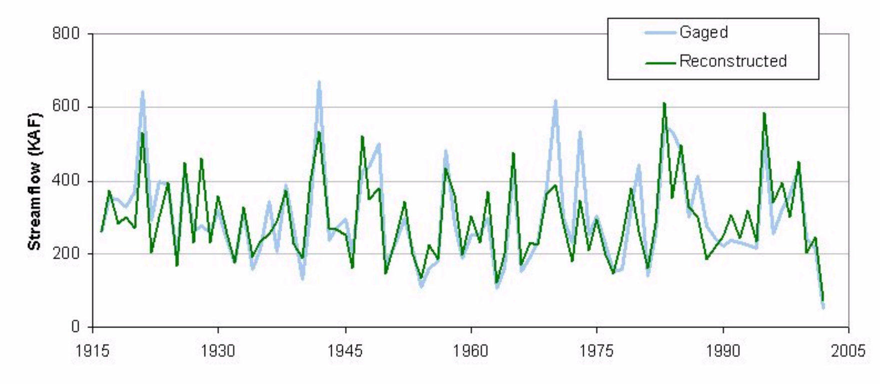
Tree-ring reconstructions of streamflow and climate and their application to Colorado River Basin water management



US Bureau of Reclamation, Lower Colorado Regional Office
November 13, 2008

Jeff Lukas - University of Colorado-INSTAAR and Western Water Assessment

Connie Woodhouse – University of Arizona and Western Water Assessment

INSTAAR University of Colorado Boulder

Western Water Assessment

THE UNIVERSITY OF ARIZONA.

Agenda

Welcome, background and purpose of workshop

Morning session: “Tree-Ring 101”

- How tree rings record hydroclimatic information
- Building the tree-ring chronology
- How reconstructions of climate and streamflow are generate
- Uncertainties in the reconstructions
- What reconstruction data are available for the CRB and the West
- What the latest reconstructions for Lees Ferry show

Invited presentations on analyses and applications of tree-ring reconstructions for the Colorado River basin

Group Q & A and discussion – What else do you need to know about the reconstructions and their application? How can the tree-ring data be used more effectively in the CRB?

Acknowledgements

Support for this Workshop:

Bureau of Reclamation (Terry Fulp, Doug Blatchford, Paul Miller)

Western Water Assessment (NOAA Climate Program Office – RISA Program)

Partners and Collaborators over the years:

Denver Water, Northern Colorado Water Conservancy District, Rio Grande Water Conservation District, City of Westminster, City of Boulder, Hydrosphere Resource Consultants (AMEC), Wright Water Engineering, CA Dept. of Water Resources, NM Interstate Stream Commission, Bureau of Reclamation, US Geological Survey

Support for Data Development:

NOAA Climate Program Office: Western Water Assessment and Climate Change Data and Detection (GC02-046); Denver Water; US Geological Survey; US Bureau of Reclamation; California DWR; National Science Foundation

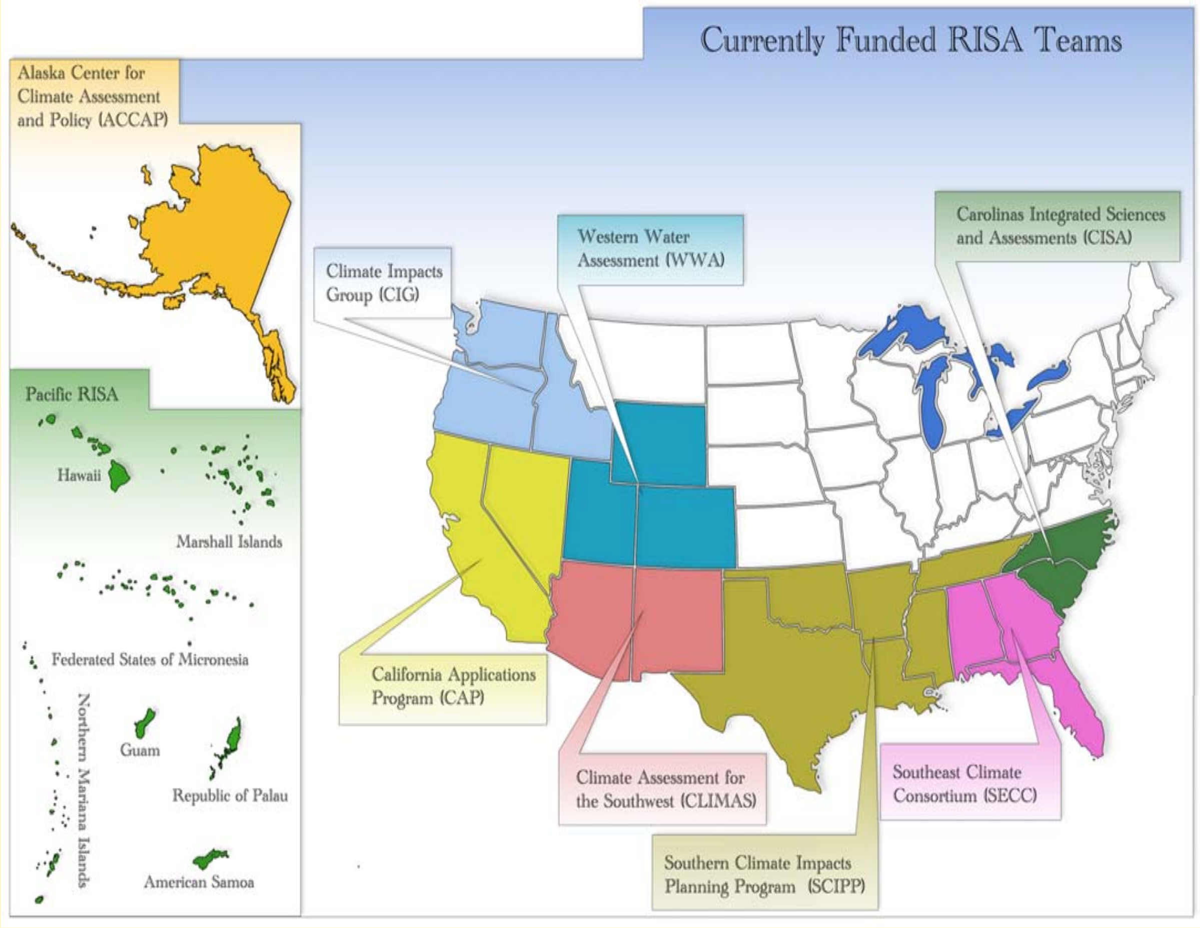
About the Regional Integrated Sciences & Assessments (RISA) Program

RISAs are NOAA-funded programs that conduct and communicate climate-related research to support regional decision-making

WWA – CO, UT, WY (U. of Colorado)

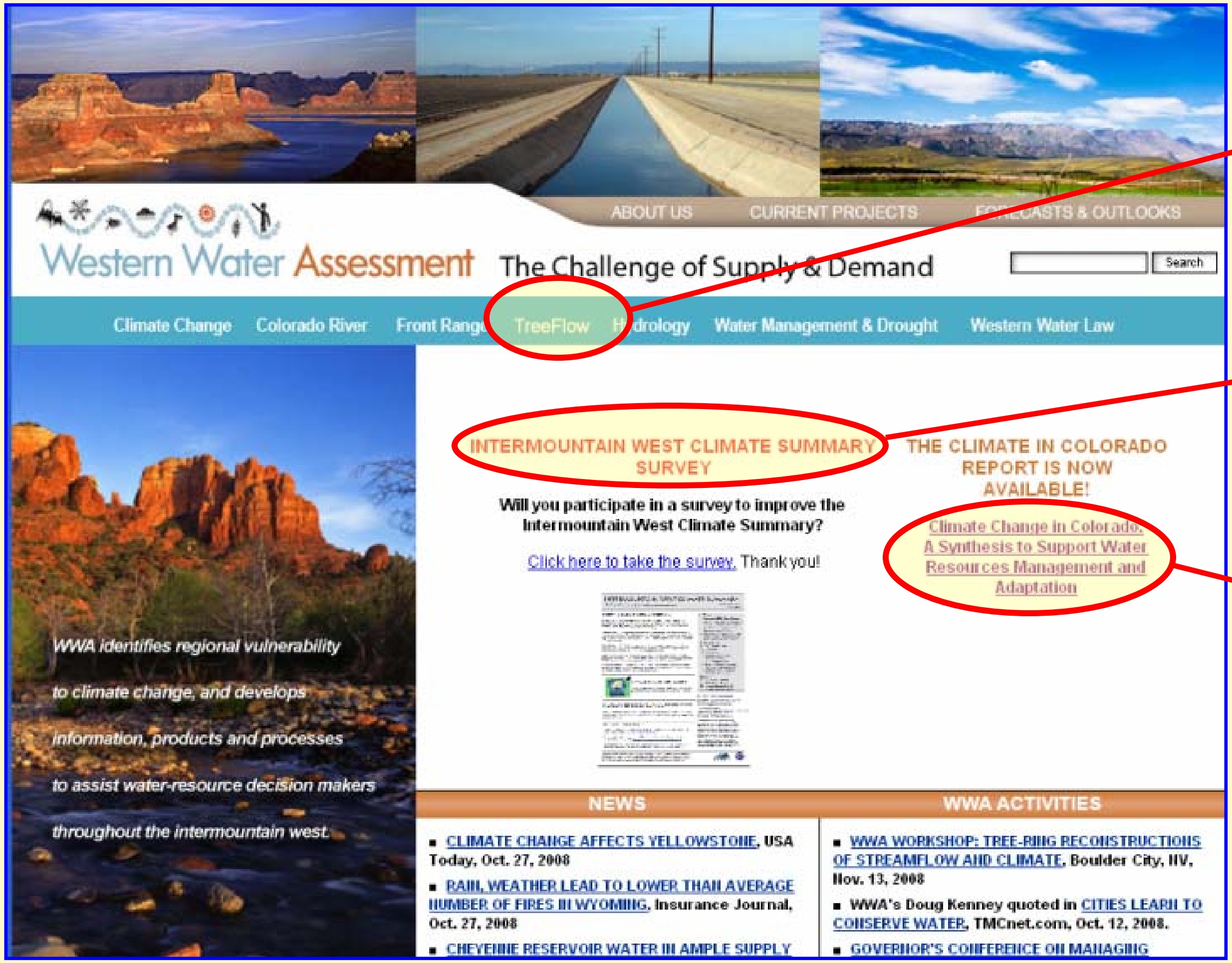
CLIMAS – AZ, NM (U. of Arizona)

CAP – CA, NV (UCSD/Scripps)



Western Water Assessment (WWA)

http://wwa.colorado.edu



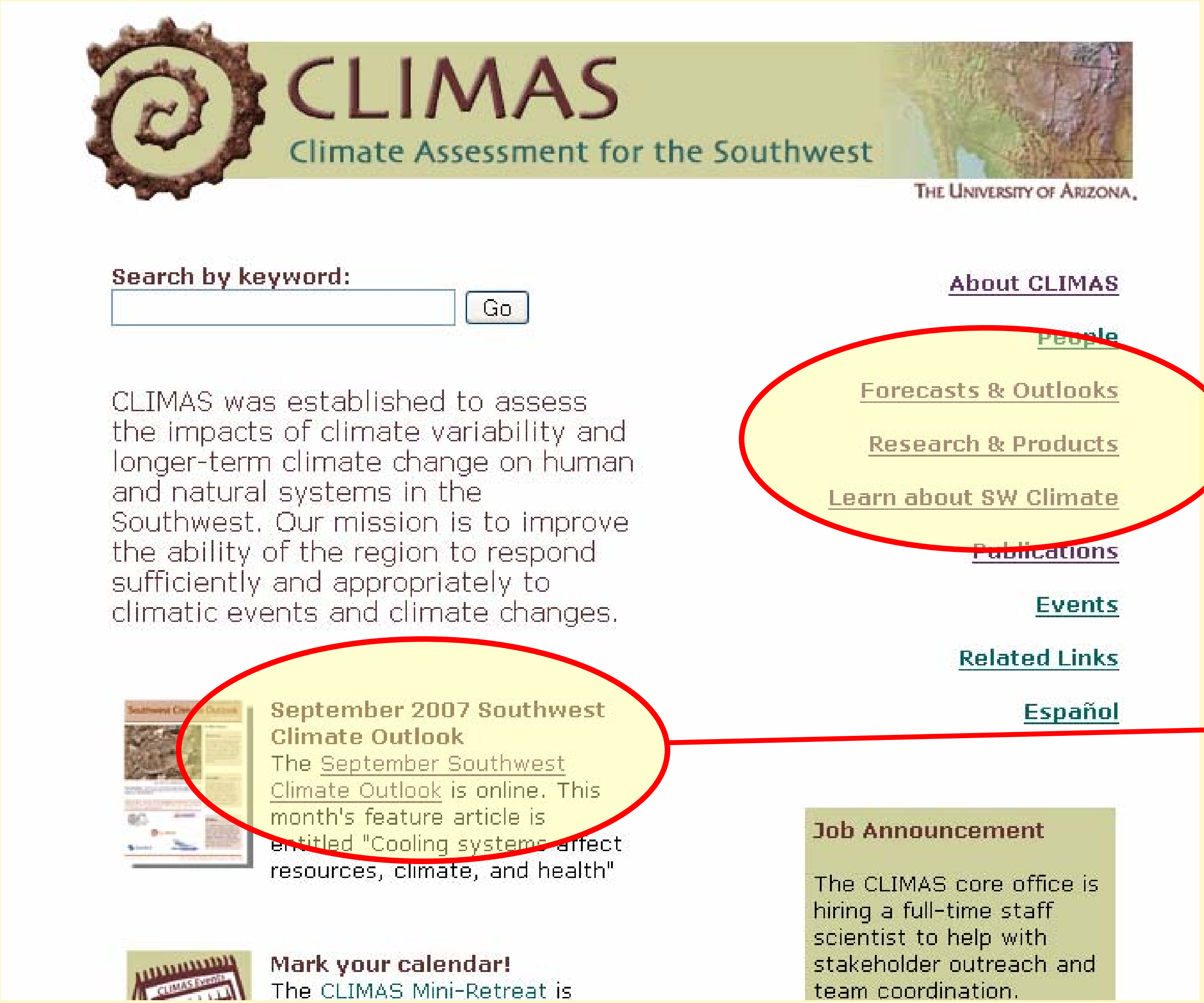
TreeFlow web pages

Intermountain West Climate Summary

Climate Change in Colorado report

Climate Assessment for the Southwest (CLIMAS)

http://www.climas.arizona.edu

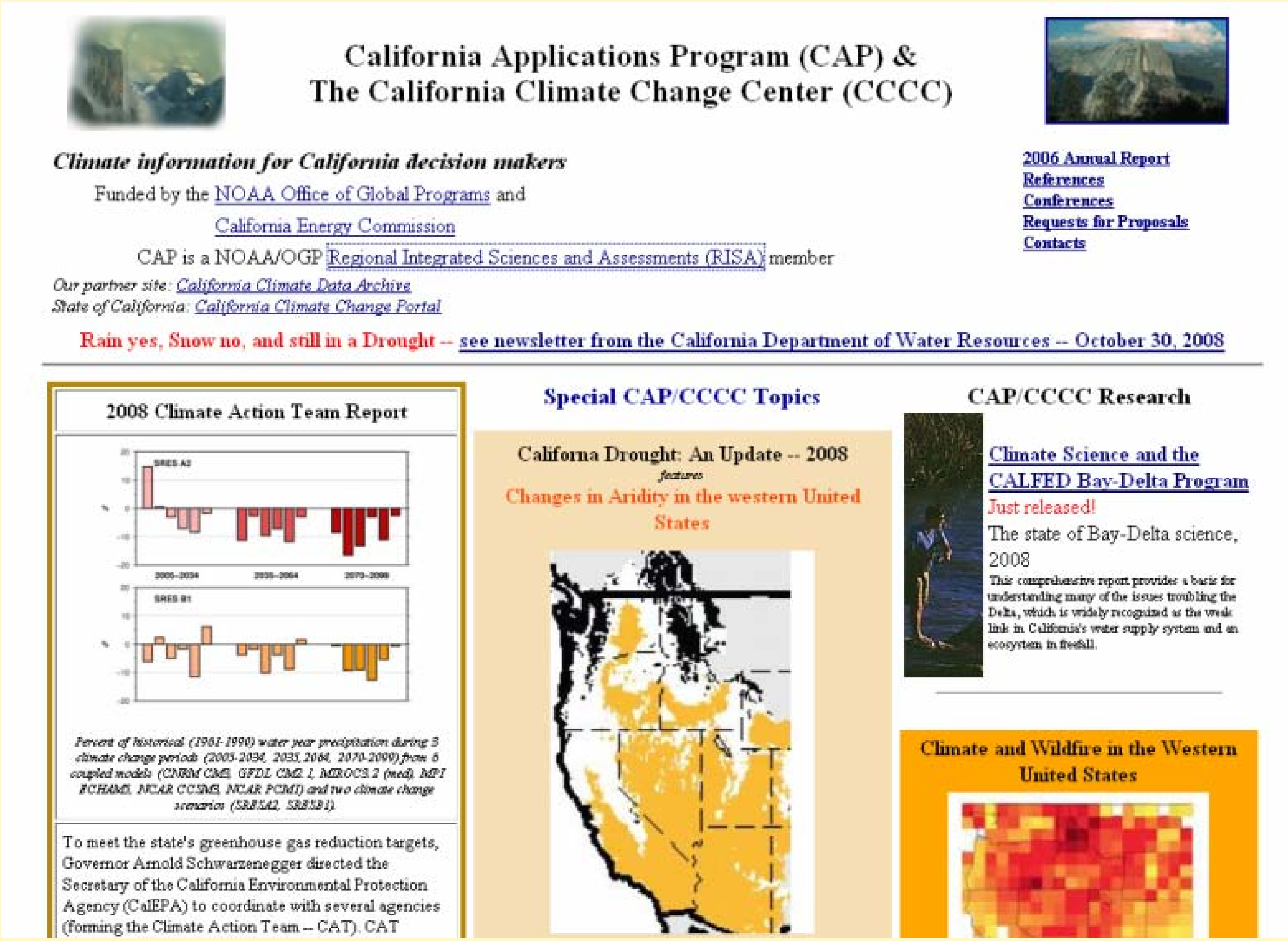


Other projects and resources

Southwest Climate Outlook

California Applications Program (CAP)

http://meteora.ucsd.edu/cap/



History behind this workshop

2005

- First workshop for water managers:

Planning Workshop to Develop Hydroclimatic Reconstructions for Decision Support in the Colorado River Basin, in Tucson

2006

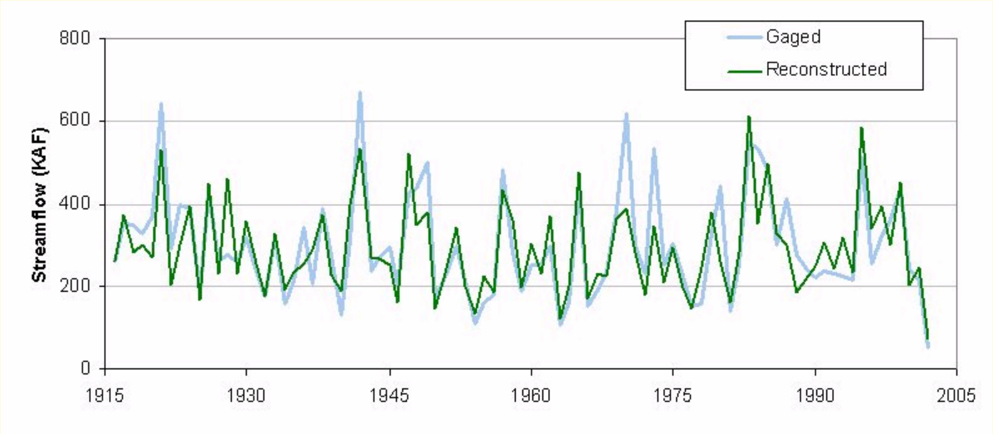
- One-day technical workshops on streamflow reconstructions (CO, AZ)
- Updated Streamflow Reconstructions for the UCRB (Woodhouse et al.)
- NRC report on the Colorado River

2007-2008

- Meko et al. extended Lees Ferry Reconstruction
- More workshops (CO, WY, UT, NM)

Part 1:

