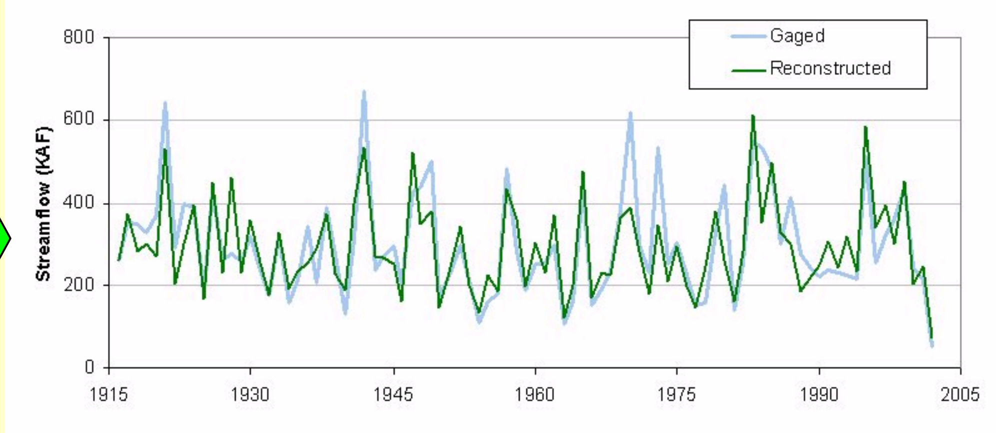
Tree-ring reconstructions of streamflow and their use in water management



US Bureau of Reclamation Upper Colorado Regional Office, March 27, 2008

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INSTAAR, University of Colorado

and Western Water Assessment

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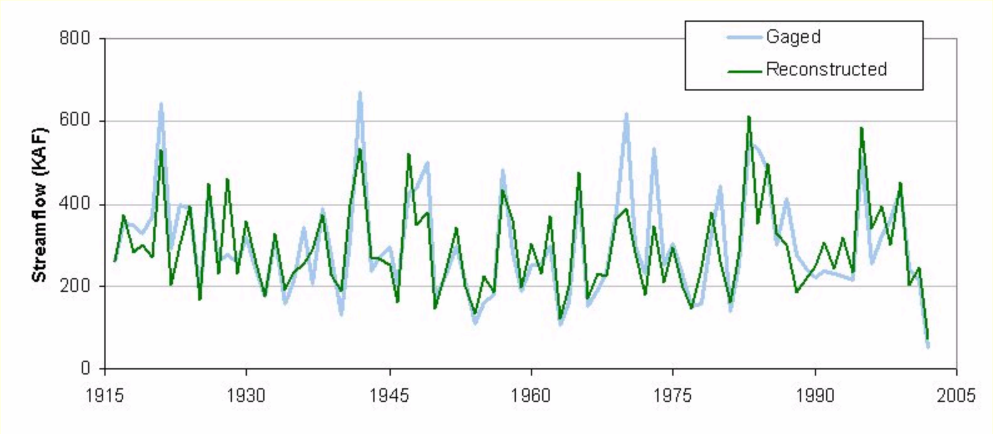
Outline

- Why use tree-ring reconstructions (paleohydrology)?
- Generating streamflow reconstructions from tree rings
- How these records are being used in water management

Part 1:

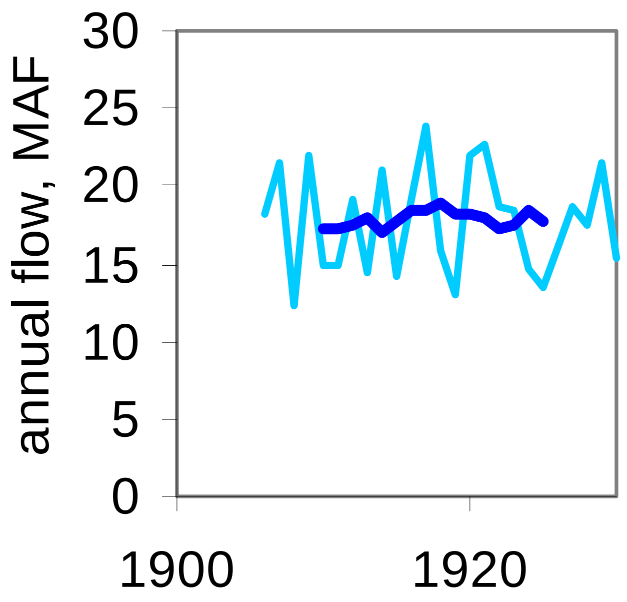
Why use tree-ring reconstructions (paleohydrology)?



How much “hydrologic experience” is enough?

Colorado River at Lees Ferry, AZ

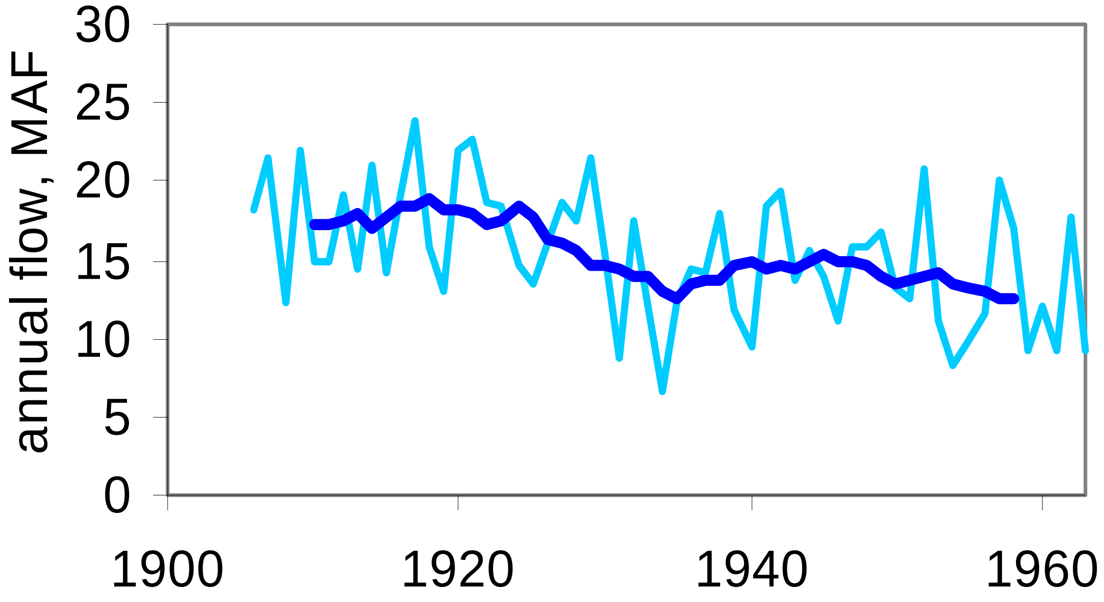
Gaged (natural flow) record, 1906-1930



How much “hydrologic experience” is enough?

Colorado River at Lees Ferry, AZ

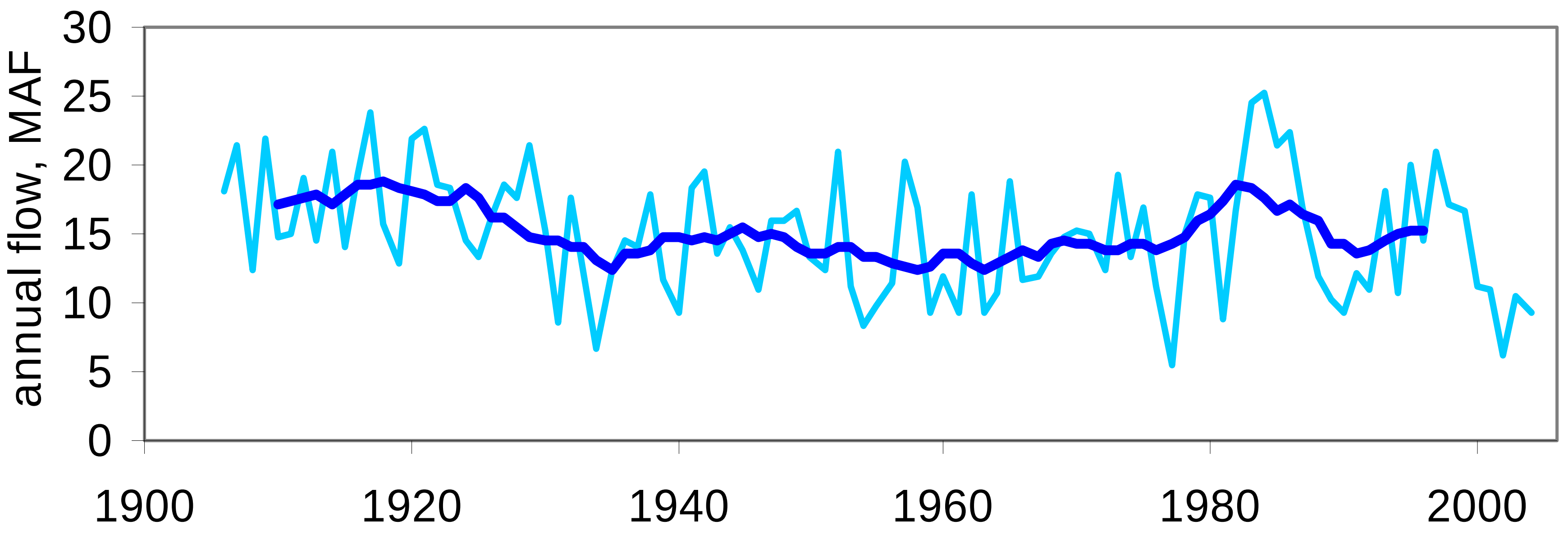
Gaged (natural flow) record, 1906-1963



How much “hydrologic experience” is enough?

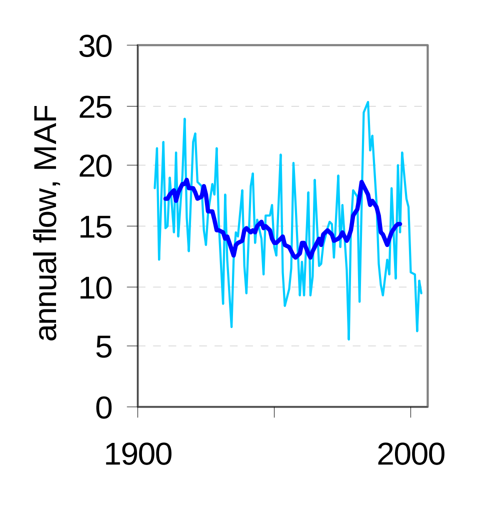
Colorado River at Lees Ferry, AZ

Gaged (natural flow) record, 1906-2004



Even ~100 years of gaged hydrology fails to capture the range of variability

Paleohydrology - a surrogate for experience



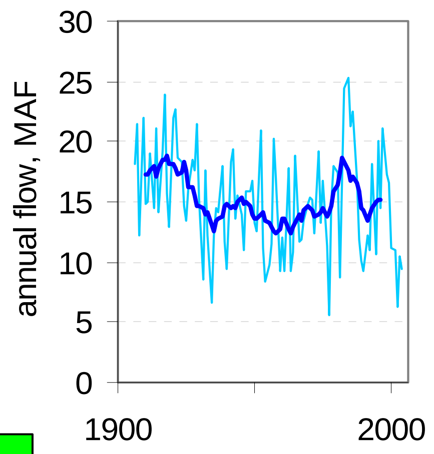
Colorado at Lees Ferry

Gaged (natural flow) record

1906-2004

Paleohydrology - a surrogate for experience

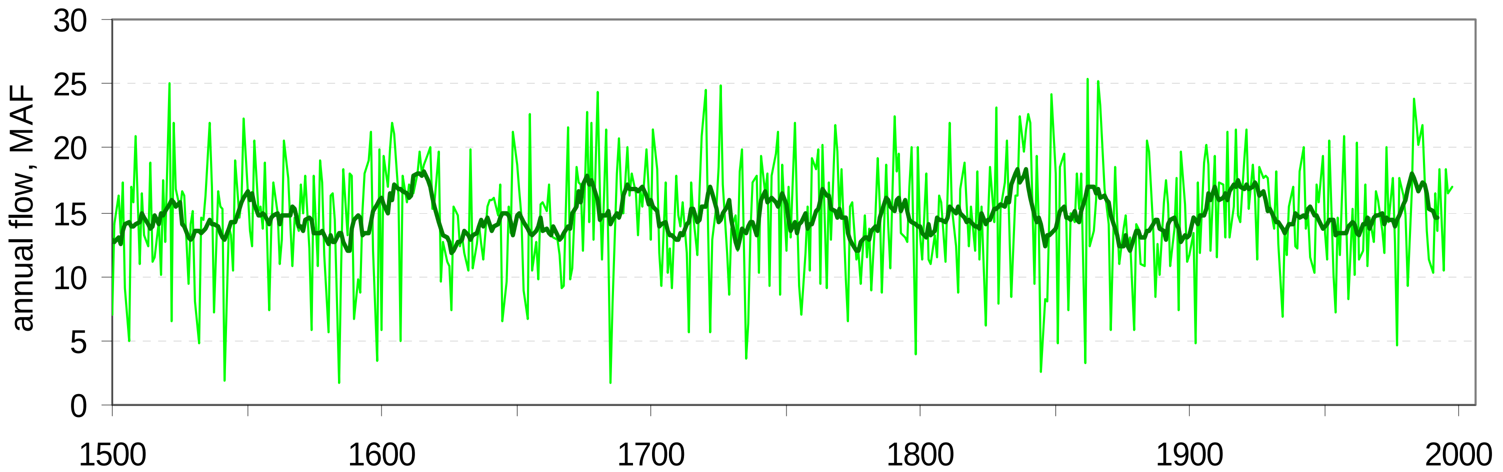
By extending the gaged hydrology by hundreds of years into the past, paleo-records provide a more complete picture of hydrologic variability



