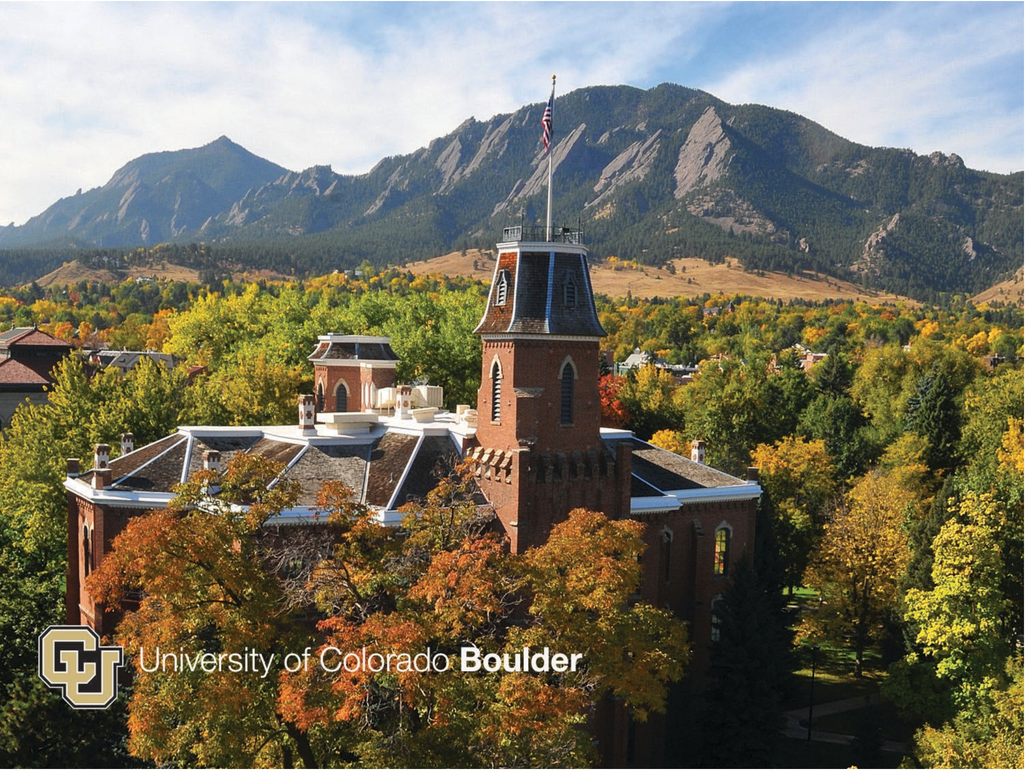

The Future of Drought in the U.S. Paleoclimate Perspectives from Western US

(Drought and Non-Stationarity)

Prof. Balaji Rajagopalan

The Future of Drought in the U.S.
National Academies
Aug 26, 2025

What is past is prologue – William Shakespeare (The Tempest)

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The Sequence

The context – "Millennium Drought" Since 2000

- Current Water Crisis

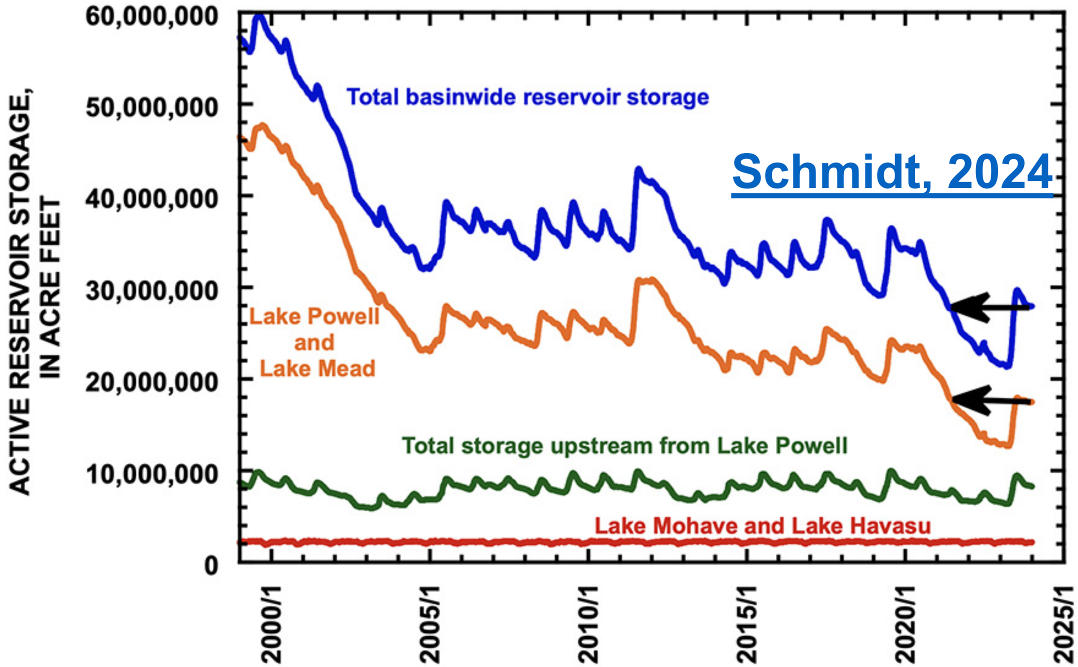
Nonstationarity

- Paleoclimate Variability
  - Reconstruction
- In the context of future variability

Use in Water Management

- Closing Thoughts

Current Crisis

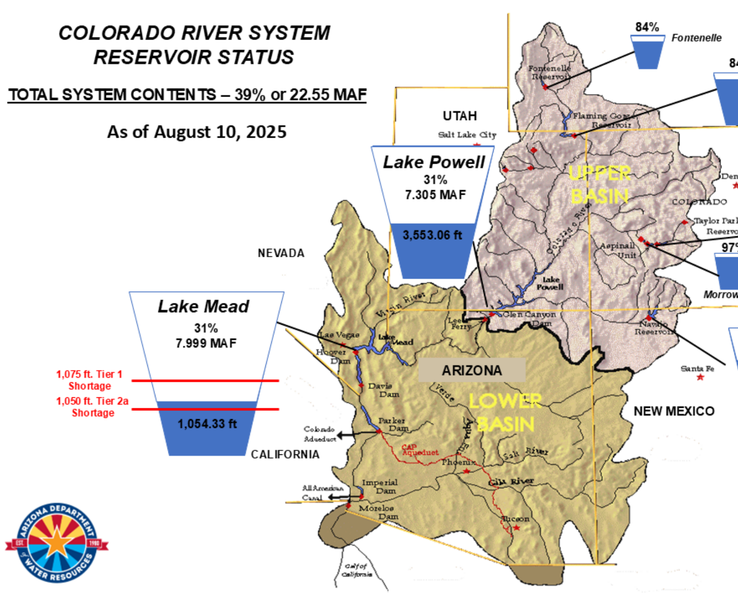


Jan 2000:
Powell+Mead 90% Full, 47 MAF

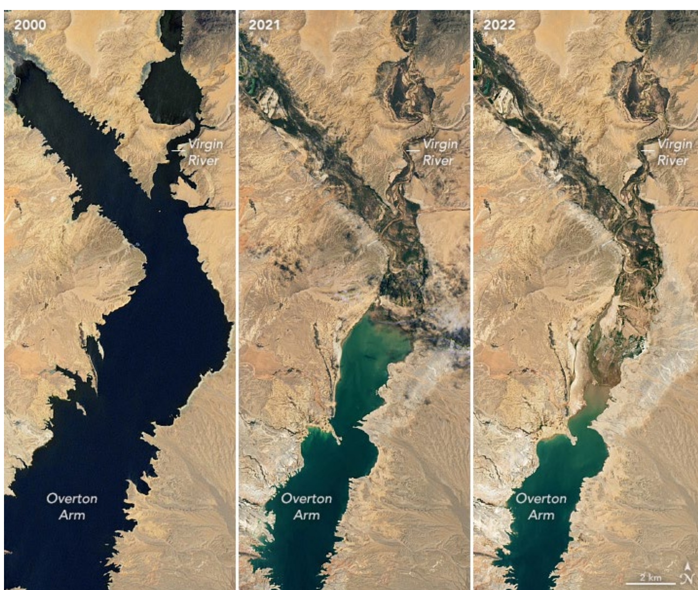
April 2022:
Powell+Mead less than 30% Full, 15 MAF

Loss of 32 MAF or 1.4 MAF/Year

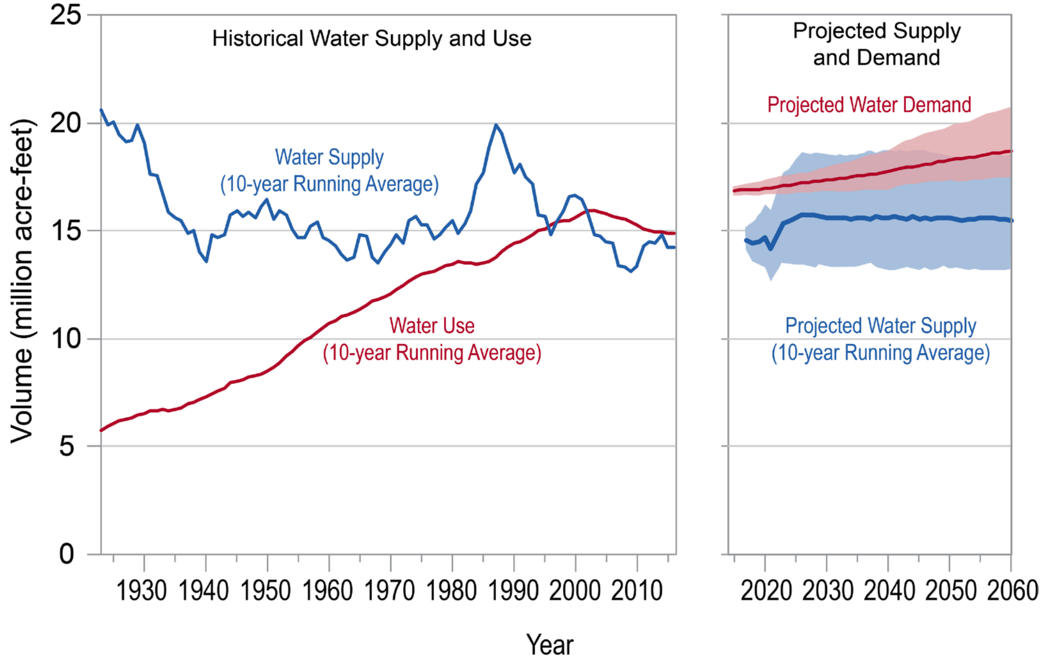
Present ~40%



Reservoir Storage (MAF)			
Reservoir	Current	Last Year	Maximum
Mead	7.999	8.539	26.120
Powell	7.305	9.520	23.314
Fontenelle	0.281	0.279	0.334
Flaming Gorge	3.096	3.220	3.671
Blue Mesa	0.502	0.602	0.827
Morrow Point	0.114	0.111	0.117
Navajo	0.958	1.144	1.648

