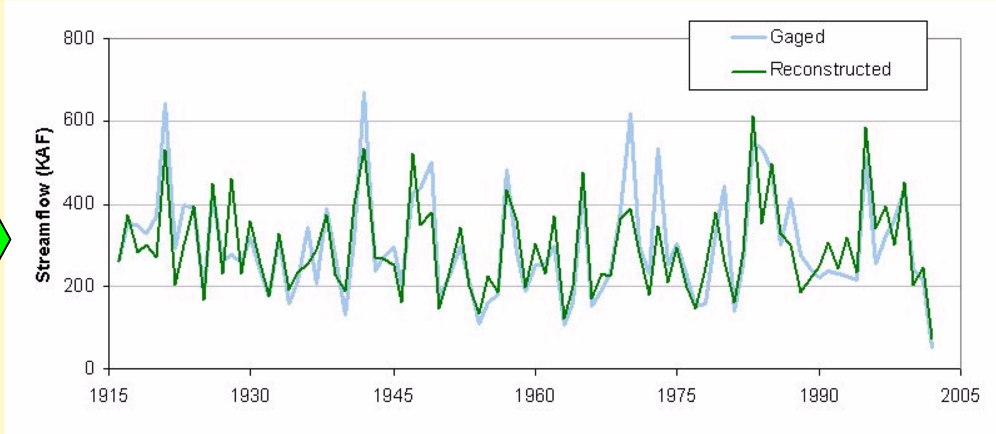
Tree-ring reconstructions of streamflow and their use in water management



US Bureau of Reclamation Upper Colorado Regional Office,
March 26, 2008

Jeff Lukas

INSTAAR, University of Colorado

and Western Water Assessment

Agenda

- Introduction: Welcome, group introductions, purpose
- Background; How tree rings record climate information
- Building the tree-ring chronology

    Break

- Generating the reconstruction of streamflow
- Reconstructions for the UCRB and the West
- Paleohydrologic research in the Wasatch (Matthew Bekker)

    Lunch

- How the reconstructions are being applied to water management in the West
- Forthcoming tree-ring data, applications, and resources
- Discussion – Where to go with tree-ring work for the UCRB and the West?

Please ask questions throughout!

Acknowledgements

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About RISAs

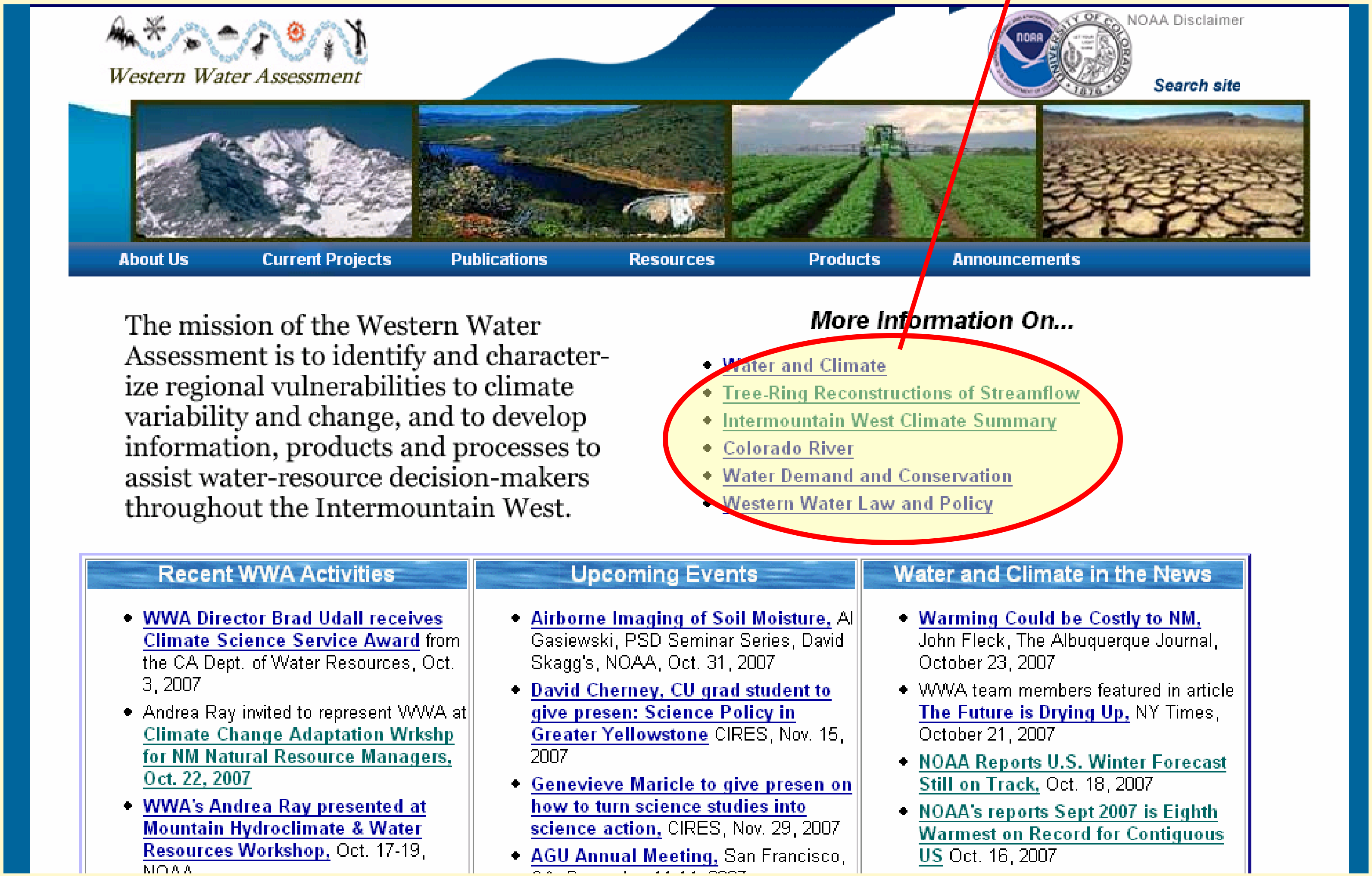
- RISAs (Regional Integrated Sciences & Assessments) are NOAA-funded programs that conduct climate-related research that supports decisionmaking at a regional level

- **Western Water Assessment** – CO, UT, WY

Western Water Assessment

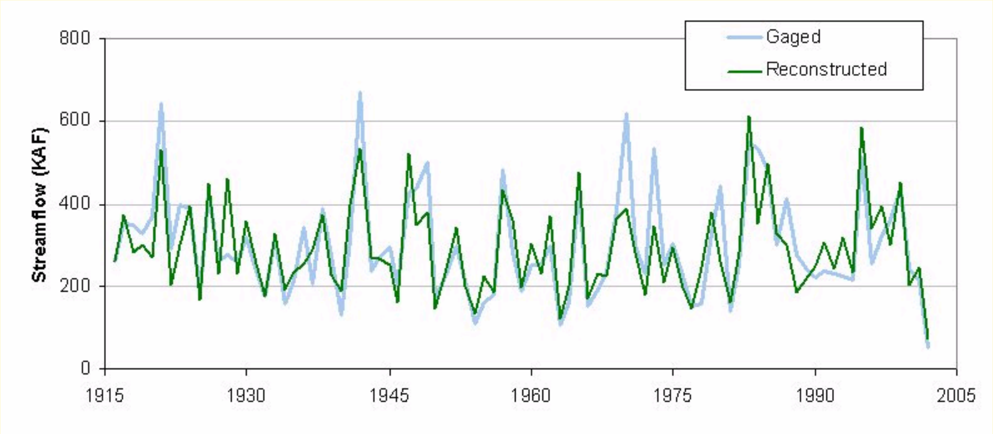
http://wwa.colorado.edu

Quick links to main projects and resources



Part 1:

Context and Background



The problem of management

We need to make decisions about the future, but we don't know much about it.

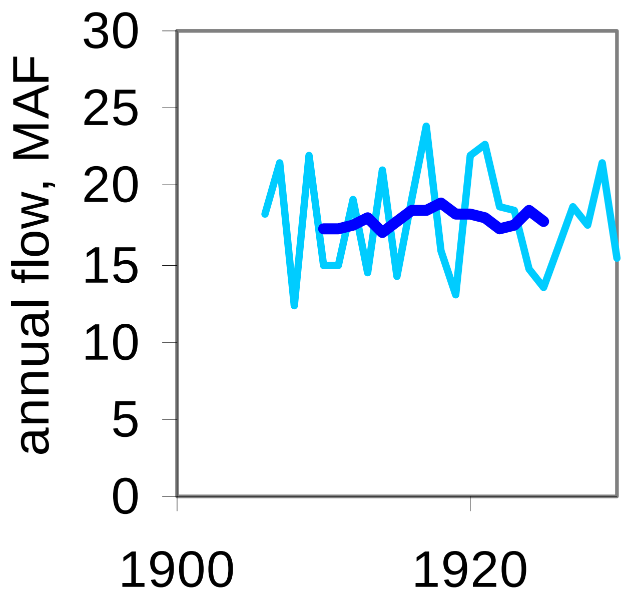
So how do we make decisions?

Based on past experience.

Learning from experience in water management

Colorado at Lees Ferry

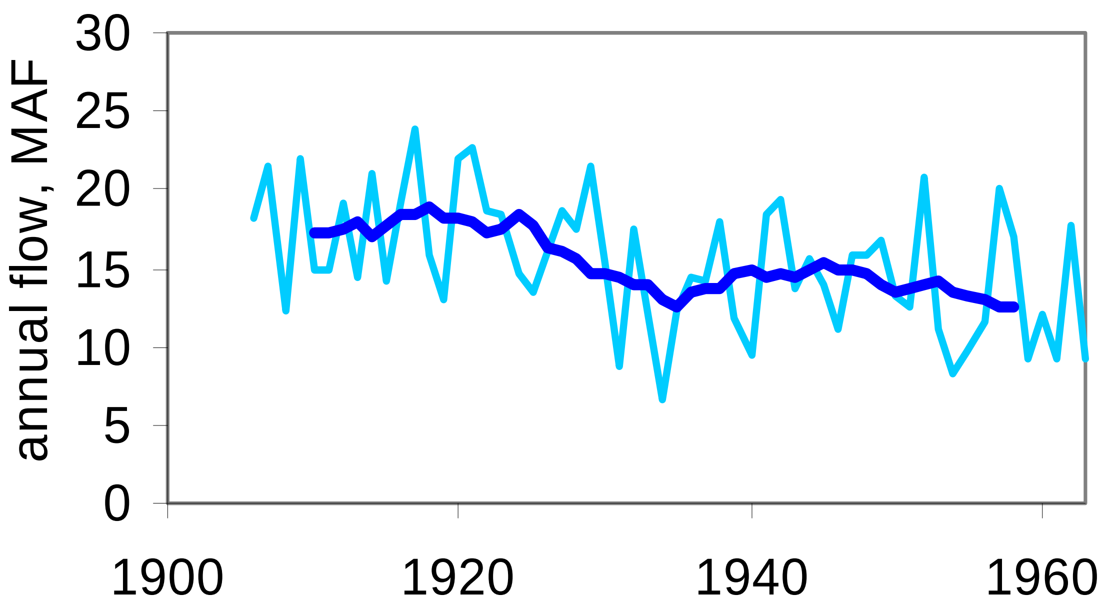
Gaged (natural flow) record, 1906-1930



Learning from experience in water management

Colorado at Lees Ferry

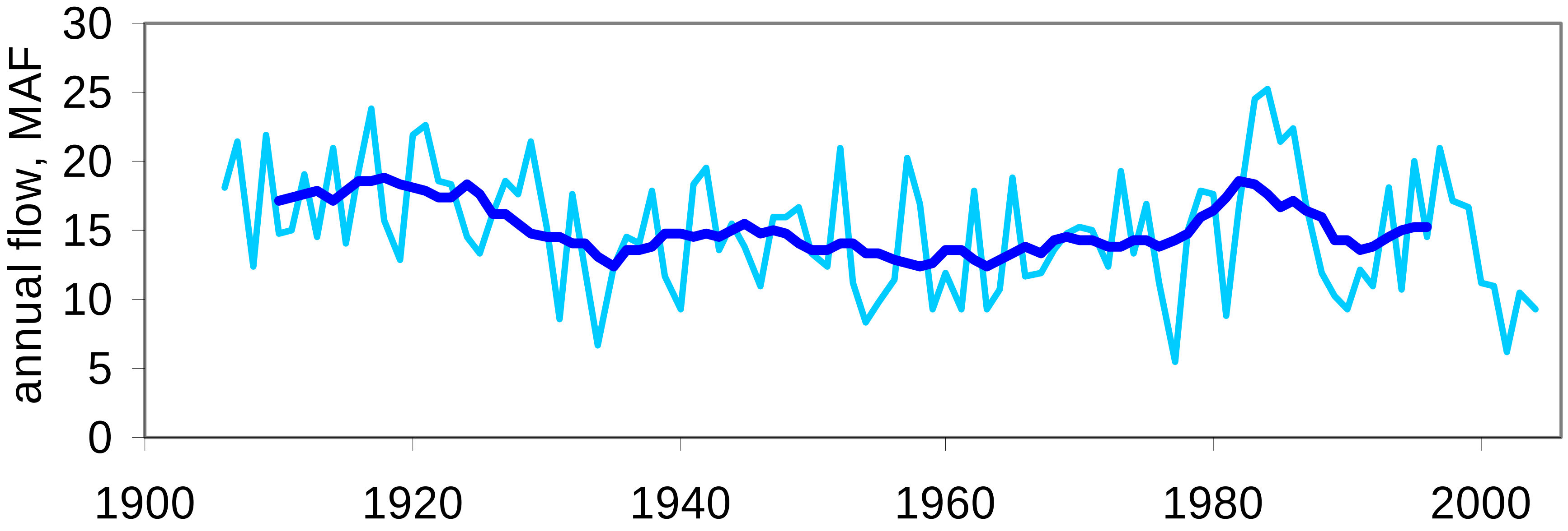
Gaged (natural flow) record, 1906-1963



Learning from experience in water management

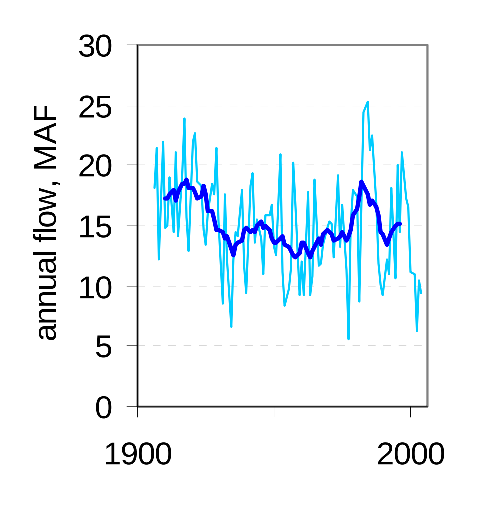
Colorado at Lees Ferry

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



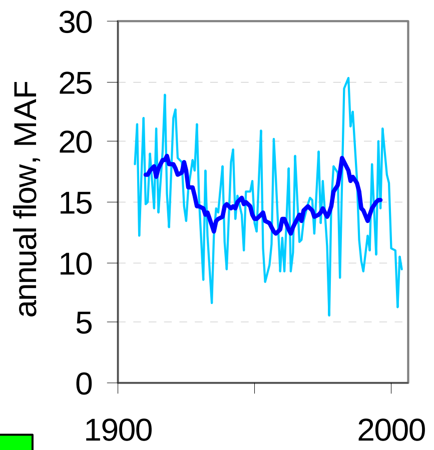
Colorado at Lees Ferry

Gaged (natural flow) record

1906-2004

Tree-ring reconstructions - a surrogate for experience

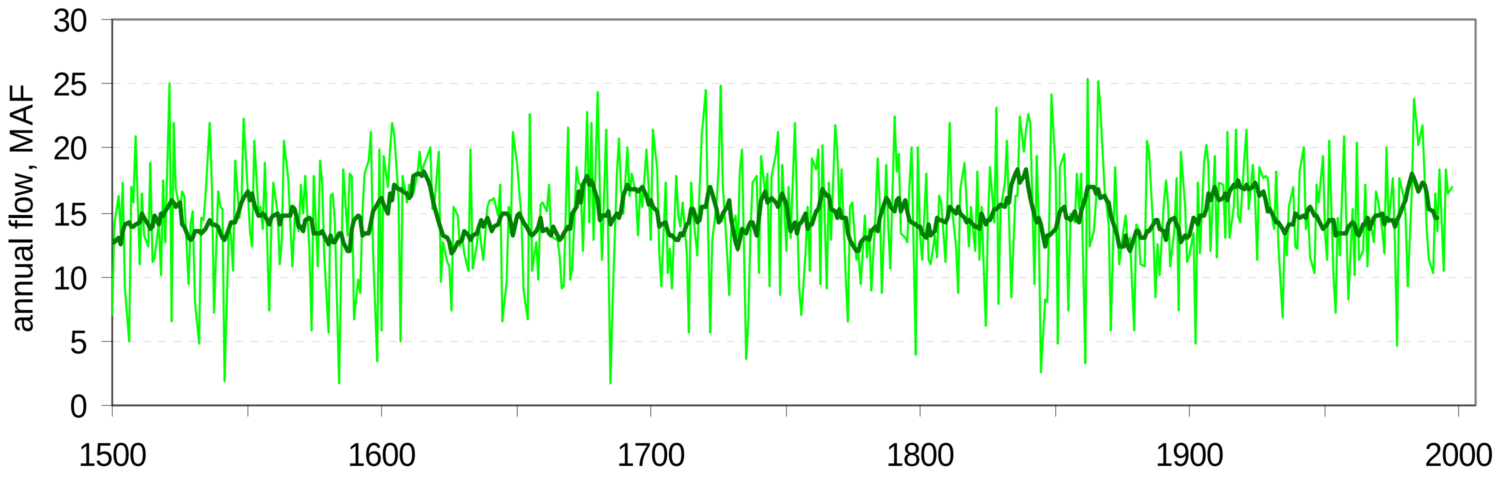
By extending the gaged hydrology by hundreds of years into the past, the reconstructions provide a more complete picture of hydrologic variability