Colorado River at Lees Ferry

Gaged (natural flow) record

1906-2004



Tree-ring reconstruction

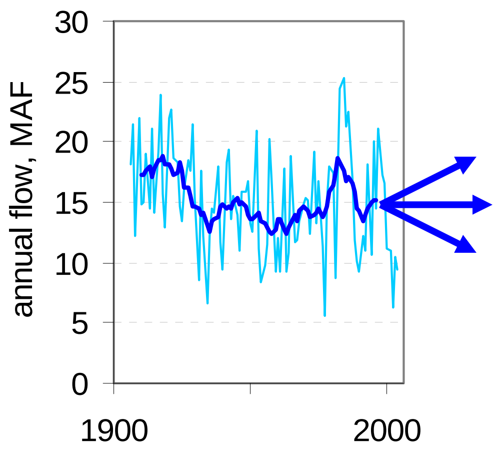
1490-1997

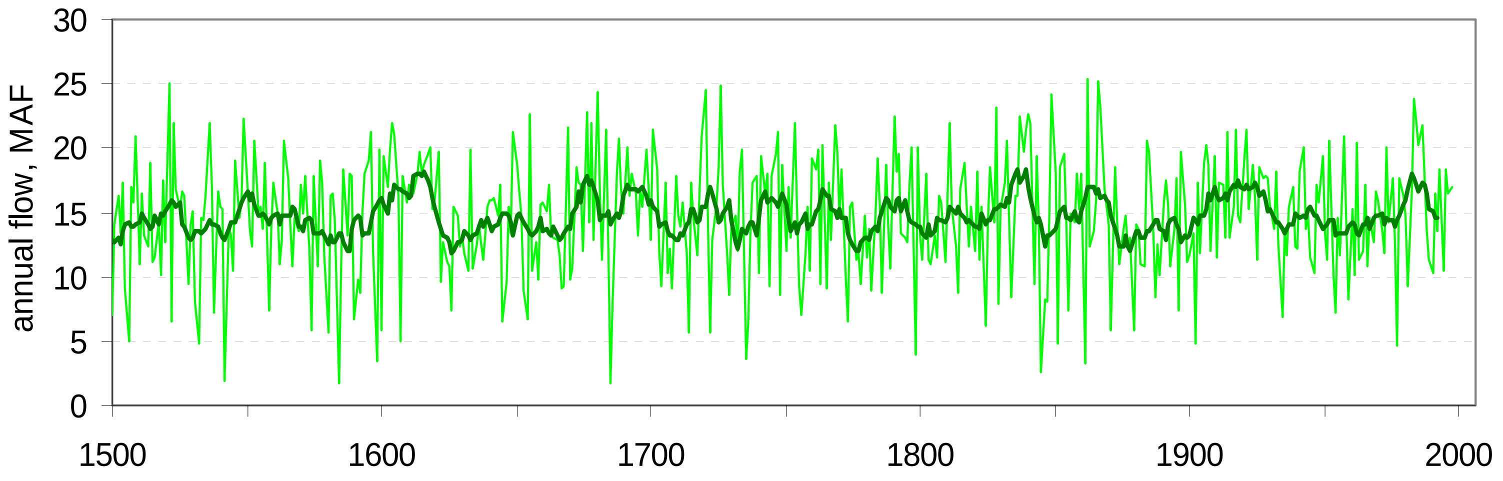
Paleohydrology - a surrogate for experience

Benefits:

- Better *anticipation* (not *prediction*) of future conditions

- Better assessment of *risk*





Tree-ring reconstruction

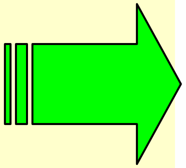
1490-1997

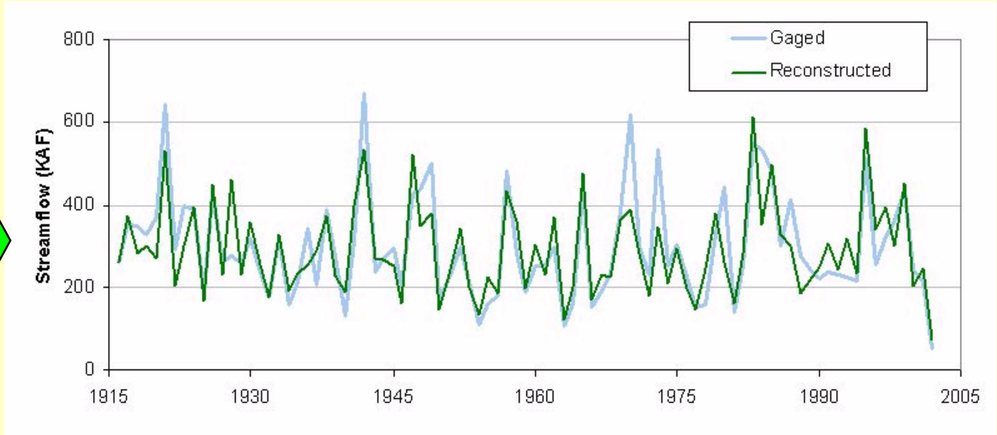
Attributes of tree rings useful for paleohydrology

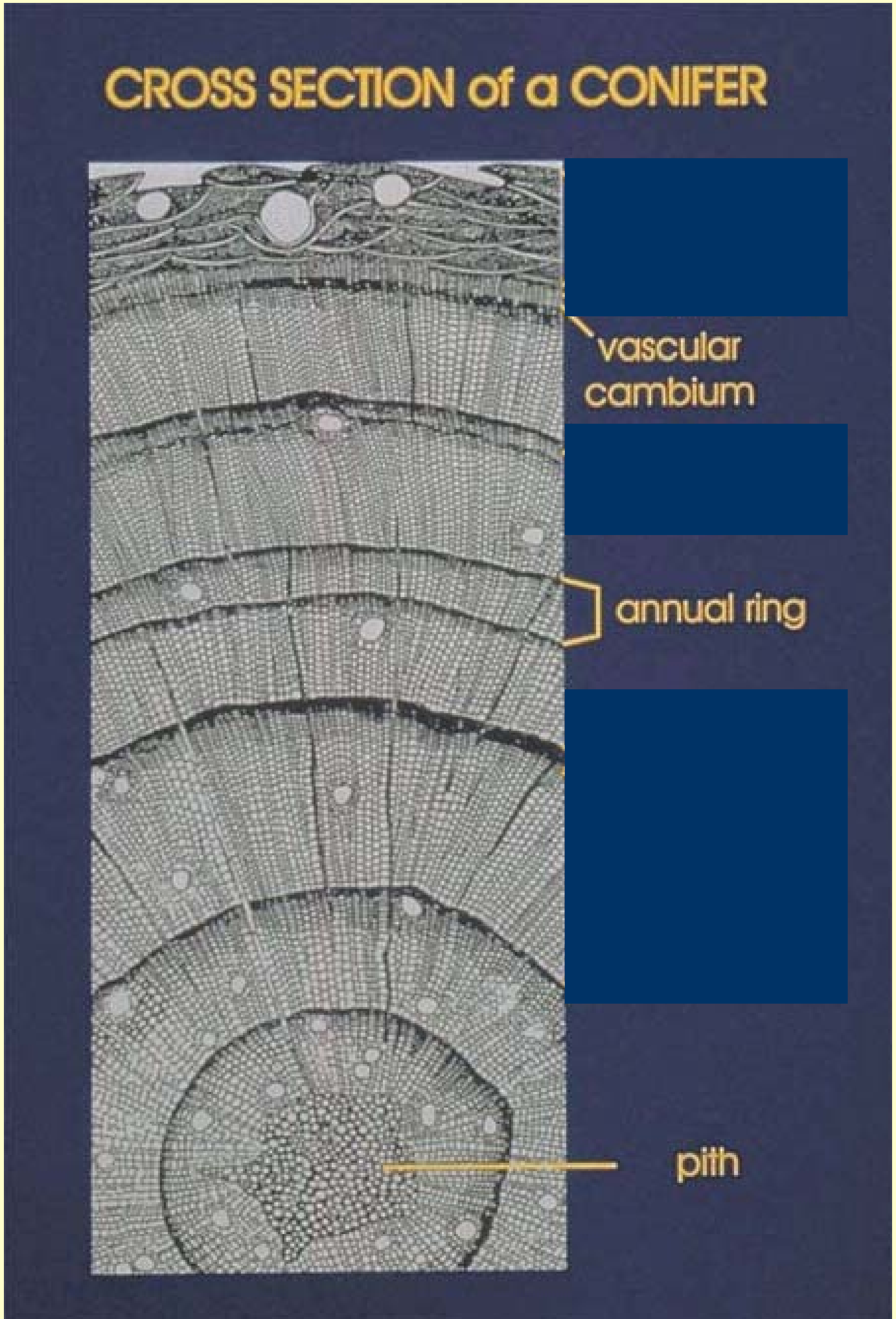
- Annual resolution and absolute dating
- Long, continuous records (300-10,000 yrs)
- Widespread distribution
- High sensitivity and fidelity to climate variability

Part 2:

Generating streamflow reconstructions from tree rings







The formation of annual growth rings

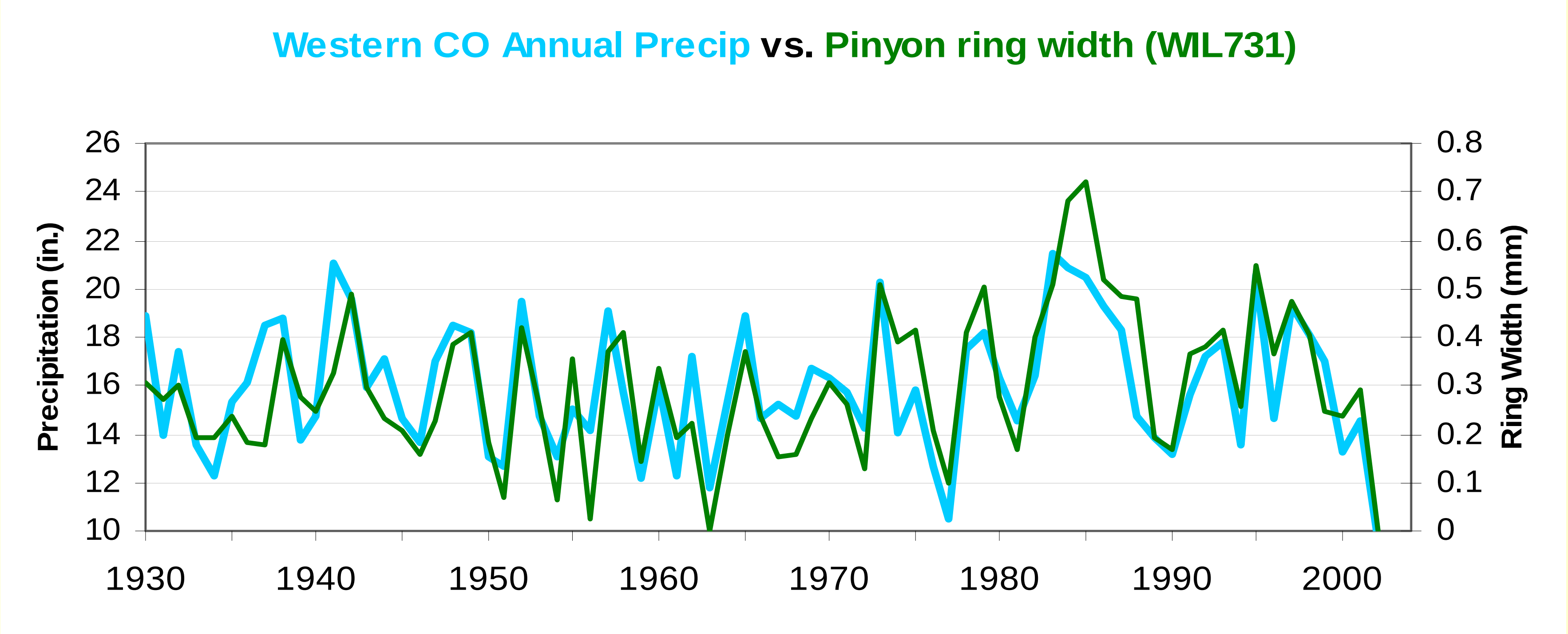
- New wood forms in the vascular cambium, underneath the bark
- In temperate climates, a growth ring = *annual ring*
- Rings have varying widths when a *limiting factor* on growth varies in magnitude from year to year

Climate is often the limiting factor on tree growth

- At high elevations and high latitudes, growth is typically limited by summer warmth and length of the growing season (“temperature-sensitive”)

- At lower and middle elevations in the mid-latitudes, growth is more limited by moisture availability (“moisture-sensitive”)

The moisture signal recorded by trees in the southwest US is particularly strong



- The “raw” ring widths from *one* tree are very closely correlated with annual basin precipitation (r = 0.78) from 1930-2002
- Our job is to *capture* and *enhance* the moisture signal, and reduce noise, through careful sampling and data processing