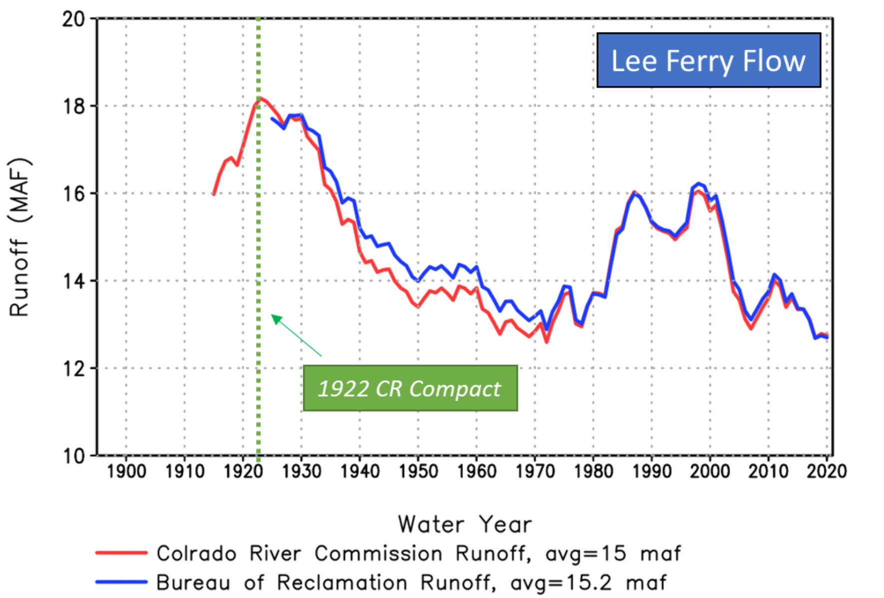


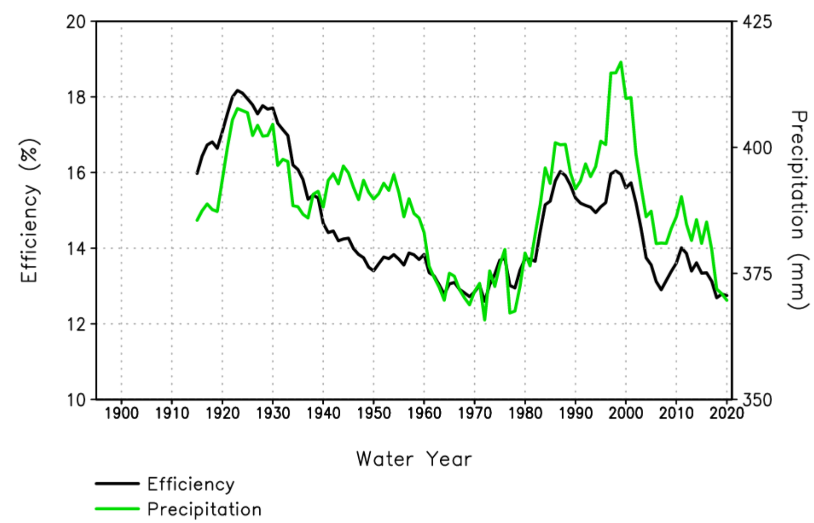
Colorado River Water Crisis



- **Average runoff Efficiency is ~16%**
  - Declining flows and efficiency in recent decades
- **How unusual?**
- **Must Peer into the past**

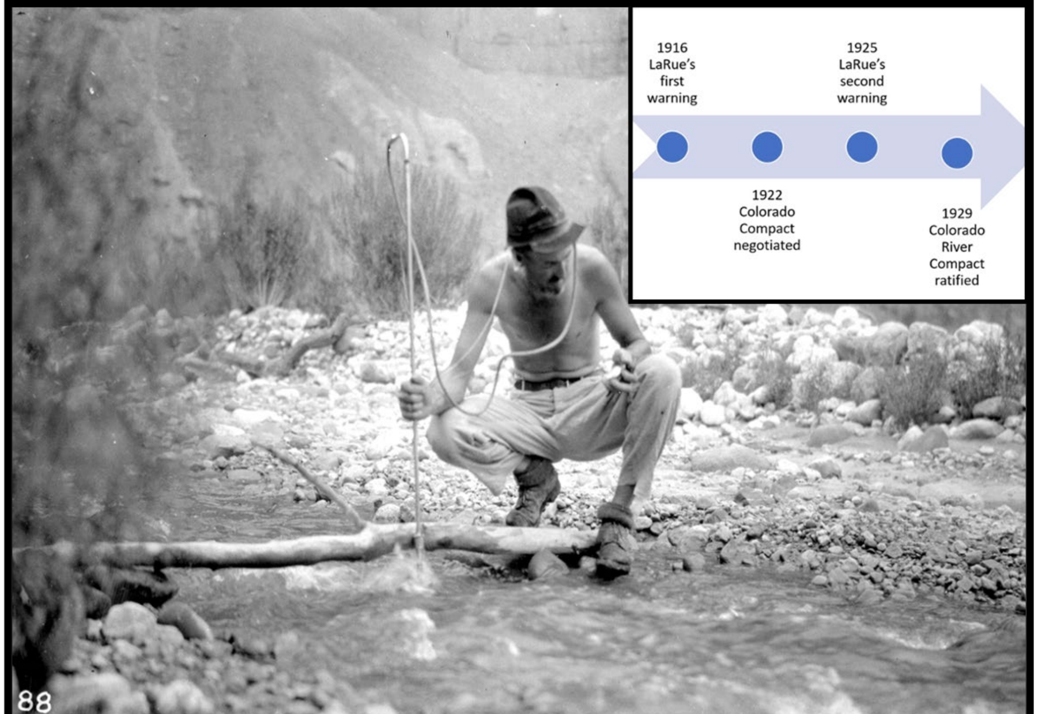
What is past is prologue – William Shakespeare (The Tempest)





Data sources: Colorado River Commission, 1895-2020; USBR 1906-2020

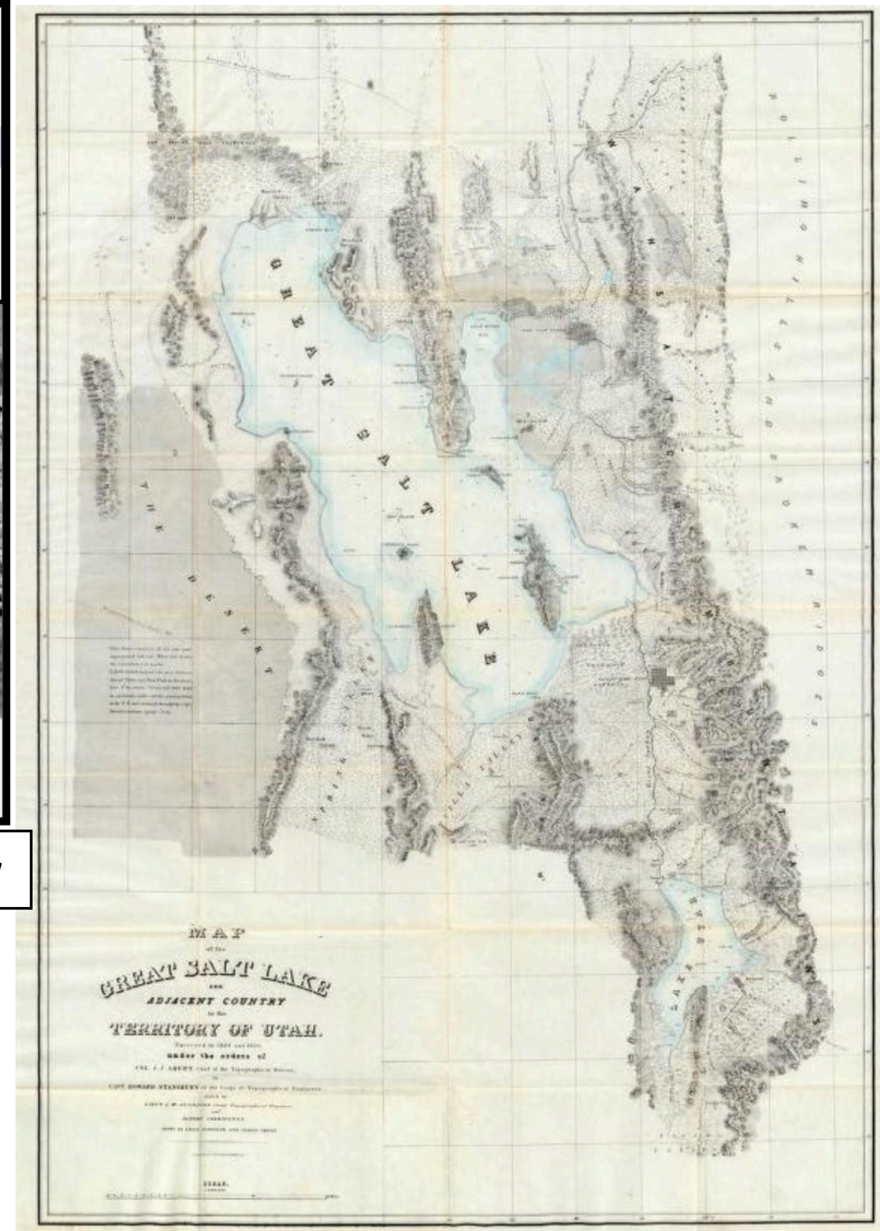
Plot shows moving 20-yr averaged naturalized Lee Ferry flow (maf)



Grand Canyon National Park, Arizona. E.C. LaRue measuring the discharge of Nankoweap Creek. Every stream adjoining the Colorado River in the Grand Canyon region was measured. August 12, 1923. Colorado River Survey of 1923 (Birdseye). Courtesy USGS

EC La Rue's Proxy Reconstruction of Lee Ferry Flow

- Great Salt Lake Elevations Measurements since 1875
- Stockmen journals reconstruct GSL elevation to 1851
- Annual inflow to GSL 1851-1922
- GSL inflow from Wasatch; proxy for CORiver Wasatch inflow
- Correlation of GSL elevation w/Yuma gage 1895-1922
- Identifies 1886-1905 dry period; ~ 2 to 3 *maf < 1895-1922*
- Studies 10-yr windows of flow (mimicking Compact delivery)