Colorado at Lees Ferry

Gaged (natural flow) record

1906-2004



Tree-ring reconstruction

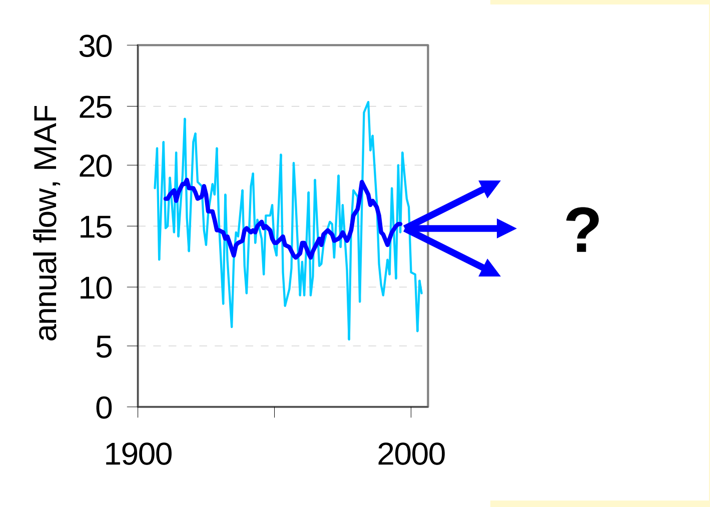
1490-1997

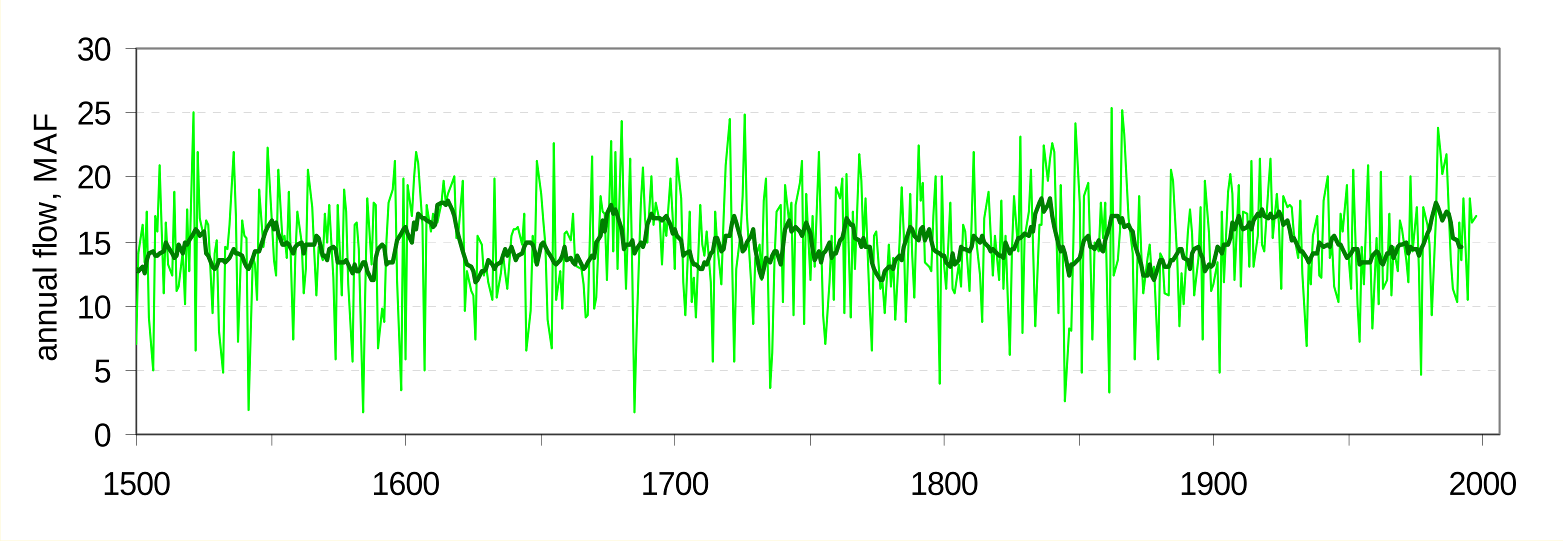
Tree-ring reconstructions - a surrogate for experience

Payoff:

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

- Better assessment of *risk*

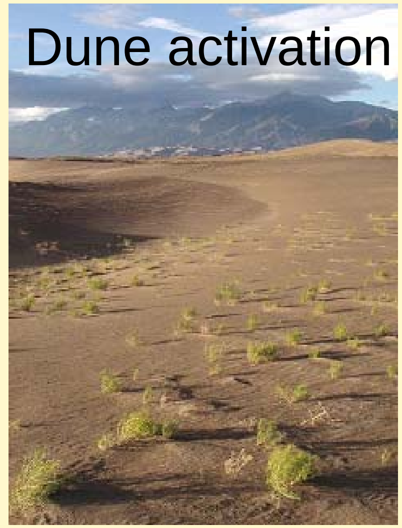


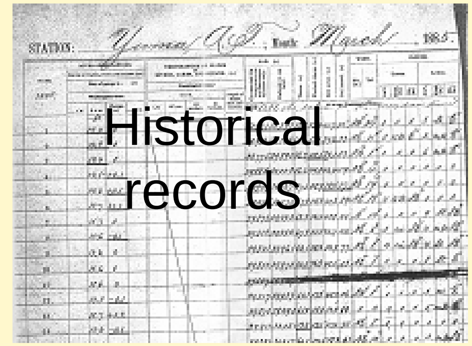


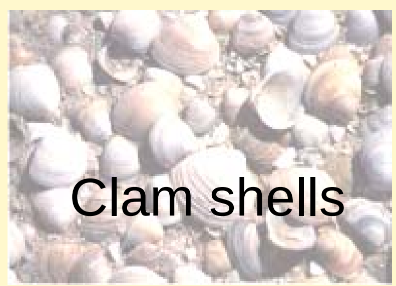
Tree-ring reconstruction

1490-1997

Paleoclimatology: analysis of pre-instrumental climate, mainly using environmental proxies







Paleoclimatology reveals what has actually happened

Jonathan Overpeck

Key attributes of tree rings as a proxy for climate and hydrology

- Annual resolution
- Continuous records (100-10,000 yrs)
- High sensitivity and fidelity to climate variability
- Widespread distribution

Dendrochronology:

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

Fritts 1976

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Fritts 1976

Main products:

Continuous time-series of environmental variables

or *discontinuous time-series of environmental events*

Key advances leading to modern tree-ring reconstructions of streamflow

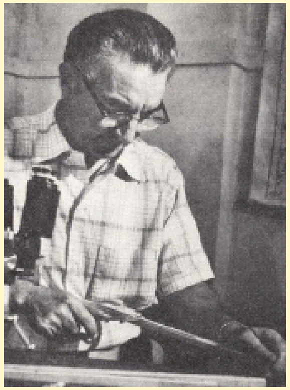
1905-1920 - Douglass establishes modern tree-ring science; links tree-growth and climate in Southwest

1930s - First studies correlating tree growth with runoff in western US

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

1960s - Fritts models physiological basis of trees' sensitivity to climate; develops modern statistical methods for climate reconstruction

A.E. Douglass



E. Schulman

Key advances leading to modern tree-ring reconstructions of streamflow

1976 - Stockton and Jacoby reconstruction of Lees Ferry streamflow

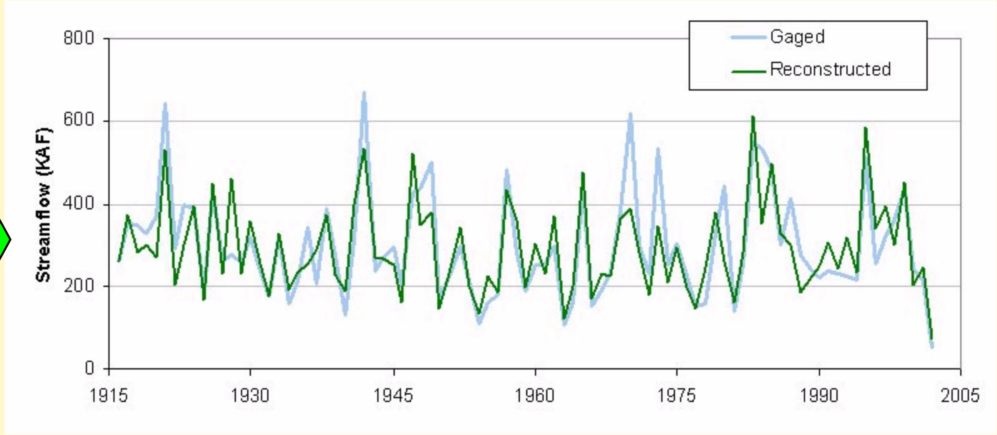
1980s - Cook and Meko refine statistical tools for chronology development and reconstructions

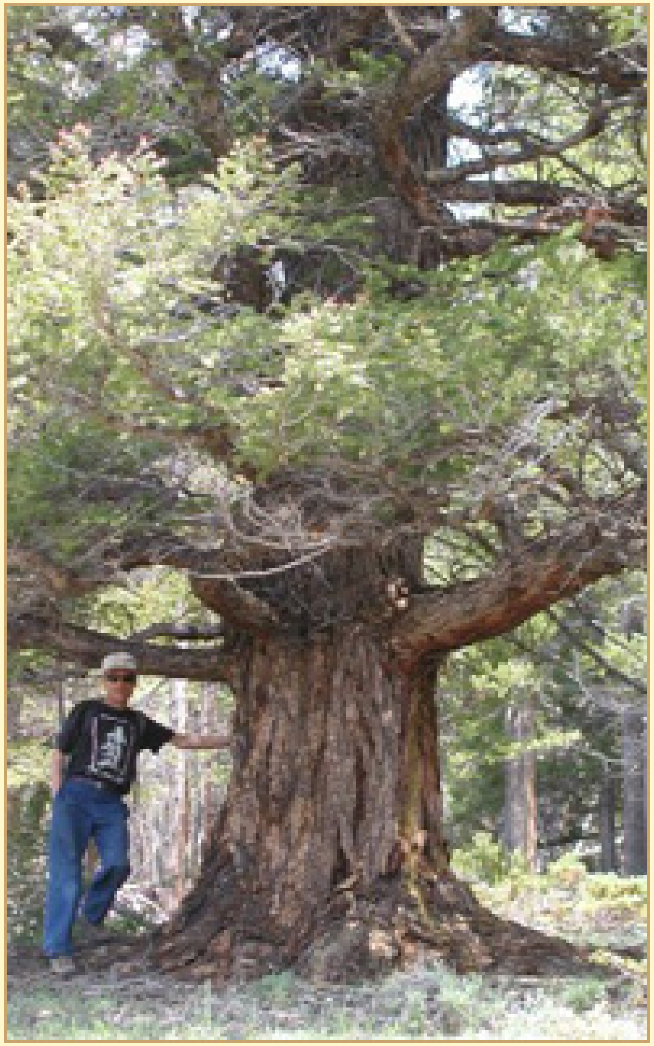
2000s - Many new flow reconstructions for western US and Colorado

2006 - Woodhouse et al. reconstruction of Lees Ferry and other Colorado basin gages

Part 2:

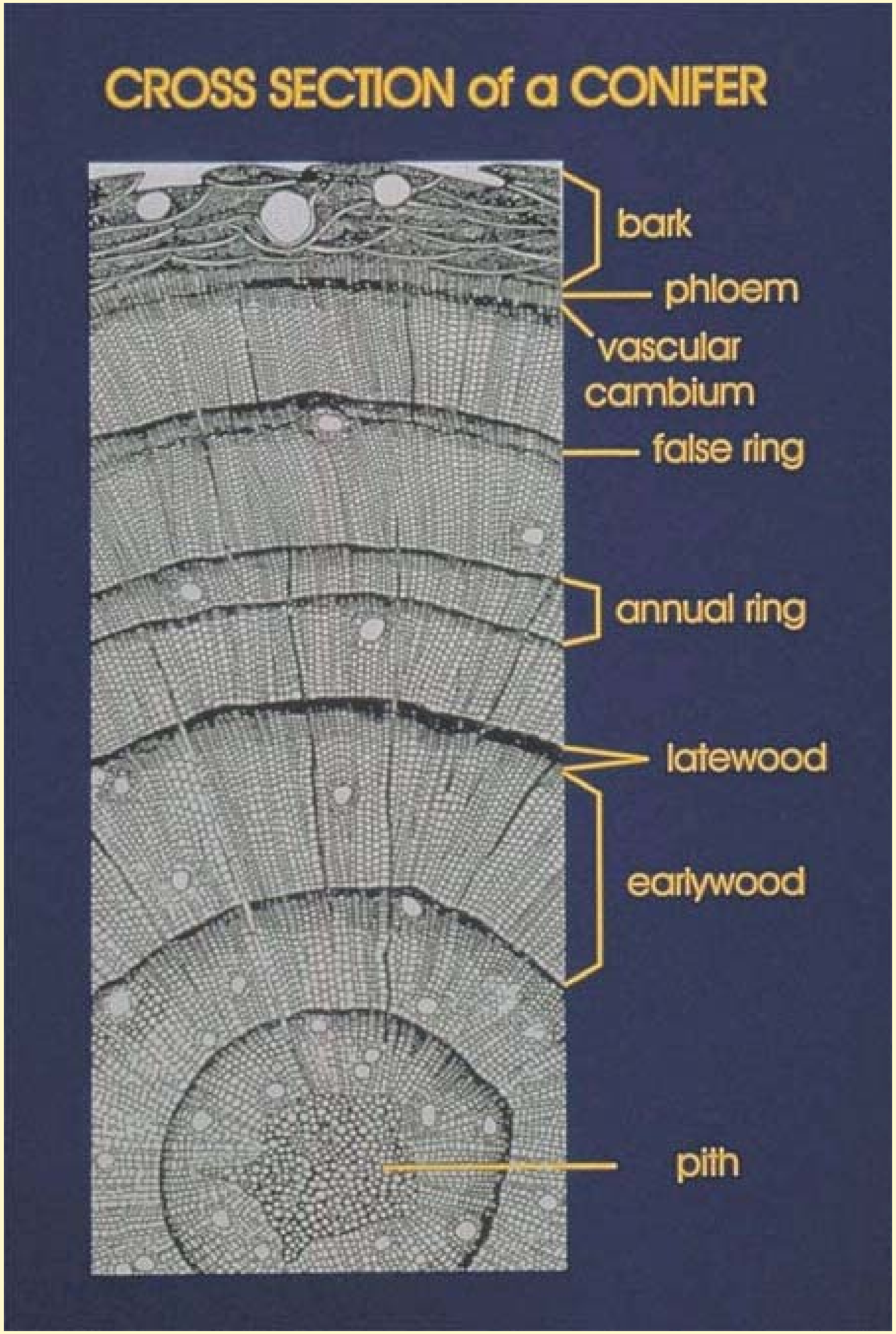
How tree rings record climate information





The tree

- A sophisticated mechanism for converting CO_2 + water + nutrients into oxygen + carbohydrates
- Carbohydrates are allocated within the tree to various functions
  - Regrowing foliage
  - Regrowing fine roots
  - Reproductive structures
  - Height growth
  - Diameter growth
- Diameter growth is fairly low on the allocation list, so it is more sensitive to environmental factors which limit overall carbohydrate production



The formation of annual growth rings

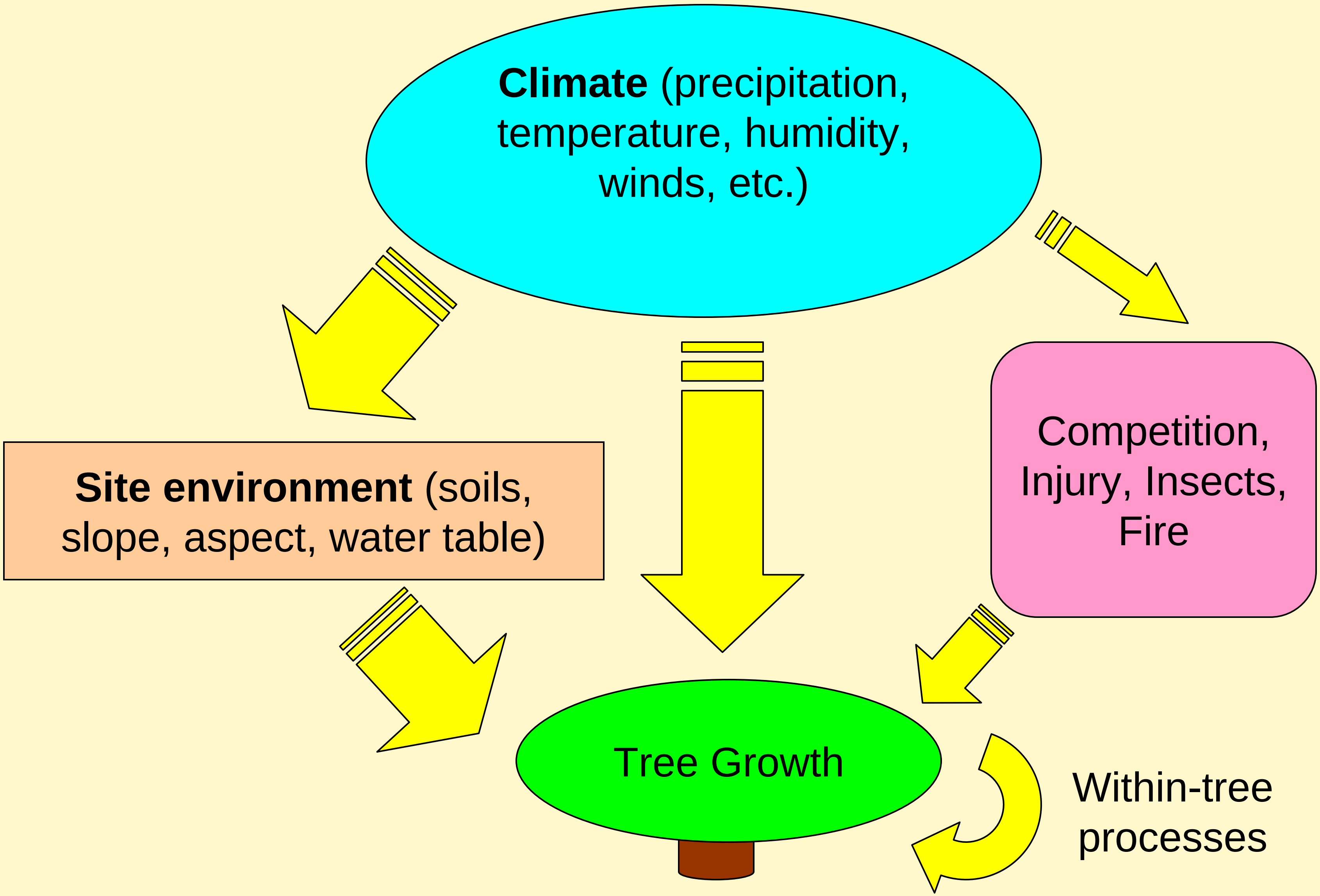
- New wood forms in the vascular cambium, underneath the bark
- Earlywood + latewood = growth ring
- In temperate climates, growth ring = *annual ring*
- Rings have varying widths when a limiting factor on growth varies in magnitude from year to year