Ring-width and streamflow - an indirect but robust relationship

- Like ring width, streamflow integrates the effects of precipitation and evapotranspiration, as mediated by the soil

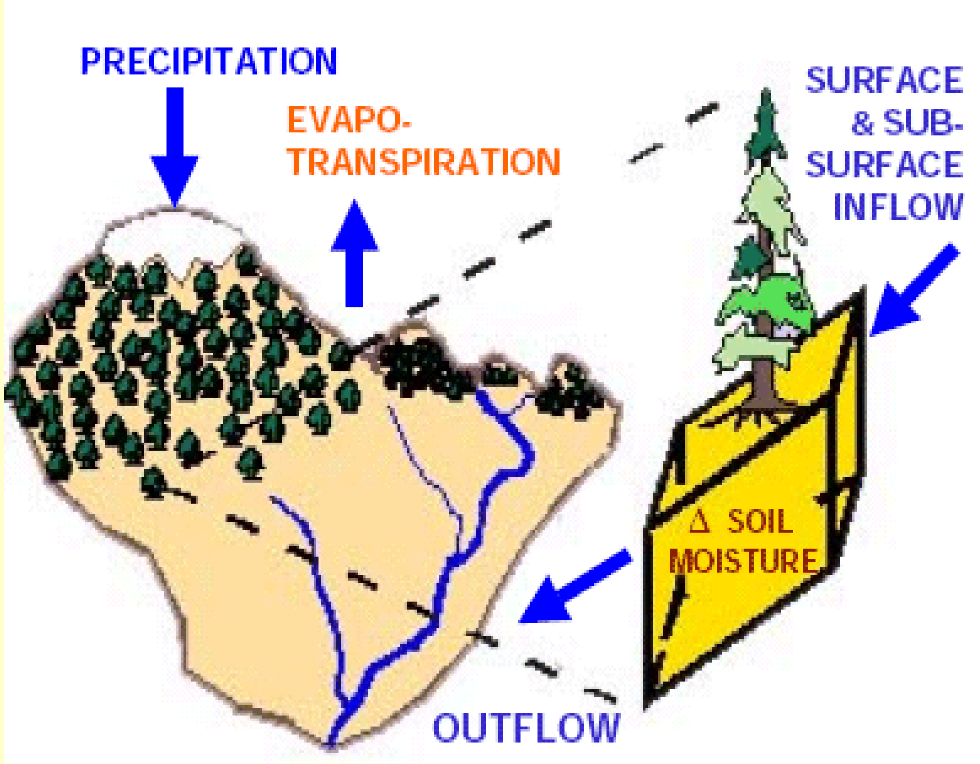
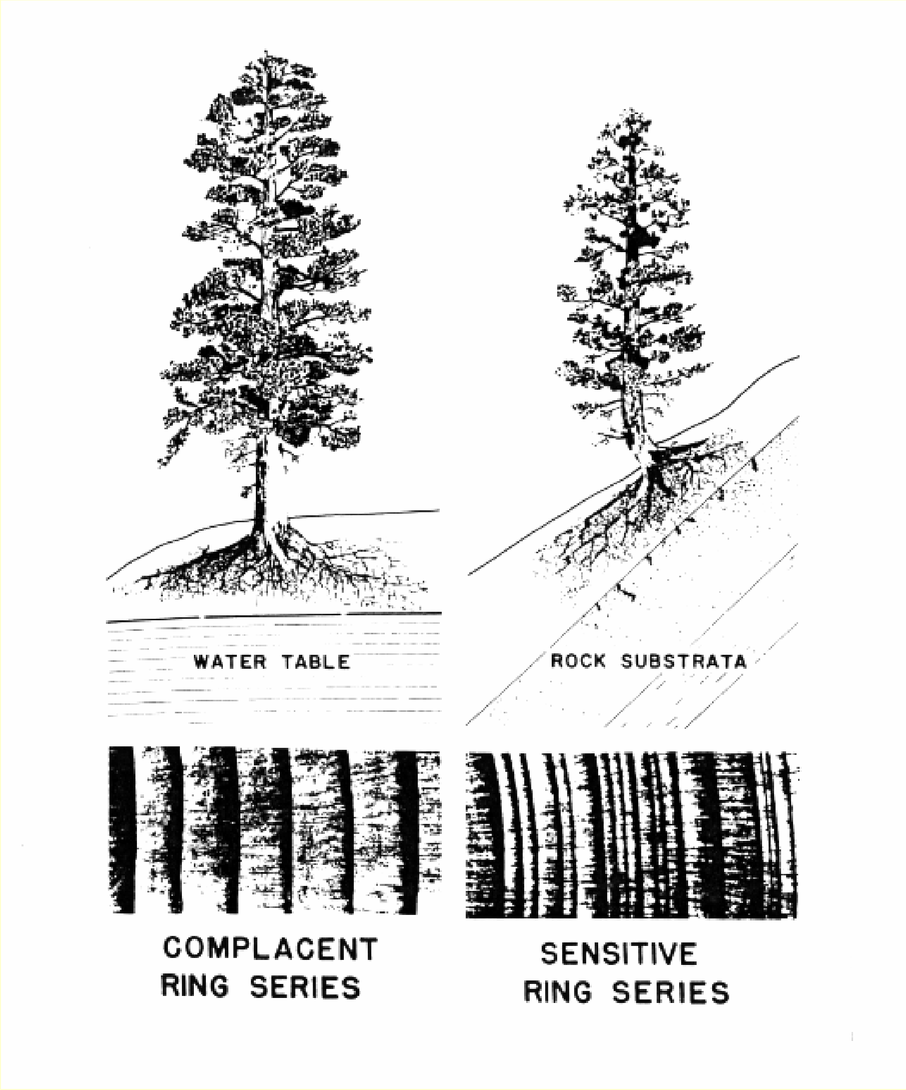


Image courtesy of D. Meko (U. AZ)

Stressful sites produce ring series with greater sensitivity (higher signal:noise ratio)



from *Fritts 1976*

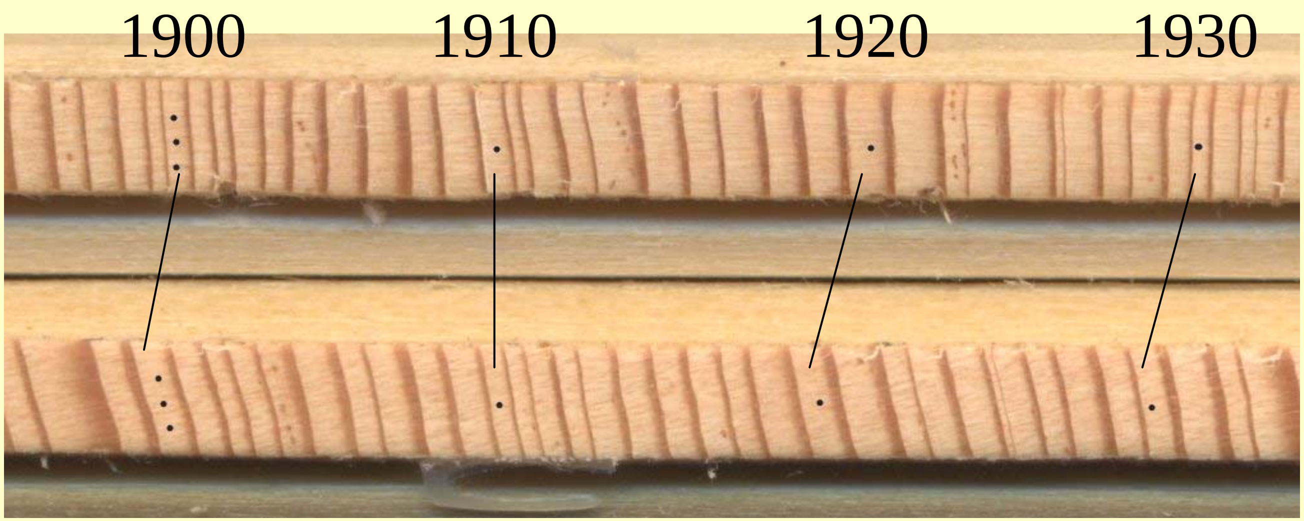
Sampling the trees for a site *chronology*

- Core 10-30+ trees at a site, same species
- Goal: maximize the number of cores throughout the chronology (300-800+ years)
- Can also core or cut cross-sections from dead trees

Crossdating the samples

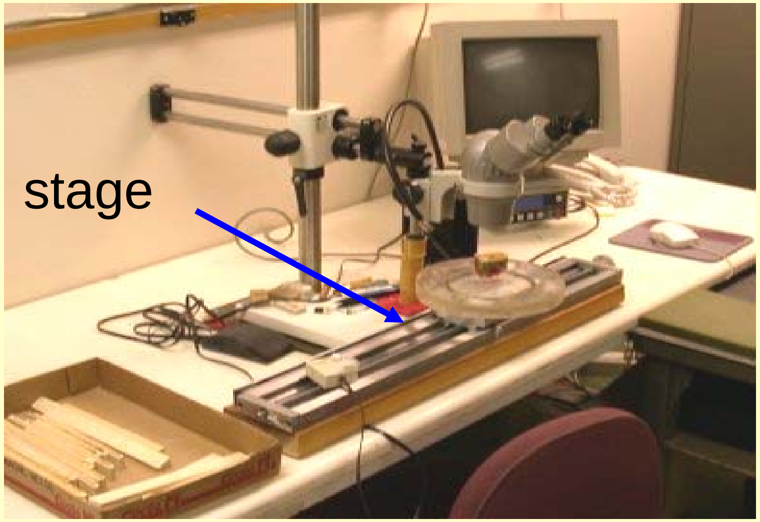
- Because of the common climate signal, the pattern of wide and narrow rings is highly replicated between trees at one site, and between nearby sites

- This allows *crossdating:* the assignment of absolute dates to annual rings (not just ring-counting)

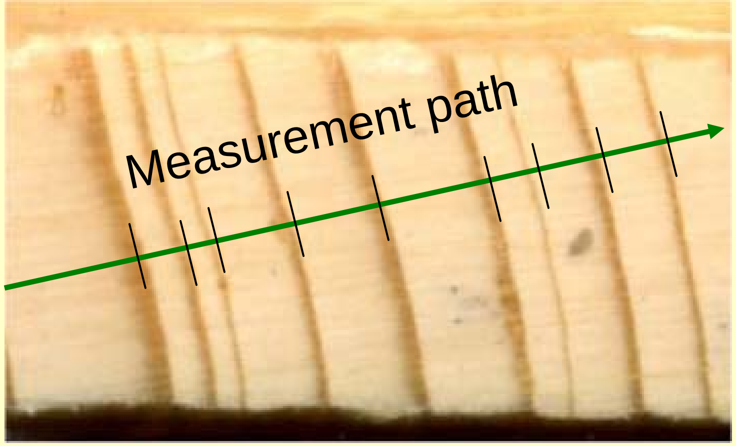


Two Douglas-fir trees south of Boulder, CO

Measuring the samples

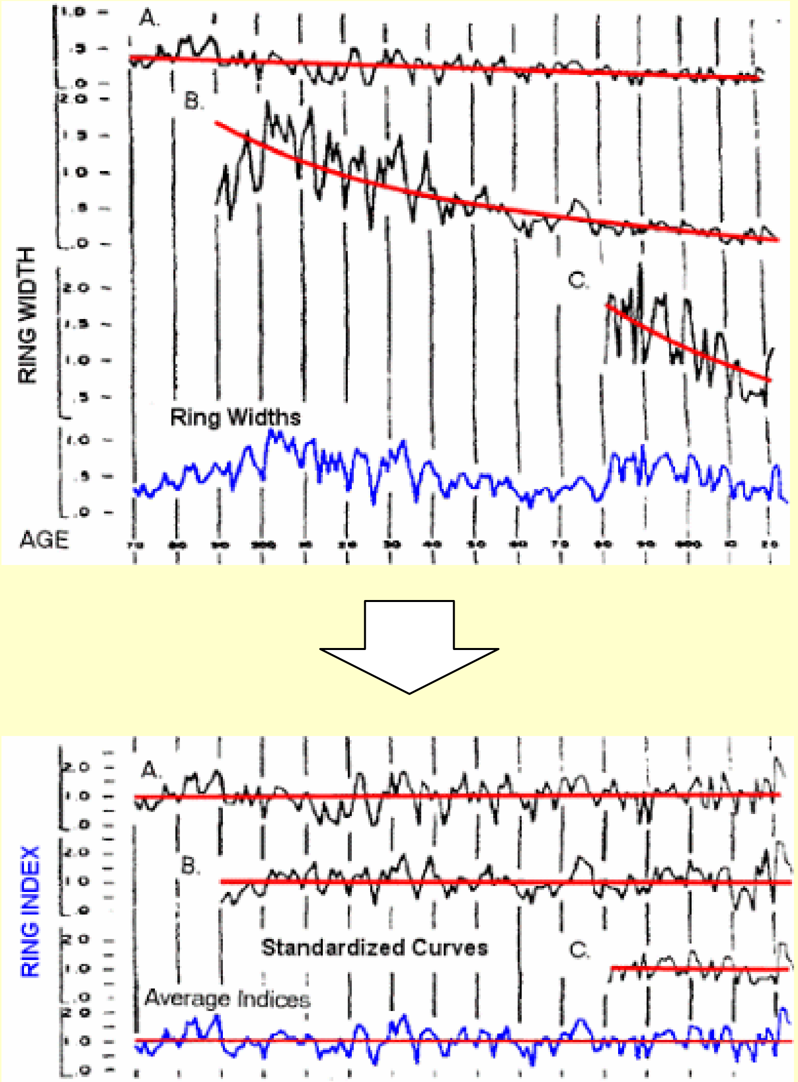


- Computer-assisted measurement system with sliding stage
  - captures position of core to nearest 0.001mm (1 micron)