1852

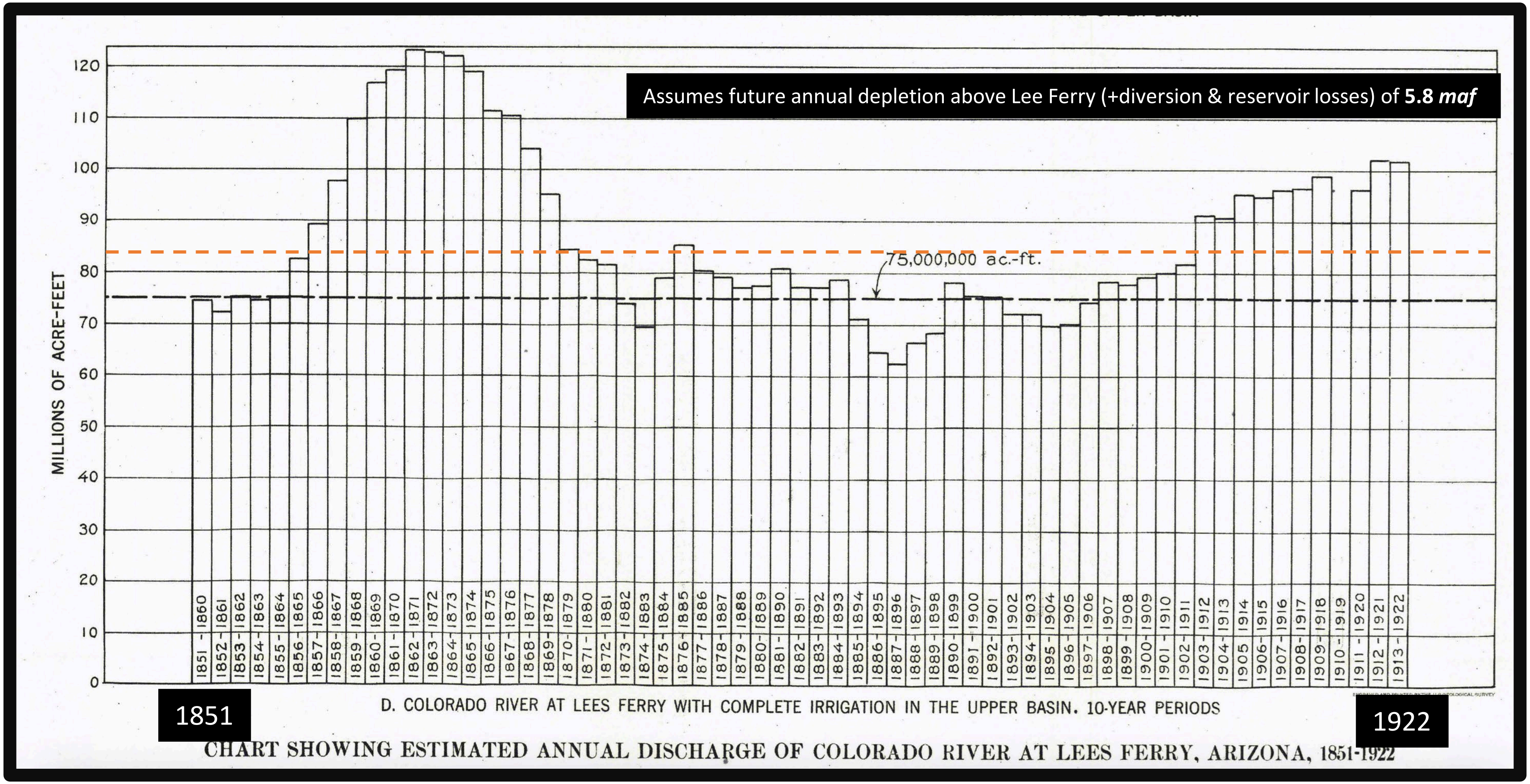
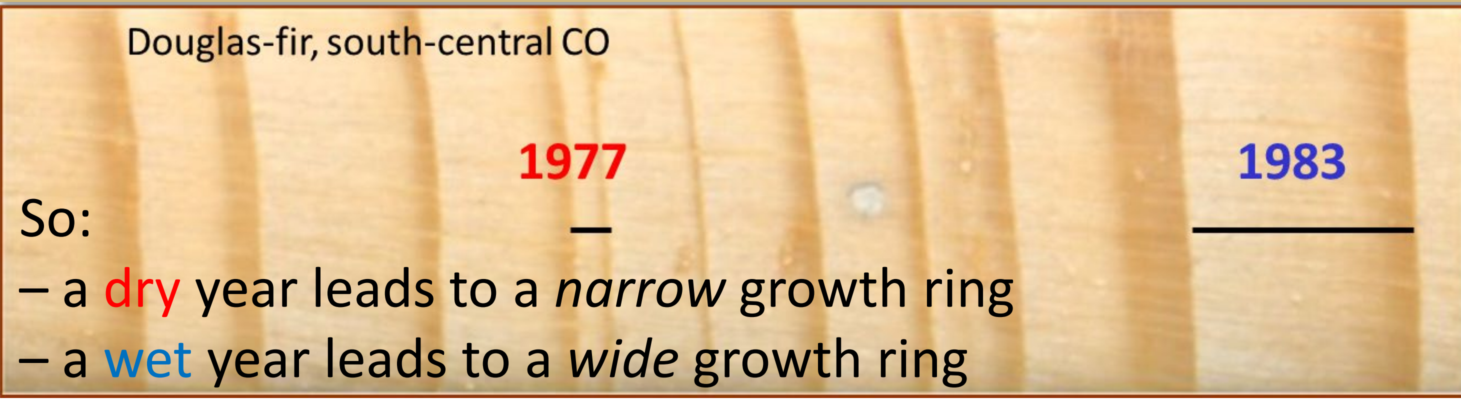


Plate LXXIV from WSP 556 LaRue, 1925

Tree-ring science and streamflow reconstructions are not new

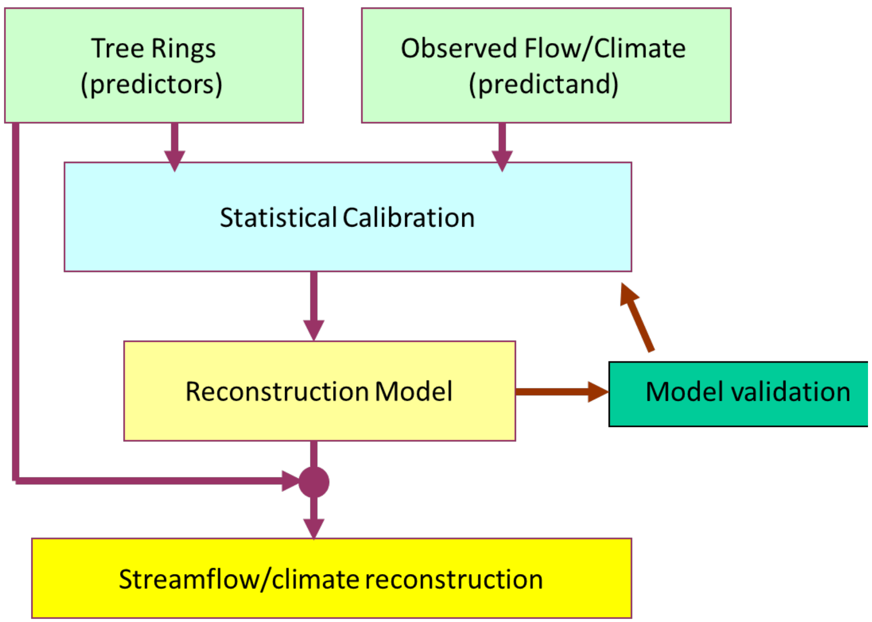


So:

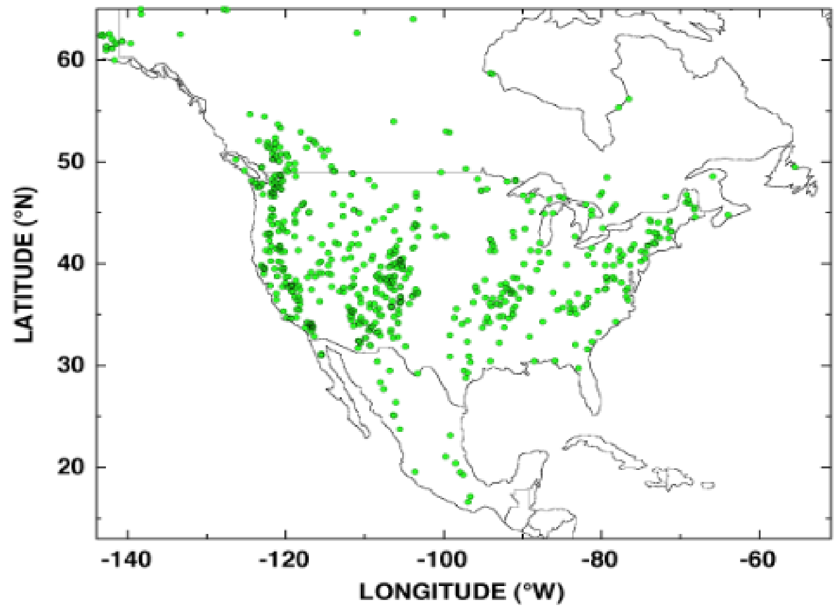
– a dry year leads to a *narrow* growth ring

– a wet year leads to a *wide* growth ring

Overview of reconstruction methodology



Adapted from graphic by David Meko



Moisture-sensitive tree-ring chronologies across North America (as used in the Cook et al. 2004 PDSI reconstructions)

