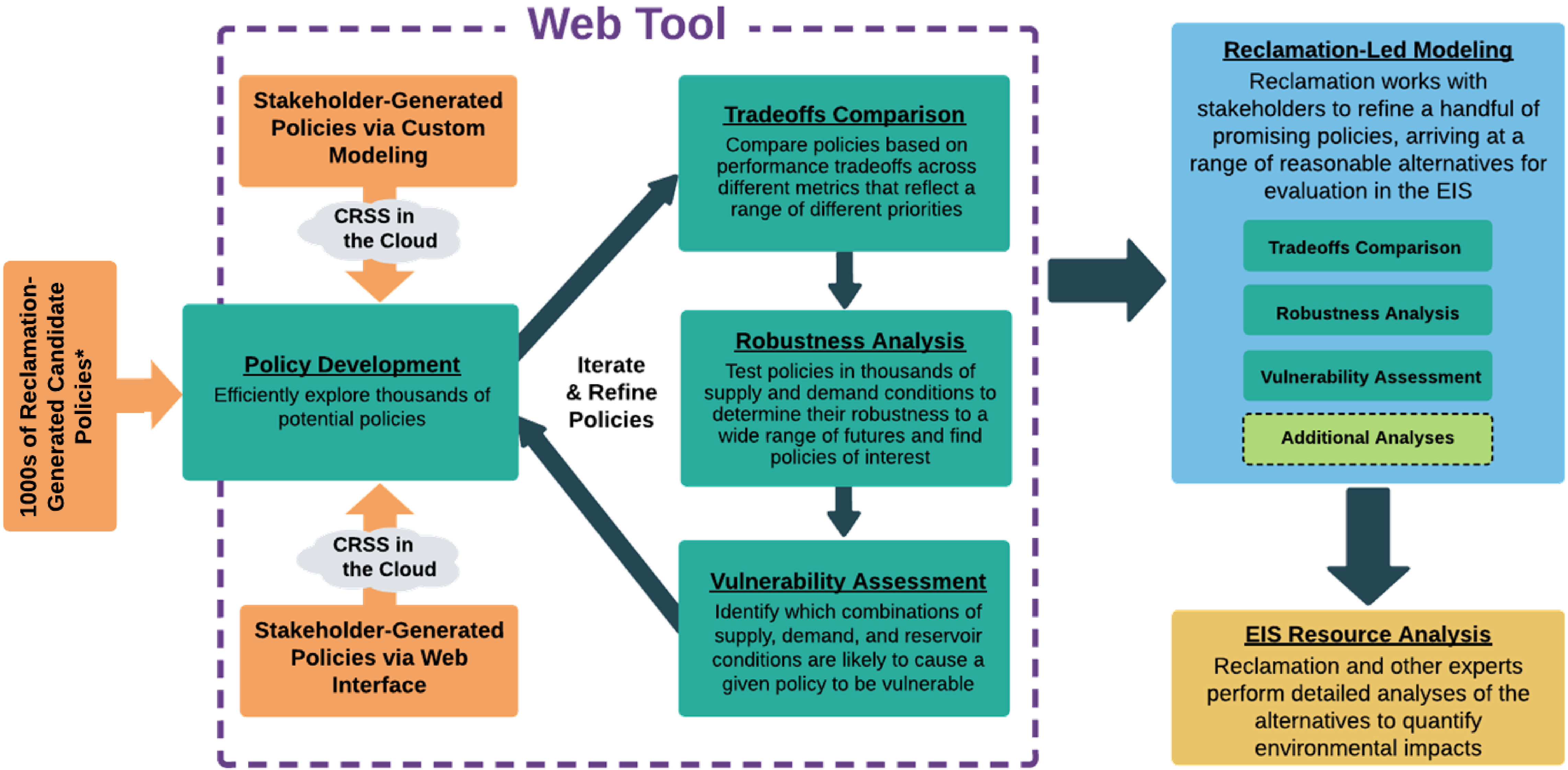
- Consider a *wide range* of future conditions without assigning likelihood beforehand
- Prioritize *robustness*, or the ability of a policy to perform acceptably well in a wide range of conditions
- Assess the *vulnerability* of a policy: what uncertain future conditions might cause it to perform poorly?

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]

MORDM & the Web Tool in the Post-2026 Process



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

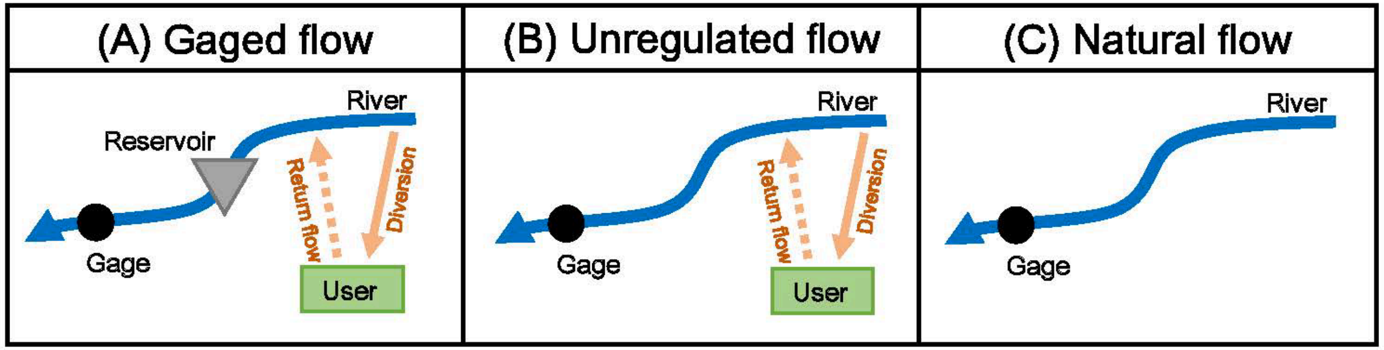
Important Context for the Post-2026 Web Tool

- 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 alternatives
  - 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

Overview of Historical Hydrology

Hydrology for Long-Term Planning

- Different modeling studies serve a range of purposes and use different hydrologic data sources
- When projecting 2 to 5 years into the future, Reclamation uses "unregulated" flow data from the Colorado Basin River Forecast Center
- Long-term planning studies use "natural flow", which allows modeling studies to combine different assumptions about supply, demand, and policy
- Reclamation maintains the dataset of historical natural flow computed from USGS gages, reservoir regulation, and consumptive uses and losses



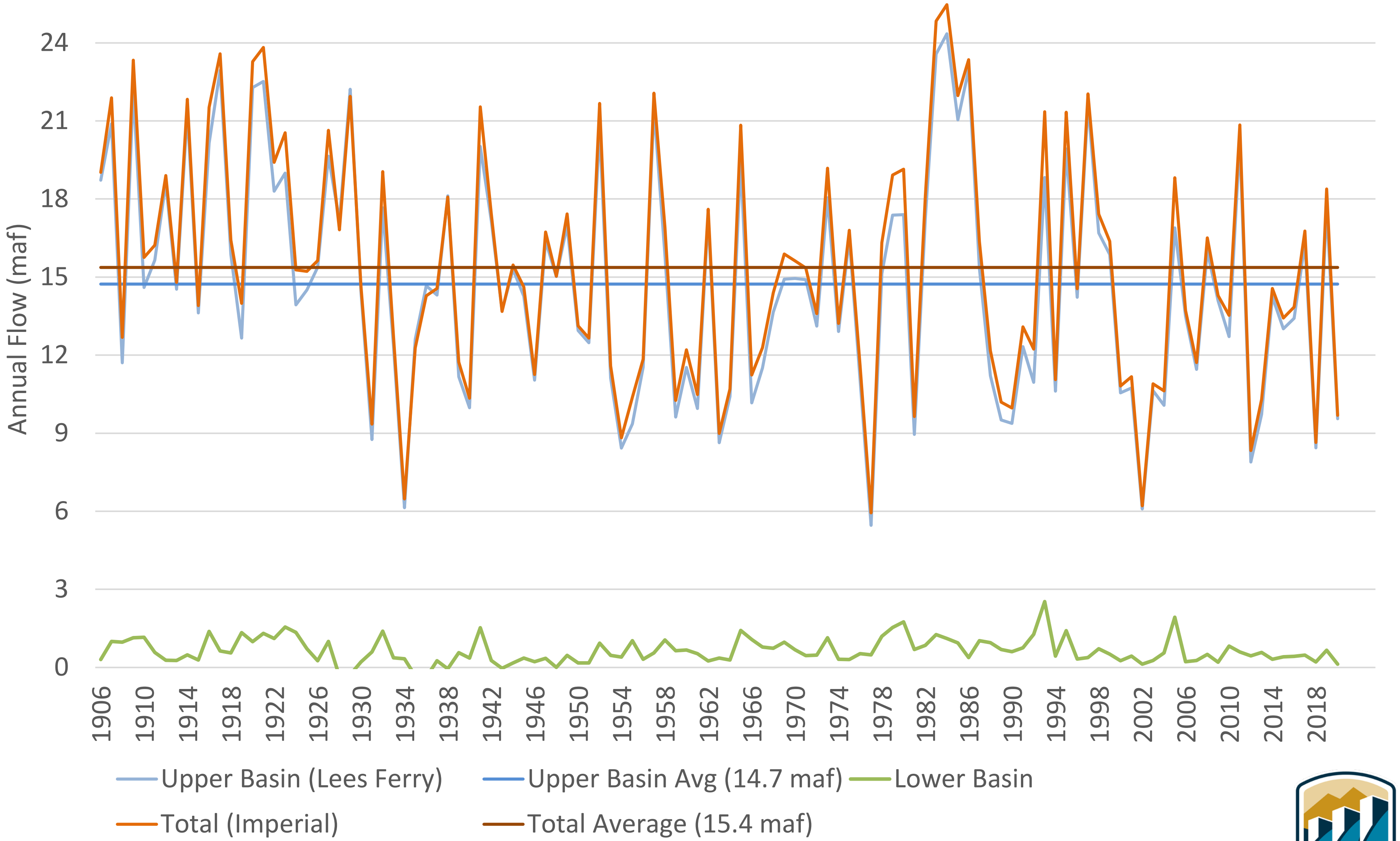
(A) Gaged flow – the flow measured by a stream gage with actual reservoir operations and diversions

(B) Unregulated flow – the flow that would have been observed at a stream gage if there were no upstream reservoirs present (includes evaporation and bank storage)

(C) Natural flow – the flow that would have been observed at a stream gage if there were no upstream reservoirs or diversions present

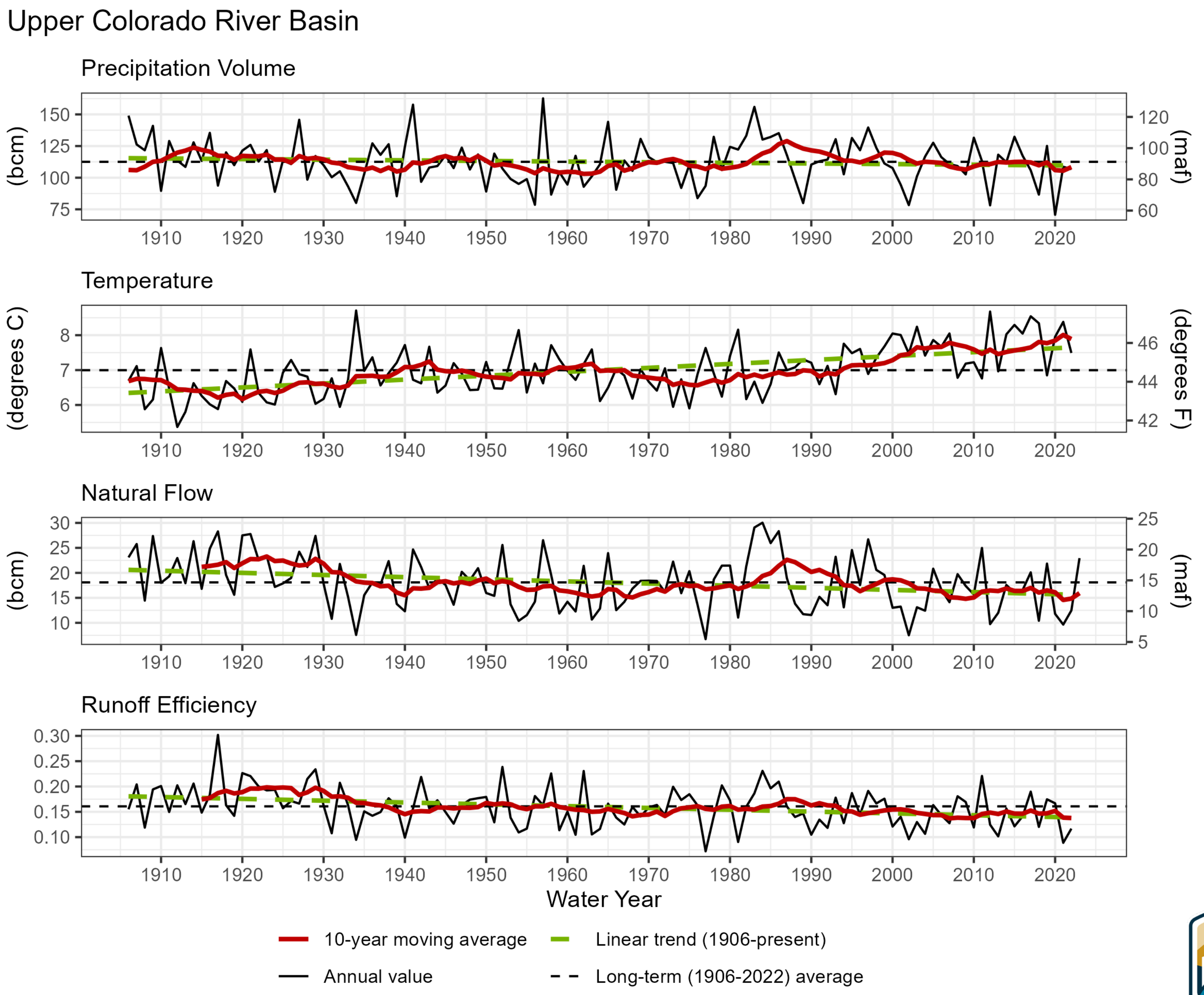
Upper and Lower Basin Natural Flow

- Approximately 96% of the natural flow occurs in the Upper Basin (above the gage at Lees Ferry, AZ)
- Annual flow at Lees Ferry is commonly used indicator of overall hydrologic conditions in the Basin



Hydroclimatic conditions over time (1906 – present)

- Precipitation and temperature are two variables that significantly affect natural flow
- Relationships between precipitation, temperature, and flow over the long-term historical record provide important context for understanding potential future flows
- Runoff efficiency indicates how much runoff occurs for a given amount of precipitation

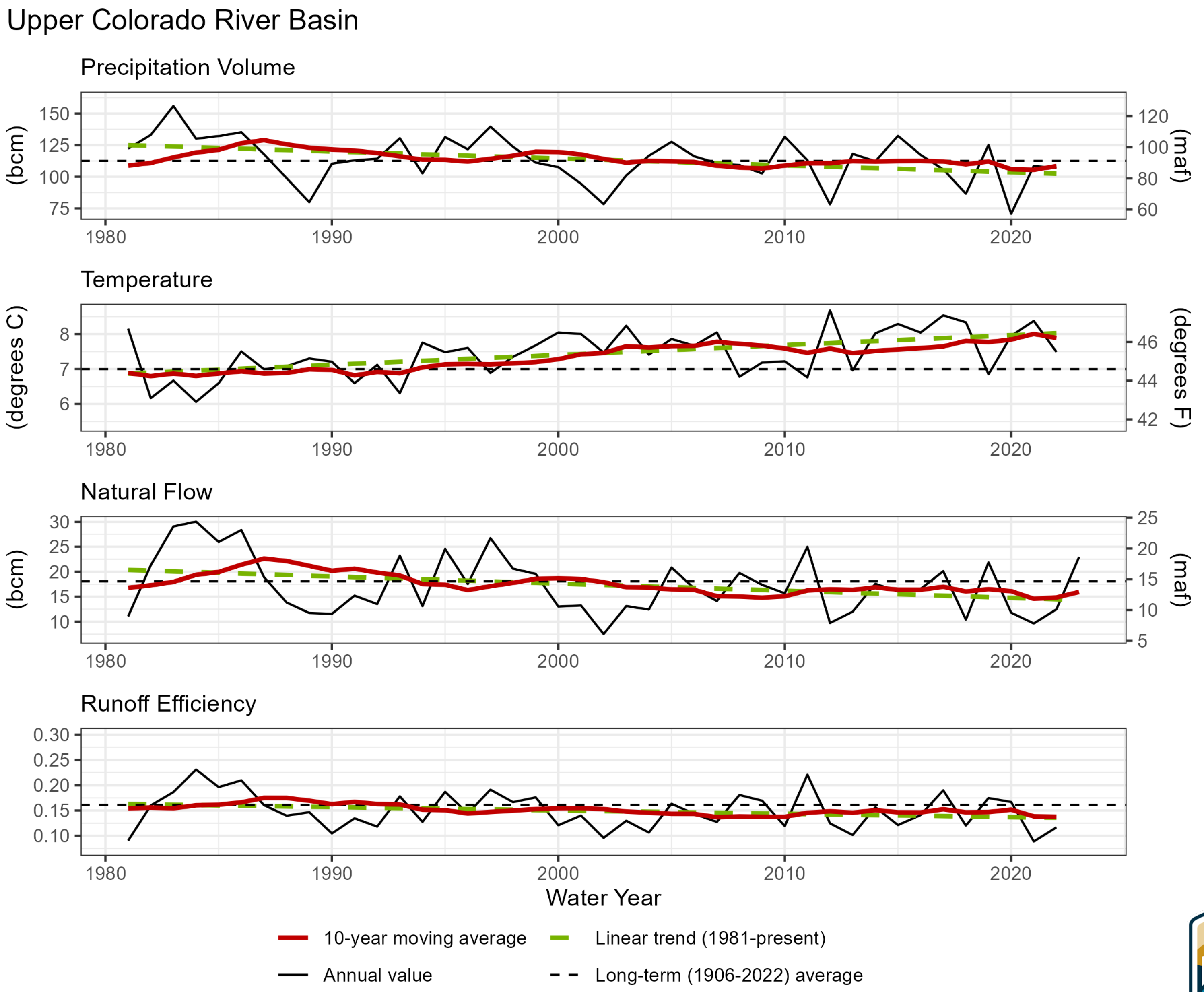


Precipitation and temperature are from PRISM (https://prism.oregonstate.edu/); natural flow are from Bureau of Reclamation (https://www.usbr.gov/lc/region/g4000/NaturalFlow/current.html); runoff efficiency = natural flow / precipitation volume. Figure adapted from Udall and Overpeck (2017).

Hydroclimatic conditions over time (1981 – present)

- Recent trends in precipitation (downward), temperature (upward), natural flow (downward), and runoff efficiency (downward) all indicate we can expect less runoff in the future

- Projections of future hydrology used in the Post-2026 Web Tool will incorporate assumptions about how these trends may continue or change in the future



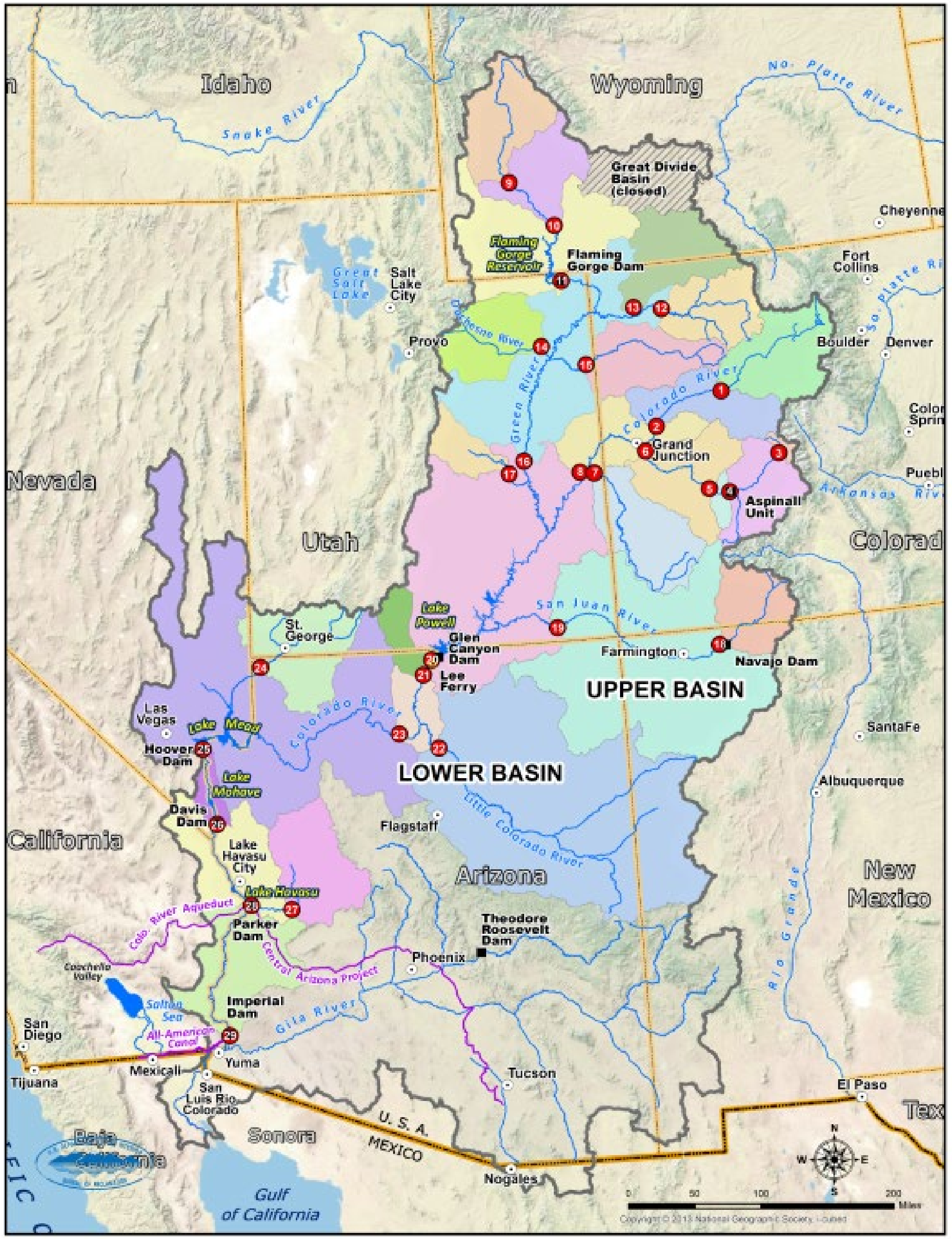
Precipitation and temperature are from PRISM (https://prism.oregonstate.edu/); natural flow are from Bureau of Reclamation (https://www.usbr.gov/lc/region/g4000/NaturalFlow/current.html); runoff efficiency = natural flow / precipitation volume. Figure adapted from Udall and Overpeck (2017).

Calculating Historical Natural Flow

Hydrology and CRSS

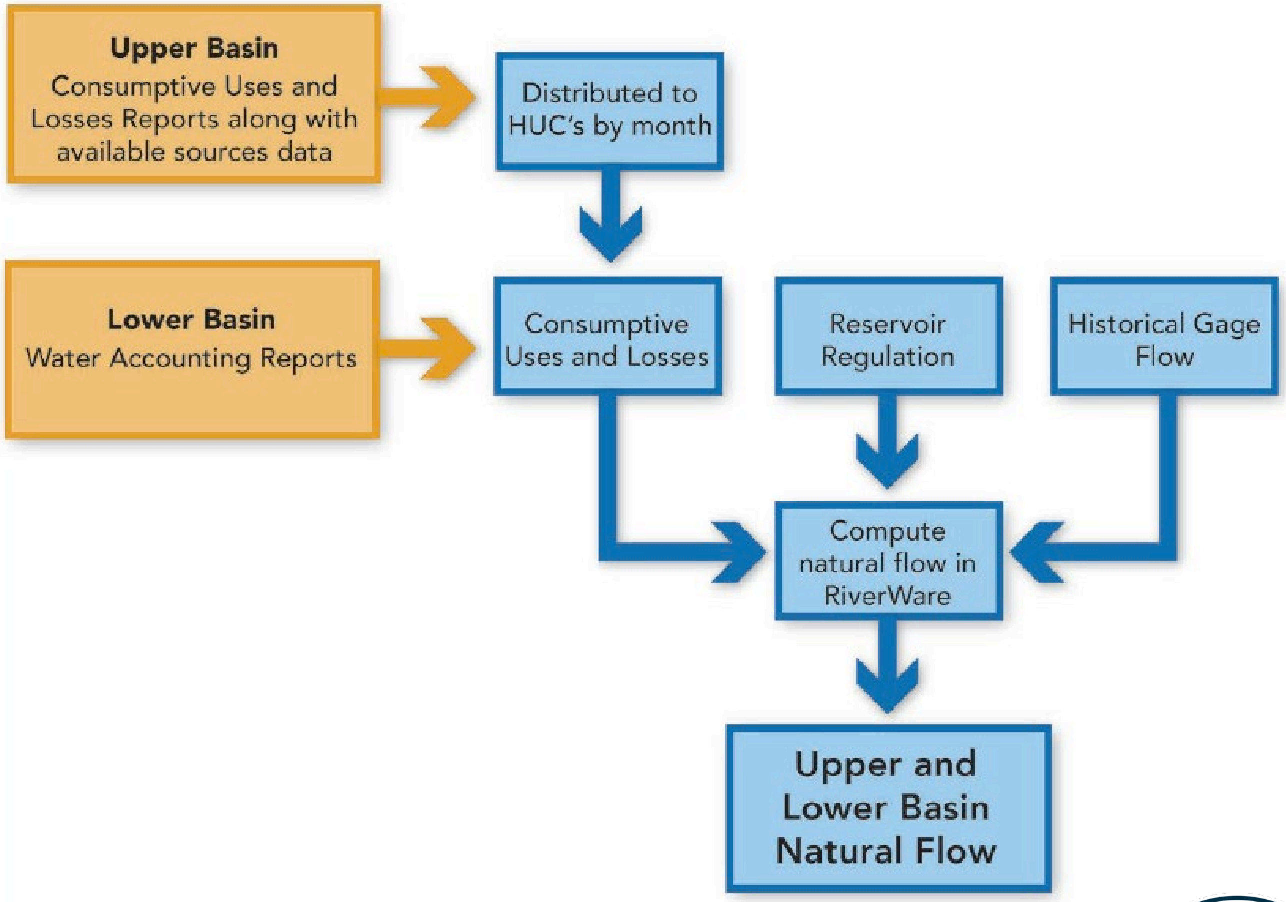
- Upper Basin: 21 natural flow points
- Lower Basin: 8 inflow points for gaged and intervening flows
- Using natural flow allows CRSS to model potential changes to reservoir operations under varying projections of both supply and demand

Note: also requires natural flow for St. Vrain at Lyons and the Sacramento Index



How Historical Natural Flow is Calculated

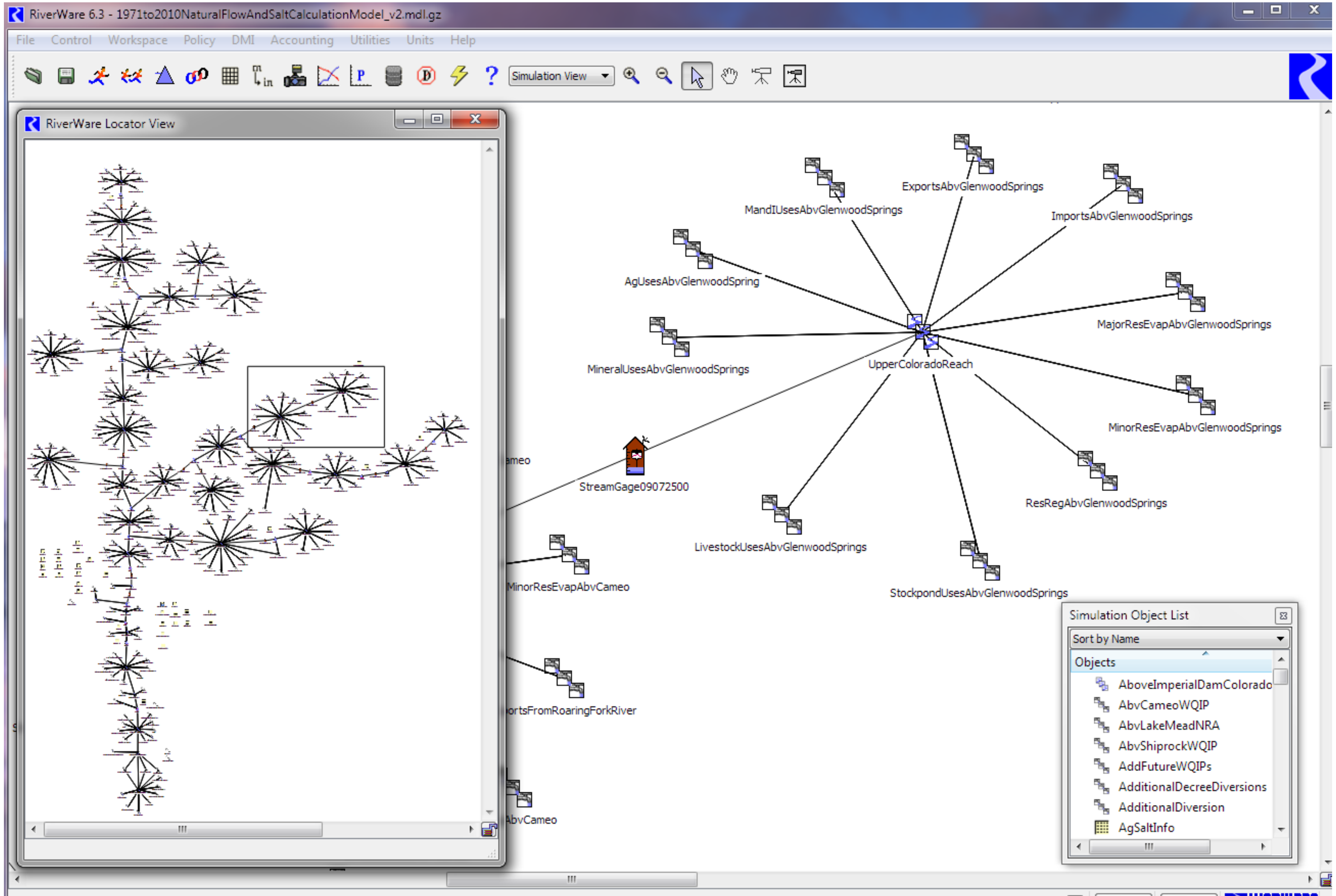
- Reclamation's natural flow and salt calculation model[3]
- Required historical inputs
  - **Upper Basin** consumptive uses and losses by 8-digit HUC as report by Reclamation
  - **Lower Basin** water accounting reports' diversion and depletion by contractor
  - Reservoir outflow and pool elevation
  - USGS gage and Reclamation acoustic velocity meter (AVM) data



Adapted from April 2020, Colorado River Basin Climate and Hydrology State of the Science Report, Figure 5.18