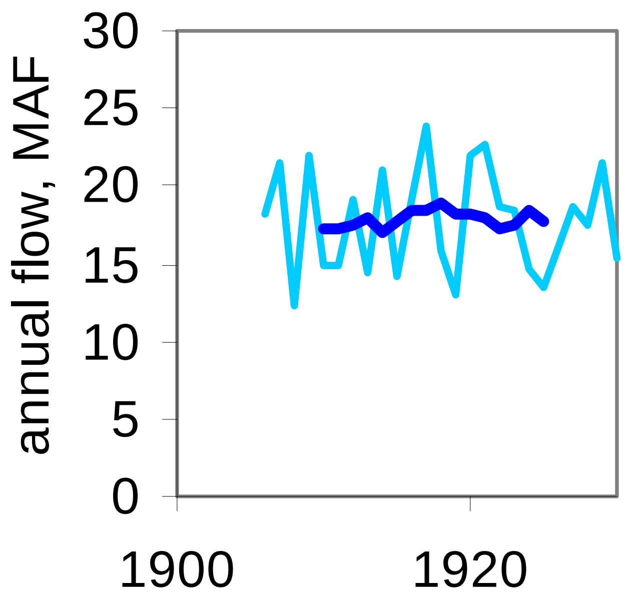
Context and Background



Learning from experience in water management

Colorado at Lees Ferry

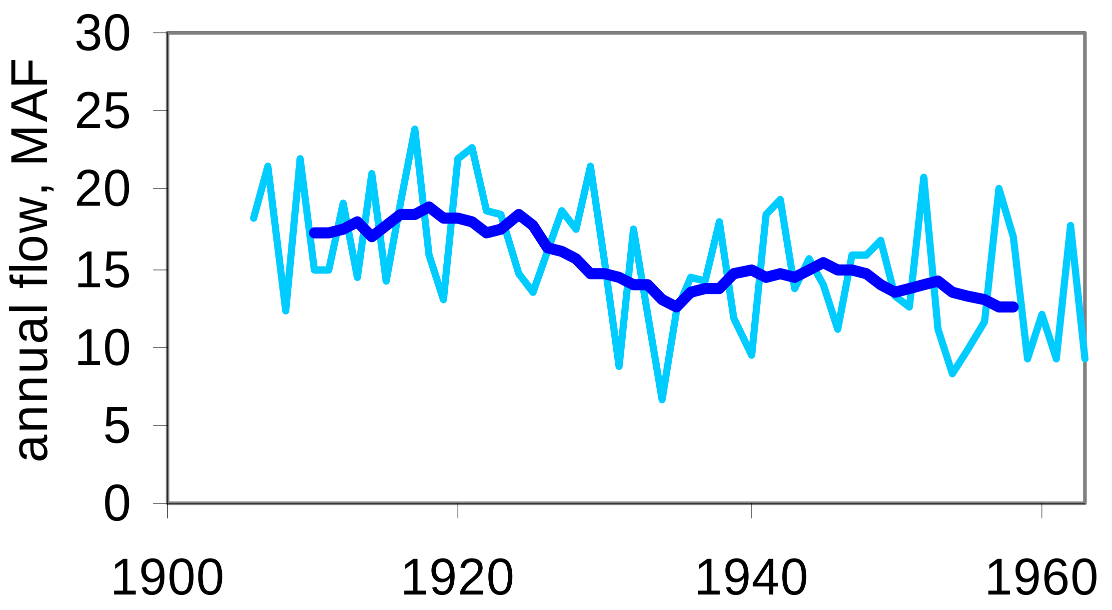
Gaged (natural flow) record, 1906-1930



Learning from experience in water management

Colorado at Lees Ferry

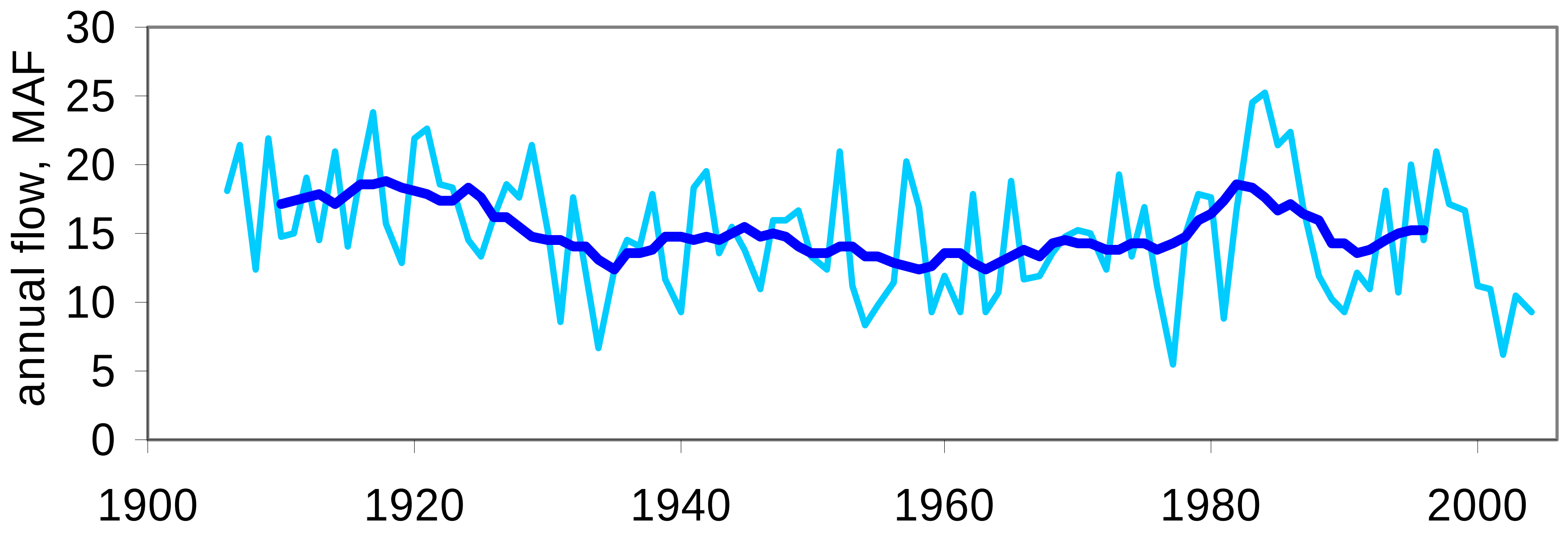
Gaged (natural flow) record, 1906-1963



Learning from experience in water management

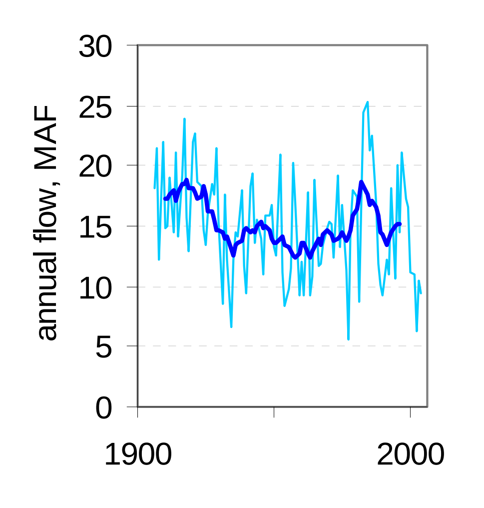
Colorado at Lees Ferry

Gaged (natural flow) record, 1906-2004



100 years is not enough experience to capture the full range of hydrologic variability

Tree-ring reconstructions - a surrogate for experience



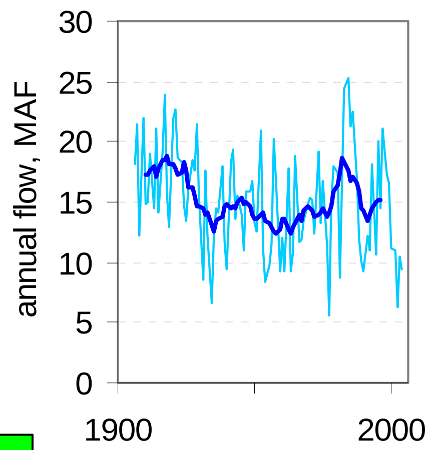
Colorado at Lees Ferry

Gaged (natural flow) record

1906-2004

Tree-ring reconstructions - a surrogate for experience

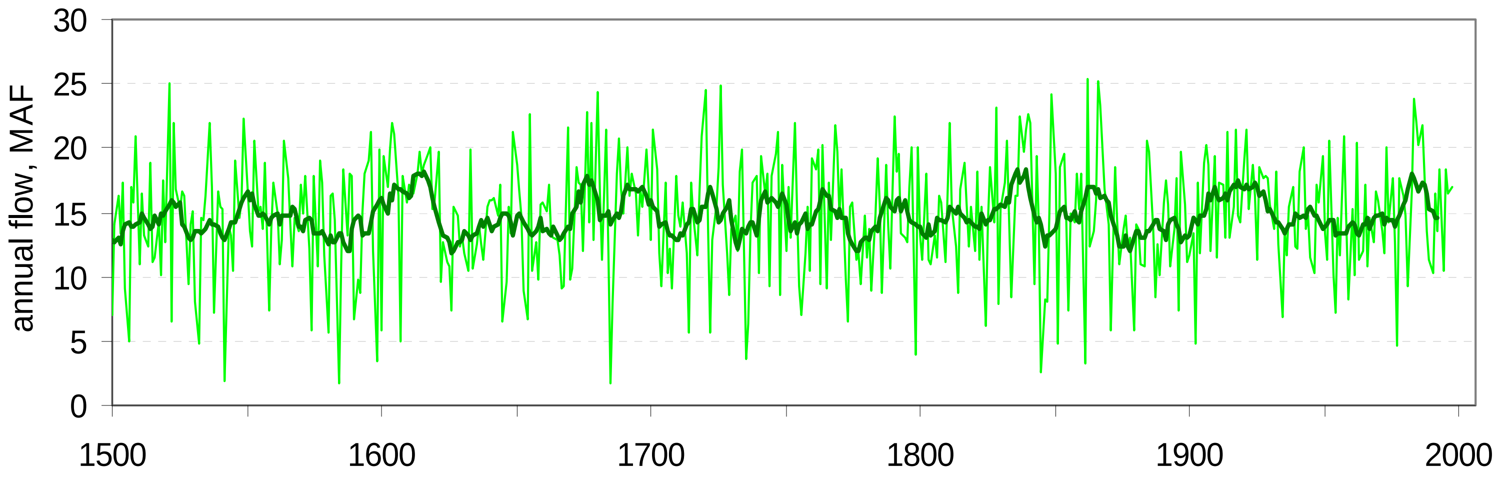
By extending the gaged hydrology by hundreds of years into the past, the reconstructions provide a more complete picture of hydrologic variability



Colorado at Lees Ferry

Gaged (natural flow) record

1906-2004



Tree-ring reconstruction

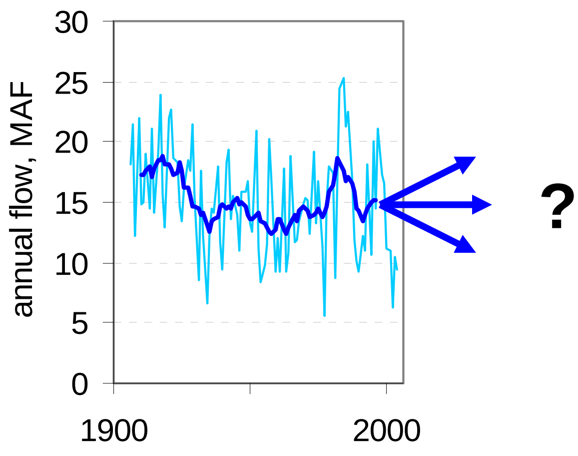
1490-1997

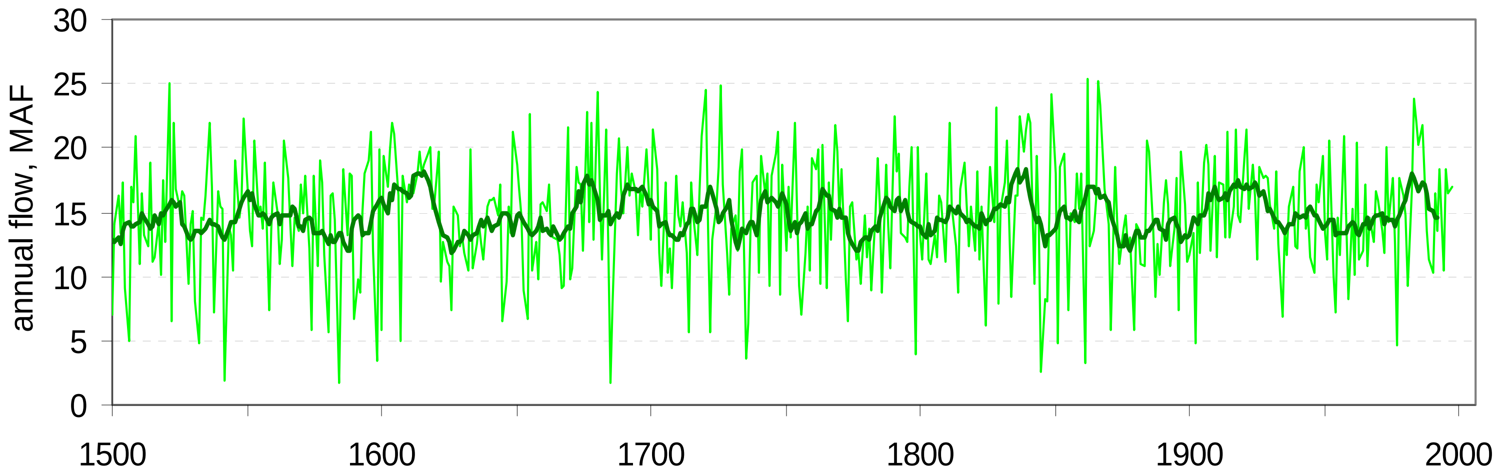
Tree-ring reconstructions - a surrogate for experience

Payoff:

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

- Better assessment of *risk*





Tree-ring reconstruction

1490-1997

Dendrochronology:

the science that deals with the dating and study of annual growth layers in wood

Fritts 1976

Main products:

- Reconstructions of past conditions; continuous time-series of environmental variables (e.g., climate, hydrology)

- Dates of environmental and human events (e.g., fires, infestations, prehistoric settlement)

Tree-ring science and streamflow reconstructions are not new

1900s - Douglass links tree growth and climate in Southwest

1930s - First studies relating tree growth to runoff in West

1940s - Schulman investigates history of Colorado River flow using tree rings

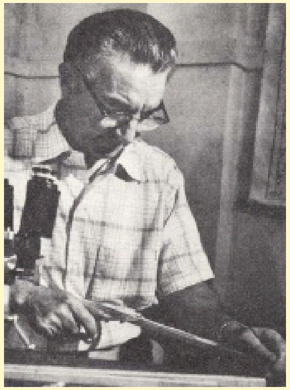
1960s - Fritts develops modern statistical methods for climate reconstruction

1976 - Stockton and Jacoby reconstruction of Lees Ferry streamflow

1980s – Further refinement of analytical techniques
1990s

2000s - New flow reconstructions for western US and CRB; major increase in applications to water management

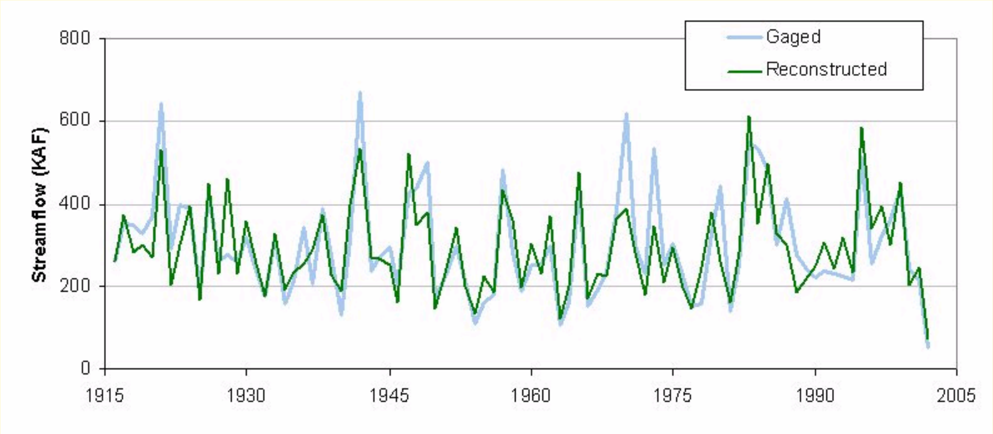
Douglass



Schulman

Part 2:

How tree rings record climate information



In dry climates, annual tree growth is generally limited by moisture availability

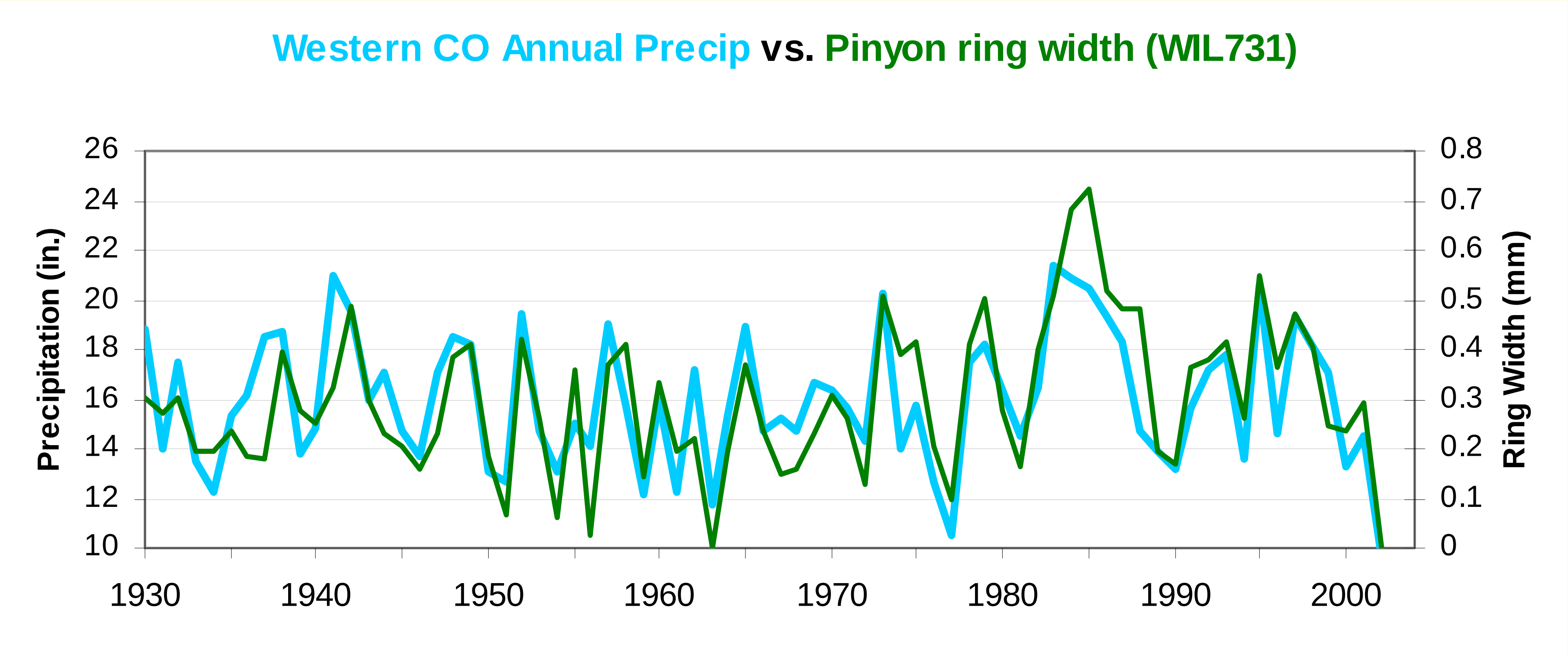
So:

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

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

In the Colorado River basin, ring width mainly reflects precipitation from previous fall-winter-spring = soil moisture at start of growing season

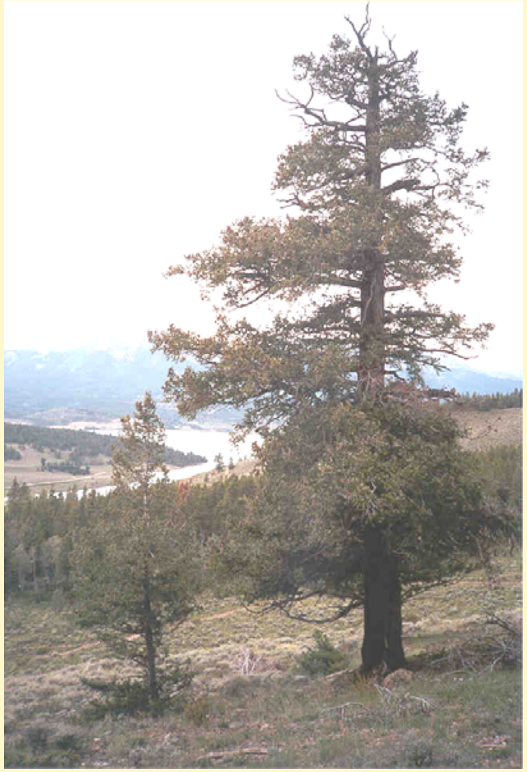
The moisture signal recorded by trees in the interior West is particularly strong

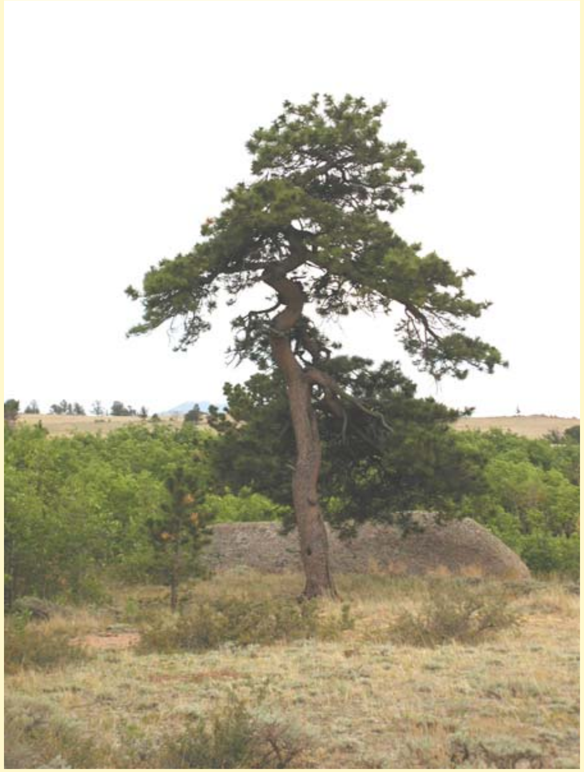


- Here, the “raw” ring widths from *one* tree are closely correlated to the annual basin precipitation (r = 0.78) from 1930-2002

- Our goal is to *capture* and *enhance* the moisture signal, and reduce noise, through careful sampling and data processing

Main moisture-sensitive species in the interior West

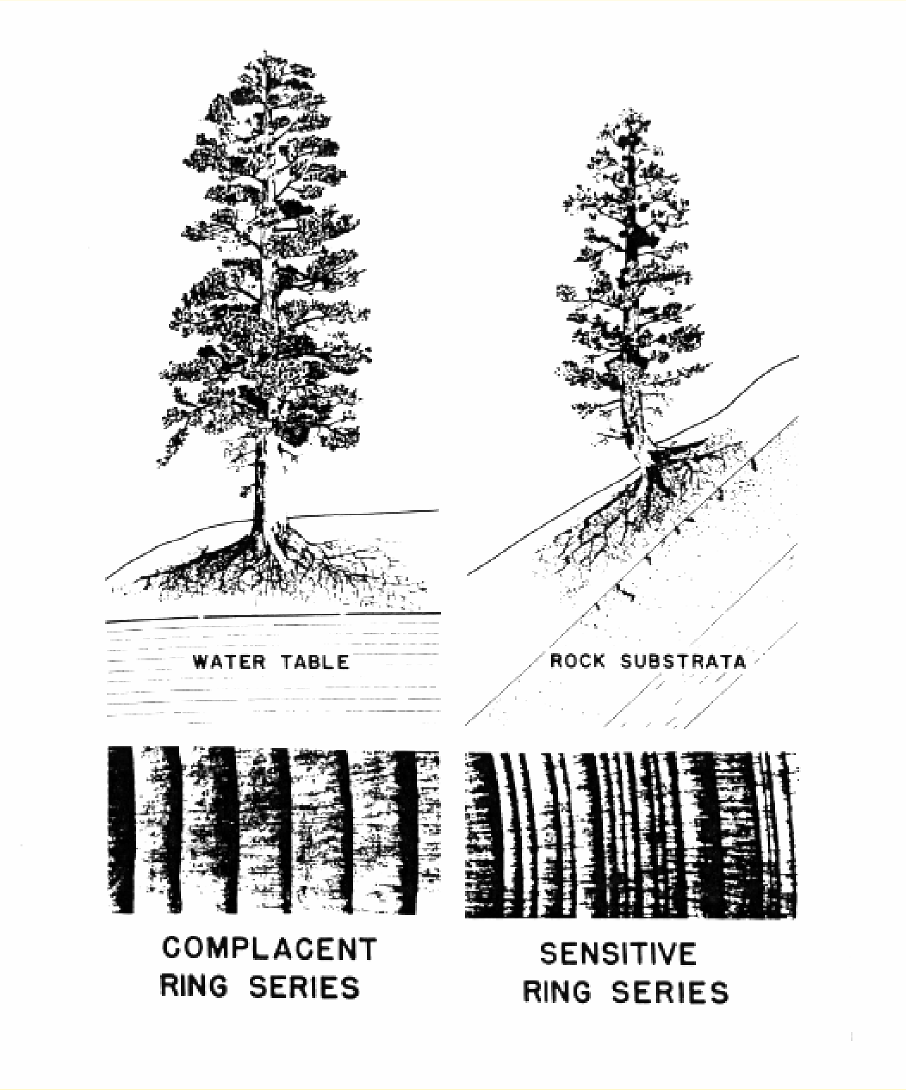




Douglas-fir **Ponderosa Pine** **Pinyon Pine**

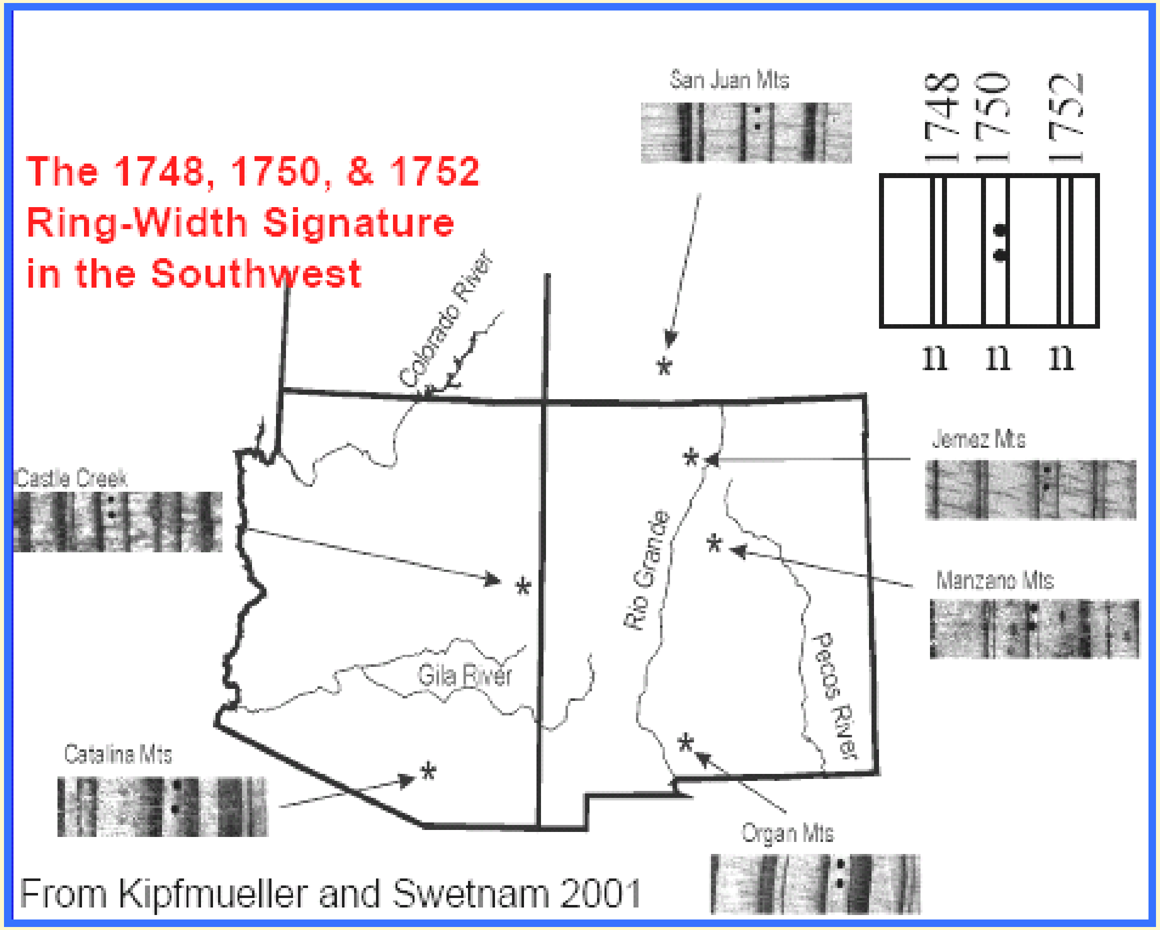
- All have maximum ages of 800-1000 years; old trees are typically 400-700 years