Lees Ferry Flow Reconstruction - Regression

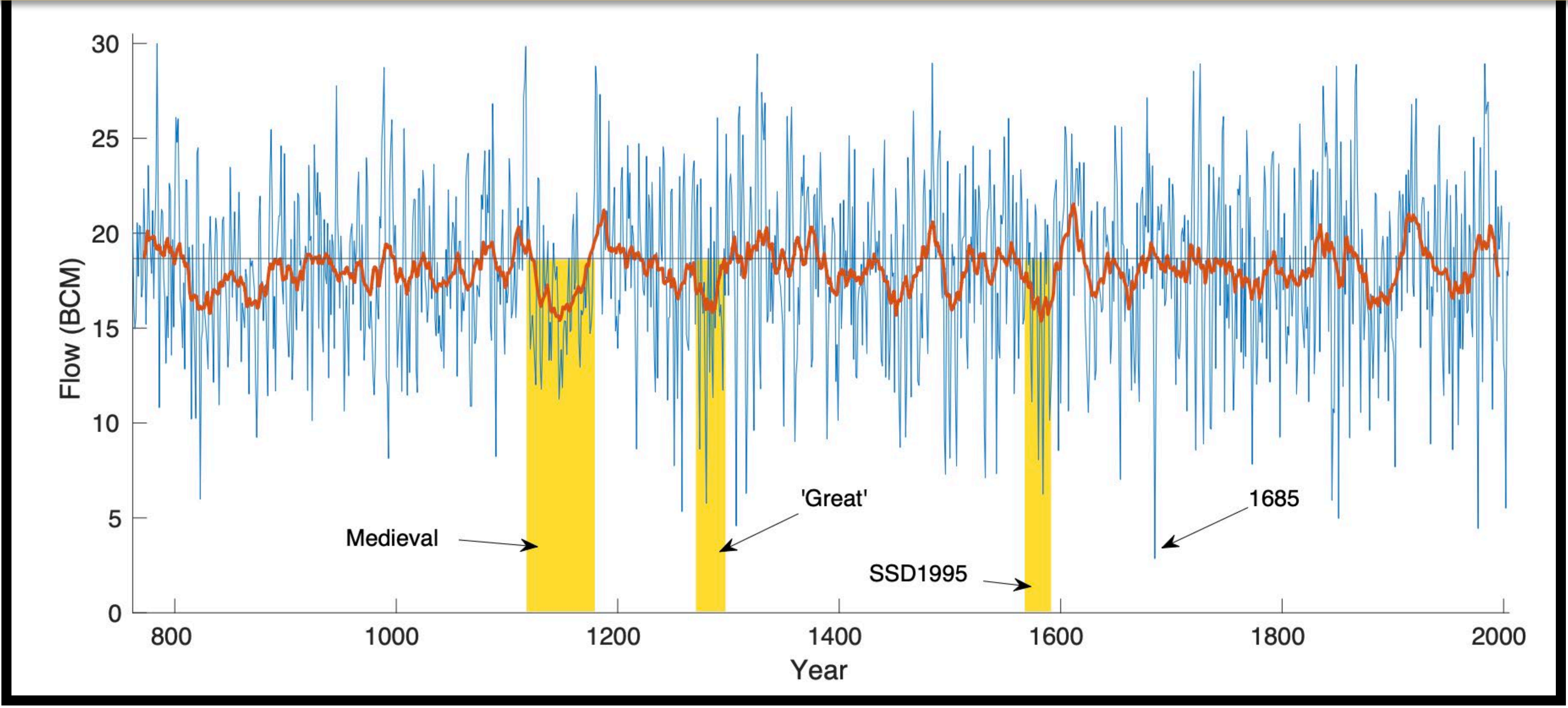
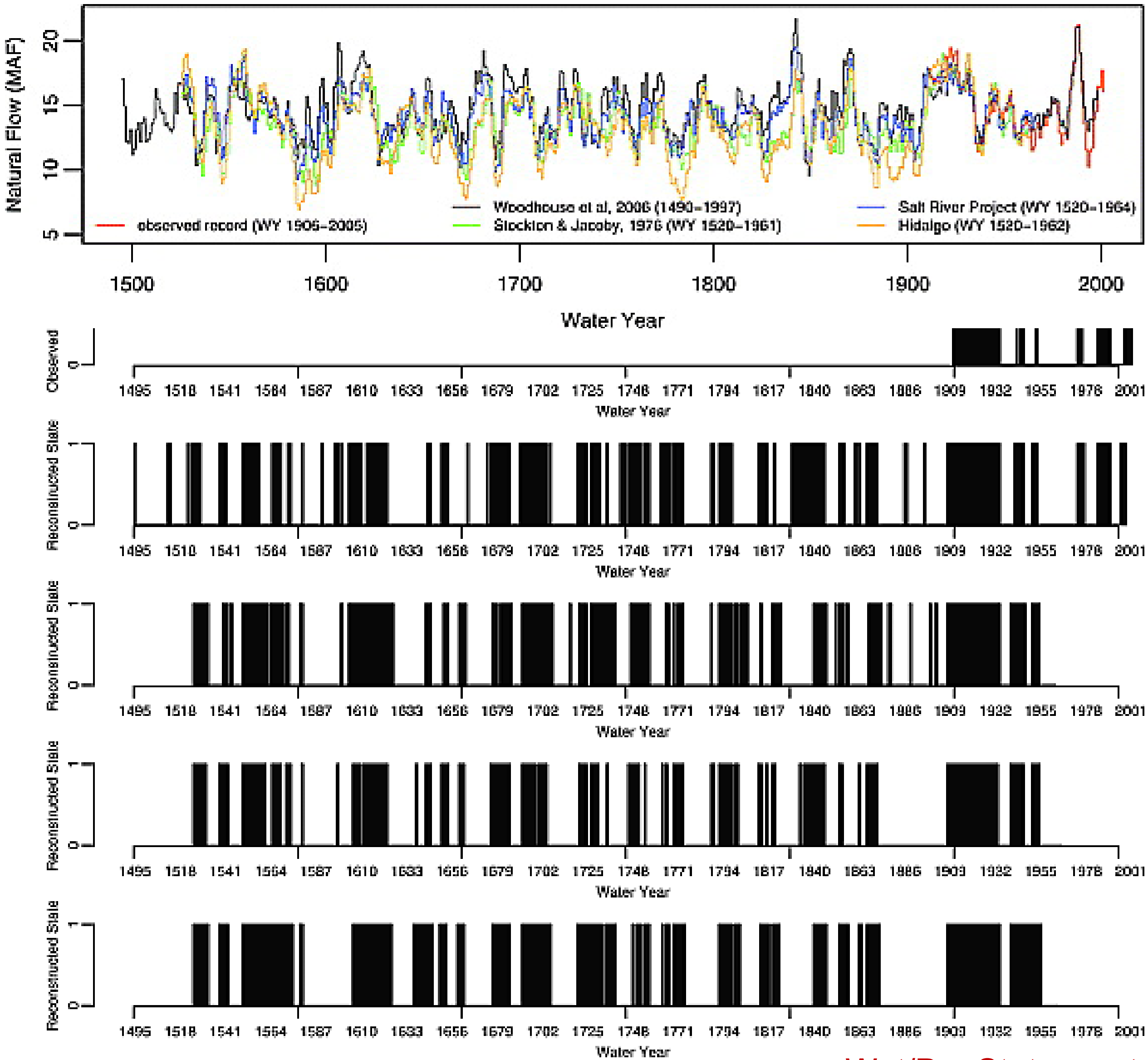


Fig 5 of Meko et al. (2022, JAWRA) Tree Ring Reconstruction of Colorado River flow at Lee Ferry 762-2005 by Meko et al. (2007)

- Six 10-year periods before 1900 with reconstructed mean flow lower than 12 MaF (lowest: 1146-1155)
- 1905-1930 one of the three wettest ~25-year periods in 1200 years
- Mid-1100s: 57-year period with mean flow of ~13 MaF
- Century-scale non-stationarity: 100-year mean varies from 13.9 to 15.4 MaF

Lees Ferry Flow Reconstructions – Common Ground



http://treeflow.info

- Wet/Dry States match across reconstructions
- Trees are robust in capturing the '*state*'

Prairie et al. (2008, Water Resour. Res.)

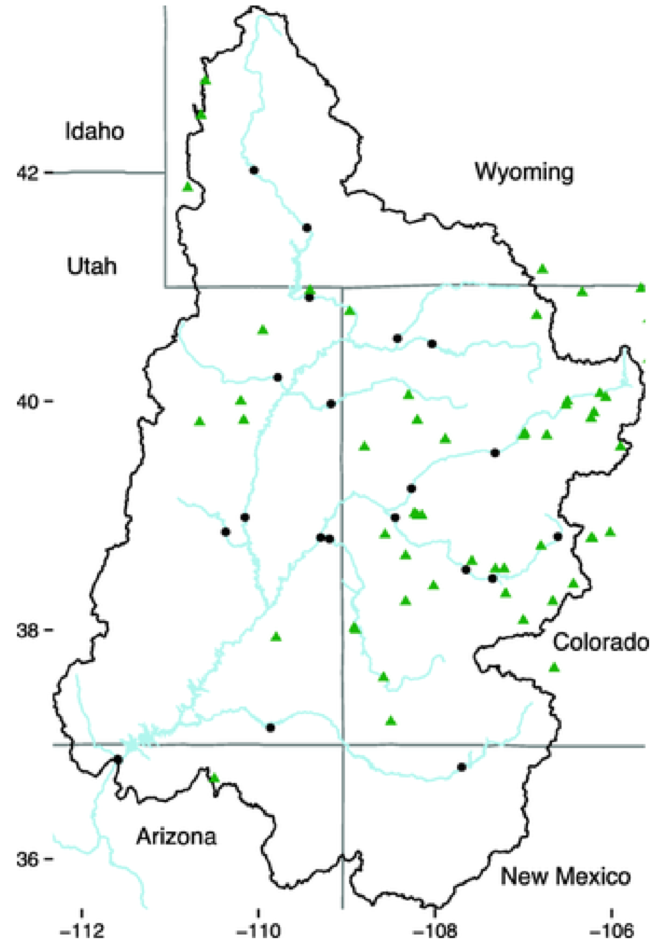
Bayesian Hierarchical Nonhomogeneous Hidden Markov Model - Study Region / Data

Outline

- Bayesian Hierarchical Model for annual Streamflow
    - BHNHMM
    - Reconstruct past streamflow
      1473 ~ 1997

Streamflow

- Annual(Oct-Sep) streamflow at 20 gauges in the Colorado River Basin
- Period 1906 – 1997
- Tree ring data from 50 sites
- Tree rings are an excellent integrator of climate and hydrology. Thus, capture the streamflow variability very well



Traditional Methods

- Individual linear regression on streamflow at each gauges as a function of tree rings

Bracken et al., 2016 (WRR)

BHNHMM

Y_{st}* are streamflow at location *s*, in year *t
Z_{st}* are the hidden state (i.e. state PDF) at location *s*, in year *t

Data Layer:

$$P(Y_{st}=y_{st}|Z_{st}=z_{st},\mathbf{x}_t=\mathbf{x}_t)=\mathrm{LogNormal}(\mu_{sk}+\mathbf{w}_{sk}\mathbf{x}_t,\sigma_{sk})$$

Pocess Layer:

$$P(Z_{st}=i|Z_{s(t-1)}=j,\mathbf{x}_t=\mathbf{x}_t)=\rho_{ij}^{(st)}=\frac{\exp\left(\beta_{ij}^{(s)'}\mathbf{x}_{st}\right)}{\sum_{\ell=1}^{K}\exp\left(\beta_{i\ell}^{(s)'}\mathbf{x}_{st}\right)}$$