Climate is typically the main limiting factor on tree growth in the West

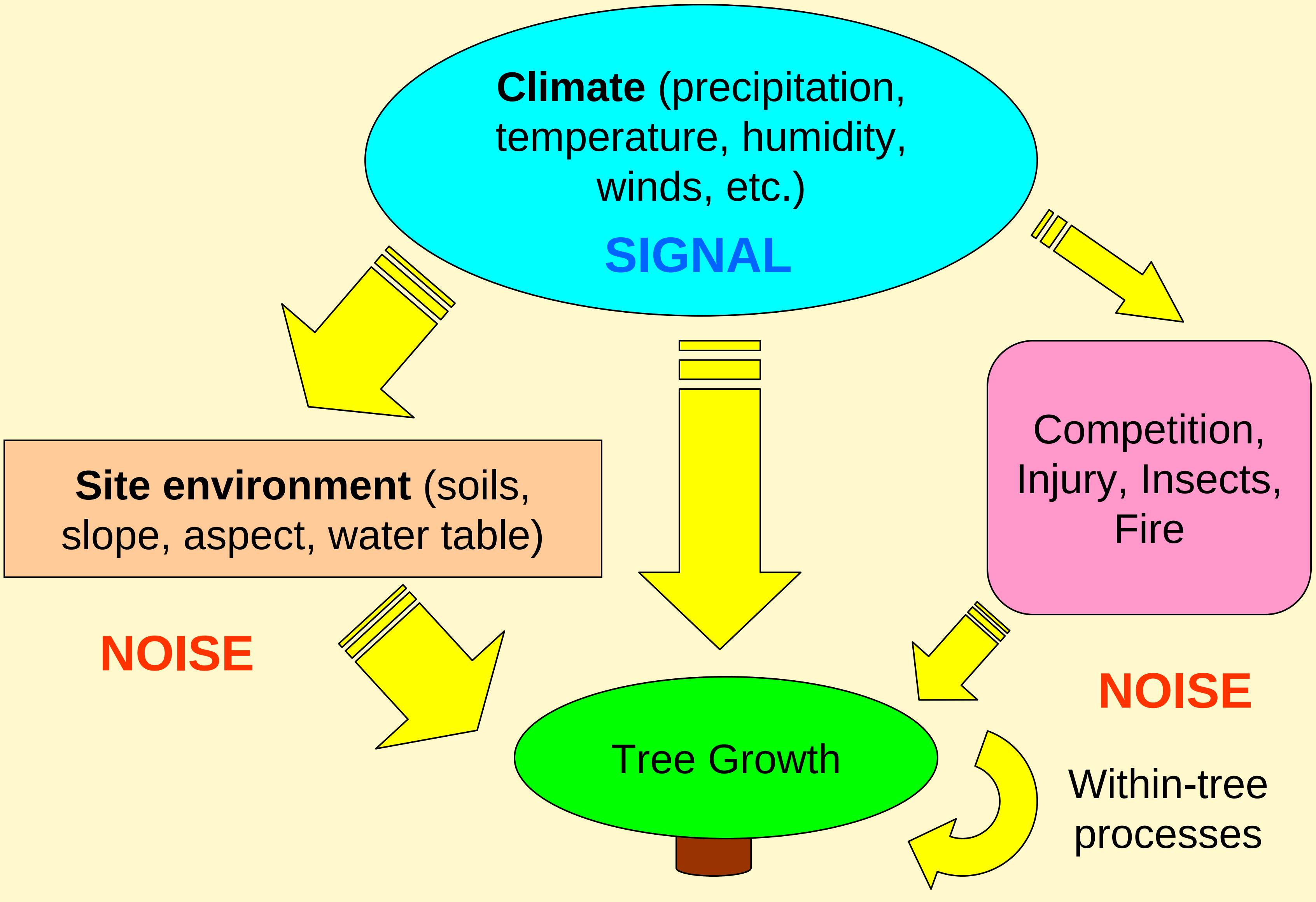
- At high elevations, growth is typically limited by summer warmth and length of the growing season

- At lower elevations, growth is typically limited by *moisture availability*

Climate is not the only *influence* on growth



Our main goal is to increase Signal:Noise ratio



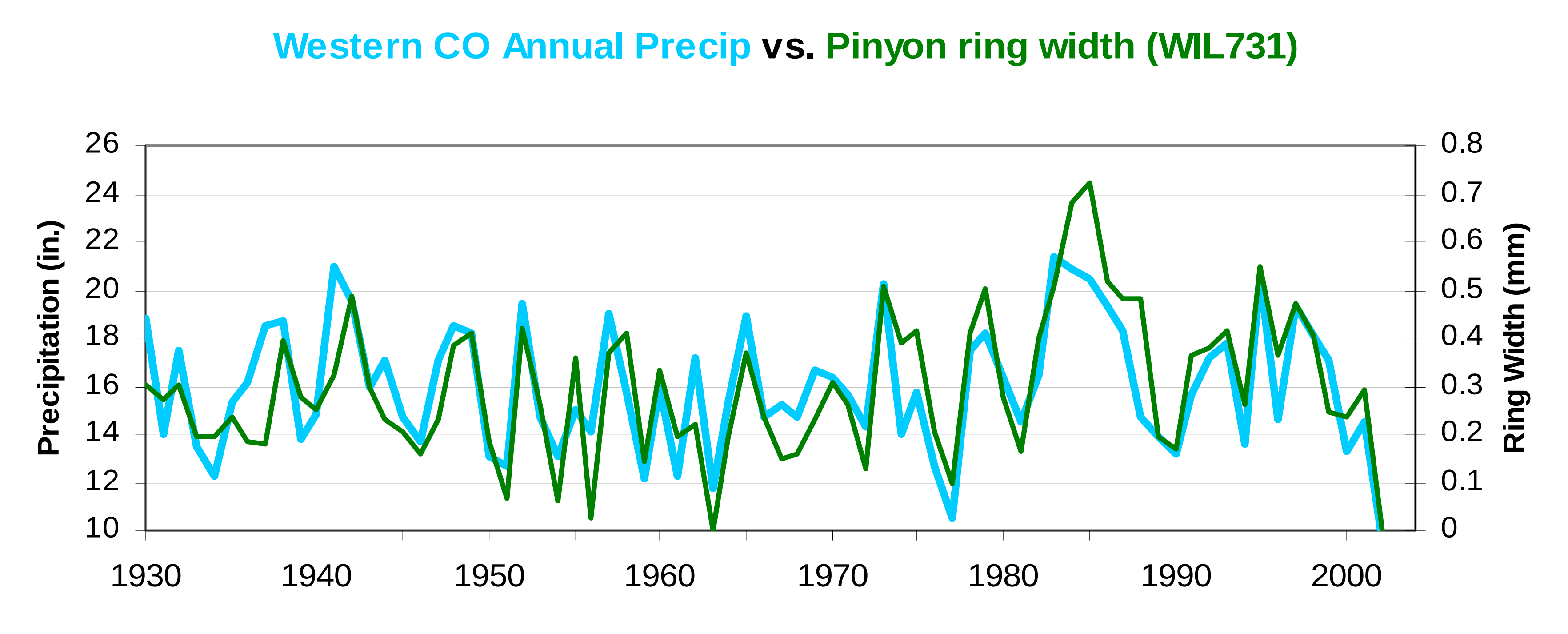
Moisture sensitivity

- “Moisture-sensitive” trees are ones whose year-to-year ring-width variability mainly reflects changes in moisture availability

- These changes are driven mainly by *precipitation*

- Temperature, humidity, and wind play lesser roles, by modifying *evapotranspiration* (moisture losses from soil and directly from tree)

The moisture signal recorded by trees in the interior western 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, replication, and data processing

This moisture signal can be a proxy for multiple moisture-related variables

- Annual or seasonal precipitation
- Drought indices (e.g., PDSI)
- Snow-water equivalent (SWE)
- Annual 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

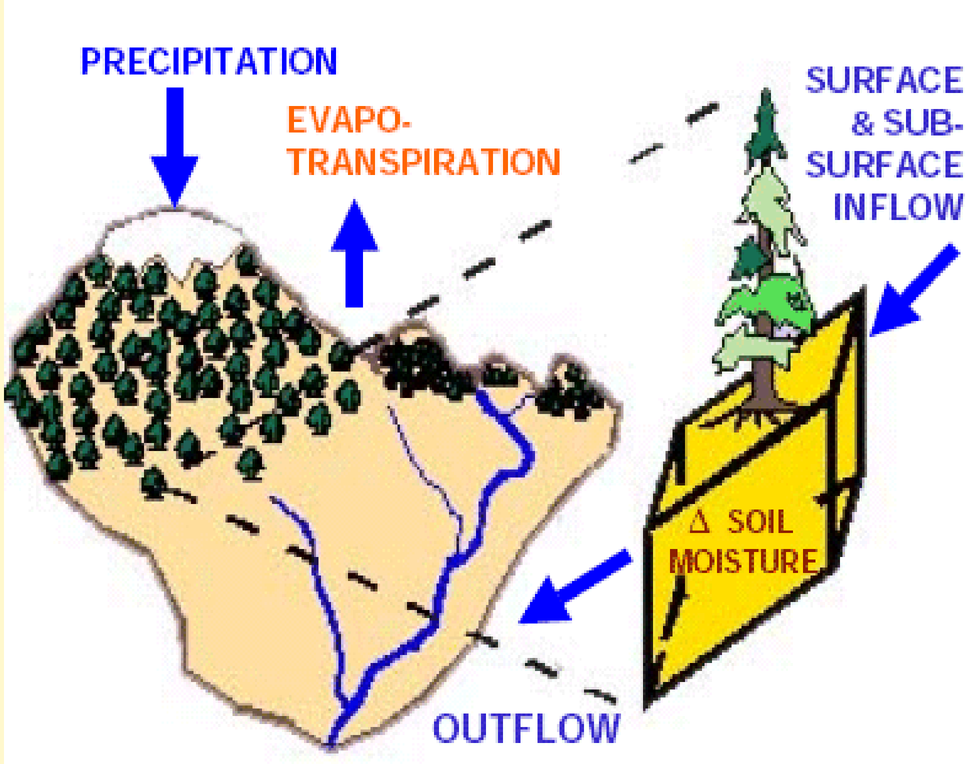
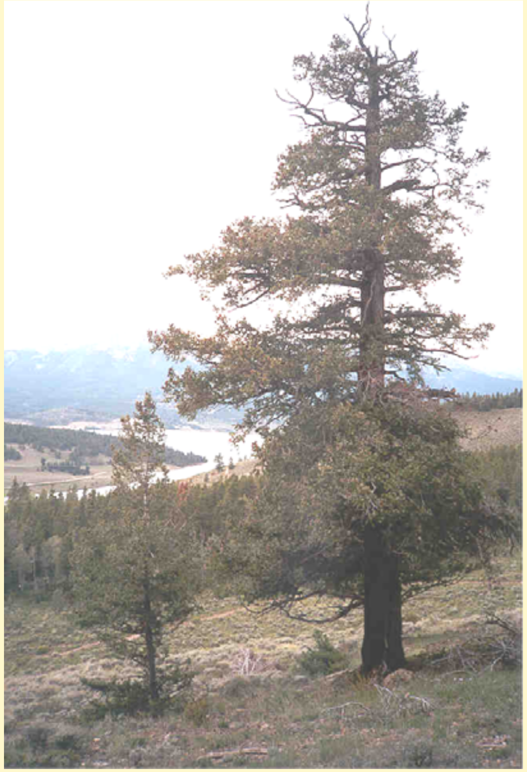


Image courtesy of D. Meko (U. AZ)