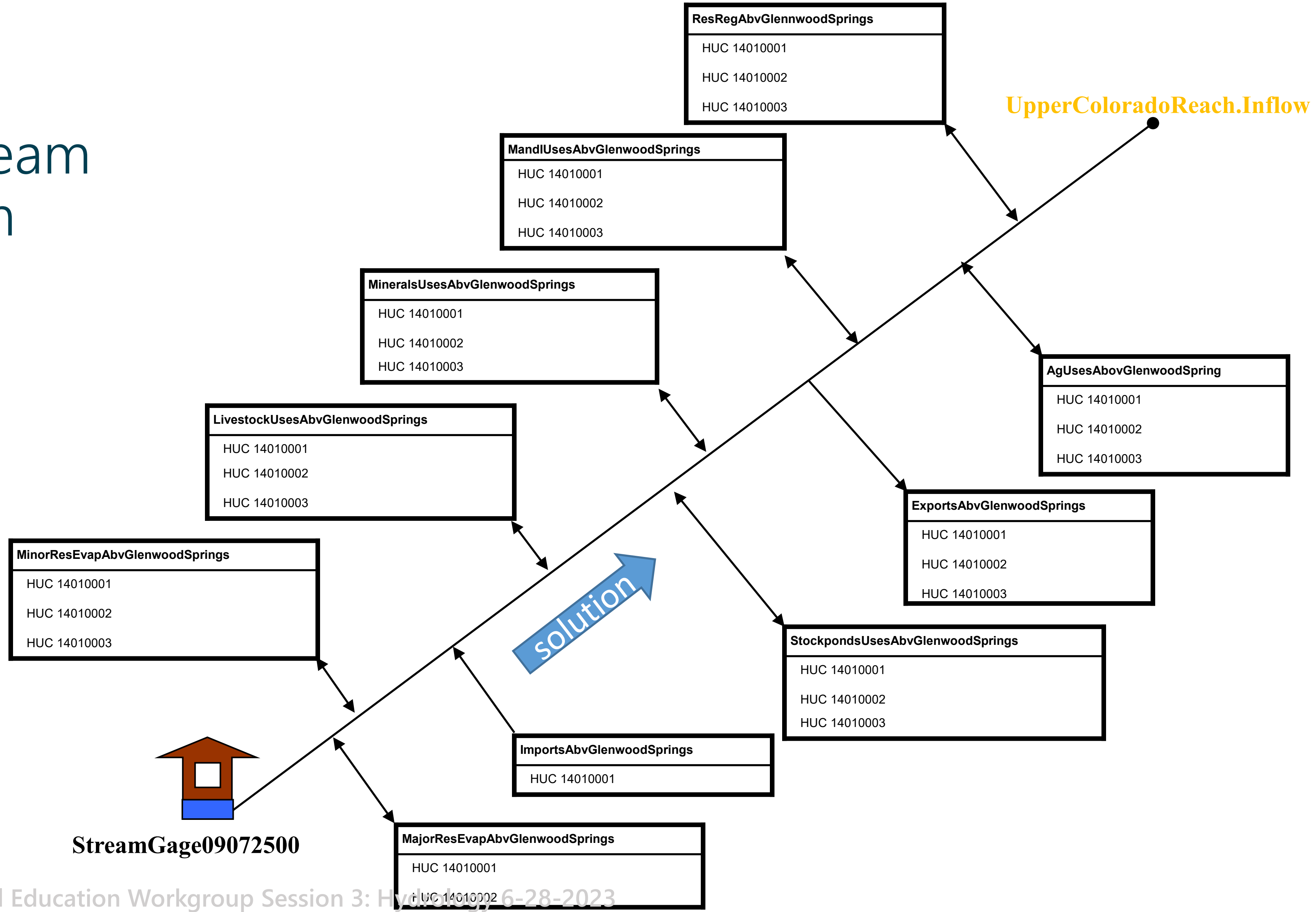
Natural Flow And Salt Model Layout

Highlighting reach above Colorado River near Glenwood Springs, CO



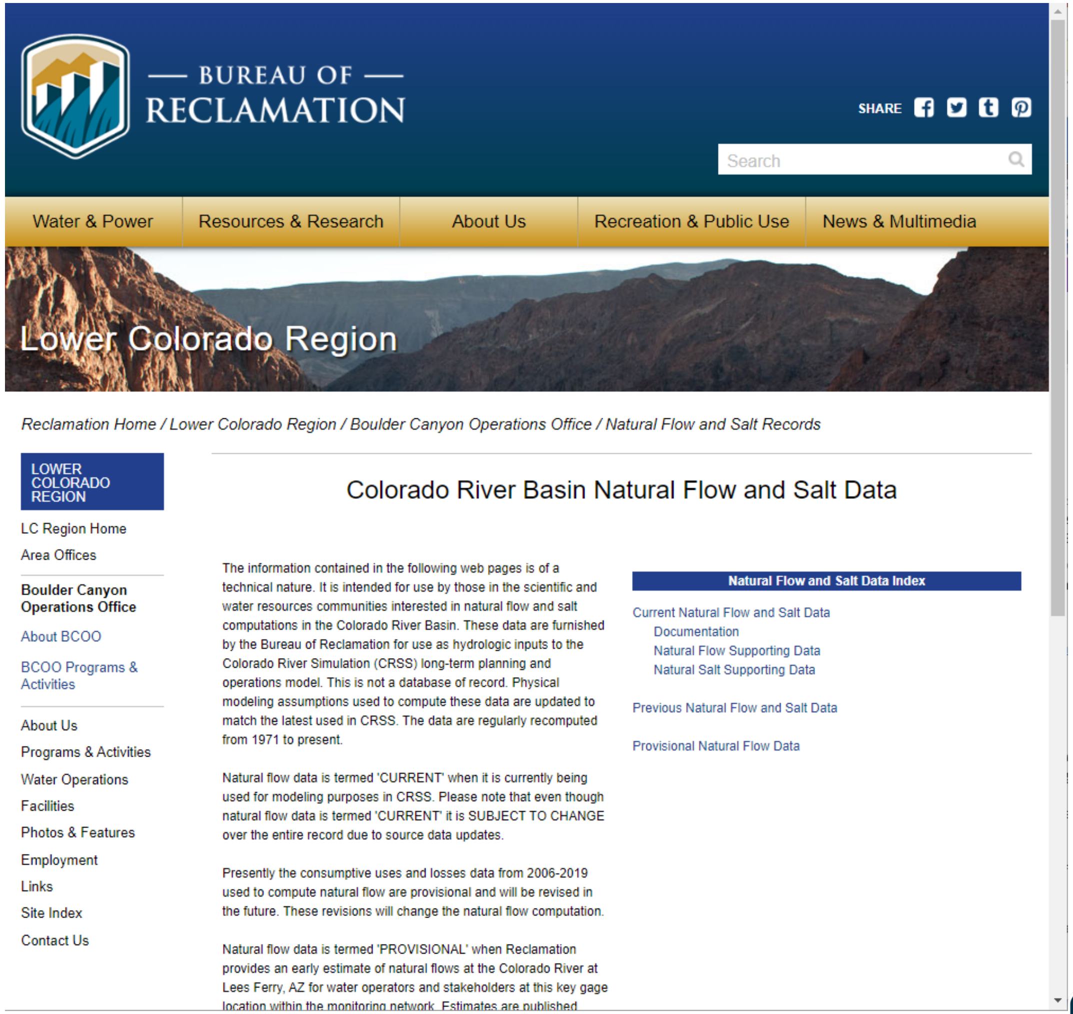
Natural Flow And Salt Model Line Diagram

Natural flow solves upstream starting from gage flows



Historical Natural Flow Updates

- Reclamation strives to update natural flow annually
- Provisional natural flows, typically based on unregulated inflow forecasts, are released 3 times per year, January, April and August
- Natural flow is posted to Reclamation's Natural Flow and Salt Webpages: https://www.usbr.gov/lc/region/g4000/NaturalFlow/index.html



Uses of Natural Flows

- Historical natural flows are a foundational dataset to many other researchers and flow ensemble development
  - Paleo streamflow reconstructions
    - Natural flow needed to calibrate tree-ring chronologies with observed natural hydrology
  - Global Climate Model base hydrology
    - Hydrologic Model used for downscaling calibrated to observed natural hydrology
    - Secondary streamflow bias correction trained on observed natural hydrology
  - Direct and Indirect resampling methods
    - Index sequential method and nonparametric paleo-conditioned resampling method both rely on natural flow data during their hydrology ensemble creation
- Historical natural flow is a foundational dataset that serves both hydrology studies but also water quality and environmental models and analysis throughout the basin

Future Hydrology Ensembles

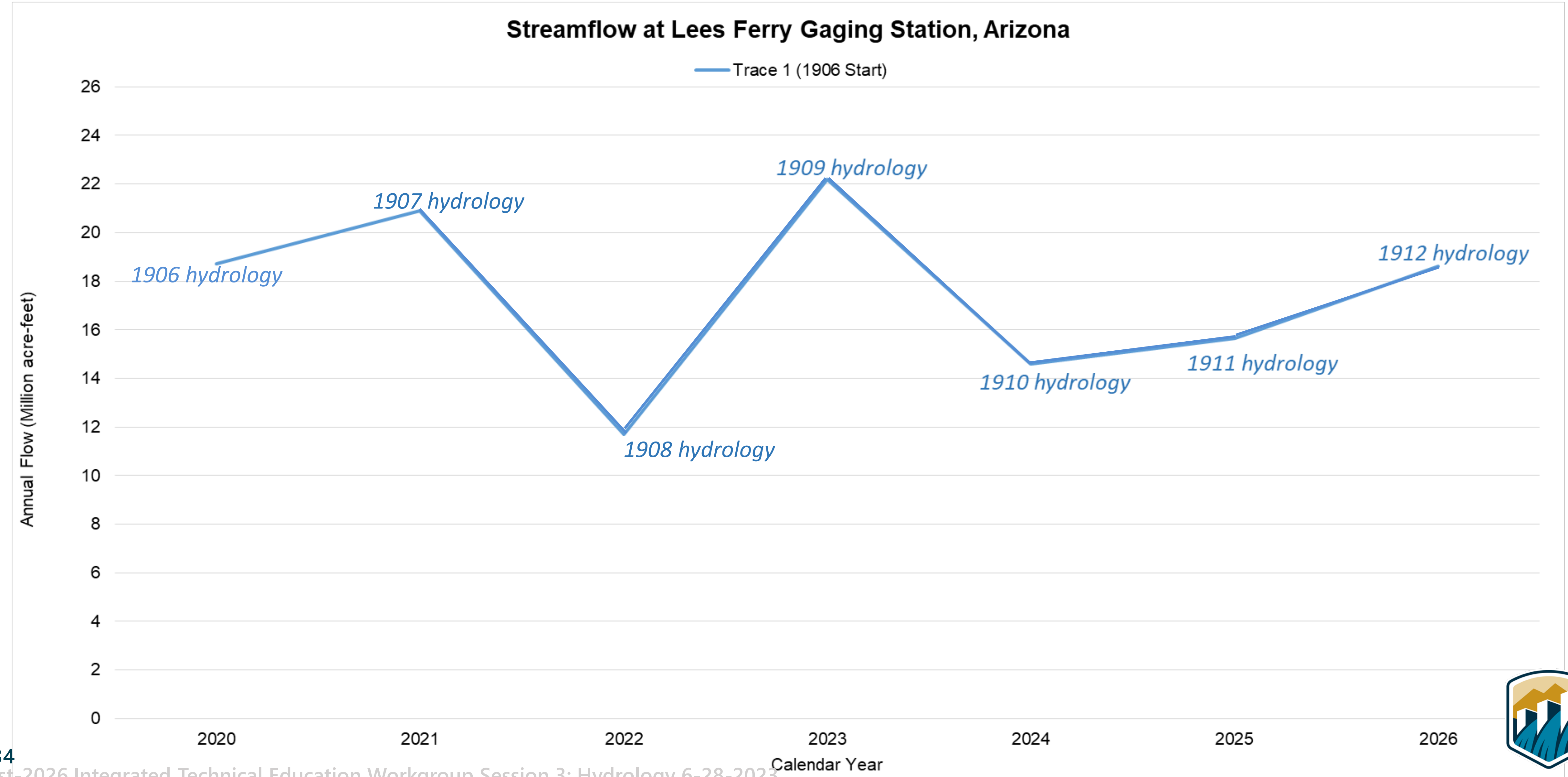
Hydrology Traces and Ensembles

- CRSS projections are most sensitive to assumptions about future hydrology (i.e., supply)
- To account for an uncertainty future hydrology, hydrology scenarios are developed that consist of 100s of hydrology traces
  - A trace is a single timeseries of future natural flow
  - Traces are combined to create an ensemble
- CRSS is run using each hydrology trace resulting in projections of system conditions (e.g., reservoir elevations, releases, etc.)

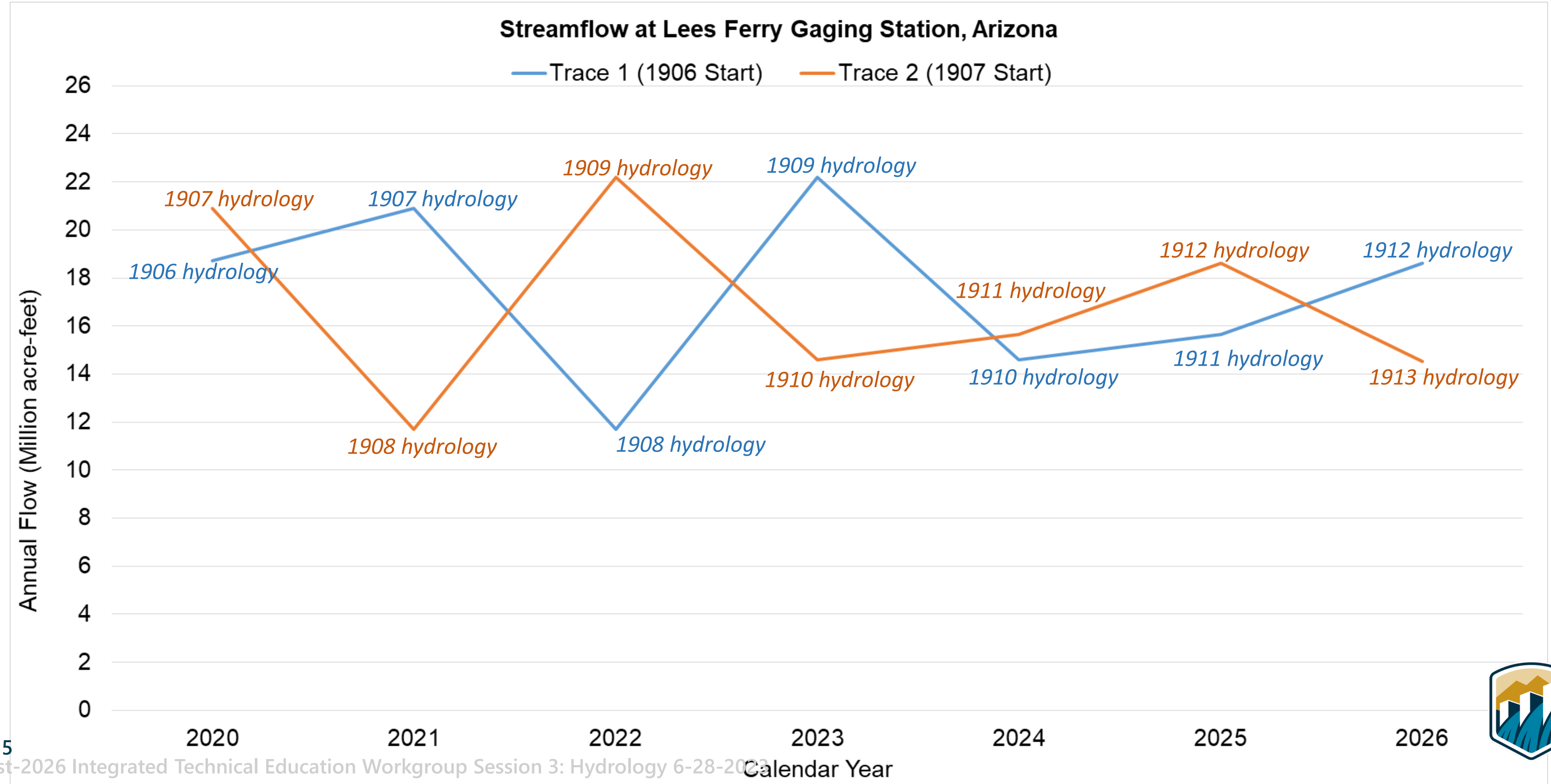
Example of an Ensemble Using the Full Hydrology Scenario

- Generate an ensemble based on the 1906-2020 natural flow record by applying a resampling method called the Index Sequential Method (ISM)[4]
  - 115 hydrologic traces
  - Volumes and wet/dry sequences match the observed record

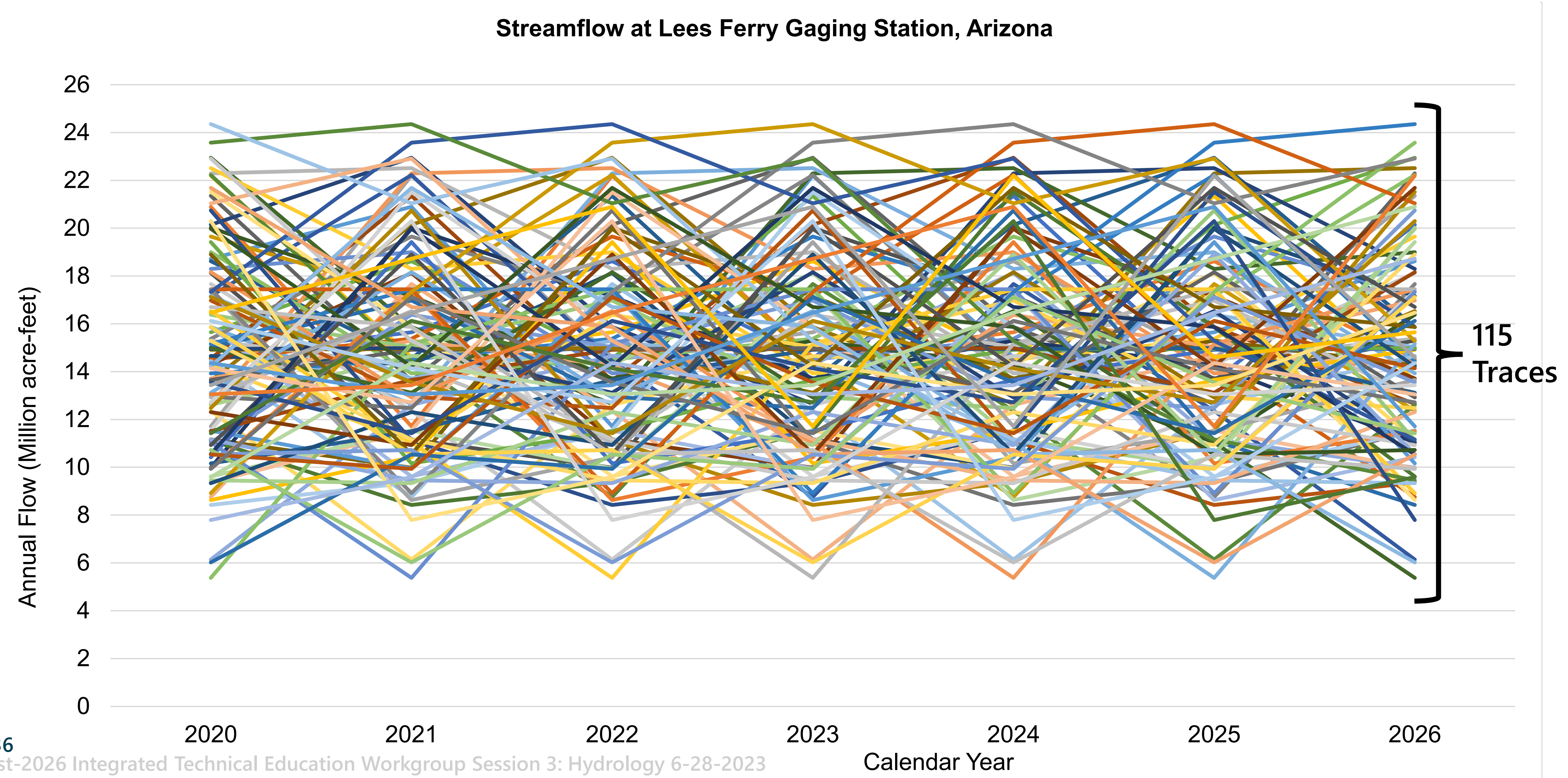
Full Hydrology – Trace 1



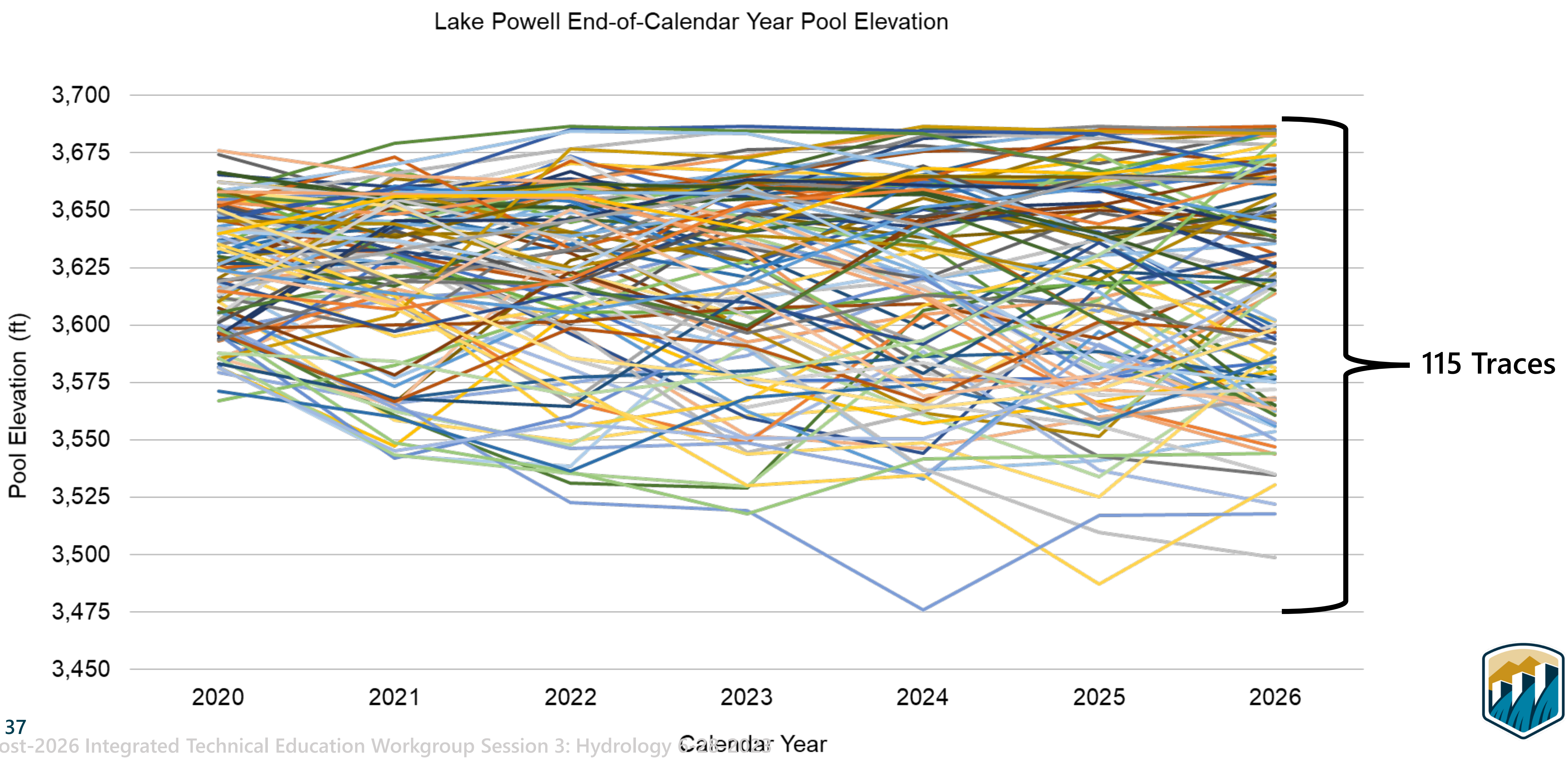
Full Hydrology – Traces 1 and 2



Full Hydrology – All Full Hydrology Traces



Full Hydrology – CRSS Projections



Hydrology Ensembles Overview

- Observed Historical Ensembles
  - Full
  - Pluvial removed
  - Stress test
  - Millennium drought
- Paleohydrology Ensembles
  - Paleo
  - Paleo-conditioned
- Climate Model-Informed Ensembles
  - CMIP3
  - CMIP5
- Recently Developed Ensembles
  - Temperature Adjusted Ensembles
  - Utah State University Drought Ensembles

Note: For an ensemble to be used in a Reclamation study it must include all 29 CRSS inflow points. The ensembles described in this presentation meet this requirement.

For more information, see the Colorado River Basin Climate and Hydrology: State of the Science Report[5]

Observed Historical Ensembles

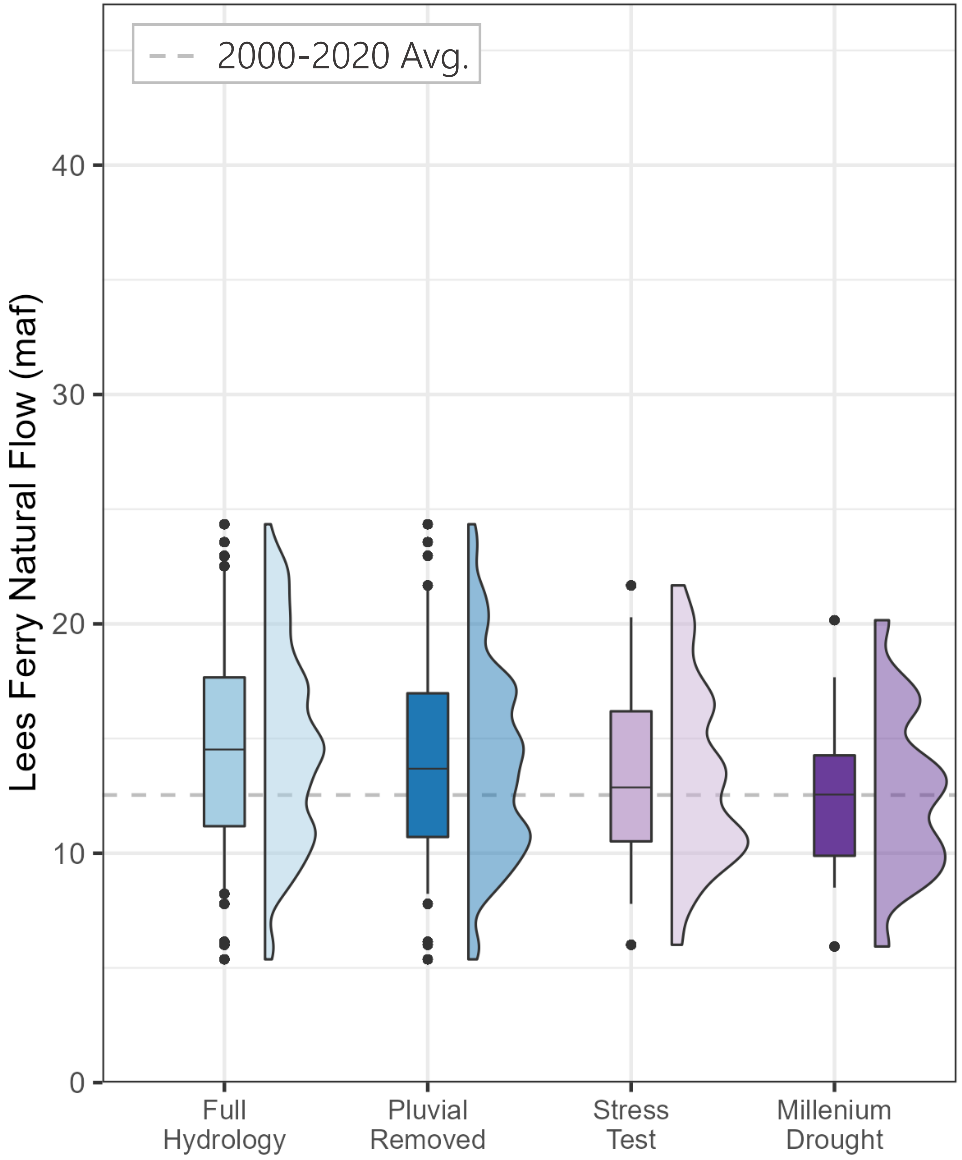
- Created using ISM to resample historical natural flow
- Assumes historical mean and variability is stable through time

<u>Ensembles:</u>

- Full (1906-2020): 115 traces
- Pluvial Removed (1931-2020): 90 traces
- Stress Test (1988-2020): 33 traces
- Millennium Drought (2000-2020): 21 traces

Observed Historical Ensembles

- Advantages
  - Provides a baseline for projections since projections relate to historical context (e.g., “what if the next 20 years were like the last 20 years?”)
  - Readily available and data is trusted and well vetted
- Limitations
  - Does not capture the full range of natural variability or the effects of climate change



Paleohydrology Ensembles

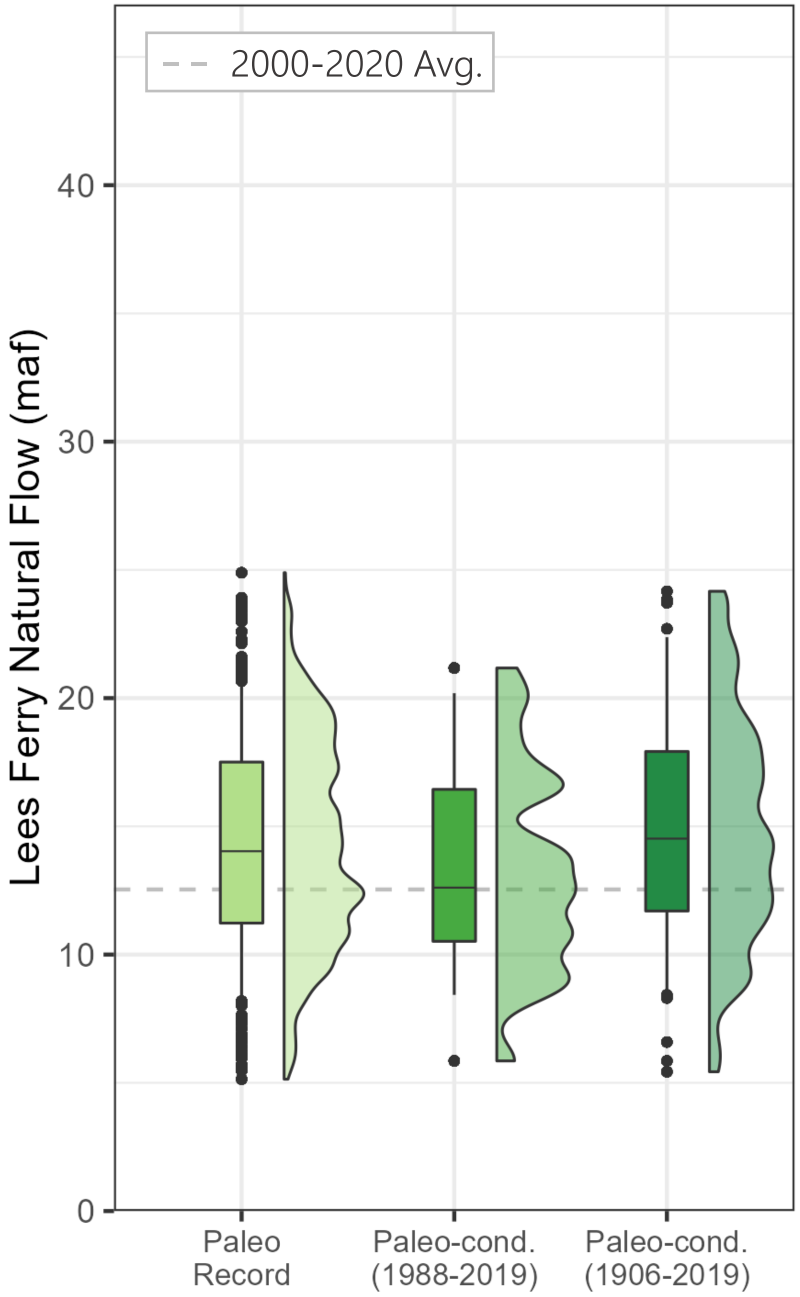
- Ensemble informed by pre-1900 hydrology, including severe droughts and shifts in mean and variability
- Paleohydrology records reconstruct hydrology from historical periods before modern observations using tree-ring data
- There are many different paleohydrology records[6, 7, 8, 9] based on different methodologies for handling tree-ring data and translating to streamflow
  - Meko et al., 2017 for this these ensembles, but other records could be used

<u>Ensembles:</u>

- Paleo Record: 1416 – 2015 paleo record (600 traces)
  - Resampling of paleo record using ISM
- Paleo-conditioned[10]: blend of paleo record and natural flow record (100 traces)
  - Takes state-transition (wet-dry) information from the paleo record and resamples the historical hydrology to create new sequences that reflect paleo-variability but maintains the mean from the historical period

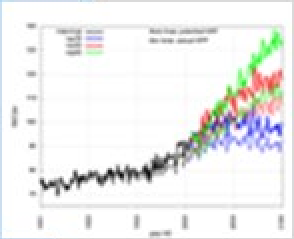
Paleohydrology Ensembles

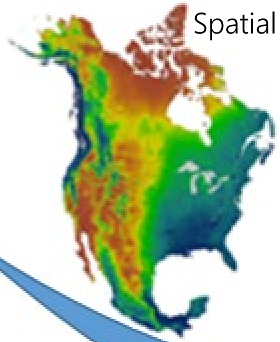
- Advantages
  - Broader range of natural variability than the observed record
  - Provides many, longer sequences of wet and dry years
- Limitations
  - Uncertainty in paleohydrology data
  - Does not reflect effects of future climate change

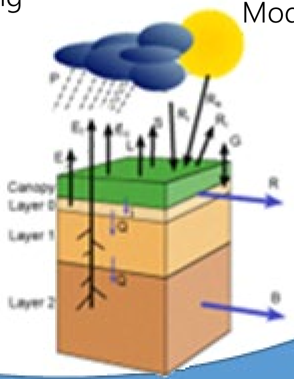


Climate Model-Informed Ensembles
Global Climate Models to Hydrology Ensembles

- The Coupled Model Intercomparison Project (CMIP) is a systematic approach to comparing climate model outputs
- CMIP experiments specify inputs (emissions scenarios) that are used by individual institutions that develop global climate models (GCMs)
- As GCMs evolve, additional CMIP experiments are run with updated models
- The Intergovernmental Panel on Climate Change (IPCC) periodically releases comprehensive reports that use CMIP output to assess the science related to climate change







Comparison of CMIP Experiments		
	CMIP3	CMIP5
Emissions Scenarios	5	4
Number of Models	16	36
Ensemble Traces	112	231