State Transitions

$$\mathbf{Y}_t=(Y_{1t},\ldots,Y_{St})$$

$$F_C(\mathbf{y}_t)=\Phi_\Sigma(\mathbf{u}_t)$$

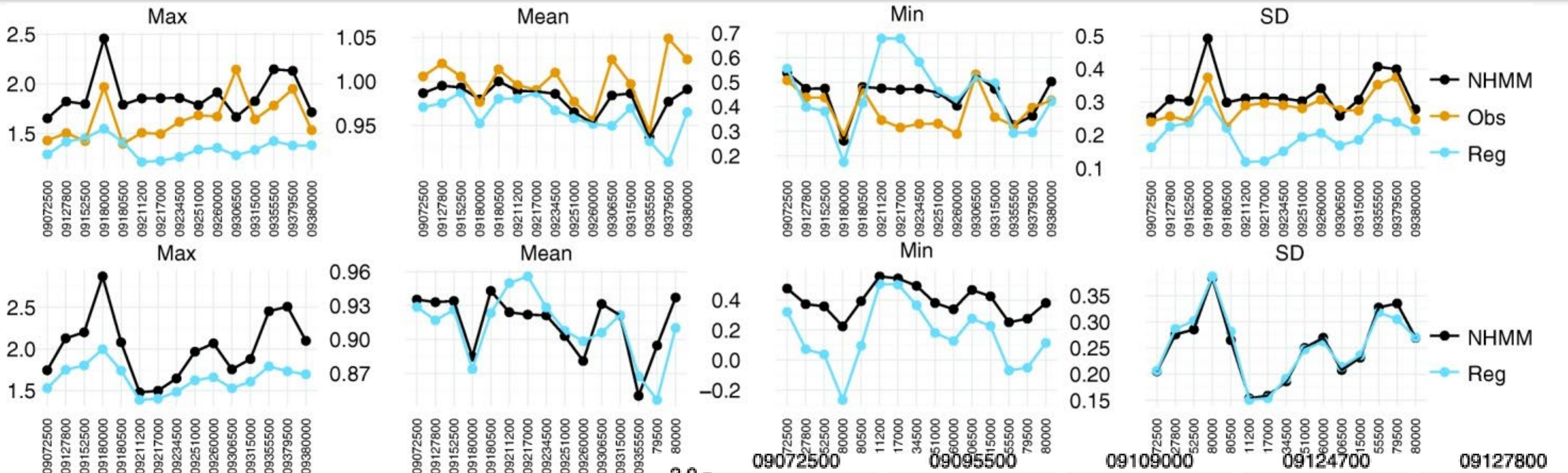
Spatial Model

where is the joint cdf of an *S*-dimensional multivariate normal distribution with covariance matrix ***Σ***

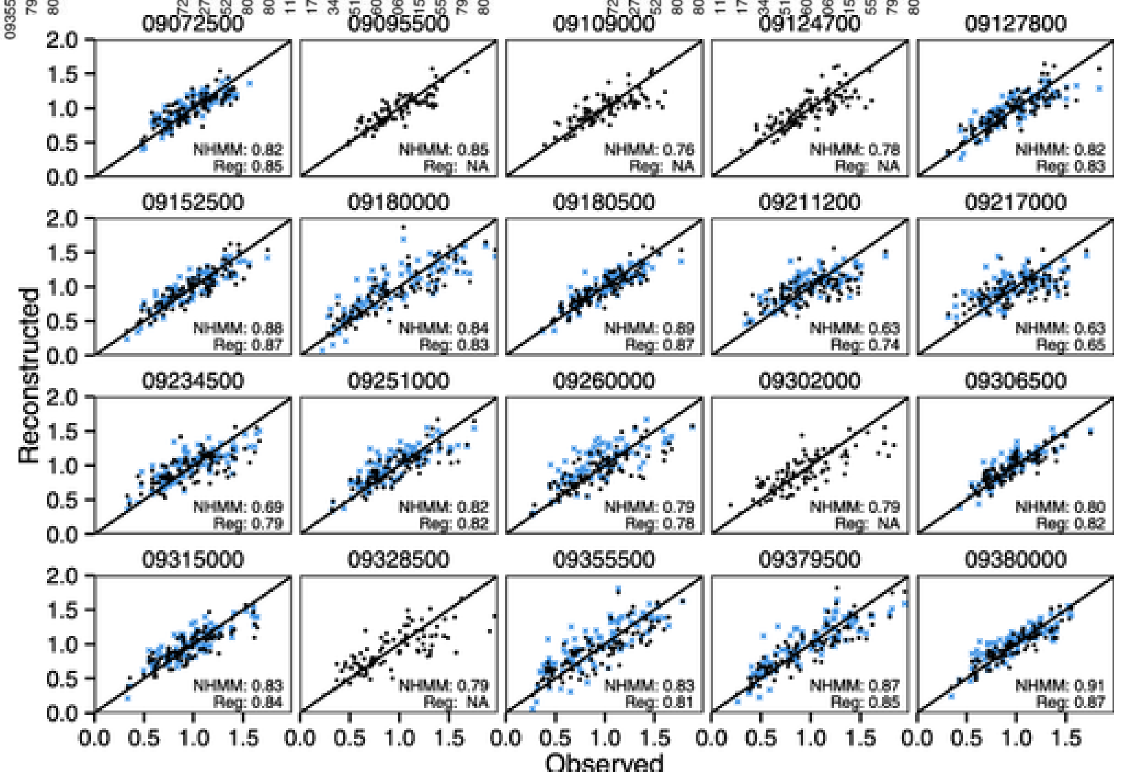
$$\Sigma(i,j)=\exp\left(-\|\mathbf{s}_i-\mathbf{s}_j\|/a_0\right)$$

- **Suitable Priors**
- **Likelihood and MCMC to obtain posteriors of the parameters the flow**

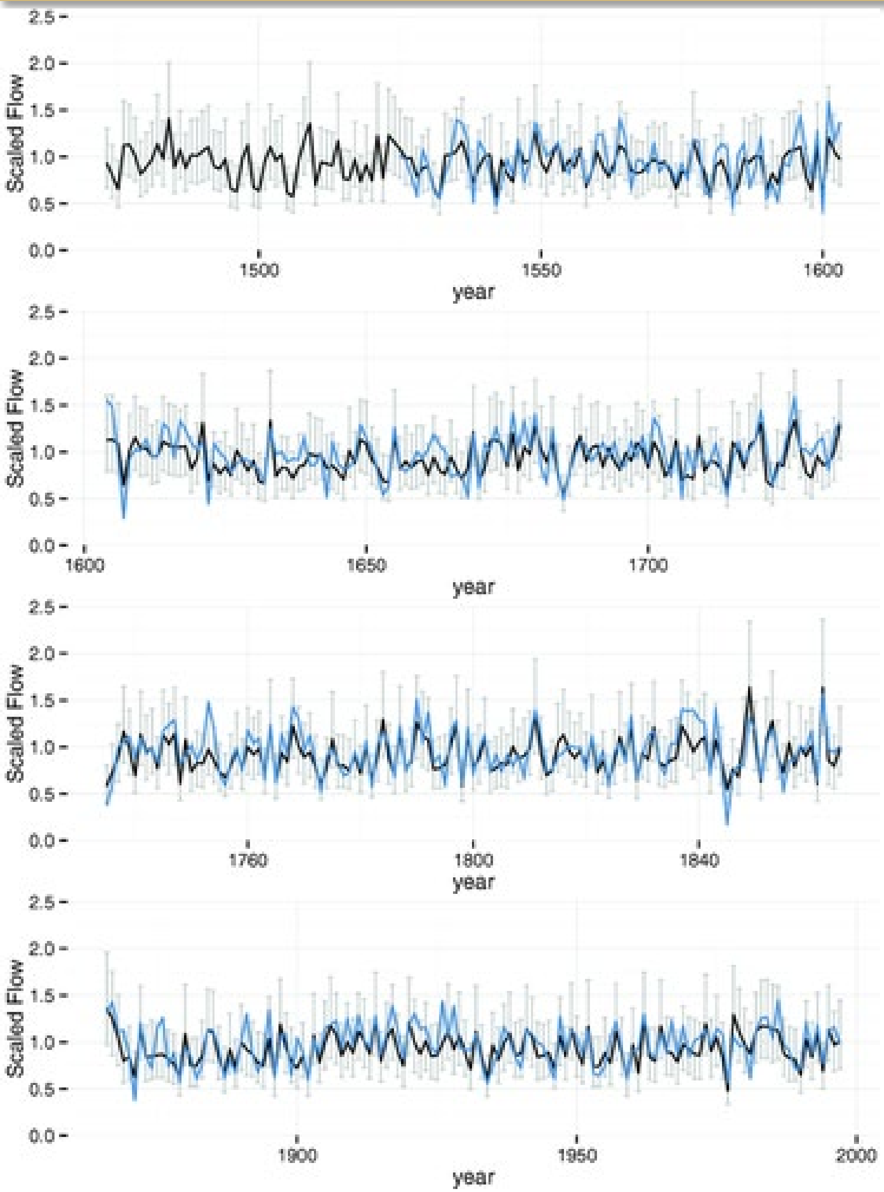
Lees Ferry Flow Reconstructions



- In the historical period (1906 – 1997) BHNMM Captures
    - Basic Statistics
    - Reconstructions are closer to observed, relative to a linear regression-based model