Stressful sites produce ring series with a stronger moisture signal



from *Fritts 1976*

Regional scale of moisture variability = regional coherence in the moisture signal



- 1748, 1750, 1752: narrow rings = dry years
- Fire history records show widespread fire occurrence in all three years

Image courtesy of K. Kipfmueller (U. MN) and T. Swetnam (U. AZ)

This moisture signal in tree rings can serve as a proxy for multiple moisture-related variables

- Annual (water-year) or winter precipitation
- Drought indices (e.g., summer PDSI)
- Snow-water equivalent (SWE)
- Annual (water-year) streamflow

These variables are closely correlated in this region, and trees whose ring widths are a good proxy for one tend to be good proxies for all of them

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

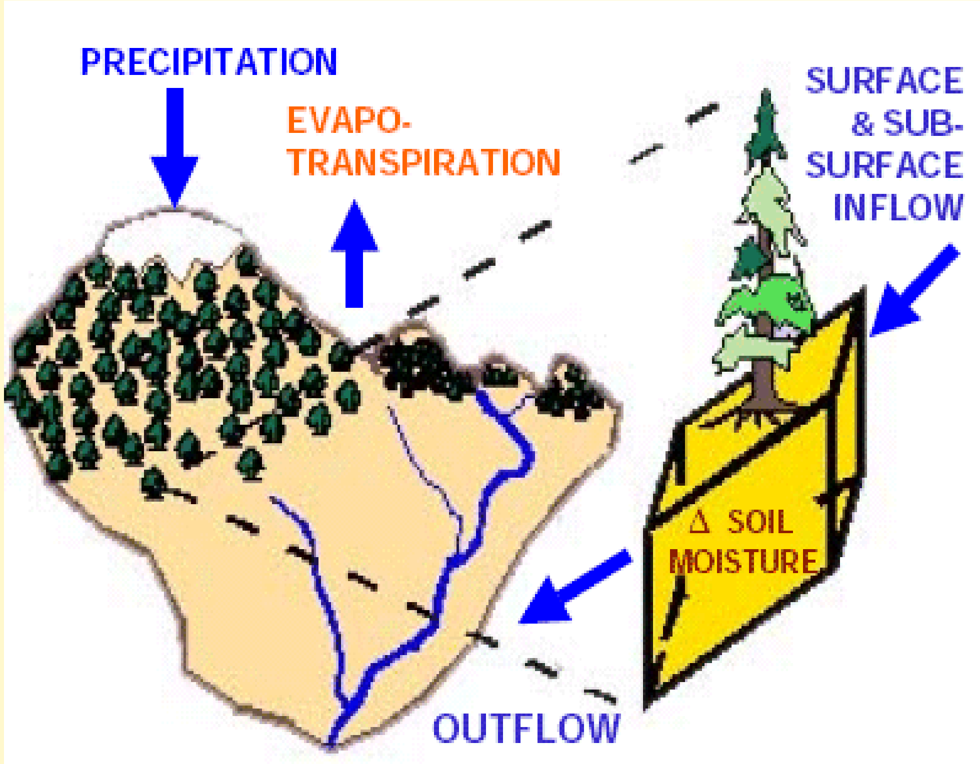
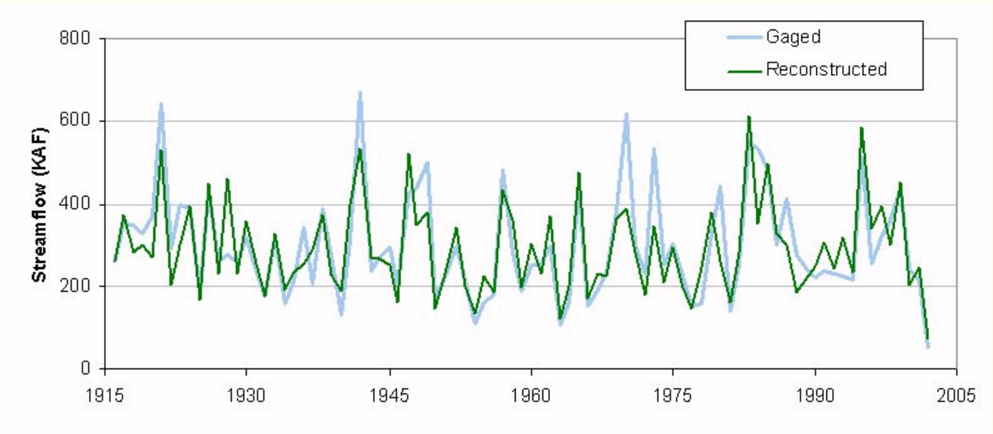


Image courtesy of D. Meko (U. AZ)

Part 3:

Building a tree-ring chronology



Chronology: time-series of *site* ring-width variability and "building block" for the reconstruction

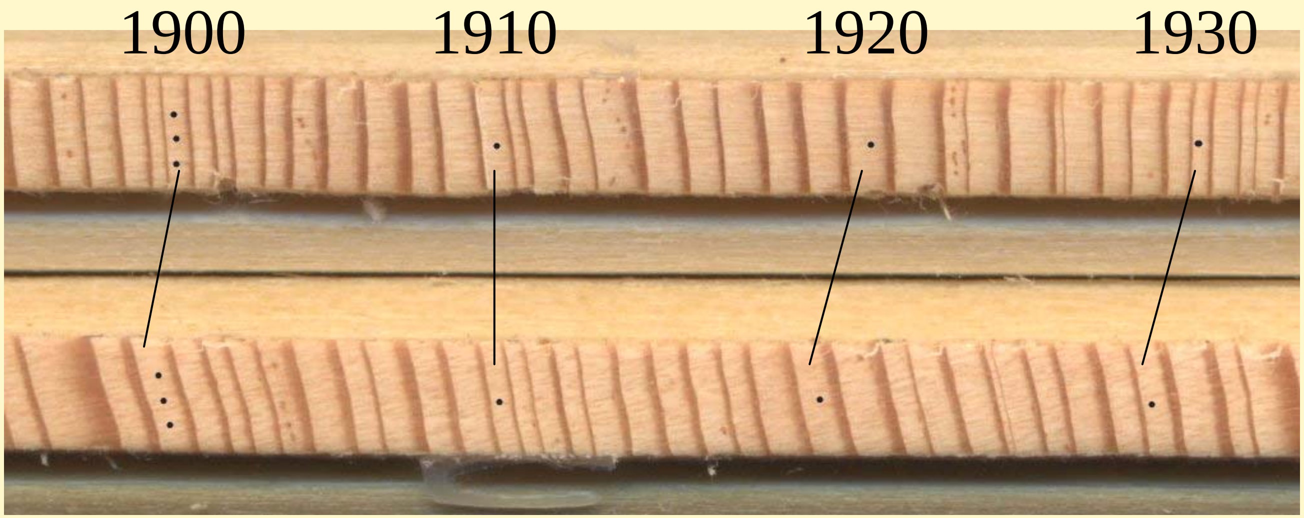
1) Sampling the trees

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

2) Crossdating the samples

- Because of the common climate signal, the pattern of wide and narrow rings is highly replicated between trees at a 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

- *When cored, the current year of growth is the first ring next to the bark*

Crossdating allows the extension of tree-ring records back in time using living and dead wood

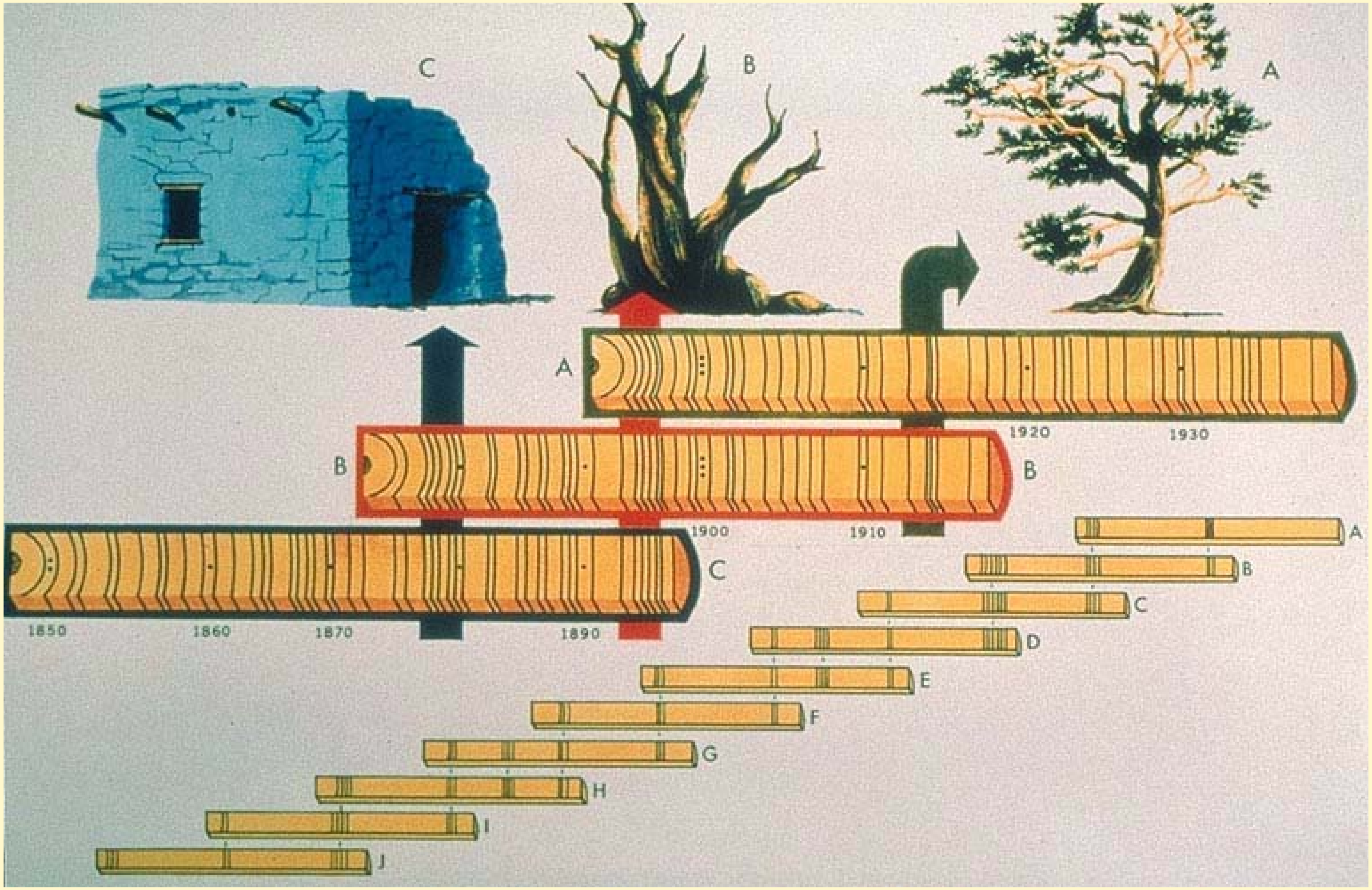
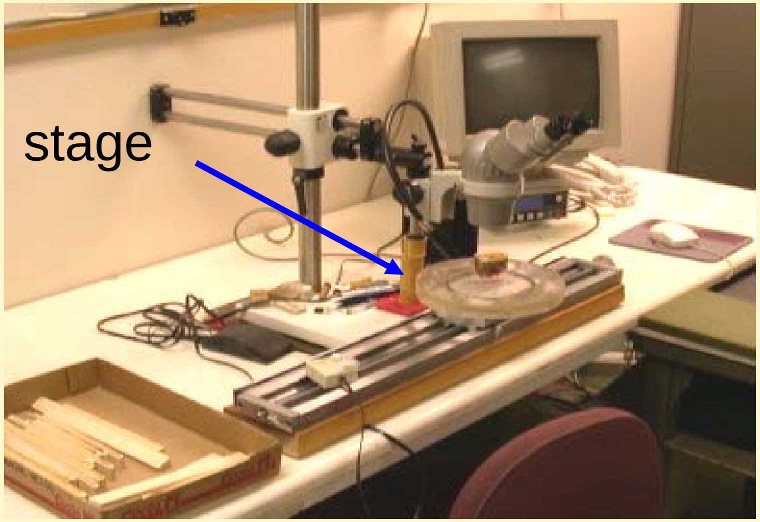


Image courtesy of LTRR (U. AZ)

3) Measuring the samples



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

4) Detrending the measured ring-width series

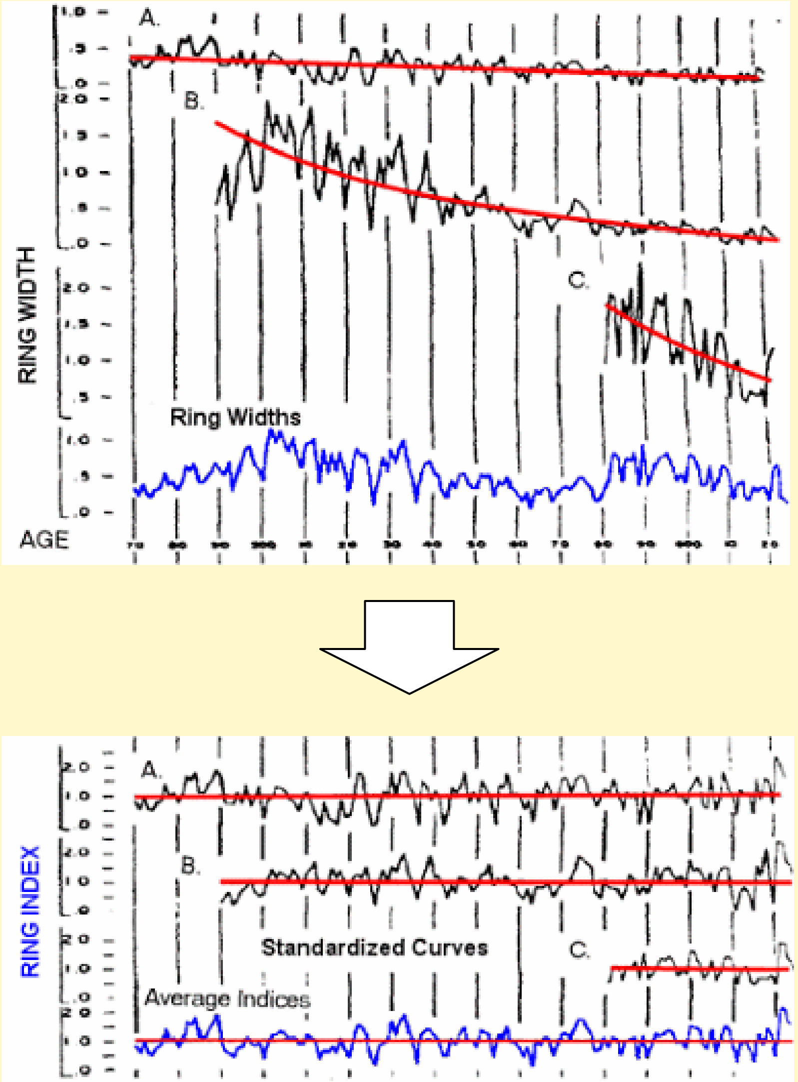


Image courtesy of LTRR (U. AZ)

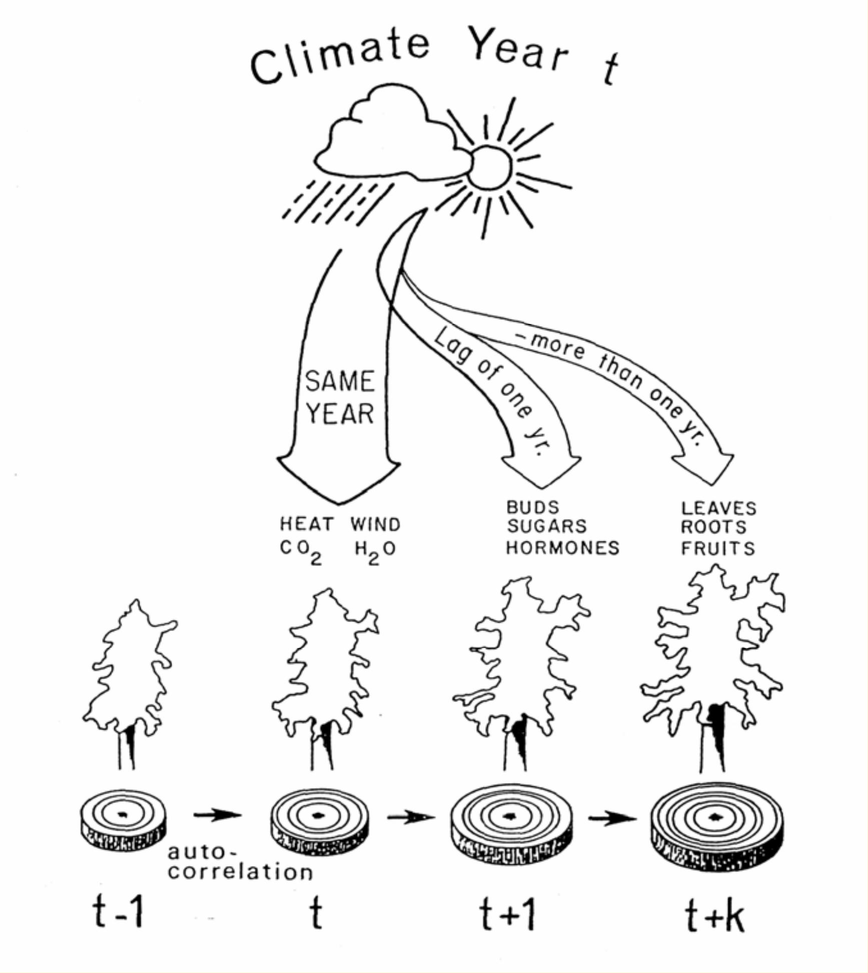
- Ring-width series typically have a declining trend with time because of tree geometry
- These are low-frequency *noise* (i.e. non-climatic)

- Raw ring series are detrended with straight line, exponential curve, or spline

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

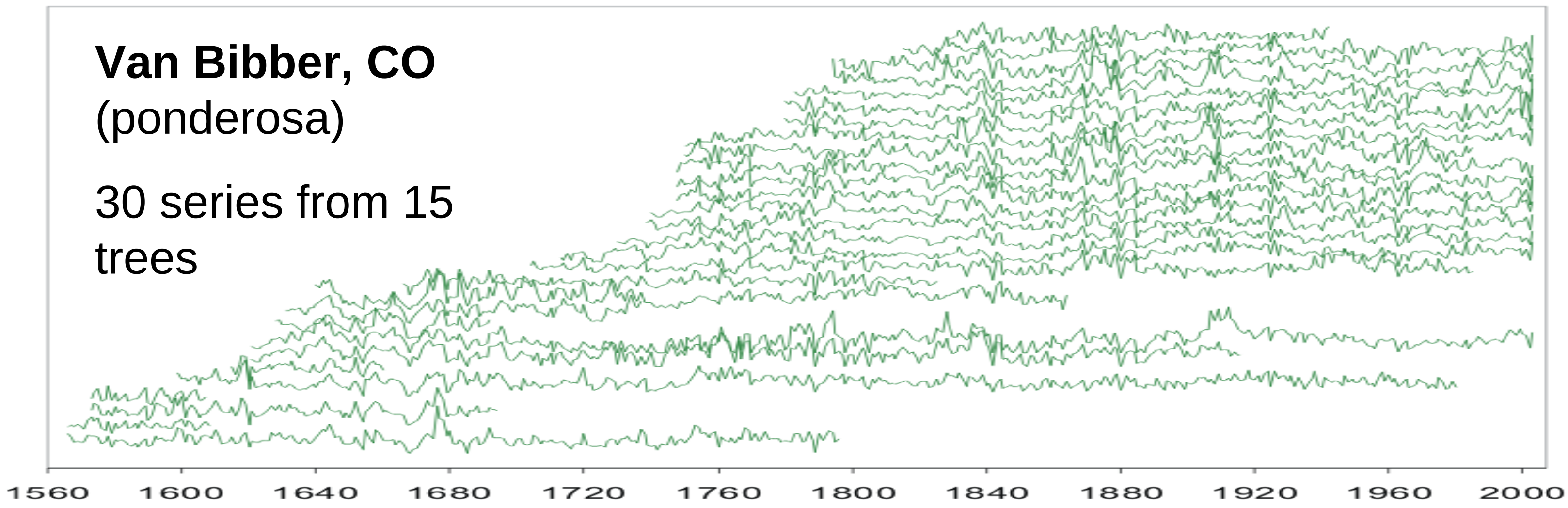
Other data treatment may be used to address persistence in tree growth from year to year

- The climate in a given year (t) can also influence growth in succeeding years (t+1, t+2, etc.) through storage of sugars and growth of needles
- This persistence is typically greater than the persistence in hydrologic time series
- Terminology:
  - *Standard* chronology*:* persistence in the ring-width series is retained
  - *Residual* chronology*:* first-order persistence is removed