- Measurement path is parallel to the rows of cells (and perpendicular to the ring boundaries)

Detrending the measured ring-width series

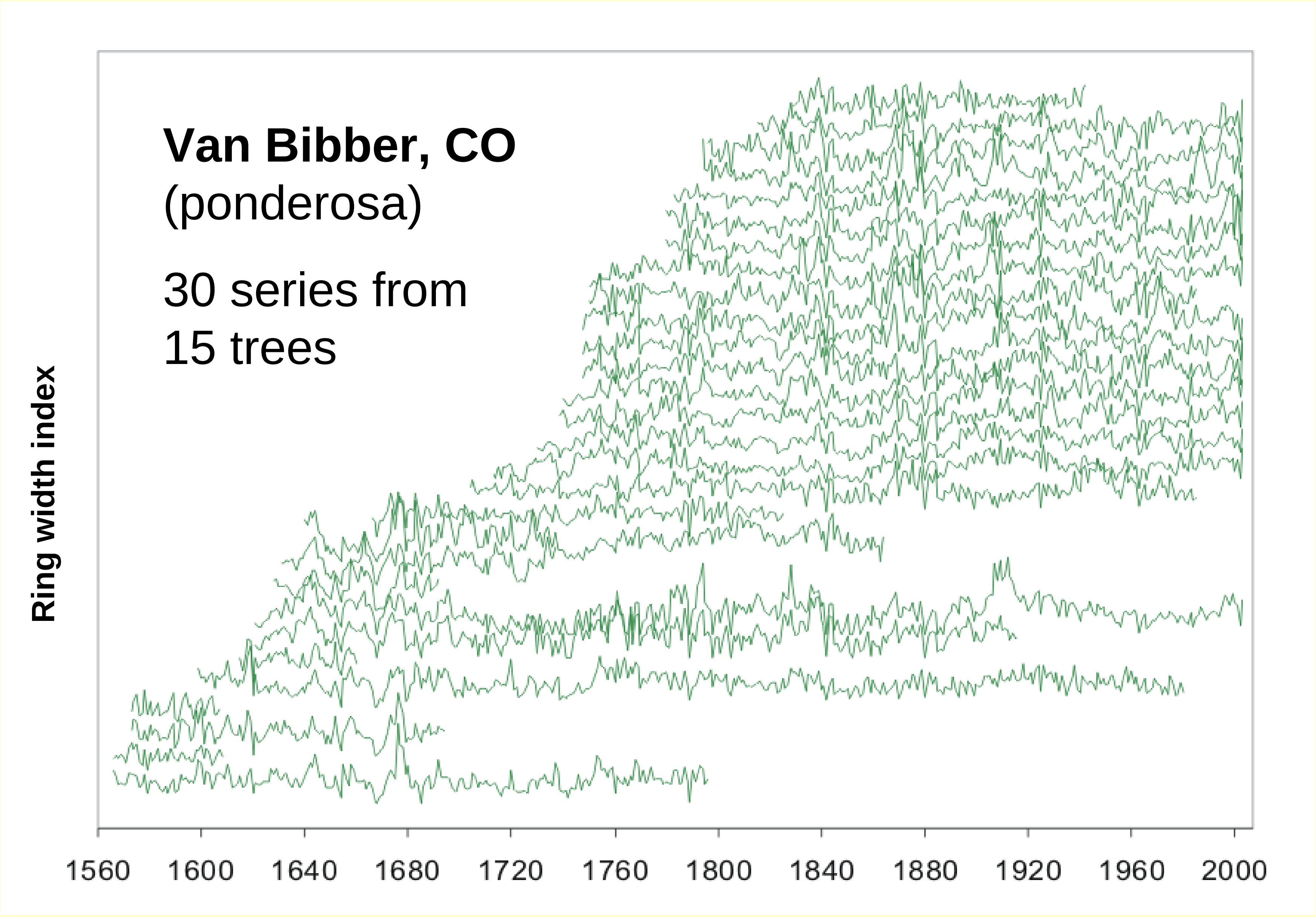


- Ring-width series typically have a declining trend with time because of changing tree geometry and aging
- These are low-frequency *noise* (i.e. non-climatic)

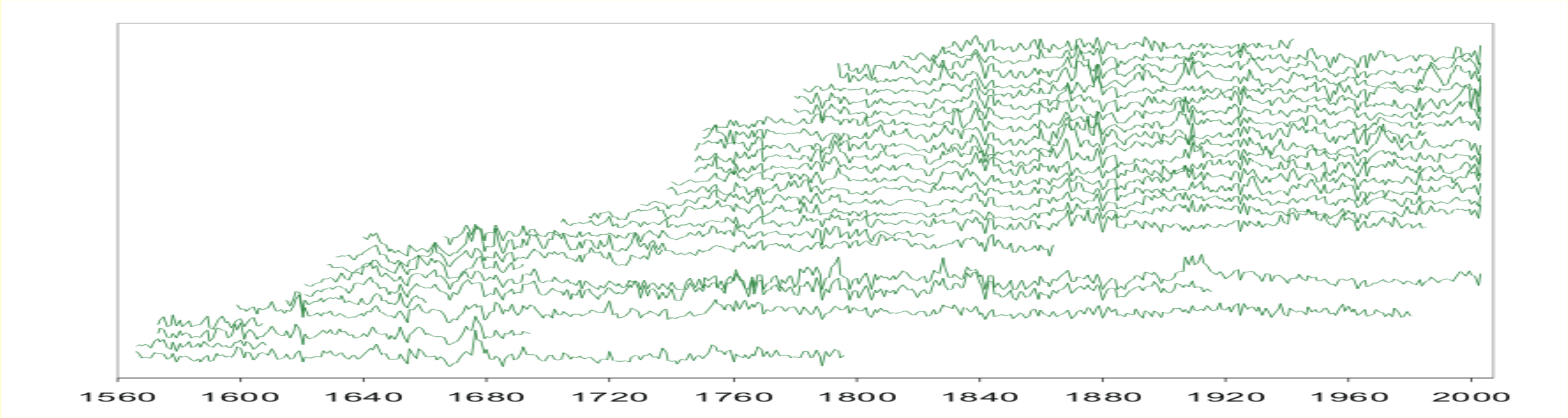
- Measured ring series are detrended to remove the growth trend

- These *standardized* series are compiled into the site chronology

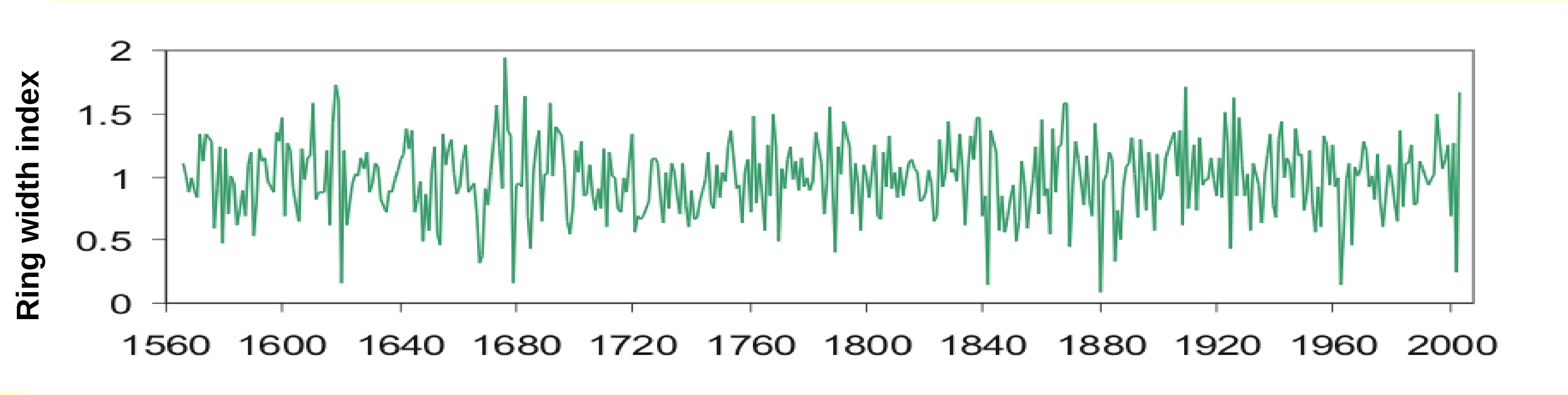
By compiling the measurements from many trees...



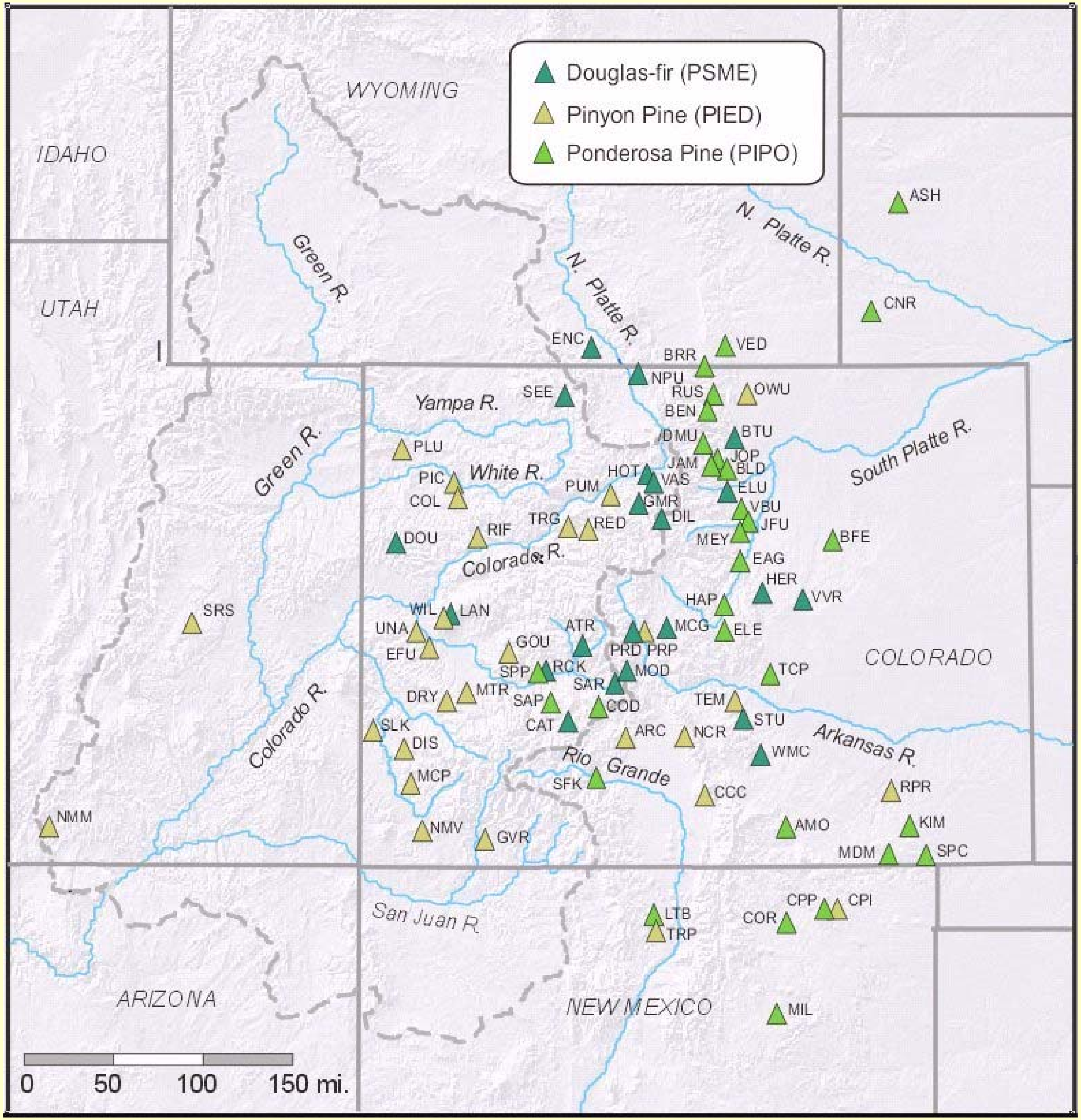
…we enhance the common (climate) signal in the resulting site chronology