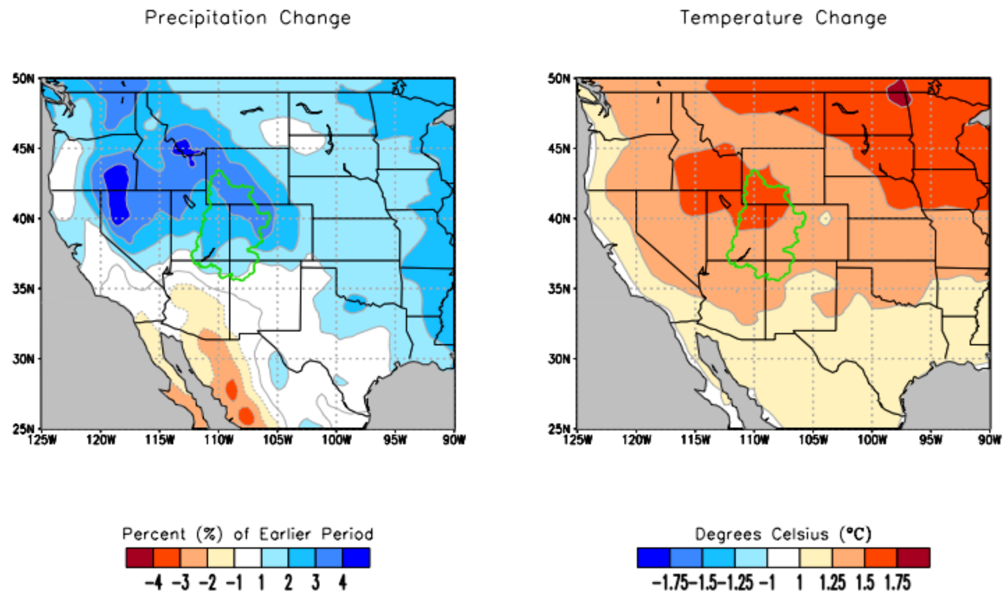
Past streamflow reconstruction



Bracken et al., 2016, WRR

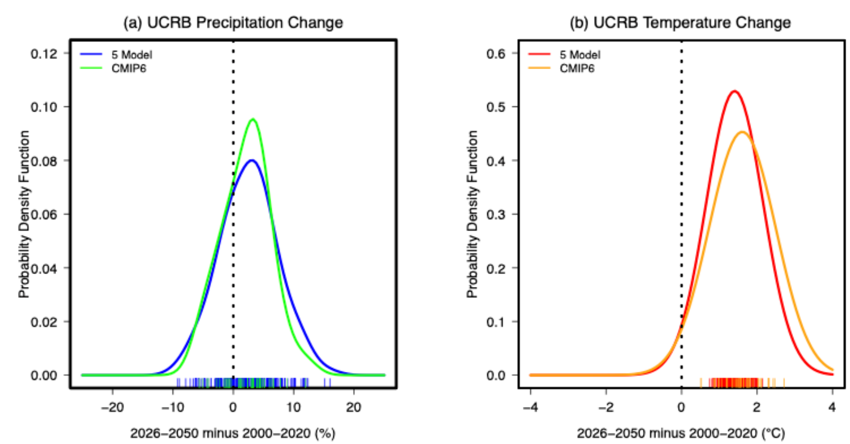
- Rich Temporal Variability along with uncertainties
- Sustained dry and wet epochs with regularity
- Provides context for assessment

The TreeFlow web resource -
http://treeflow.info

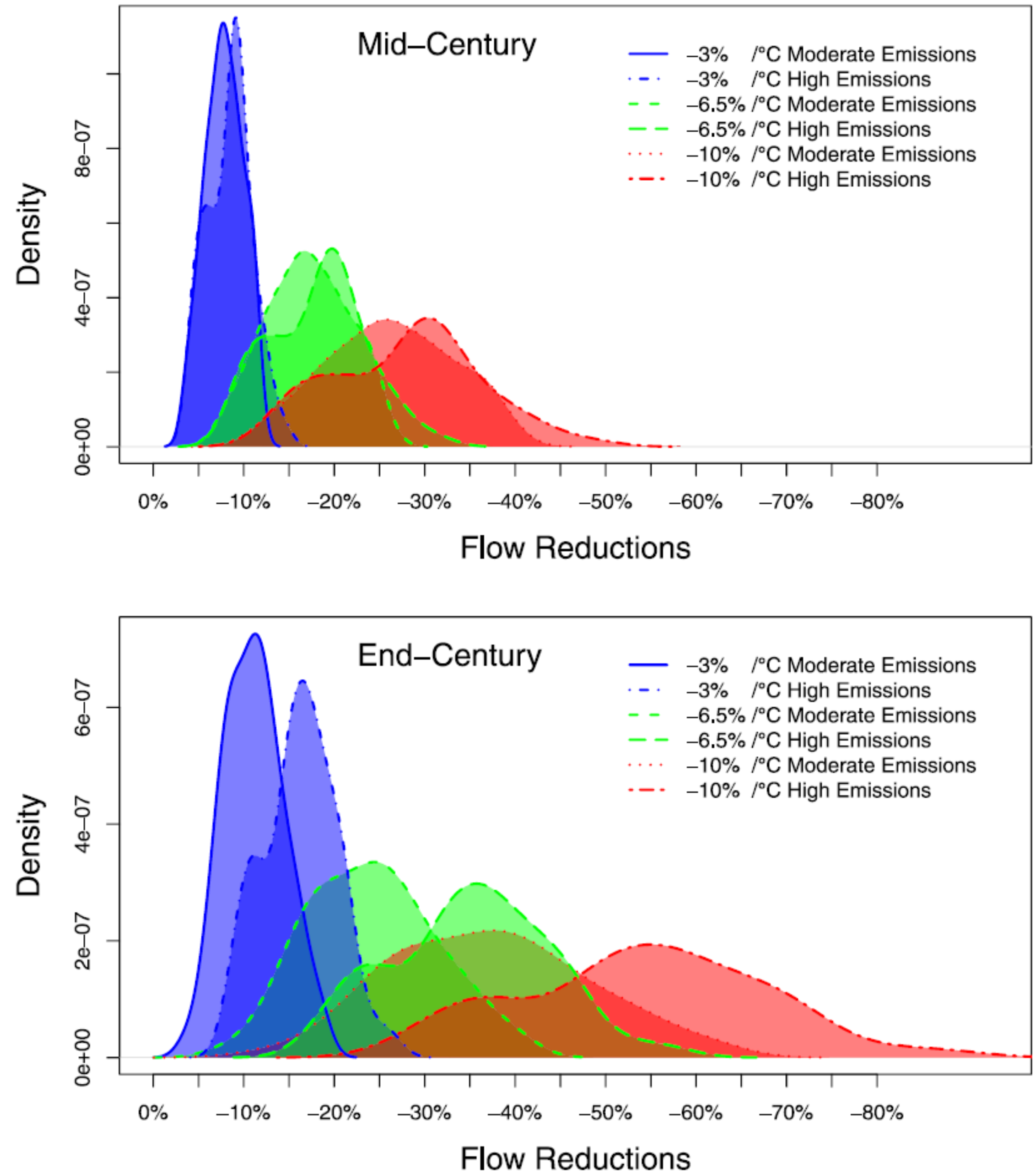


GCM simulations

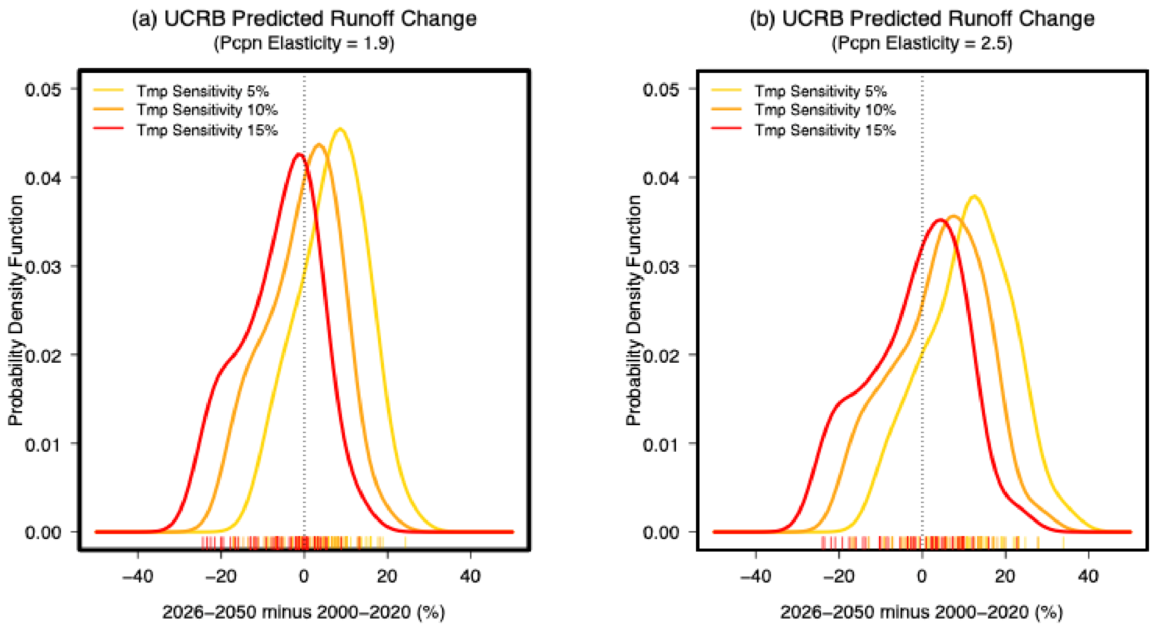
Ensemble average precipitation departures (%, left) and surface temperature departures (°C, right) for 2026–2050 relative to 2000–2020 based on the multi-model average of five large ensemble model simulations.



(Hoerling et al., 2024, J. Climate)