Climate Model-Informed Ensembles

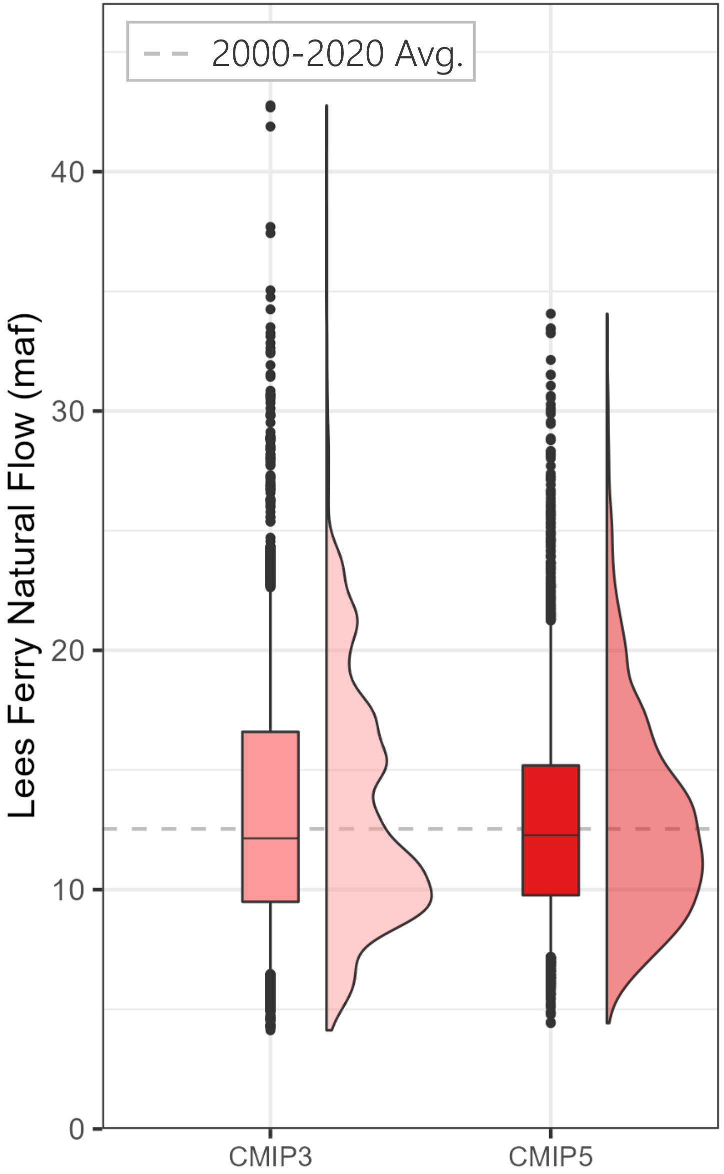
- All models are experimental and that is why CMIPs use multiple models
- Ensembles are made up of different combinations of climate models and emissions scenarios and cover a wide range of potential future conditions
- Reclamation has selected certain models and downscaling methods based on expert analysis

<u>Ensembles:</u>

- CMIP3[11] (112 traces)
  - Three emissions scenarios and downscaled using Bias-Corrected and Spatial Disaggregation (BCSD) method and processed into streamflows
- CMIP5[12] (64 traces)
  - Three emissions scenarios, models culled based on skill, and downscaled using the Localized Constructed Analog (LOCA) method and processed into streamflows

Climate Model-Informed Ensembles

- Advantages
  - Best source of information about potential effects of future climate change on hydrology
- Limitations
  - Large uncertainty in potential climate change impacts, including flows far above observations
  - GCMs lack skill in projecting future climate, especially precipitation
  - No consensus on best downscaling method
  - Complex datasets that are difficult to obtain, analyze, and interpret



Recently Developed Ensembles

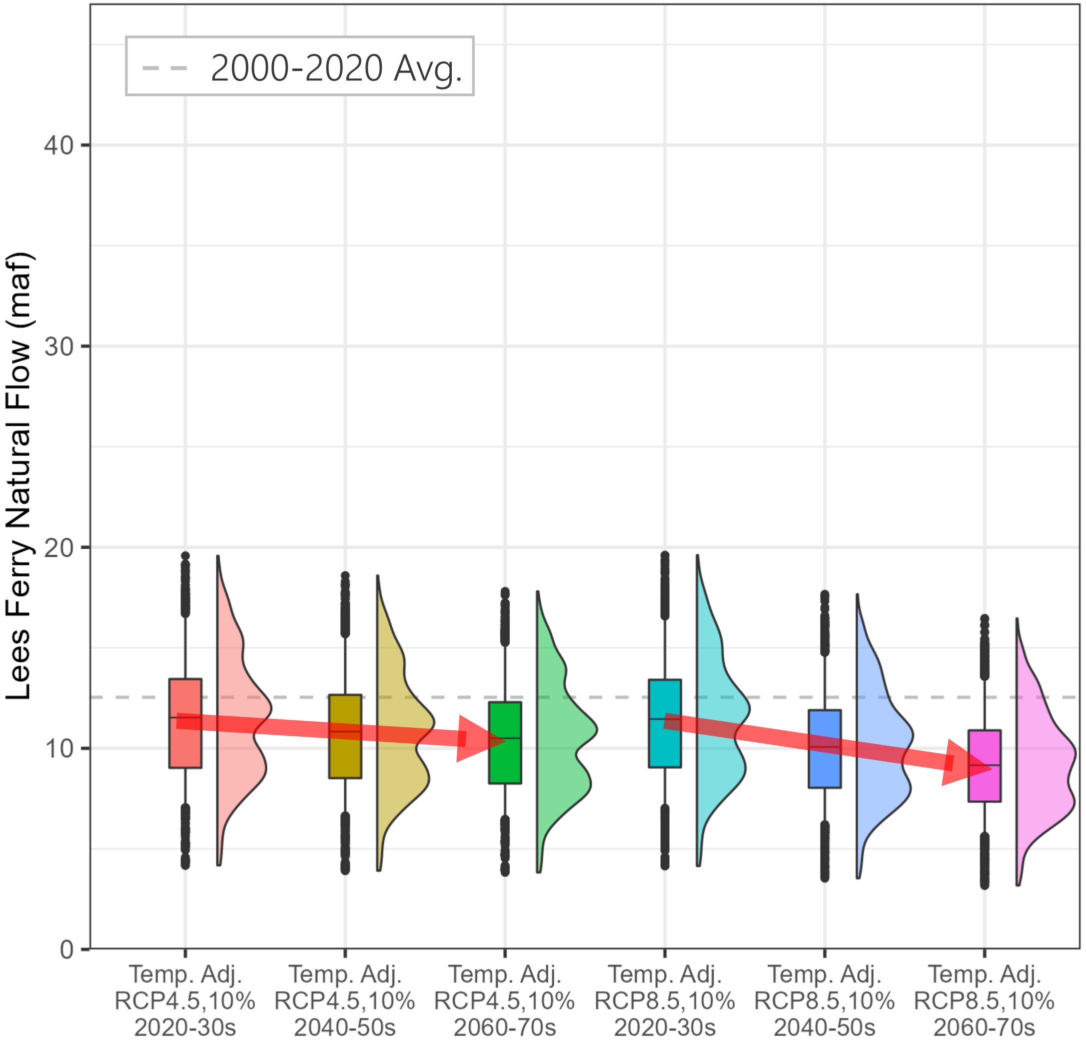
- Efforts beyond Reclamation studies have used a variety of approaches to generate natural flow inputs for CRSS
- Different ensembles correspond to different modeling needs

Ensembles:

- Temperature Adjusted Ensembles[13] (114 traces)
  - Proportionally reduces the natural flow ISM ensemble by applying runoff-temperature sensitivities (% runoff change/degree C) to warming trend from GCMs
- Utah State University Drought Ensembles[14] (100 traces)
  - Resampled past droughts (20- to 25-year periods) from historical and paleo records that exhibit longer dry sequences than seen in recent periods

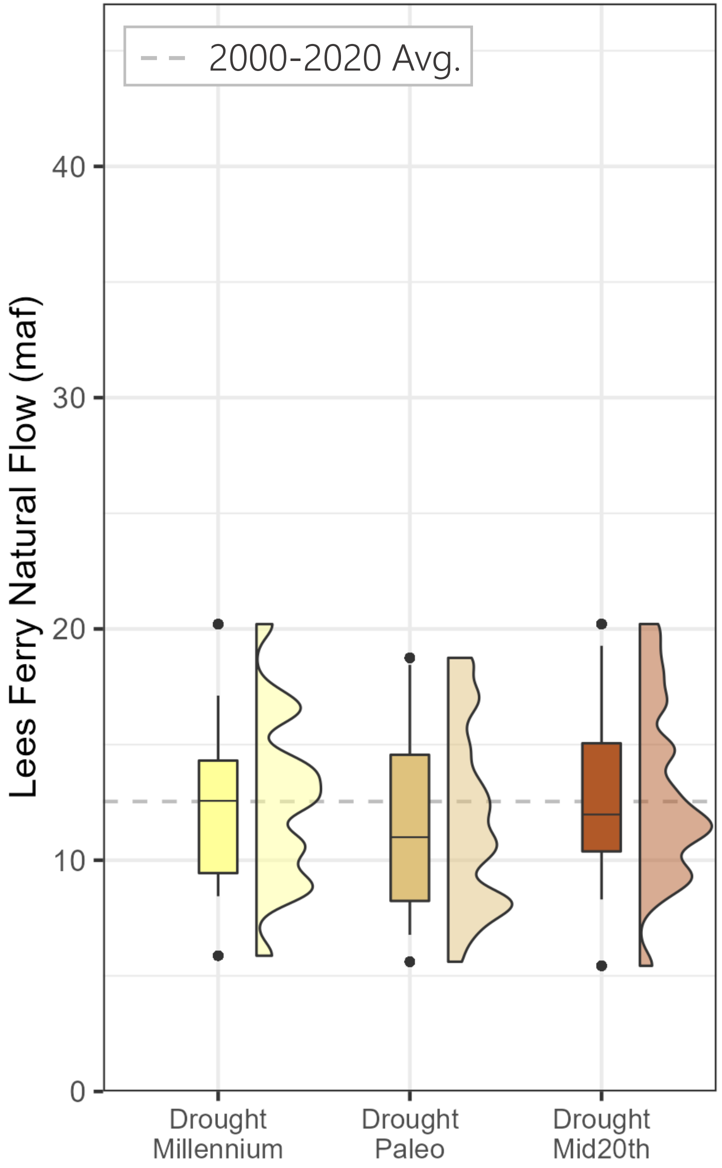
Temperature Adjusted Ensembles

- Advantages
  - Applies a downward trend to natural flow record
  - Makes use of GCM temperature outputs that are more reliable without using less reliable precipitation outputs
- Limitations
  - Dampens year-to-year variability and unjustifiably eliminates high flows
  - Simplistic statistical approach that does not account for complex physical process that will be affected by climate change



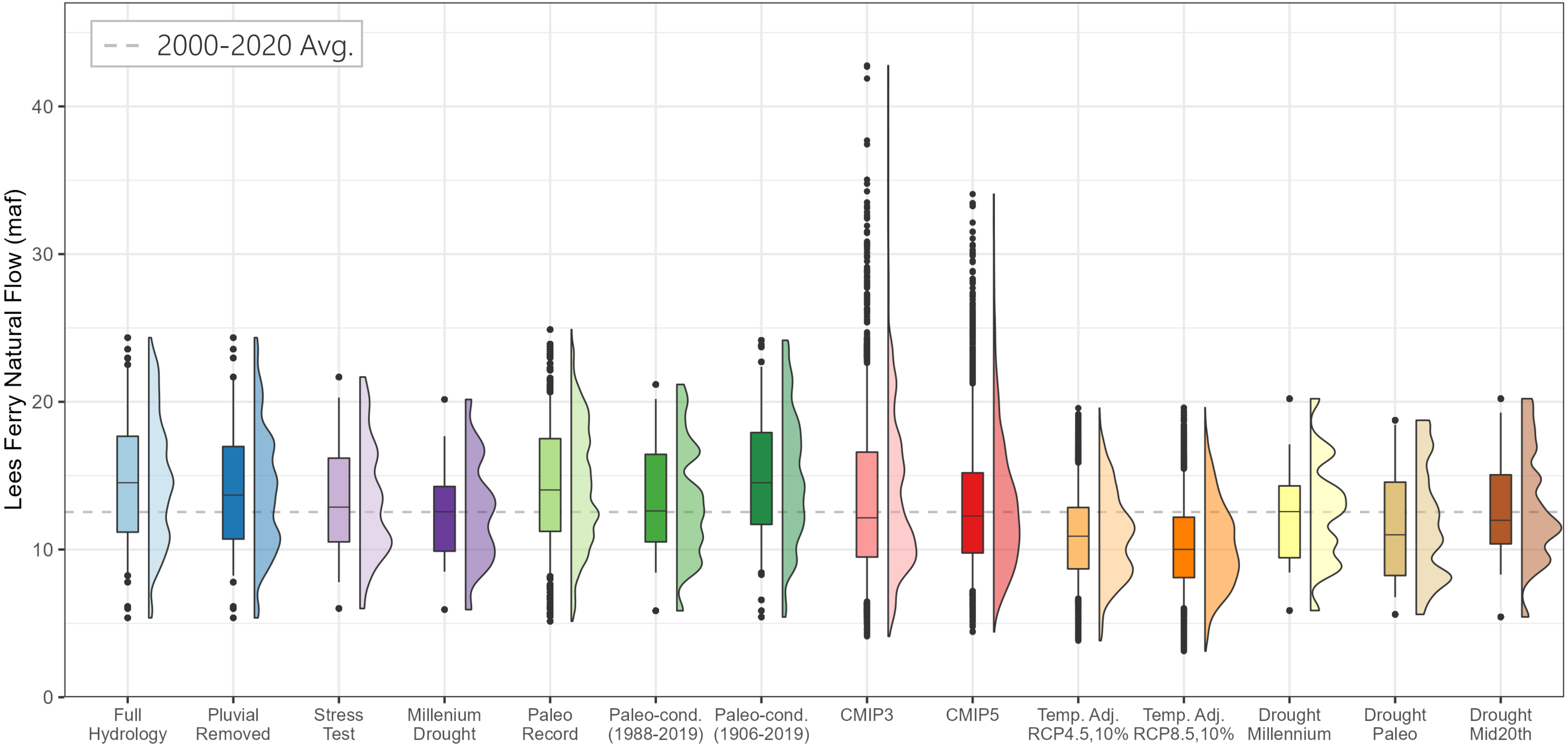
Utah State University Drought Ensembles

- Advantages
  - Severe drought that contains longer dry sequences than those in the historical record
  - Testing the system in drought without being prescriptive about the how the drought will unfold
- Limitations
  - Resamples a small number of observations which limits variability in droughts
  - Alone the ensembles do not represent enough potential future conditions



Hydrology Ensemble Summary

- Using multiple ensembles for analysis allows us to analyze a range of different future hydrology conditions that may have different characteristics
- Ensembles can come from different data sources and use different methods



Approach to Hydrology in the Post-2026 Web Tool

Using Ensembles in Long-Term Planning

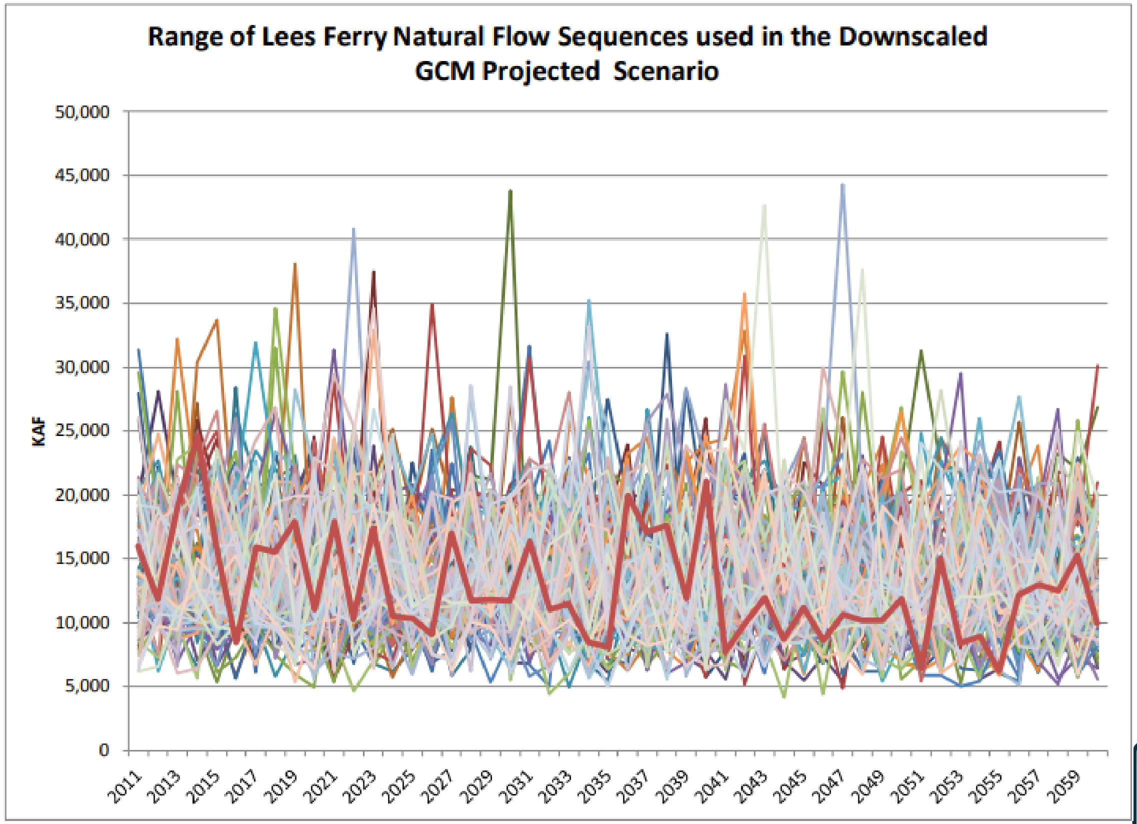
- Ensembles are used in long-term modeling to capture uncertainty
- Using an ensemble to represent the future implies that:
  - the specific statistics, e.g., average flow, range, and frequency, are informative, and
  - the method used to generate it is reliable.
- Ensembles can be interpreted as "stories", e.g., the Stress Test story:

  "If we expect to see flows similar to what we have experienced since 1988, and with the exact same likelihood, then the impact to the system would be…"

- Ensemble stories can be useful if carefully interpreted, but ensemble-based analysis has limitations

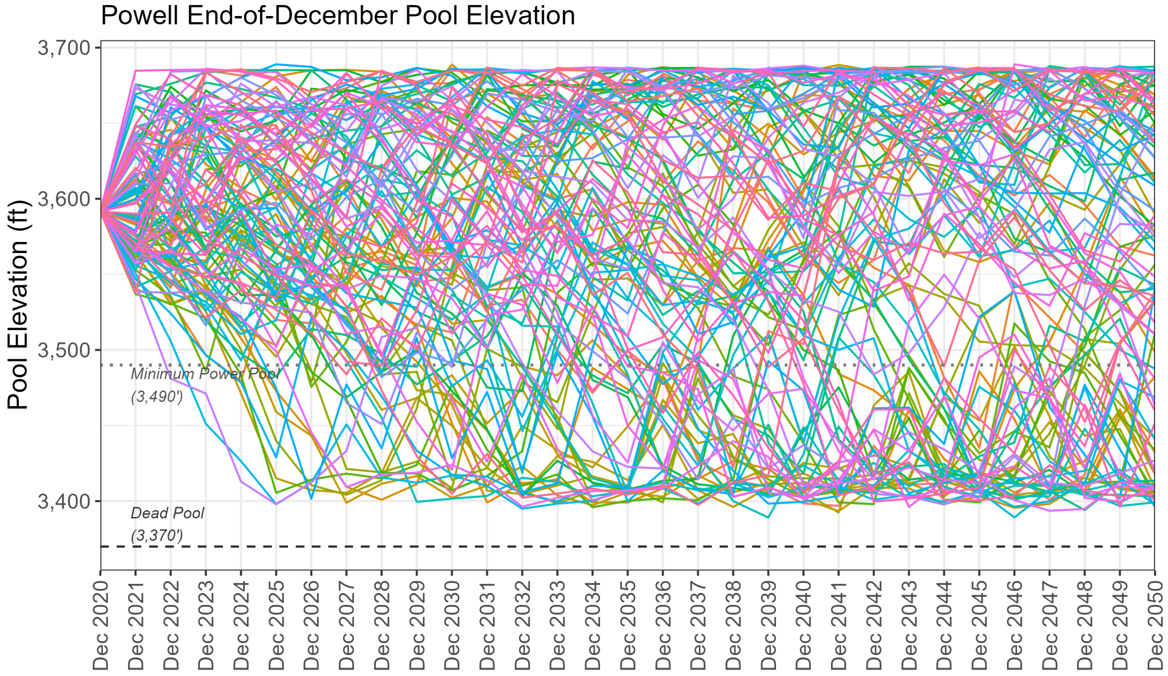
CMIP3 Hydrology Traces

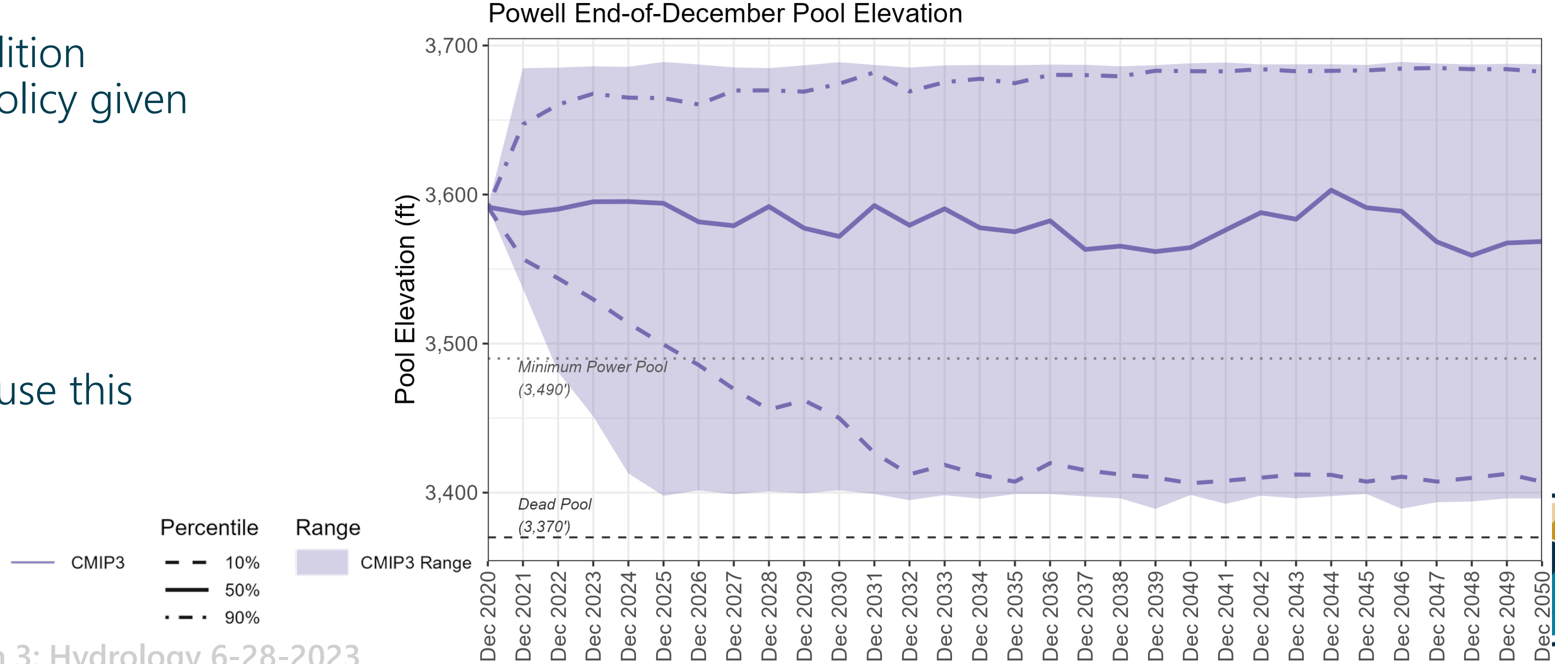
FIGURE B-44 (2012 Basin Study)
Colorado River at Lees Ferry, Arizona Natural Flow for 112 Sequences for the Downscaled GCM Projected Scenario
The bolded line indicates a representative trace.



Ensemble-Based Analysis

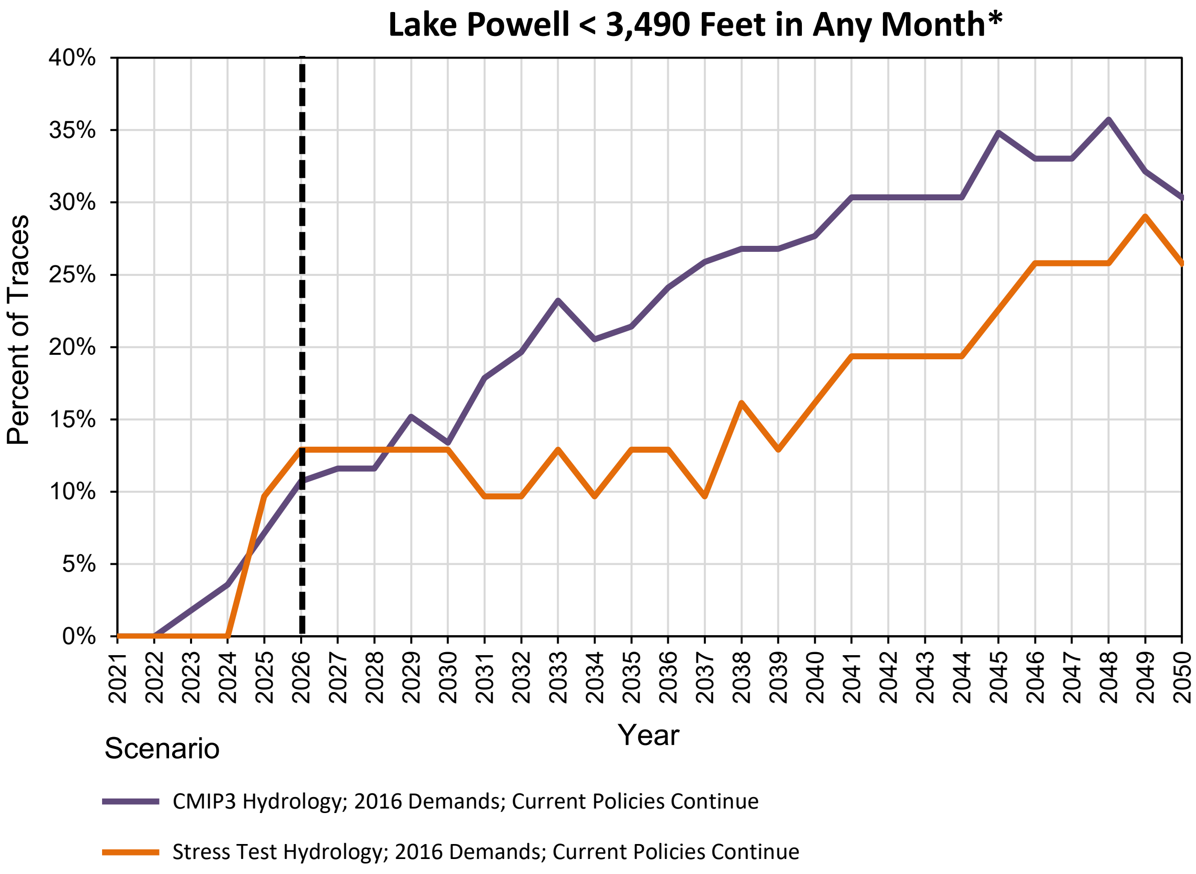
- Questions that can be answered:
  1. What is the range (*not probability!*) of elevations that could occur in the future under this policy and this ensemble?
  2. How often does an undesirable condition occur under this policy and this ensemble? How does that frequency change under a different ensemble?
  3. How often does an undesirable condition occur under this policy vs. another policy given this ensemble?
- Questions that cannot be answered:
  - How robust is this policy?
  - What are the conditions that could cause this policy to perform poorly?





Ensemble-Based Analysis

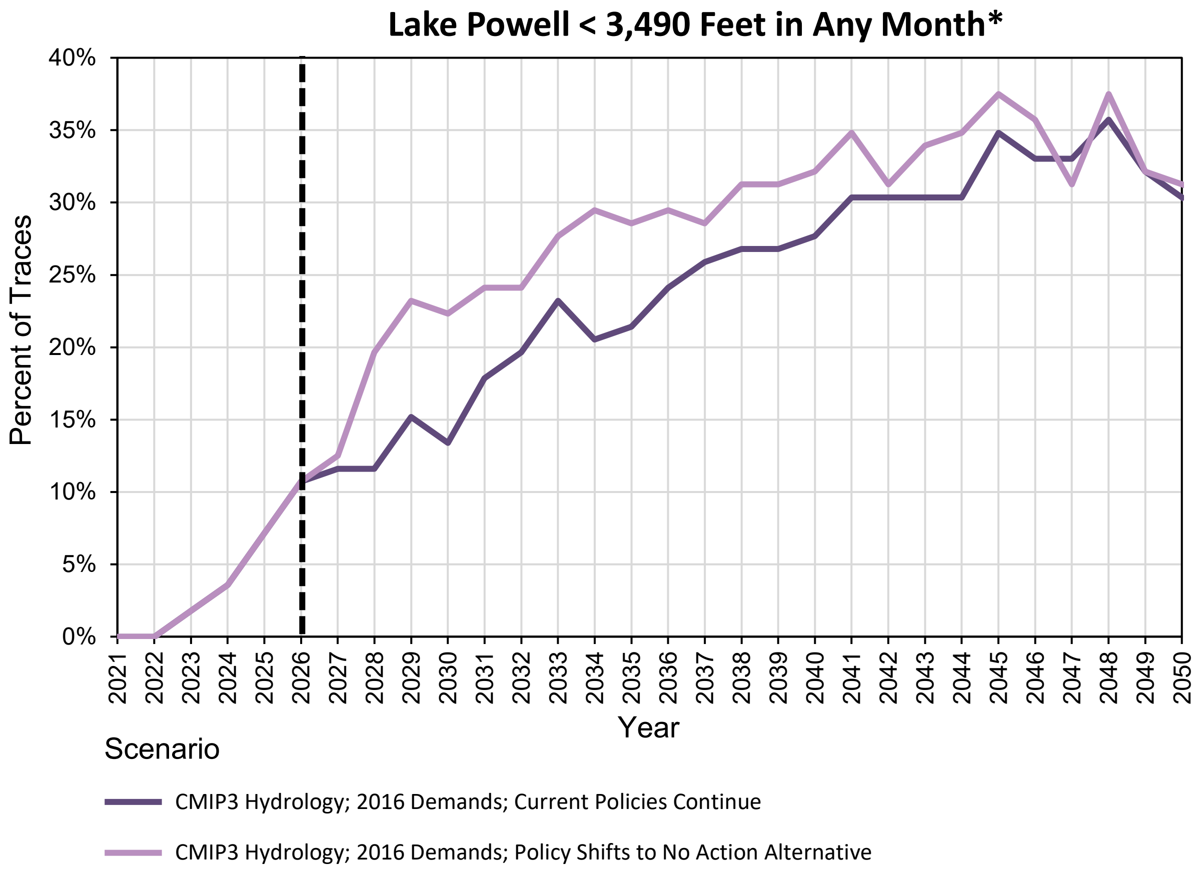
- Questions that can be answered:
    1. What is the range (*not probability*) of elevations that could occur in the future under this policy and this ensemble?
    2. How often does an undesirable condition occur under this policy and this ensemble? How does that frequency change under a different ensemble?
    3. How often does an undesirable condition occur under this policy vs. another policy given this ensemble?
- Questions that cannot be answered:
    - How robust is this policy?
    - What are the conditions that could cause this policy to perform poorly?



*Based on August 2020 CRSS modeling

Ensemble-Based Analysis

- Questions that can be answered:
    1. What is the range (*not probability*) of elevations that could occur in the future under this policy and this ensemble?
    2. How often does an undesirable condition occur under this policy and this ensemble? How does that frequency change under a different ensemble?
    3. How often does an undesirable condition occur under this policy vs. another policy given this ensemble?
- Questions that cannot be answered:
    - How robust is this policy?
    - What are the conditions that could cause this policy to perform poorly?