Robustly weighted mean

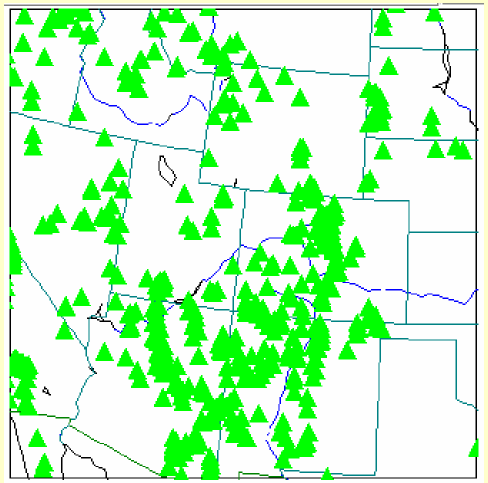


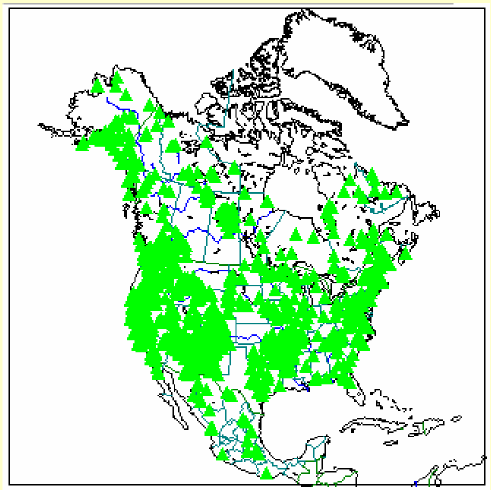
Moisture-sensitive chronologies developed 2000-2006 by CU-INSTAAR Dendro Lab

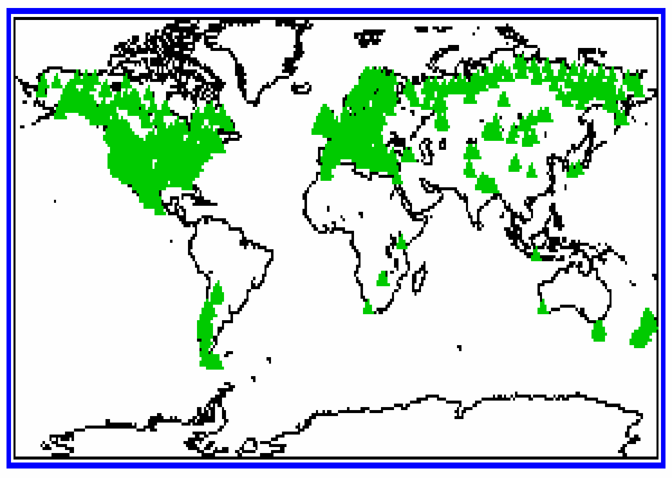


The larger world of tree-ring chronologies

International Tree-Ring Data Bank (ITRDB)
http://www.ncdc.noaa.gov/paleo/treering.html

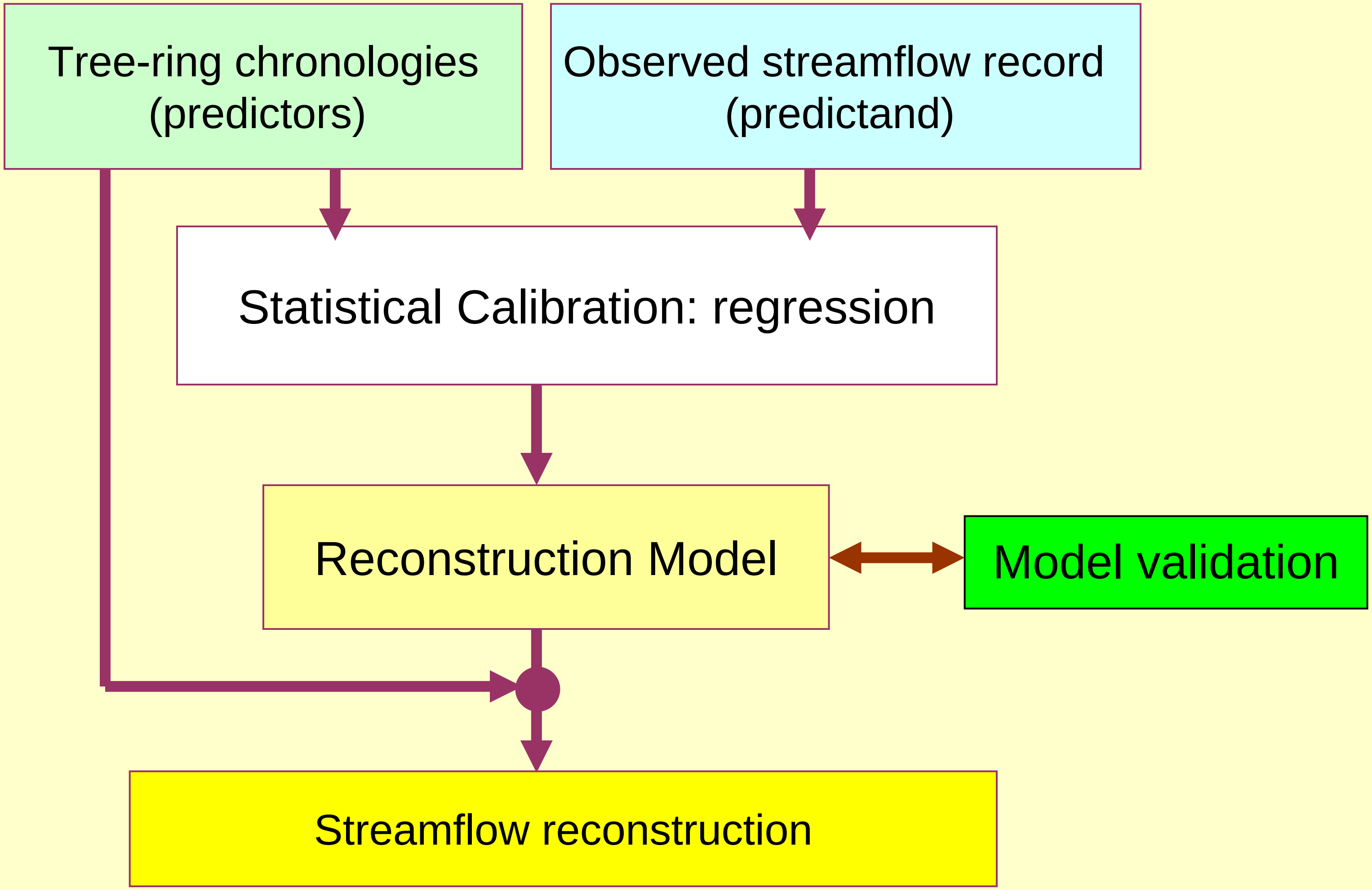






- 2500 chronologies contributed from all over the world
- Can be searched by moisture-sensitive species, location, years

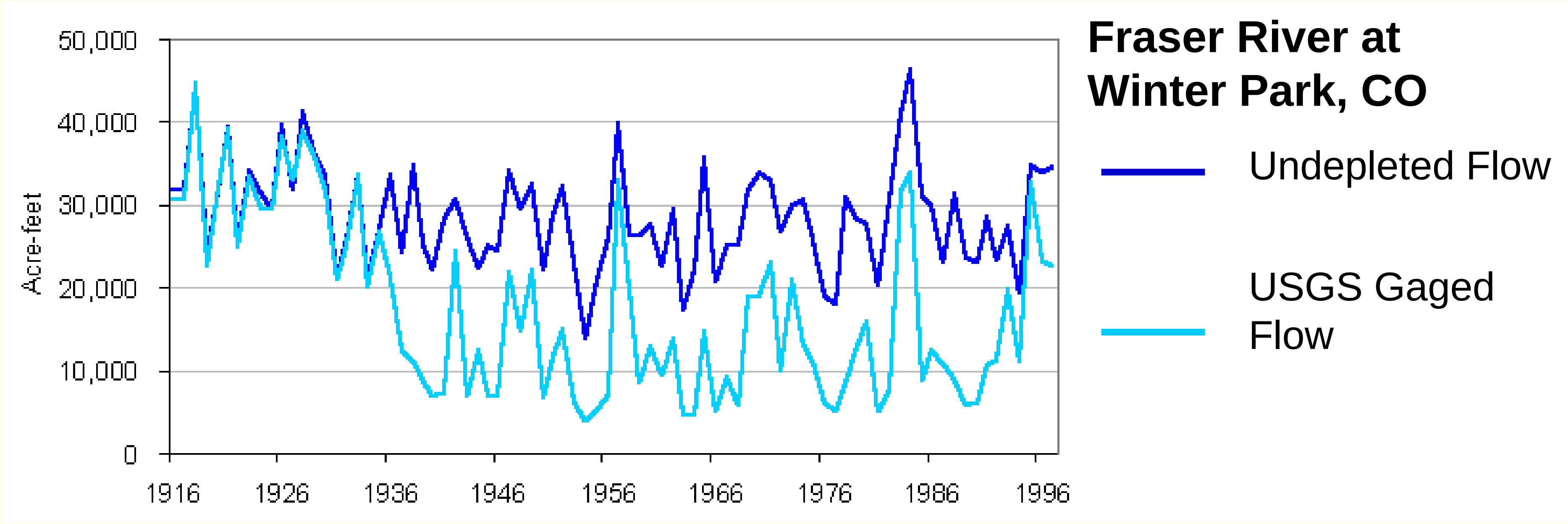
Overview of reconstruction methodology



based on Meko 2005

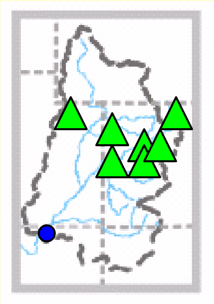
Requirements for observed streamflow record

- **Length** – minimum 50 years for robust calibration with tree-ring data
- **Natural/undepleted record** – must be corrected for depletions, diversions, evaporation, etc.



- *The reconstruction can only be as good as the flow record on which it is calibrated*

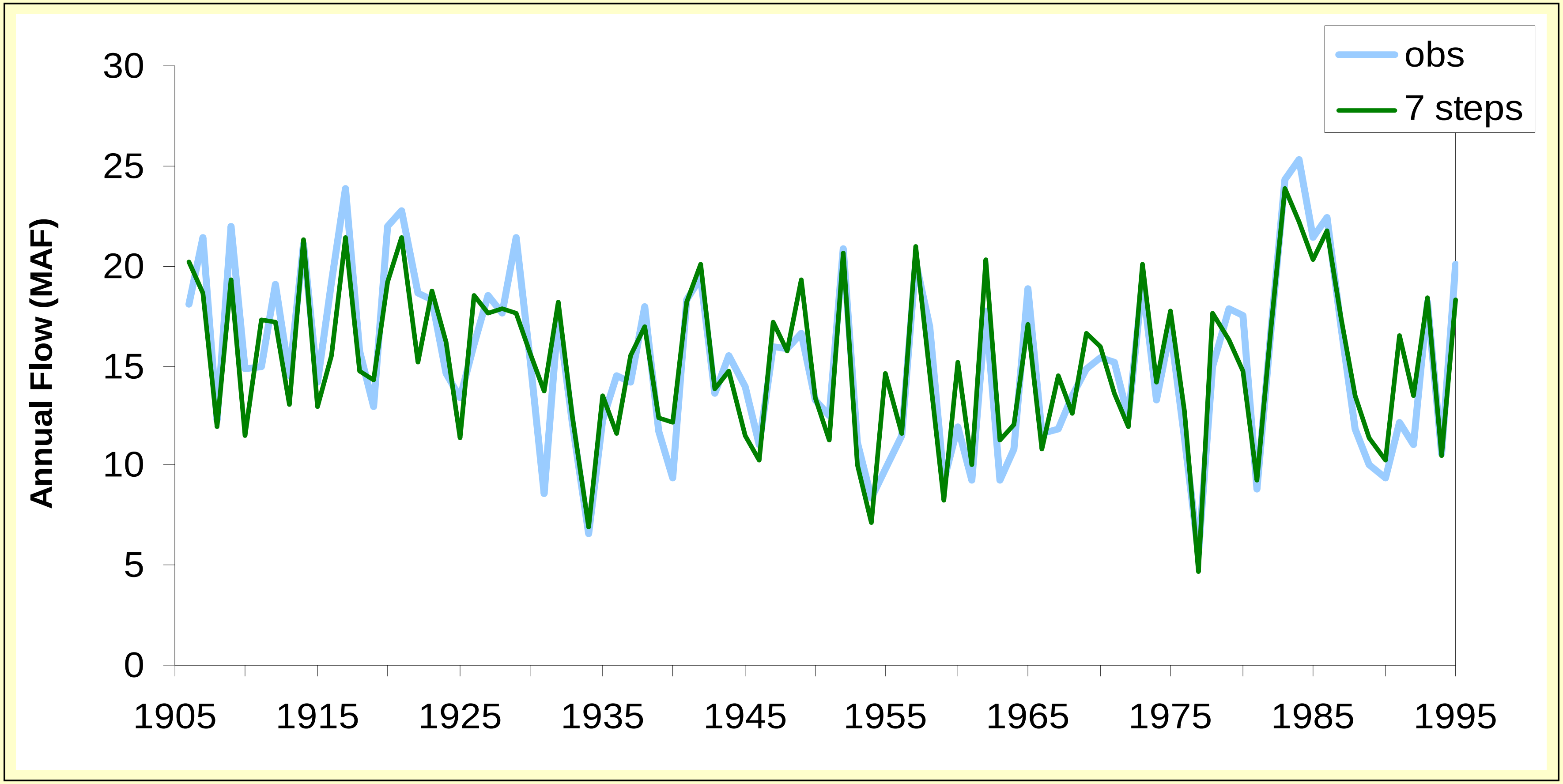
Colorado at Lees Ferry - forward stepwise regression



Variance Explained

TRG + WIL + DJM + DOU + NPU + RED + PUM

81%



How does the model validate on data not used to calibrate the model?