Udall and Overpeck, 2017
Water Resur. Research



Precipitation Control

- **Rich Variability**

Nonlinearity begets Completeness,

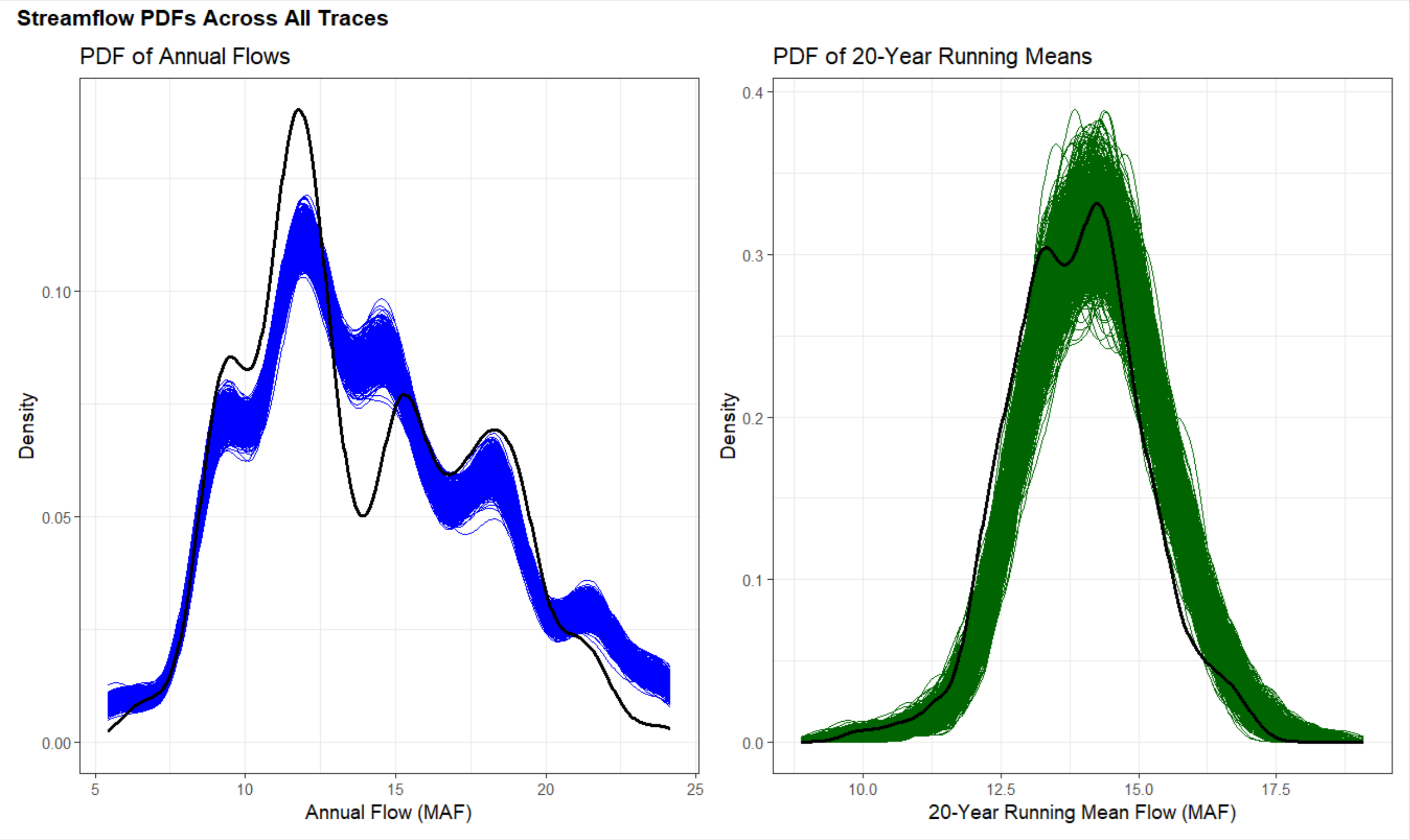
Misjudgment creates Linearity

-- Lao Tsu

predicted Lee Ferry flow changes (%) based on the combined effects of large-ensemble model UCRB precipitation and temperature changes and conditioned on dry initial conditions during 2000–2020 in analogy to observations. Results assuming elasticity = 1.9 (2.5) shown in left (right) panels. Results are displayed for three temperature sensitivities (-5%/°C, -10%/°C, and -15%/°C). Changes are % differences of 2026–50 relative to 2000–2020.

(Hoerling et al., 2024, J. Climate)

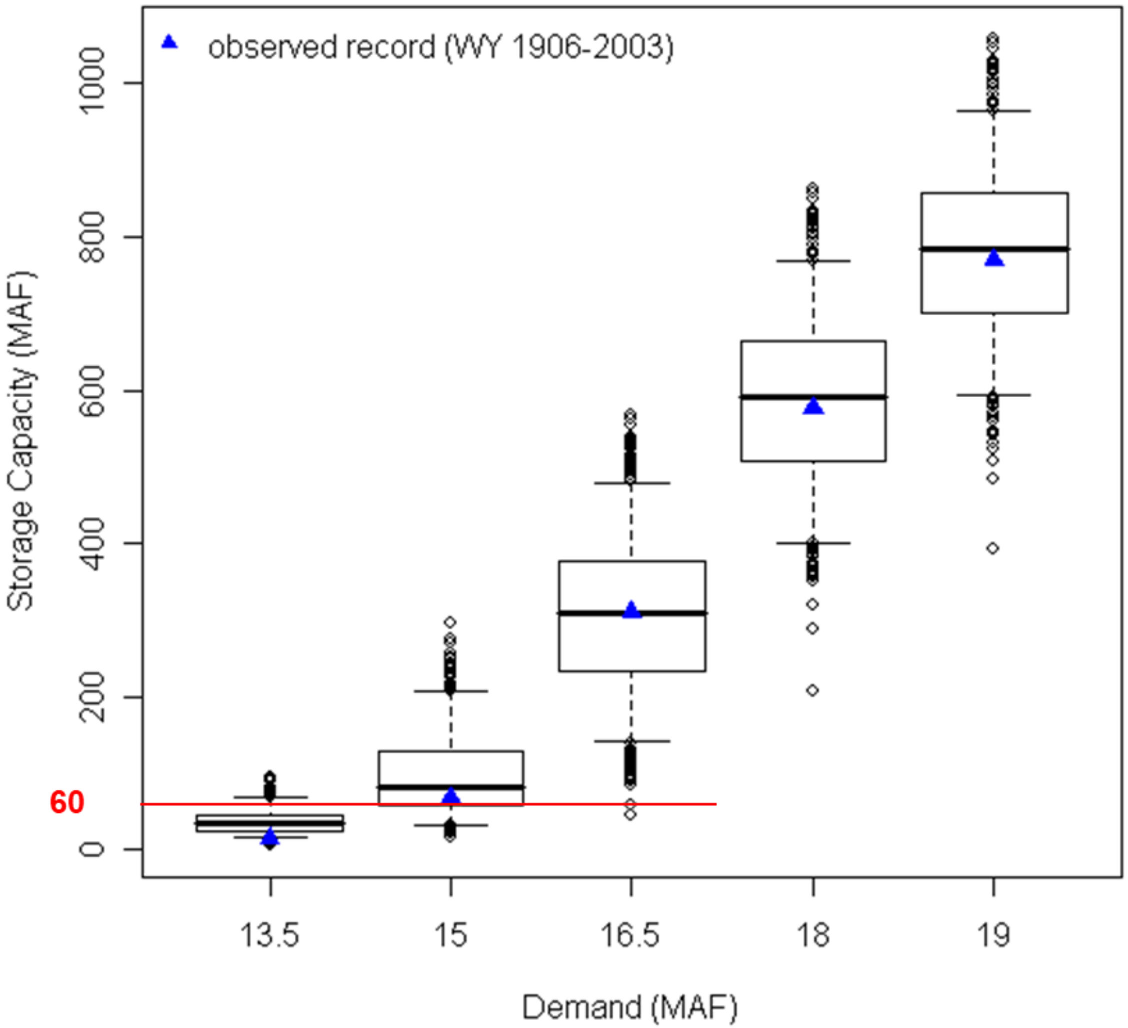
Past Variability



Tree Ring Reconstruction of Colorado River flow at Lee Ferry 762-2005 by Meko et al. (2007)

- **Rich and wide range of variability**
- **Comparable to those projected by climate change**
  - **-40% to 25%**
- **Higher probability of 20-year mean flows below 12.5MAF**

Flow simulation combining Paleo and observed flows

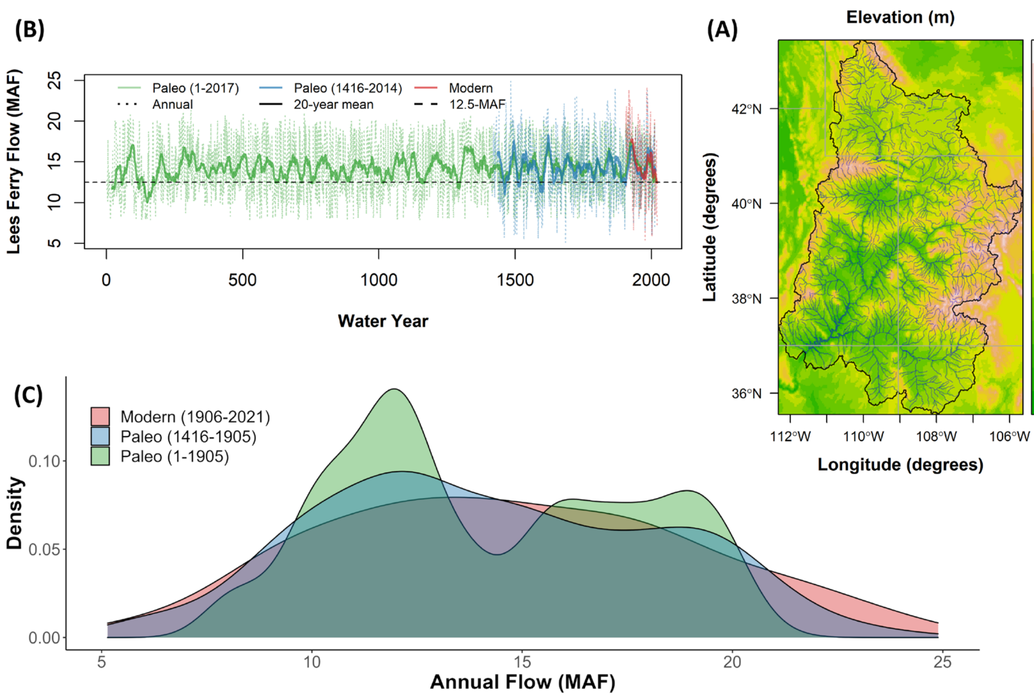


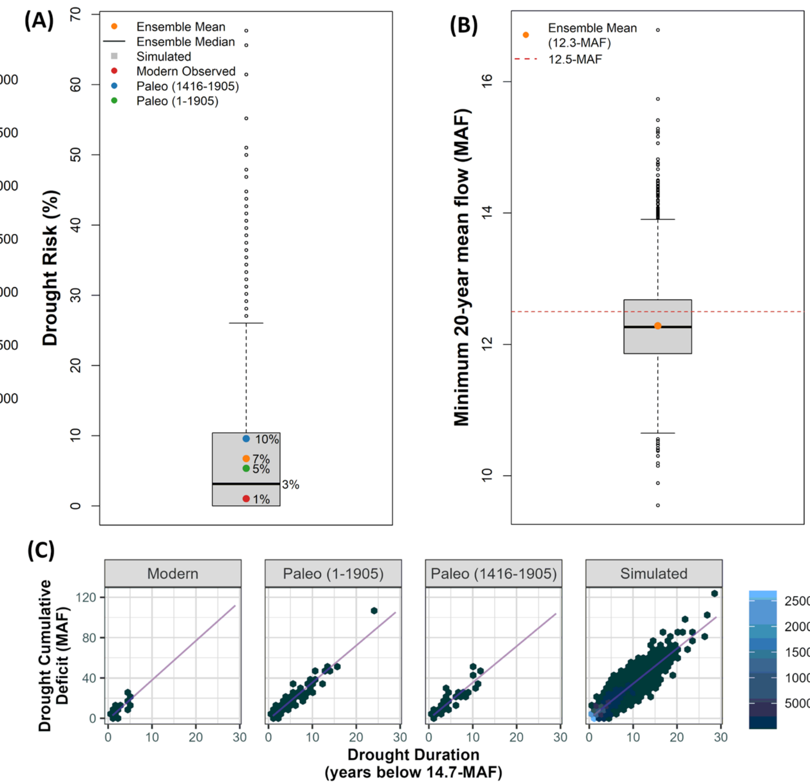
- 60MAF storage can reliably meet demand of ~13.5MAF or lower