Principal moisture-sensitive species - CO, UT, AZ, NM

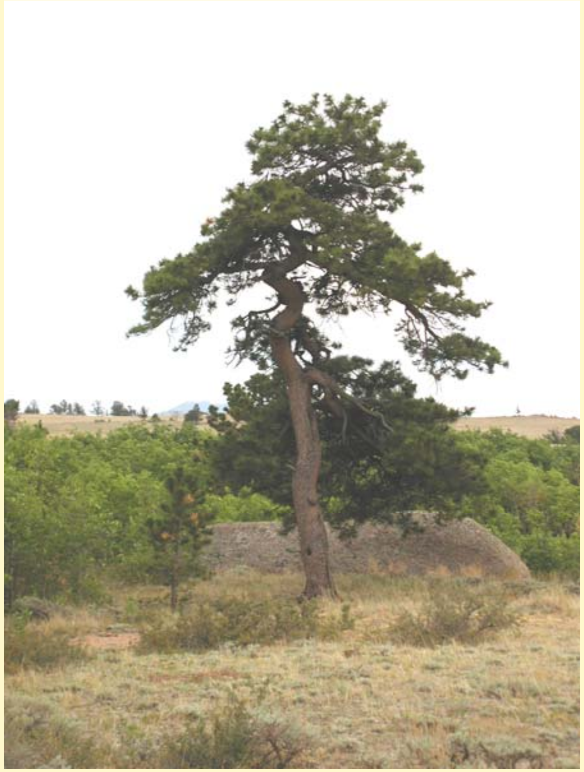


Douglas-fir

500-800 years

Pinyon Pine

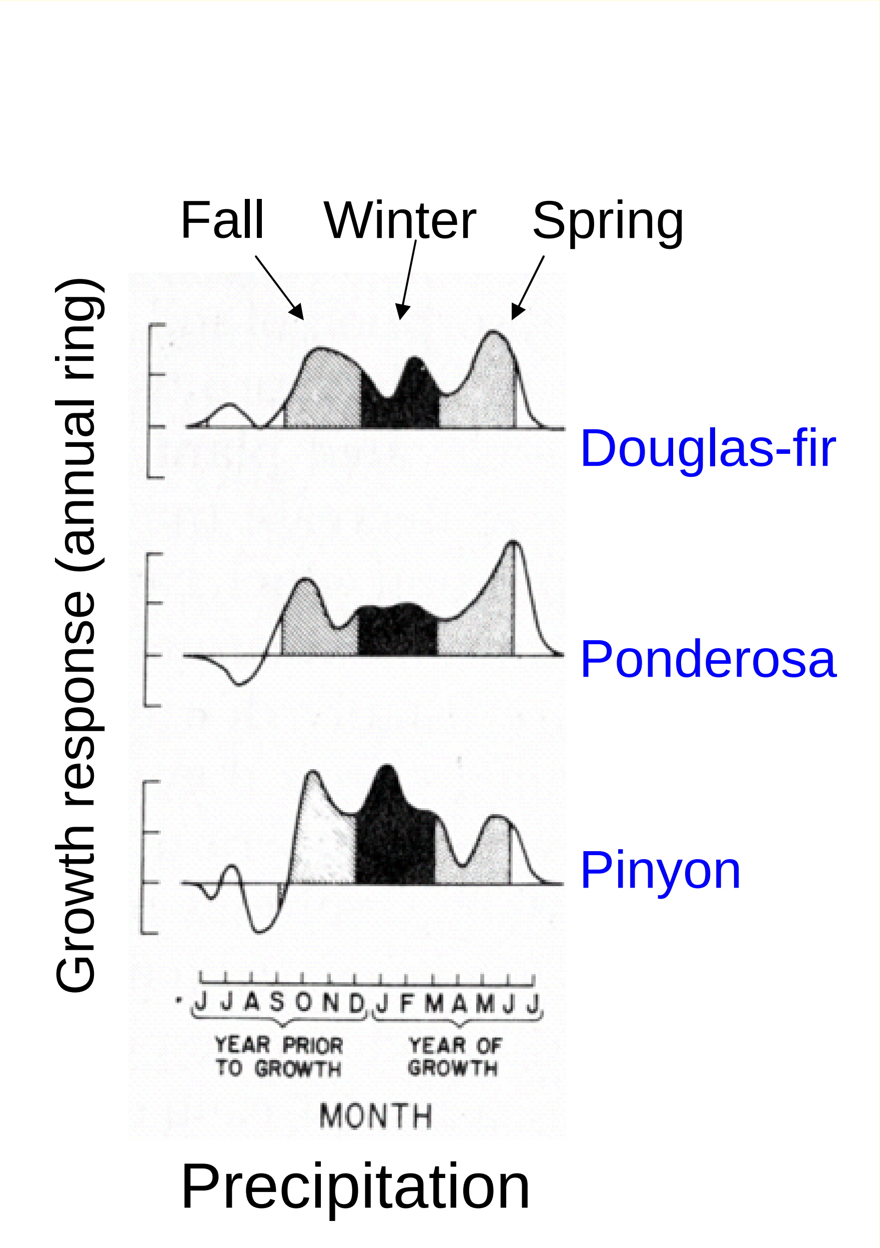
500-800 years



Ponderosa Pine

300-600 years

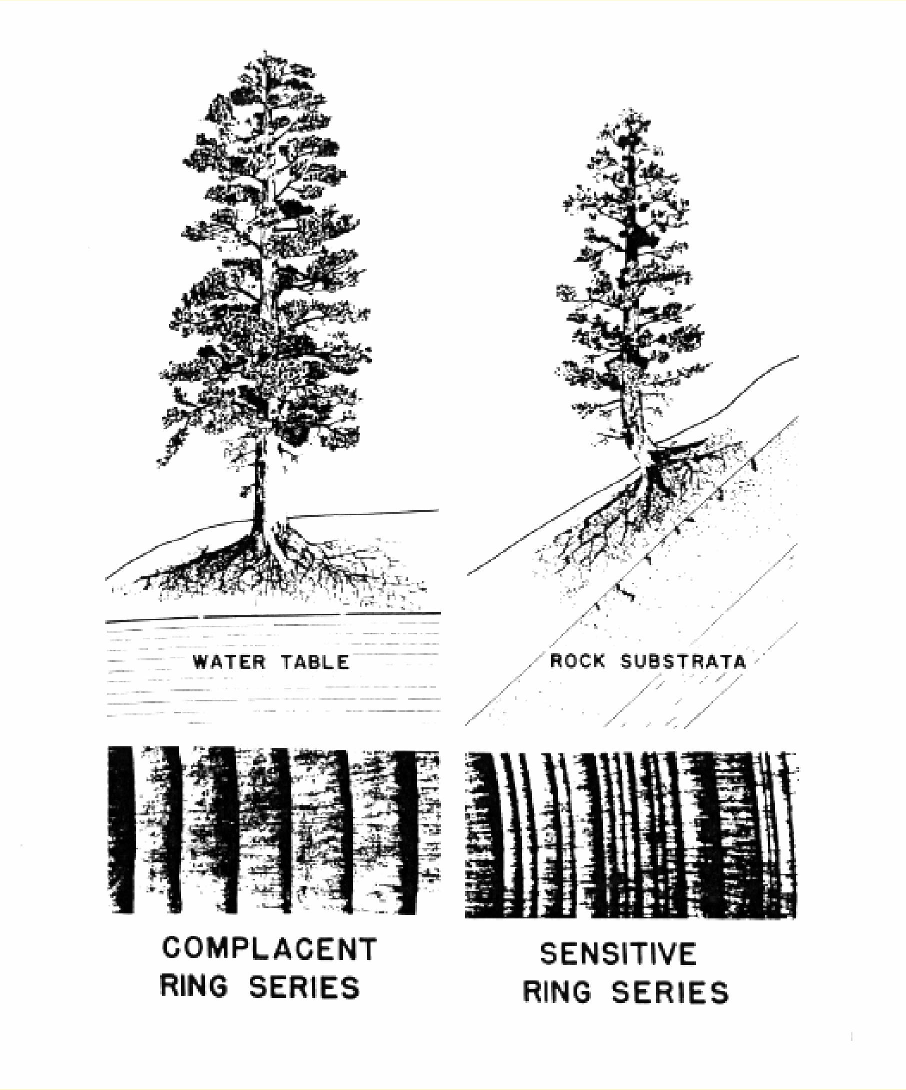
Seasonal climate responses by species - western US



- All species' growth responds mainly to precipitation in fall/winter/spring prior to growing season
- Some variation in shape of the seasonal response curve

from *Fritts 1976*

Stressful sites produce ring series with greater sensitivity (higher Signal:Noise ratio)



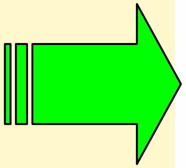
from *Fritts 1976*

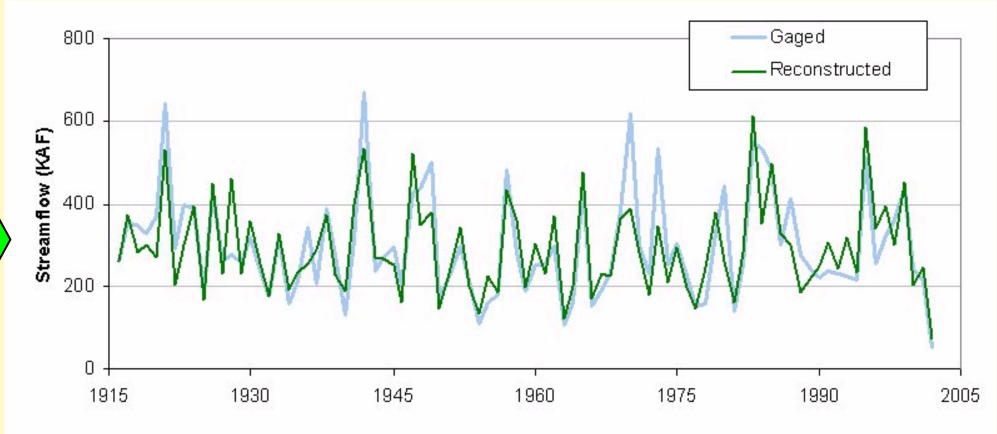
Characteristics of stressful sites

- Uplands, not near stream
  - well above water table
- Thin, rocky soils
  - low retention of soil moisture
- Steep slopes
  - low retention of soil moisture
- South- or west- facing
  - greater heating, more stress
- Low tree density
  - less noise from competition, fire, insects

Part 3:

Building a tree-ring chronology





Chronology = basic unit of tree-ring data, “building block” for the flow reconstruction

Steps in Building a Tree-Ring Chronology

Multiple samples at a site

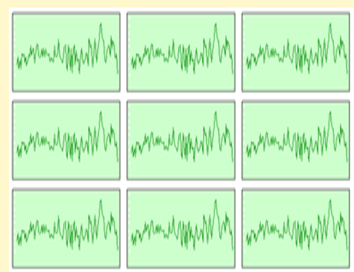
Preparing samples

Crossdating

Measuring

Detrending

Series (of ring-width indices)



Quality Control

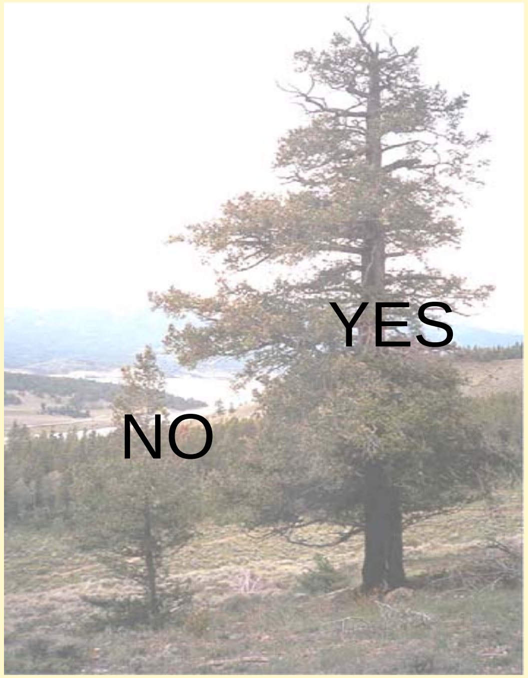
Compilation

Chronology (weighted average of all series)

Sampling to develop a site chronology

- Sample 10-30+ trees at a site, same species

- Select old-appearing trees
- Goal: maximize the sample depth throughout the chronology (300-800+ years)
  - chronology quality is a function of sample depth
  - depth always declines going back in time, since oldest trees are rarer



Sampling living trees

Image courtesy of K. Hirschboeck (U. AZ)

- Increment borer collects core 4-5mm in diameter, up to 20" long
- Causes minimal injury to the tree
- Collect *two* cores (radii) from each tree, extending to the pith

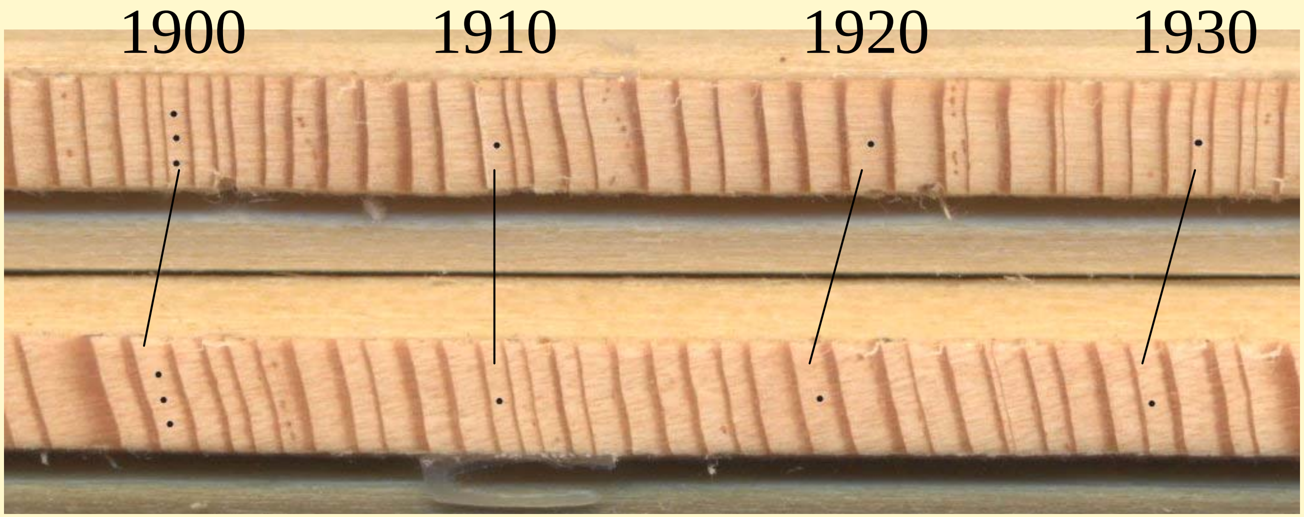
Sampling “remnant” wood

- Can sometimes use borer
- Saw more useful on very old/eroded material

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



Two Douglas-fir trees south of Boulder, CO

Regional climate patterns = regional crossdating

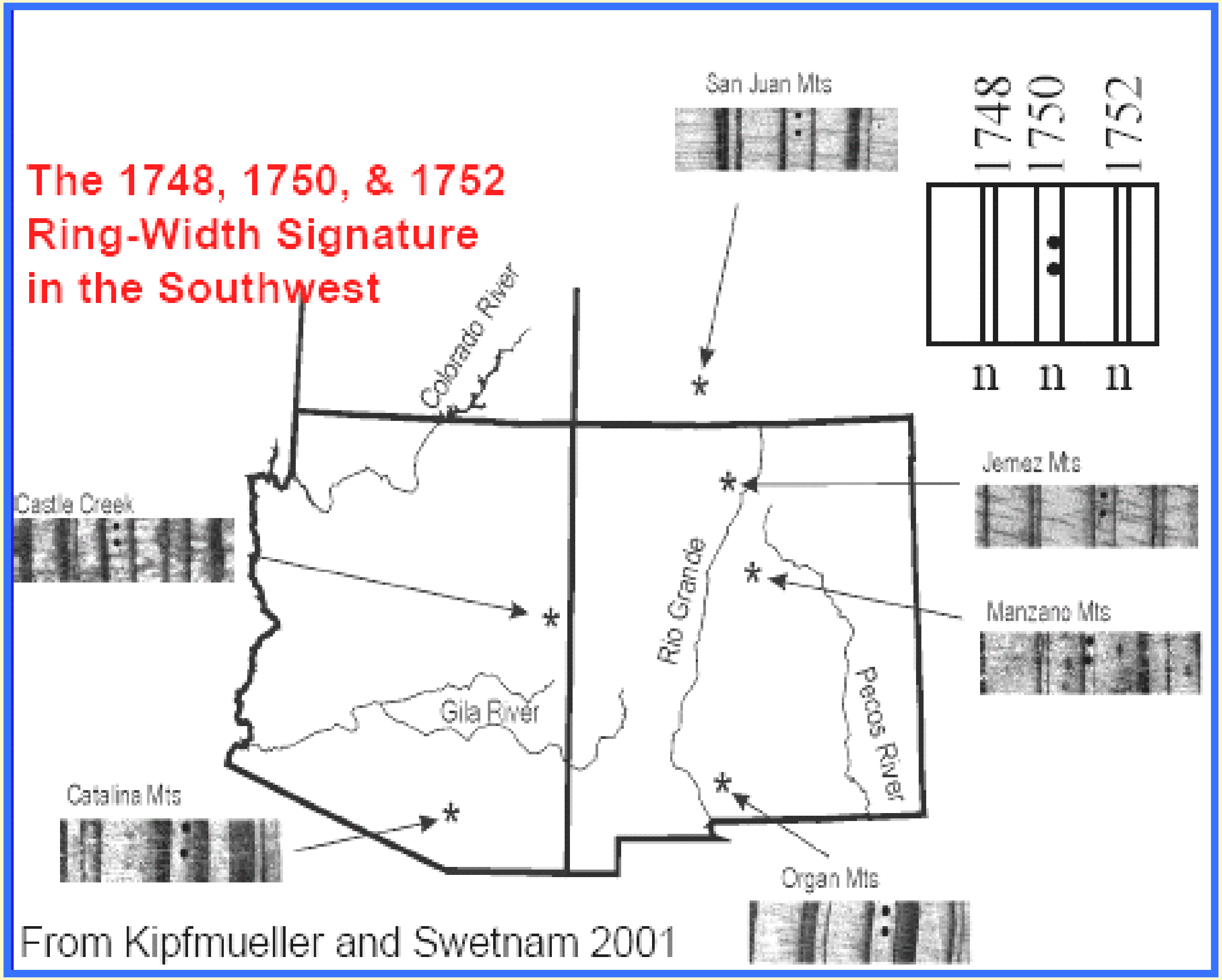


Image courtesy of K. Kipfmueller (U. MN) and T. Swetnam (U. AZ)

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

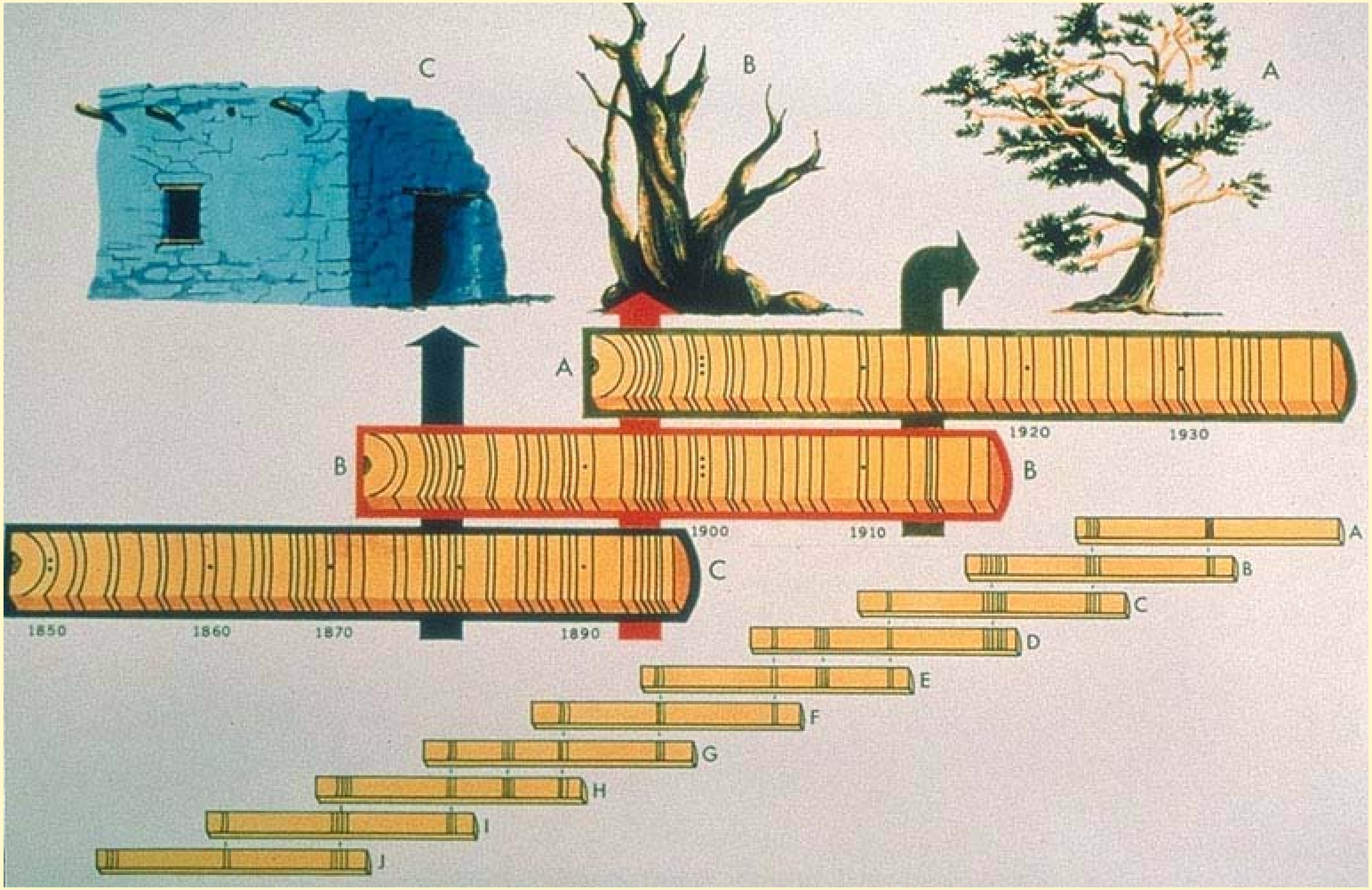
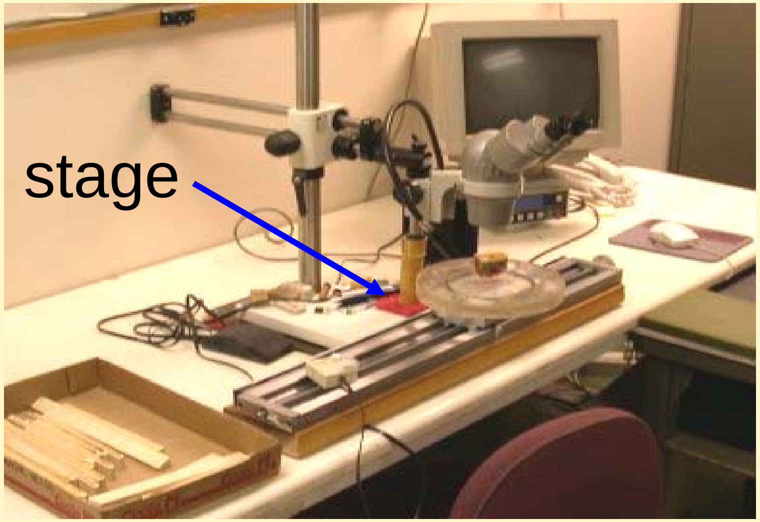
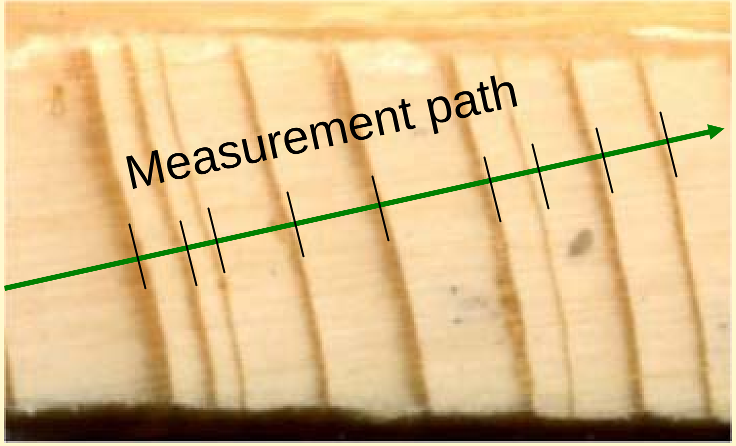