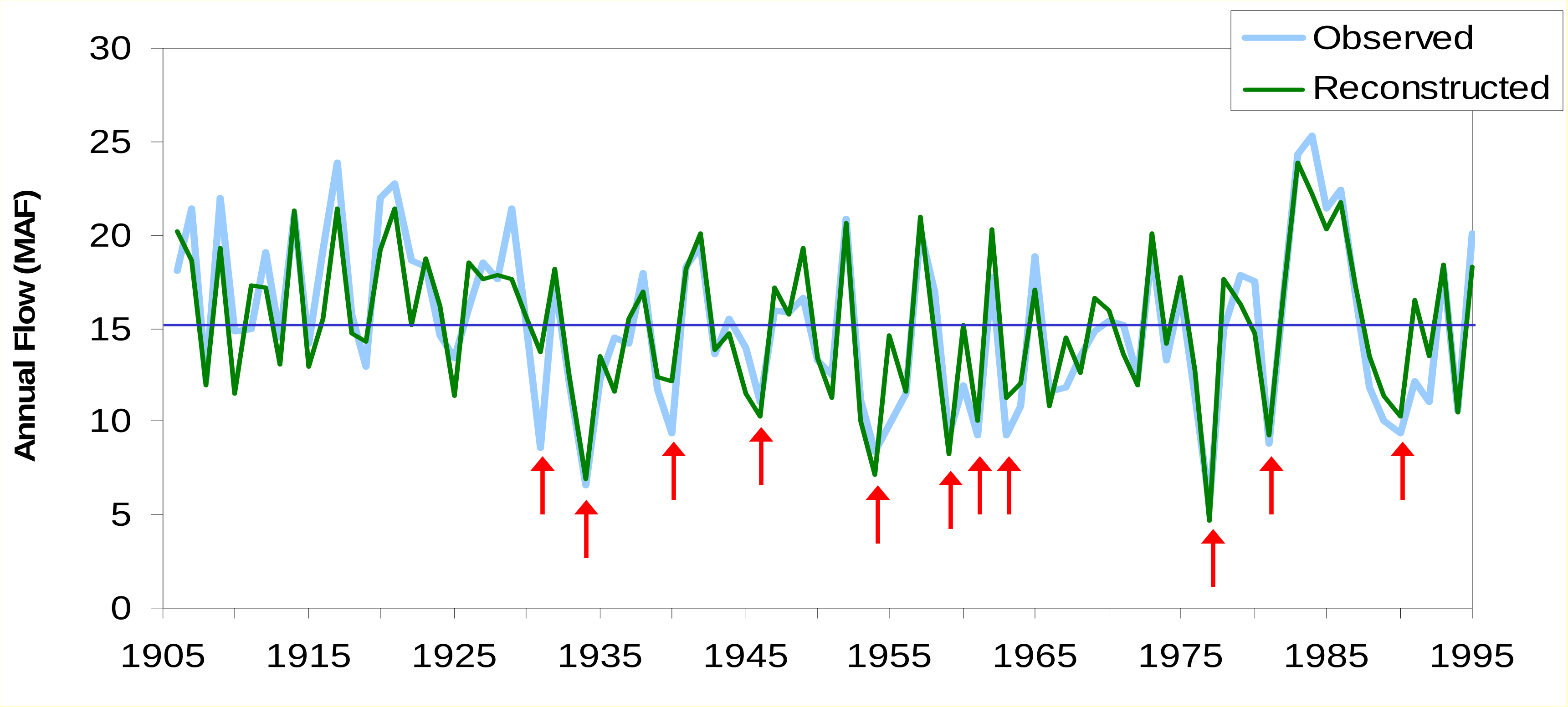
Validation statistics – based on withheld data or data generated in cross-validation process, compared to observed data

	Calibration	Validation
Gage	**R^2**	**RE***
Boulder Creek at Orodell (CO)	0.65	0.60
Rio Grande at Del Norte (CO)	0.76	0.72
Colorado R at Lees Ferry (AZ)	0.81	0.76
Gila R. near Solomon (AZ)	0.59	0.56
Sacramento R. CA)	0.81	0.73

R^2 and RE should be similar, and ideally above 0.50, though much above 0.80 suggests overfitting

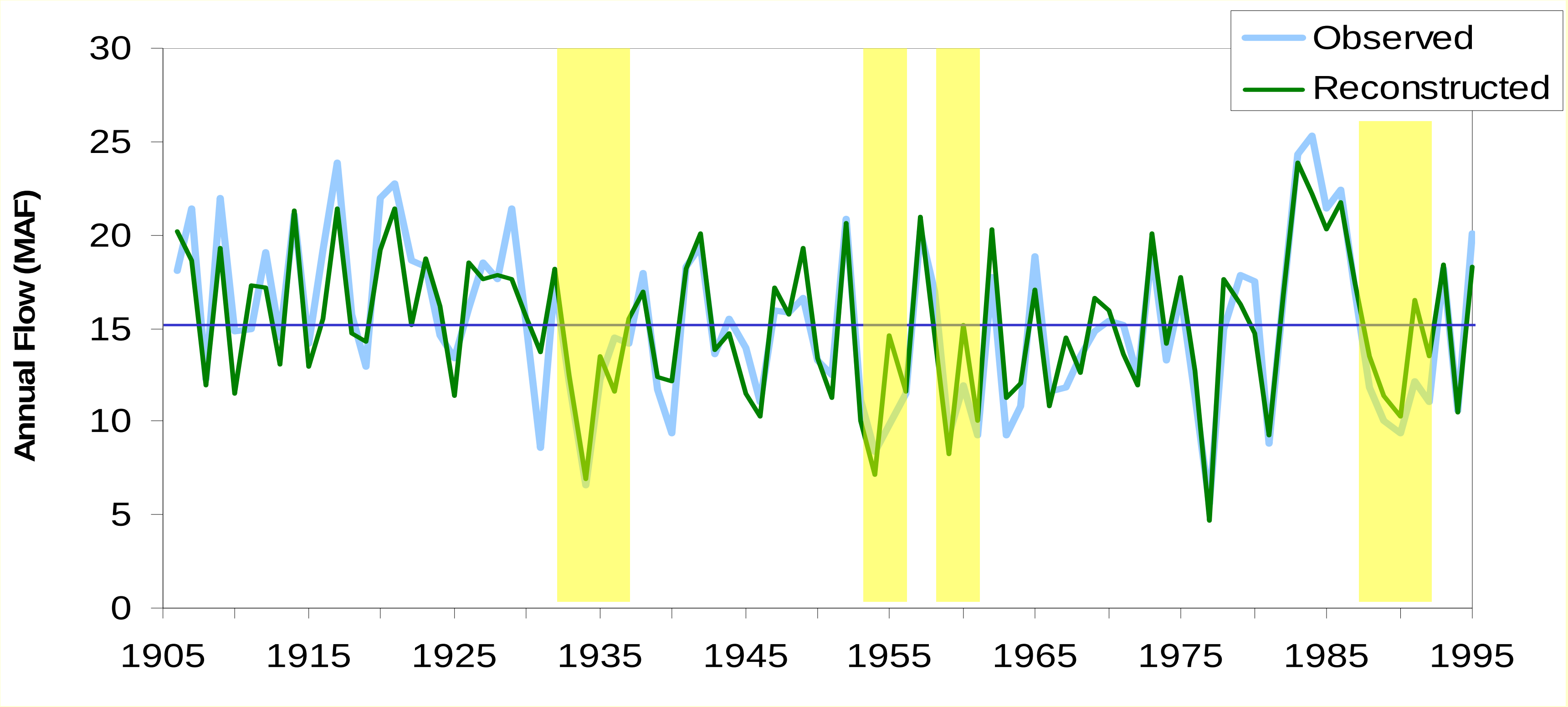
*RE is Reduction of Error statistic; tests model skill against “no knowledge”

Subjective assessment of model quality



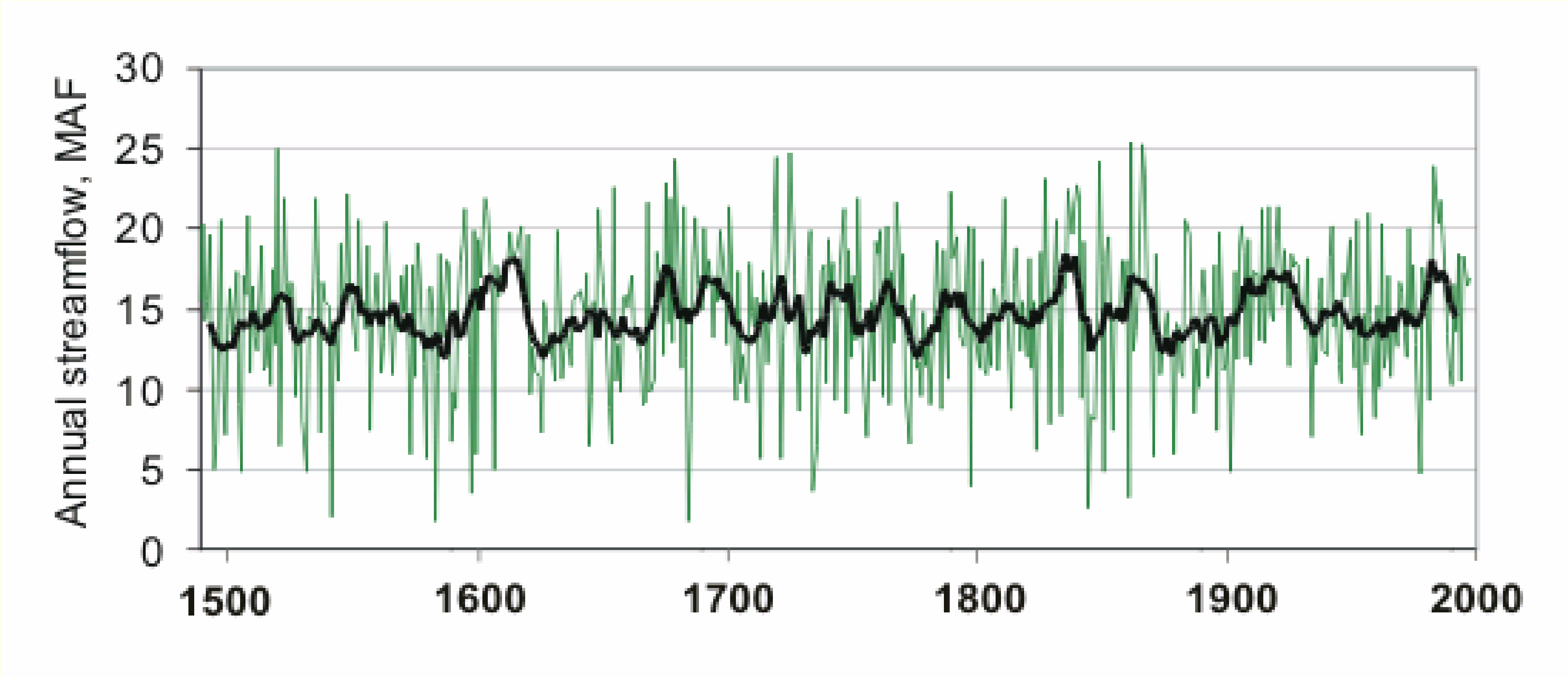
- Are severe drought years replicated well, or at least correctly classified as drought years?

Subjective assessment of model quality



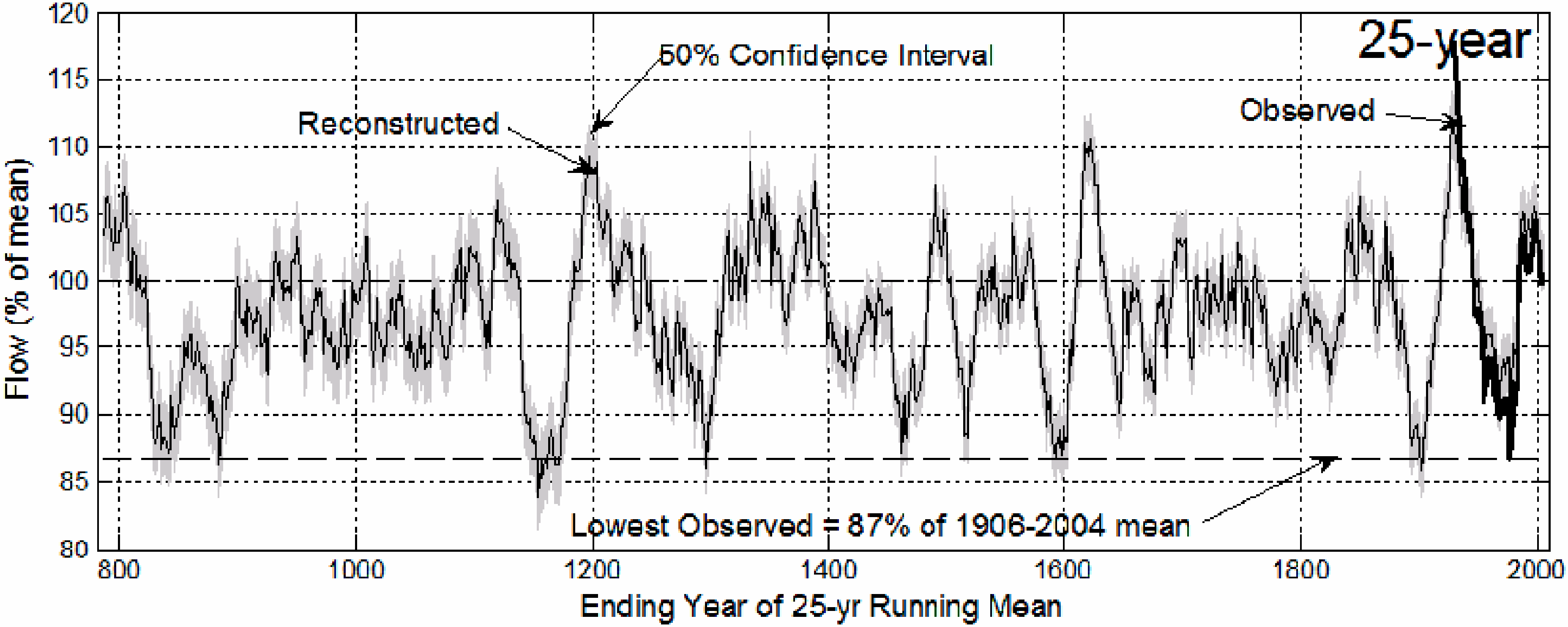
- Are the lengths and total deficits of multi-year droughts replicated reasonably well?