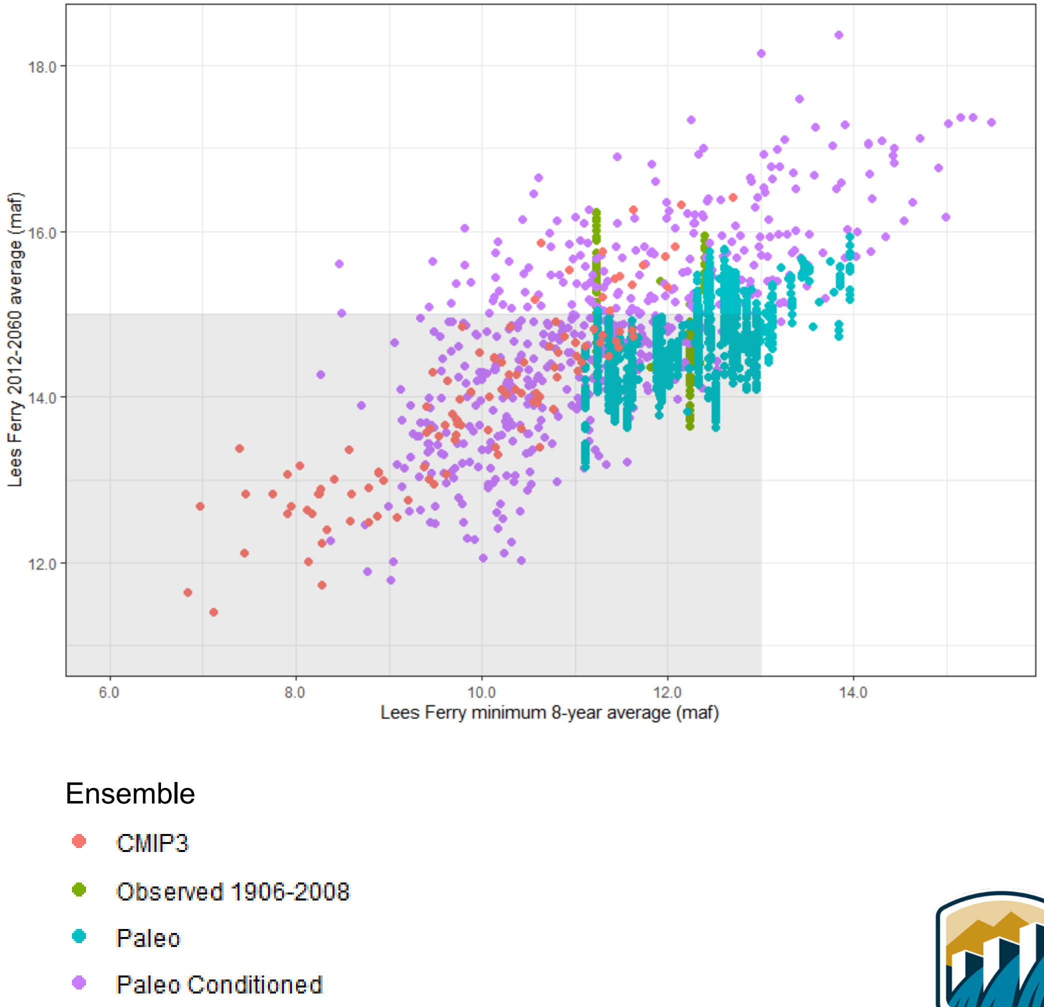


*Based on August 2020 CRSS modeling

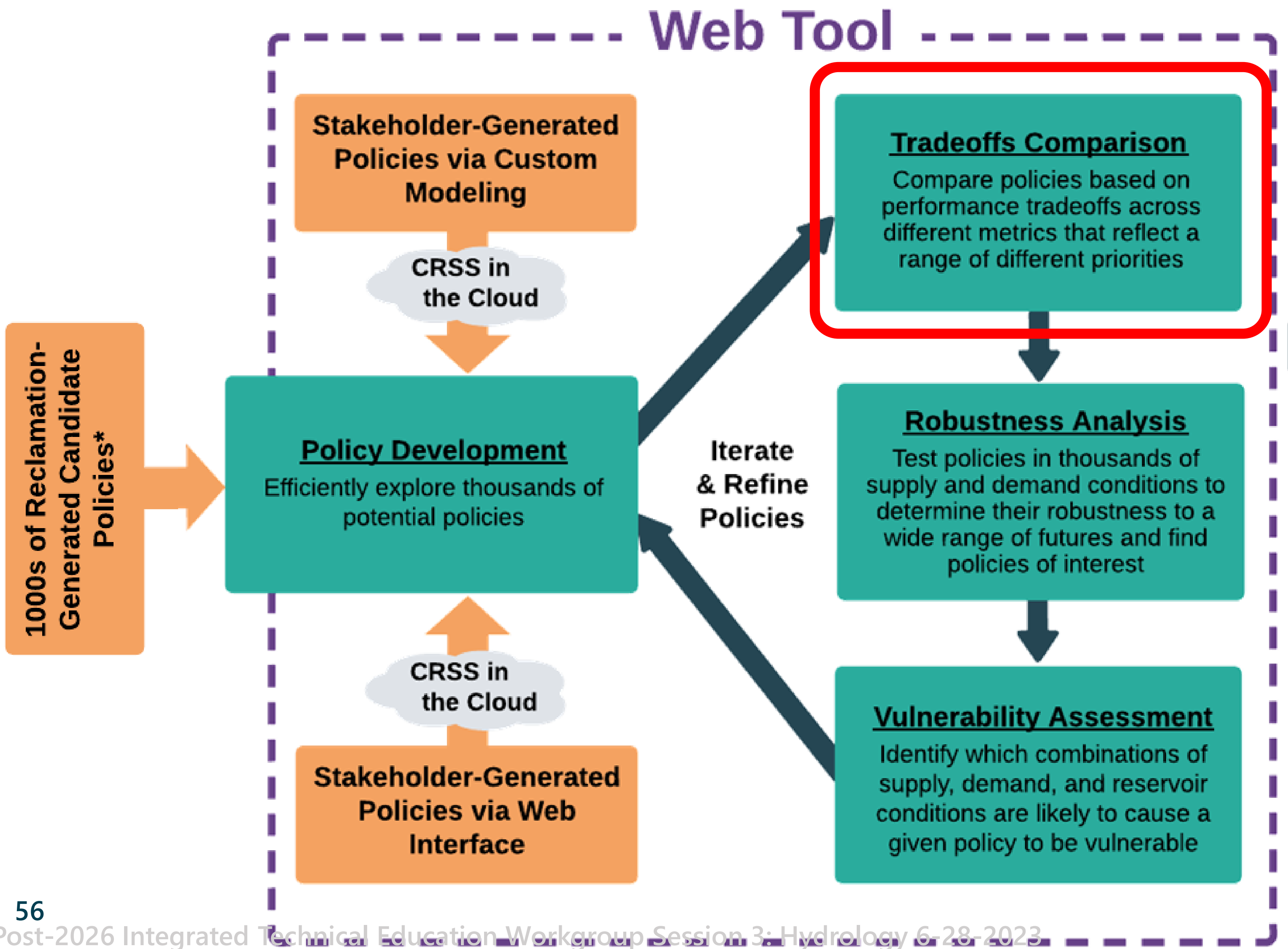
Thinking Outside the Ensemble

- Think about each trace as a *potential* future, not *the* future, and analyze each trace as an individual data point
- Characterize each hydrology trace using quantitative measures, e.g.,
    - Long-term average annual Lees Ferry flow
    - Worst eight-year drought
- Use hundreds of traces that span a wide range of the characteristics and have good coverage of all the spaces in between the extremes
- Approach the analysis from a different direction to answer important questions:
    - Will this policy be acceptable in a wide range of conditions?
    - Will this policy be effective in an X-maf future?

Vulnerable Conditions for Lake Mead <1,000 ft[15]

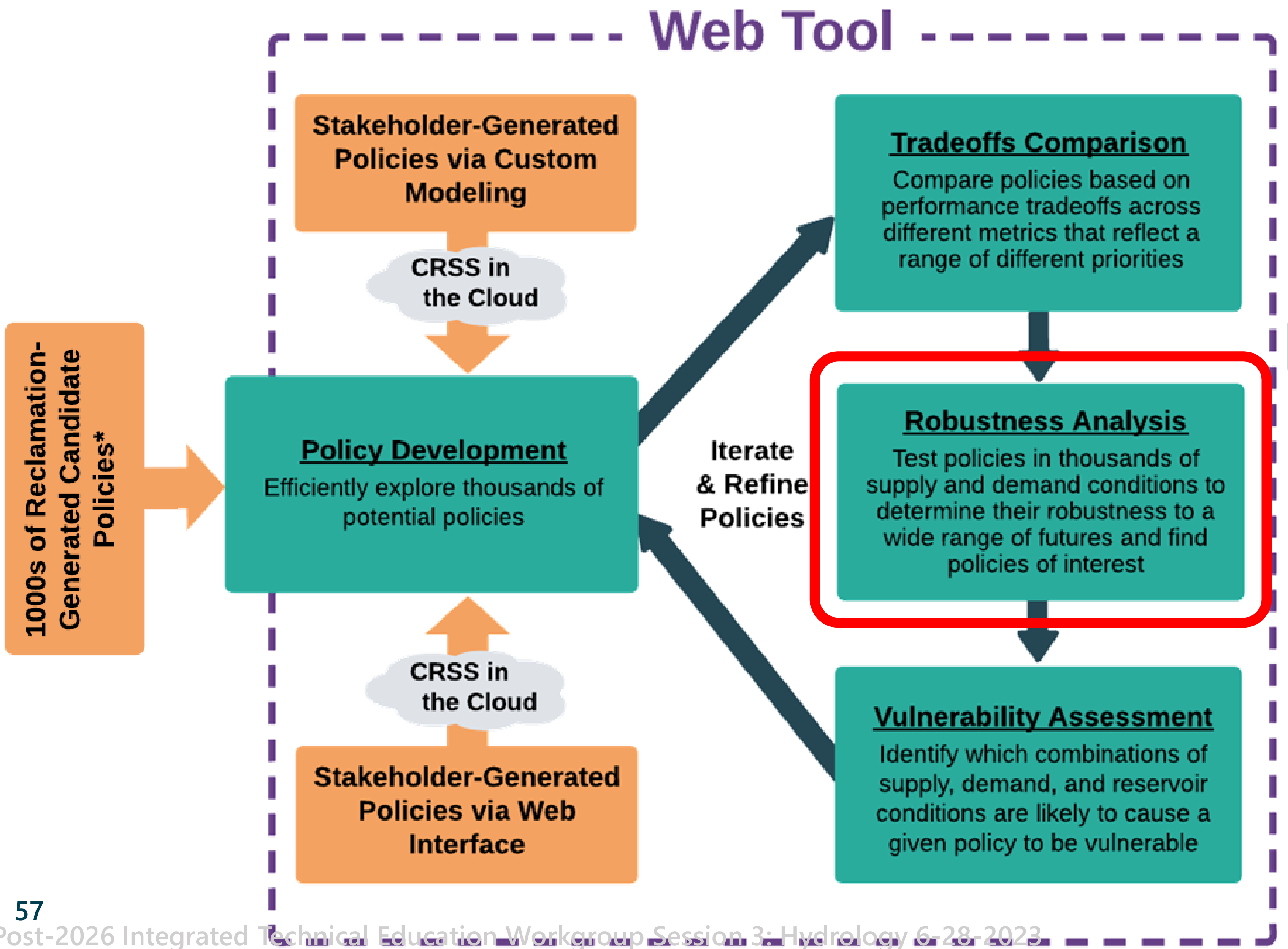


How Hydrology Will be Used in Policy Analysis for the Post-2026 Process



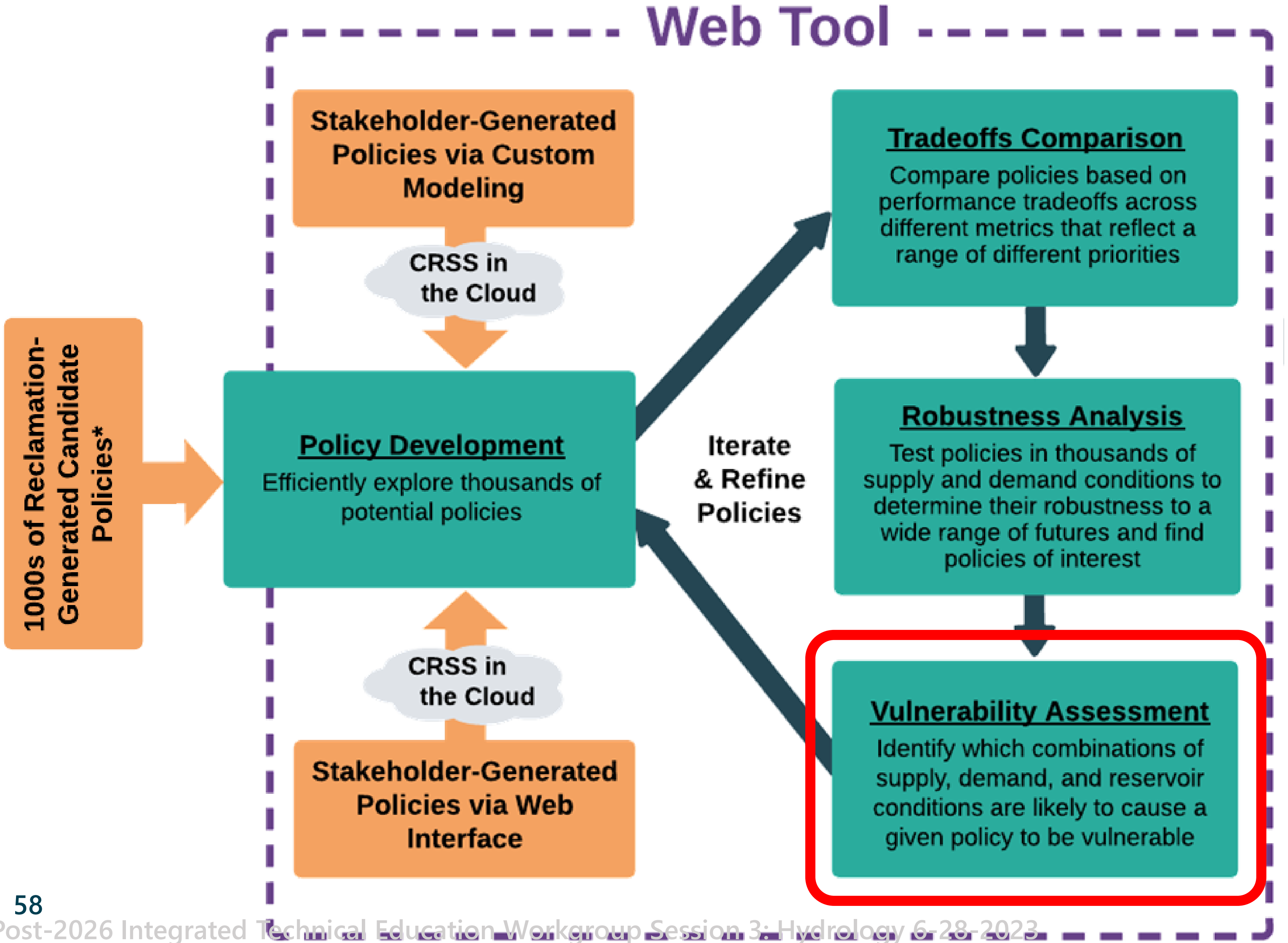
- Simulate policies in a subset of all traces, calculate mean or "worst" performance
- Why are few traces and summary statistics ok?
  - Next stages expand on this
  - Purposes of this stage of analysis
    - Screening performance at a high level – if a policy doesn't perform well under a handful of traces, it is unlikely to be robust
    - Comparing policies to each other
    - Understanding tradeoffs across metrics

How Hydrology Will be Used in Policy Analysis for the Post-2026 Process



- Simulate policies in hundreds of traces, calculate percent of traces where policies succeed in meeting robustness criteria
- Why is it ok to use percents of traces?
  - Next stage expands on this
  - Purpose of this stage of analysis is to compare policies, so relative percents are meaningful

How Hydrology Will be Used in Policy Analysis for the Post-2026 Process



- Analyze the subset of robustness traces in which policies resulted in undesirable conditions
- Learn which characteristics lead to vulnerabilities

Going from Individual Ensembles to a Wide Range of Individual Futures

Not Enough	Appropriate in some contexts	Good	Great in DMDU analysis
Single ensemble using only summary statistics →	Multiple ensembles using only summary statistics →	Multiple ensembles analyzed as individual traces →	Multiple carefully chosen ensembles analyzed as individual traces

Not Enough

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

Appropriate in some contexts

- 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

- 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

- 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

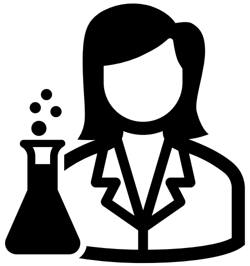
- Ensembles have many characteristics that inform whether they are appropriate or useful for our analysis
  - Data source
  - Previous applications
  - Range, distribution, trends, etc. (violin plots)
  - Static characteristics (5-yr avg, long-term avg)
  - Patterns

- 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

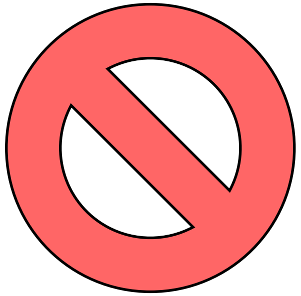
- To ensure that the overall **group of traces** fully captures characteristics and patterns needed for sound analysis, additional ensembles may be developed

Using Advanced Characteristics to Inform Selection of Hydrology Ensembles

How are Hydrology Ensembles Used for Robustness and Vulnerability?



Find the most likely future



How are Hydrology Ensembles Used for Robustness and Vulnerability?

Find the most likely future

Simulate every possible future

How are Hydrology Ensembles Used for Robustness and Vulnerability?

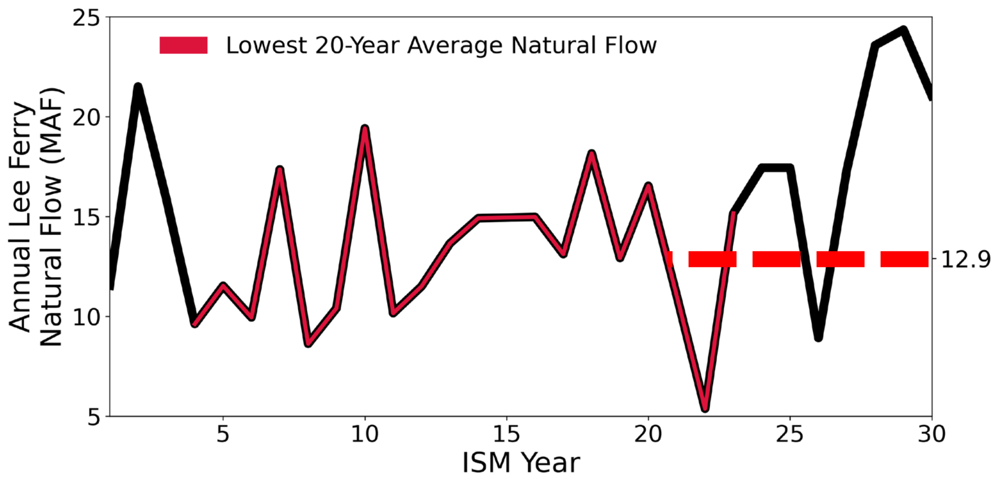
Find the most likely future

Simulate every possible future

Identify the *conditions* that cause undesirable outcomes

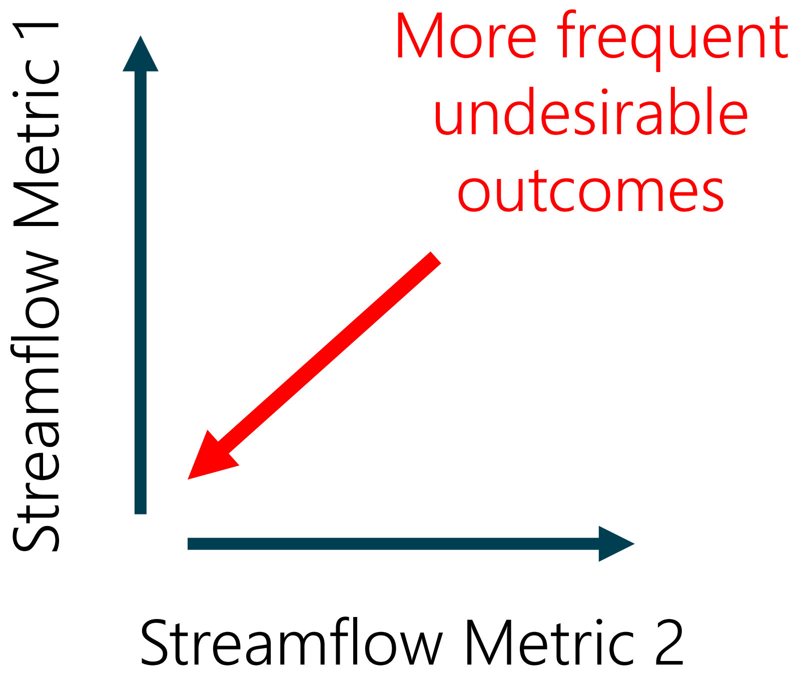
Selection of Hydrology Ensembles for Policy Comparison

- How do we quantify hydrologic conditions?
  - Lees Ferry natural flows summarize conditions across space (Upper Basin)
  - Basic streamflow metrics over variable time windows summarize conditions through time



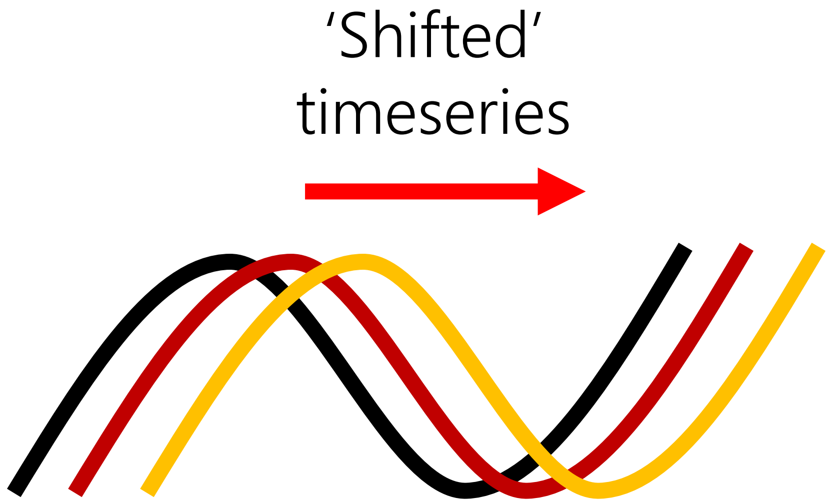
Selection of Hydrology Ensembles for Policy Comparison

- How do we quantify hydrologic conditions?
  - Lees Ferry natural flows summarize conditions across space (Upper Basin)
  - Basic streamflow metrics over variable time windows summarize conditions through time
- How do we use streamflow metrics to identify and communicate policy vulnerabilities?
  - Define the range of hydrologic conditions to give a full picture of vulnerability



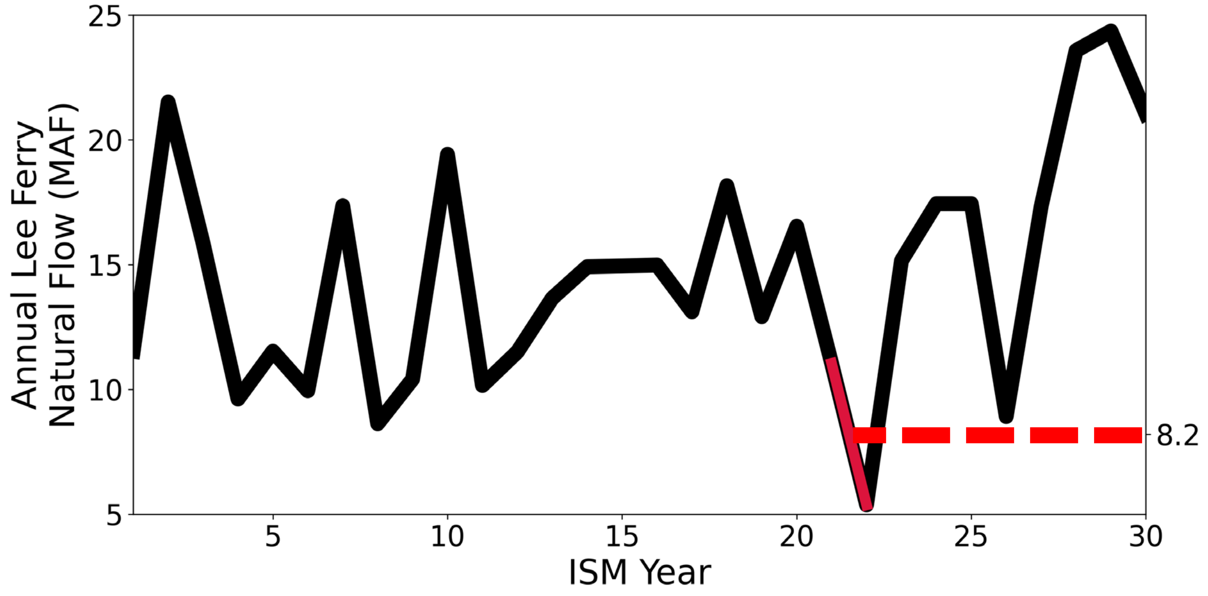
Selection of Hydrology Ensembles for Policy Comparison

- How do we quantify hydrologic conditions?
  - Lees Ferry natural flows summarize conditions across space (Upper Basin)
  - Basic streamflow metrics over variable time windows summarize conditions through time
- How do we use streamflow metrics to identify and communicate policy vulnerabilities?
  - Define the range of hydrologic conditions to give a full picture of vulnerability
- Vulnerability is driven as much by the pattern of droughts as their individual magnitudes
  - Can we consider both the size of individual droughts and their patterns over time?



Streamflow Metrics: Drought Length + Size

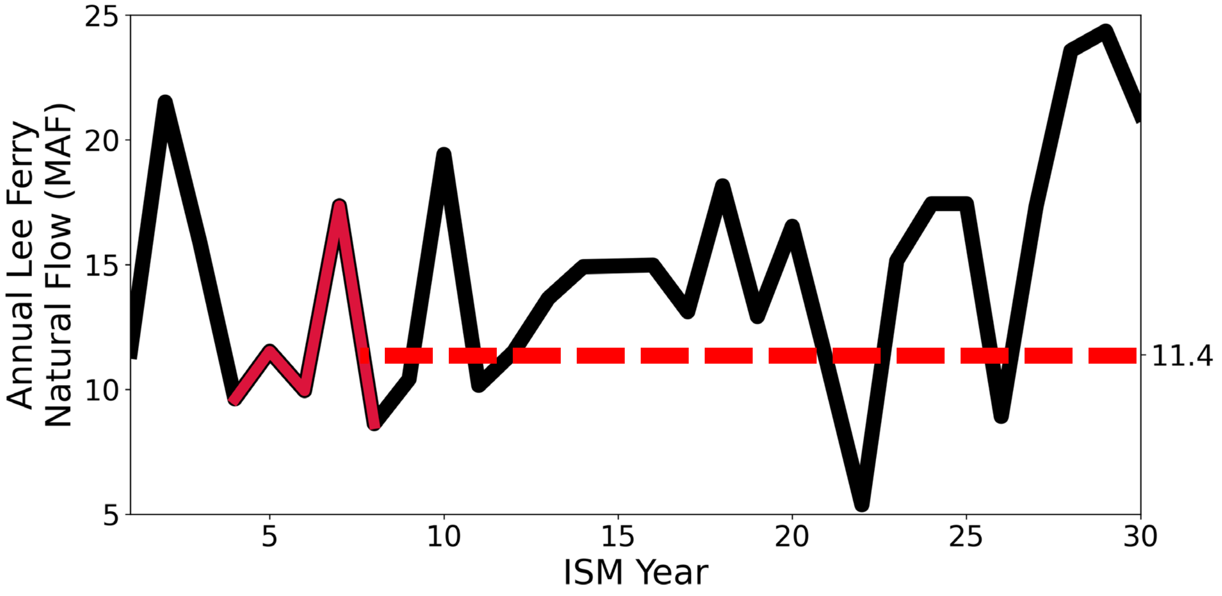
- Measuring minimum flow:
  - 2 year rolling window



Measures the worst drought of a given length in each trace

Streamflow Metrics: Drought Length + Size

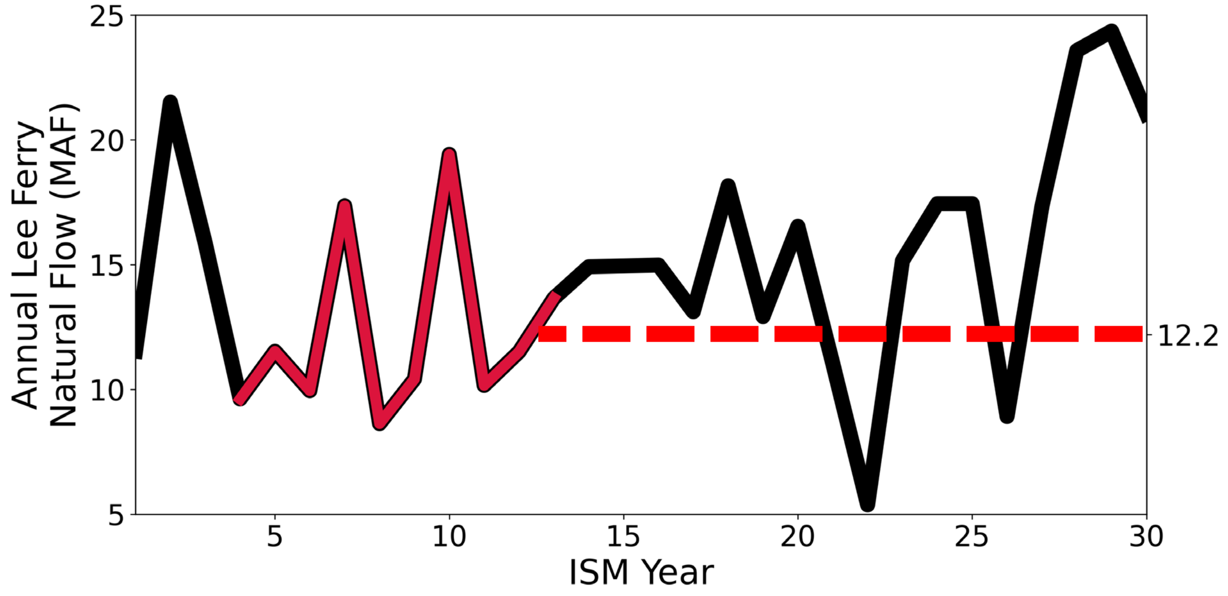
- Measuring minimum flow:
  - 2 year rolling window
  - 5 year rolling window



Measures the worst drought of a given length in each trace

Streamflow Metrics: Drought Length + Size

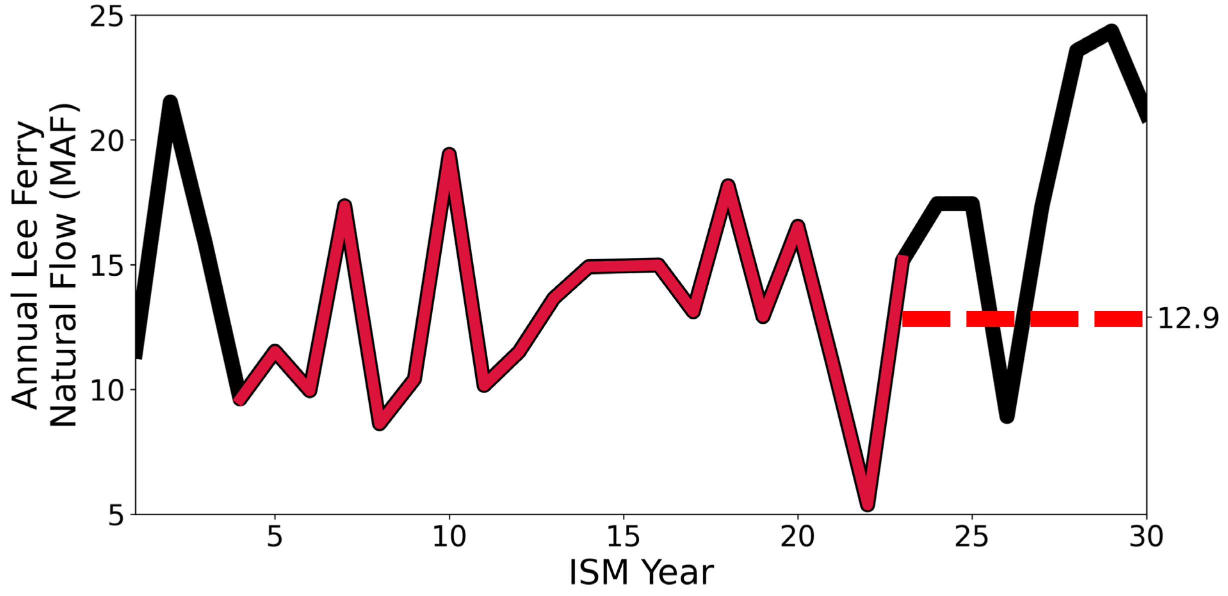
- Measuring minimum flow:
  - 2 year rolling window
  - 5 year rolling window
  - 10 year rolling window



Measures the worst drought of a given length in each trace

Streamflow Metrics: Drought Length + Size

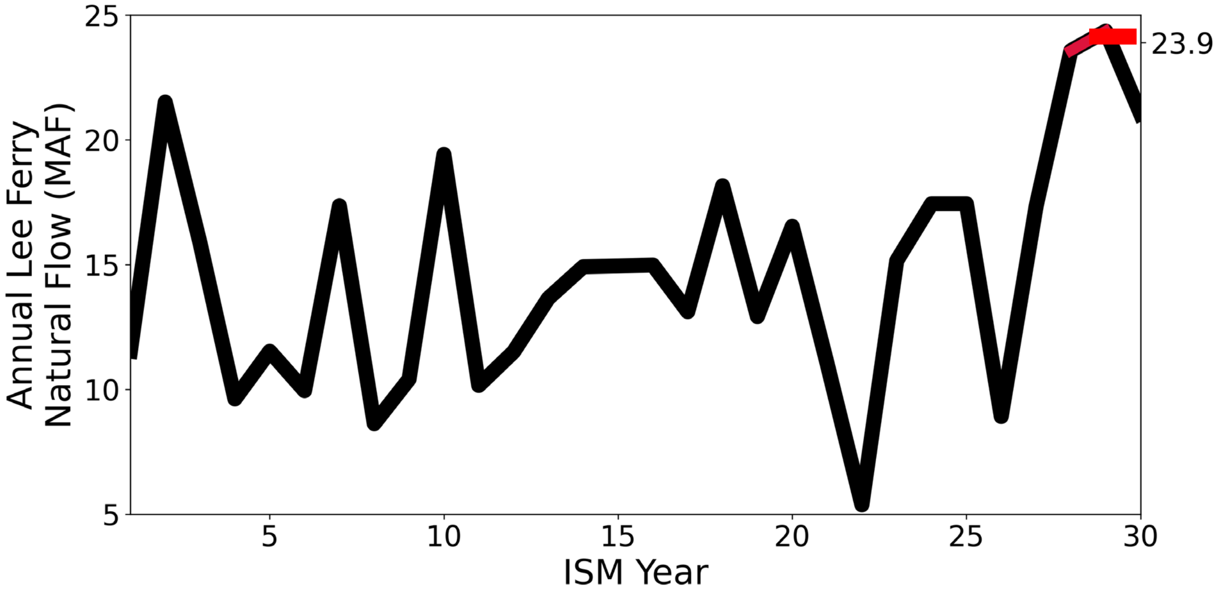
- Measuring minimum flow:
  - 2 year rolling window
  - 5 year rolling window
  - 10 year rolling window
  - 20 year rolling window