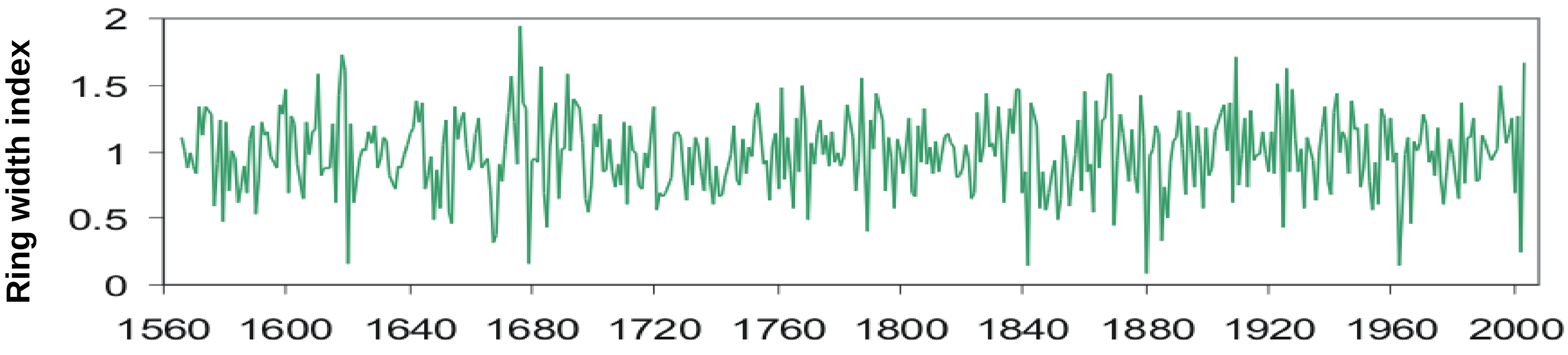


Other issues such data that are not normally distributed may also require treatment

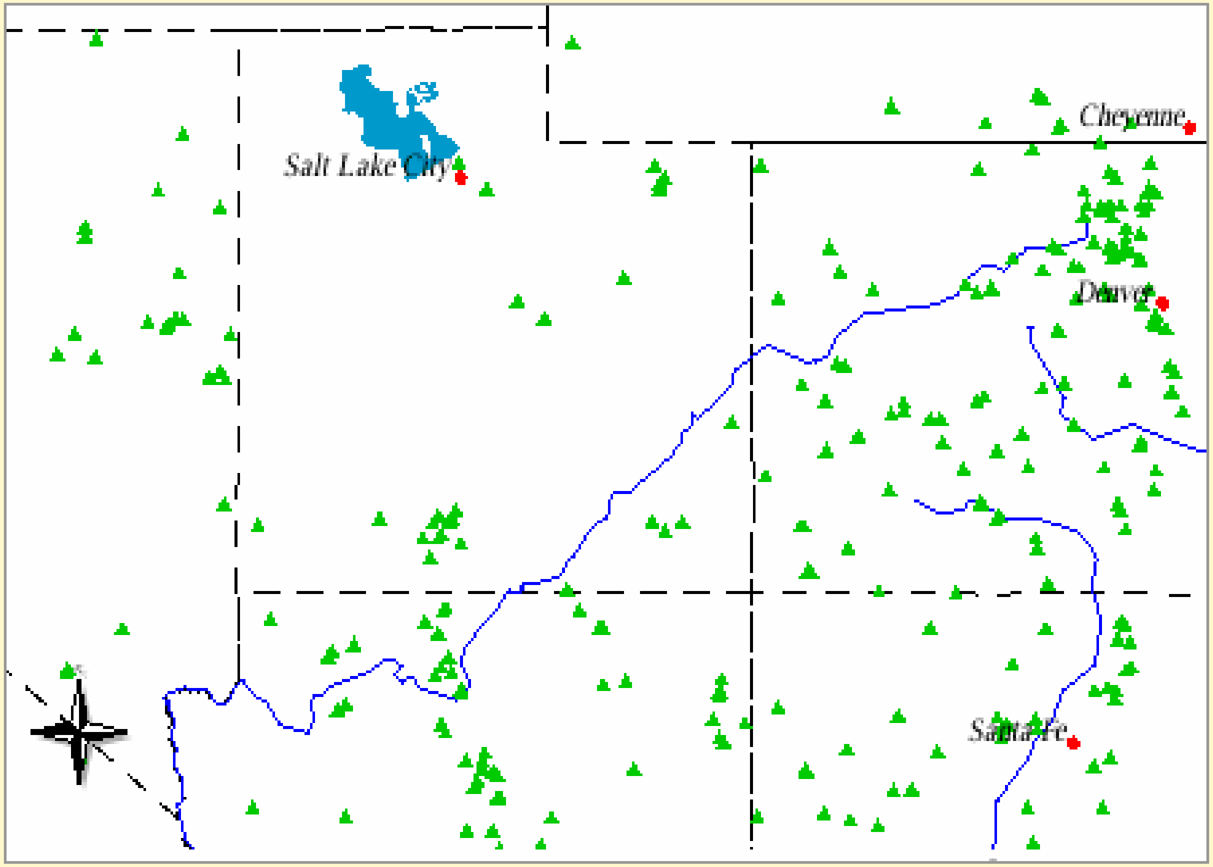
5) Compiling the ring-width series into the *chronology*



Robust averaging



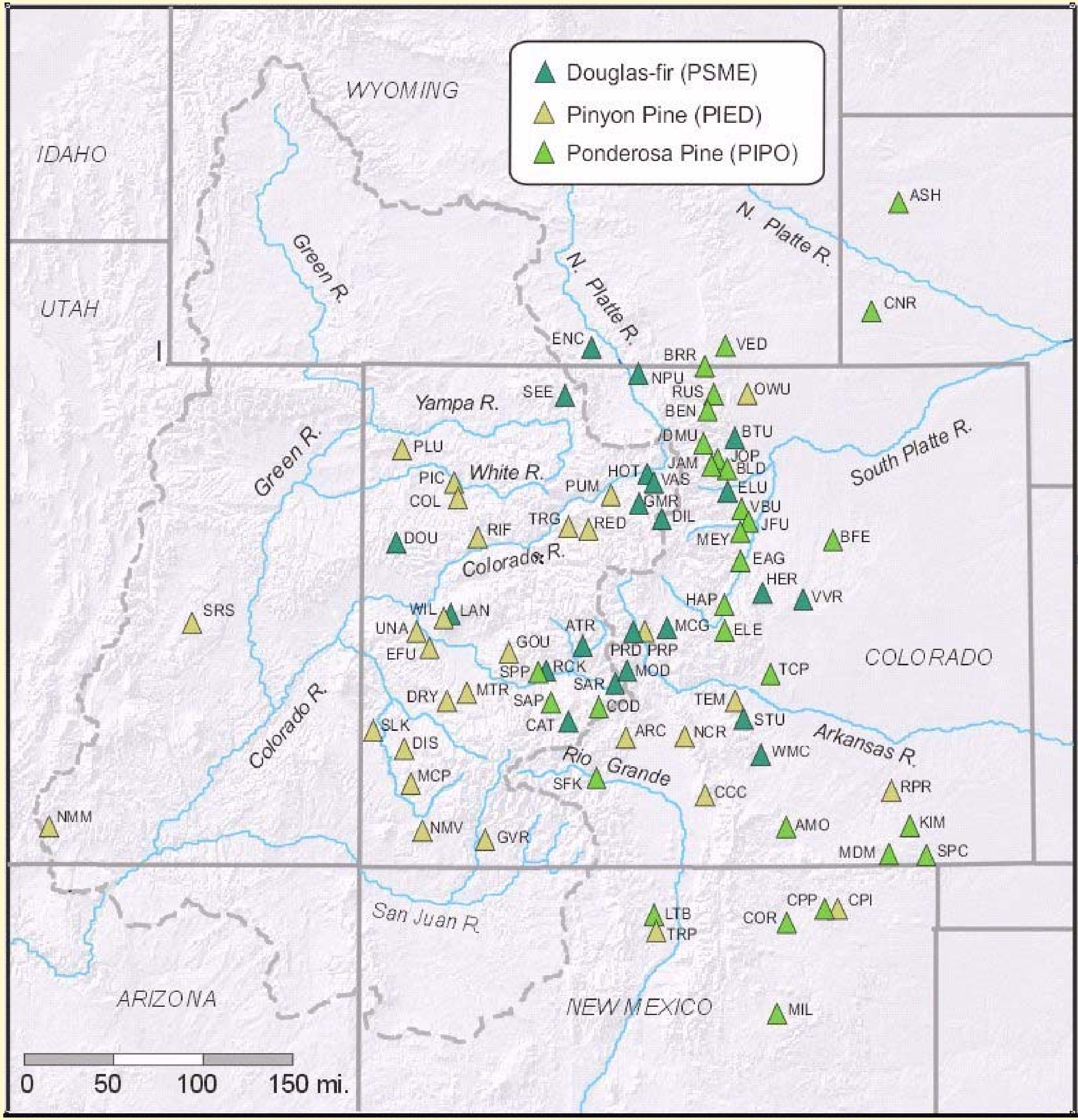
Tree-ring chronologies for Colorado River basin and vicinity archived in the International Tree-Ring Data Bank (ITRDB)



- Includes all species
- Variable start and end dates
- Many are useful for streamflow and precipitation reconstructions

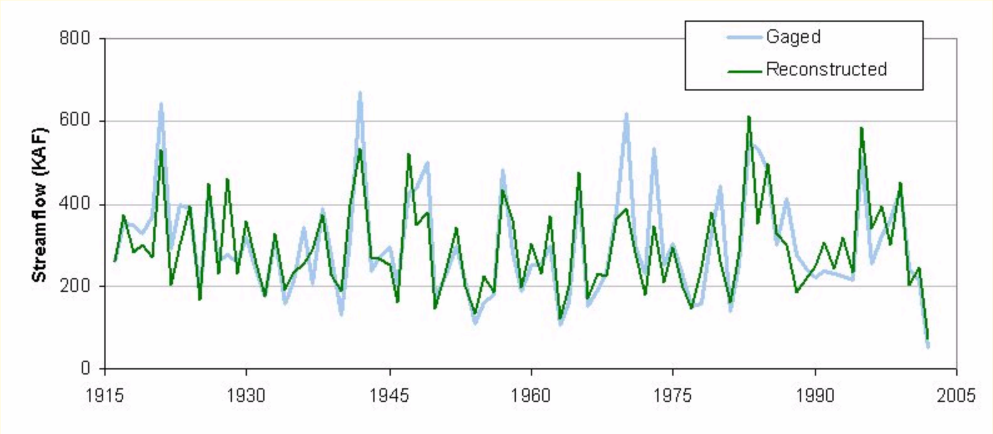
National Climatic Data Center, Paleoclimatology Branch: http://www.ncdc.noaa.gov/paleo/treering.html

Subset of recently collected chronologies, including many of those used in the latest Colorado River reconstructions



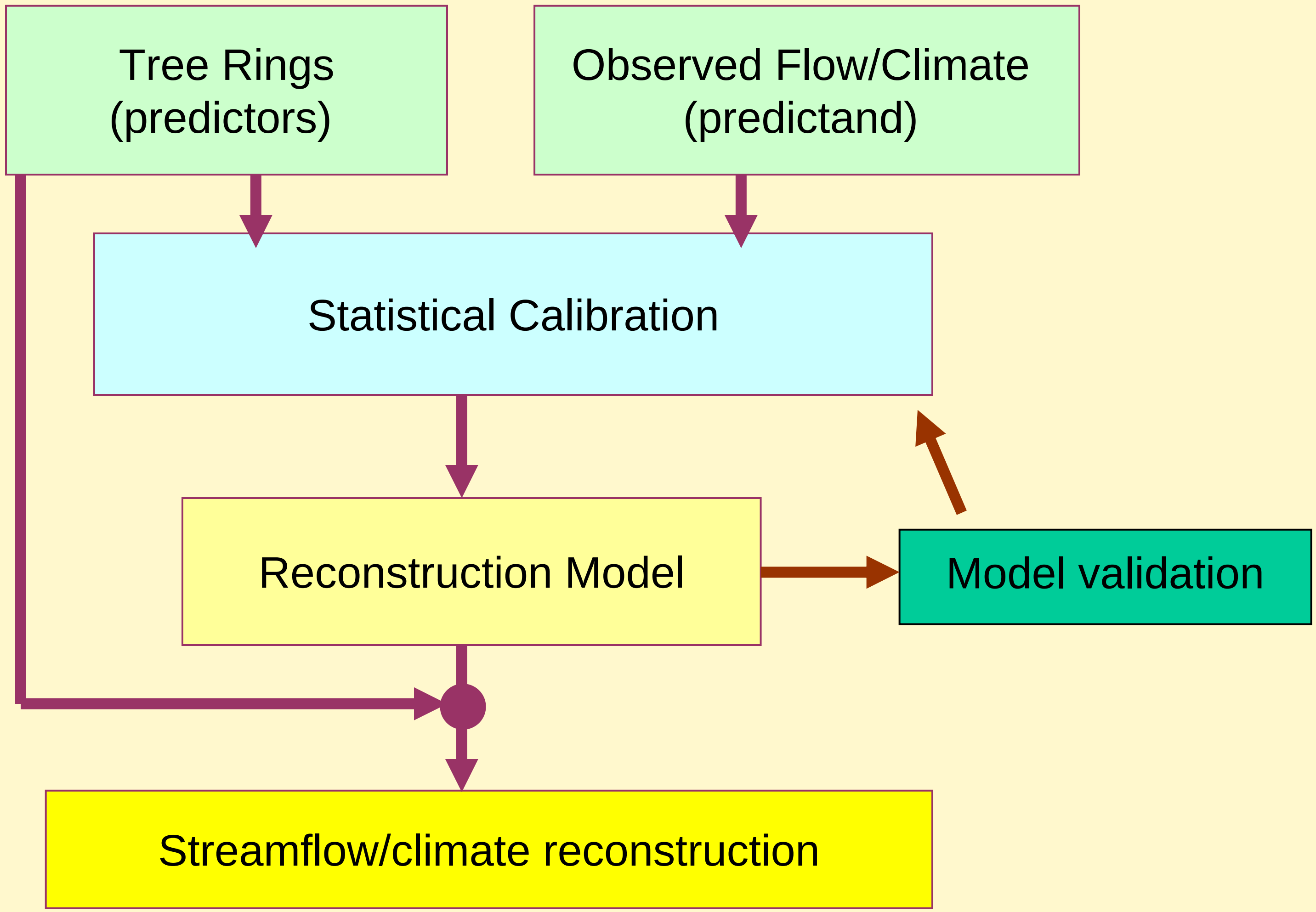
Part 4:

Generating the streamflow or climate reconstruction



Reconstruction: estimate of past hydrology or climate, based on the relationship between tree-ring data and an observed record

Overview of reconstruction methodology



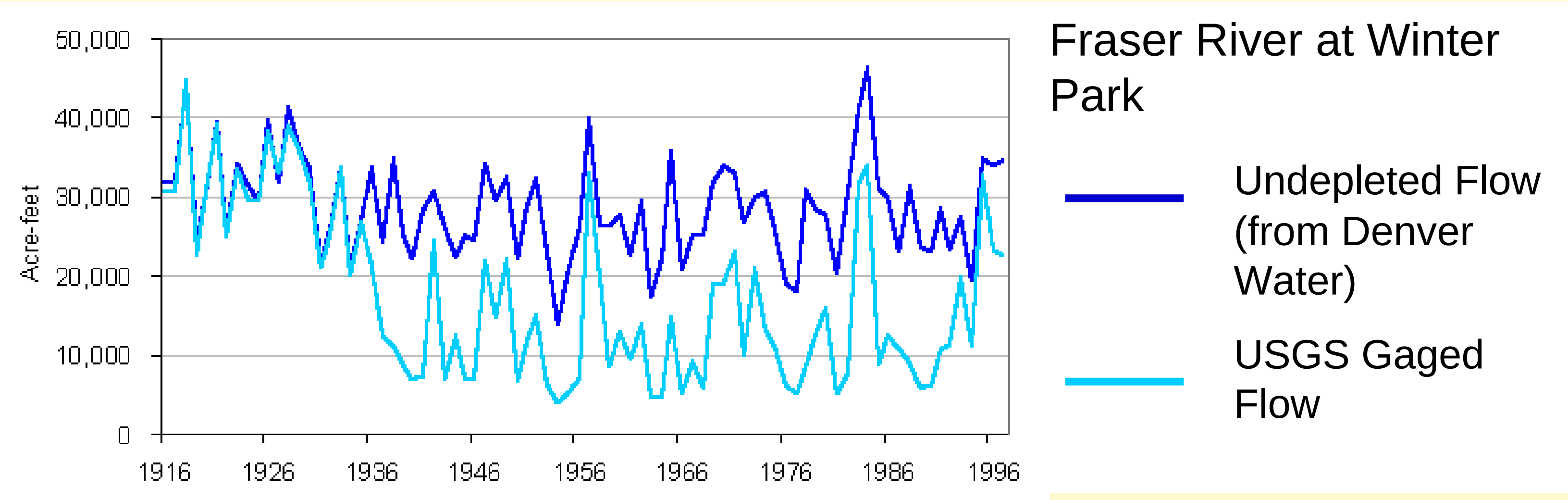
based on Meko 2005

Requirements: Tree-ring chronologies

- **Moisture sensitive species**
- **Location**
  - From a region that is climatically linked to the gage of interest
  - Because weather systems cross watershed divides, chronologies do not have to be in same basin as gage
- **Length**
  - Last year close to present for the longest calibration period possible
  - First year as early as possible (>300 years) but in common with a number of chronologies
- **Significant correlation with observed record**

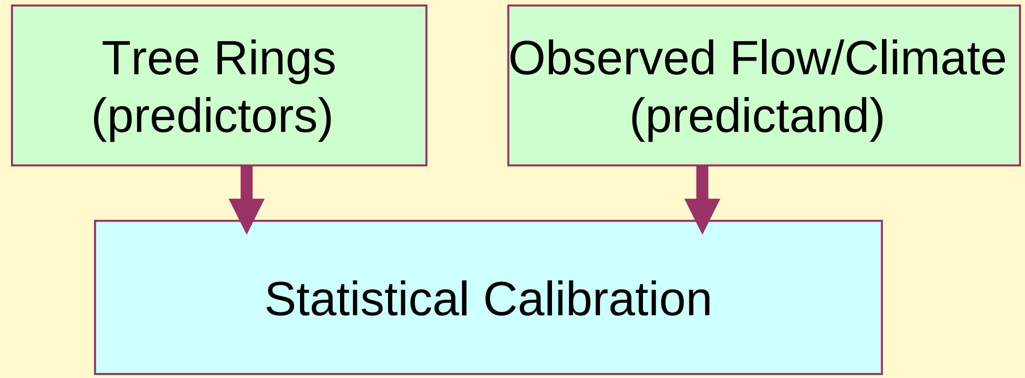
Requirements: Observed streamflow/climate record

- **Length** – minimum 30-40 years in common with tree-ring data for robust calibration
- **Natural/undepleted record** – flows must be corrected for depletions, diversions, evaporation, etc.
- **Homogeneous climate record** – inspected for station moves, changes in instrumentation



The reconstruction quality relies on the quality of the observed record.

Reconstruction modeling strategies



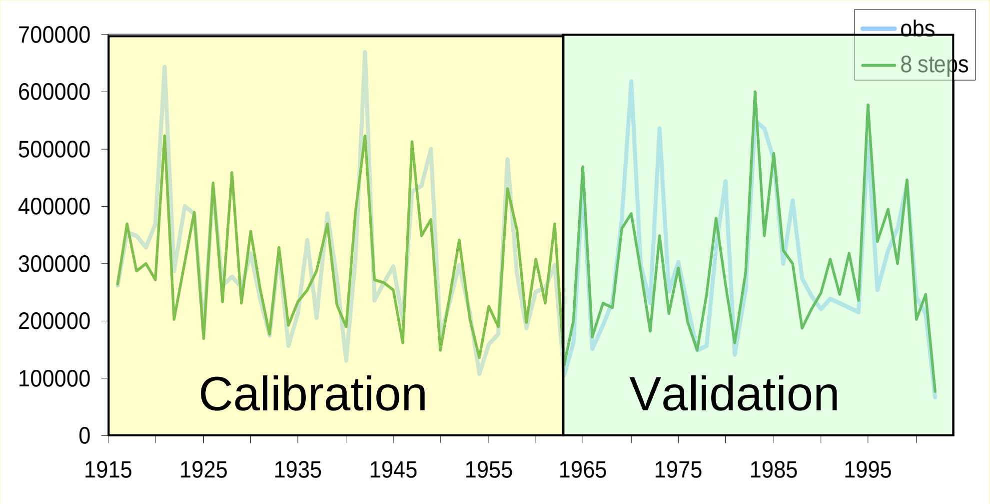
- **Tree-ring data are used to predict or estimate observed streamflow**
  - **Individual chronologies** are used as predictors in a statistical model, or
  - A set of chronologies is reduced through averaging or Principal Components Analysis (PCA), and **the average or principal components** (representing modes of variability) are used as predictors in a statistical model
- **Tree-ring data are calibrated with an observed streamflow record to generate a statistical model**
  - Most common statistical method: **Linear Regression**
  - Other approaches: neural networks, non-parametric

Model validation and skill assessment

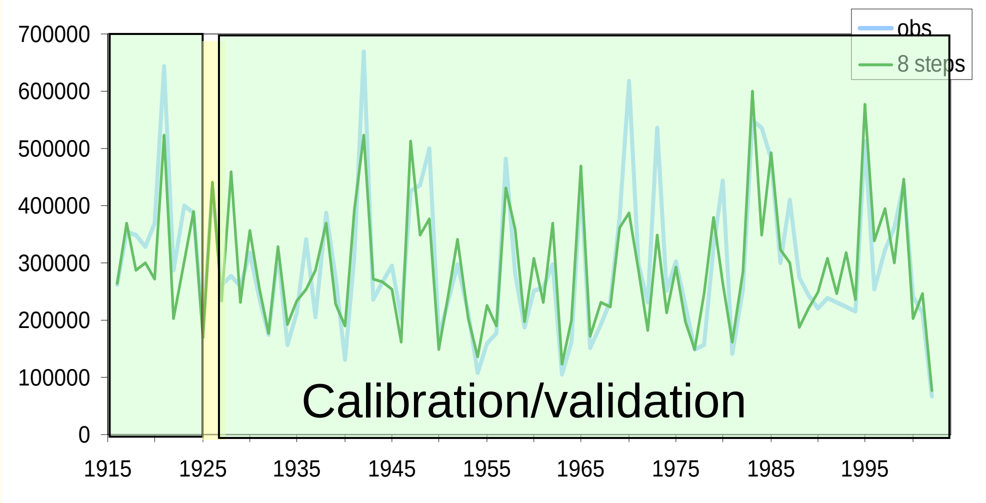
- Are regression assumptions satisfied?
- How does the model validate on data not used to calibrate the model?
- How does the reconstruction compare to the gage record?