Full Colorado R. at Lees Ferry streamflow reconstruction, 1490-1997 (Woodhouse et al. 2006)



- Annual values in green, 10-year running mean in black

Meko et al. 2007 - Colorado River at Lees Ferry, AD 762 - 2005



25-yr running means of reconstructed and observed annual flow of the Colorado River at Lees Ferry, expressed as percentage of the 1906-2004 observed mean.

From: Meko et al. 2007. Medieval Drought in the Upper Colorado River Basin, *Geophysical Research Letters*

Uncertainty in the reconstructions

- Tree-ring data are imperfect recorders of climate and streamflow, so there will always be uncertainty in the reconstructed values

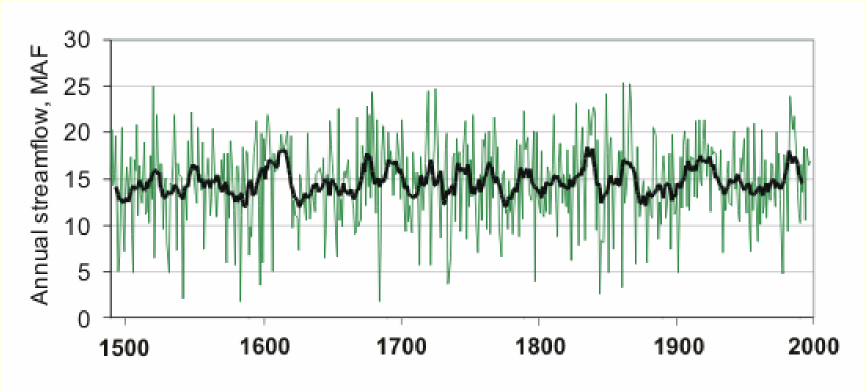
- The statistical uncertainty in the reconstruction model can be estimated from the validation errors (RMSE)

- The reconstructed flows are also sensitive to the decisions made in the data selection and modeling

- *A reconstruction is a plausible estimate of flows using a given set of data and modeling decisions; there is no one “right” reconstruction (though higher RE values usually indicate a better one)*

Part 3:

How reconstructions are being used in water management in the western US



Reconstruction data

?

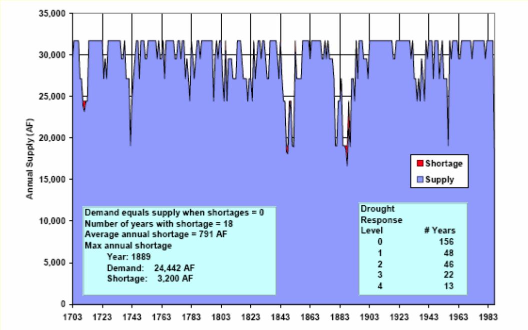


Figure 5. Demands & Supplies: 15% Reduced Flow Hydrology, Current Trends Scenario (demand = 31,700 AF/year).

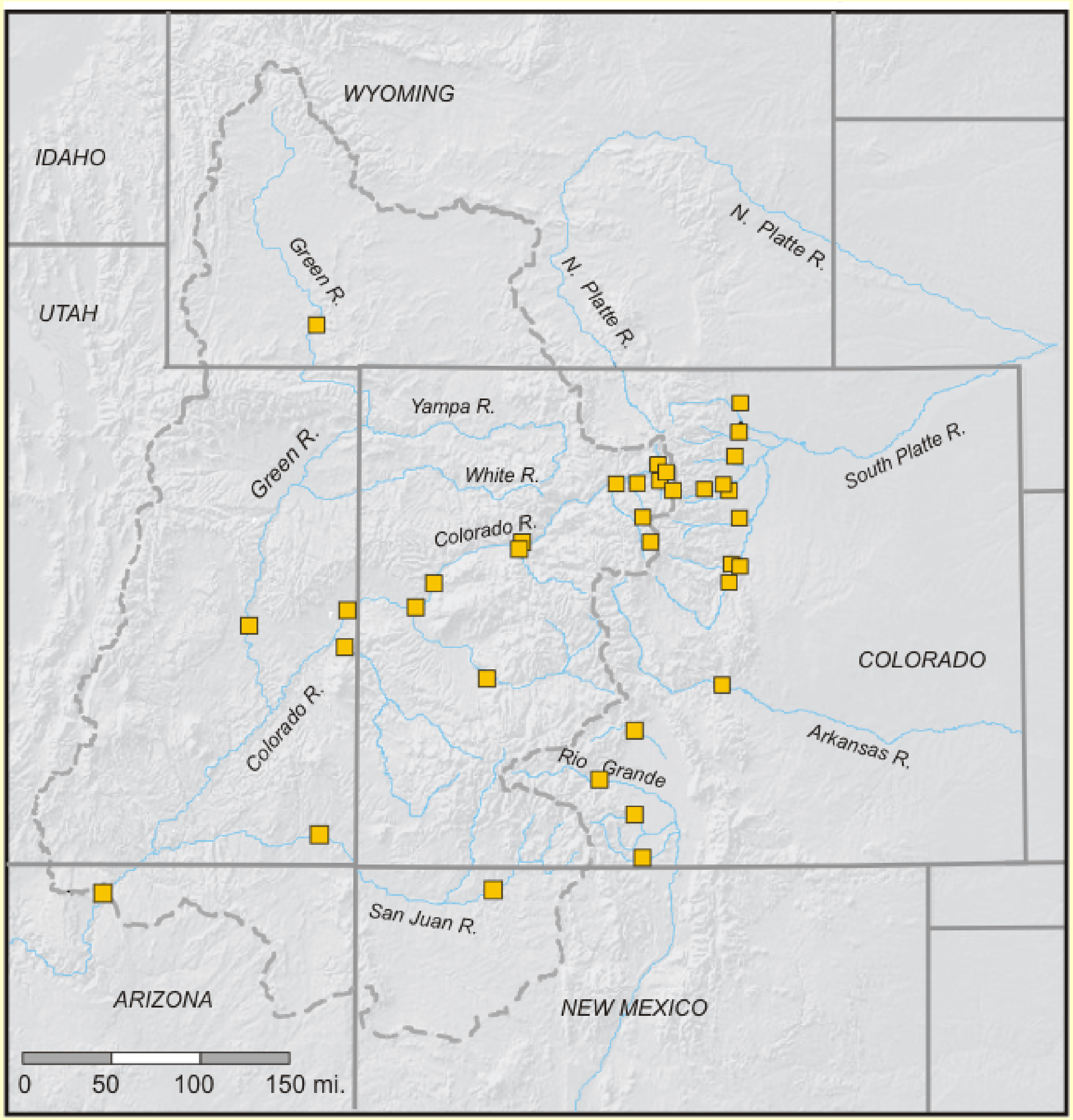
Policy analysis

New (>2000) tree-ring reconstructions of streamflow

- Over 30 reconstructions, representing nearly all of the streamflow leaving Colorado

And 4 reconstructions for central AZ

(Meko & Hirschboeck)



Who's using these streamflow reconstructions?

Colorado

Denver Water
Northern Colorado Water Conservancy District
Colorado River Water Conservation District
Rio Grande Water Conservation District
U.S. Bureau of Reclamation – Aspinall Unit
City of Boulder
City of Westminster

Arizona

Salt River Project (Phoenix)
City of Chandler

California

California Department of Water Resources

Multi-state

U.S. Bureau of Reclamation – Upper and Lower Colorado

Using the reconstructions - two degrees of difficulty

1) Provide long-term context for the gage record

- can be qualitative or quantitative

2) Input into a model to assess management scenarios

- requires further processing of the reconstruction data if operational system model is used
- creates more effective communication of risk

2) Reconstructions as input into models, to assess management scenarios - three examples from the western US

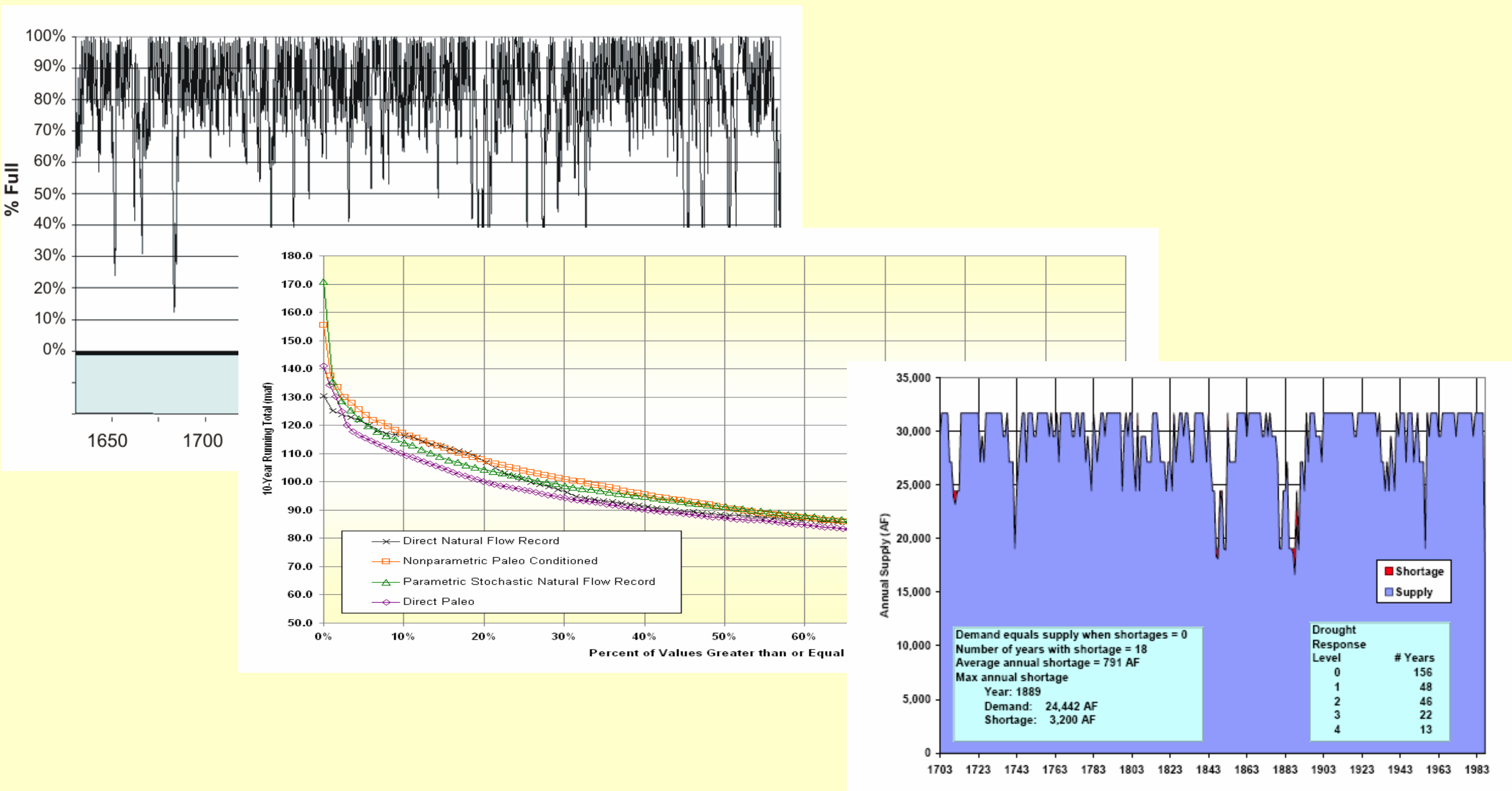


Figure 5. Demands & Supplies: 15% Reduced Flow Hydrology, Current Trends Scenario (demand = 31,700 AF/year).