Image courtesy of LTRR (U. AZ)

Measuring the samples





- Computer-assisted measurement system
  - linear encoder captures position of core to nearest 0.001mm (1 micron)
  - real-world precision is ~3 microns
  - typical ring-width is 500-1000 microns
- Measurement path is parallel to the rows of cells (and perpendicular to the ring boundaries)

Assessing the quality control of dated/measured series

- The program COFECHA runs correlations for each series with a master chronology derived from the other series

- Easy to identify the rare series that has been mis-dated or mis-measured or simply does not follow the common site signal

PART 5: CORRELATION OF SERIES BY SEGMENTS: vbu5   11:21 Fri 23 JUL 2004

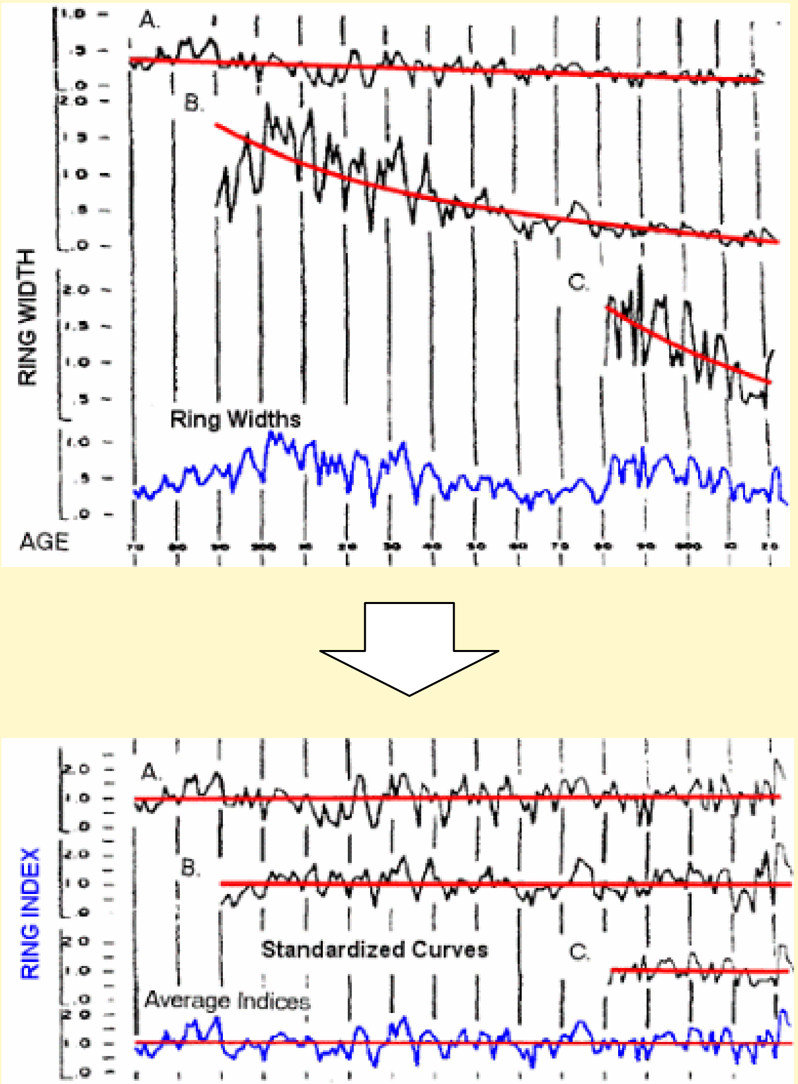
Correlations of 50-year dated segments, lagged 25 years
Flags: A = correlation under .3281 but highest as dated; B = correlation higher at other than dated position

Seq	Series	Time_span	1550 1599	1575 1624	1600 1649	1625 1674	1650 1699	1675 1724	1700 1749	1725 1774	1750 1799	1775 1824	1800 1849	1825 1874	1850 1899	1875 1924	1900 1949	1925 1974	1950 1999	1975 2024
1	vbu032	1750 1985									.76	.80	.84	.89	.89	.82	.79	.86	.83	
2	vbu031	1763 2003									.71	.70	.71	.78	.81	.69	.67	.78	.73	.77
3	vbu041	1748 2003								.69	.70	.76	.80	.76	.80	.83	.75	.82	.75	.79
4	vbu042	1794 2003										.78	.77	.85	.81	.72	.78	.85	.77	.80
5	vbu051	1730 2003								.65	.70	.69	.75	.84	.85	.80	.78	.85	.85	.87
6	vbu052	1713 2003							.59	.64	.61	.70	.85	.88	.87	.85	.83	.84	.81	.83
7	vbu131	1640 1864				.86	.86	.87	.76	.79	.78	.68	.73	.84						
8	vbu142	1566 1796	.73	.77	.76	.76	.76	.67	.58	.67	.77									
9	vbu143	1566 1608	.60																	
10	vbu161	1740 2003								.61	.59	.64	.67	.84	.91	.86	.76	.71	.66	.67
11	vbu162	1739 2003								.60	.68	.65	.75	.85	.85	.76	.73	.77	.66	.71
12	vbu153	1704 1985							.72	.64	.63	.74	.80	.82	.87	.86	.84	.89	.83	
13	vbu121	1796 2003										.70	.71	.88	.93	.87	.82	.85	.83	.85
14	vbu172	1815 2003											.75	.78	.78	.73	.65	.78	.74	.76
15	vbu141	1666 1825					.73	.81	.71	.75	.80	.72	.72							
16	vbu151	1829 1942												.82	.87	.83	.74			
17	vbu181	1573 1694	.71	.71	.65	.73	.84													
18	vbu183	1573 1607	.66																	
19	vbu183	1615 1660			.64															
20	vbu011	1748 2003								.82	.83	.87	.82	.79	.80	.75	.74	.84	.79	.80
21	vbu012	1748 2003								.84	.85	.84	.82	.85	.86	.83	.82	.87	.84	.86
22	vbu021	1750 2003									.54	.66	.72	.79	.86	.85	.86	.89	.82	.84
23	vbu123	1621 1916			.71	.70	.83	.75	.64	.70	.78	.73	.72	.84	.89	.87				
24	vbu122	1621 2003			.70	.67	.80	.73	.69	.75	.71	.73	.79	.88	.93	.79	.73	.87	.82	.83
25	vbu111	1628 1692				.74	.73													
26	vbu152	1599 1980		.63	.62	.83	.75	.63	.65	.77	.80	.84	.86	.82	.80	.82	.85	.79	.76	
27	vbu132	1631 1737				.70	.77	.73	.66											
28	vbu171	1783 2003										.60	.72	.79	.72	.69	.71	.75	.80	.83
29	vbu201	1780 2003										.84	.85	.84	.78	.72	.80	.75	.72	.75
30	vbu202	1780 2003										.80	.77	.75	.81	.78	.79	.86	.89	.90

1850 1899	1875 1924	1900 1949	1925 1974	1950 1999	1975 2024
.89	.82	.79	.86	.83	
.81	.69	.67	.78	.73	.77
.80	.83	.75	.82	.75	.79
.81	.72	.78	.85	.77	.80
.85	.80	.78	.85	.85	.87
.87	.85	.83	.84	.81	.83

Typical COFECHA output, from VBU

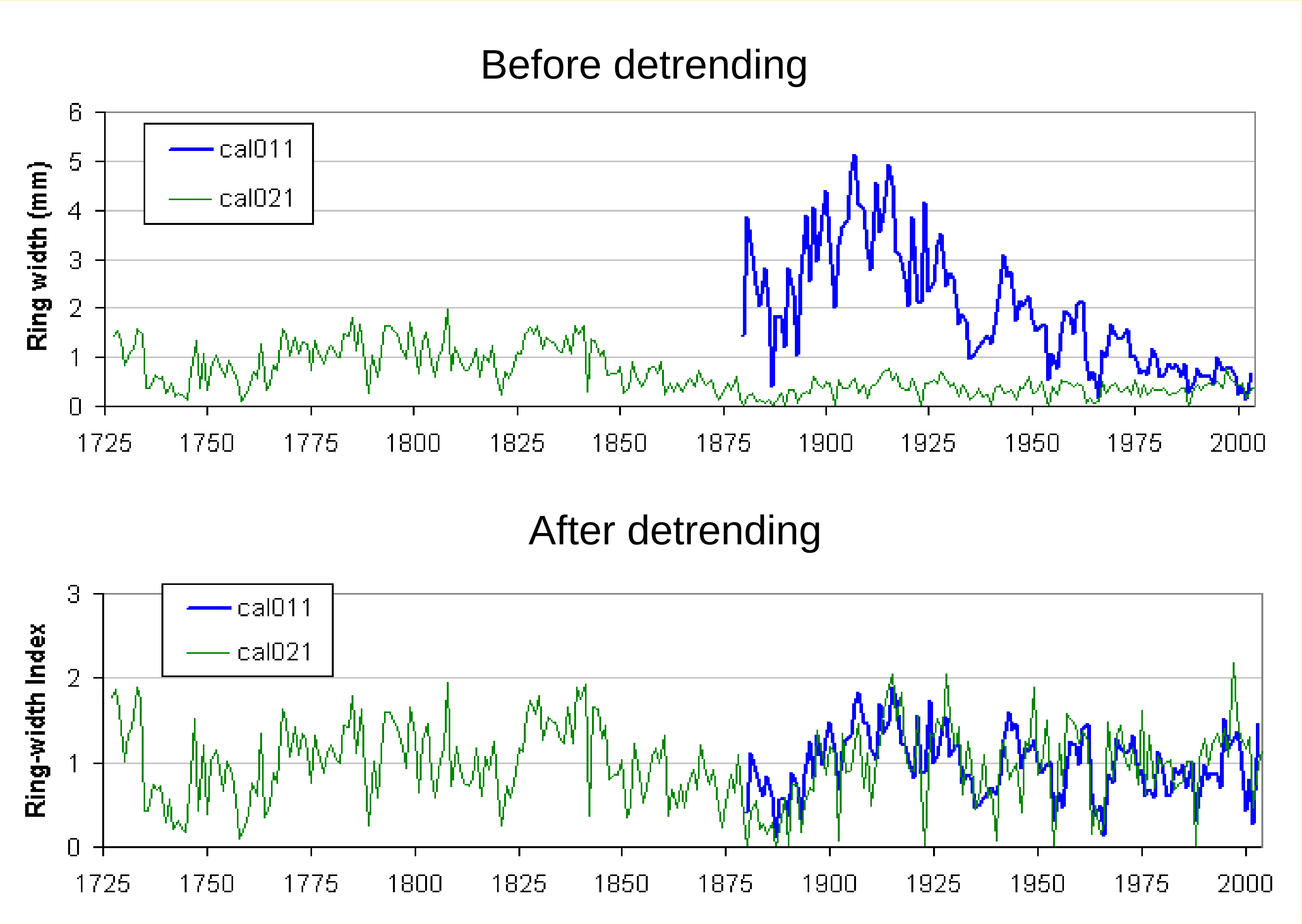
Detrending the measured series



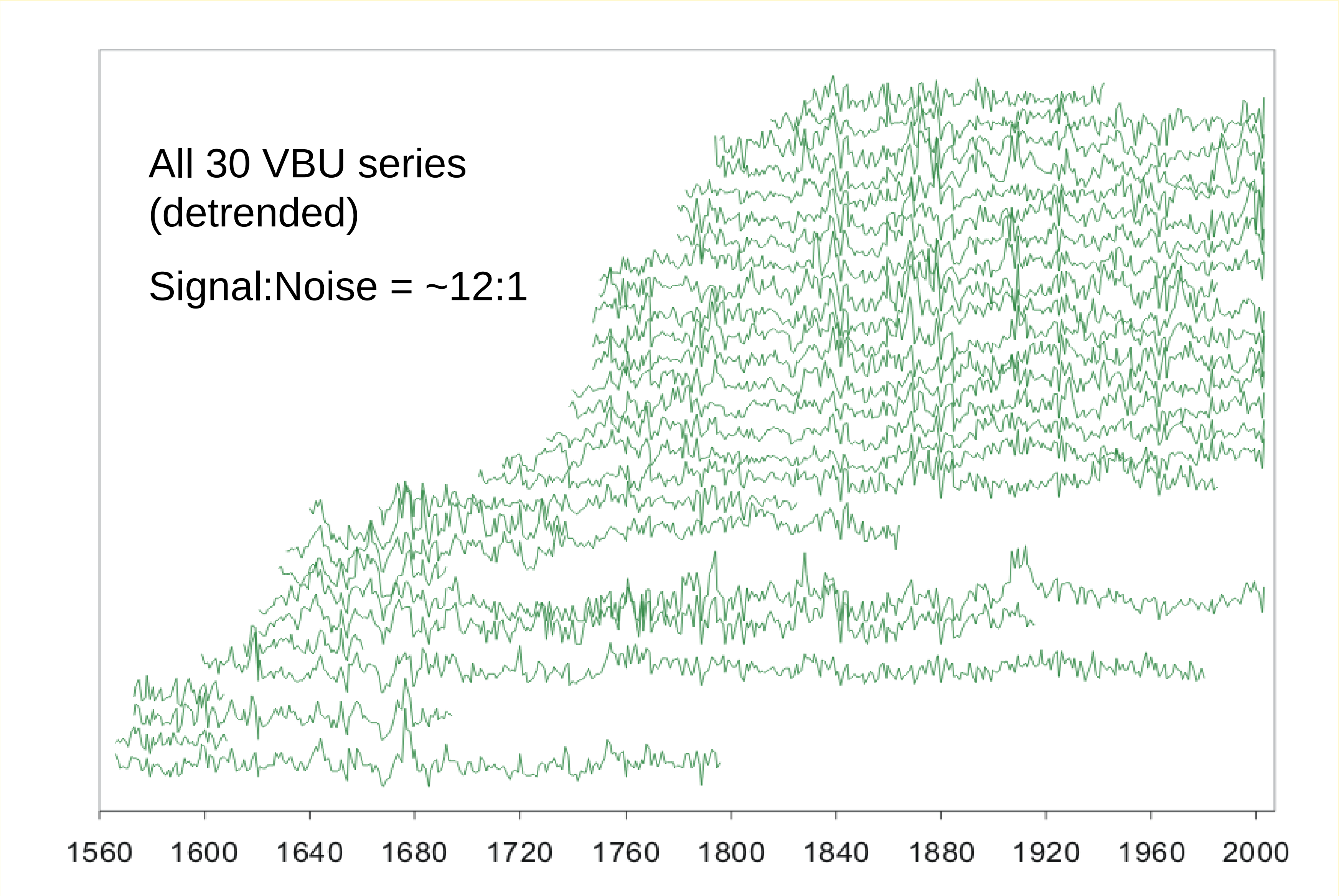
- Ring-width series typically have a declining trend with time due to tree geometry
- These trends are low-frequency noise (i.e. non-climatic)

- Raw ring series are detrended with straight line, exponential curve, or spline
- These standardized curves are compiled into the site chronology
- *Side effect:* low-frequency climate information not retained