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

Split-sample with independent calibration and validation periods



Cross-validation: “leave-one-out” method (or more than one), iterative process



Two statistics for model assessment

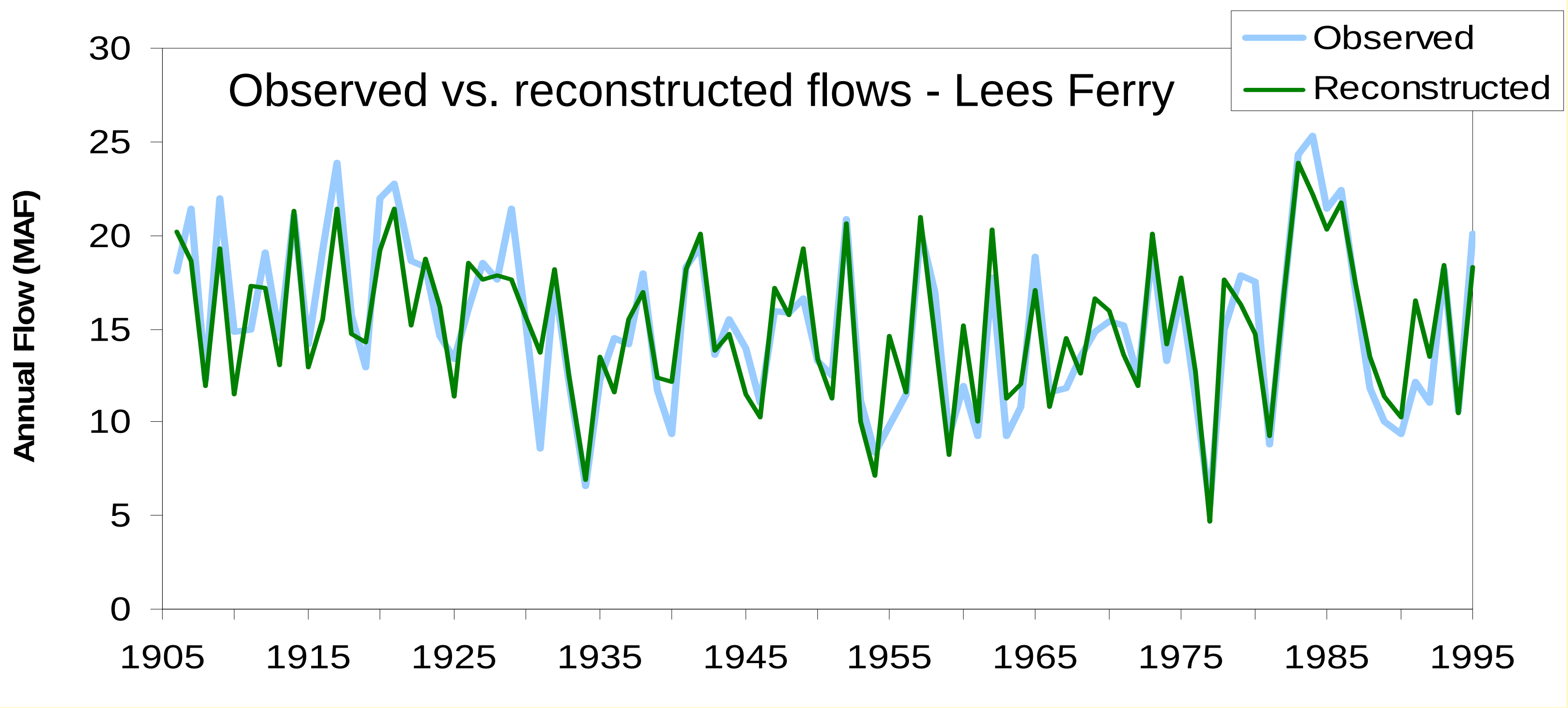
- Calibration: Explained variance: R^2
- Validation: Reduction of Error (RE): model skill compared to no knowledge (e.g., the calibration period mean)

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

What are desirable values?

Of course, higher R^2s are best, and positive value of RE indicates some skill (the closer to R^2 the better)

How does the reconstruction compare to the gage record?

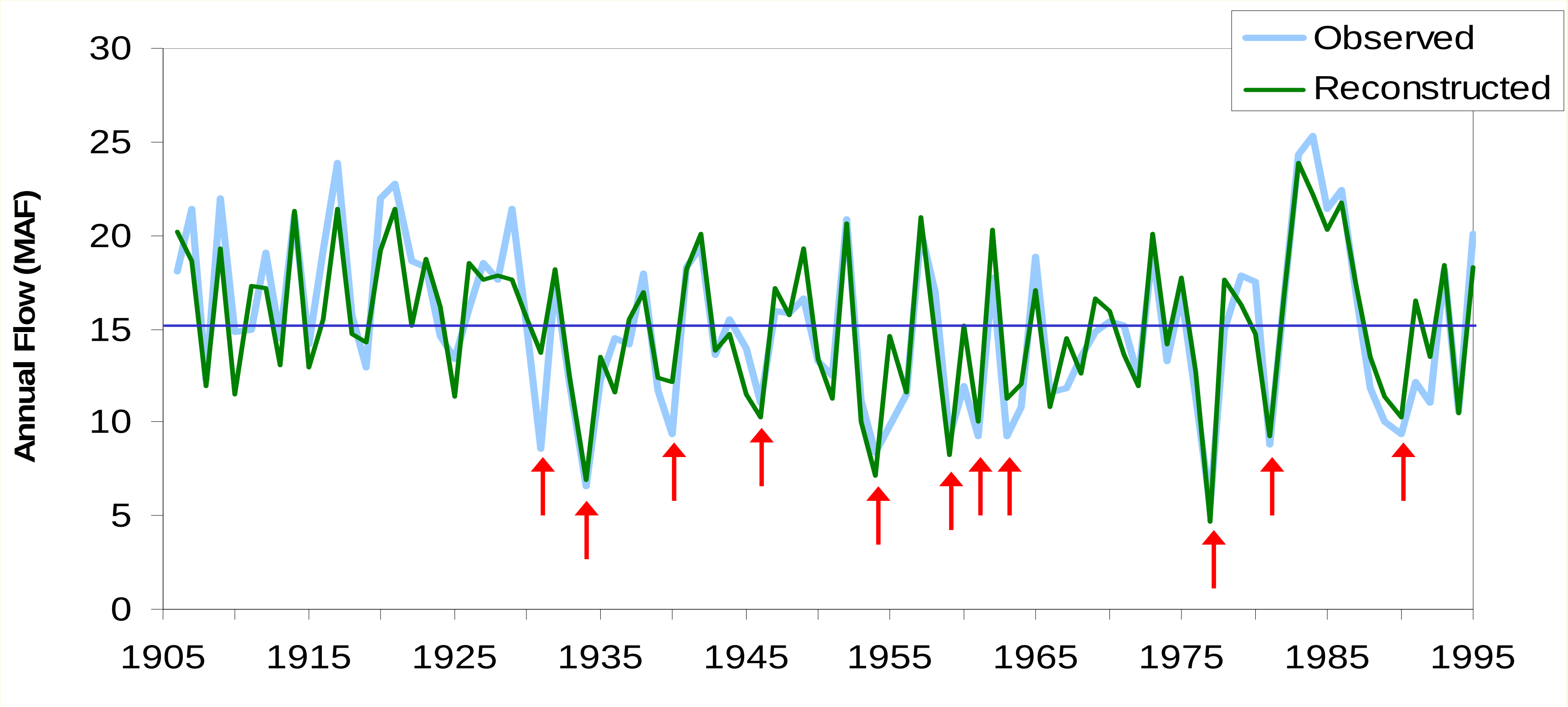


	Observed	Recon'd
Mean	15.22	15.22
Max	25.27	23.91
Min	5.57	4.71
StDev	4.32	3.88

The means are the same, as expected from the the linear regression

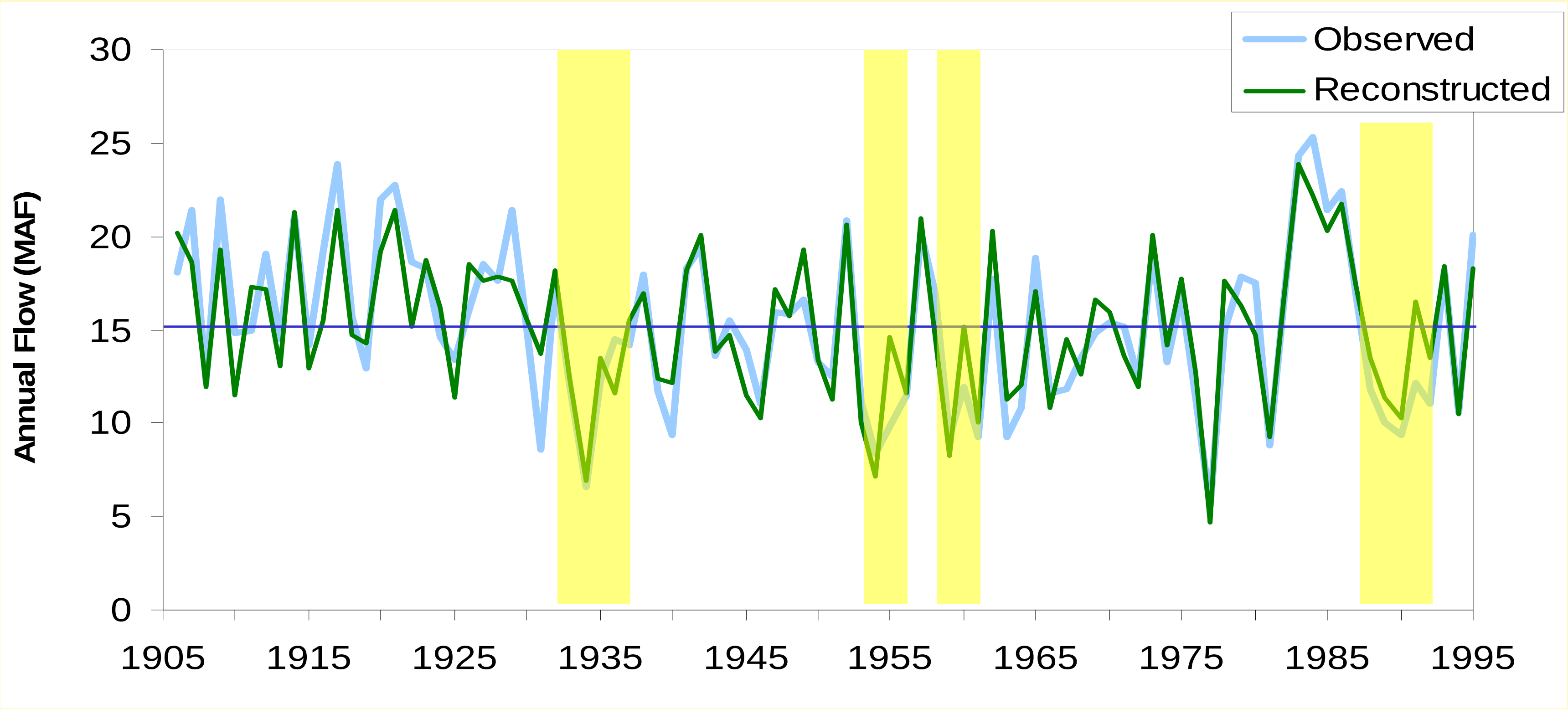
Also as expected, the standard deviation (variance) in the reconstruction is lower than in the gage record

Subjective assessment of model quality



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

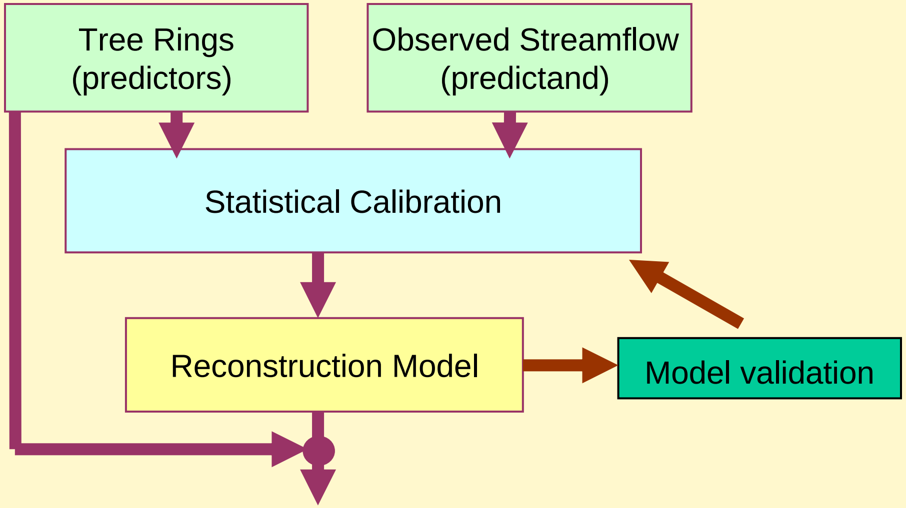
Subjective assessment of model quality

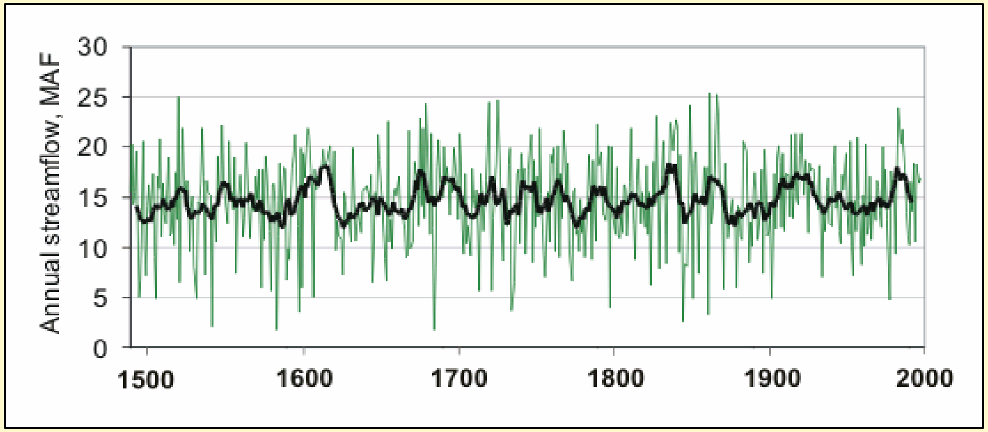


- Are the lengths and total deficits of multi-year droughts replicated reasonably well?

From model to full reconstruction

When the regression model has been fully evaluated, the model is applied to the full period of tree-ring data to generate the reconstruction





Part 5

Uncertainty in the Reconstructions

How accurate are the reconstructions?

What are sources of uncertainty?

What are the confidence intervals for the reconstruction models?

Sources of Uncertainty

• Trees are imperfect recorders of climate and streamflow.

• The reconstruction model does not explain 100% of the variance in the observed record.

• Streamflow or climate data may contain errors.

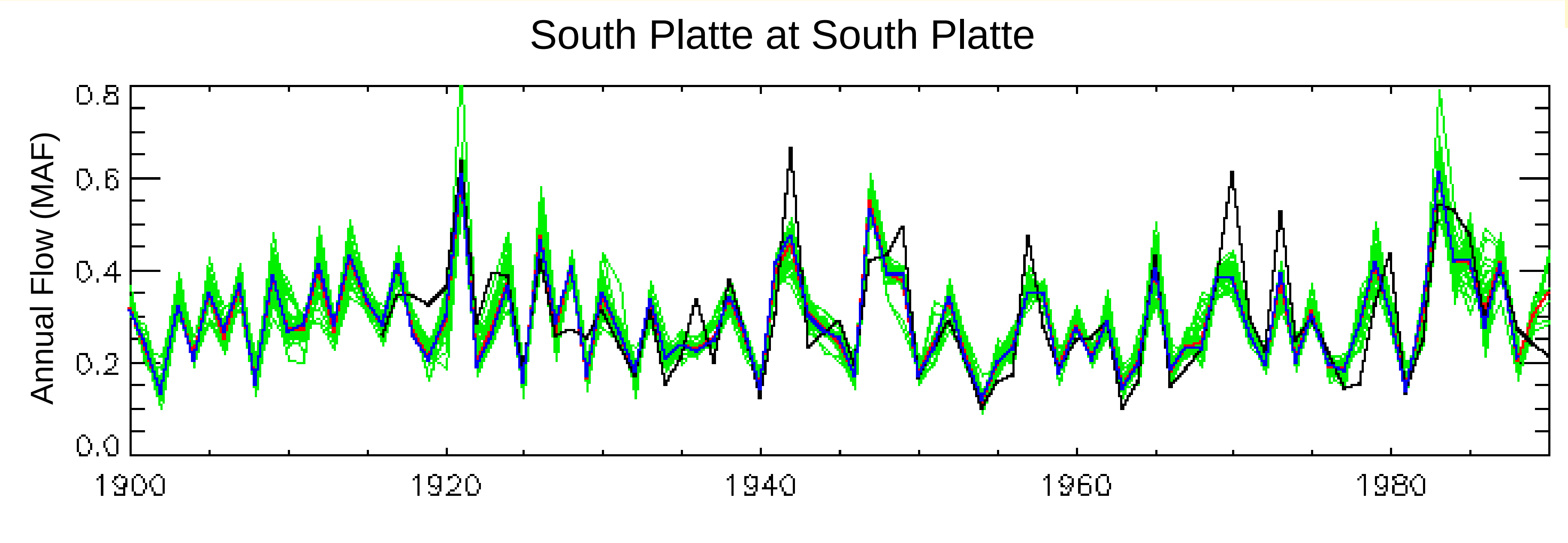
• A variety of decisions are made in the reconstruction process all of which can have an effect on the final reconstruction.

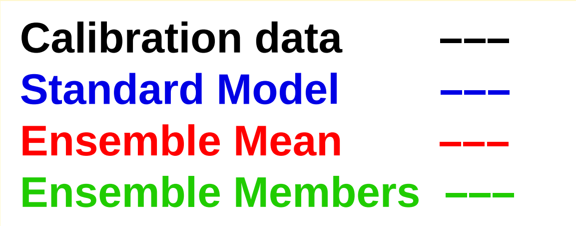
Sensitivity of the reconstruction to choices made in the reconstruction modeling process

- calibration data
- span of years used for the calibration
- selection of tree-ring data
- treatment of tree-ring data
- statistical approach used

Choices are made based on available data, statistical properties of data, and model validation results, but often, there is no clear “best” model. Instead, there are tradeoffs.

Sensitivity to calibration period



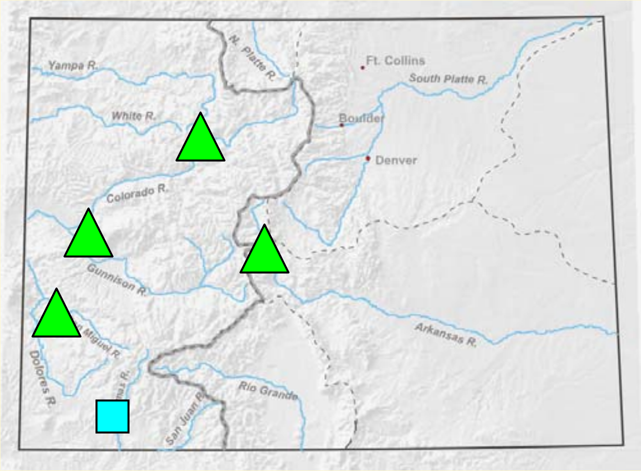


- Each of the 60 traces is a model based on a different calibration period
- All members have similar sets of predictors

Sensitivity to available predictors

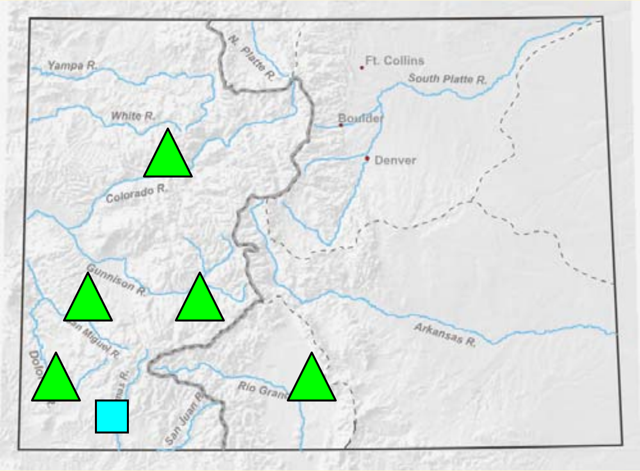
- How sensitive is the reconstruction to the specific predictor chronologies in the pool and in the model?

Animas River at Durango – two independent models



Best stepwise model

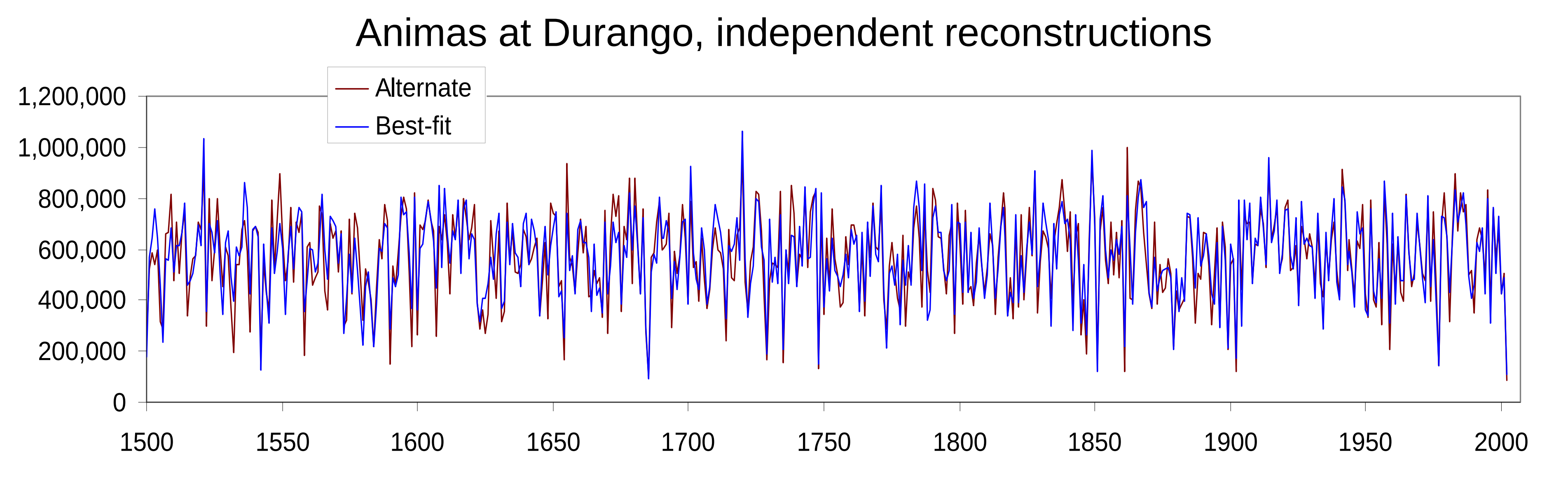
R2 = 0.82



Alternate stepwise model - predictors from best model excluded from pool

R2 = 0.79

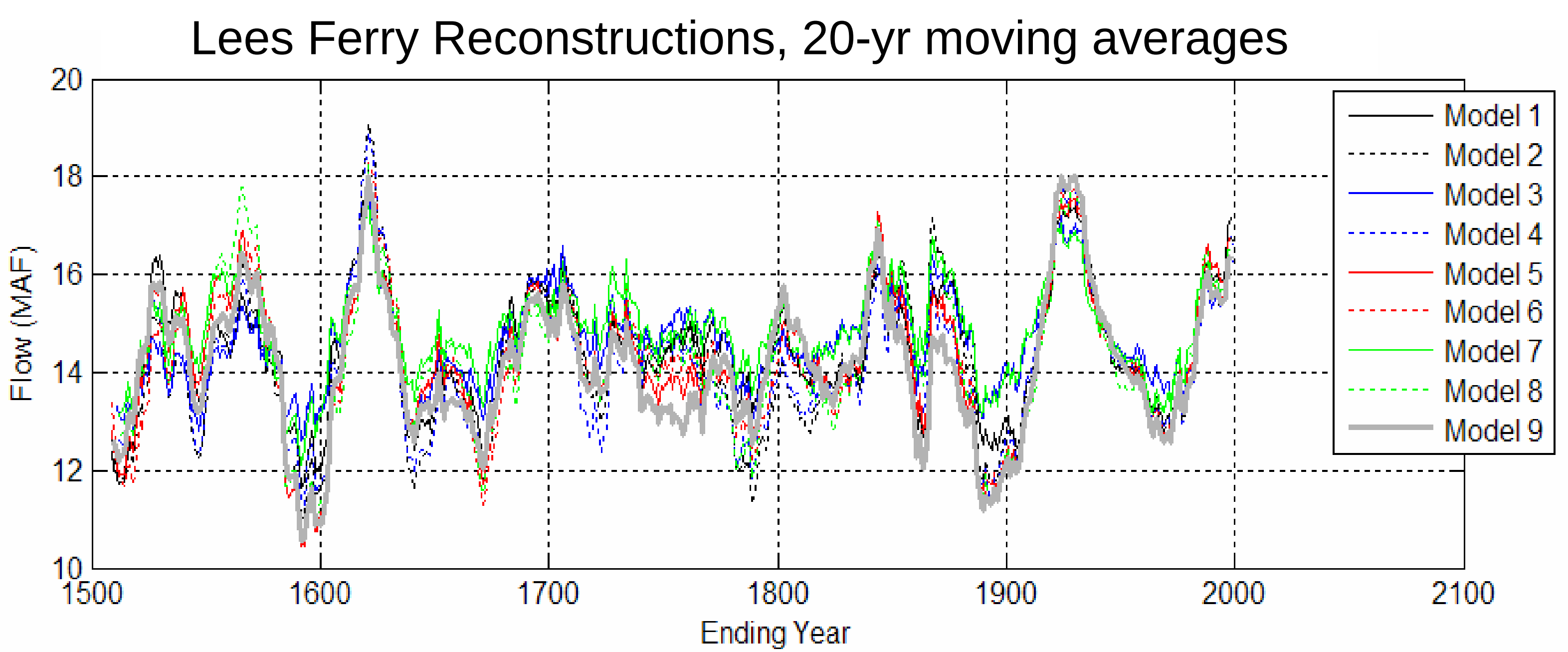
Sensitivity to available predictors



- The two models correlate at *r* = 0.89 over their overlap period, 1491-2002
- Completely independent sets of tree-ring data resulted in very similar reconstructions