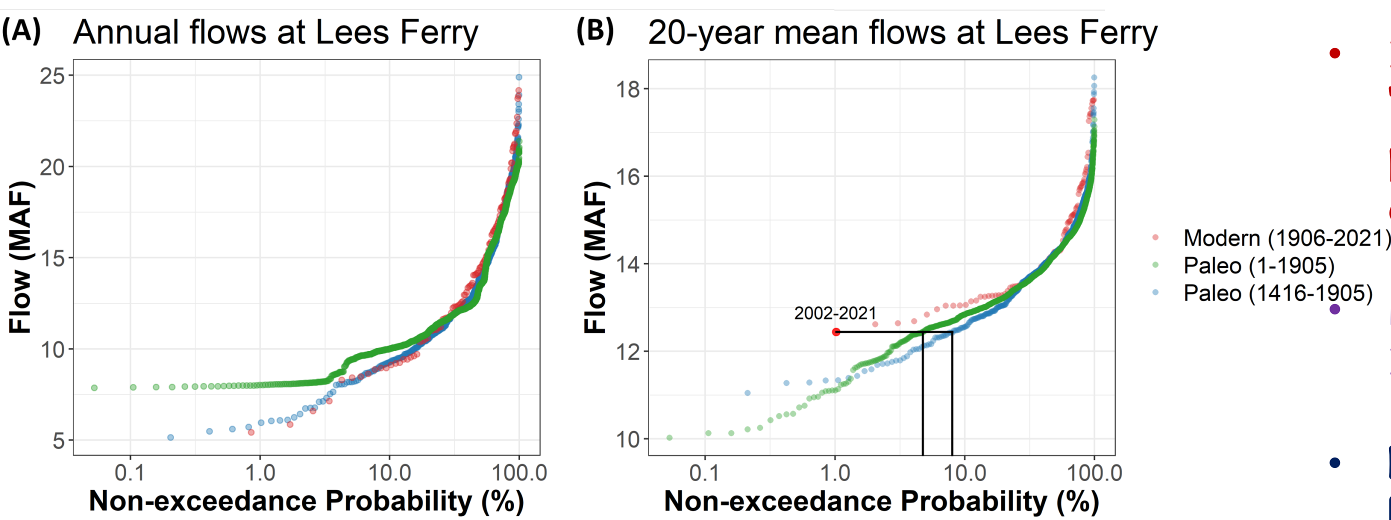
Prairie et al. (2008, Water Resour. Res.)

Risk Assessment – Implications for Water Resources Management

(Woodson et al., 2025, NPJ in review)

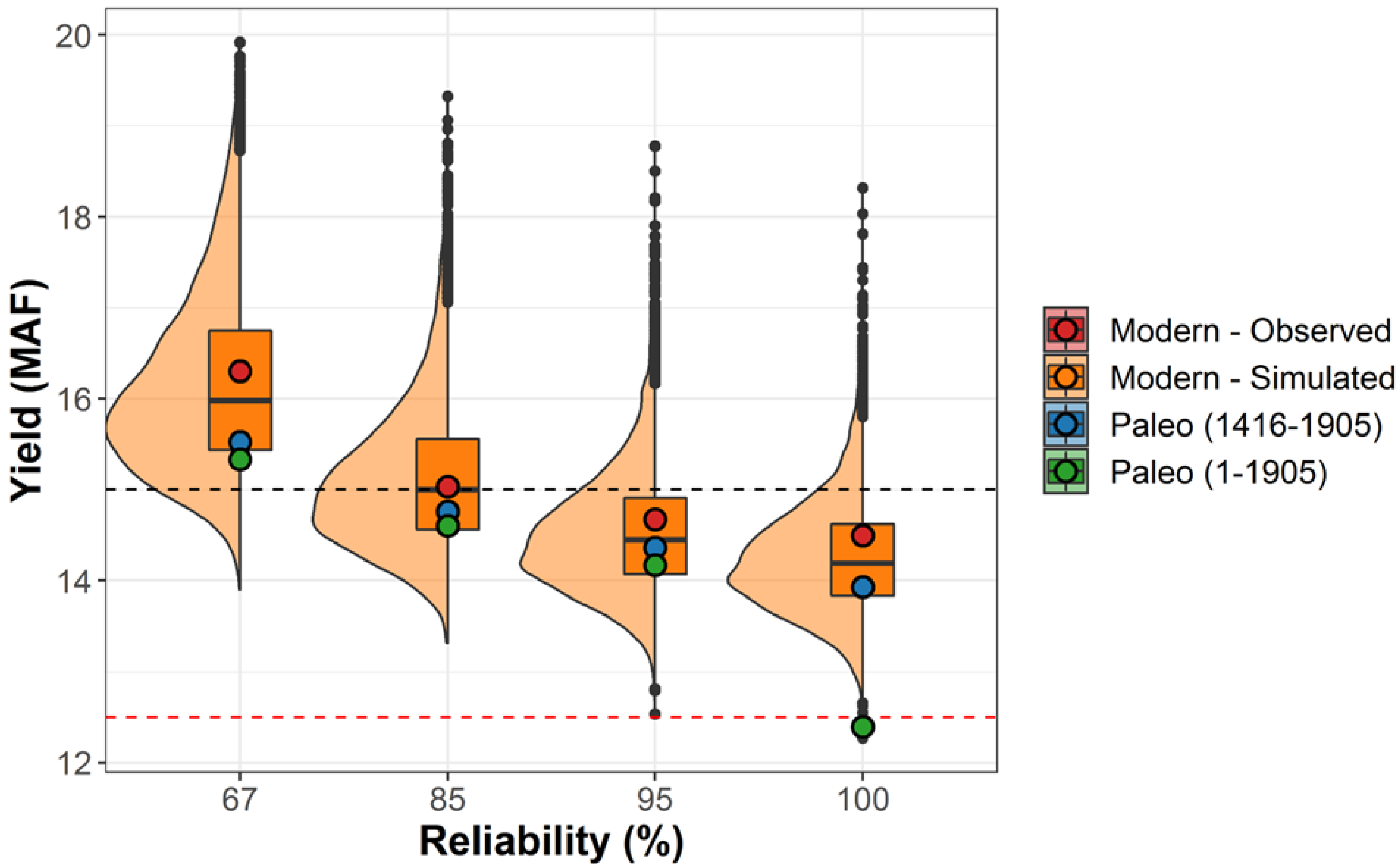






- 10X higher risk of 'millennium drought' in paleo record relative to current
- Frequent 20-year mean of 12.5MAF and lower
- **Need effective risk-based management**

Yield Reliability



- 15MaF is ~85% reliable
- 12.5MaF is ~100% reliable (current discussion!)
- 13.8 ~ 14.6MaF likely range of firm yield
- Risk of current allocations need to be clearly understood

(Woodson et al., 2025, NPJ in review)

The New York Times

A Breakthrough Deal to Keep the Colorado River From Going Dry, for Now

The agreement on cuts, aided by a wet winter and $1.2 billion in federal payments, expires at the end of 2026.

Give this article 1.2K

CLIMATE | A Breakthrough Deal to Keep the Colorado River From Going Dry, for Now

- Latest agreement – May 25th 2023
- 2 ~ 3 MAF of water use will be cut
- **$1.2B will be given to farmers and native American tribes to use less water**

Center for COLORADO RIVER Studies

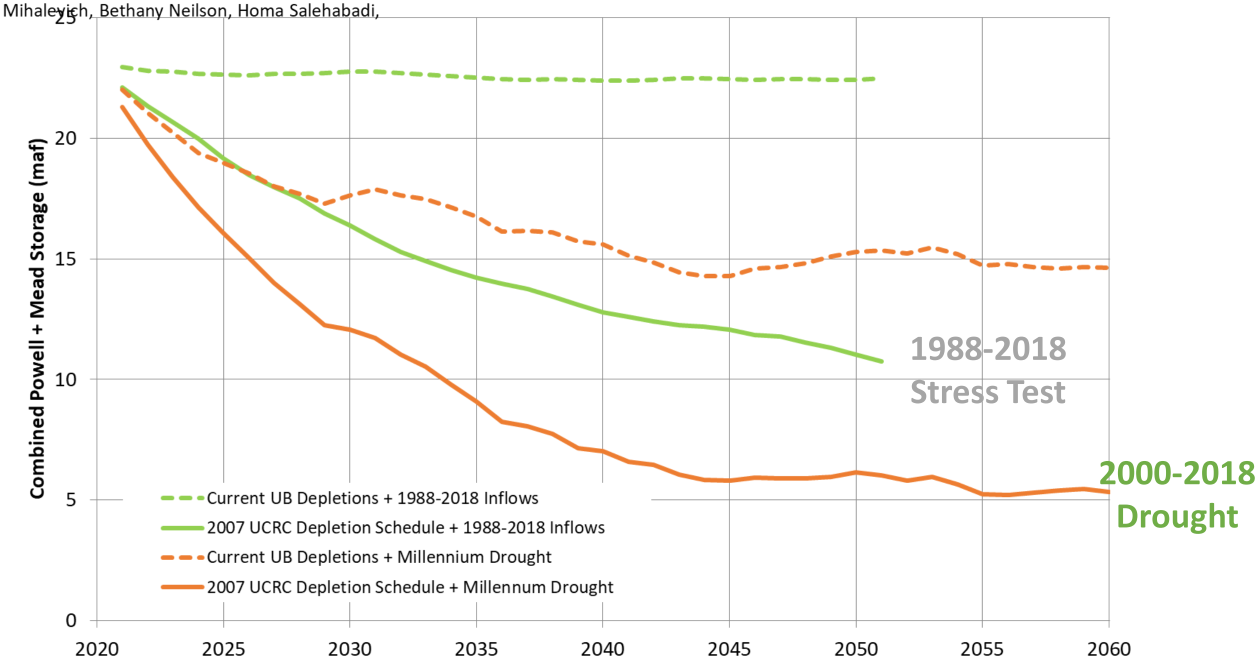
Wheeler et al, 2022 - White paper #6

White Paper #6:
Alternative Management Paradigms for the Future of the Colorado and Green Rivers

Kevin Wheeler, Eric Kuhn, Lindsey Bruckerhoff, Brad Udall, Jian Wang, Lael Gilbert, Sara Goeking, Alan Kasprak, Bryce Mihalevich, Bethany Neilson, Homa Salehabadi, John C. Schmidt

Existing Supply – Demand Balance is tenuous

Combined Mead + Powell Storage



With UCRC Projections

No Upper Basin Increase

MAIN MESSAGE:
If Upper Basin demands do not increase
AND
recent flows are representative of future runoff, then the system would stay at "sustainable" but low levels

Closing Thoughts

- Paleo reconstructed flows offer rich and robust range of variability
  - Consistent (and even larger) than from climate change projections
- Large (Mega) droughts have occurred in the past with higher probability and will likely occur
- Stochastic models simulate the rich nonstationarity. They form a good baseline to assess future climate projections
- Thoughtful water management can enable sustainable and resilient water supply
- Need to manage demand and growth

Nonlinearity begets Completeness,
Misjudgment creates Linearity
-- Lao Tsu

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