Measures the worst drought of a given length in each trace

Streamflow Metrics: Wet Periods

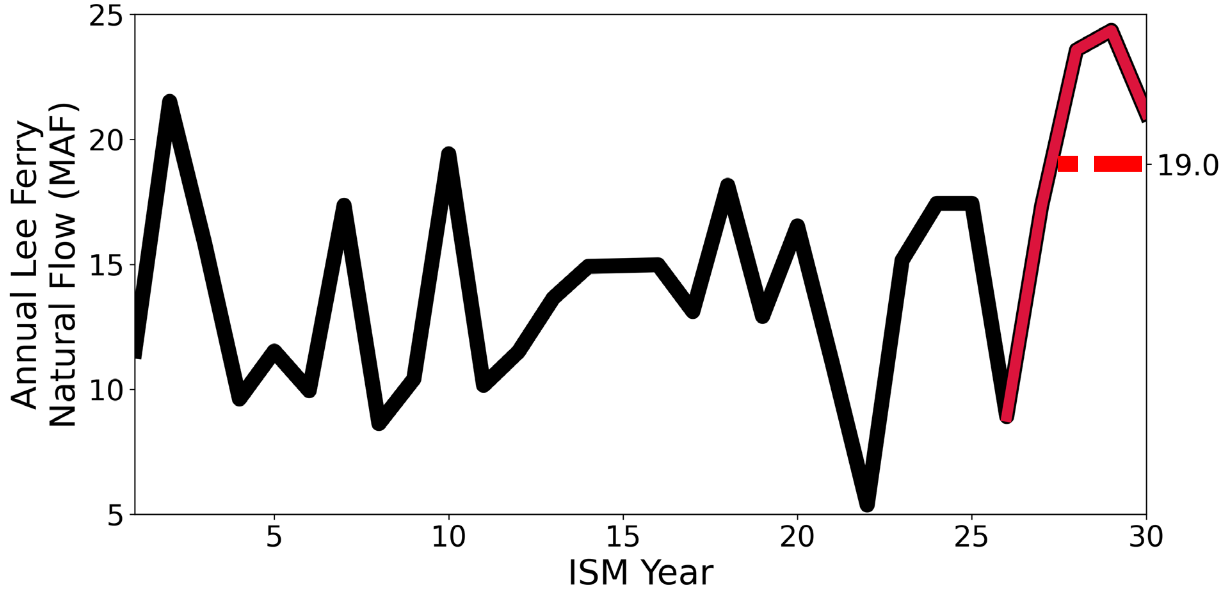
- Measuring minimum flow
- Measuring maximum flow:
    - 2 year rolling window



Measures the fastest (potential) reservoir refilling periods in each trace

Streamflow Metrics: Wet Periods

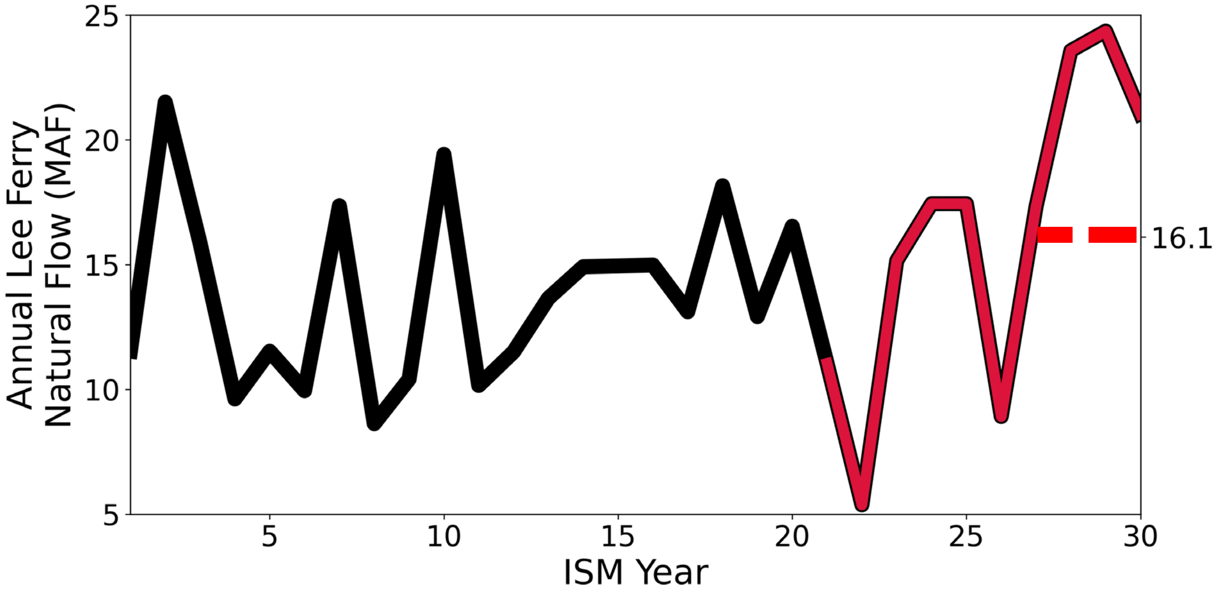
- Measuring minimum flow
- Measuring maximum flow:
  - 2 year rolling window
  - 5 year rolling window



Measures the fastest (potential) reservoir refilling periods in each trace

Streamflow Metrics: Wet Periods

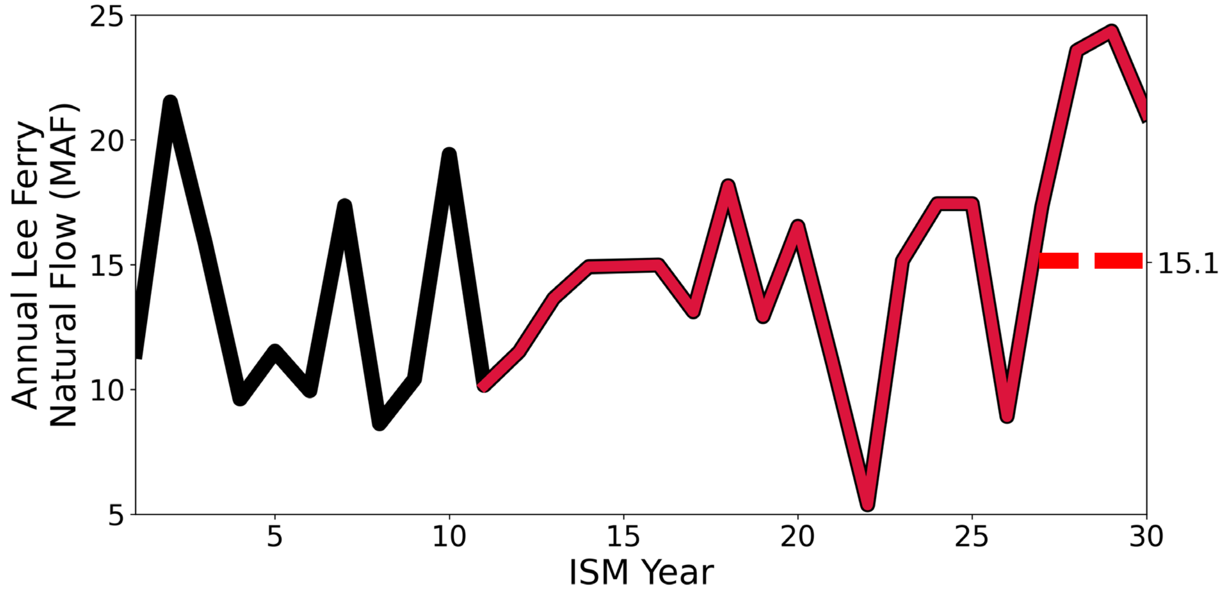
- Measuring minimum flow
- Measuring maximum flow:
  - 2 year rolling window
  - 5 year rolling window
  - 10 year rolling window



Measures the fastest (potential) reservoir refilling periods in each trace

Streamflow Metrics: Wet Periods

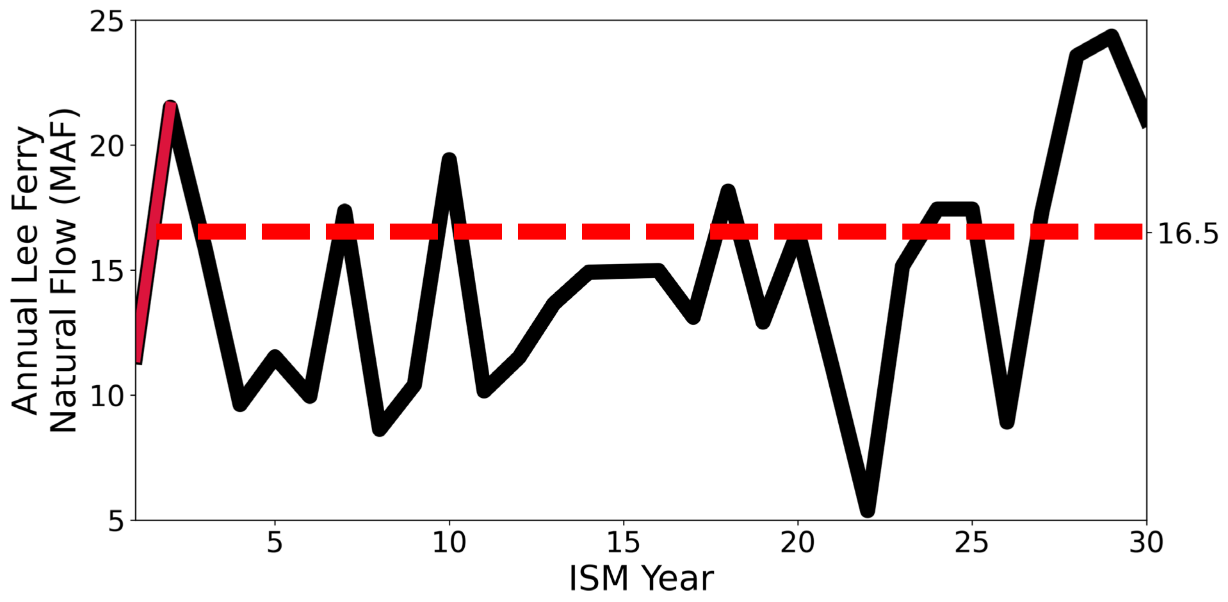
- Measuring minimum flow
- Measuring maximum flow:
  - 2 year rolling window
  - 5 year rolling window
  - 10 year rolling window
  - 20 year rolling window



Measures the fastest (potential) reservoir refilling periods in each trace

Streamflow Metrics: Initial Conditions

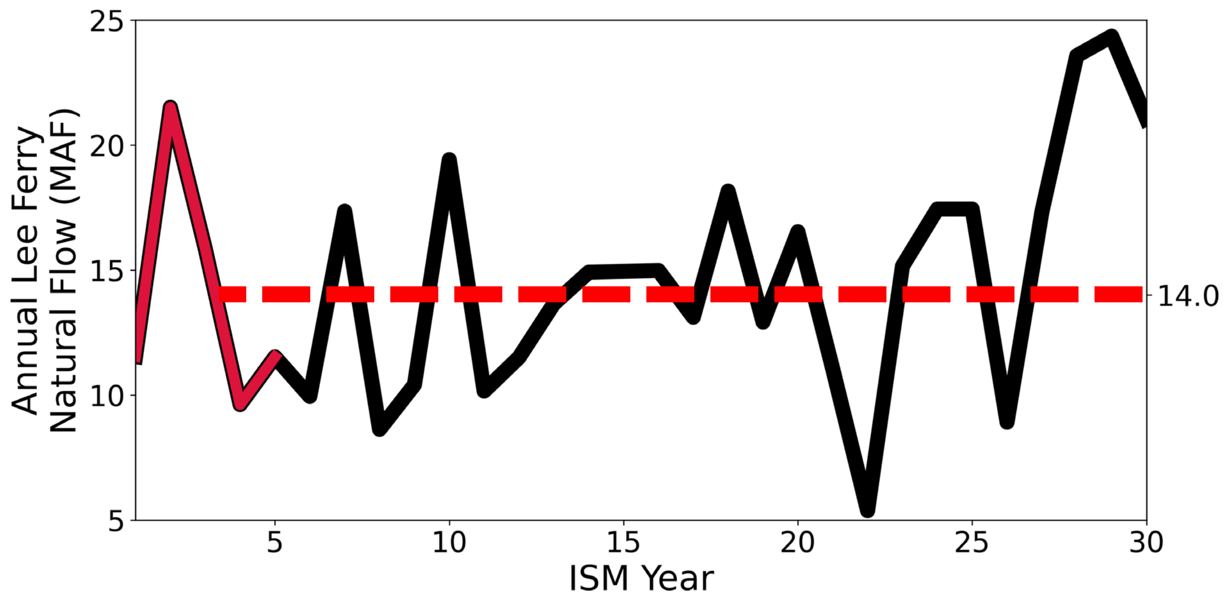
- Measuring minimum flow
- Measuring maximum flow
- Measuring median flow
- Measuring first:
  - 2 year average flow



Measures flow in the period when conditions are influenced by initial reservoir storage

Streamflow Metrics: Initial Conditions

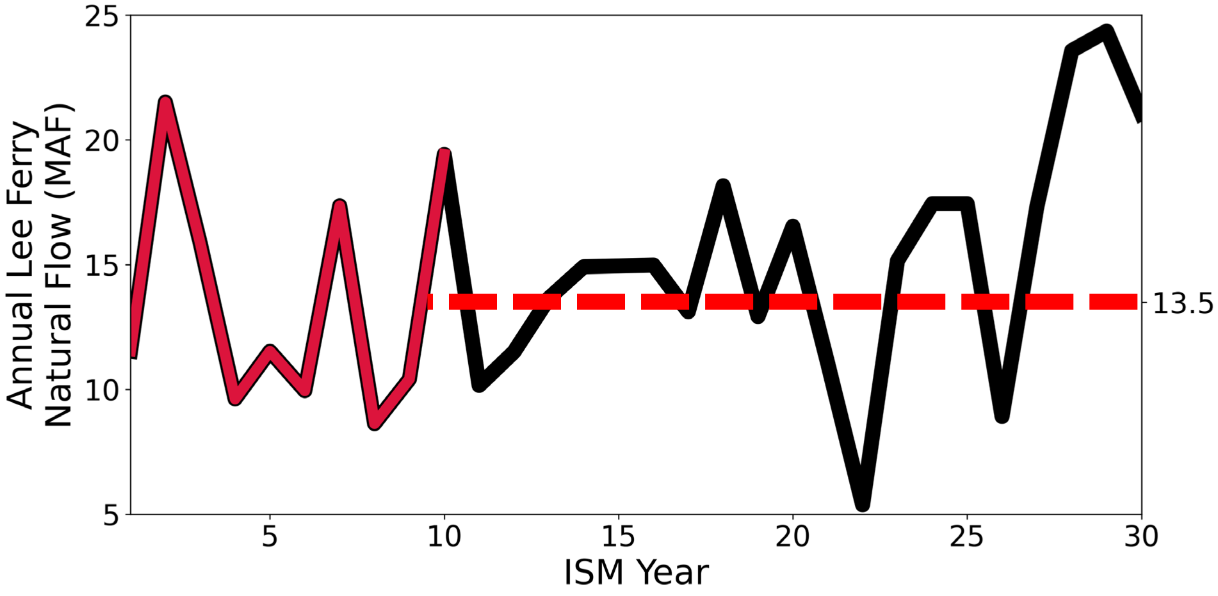
- Measuring minimum flow
- Measuring maximum flow
- Measuring median flow
- Measuring first:
  - 2 year average flow
  - 5 year average flow



Measures flow in the period when conditions are influenced by initial reservoir storage

Streamflow Metrics: Initial Conditions

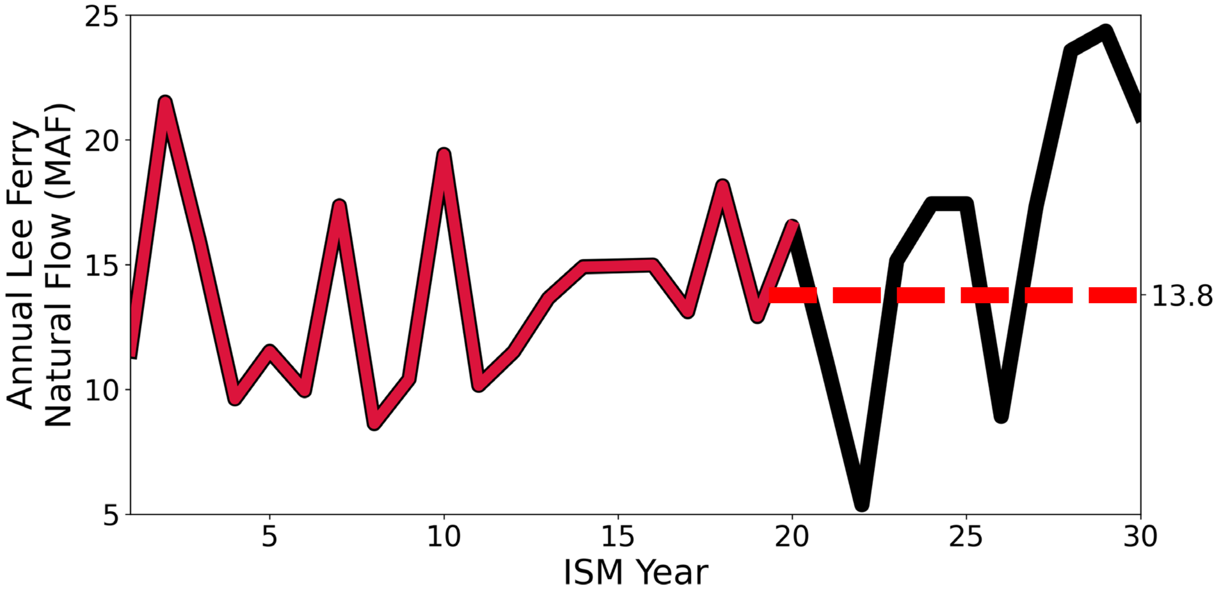
- Measuring minimum flow
- Measuring maximum flow
- Measuring median flow
- Measuring first:
    - 2 year average flow
    - 5 year average flow
    - 10 year average flow



Measures flow in the period when conditions are influenced by initial reservoir storage

Streamflow Metrics: Initial Conditions

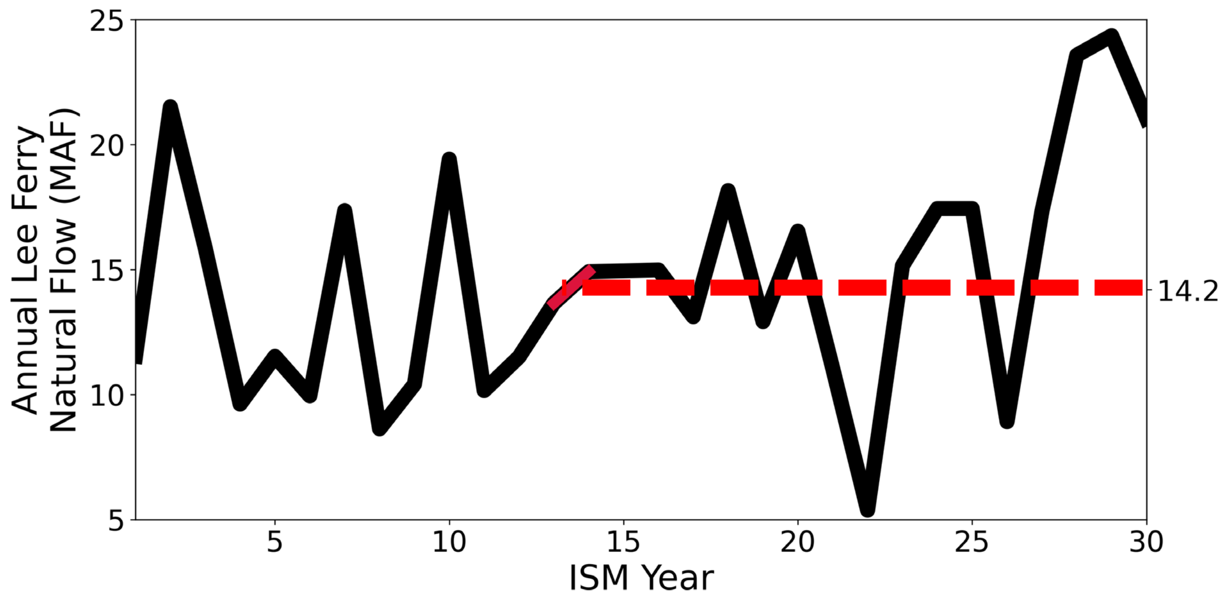
- Measuring minimum flow
- Measuring maximum flow
- Measuring median flow
- Measuring first:
  - 2 year average flow
  - 5 year average flow
  - 10 year average flow
  - 20 year average flow



Measures flow in the period when conditions are influenced by initial reservoir storage

Streamflow Metrics: Median Conditions

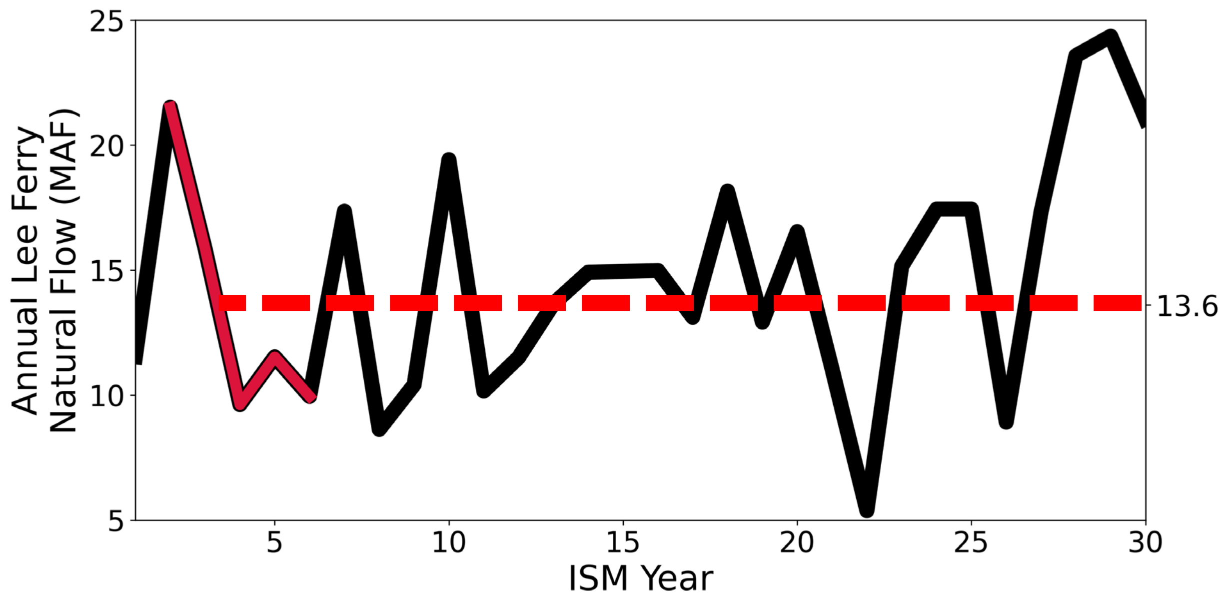
- Measuring minimum flow
- Measuring maximum flow
- Measuring first
- Measuring median flow:
  - 2 year rolling window



Measures a middle value between wet and dry flows

Streamflow Metrics: Median Conditions

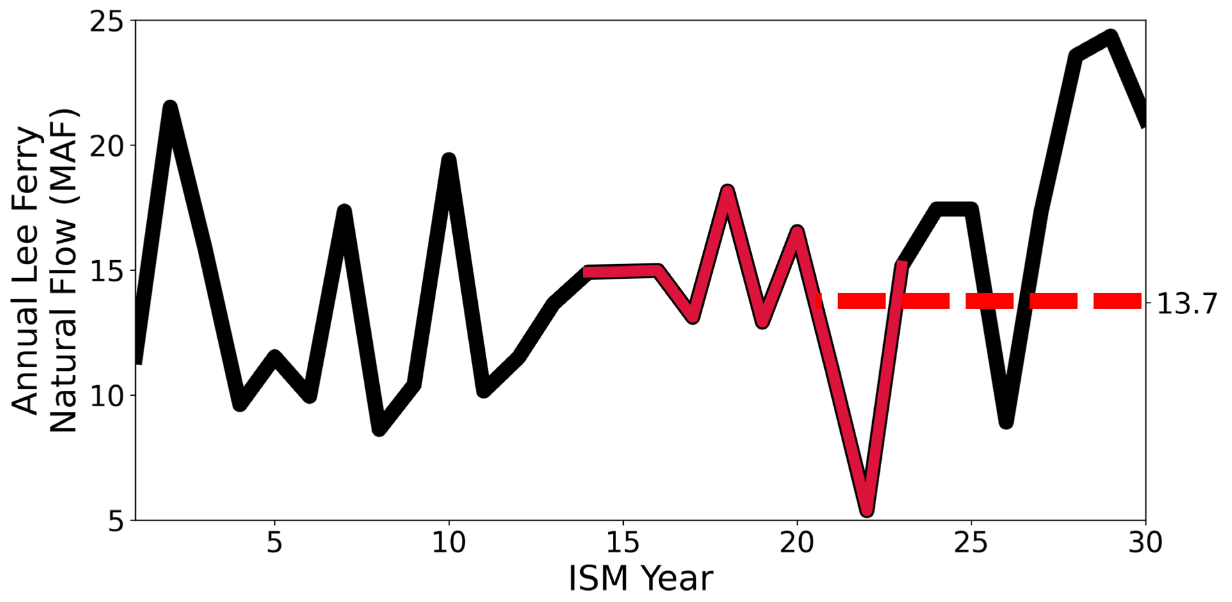
- Measuring minimum flow
- Measuring maximum flow
- Measuring first
- Measuring median flow:
  - 2 year rolling window
  - 5 year rolling window



Measures a middle value between wet and dry flows

Streamflow Metrics: Median Conditions

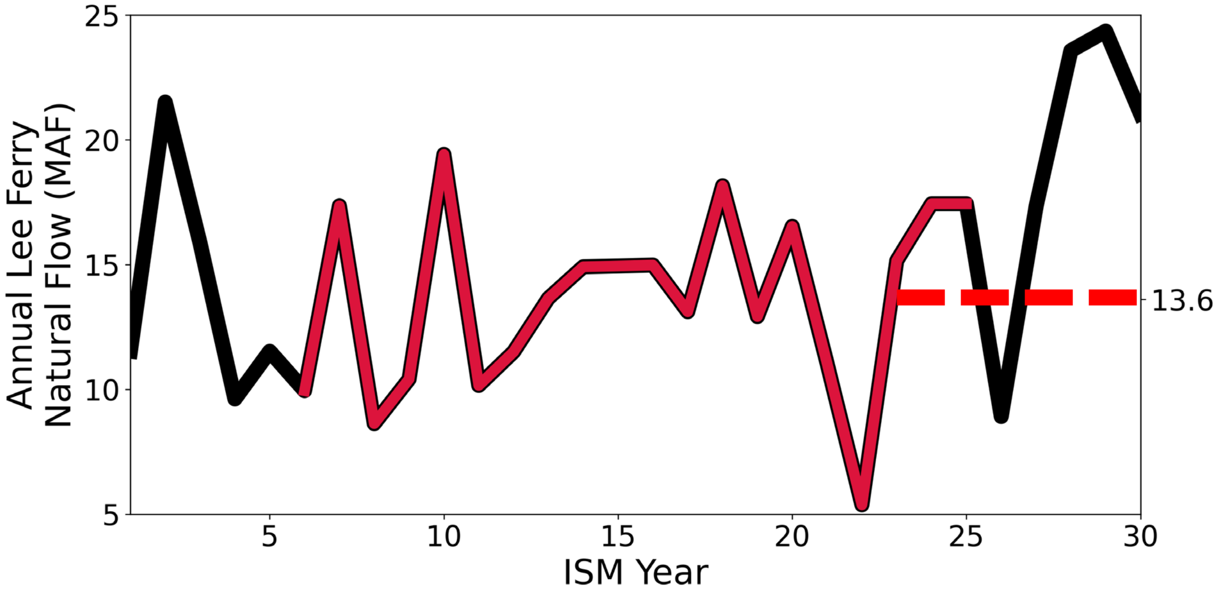
- Measuring minimum flow
- Measuring maximum flow
- Measuring first
- Measuring median flow:
  - 2 year rolling window
  - 5 year rolling window
  - 10 year rolling window



Measures a middle value between wet and dry flows

Streamflow Metrics: Median Conditions

- Measuring minimum flow
- Measuring maximum flow
- Measuring first
- Measuring median flow:
  - 2 year rolling window
  - 5 year rolling window
  - 10 year rolling window
  - 20 year rolling window

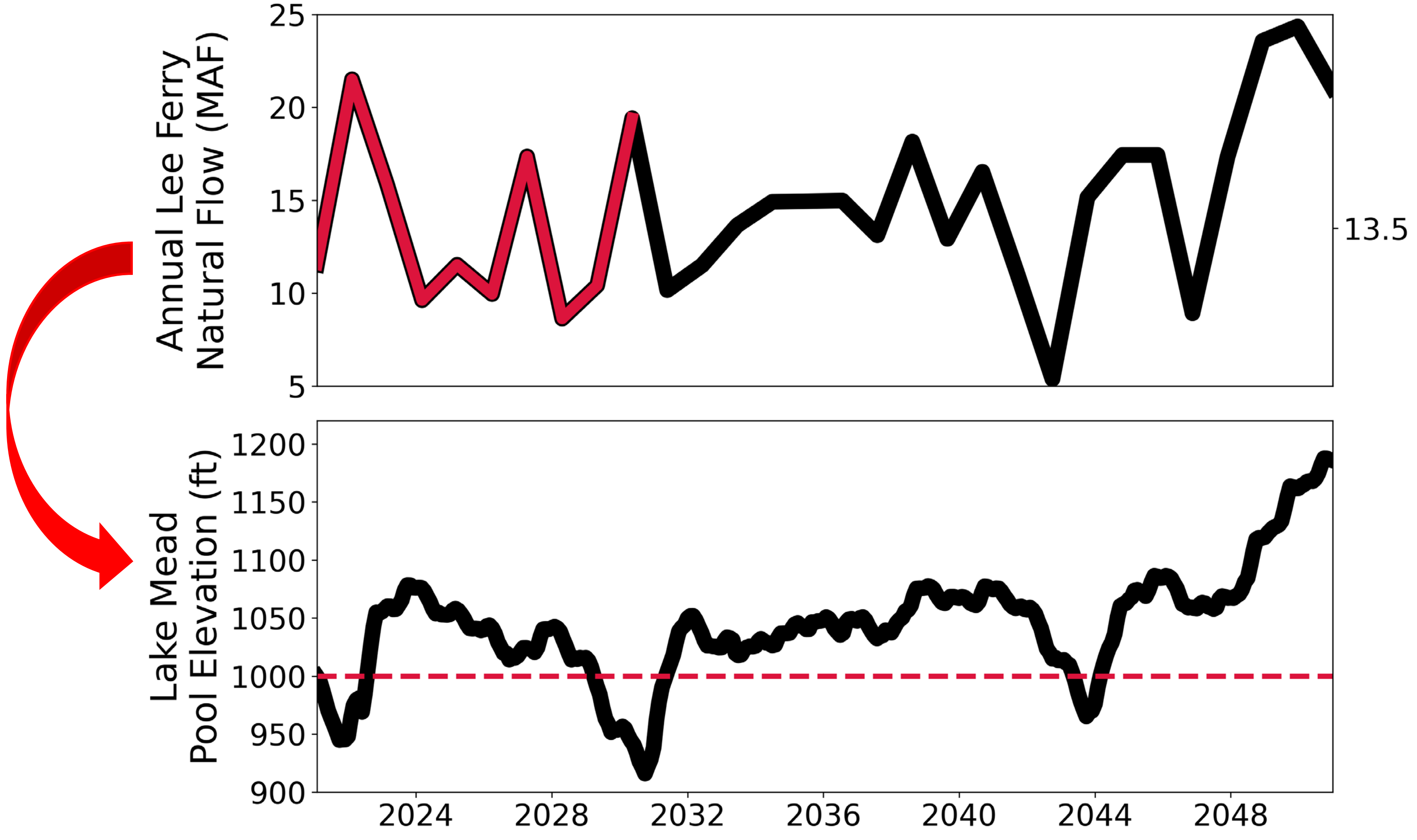


Measures a middle value between wet and dry flows

How Do Streamflow Metrics Relate to System Conditions?