Sensitivity to other choices made in modeling process

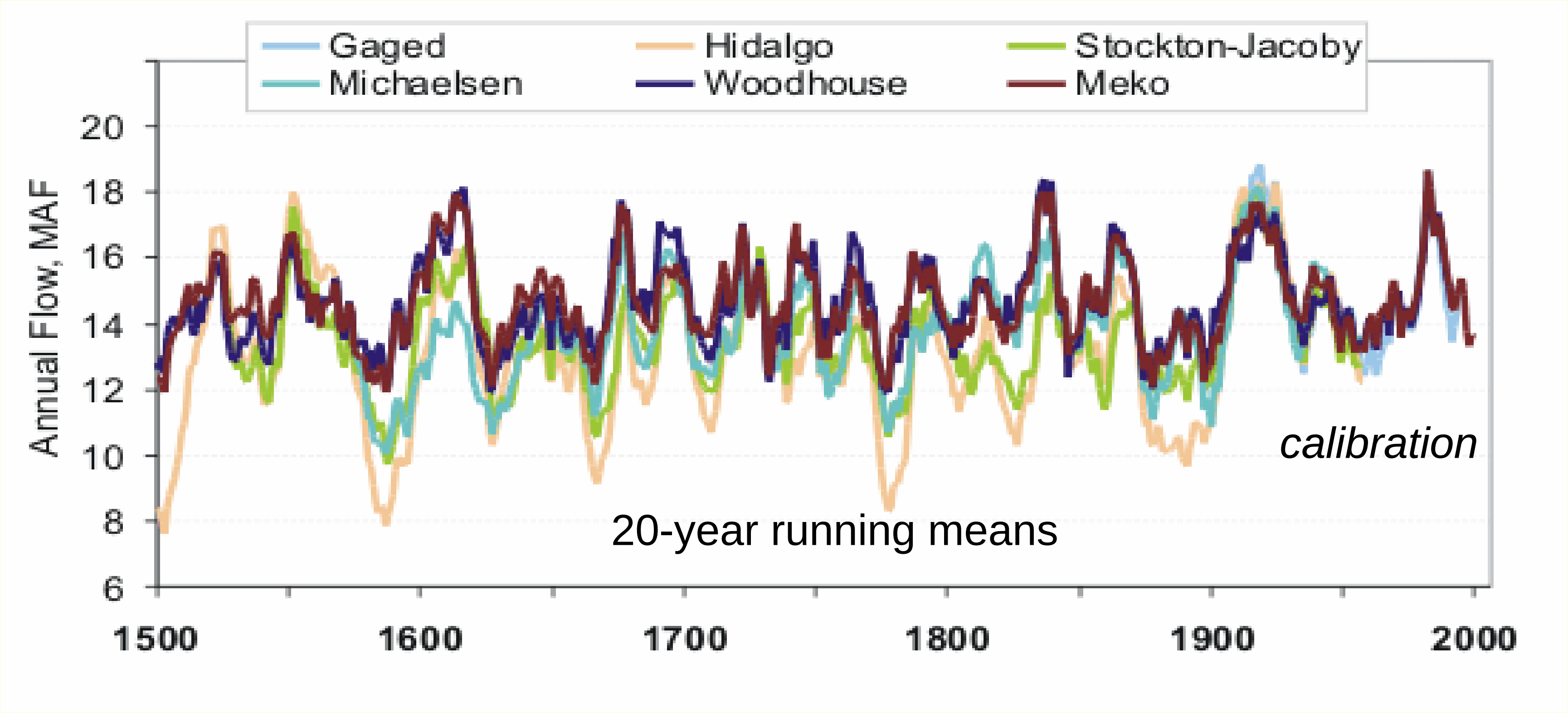
Lees Ferry reconstructions from 9 different models that vary according to chronology persistence, pool of predictors, modeling strategy



Analysis from David Meko

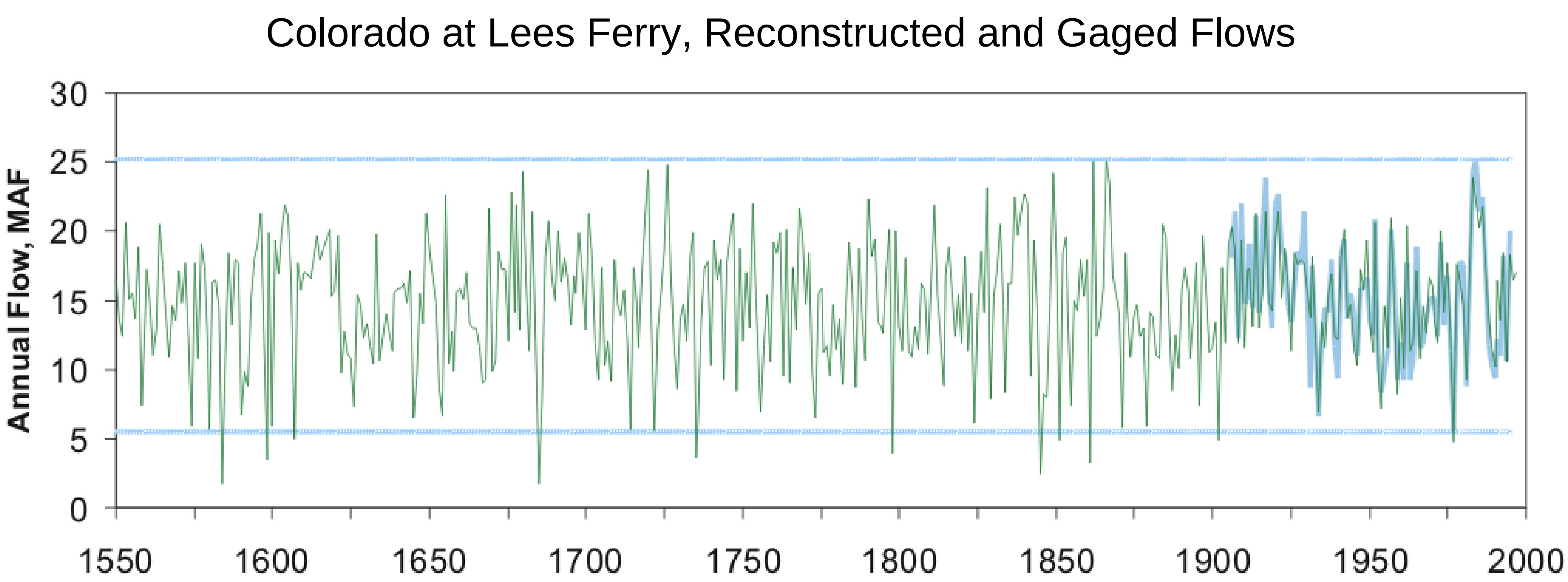
Lees Ferry reconstructions, generated between 1976 and 2007

Differences due to combinations of ***all of the factors*** mentioned



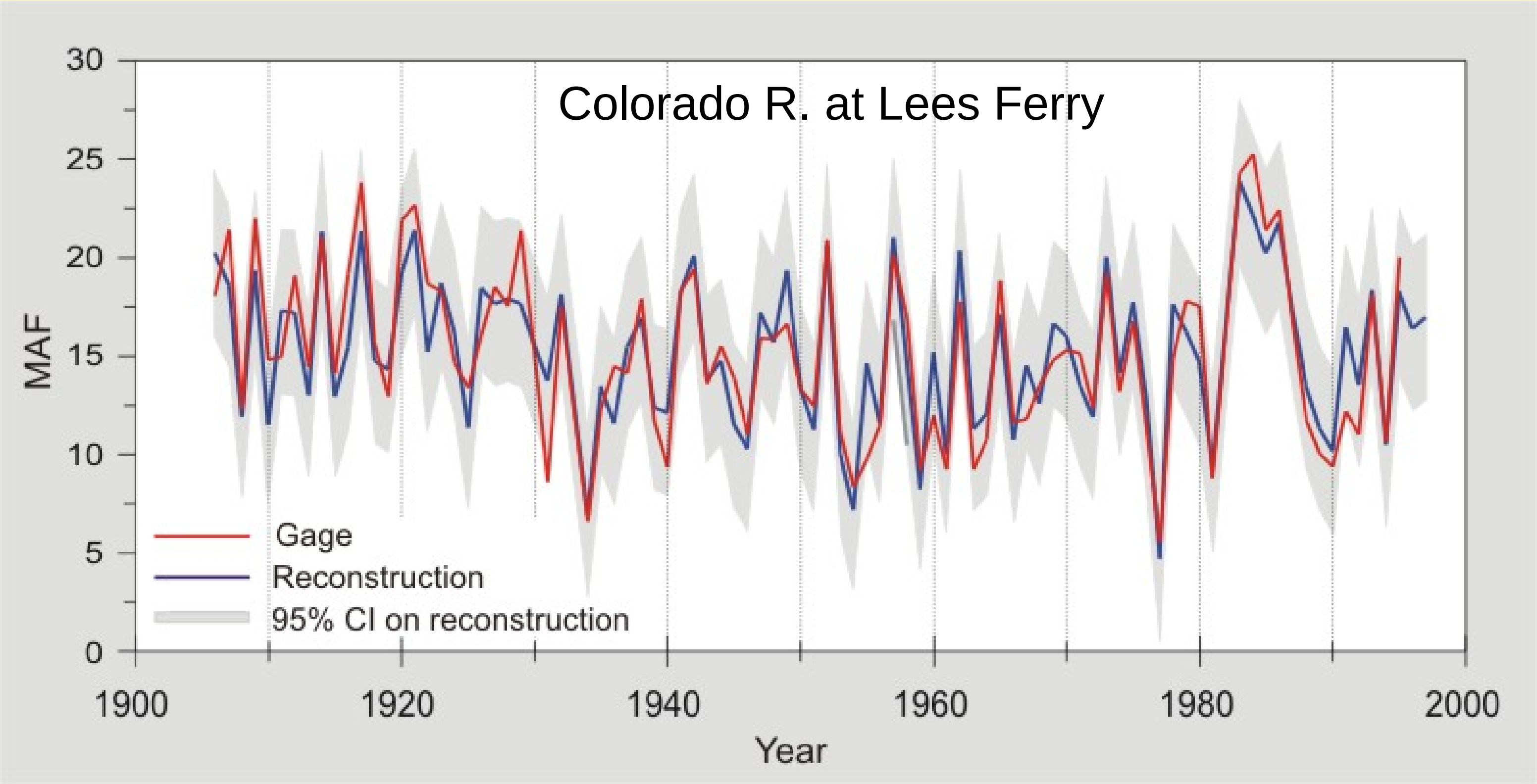
Stockton-Jacoby (1976), Michaelson (1990), Hidalgo (2001), Woodhouse (2006), Meko (2007)

Uncertainty related to extreme values



Extremes of reconstructed flow beyond the gaged record often reflect tree-ring data outside the calibration space of the model (extrapolation vs. interpolation)

Using model error to generate confidence intervals for the model

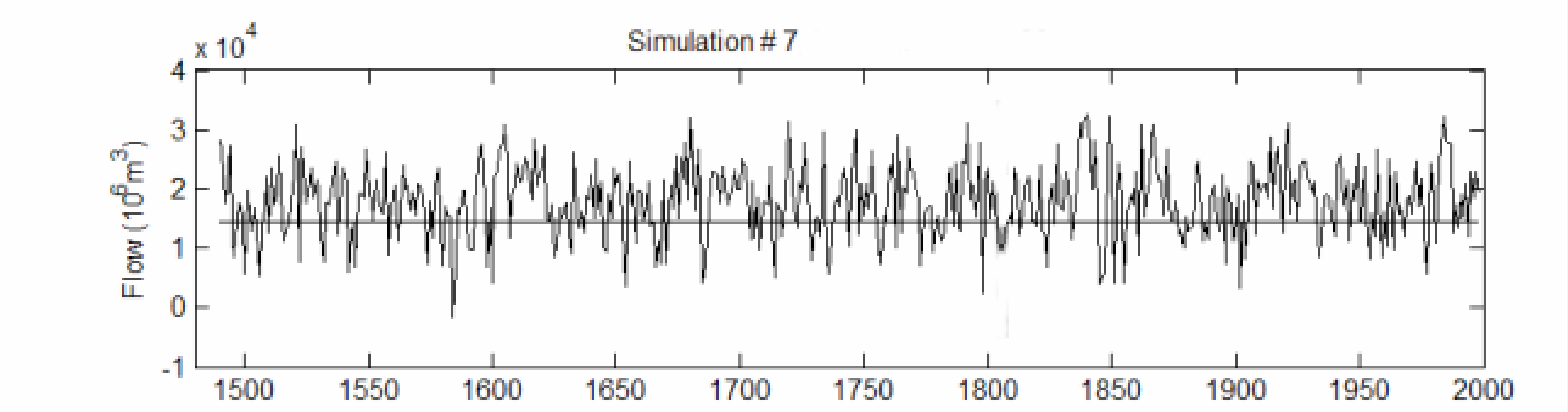


- Gray band = 95% confidence interval around reconstruction (2 x root mean squared error, RMSE)
- Indicates 95% probability that gaged flow falls within the gray band

An alternative approach to generate confidence intervals on the reconstruction

• “noise-added” reconstruction approach

• a large number of plausible realizations of true flow from derived from the reconstructed values and their uncertainty allow for probabilistic analysis.



One of 1000 plausible ensemble of “true” flows, which together, can be analyzed probabilistically for streamflow statistics

Meko et al. 2001

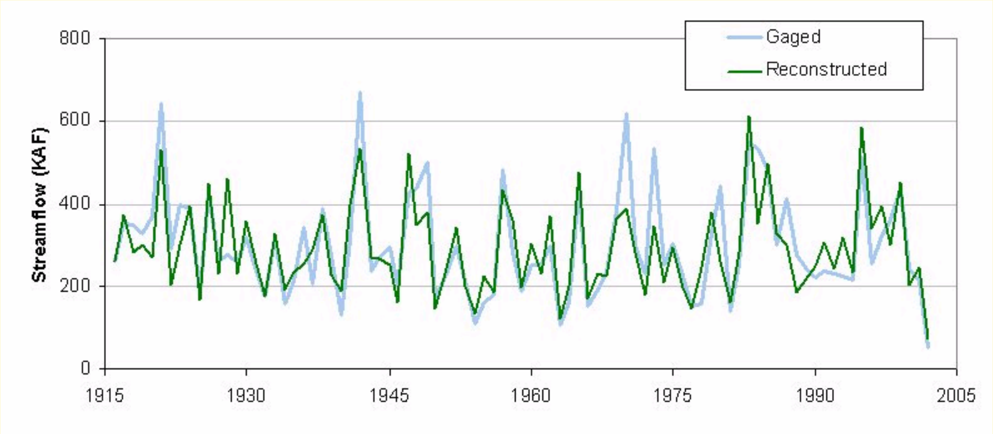
Uncertainty summary

- We can measure the statistical uncertainty due to the reconstruction model, but this does not reflect all sources of uncertainty
- There are other ways to estimate reconstruction uncertainty or confidence intervals (i.e. Meko et al. “noise added” approach)
- For a given gage, there may be no one reconstruction that is the “right one” or the “final answer”
- Some reconstructions may be more reliable than others (model validation assessment, length of longer calibration period, better match of statistical characteristics of the gage record)

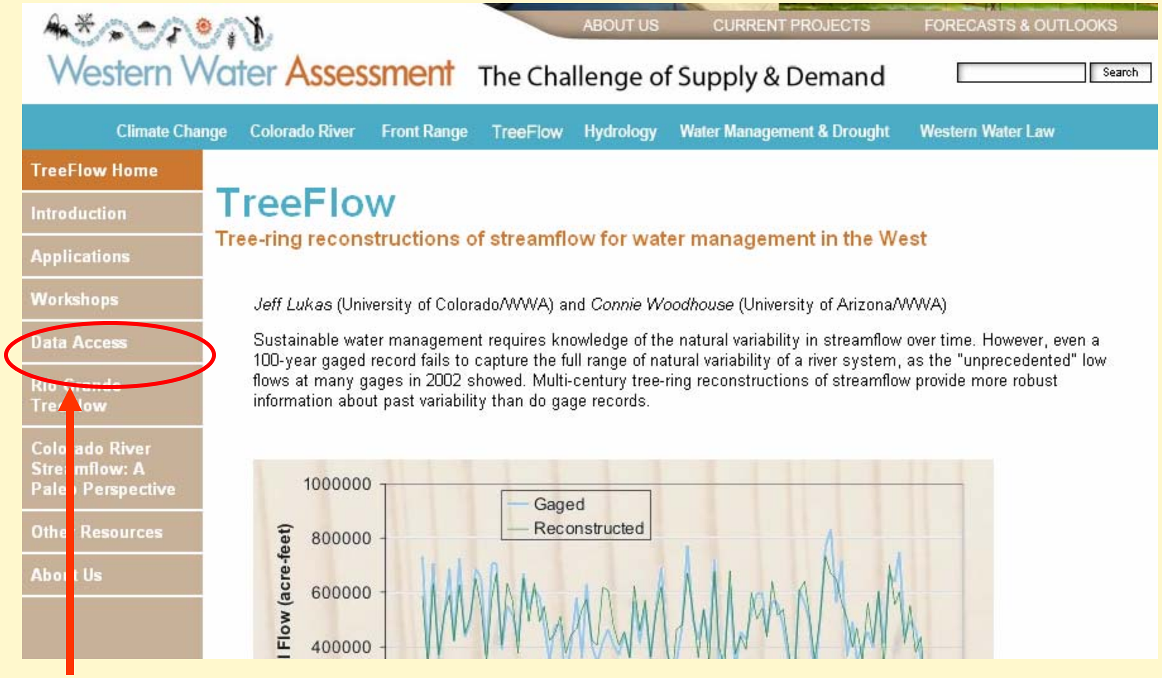
Bottom line: A reconstruction is a *plausible estimate* of past streamflow

Part 6:

Reconstructions for the Colorado River Basin and the West and how to obtain them



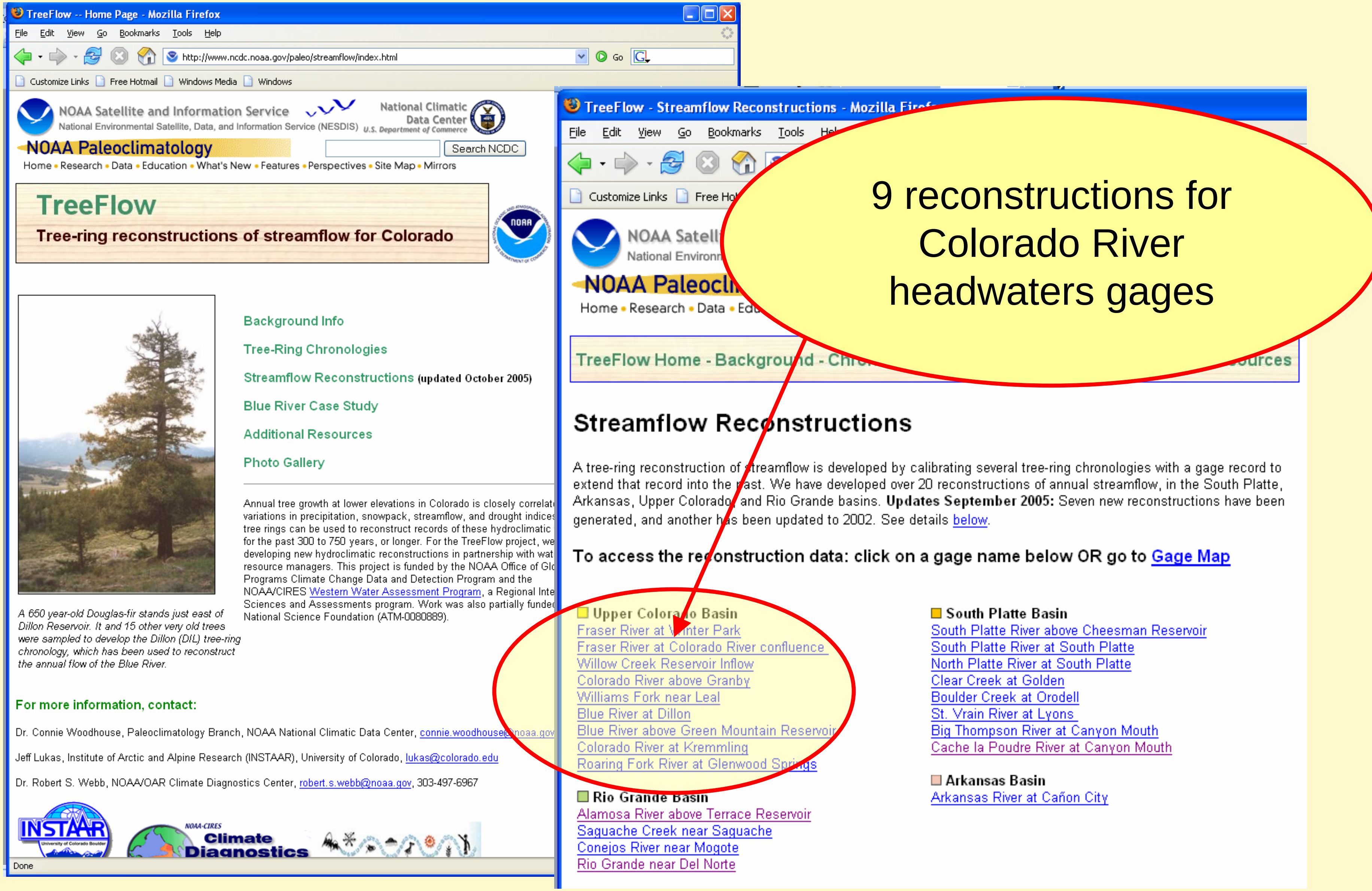
TreeFlow Web Page: http://wwa.colorado.edu/treeflow/



Data Access **page links to:**

- TreeFlow for Colorado
- Recent Lees and Upper Basin Reconstructions (Woodhouse et al. 2006 and Meko et al. 2007)
- Lower Colorado reconstructions (U. of AZ Laboratory of Tree-Ring Research Salt River Project)
- NOAA World Data Center for Paleoclimatology archives

Colorado TreeFlow



http://www.ncdc.noaa.gov/paleo/streamflow

Upper Colorado River Basin Reconstructions (2006)

NOAA Satellite and Information Service
National Environmental Satellite, Data, and Information Service (NESDIS)
National Climatic Data Center
U.S. Department of Commerce

WDC for Paleoclimatology

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Updated Streamflow Reconstructions for the Upper Colorado River Basin

Updated Streamflow Reconstructions for the Upper Colorado River Basin
Water Resources Research
Vol. 42, W05415, 11 May 2006.