Example of detrending - 2 trees, same site



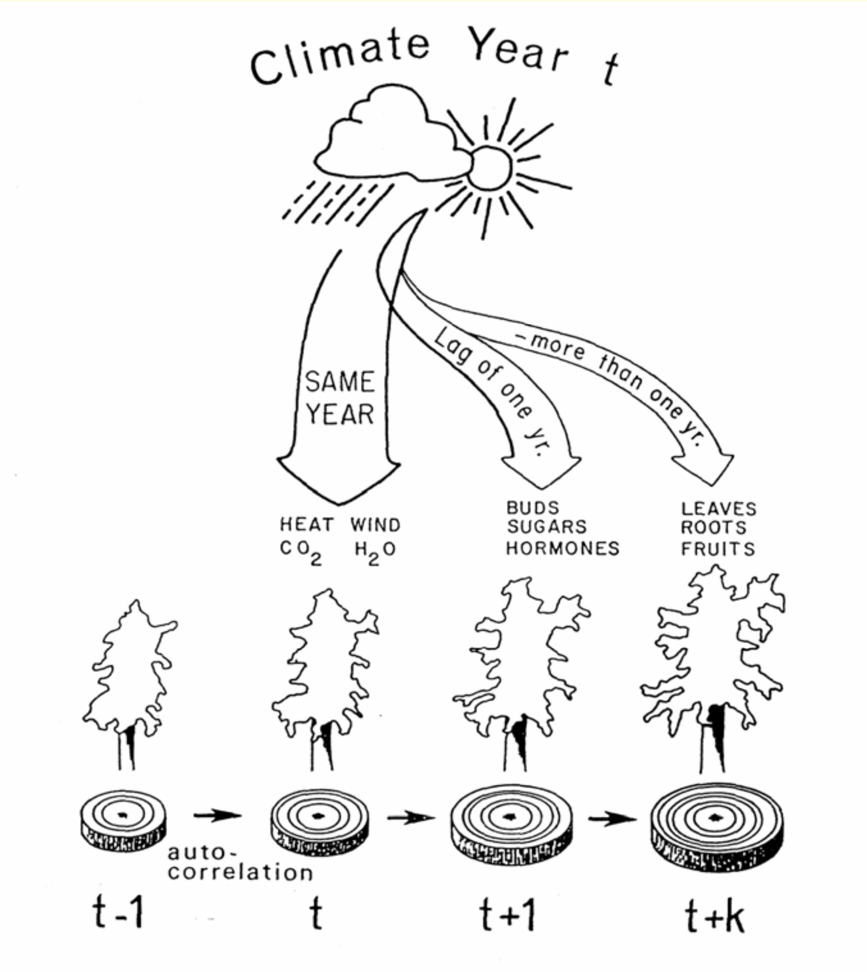
Coherence of signal among series at one site



Persistence in tree growth from year to year

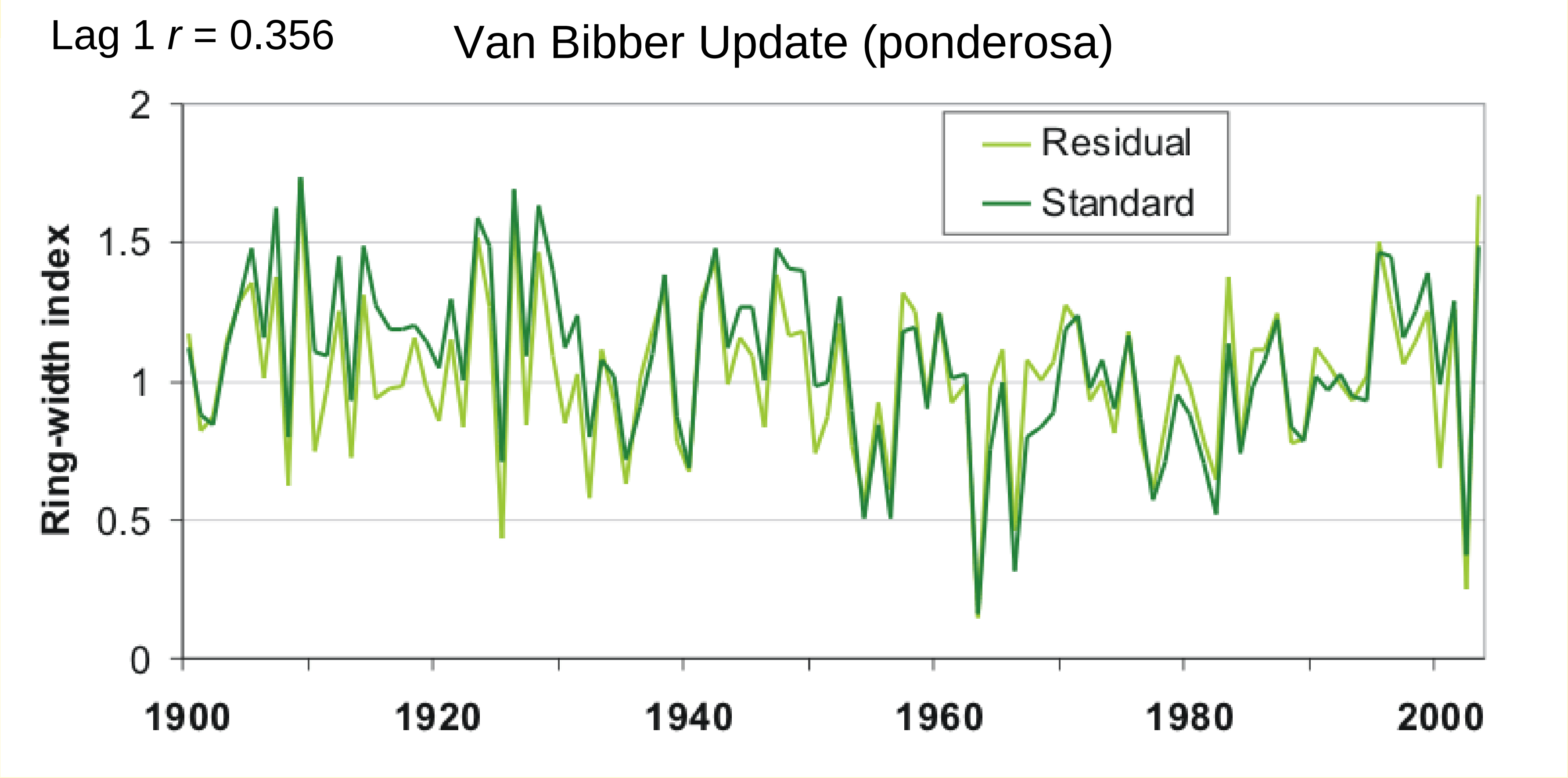
- The climate in a given year (t) can also influence growth in succeeding years (t+1, t+2, etc.) through storage of sugars and growth of needles

- This persistence is typically greater than the persistence in hydrologic time series

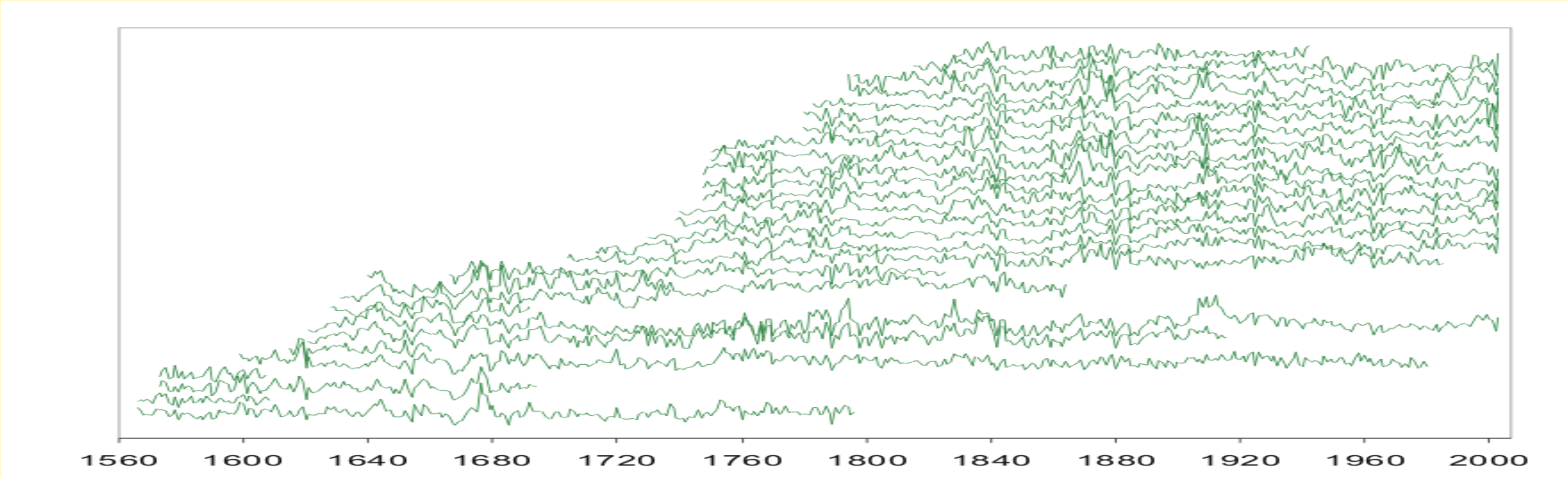


Persistence in the chronology can be retained or removed

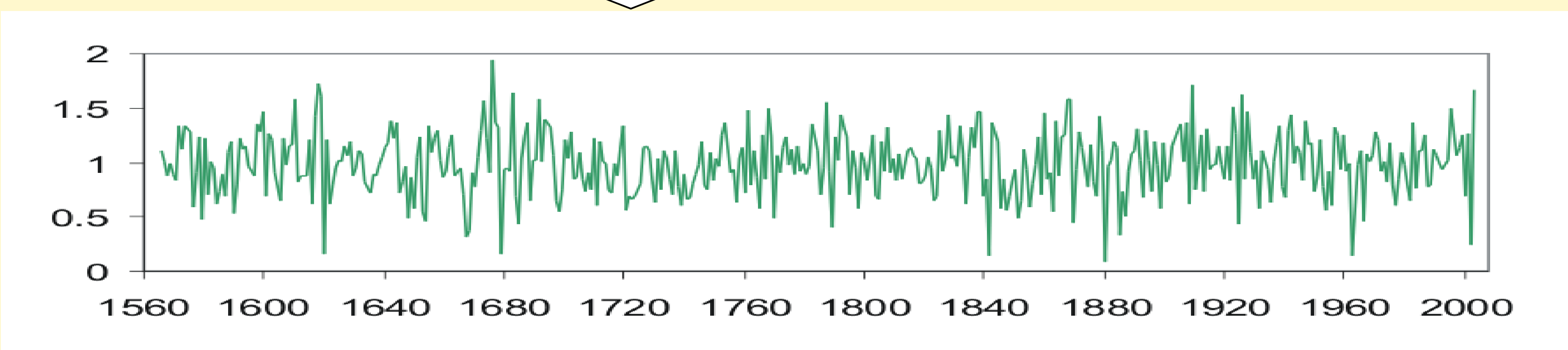
- *Standard chronology:* persistence in the series is retained
- *Residual chronology:* first-order persistence is removed from each series before the chronology is compiled



Compiling the chronology

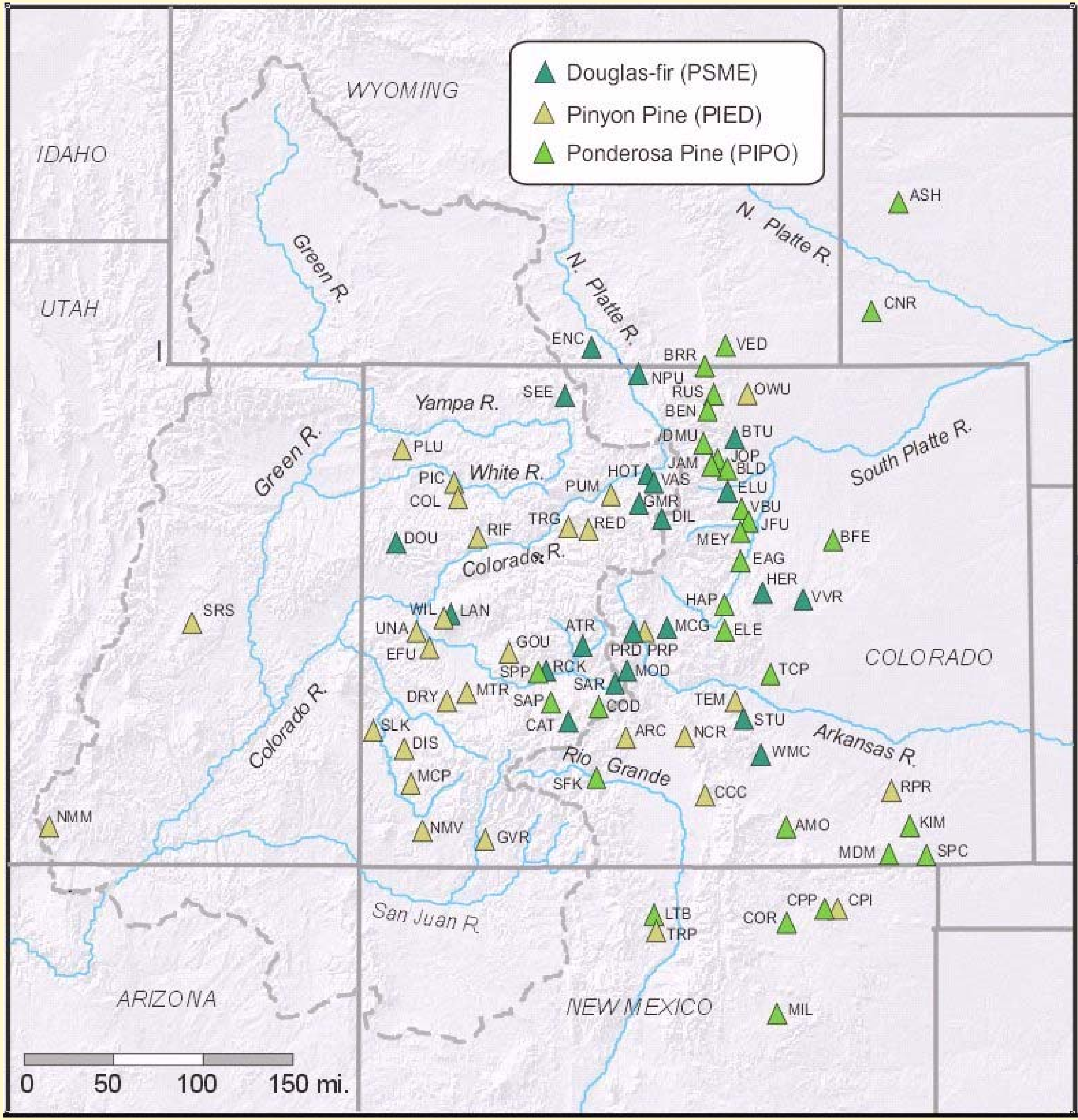


- The detrended series are robustly averaged, which reduces the effect of outliers



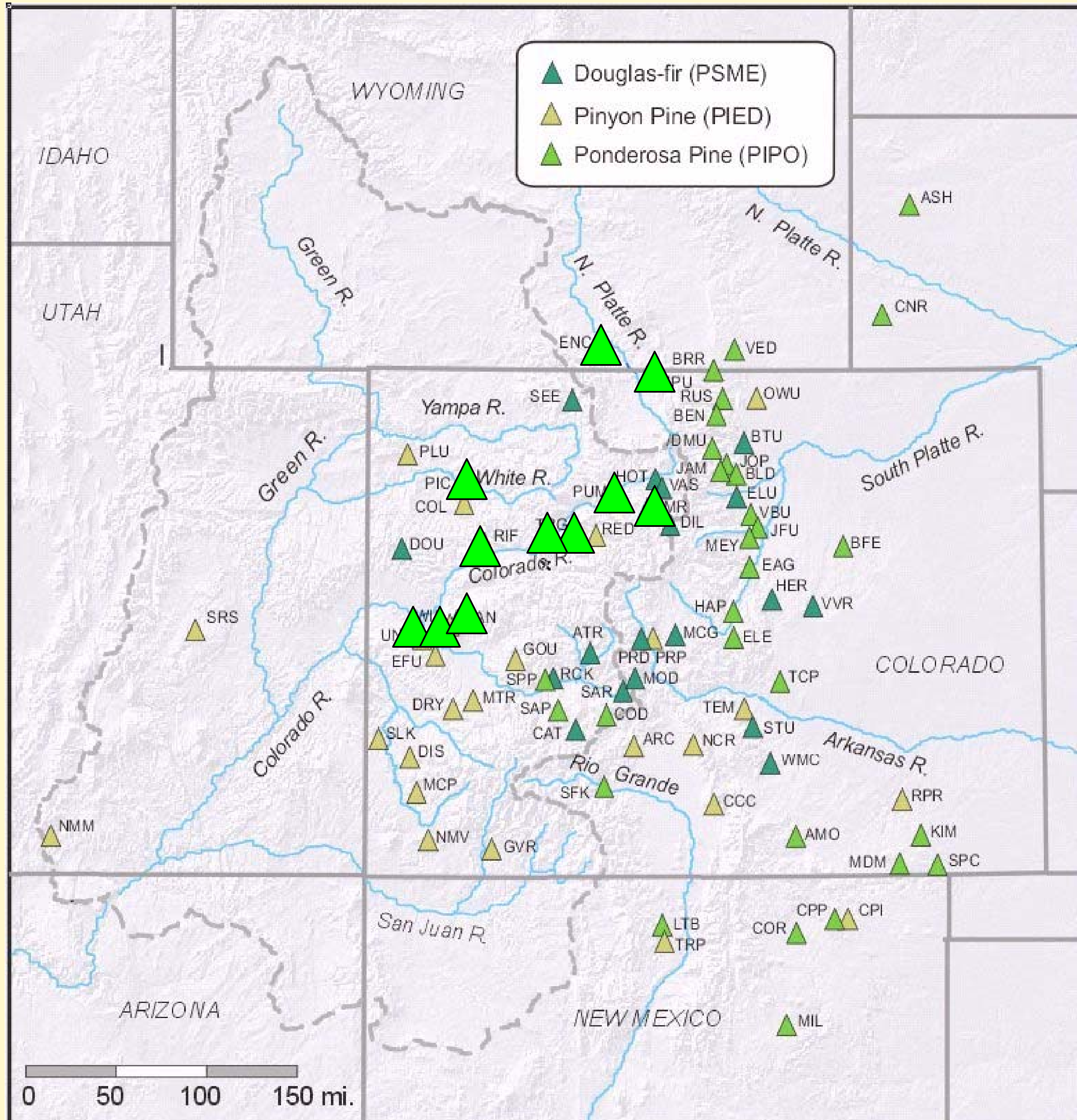
Moisture-sensitive chronologies in CO, WY, NM, UT collected since 2000 by Woodhouse and Lukas