- CRSS translates hydrology ensembles into metrics that are important to stakeholders in the basin

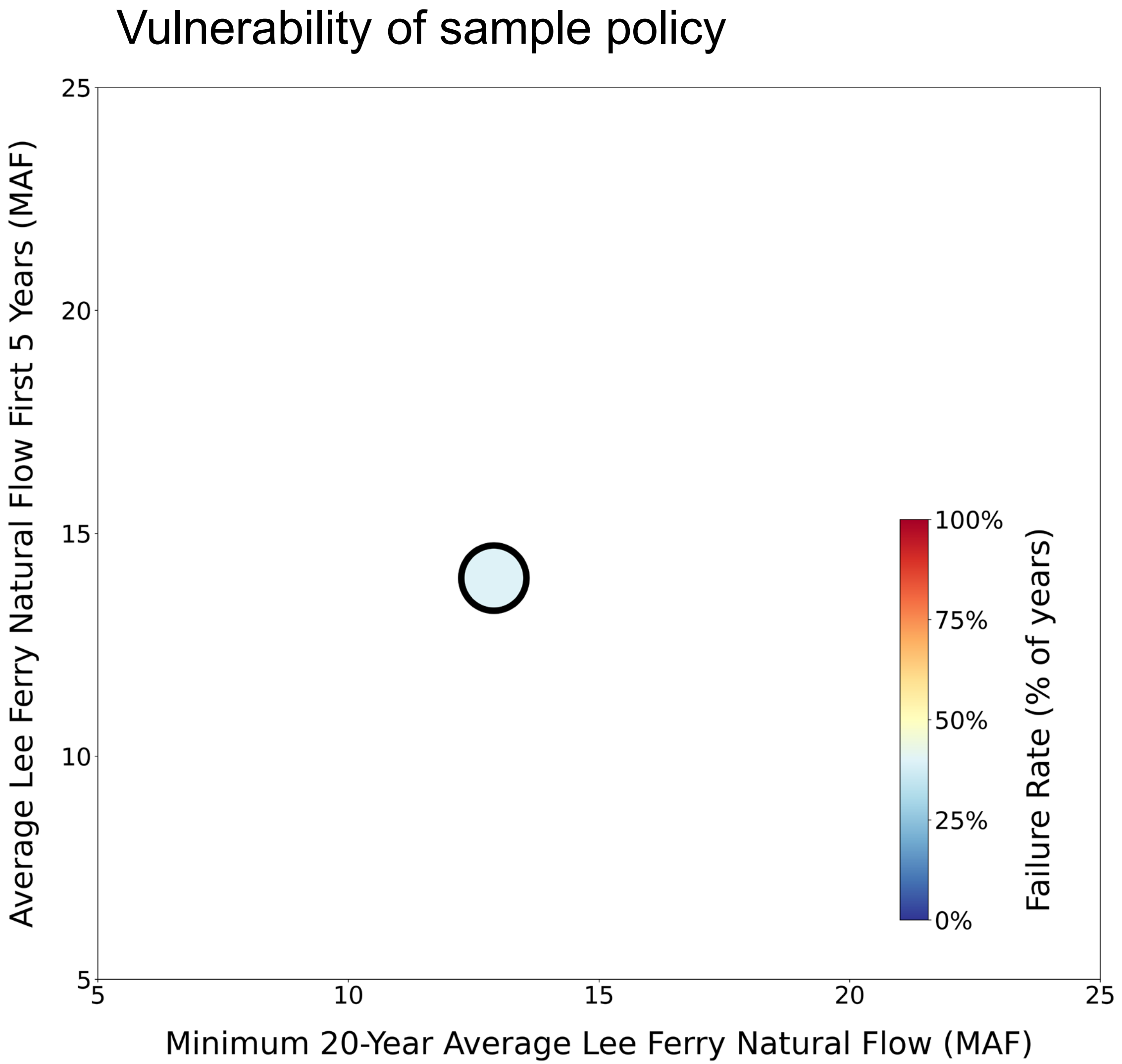
- What is the frequency of undesirable conditions? How does that relate to streamflow metrics?



How Do Streamflow Metrics Relate to System Conditions?

- By themselves, streamflow metrics don't tell us much about a hydrology ensemble

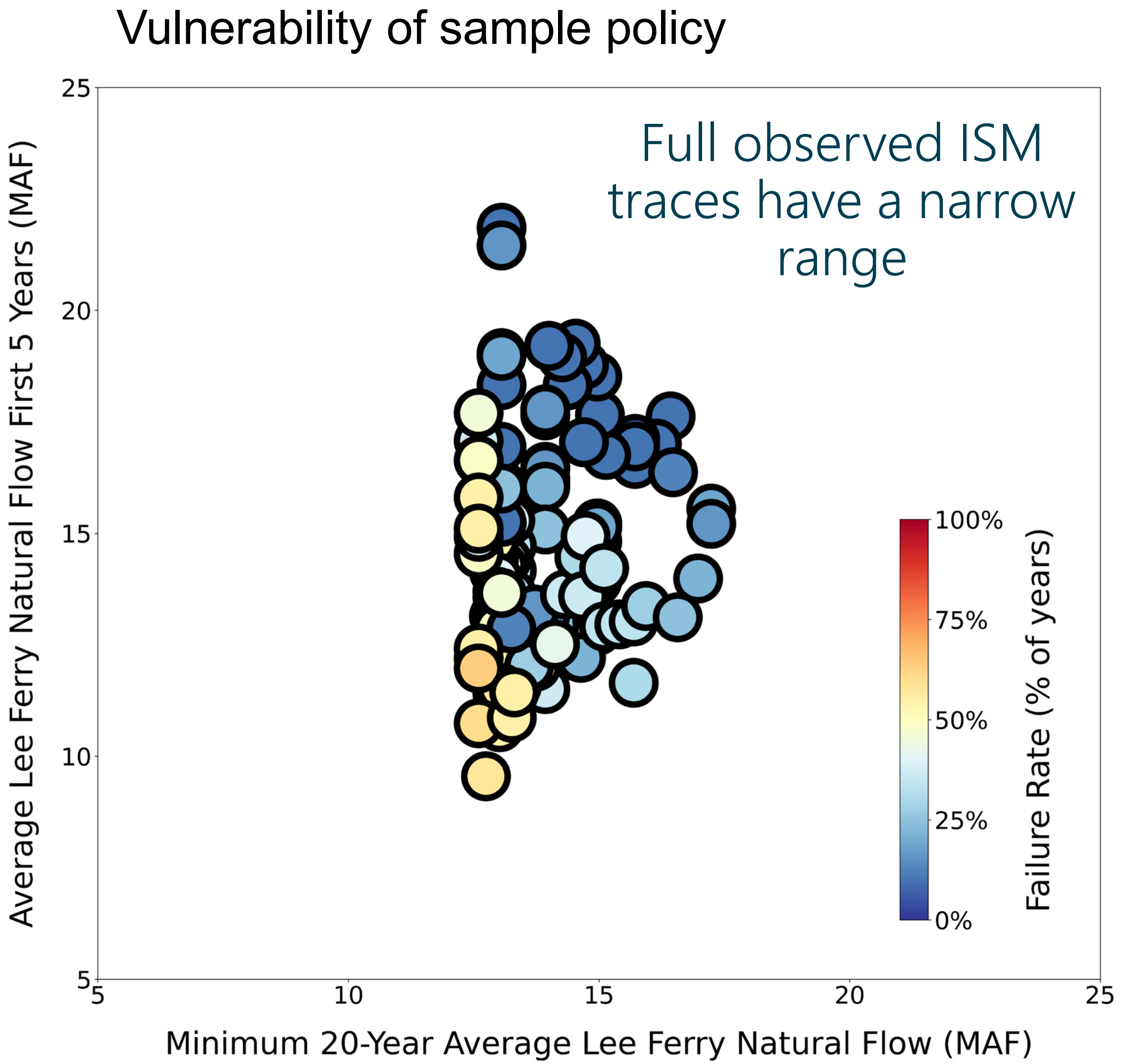
- Combining metrics together can help us make a 'map' of vulnerability



How Do Streamflow Metrics Relate to System Conditions?

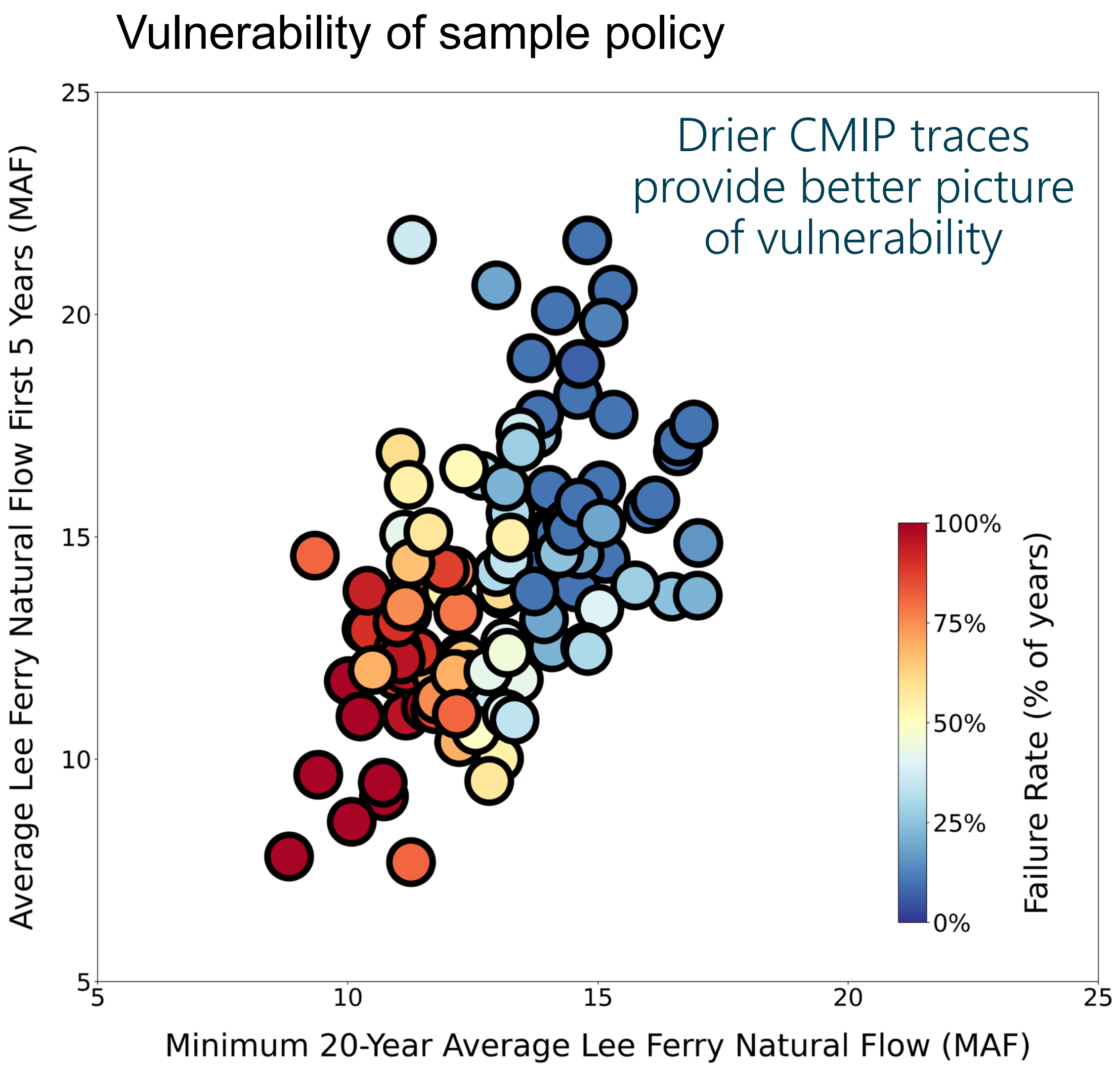
- By themselves, streamflow metrics don't tell us much about a hydrology ensemble

- Combining metrics together can help us make a 'map' of vulnerability



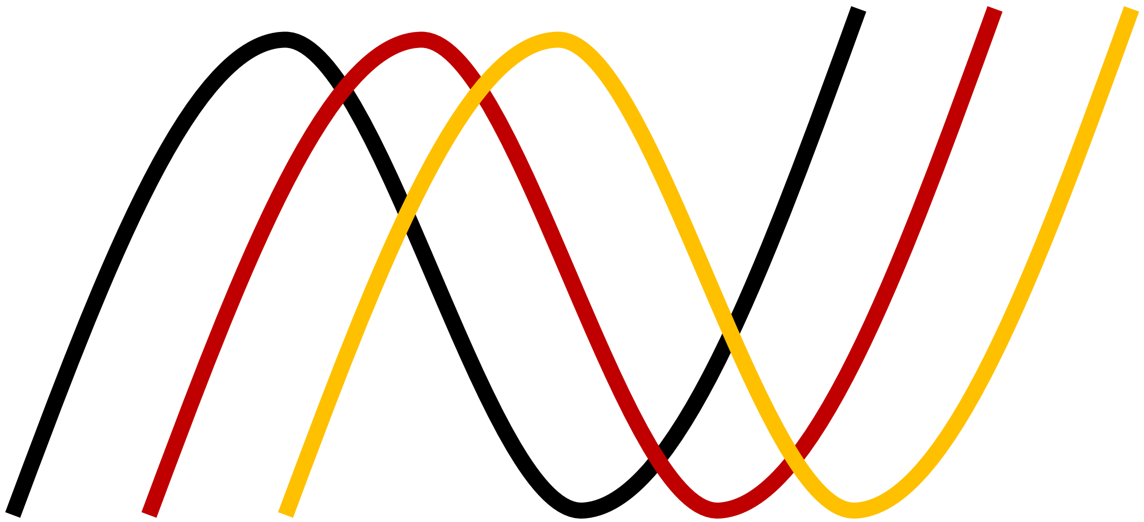
How Do Streamflow Metrics Relate to System Conditions?

- By themselves, streamflow metrics don't tell us much about a hydrology ensemble
- Combining metrics together can help us make a 'map' of vulnerability
- We want new ensembles to be able to expand the bounds of this map



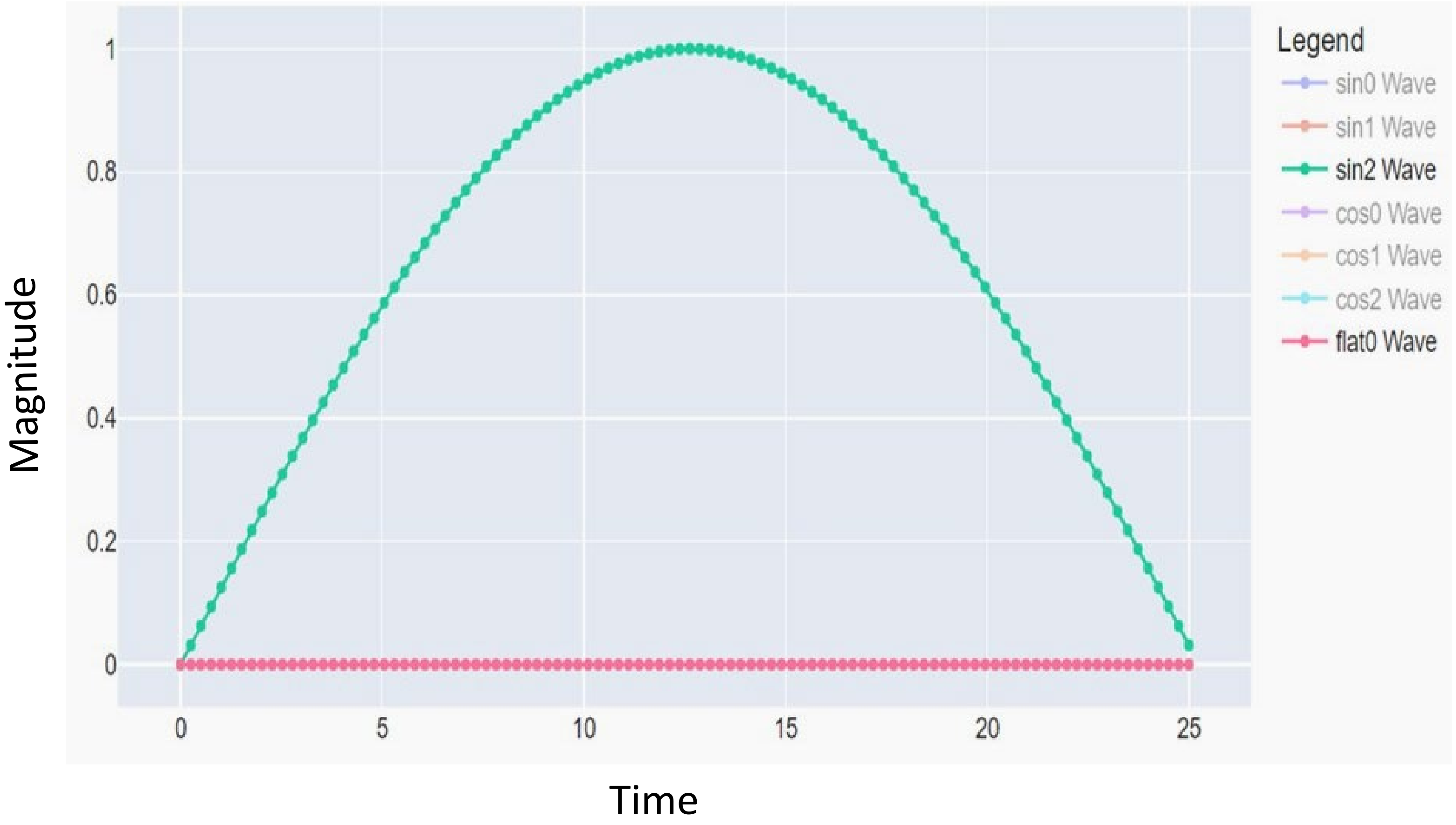
Streamflow Metrics Don't Measure Patterns

- Metrics measure average flows over defined periods
- Do not account for different patterns of wet and dry periods that test reservoir operation policies
- ISM methods repeat patterns by shifting timeseries
- How can we consider patterns when we evaluate vulnerability?

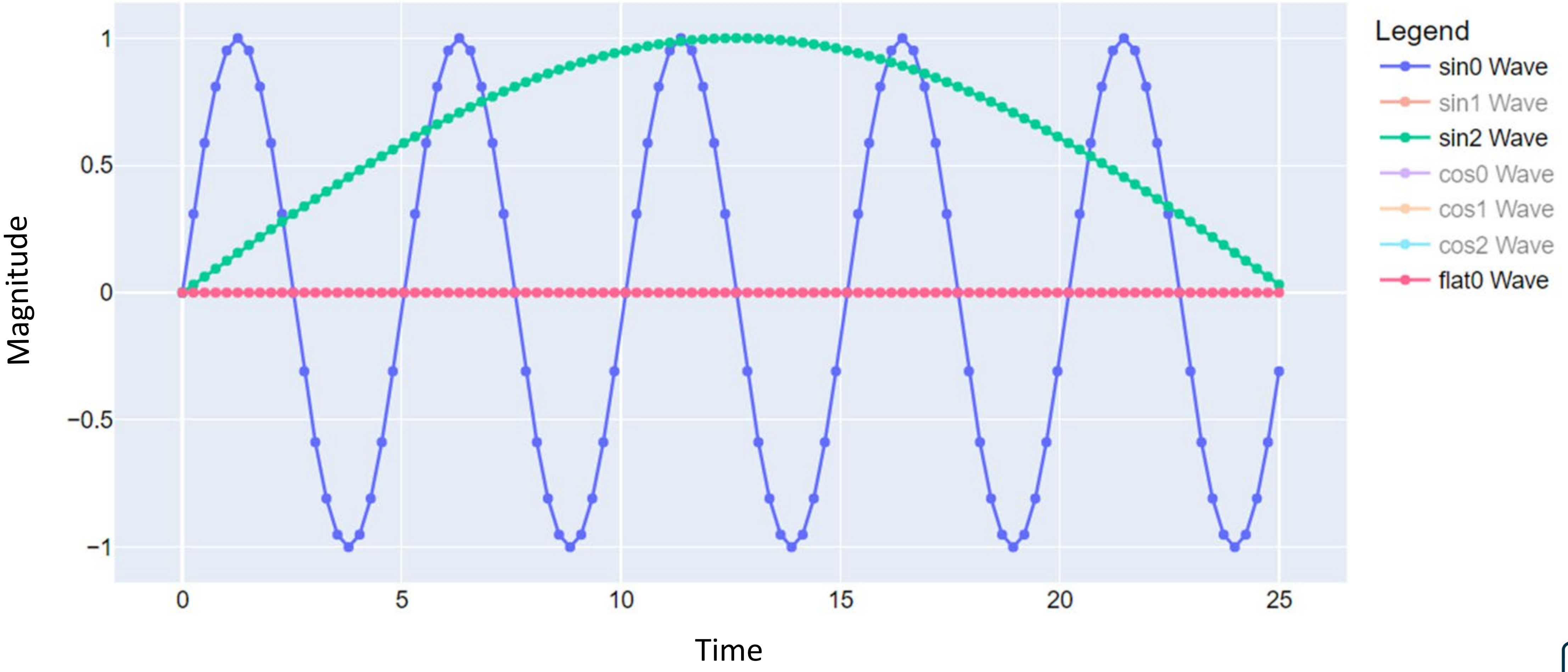


Time-series Patterns as Shapes: Simple Example

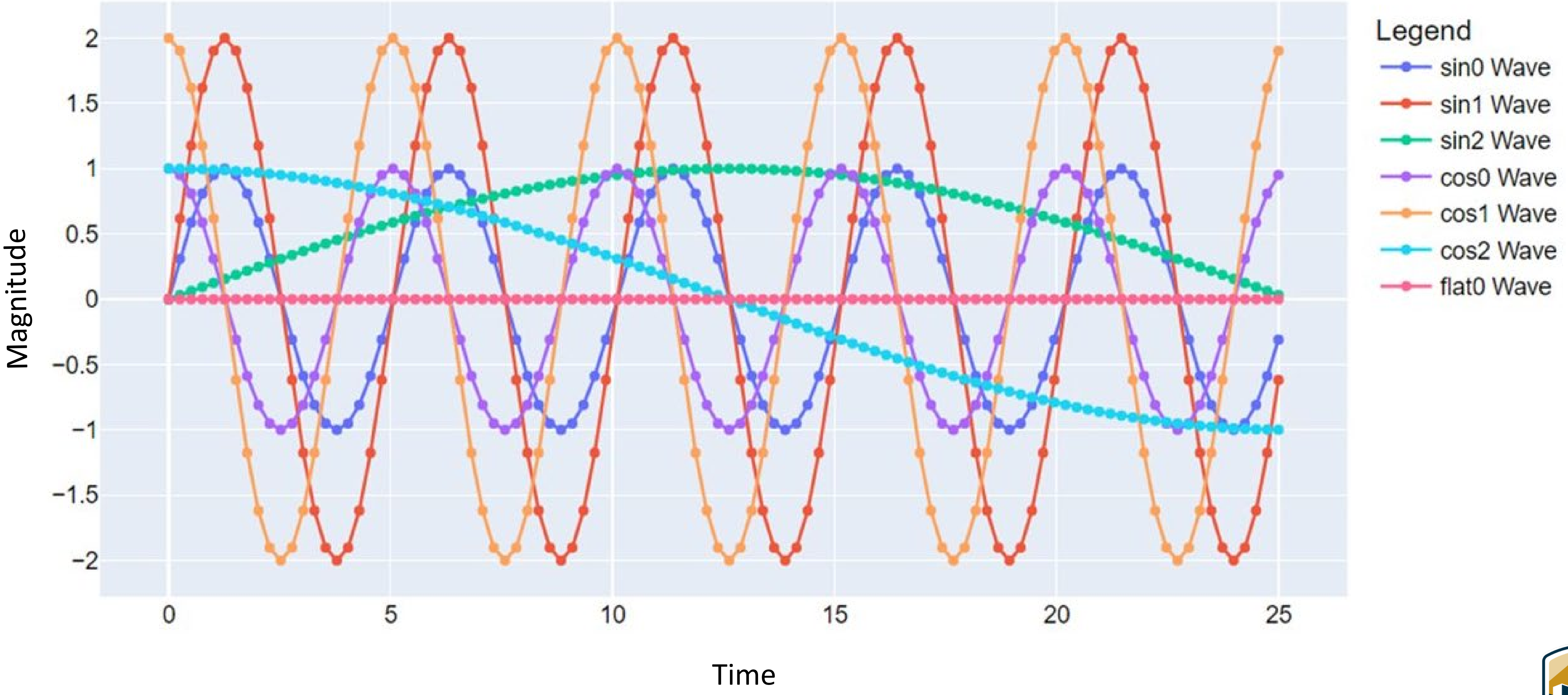
- Time-series are a sequence of data
- The sequence creates a shape
- Time-series with similar shapes have similar patterns



Adding More Time-Series



Ensembles Can Contain Many Patterns

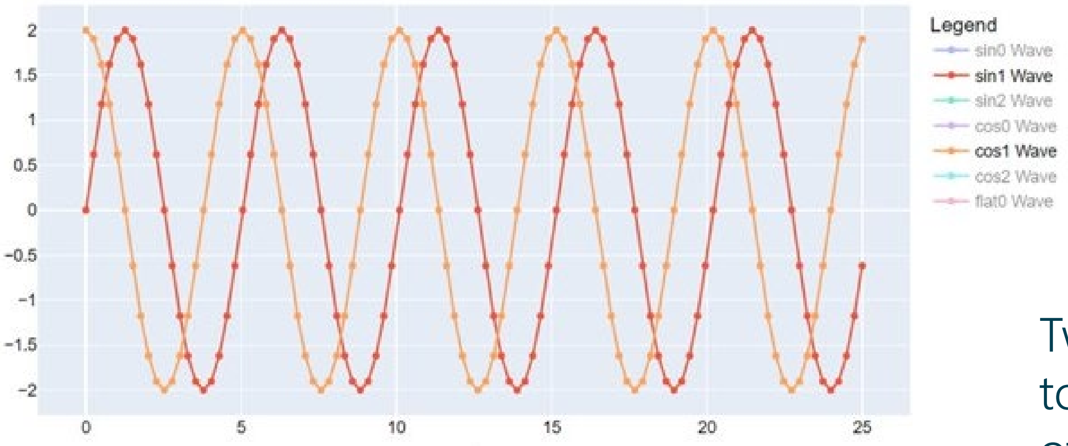


Discovering Unique Patterns in Ensembles

- There are many ensembles
- Every ensemble has some amount of unique patterns
- Ensembles may share or repeat similar unique patterns
- How to identify the unique patterns in all our ensembles?

Machine Learning : Clustering Time-Series Patterns

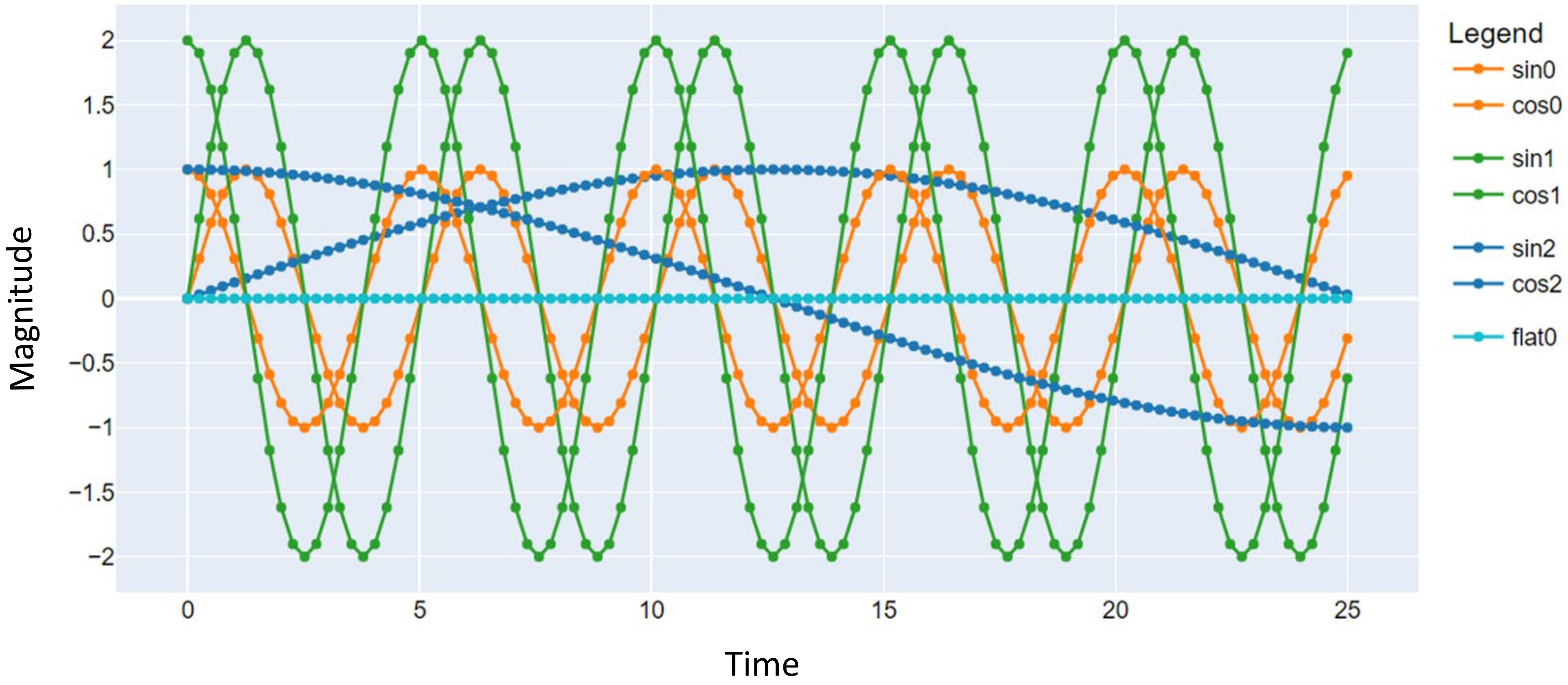
- Machine learning provides clustering algorithms
- Clustering algorithms[16] can group time-series based on patterns



Two time-series are clustered together in one group because of a similar pattern

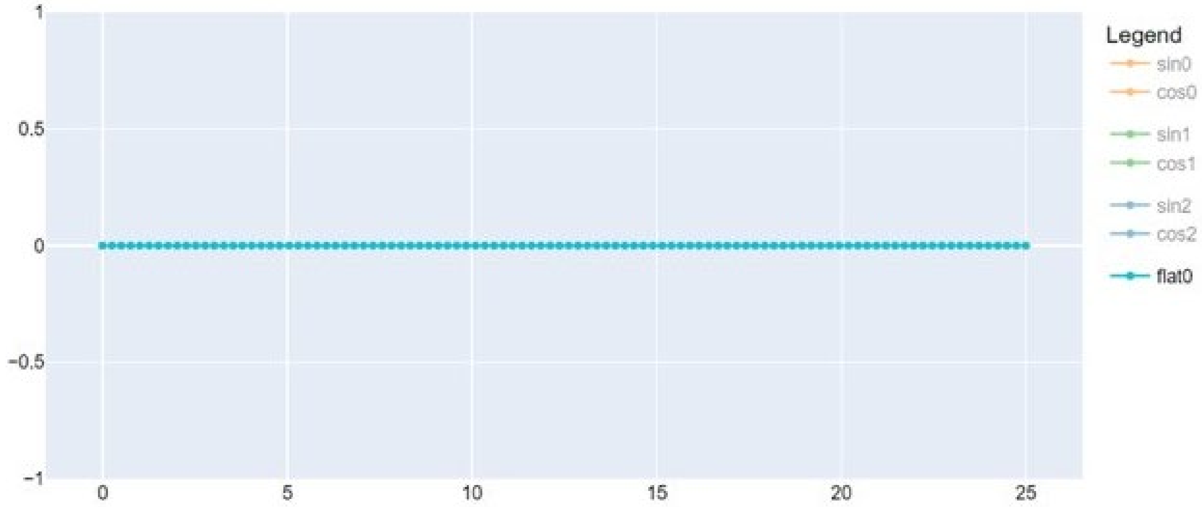
Clustering Applied to Our Simple Example

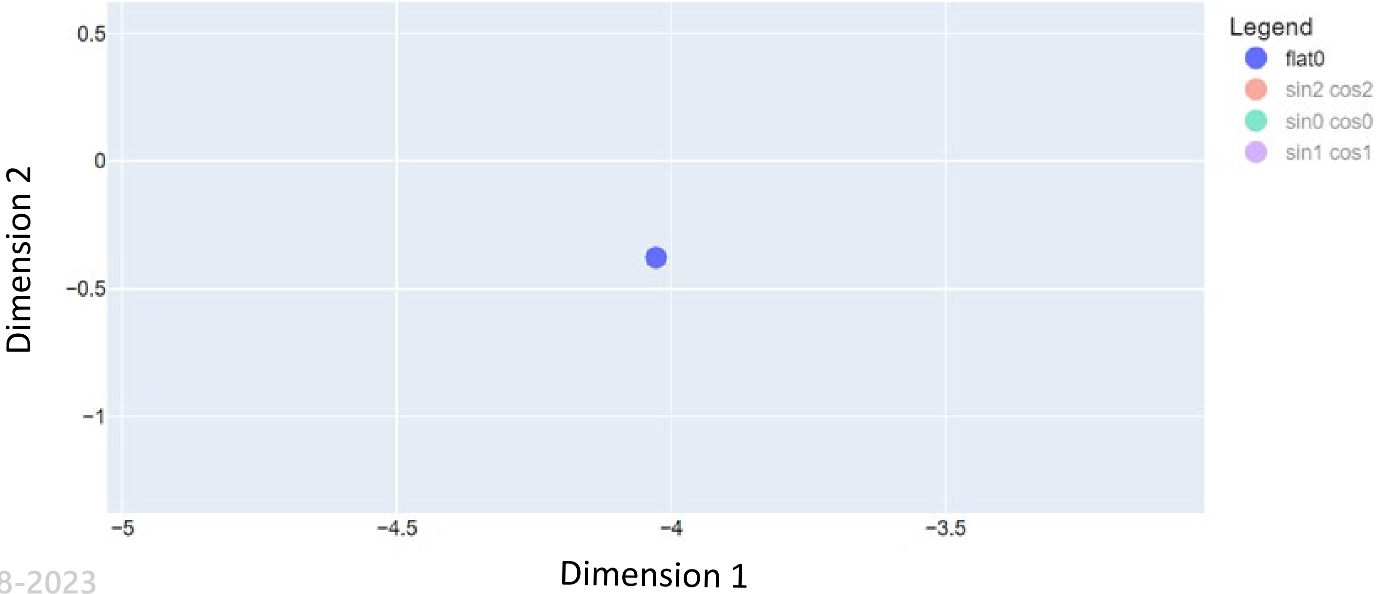
- Time-series with similar patterns are clustered together