Connie A. Woodhouse[1], Stephen T. Gray[2], David M. Meko[3]

[1] NOAA National Climatic Data Center, Boulder, CO
[2] U.S. Geological Survey, Desert Laboratory, Tucson, AZ
[3] Laboratory of Tree-Ring Research, University of Arizona, Tucson AZ

Satellite image of Lake Powell, Utah on the Colorado River above Lee's Ferry, Arizona. USGS Landsat Photo.

ABSTRACT:
Updated proxy reconstructions of water year (October-September) streamflow for four key gauges in the Upper Colorado River Basin were generated using an expanded tree ring network and longer calibration records than in previous efforts. Reconstructed gauges include the Green River at Green River, Utah; Colorado near Cisco, Utah; San Juan near Bluff, Utah; and Colorado at Lees Ferry, Arizona. The reconstructions explain 72-81% of the variance in the gauge records, and results are robust across several reconstruction approaches. Time series plots as well as results of cross-spectral analysis indicate strong spatial coherence in runoff variations across the subbasins. The Lees Ferry reconstruction suggests a higher long-term mean than previous reconstructions but strongly supports earlier findings that Colorado River allocations were based on one of the wettest periods in the past 5 centuries and that droughts more severe than any 20th to 21st century event occurred in the past.

Download data from the WDC Paleo archive:
Upper Colorado Streamflow Reconstructions in Text or Microsoft Excel format.
Supplementary Data 1. Chronology data and metadata
Supplementary Data 2. Regression equations and coefficients, PC data
Supplementary Data 3. Loadings from PCA on chronologies

To read or view the full study, please visit the AGU website.
It was published in **Water Resources Research**, Vol. 42, W05415, 11 May 2006.

10 reconstructions for UCRB:

- Colorado R. at Lees Ferry
- Colorado R. at Glenwood Spgs, CO
- Colorado R. nr Cisco, UT

- Green R. nr Green River, WY
- Green R. at Green River, UT

- Gunnison R. at Crystal Reservoir
- Gunnison R. nr Grand Junction, CO

- San Juan R. nr Archuleta, NM
- San Juan R. nr Bluff, UT
- Dolores R. nr Cisco, UT

Data in text and Excel format

http://www.ncdc.noaa.gov/paleo/pubs/woodhouse2006/woodhouse2006.html

Colorado River at Lees Ferry reconstructed flows, AD 762 – 2005 (2007)

NOAA Satellite and Information Service
National Environmental Satellite, Data, and Information Service (NESDIS)
National Climatic Data Center
U.S. Department of Commerce

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Medieval drought in the upper Colorado River Basin

Medieval drought in the upper Colorado River Basin
Geophysical Research Letters
Vol. 34, L10705, 24 May 2007.

David M. Meko[1], Connie A. Woodhouse[2], Christopher A. Baisan[1], Troy Knight[1], Jeffrey J. Lukas[3], Malcolm K. Hughes[1], and Matthew W. Salzer[1]

[1] Laboratory of Tree-Ring Research, University of Arizona, Tucson, Arizona
[2] Department of Geography and Regional Development, University of Arizona, Tucson, Arizona
[3] Institute of Arctic and Alpine Research, University of Colorado, Boulder, Colorado

ABSTRACT:
New tree-ring records of ring-width from remnant preserved wood are analyzed to extend the record of reconstructed annual flows of the Colorado River at Lee Ferry into the Medieval Climate Anomaly, when epic droughts are hypothesized from other paleoclimatic evidence to have affected various parts of western North

http://www.ncdc.noaa.gov/paleo/pubs/meko2007/meko2007.html

Lower Colorado River Reconstructions

U. of AZ Laboratory of Tree-Ring Research with Salt River Project

Upper Colorado and Salt-Verde Basins

4 reconstructions:

- Salt + Verde + Tonto
- Salt + Tonto
- Gila
- Verde

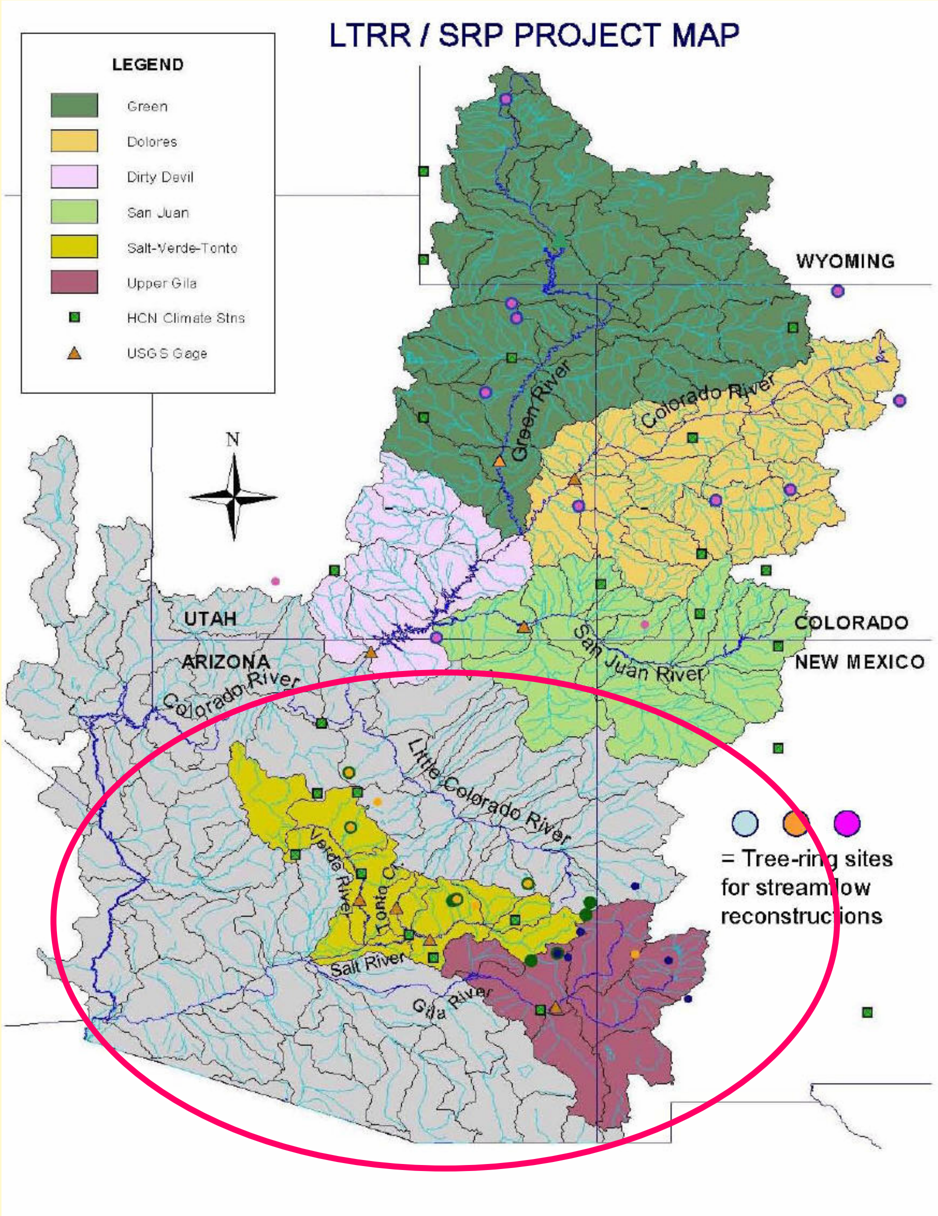
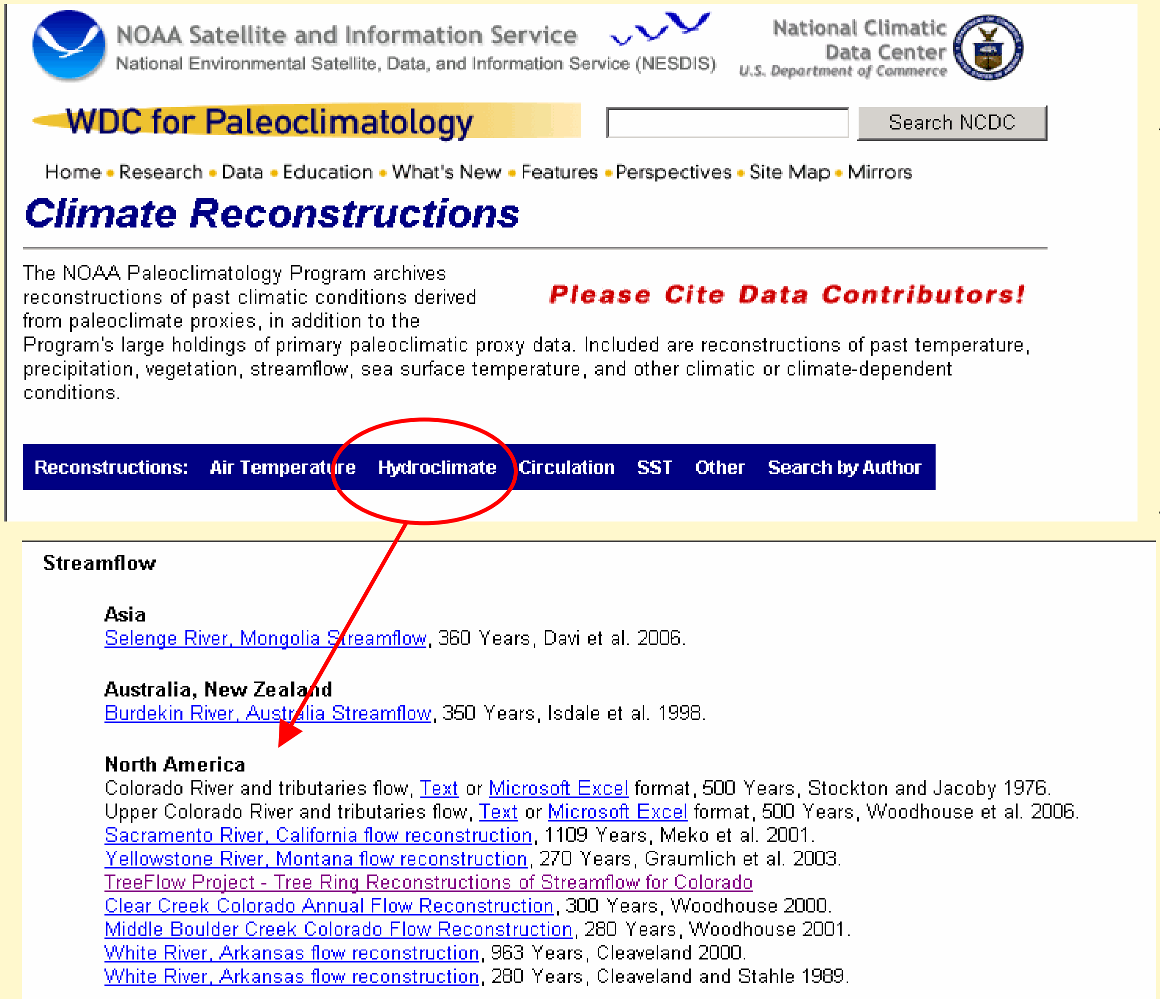


Image courtesy of K. Hirschboeck and D. Meko (U. AZ)

http://fp.arizona.edu/kkh/srp2.htm

NOAA National Climatic Data Center
World Data Center for Paleoclimatology


NOAA Satellite and Information Service
National Environmental Satellite, Data, and Information Service (NESDIS)
National Climatic Data Center
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Climate Reconstructions

The NOAA Paleoclimatology Program archives reconstructions of past climatic conditions derived from paleoclimate proxies, in addition to the Program's large holdings of primary paleoclimatic proxy data. Included are reconstructions of past temperature, precipitation, vegetation, streamflow, sea surface temperature, and other climatic or climate-dependent conditions.

Please Cite Data Contributors!

Reconstructions: Air Temperature Hydroclimate Circulation SST Other Search by Author

Streamflow

Asia
Selenge River, Mongolia Streamflow, 360 Years, Davi et al. 2006.

Australia, New Zealand
Burdekin River, Australia Streamflow, 350 Years, Isdale et al. 1998.

North America
Colorado River and tributaries flow, Text or Microsoft Excel format, 500 Years, Stockton and Jacoby 1976.
Upper Colorado River and tributaries flow, Text or Microsoft Excel format, 500 Years, Woodhouse et al. 2006.
Sacramento River, California flow reconstruction, 1109 Years, Meko et al. 2001.
Yellowstone River, Montana flow reconstruction, 270 Years, Graumlich et al. 2003.
TreeFlow Project - Tree Ring Reconstructions of Streamflow for Colorado
Clear Creek Colorado Annual Flow Reconstruction, 300 Years, Woodhouse 2000.
Middle Boulder Creek Colorado Flow Reconstruction, 280 Years, Woodhouse 2001.
White River, Arkansas flow reconstruction, 963 Years, Cleaveland 2000.
White River, Arkansas flow reconstruction, 280 Years, Cleaveland and Stahle 1989.

Available for Western US:

- Other Streamflow
- Summer PDSI
- Summer Temperature

Also:

- Circulation Indices (ENSO, PDO, AMO)
- Sea Surface Temps

http://www.ncdc.noaa.gov/paleo/recons.html

TreeFlow 2.0 Coming in 2009

User-friendly, direct, and basin-organized data access for the western US

Data Access **PLUS**

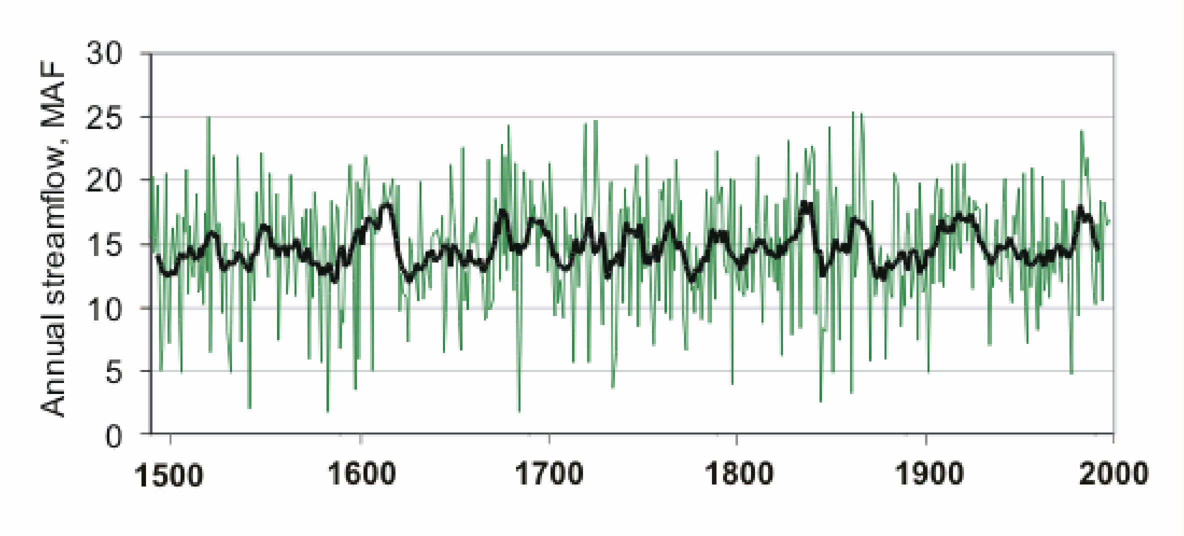
- Instructional materials
- Applications information
- Workshop archives
- Paleotools

Organized by basin (mostly):

- Upper Colorado R. basin
- Lower Colorado R. basin
- Platte River basin
- Rio Grande basin
- California rivers
- Columbia River basin

Part 7:

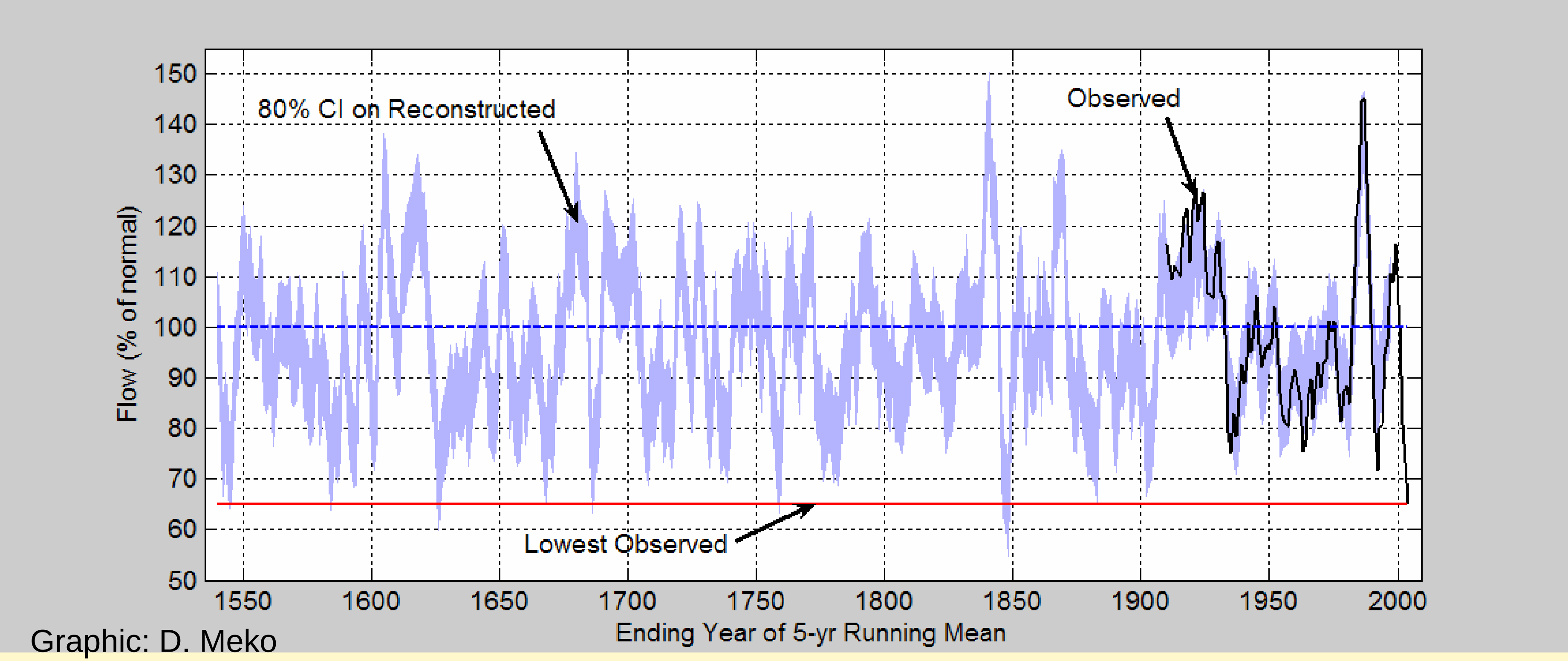
What the latest reconstructions for Lees Ferry show (Woodhouse et al. 2006, Meko et al. 2007)



An assessment of the 2000-2004 drought in a multi-century context

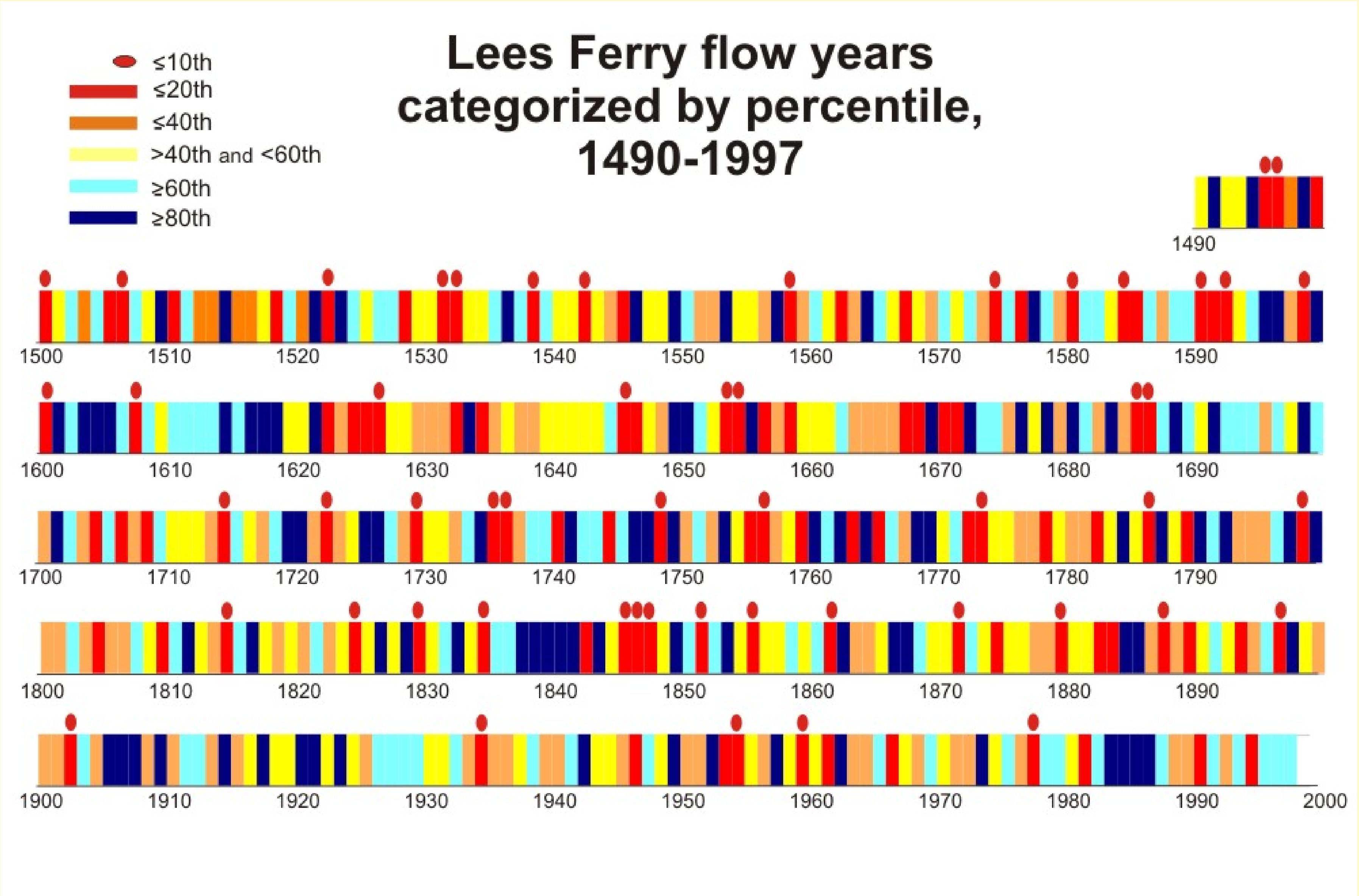
Lees Ferry Reconstruction, 1536-1997

(5-Year Running Mean)