Denver Water - water supply yield analyses

Challenge:

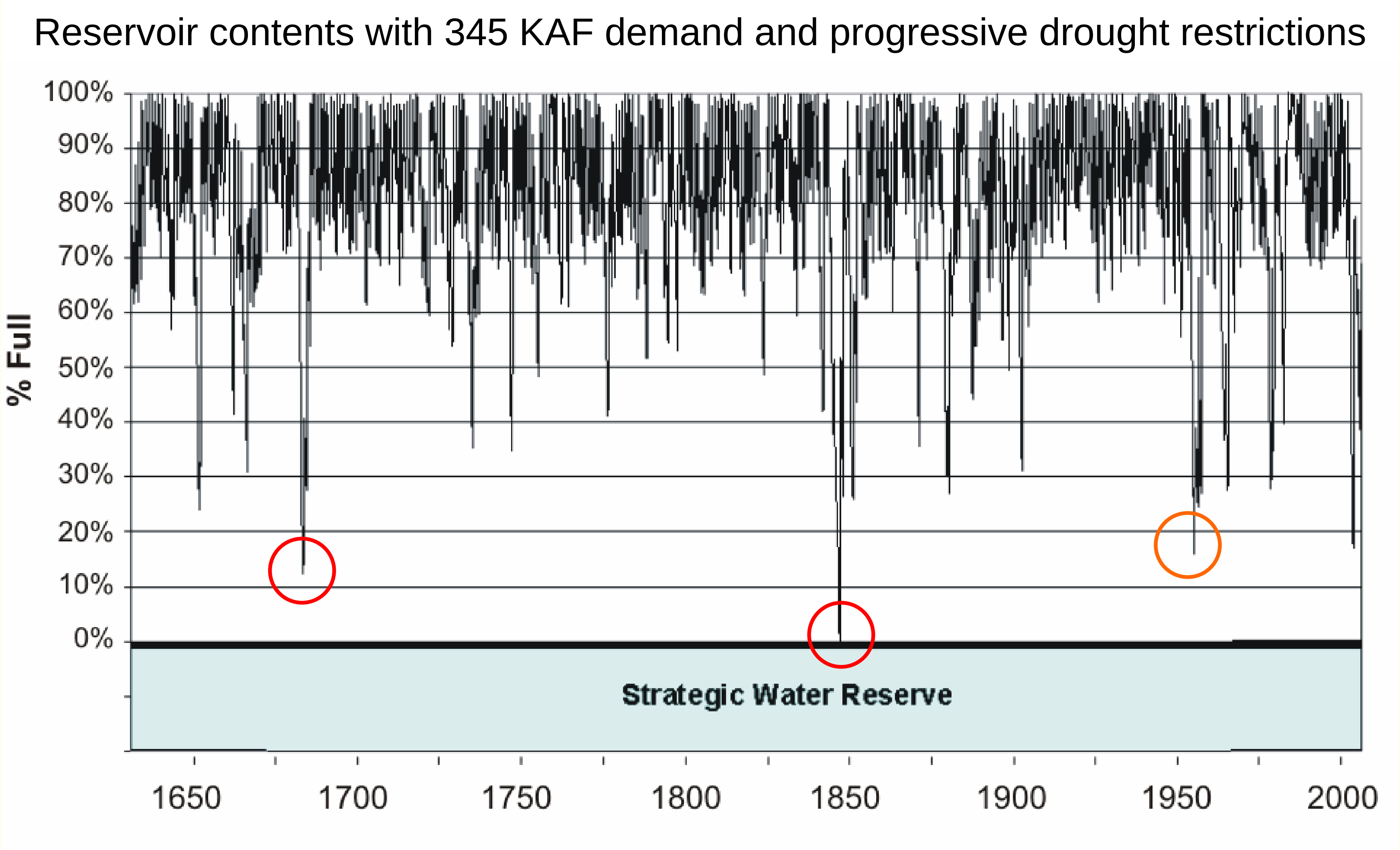
Denver Water's Platte and Colorado Simulation Model (PACSM) requires daily model input from 450 locations

Solution:

An "analogue year" approach

- Match each year in the reconstructed flows with one of the 45 model years (1947-1991) with known hydrology (e.g., 1654 is matched with 1963), and use that year's hydrology.
- Years with more extreme wet/dry values are scaled accordingly
- Data are assembled as new sequences of model years
- PACSM is used to simulate the entire tree-ring period, 1634-2002

Denver Water - water supply yield analyses



- Two paleo-droughts (1680s, 1840s) deplete contents lower than 1950s design drought

US Bureau of Reclamation - analyses for "Shortage EIS"

Challenges:

1) CRSS model requires monthly inputs at 29 model nodes

2) Less trust in reconstructed flow magnitudes than states, need to conservatively incorporate new data

Solutions:

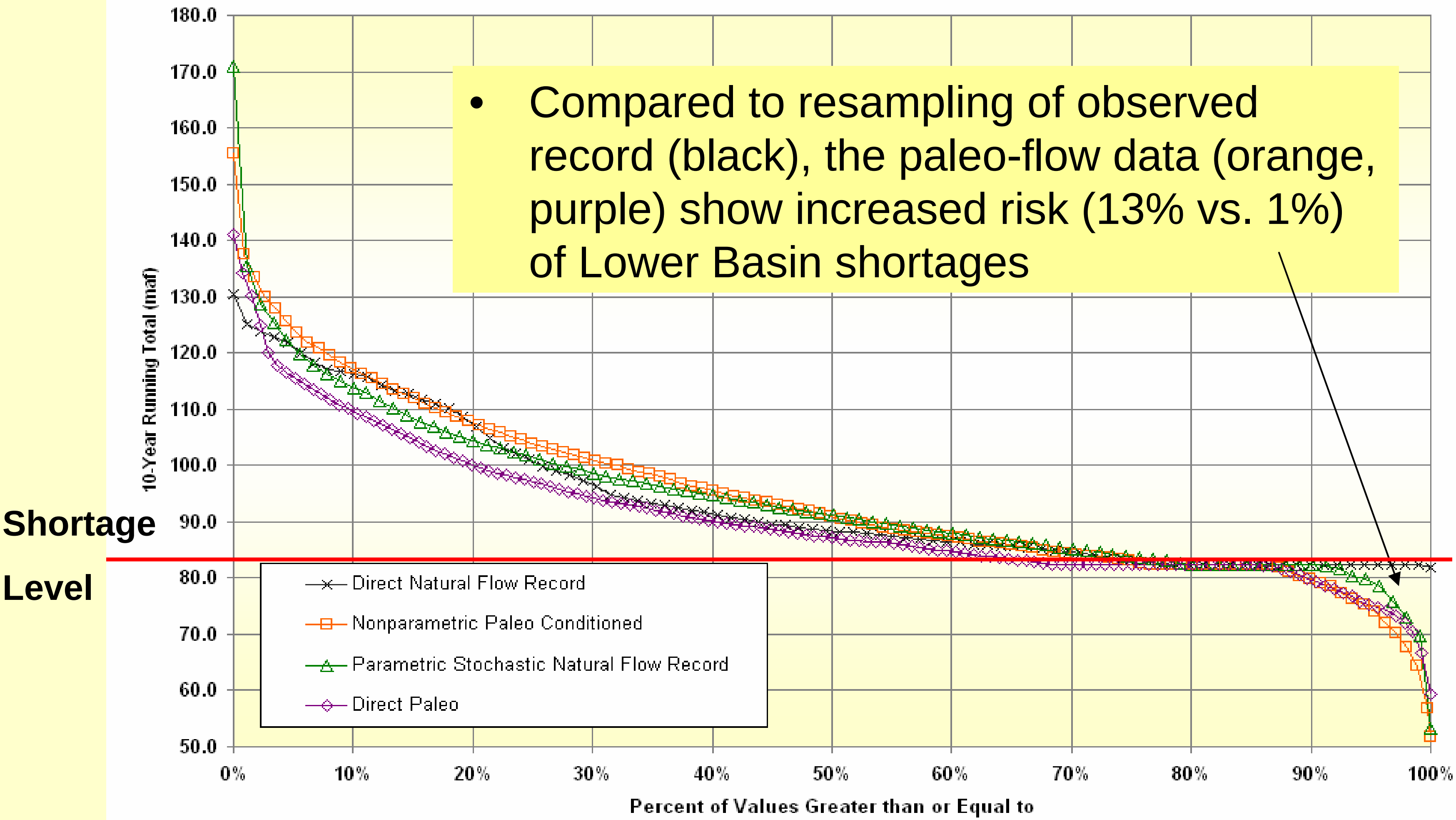
1) Non-parametric disaggregation scheme for extending annual reconstructed flows at one site to all model steps and nodes

2) Non-parametric scheme to combine the state information (wet-dry) from the tree-ring data with the observed flow values, thus creating *sequences* (e.g. sustained droughts) not seen in the observed record

US Bureau of Reclamation - analyses for “Shortage EIS”

Glen Canyon 10-Year Release Volume

No Action Alternative, *Years 2008-2060*



- Compared to resampling of observed record (black), the paleo-flow data (orange, purple) show increased risk (13% vs. 1%) of Lower Basin shortages

Courtesy of Jim Prairie, USBR

City of Boulder - water supply yield analyses

Challenges:

1) Represent potential effects of climate change on hydrology

2) Represent uncertainty in future demand

Solutions:

1) Reconstructed flows scaled up or down to create different climate change scenarios (3 scenarios)

2) Different demand scenarios (4)

City of Boulder - water supply yield analyses

15% reduced flow scenario; current trend in demand scenario; stepped drought restrictions to reduce demand

Shortages modeled during 3 paleo-droughts

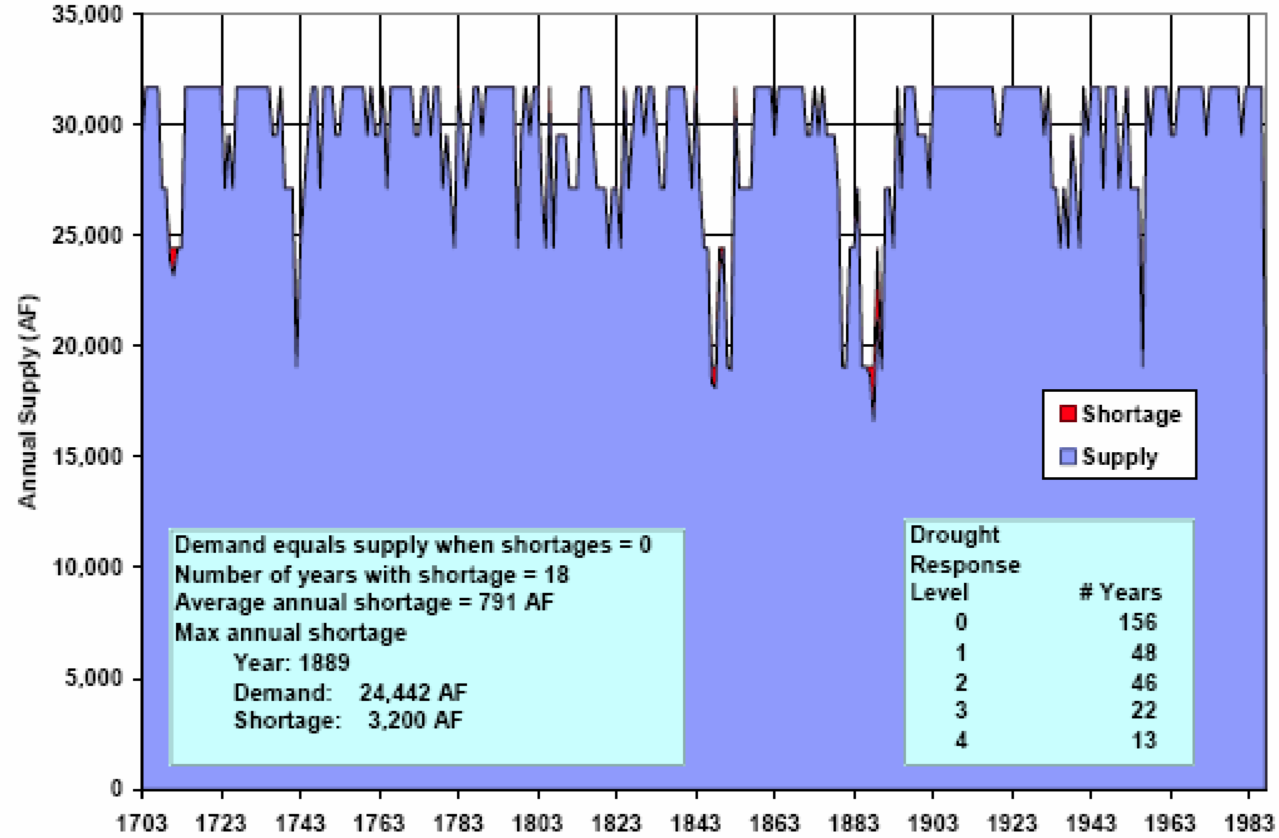


Figure 5. Demands & Supplies: 15% Reduced Flow Hydrology, Current Trends Scenario (demand = 31,700 AF/year).

From Hydrosphere Resource Consultants: Report to the City of Boulder, Sept. 2003

How can the past (tree-ring data) be relevant to planning for future climate/hydrology?

- Natural modes of variability will continue to operate alongside human-forced warming trends
- The greater variability seen in the paleohydrologic records can be a useful analogue for future variability
- The most likely changes in future climate (e.g. moderate warming) can be integrated with a tree-ring flow reconstruction in hydrologic modeling to create plausible future scenarios for water management

Summary

1) Tree-ring reconstructions of streamflow are useful in that they provide more "hydrologic experience" without the pain

2) Tree growth can be an excellent proxy for streamflow since both variables are often driven by the same climate factors

3) A tree-ring based streamflow reconstruction is a best-estimate based on the relationship between tree-growth and gaged flows

Summary

4) The reconstructions (almost) always show drought events more severe/sustained than those in the gaged record

5) There are different levels of complexity in applying the reconstructions to water management

6) Many water providers in the western US, including Reclamation, are now using tree-ring data to analyze policy alternatives, communicate risk, and assist decision making