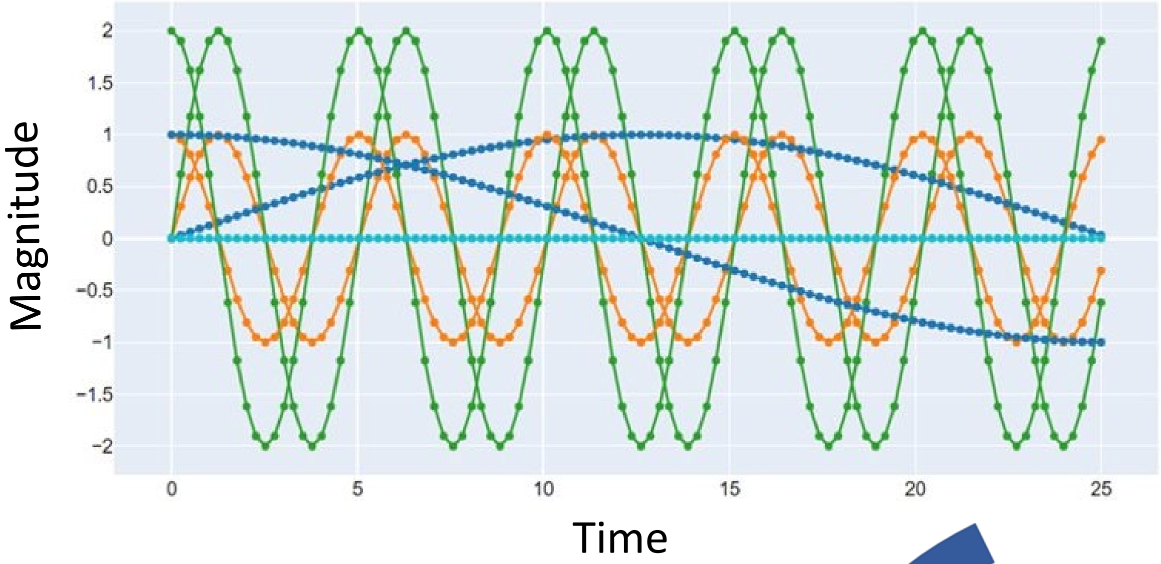
Visualizing Time-Series as Points

- Usually time-series are visualized as line graphs
- Embedding algorithms[17] allow us to visualize a time-series as a single point

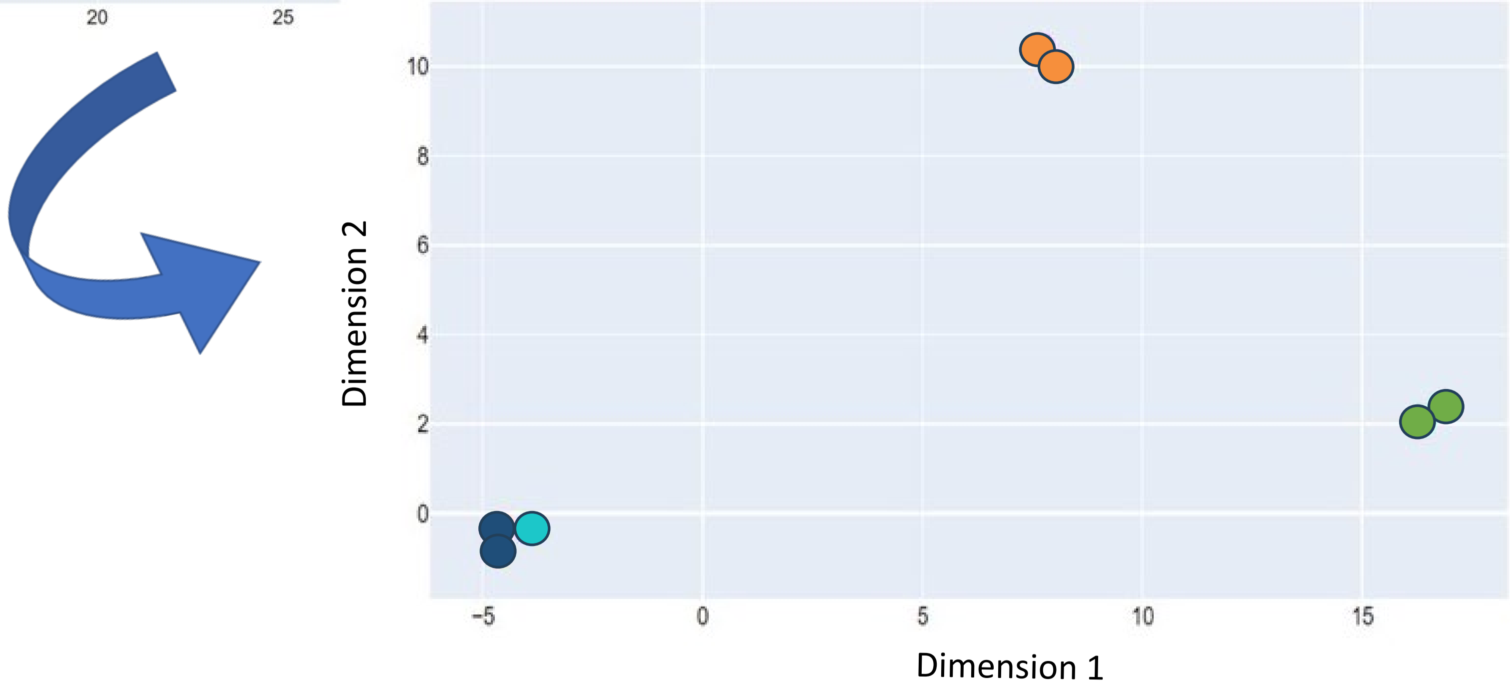




Visualizing Clusters from Our Simple Example

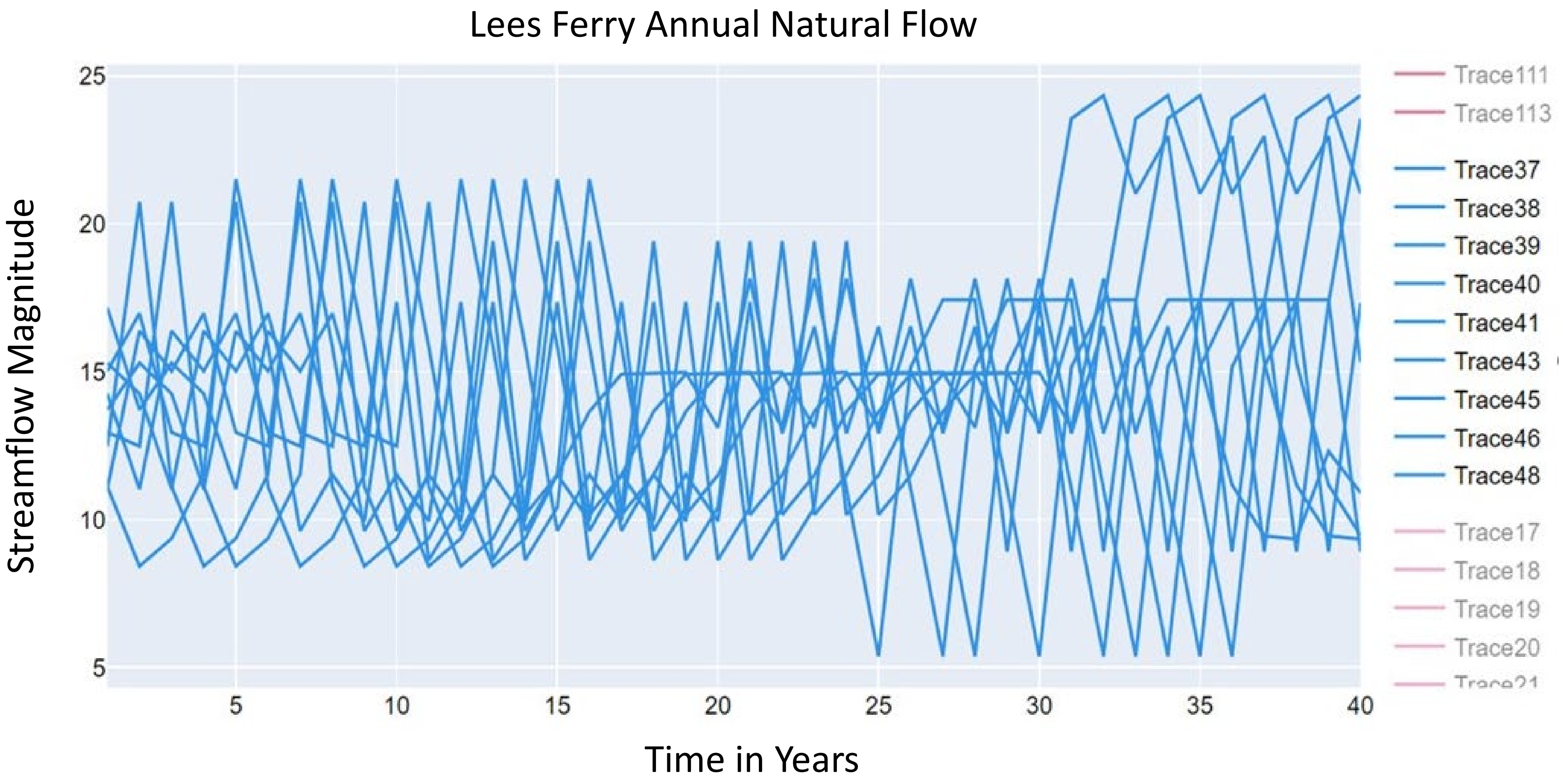


The clustering of time-series helps distinguish the uniqueness of the patterns

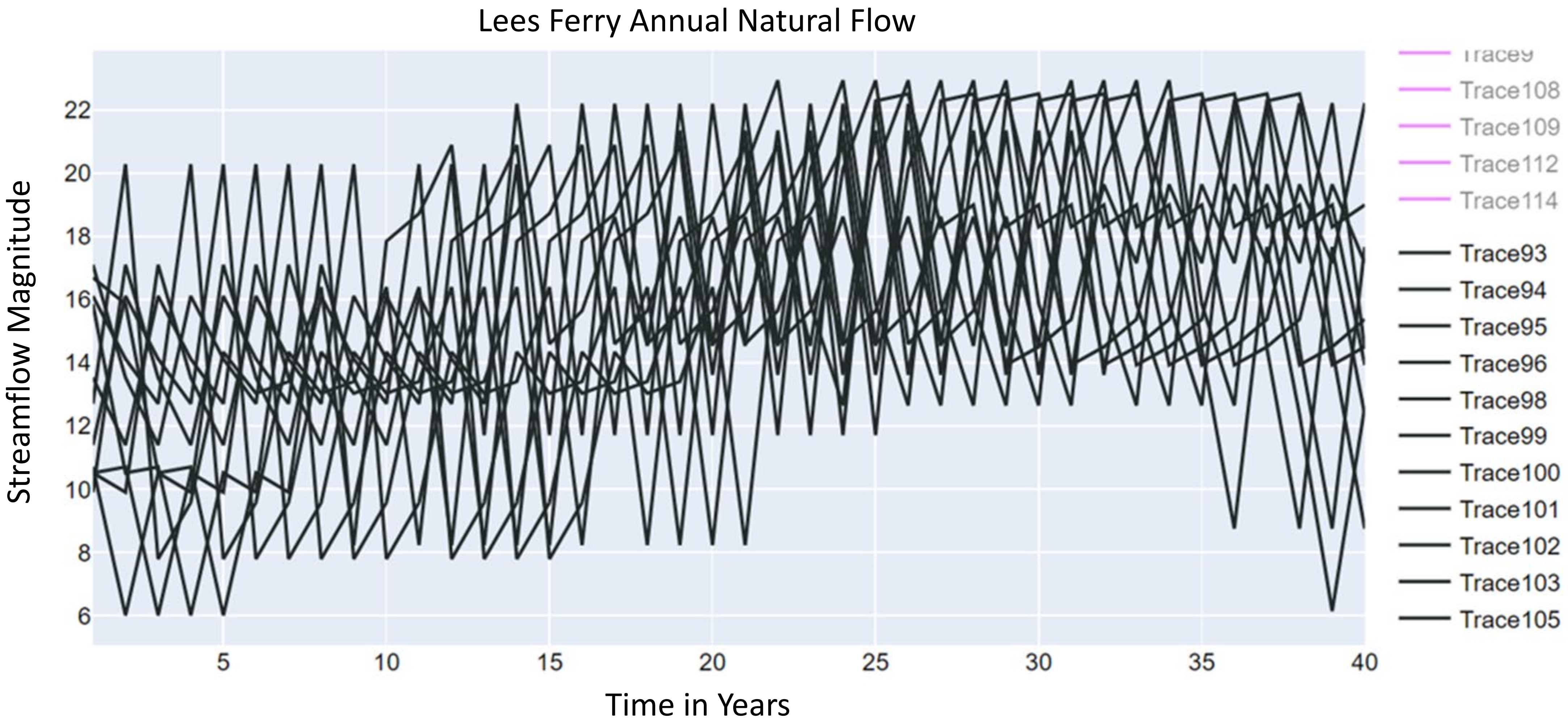


Clustering Observed Historical Full Ensemble

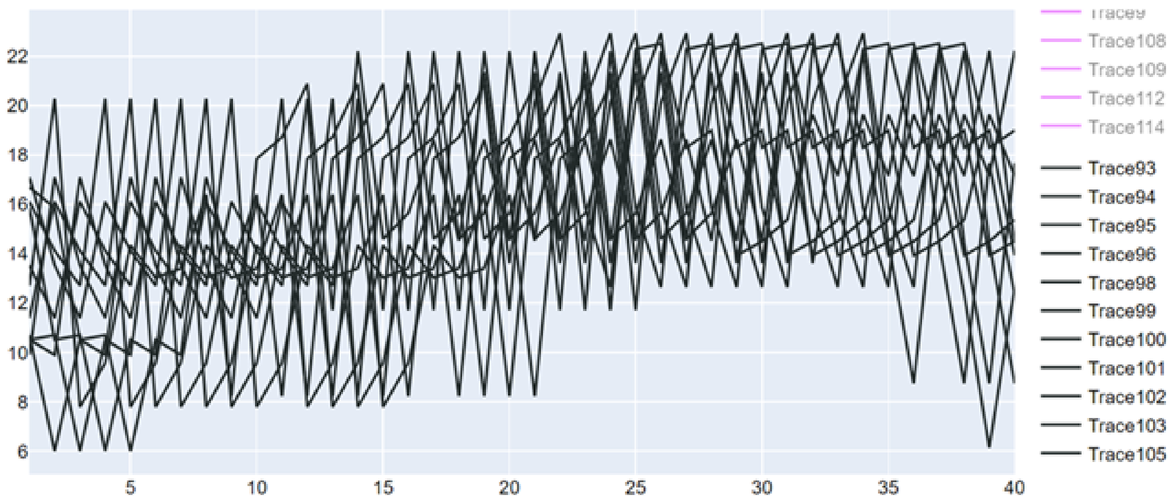
- Clustering can be applied to our Ensembles to discover groups of unique patterns



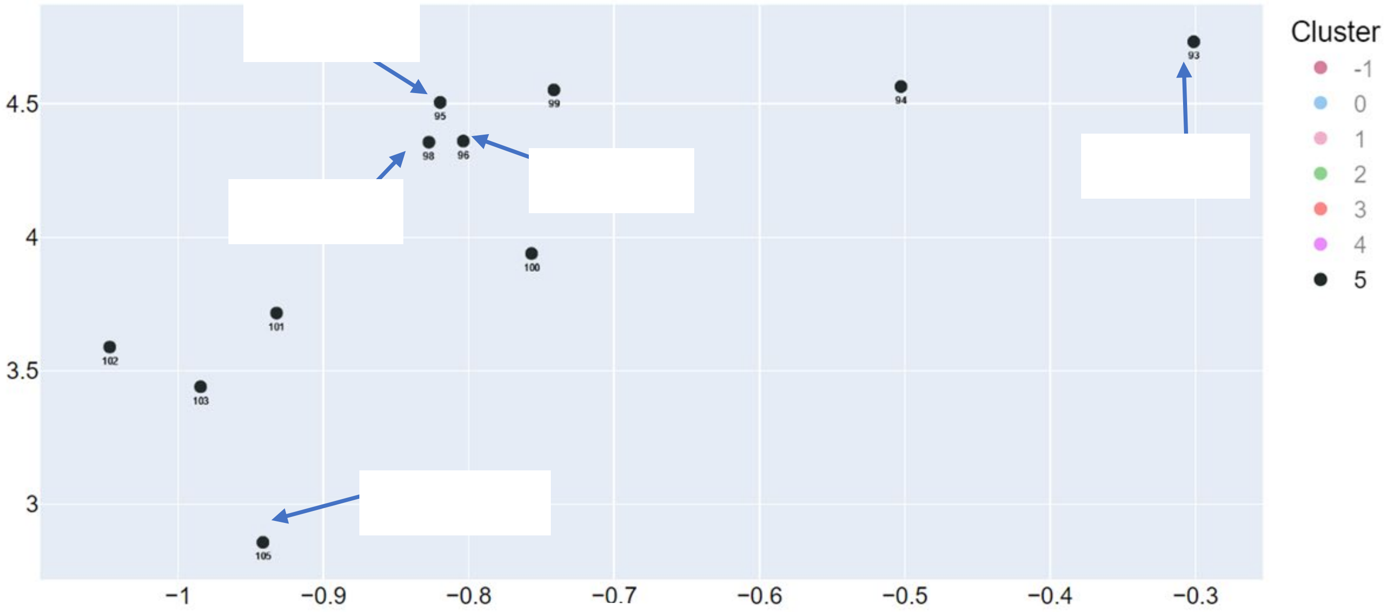
Another Cluster in Observed Historical Full Ensemble



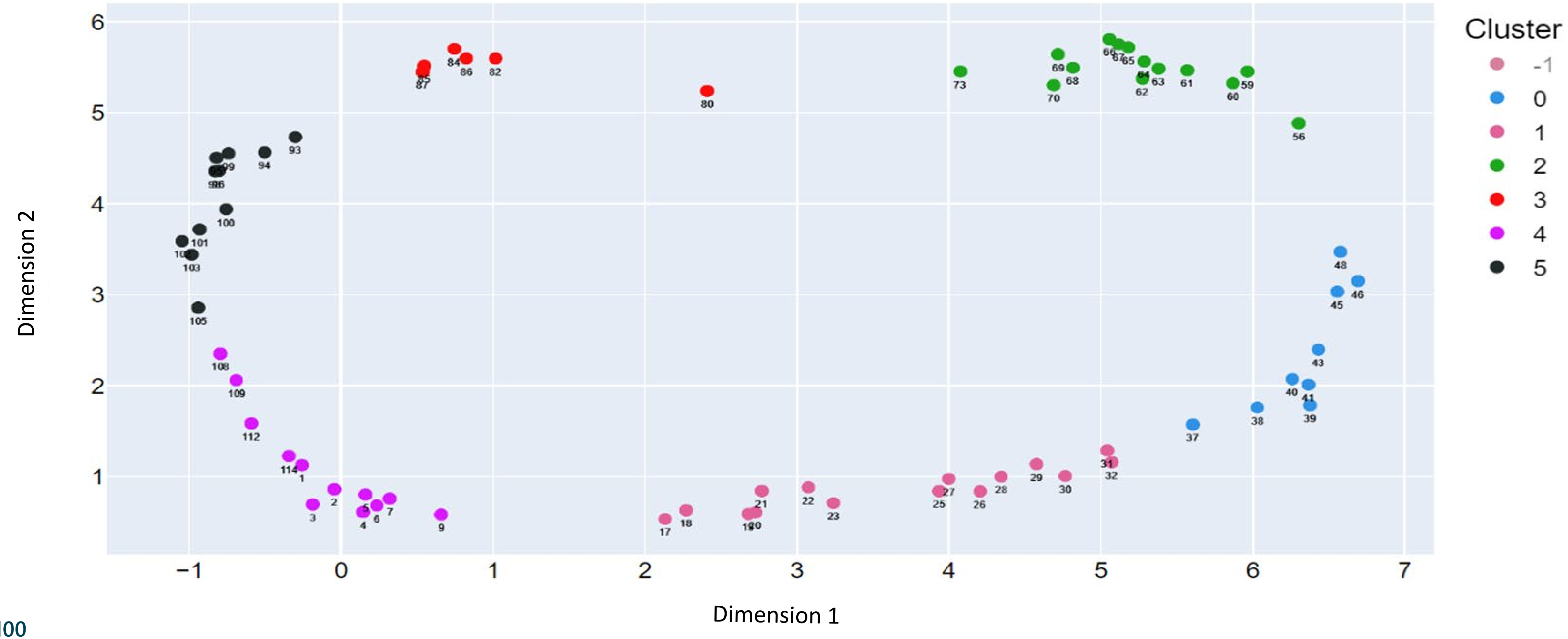
Embedding a Cluster from Observed Historical Full Ensemble



A single cluster containing many time-series of the same pattern can be embedded for visualization (notice very small axis)

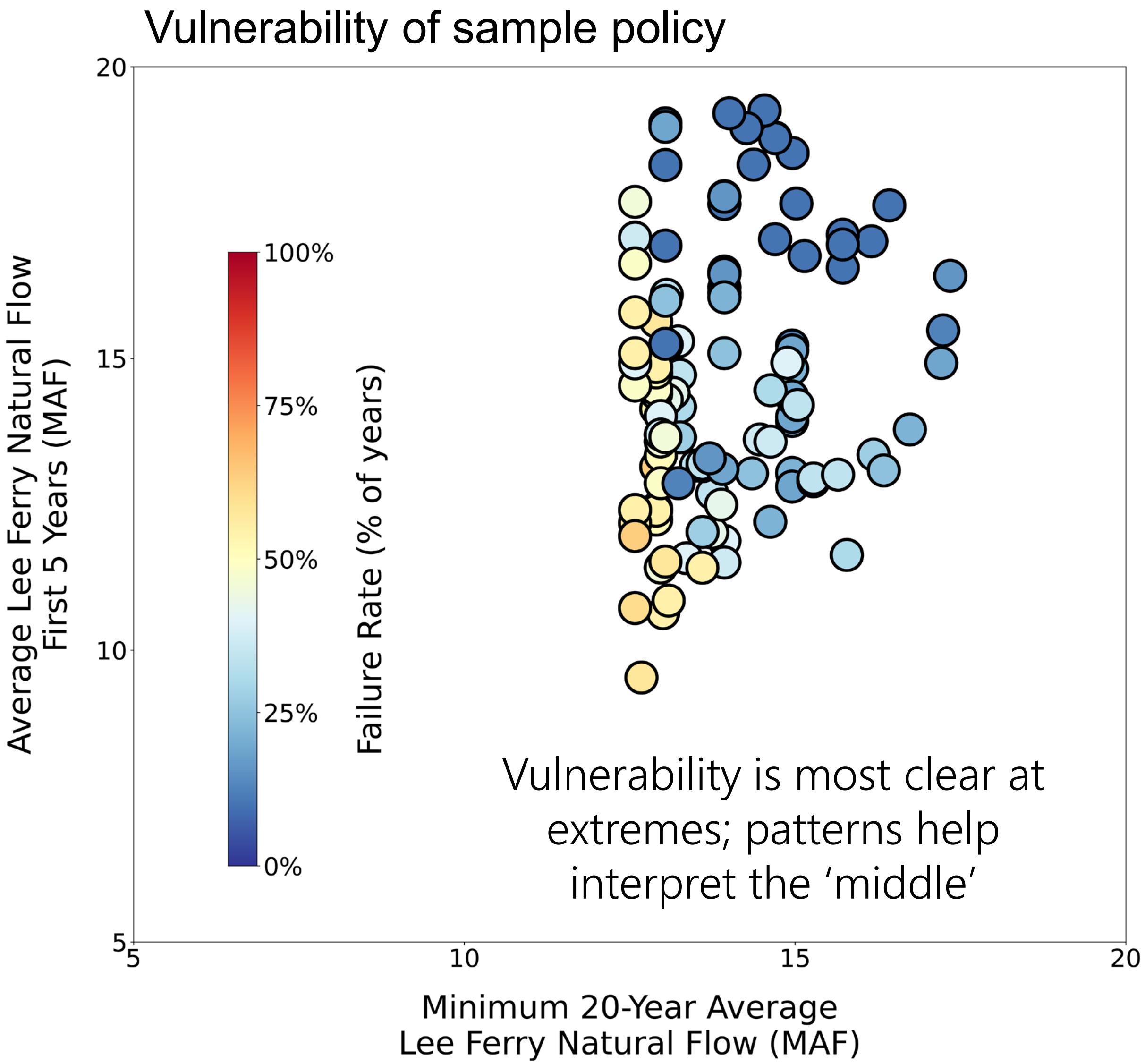


Embedding all Clusters from Observed Historical Full Ensemble



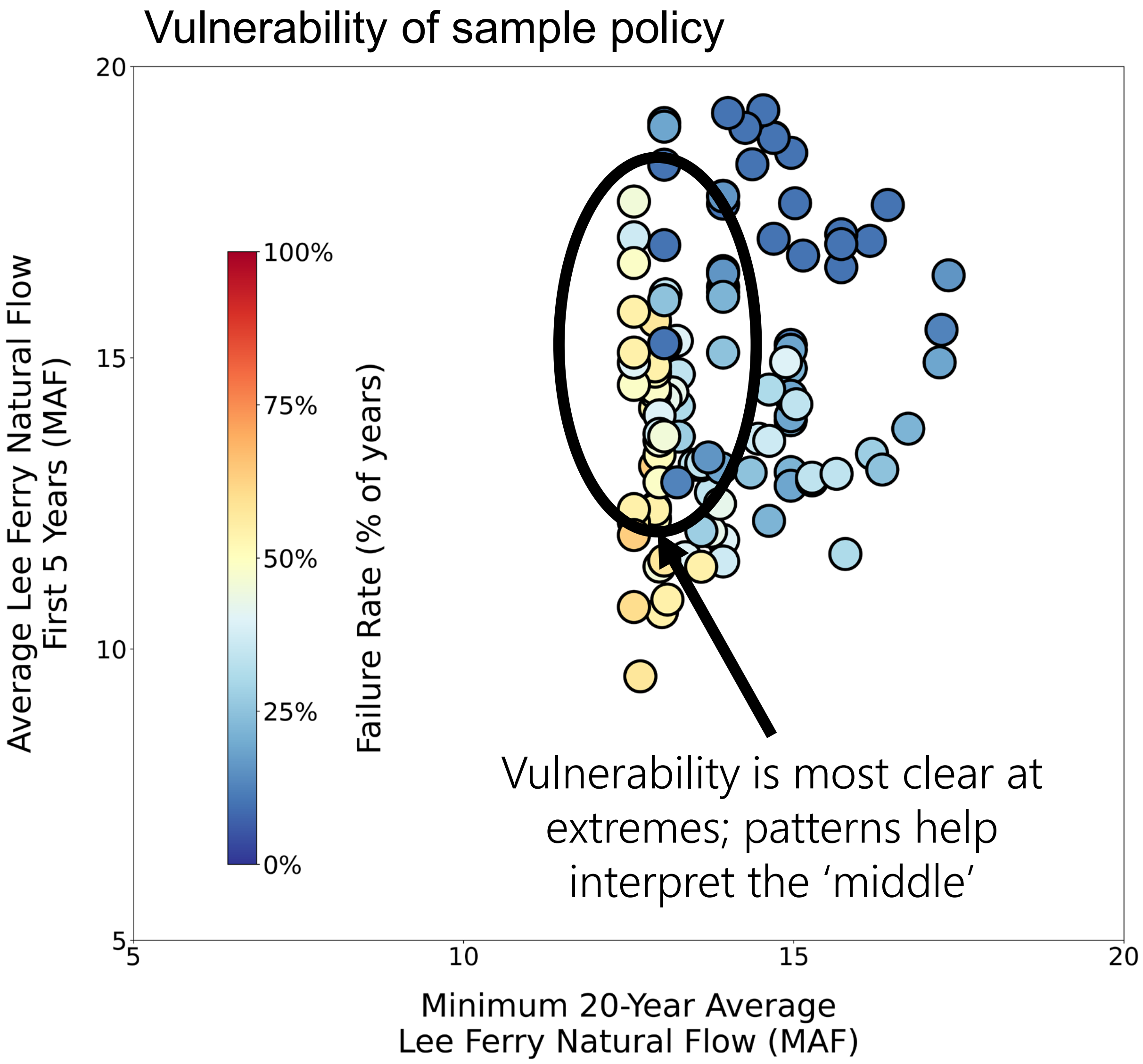
Relating Streamflow Patterns and Vulnerabilities

- Traces with similar streamflow metrics but different patterns may cause different performance



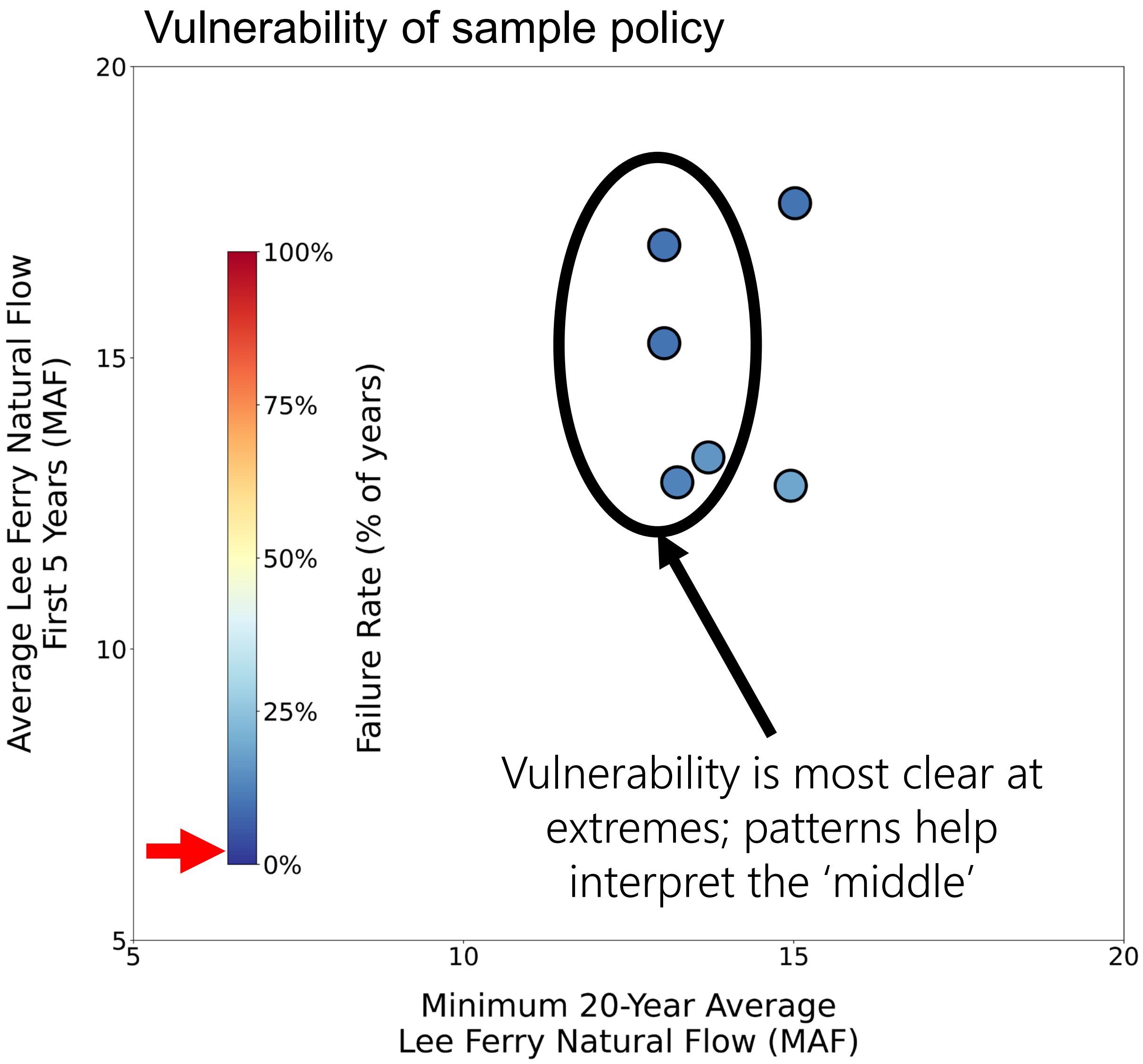
Relating Streamflow Patterns and Vulnerabilities

- Traces with similar streamflow metrics but different patterns may cause different performance