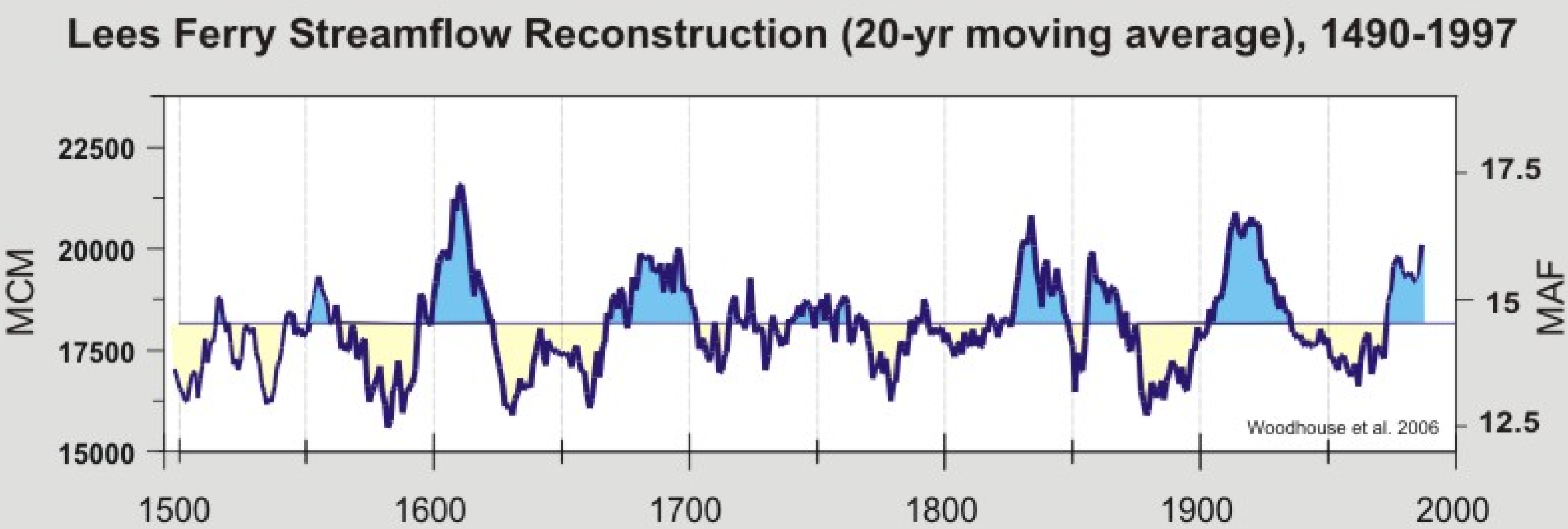


Graphic: D. Meko

Sequences of years and the distribution of extreme events or runs of wet or dry years



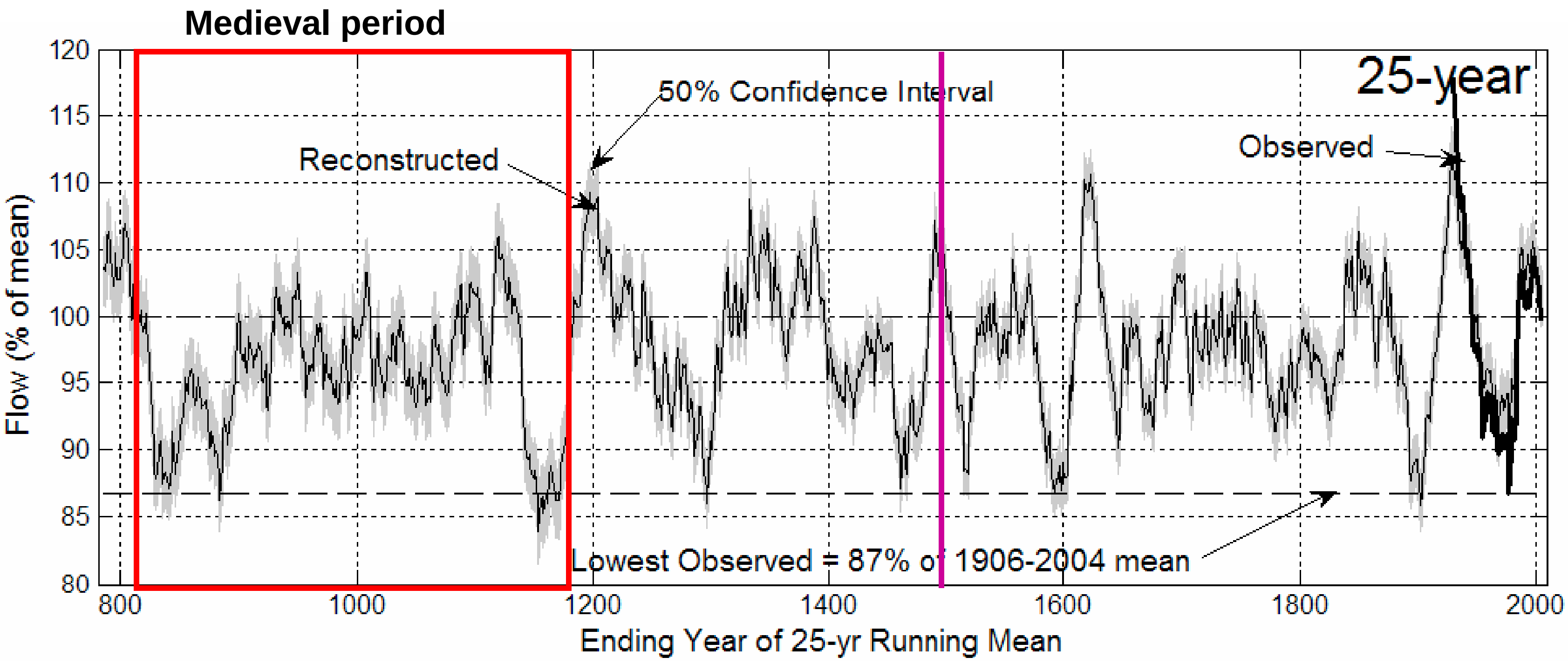
Low-frequency variability;
the 5 wettest/driest 20-yr periods



Pluvials Wettest non-overlapping 20-yr average	Droughts Driest non-overlapping 20-yr average
1602-1621	**1573-1592**
1905-1924	**1622-1641**
1825-1844	**1870-1889**
1978-1997	**1652-1671**
1687-1706	**1526-1545**
	1953-1972 (8th)

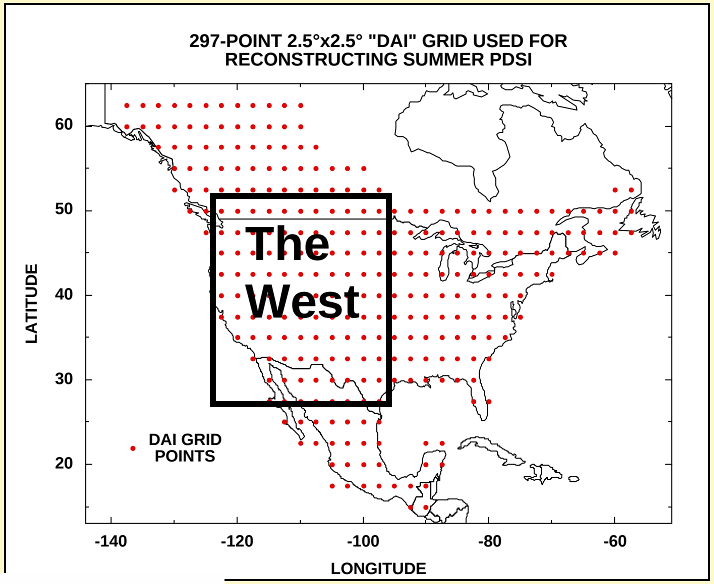
Stumps, logs, and remnants of wood were used to extend living chronologies back in time

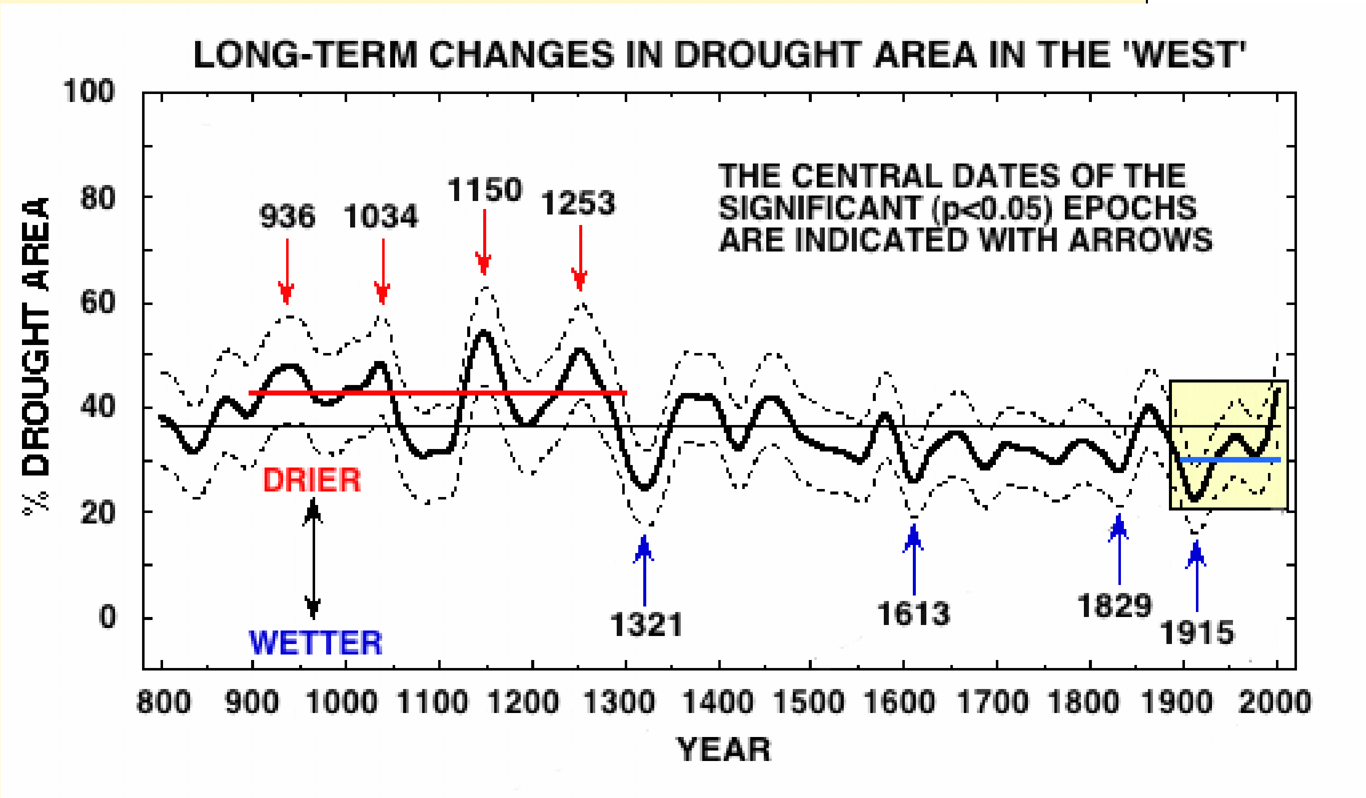
Reconstruction of Colorado River at Lees Ferry, AD 762 - 2005



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 (Meko et al. submitted).

Periods of low flow, AD 800-1200, correspond to an expanded area experiencing aridity in the western US.





From Cook et al. 2004, *Science*

New Work:

Changes in hydrologic regimes and storage requirements based on a simple hydrologic model and reconstructed Colorado River flow

• Storage requirement = the volume of storage needed to supply a given annual demand (here, 75% of 15.2 maf) at a prescribed level of reliability (here, 95%)

• changes in the **mean** are **inversely** related to storage requirements

• changes in the year-to-year **variability** are **directly** related to storage requirements

• **mean** and **variability** can **offset** each other

• changes in **persistence** can **interact** in other ways

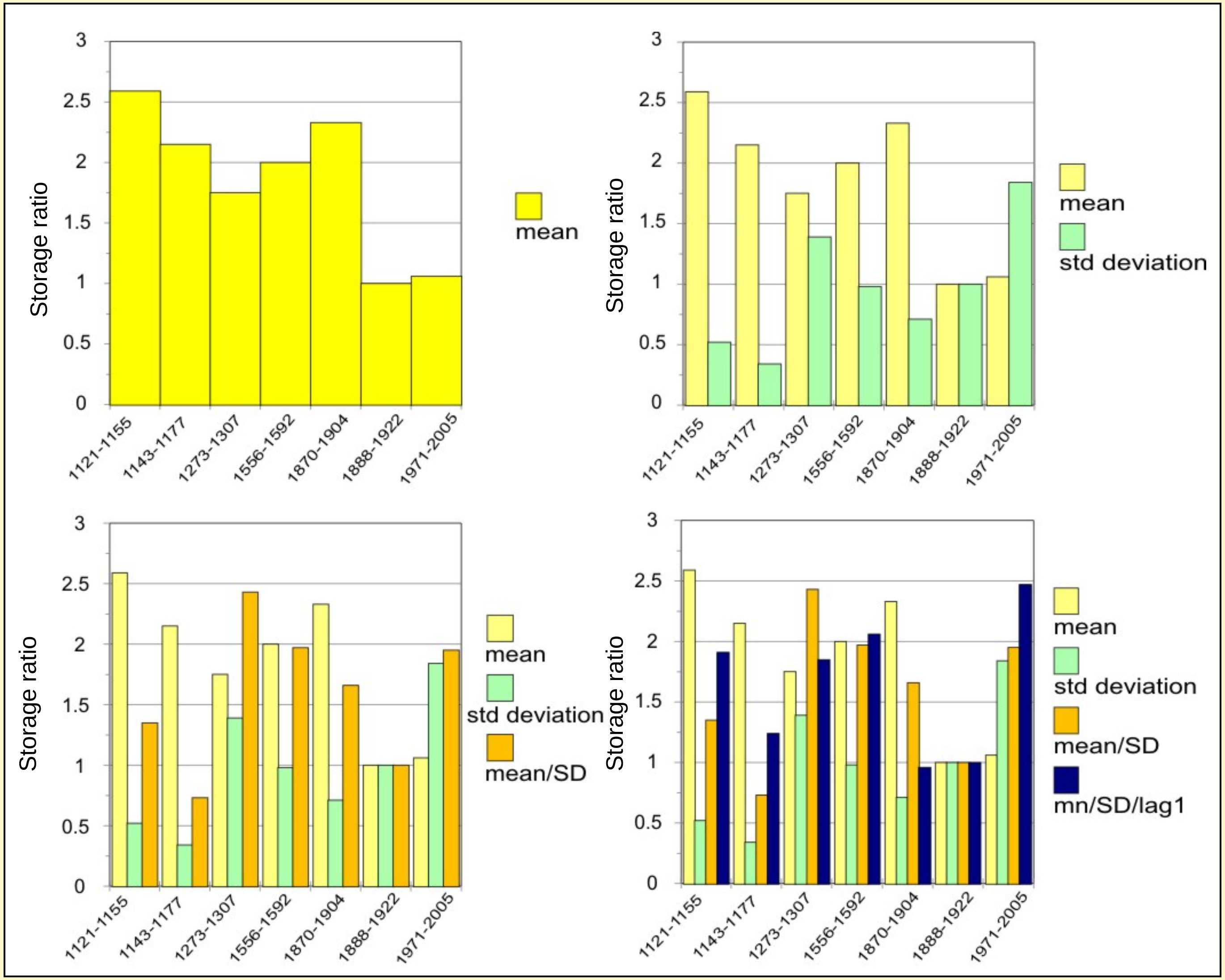
(Jain and Eisheid 2008)

Colorado River flow characteristics for selected 35-year periods (mostly very dry) compared to a base period, 1888-1922

35-yr periods	**mean**	**standard deviation**	**lag-1 correlation**
1121-1155	12.90	2.44	0.42
1143-1177	13.20	1.97	0.49
1273-1307	13.60	3.99	0.13
1556-1592	13.30	3.36	0.29
1870-1904	13.00	2.85	0.00
base period 1888-1922	**15.20**	**3.38**	**0.26**
most recent 1971-2005	**15.00**	**4.56**	**0.37**

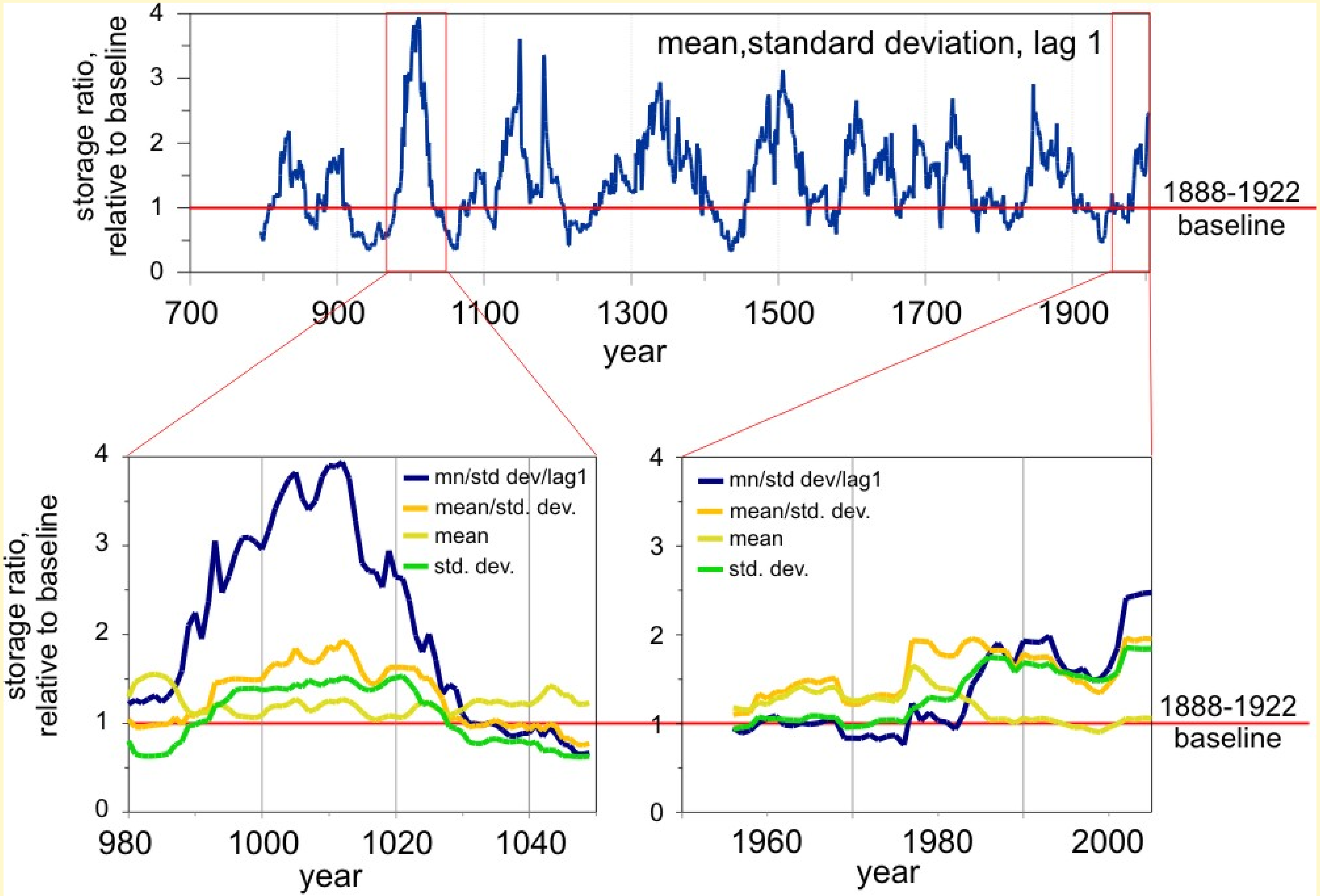
What effect do these flow characteristics have on storage requirements, relative to the base period?

Effect of changes in mean, standard deviation, and persistence on storage requirements



Storage ratio is the fraction of the baseline storage, based on 1888-1922

Storage requirements, 762-2005



High values of persistence in the 1000s lead to the highest storage ratios in the record

From 1956-2005, high standard deviation is a key factor, but relatively modest persistence and close to baseline mean flows alleviate this influence

Storage ratio is the fraction of the baseline storage, based on 1888-1922

To review…

1) Tree-ring reconstructions are useful in that they provide more “hydrologic experience” without the pain

2) Tree growth in this region is particularly sensitive to variations in moisture availability, and thus streamflow

3) The methods to develop tree-ring chronologies and streamflow reconstructions are designed to robustly capture and enhance this moisture signal

4) A reconstruction is a best-estimate based on the relationship between tree-growth and gaged flows; there is always uncertainty in the reconstructed flows

To review…

5) Many flow and climate reconstructions are available for the UCRB

6) The reconstructions show greater variability than the observed record, including drought events more severe and sustained

Relevance of tree-ring reconstructions in the face of a changing climate

The climate of the past will not be an exact analogue for the future. However, understanding the range of conditions possible under natural variability will provide a baseline for planning that will also have to consider the impact of global climate change.

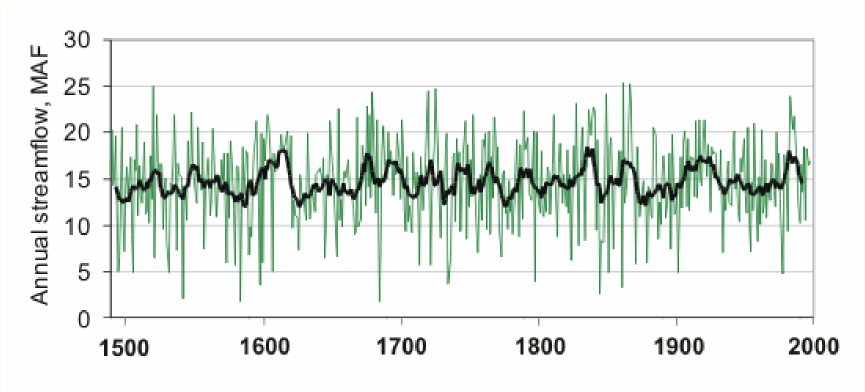
- Natural modes of variability will continue to operate, underlying human-induced warming trends

- The greater variability seen in the paleohydrologic records, compared to gaged records, can be a useful analogue for future variability

- Integrating information about past variability with projections for future climate may create plausible future scenarios for water management

Part 8:

How the reconstructions are being used in water management by Reclamation and others



Reconstruction data

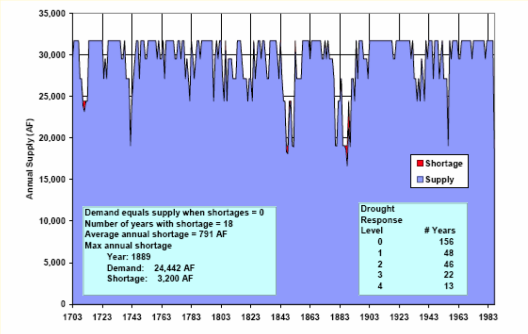


Figure 5. Demands & Supplies: 15% Reduced Flow Hydrology, Current Trends Scenario (demand = 31,700 AF/year).

Policy analysis

Applications of tree-ring reconstructions to water resource management

• Qualitative assessments; what is the range of conditions that have occurred in the past?

• Worst case drought scenarios; is the 1950s adequate?

• Input into water system models to test model resilience under a broader range of conditions than the gage record alone

• Blending information about past conditions with projections based on climate change scenarios and modeling.

Next:

• SNWA applications in eastern Nevada valleys

• Bureau 24 month model applications

• Paleoclimatic data with future projections for planning scenarios