- Average length: 550 years
- Significant correlations with annual precipitation and annual streamflow



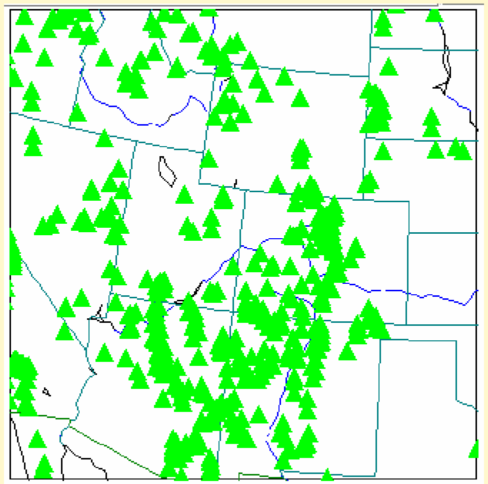
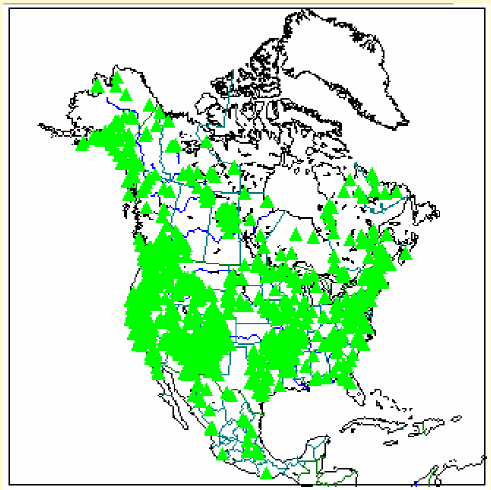
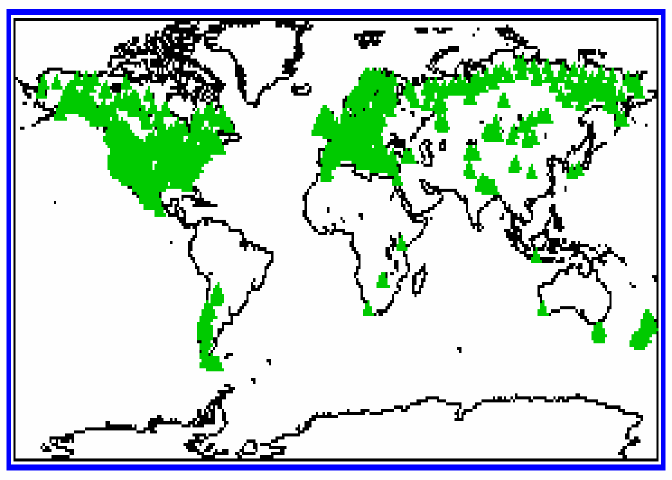
Extending moisture-sensitive chronologies using remnant wood, 2005-2007

- Average length: **1200** years
- Significant correlations with annual precipitation and annual streamflow



The larger world of tree-ring chronologies

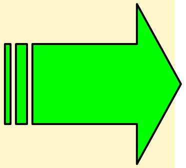
International Tree-Ring Data Bank (ITRDB)
http://www.ncdc.noaa.gov/paleo/treering.html

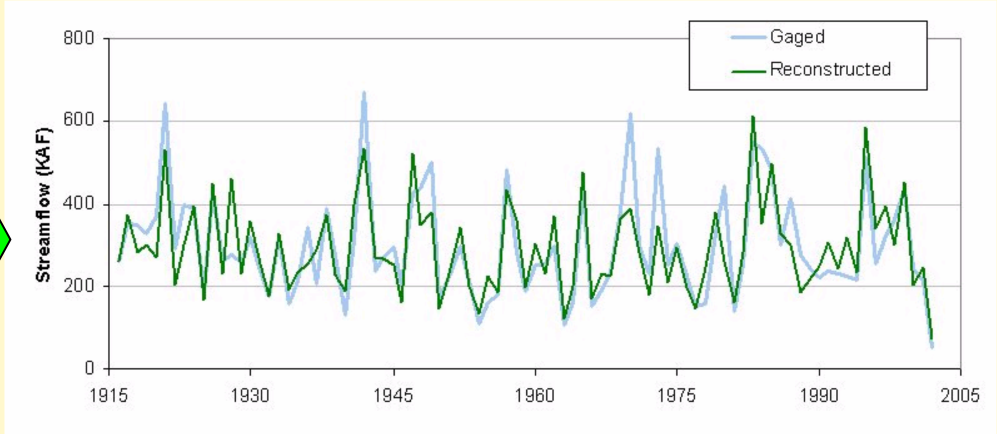




- 2500 chronologies contributed from all over the world
- Can be searched by moisture-sensitive species, location, years

Part 4:

Generating the streamflow reconstruction





Reconstruction = estimate of past flows, based on the relationship between a selected set of tree-ring data and gaged flows

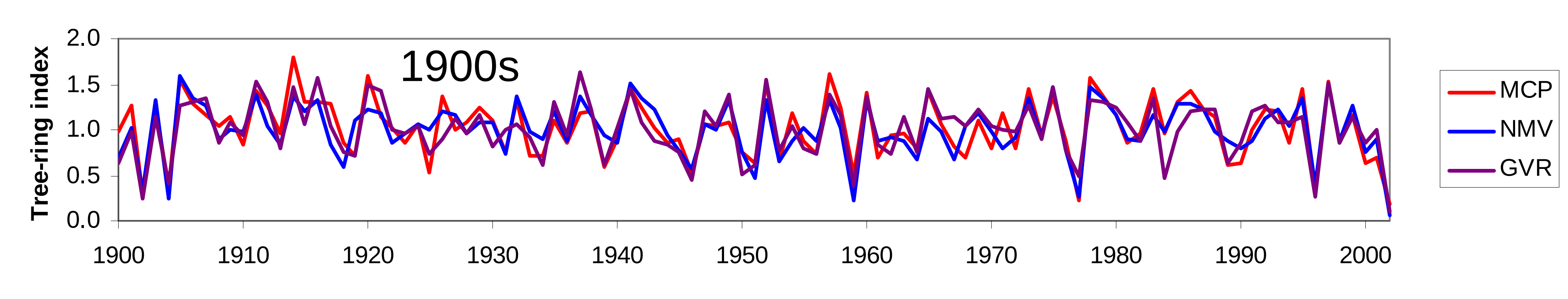
Assumptions behind the reconstruction methodology

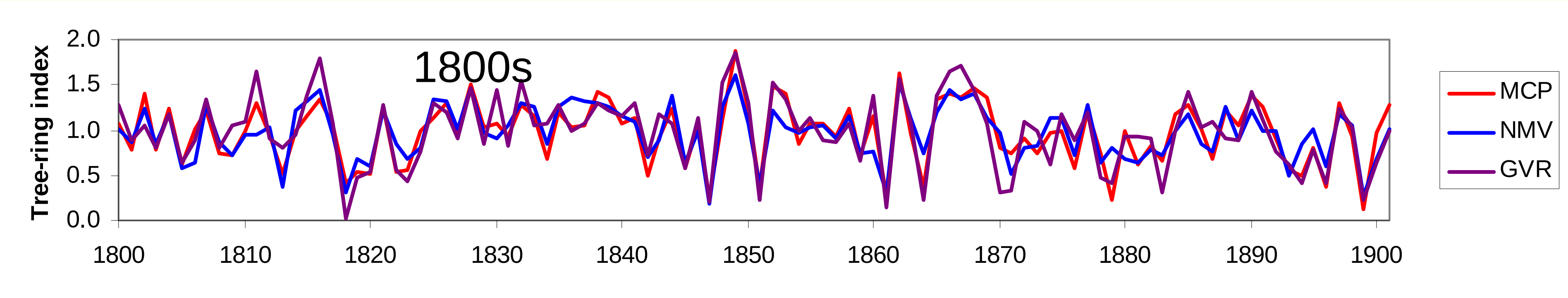
1) That the relationship between tree growth and streamflow has been stable over the past several centuries

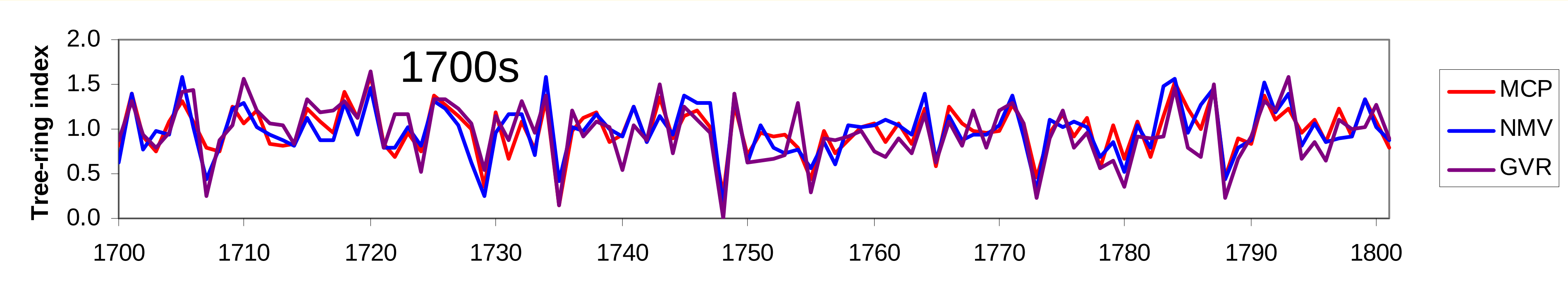
2) That the trees that do the best job of estimating the gaged flows will do the best job of estimating the flows prior to the gaged period

We can't test these assumptions directly, but coherence among the tree-ring data gives us more confidence in them

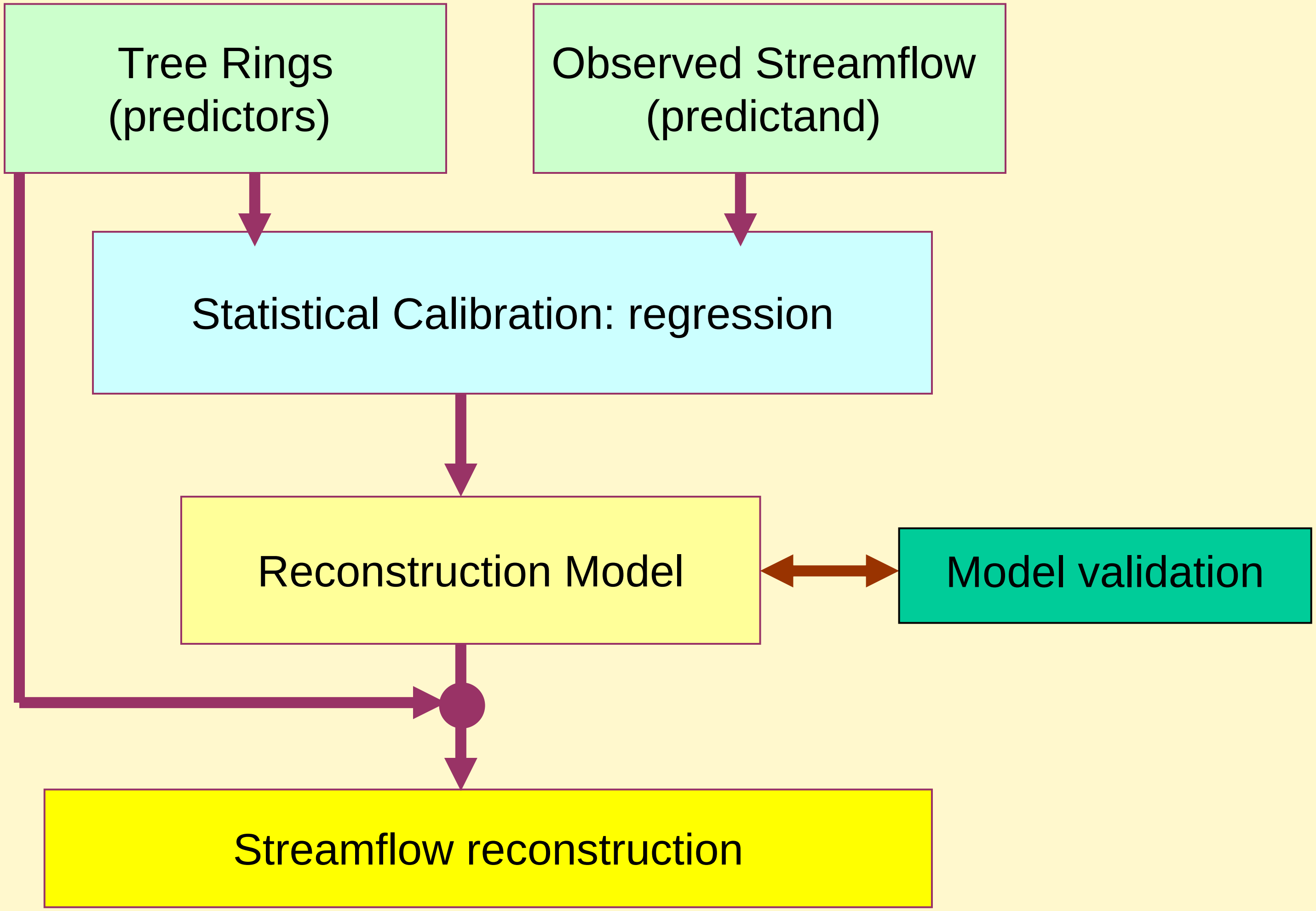
Three pinyon site chronologies near Durango, CO







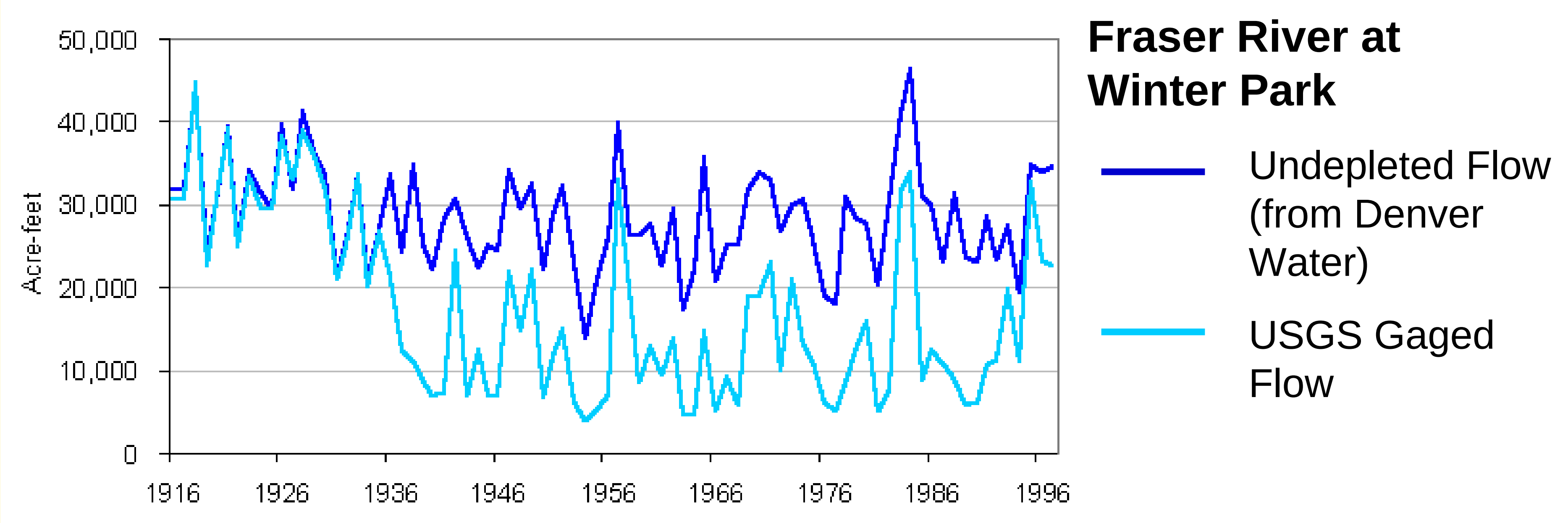
Overview of reconstruction methodology



based on Meko 2005

Data selection - 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

Data selection - tree-ring chronologies

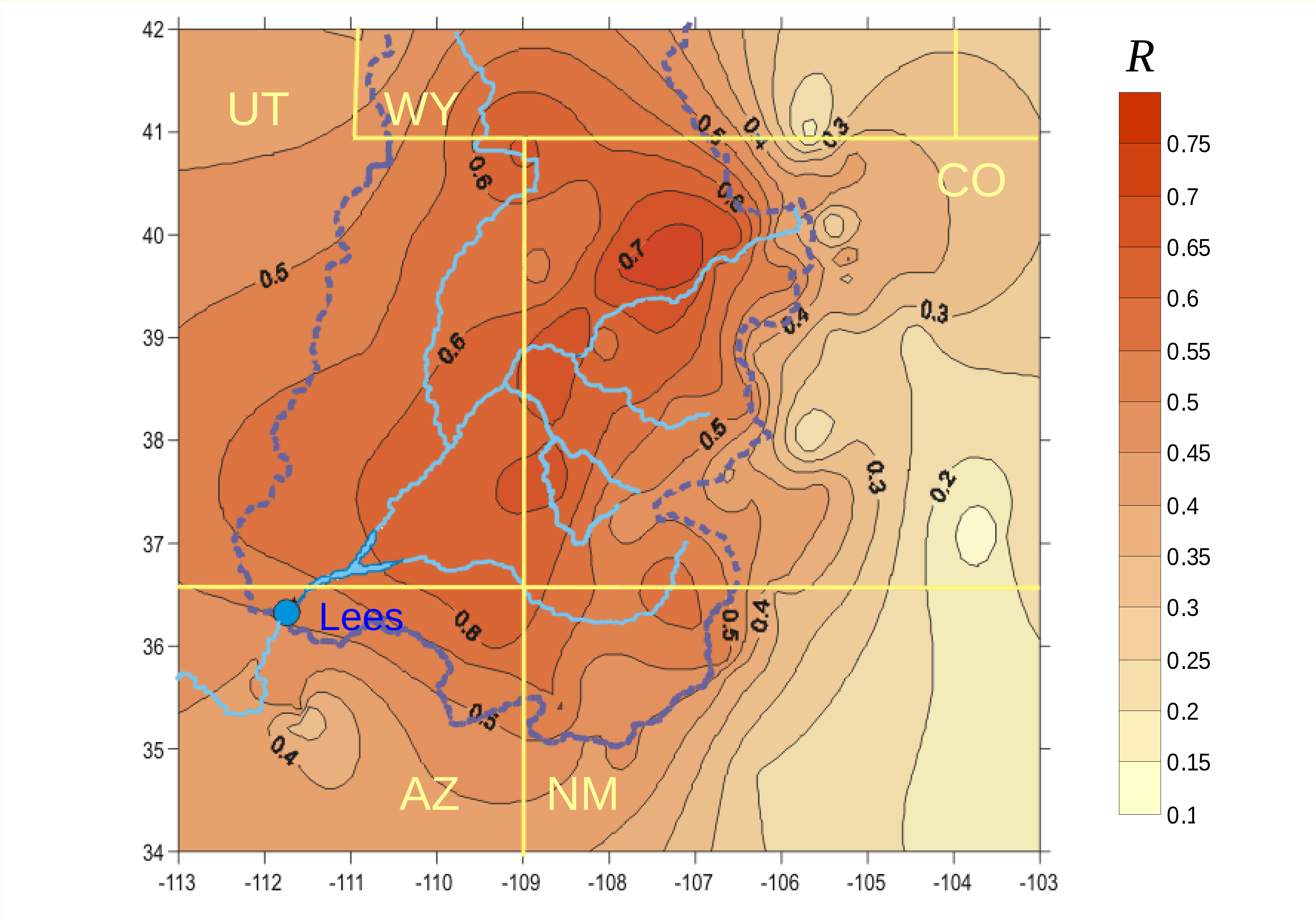
- **Moisture sensitive species** - in Colorado and Southwest: Douglas-fir, ponderosa pine, pinyon pine
- **Location** – from a region that is climatically linked to the gage of interest
  - *Because weather systems cross watershed divides, chronologies do not have to be in same basin as gage*
- **Length -**