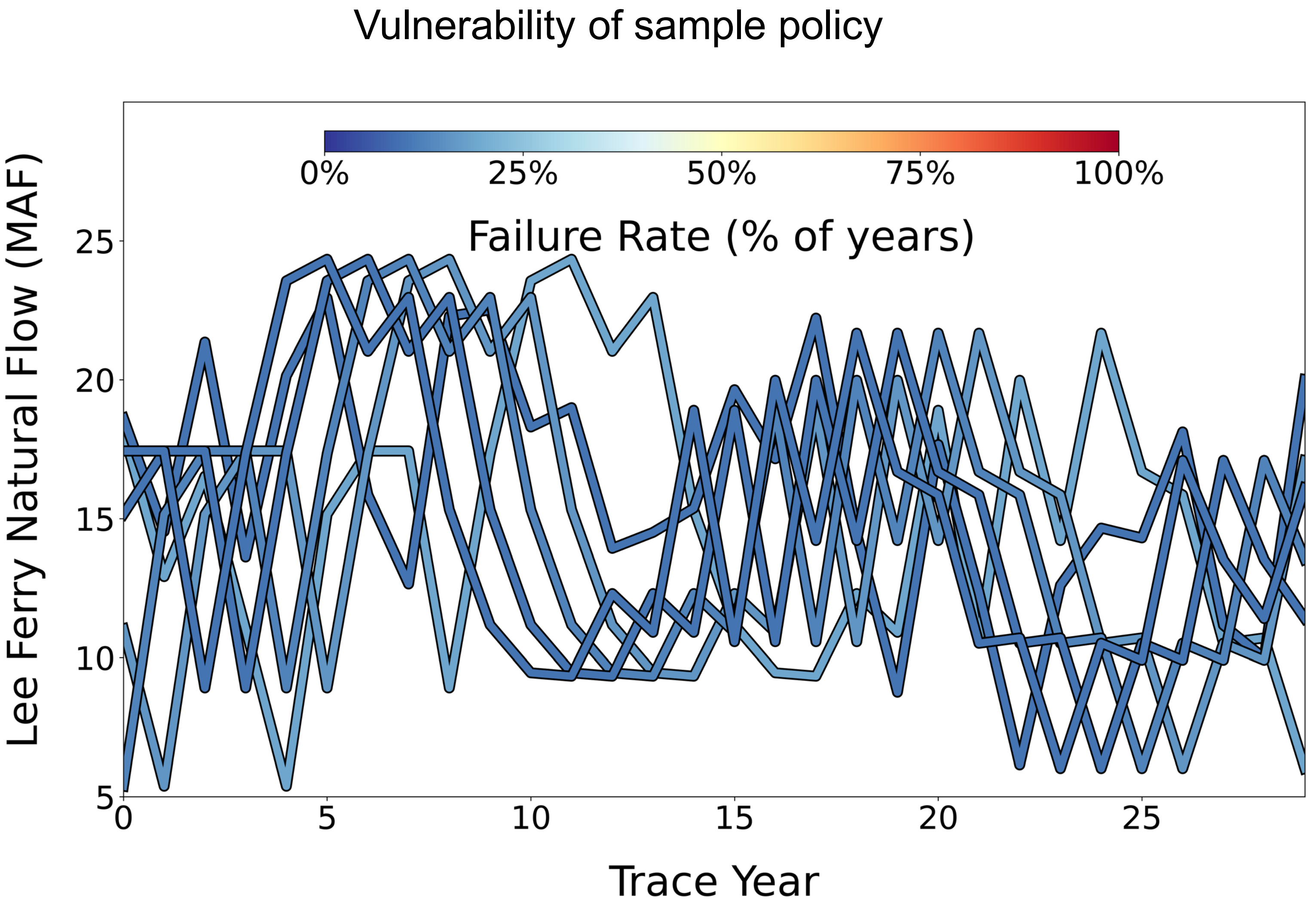
Relating Streamflow Patterns and Vulnerabilities

- Traces with similar streamflow metrics but different patterns may cause different performance



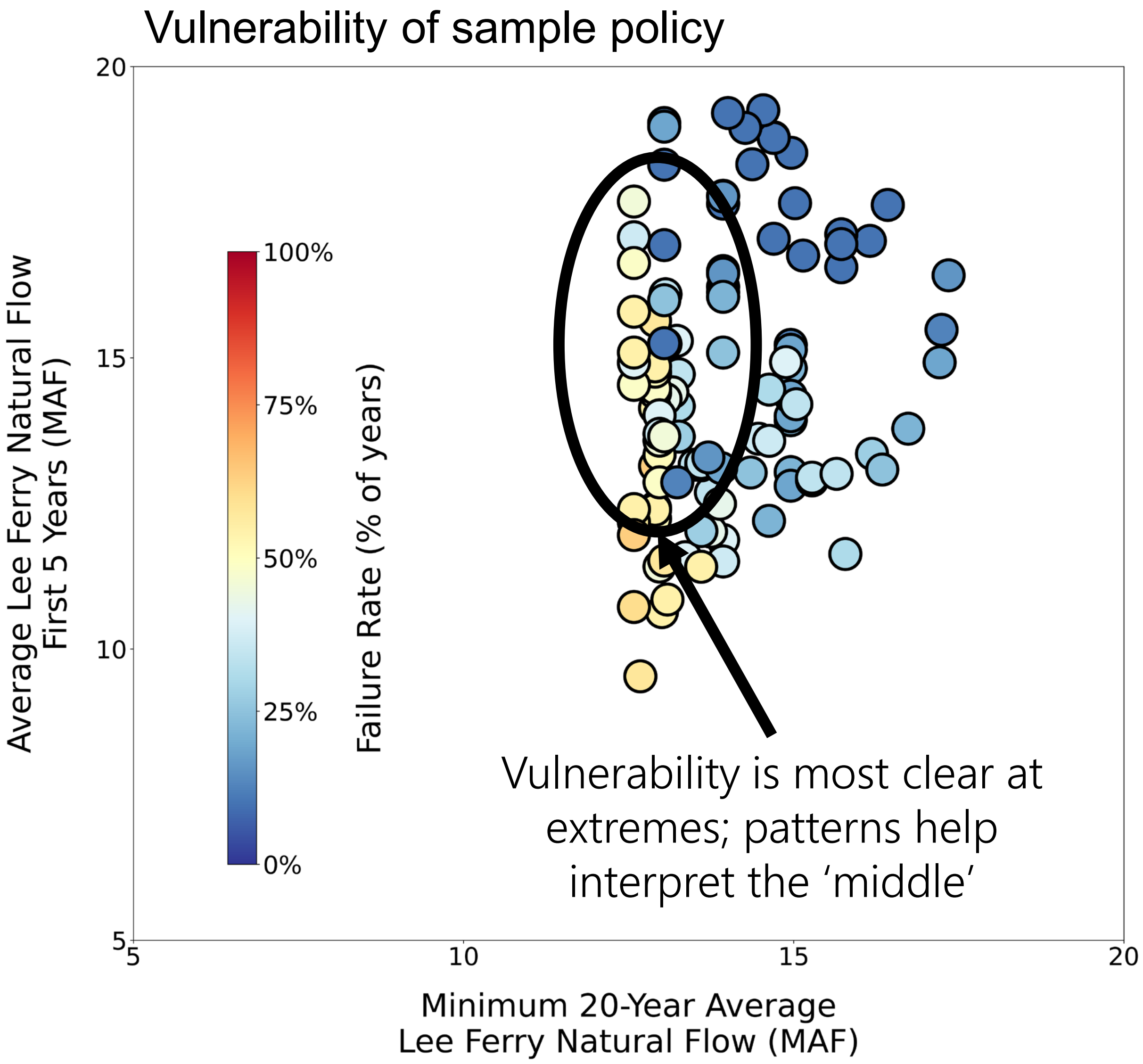
Relating Streamflow Patterns and Vulnerabilities

One group of streamflow patterns identified resulted in almost no years with undesirable outcomes



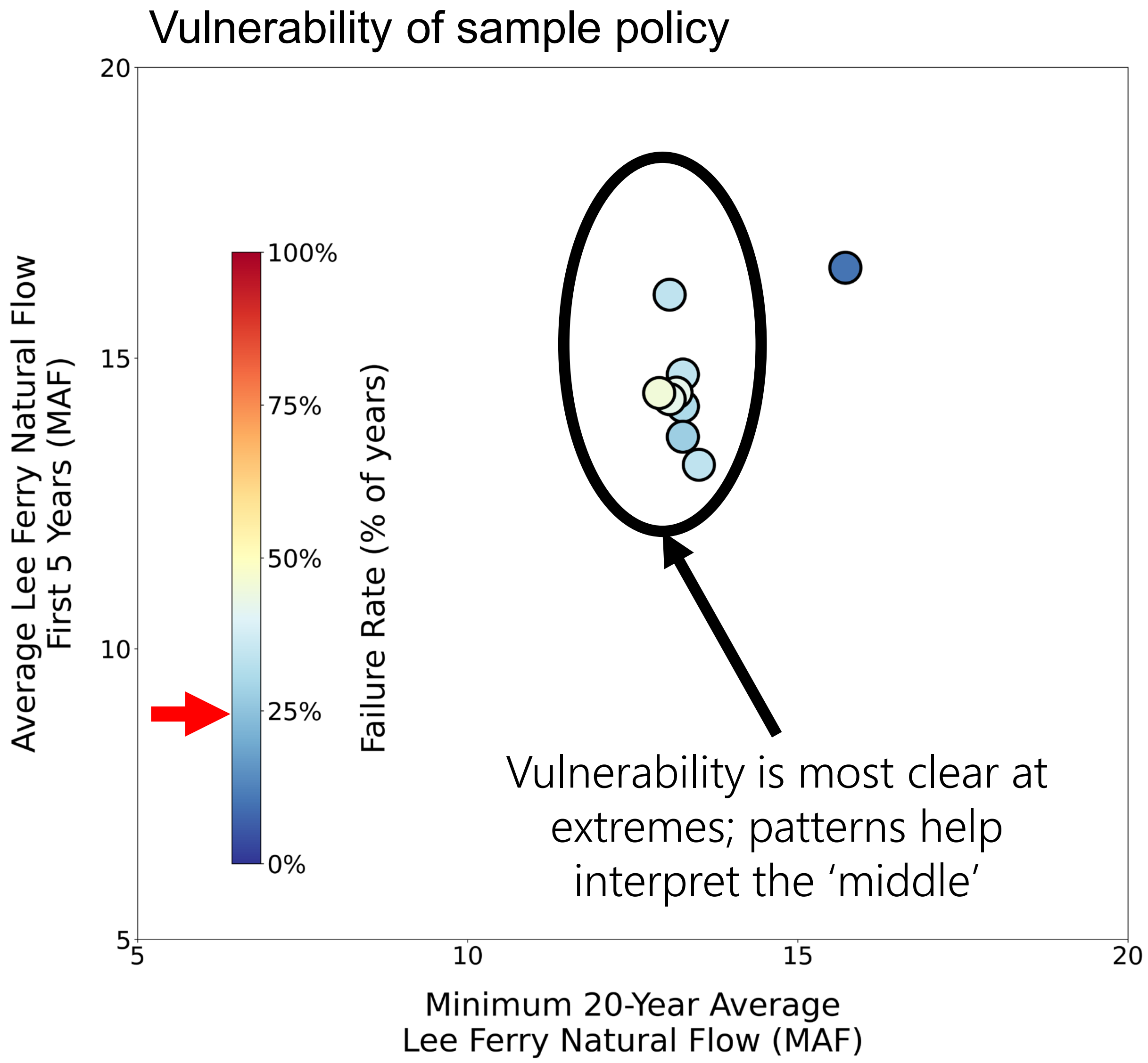
Relating Streamflow Patterns and Vulnerabilities

- Traces with similar streamflow metrics but different patterns may cause different performance
- Hydrology ensembles should contain as many examples of unique patterns as possible
- Balance between pattern diversity, streamflow metrics, and ensemble methodology to determine full suite of hydrology ensembles



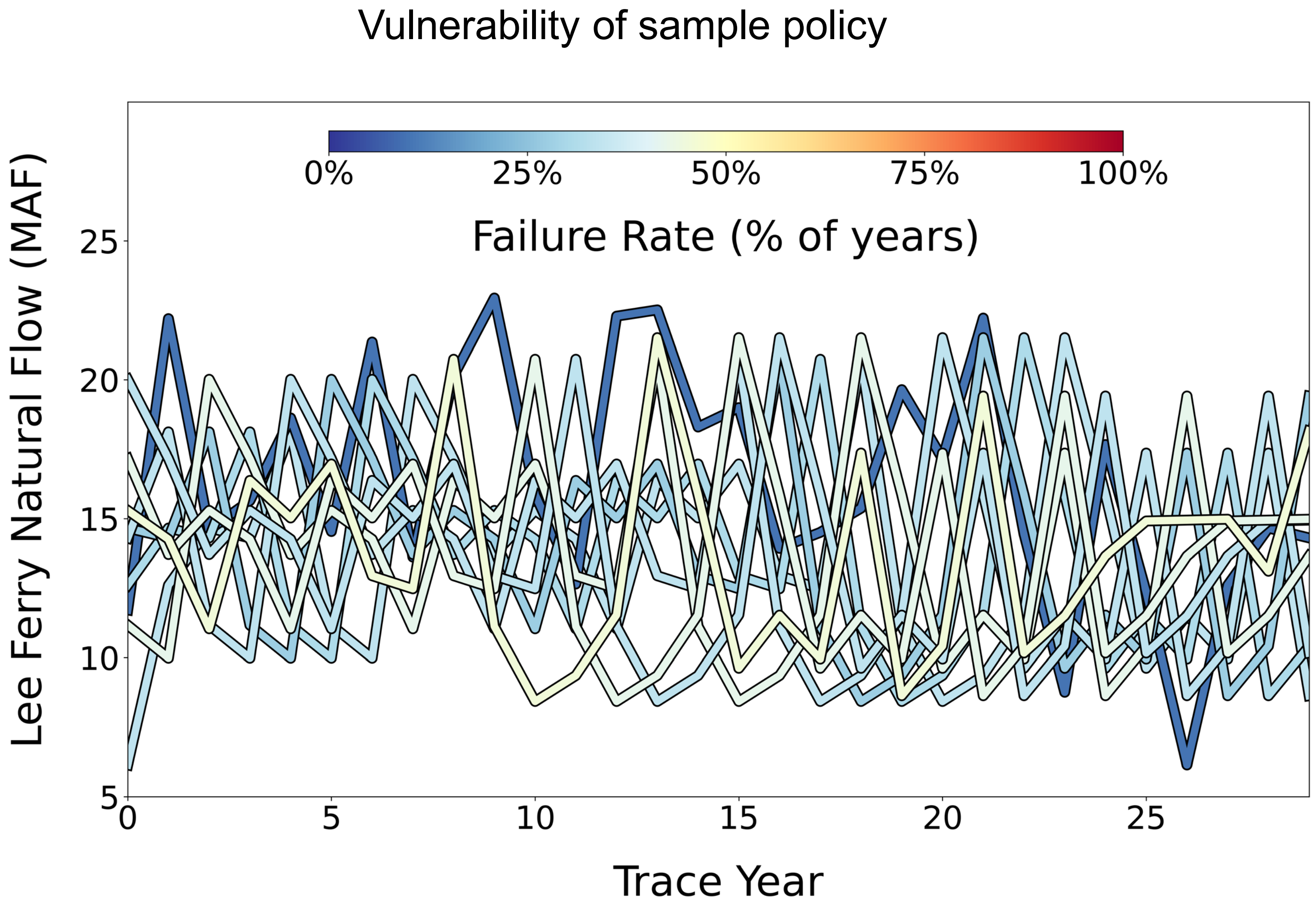
Relating Streamflow Patterns and Vulnerabilities

- Traces with similar streamflow metrics but different patterns may cause different performance
- Hydrology ensembles should contain as many examples of unique patterns as possible
- Balance between pattern diversity, streamflow metrics, and ensemble methodology to determine full suite of hydrology ensembles



Relating Streamflow Patterns and Vulnerabilities

Another group with similar streamflow metrics, but different patterns, observed an increase in years with undesirable outcomes

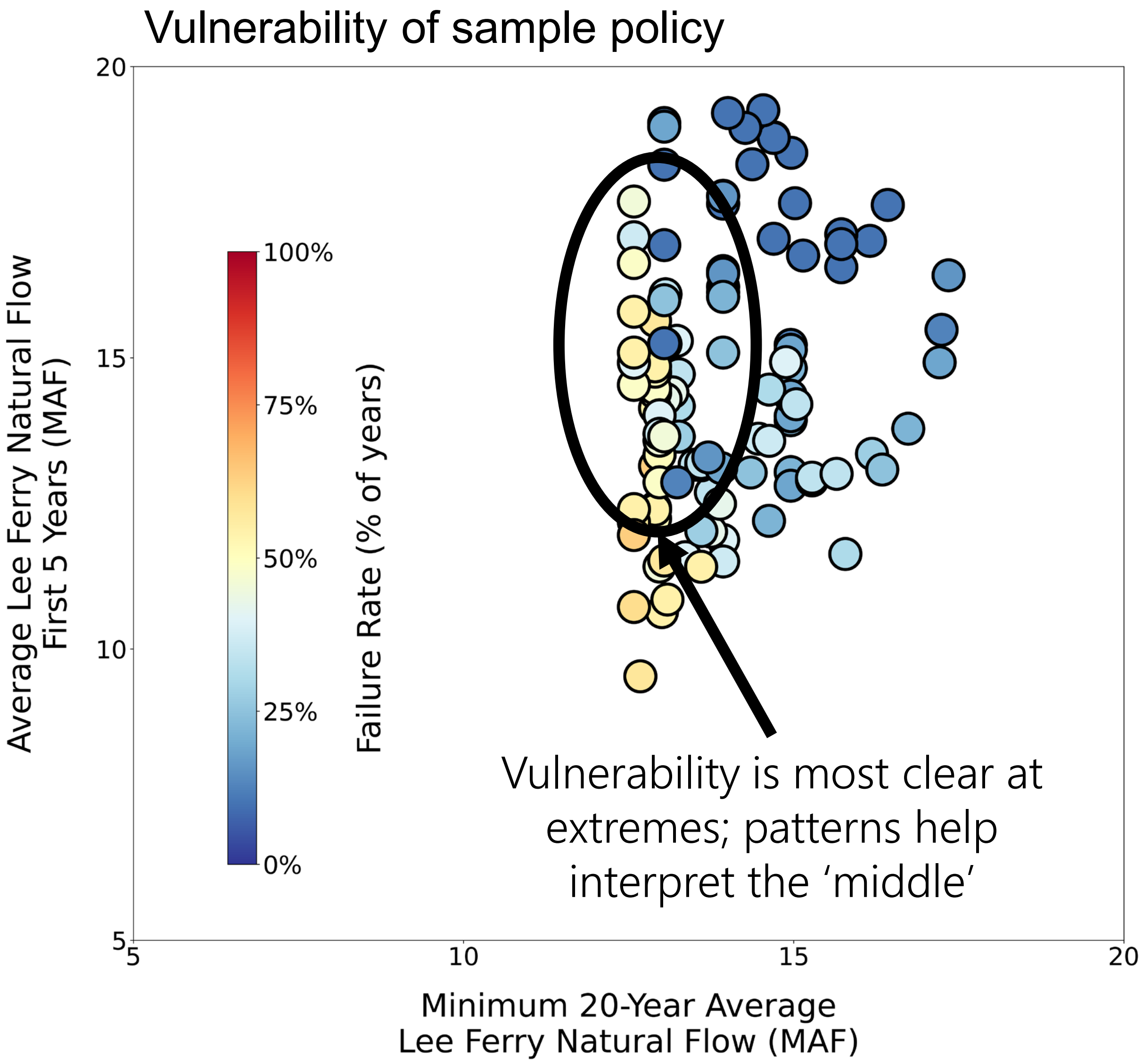


Relating Streamflow Patterns and Vulnerabilities

- Traces with similar streamflow metrics but different patterns may cause different performance

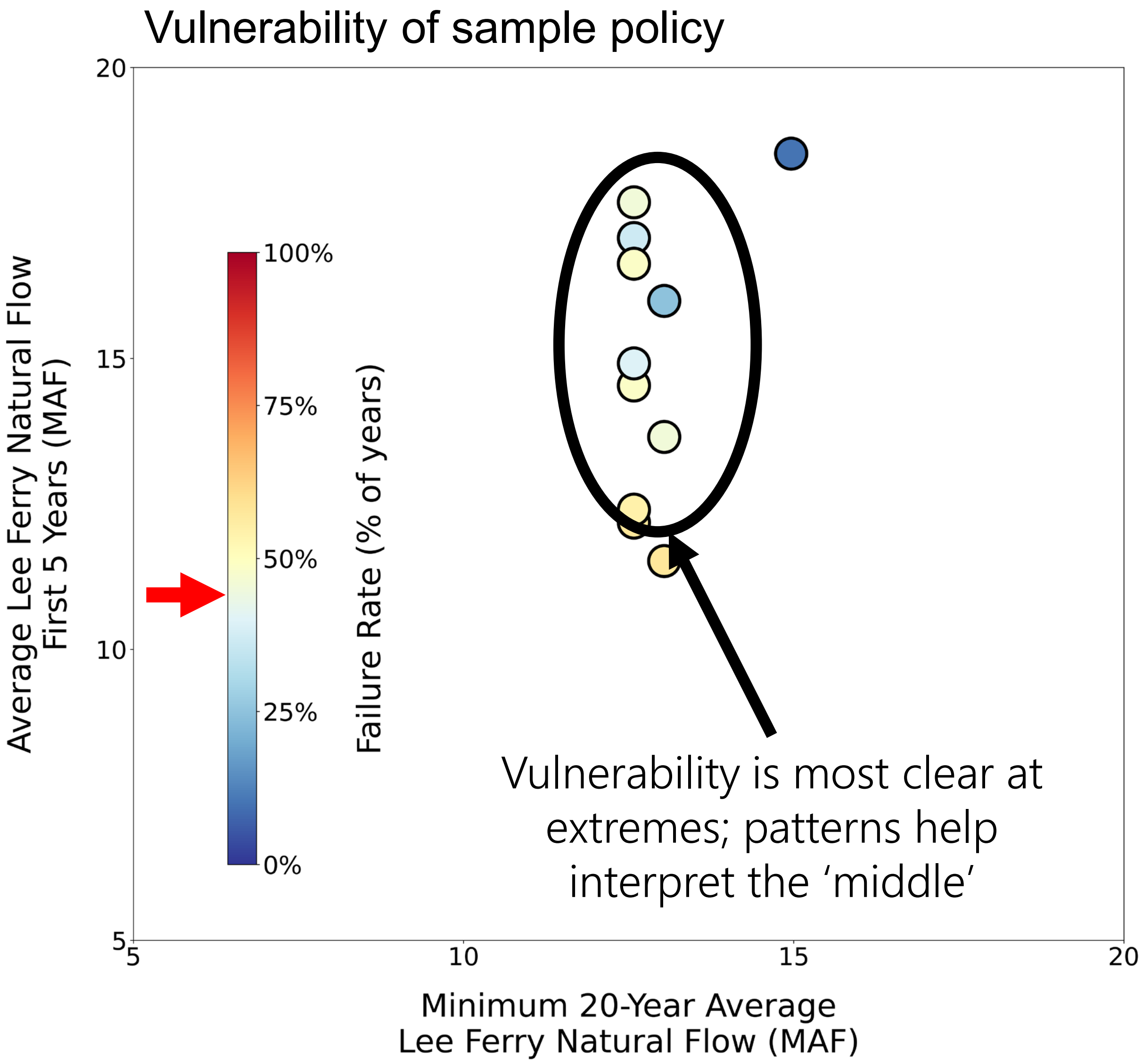
- Hydrology ensembles should contain as many examples of unique patterns as possible

- Balance between pattern diversity, streamflow metrics, and ensemble methodology to determine full suite of hydrology ensembles



Relating Streamflow Patterns and Vulnerabilities

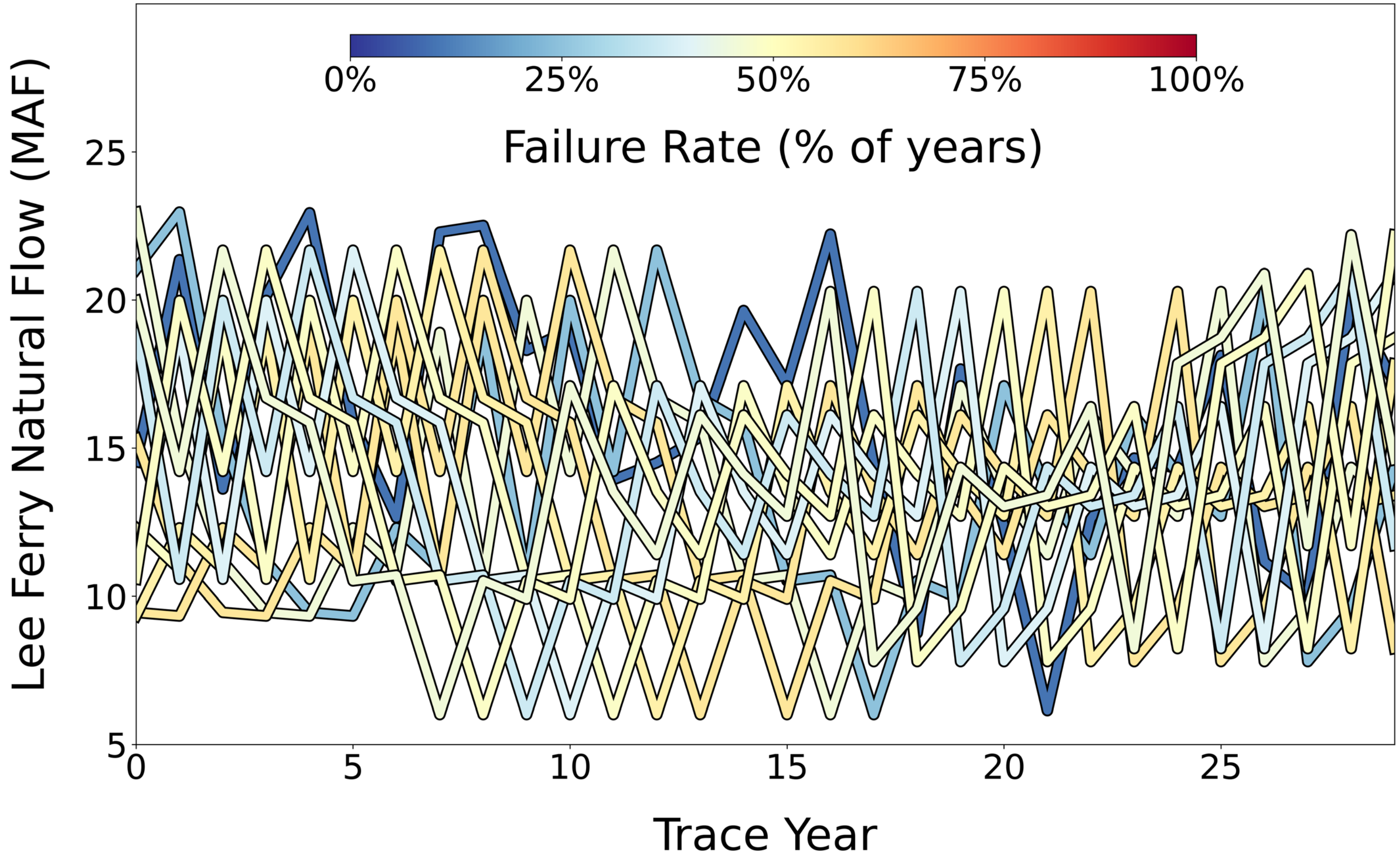
- Traces with similar streamflow metrics but different patterns may cause different performance
- Hydrology ensembles should contain as many examples of unique patterns as possible
- Balance between pattern diversity, streamflow metrics, and ensemble methodology to determine full suite of hydrology ensembles



Relating Streamflow Patterns and Vulnerabilities

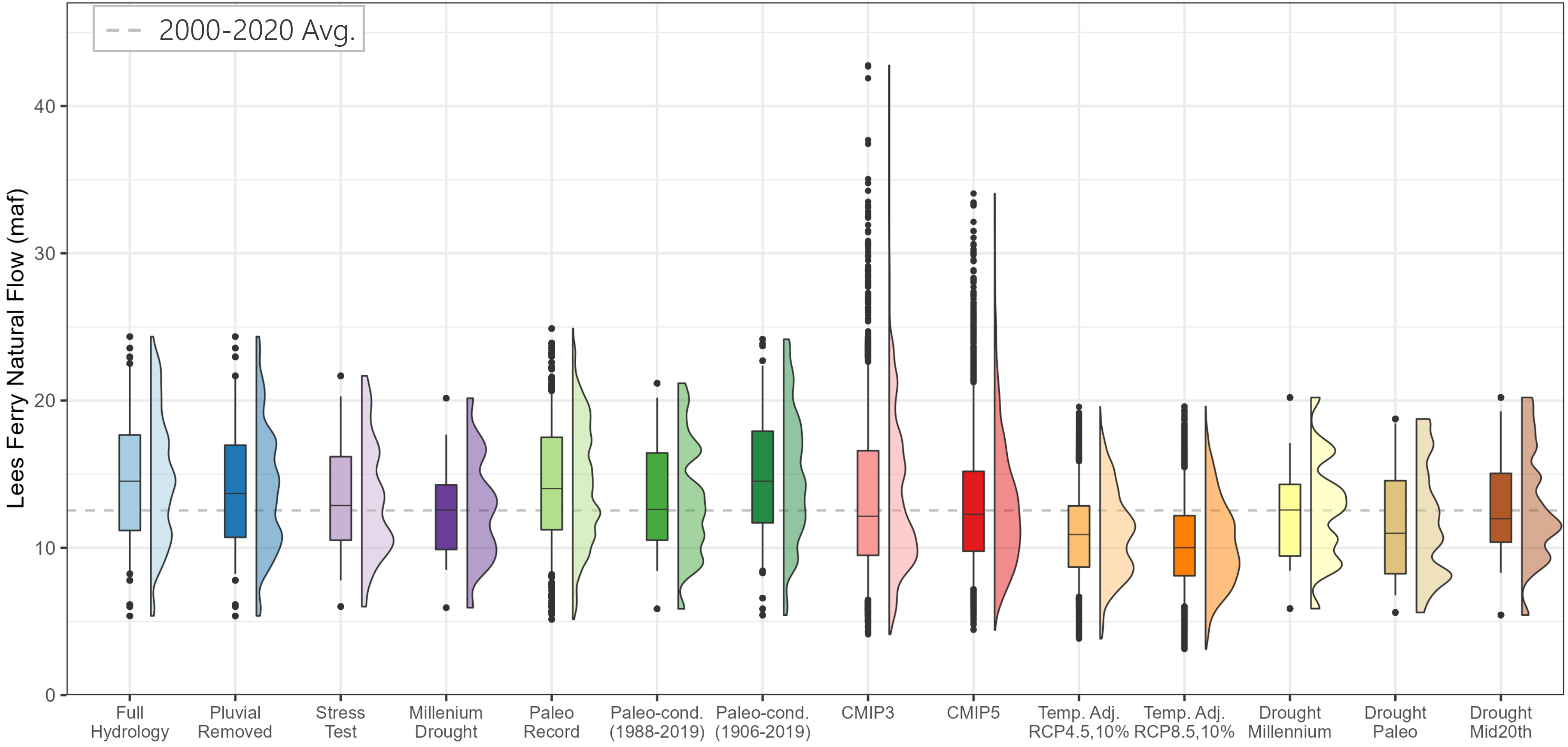
A third group with different patterns resulted in a large number of failures, even though the streamflow metrics of traces in this group were similar to others

Vulnerability of sample policy



Analysis Is Being Applied to All Ensembles

- Each of these ensembles will be analyzed to identify patterns within and across the ensembles
- Capturing a variety of patterns improves our ability to learn about what leads to vulnerabilities and which policies perform well in different contexts



Approach to Choosing Ensembles

- 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

Summary

- Reclamation calculates and maintains the historical natural flow dataset that is foundational to all other flow scenarios
- There are many sources of hydrologic ensembles that can be used for long-term planning, each with their own characteristics, strengths and limitations
- Hydrology ensembles will enable us to understand robustness and vulnerability of many policies in the Post-2026 Web Tool and alternatives development process
- Reclamation will use in-depth analyses to inform the set of ensembles used in the Post-2026 Web Tool and alternatives development process

Future Sessions and Request for Input

- Future ITEW session topics include (order TBD)
  - Demands
  - 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
  - August 2nd
  - Early September
  - Early October
  - Early November
- **We would like to learn which hydrology ensembles you think it is important to include during early phases of the Post-2026 process by early July**. Please send questions, feedback, and requests for topics to bor-sha-crbpost2026@usbr.gov


Thank you
BUREAU OF
RECLAMATION

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] Prairie and Callejo, 2005: Natural Flow and Salt Computation Methods, Calendar Years 1971-1995 (usu.edu)

[4] Ouarda et al., 2007: INDEXED SEQUENTIAL HYDROLOGIC MODELING FOR HYDROPOWER CAPACITY ESTIMATION1 - Ouarda - 1997 - JAWRA Journal of the American Water Resources Association - Wiley Online Library

[5] Colorado River Basin Climate and Hydrology: State of the Science | Western Water Assessment

[6] Meko et al., 2007: Medieval drought in the upper Colorado River Basin - Meko - 2007 - Geophysical Research Letters - Wiley Online Library

[7] Meko et al., 2017: FinalReport2018NoAppendices.pdf (arizona.edu)

[8] Gangopadhyay et al., 2022: Tree Rings Reveal Unmatched 2nd Century Drought in the Colorado River Basin - Gangopadhyay - 2022 - Geophysical Research Letters - Wiley Online Library

[9] Woodhouse et al., 2006: Updated streamflow reconstructions for the Upper Colorado River Basin - Woodhouse - 2006 - Water Resources Research - Wiley Online Library

[10] Prairie et al., 2008: A stochastic nonparametric approach for streamflow generation combining observational and paleoreconstructed data - Prairie - 2008 - Water Resources Research - Wiley Online Library

[11] Reclamation 2012: Colorado River Basin Water Supply and Demand Study - Technical Report B

[12] State of the Science Report, Chap. 11: Colorado River Basin Climate and Hydrology: State of the Science

[13] Wheeler et al., 2021: Alternative Management Paradigms for the Future of the Colorado and Green Rivers - USU white-paper-6

[14] Salehabadi et al., 2022: An Assessment of Potential Severe Droughts in the Colorado River Basin - Salehabadi - 2022 - JAWRA Journal of the American Water Resources Association - Wiley Online Library

[15] 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

[16] L. McInnes, J. Healy, S. Astels, hdbscan: Hierarchical density based clustering In: Journal of Open Source Software, The Open Journal, volume 2, number 11. 2017

[17] McInnes, L, Healy, J, UMAP: Uniform Manifold Approximation and Projection for Dimension Reduction, ArXiv e-prints 1802.03426, 2018