  Last year close to present for the longest calibration period possible

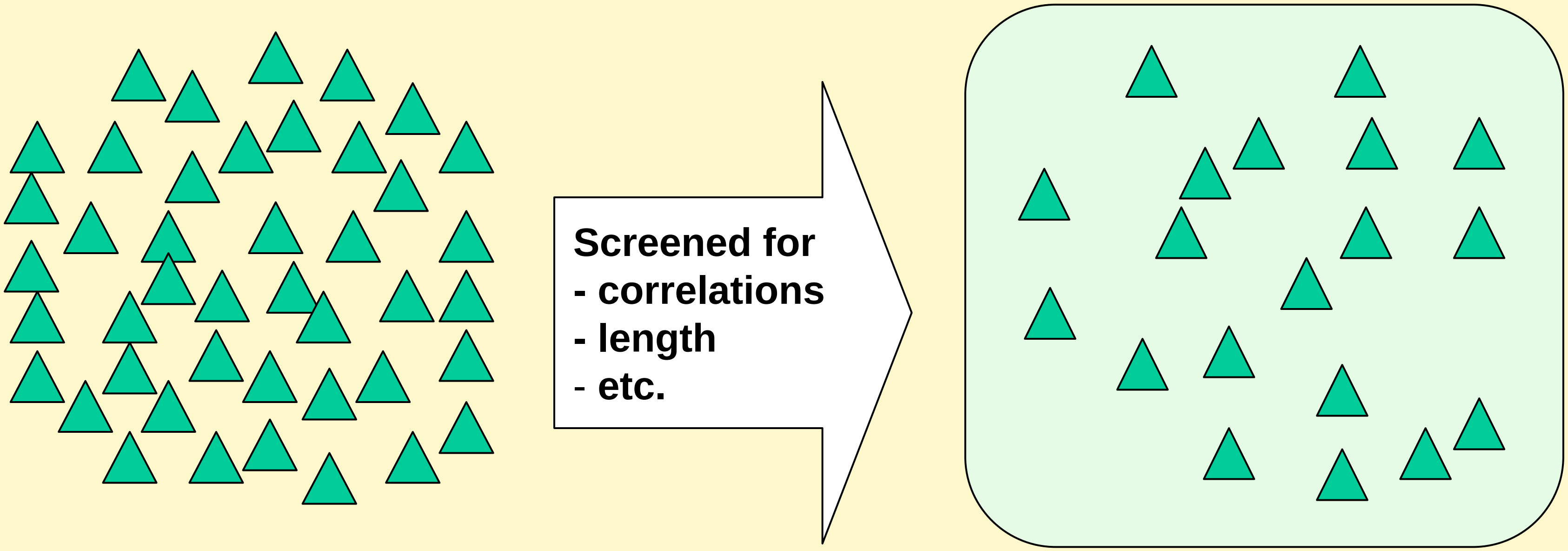
  First year as early as possible (>300 years) but in common with a number of chronologies

  - *reconstructions are limited by the shortest chronology*

Correlations: Tree-ring chronologies w/ Lees Ferry streamflow



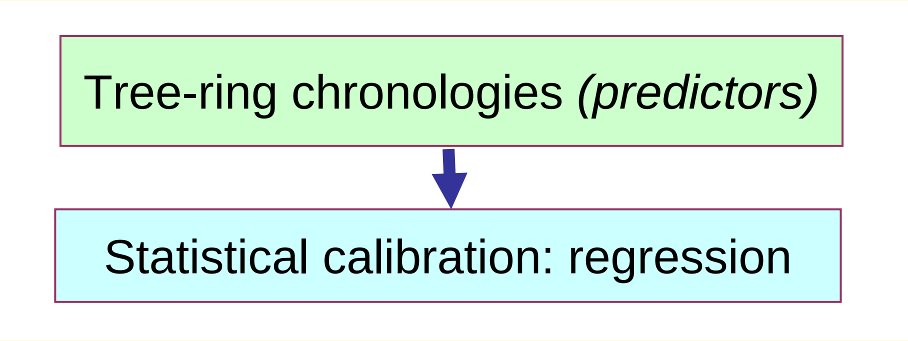
After *data selection and evaluation*, a pool of potential tree-ring predictors is generated



- Typically, the pool contains from 10-30 chronologies
- If the pool is too large (>50 chronologies), the chance of a spurious predictor entering the model increases

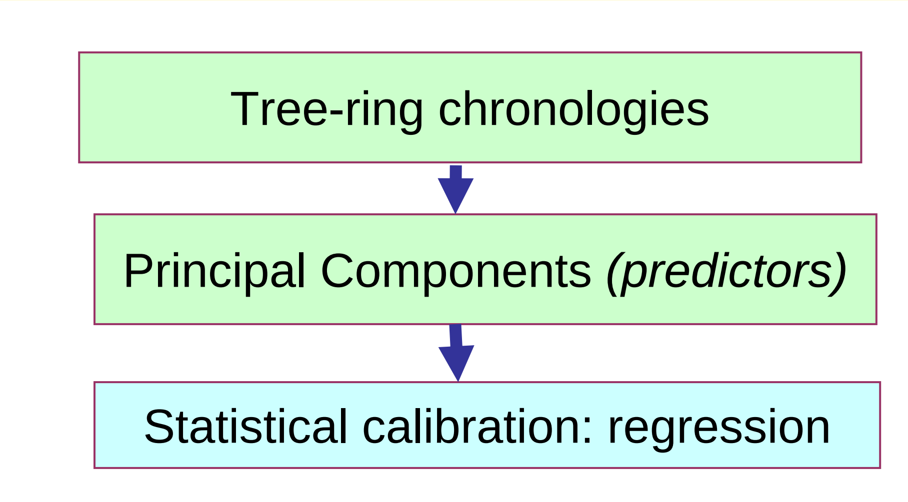
Reconstruction modeling strategies

- **Individual chronologies** are used as predictors in a stepwise or best subsets regression



OR

- **The set of chronologies is reduced** through Principal Components Analysis (PCA) and the components (representing modes of variability) are used as predictors in a regression

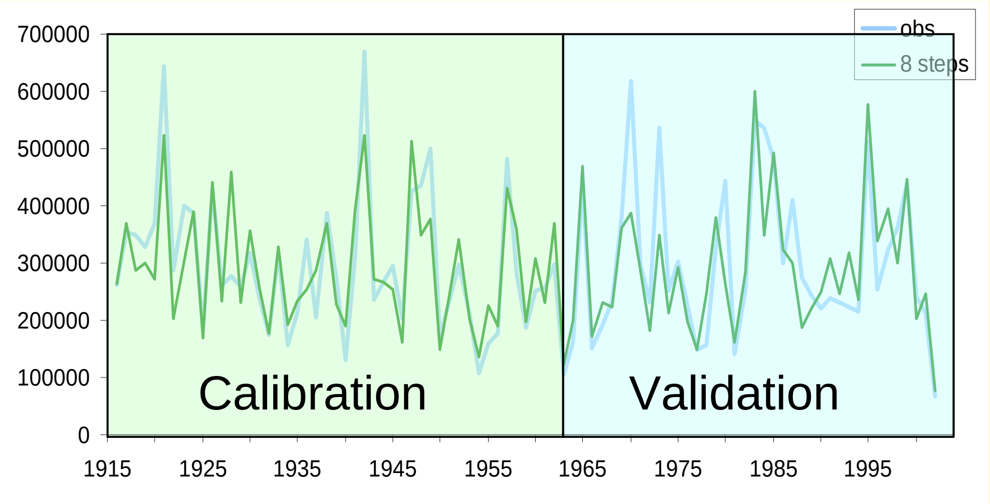


These are the most common, but many other approaches are possible (e.g., quantile regression, neural networks, non-parametric methods)

Model validation strategy

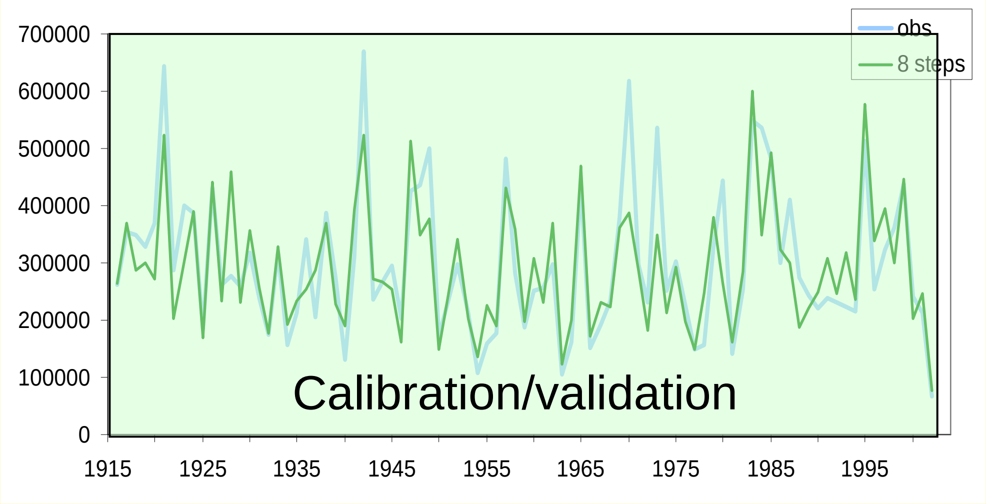
Goal: to calibrate model on a set of data, and validate the model on an independent set of data

Split-sample with independent calibration and validation periods



OR

Cross-validation ("leave-one-out") method

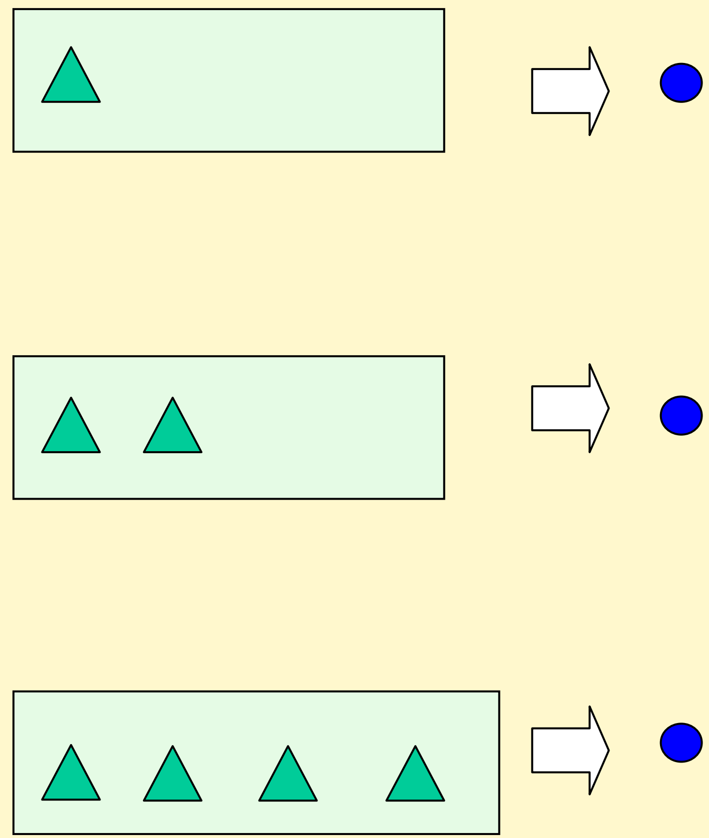


Model calibration: Forward stepwise regression

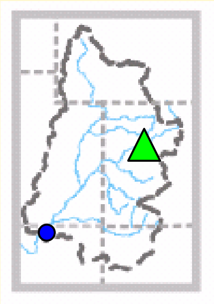
1) The chronology that explains the most variance in the flow record is selected as the first predictor in the regression

2) The chronology that explains the most *remaining unexplained* variance in the flow record is incorporated into the regression (repeat)

3) The process ends when no additional chronology significantly improves the fit of the regression to the flow record



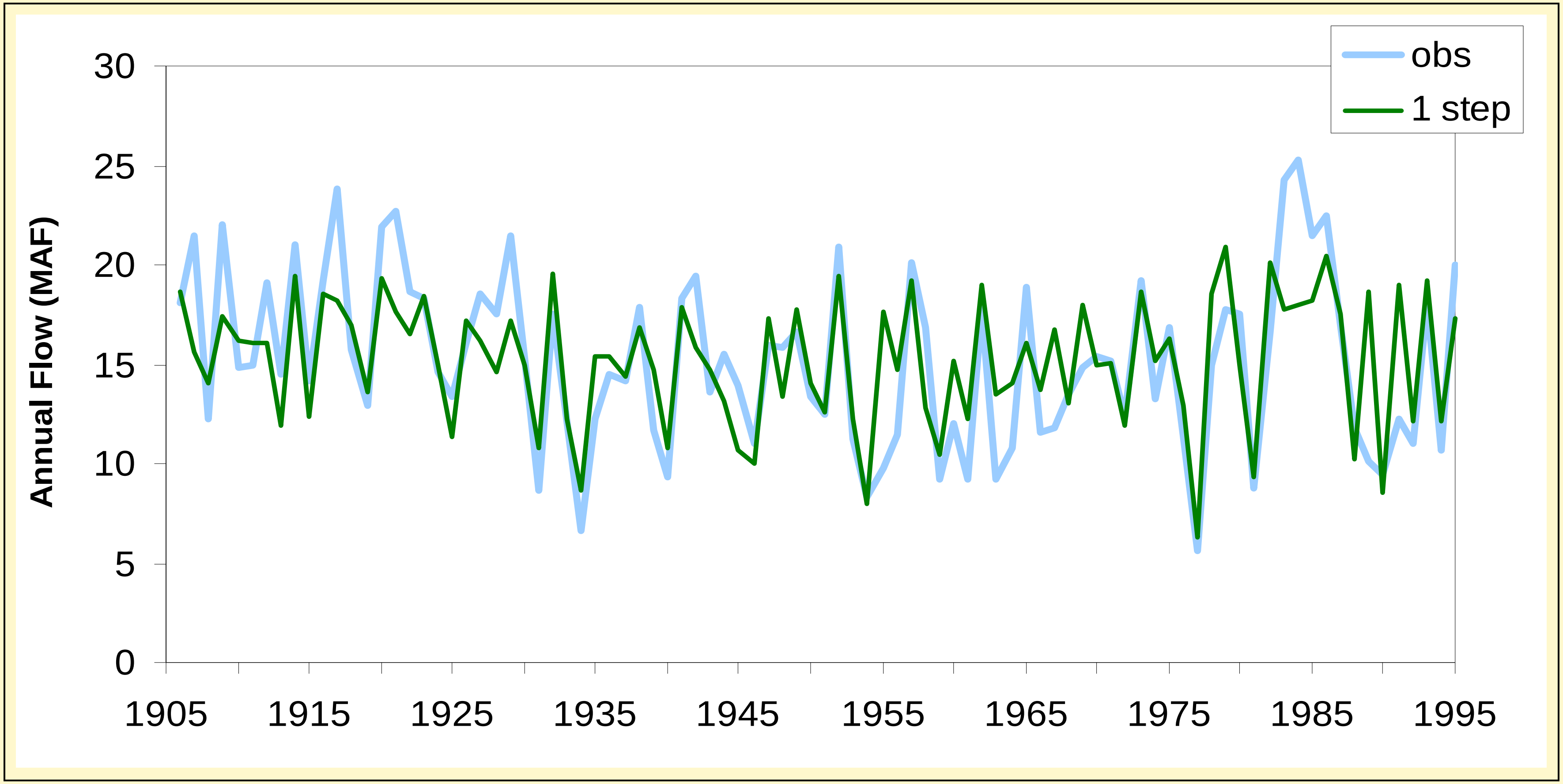
Colorado at Lees Ferry - forward stepwise regression



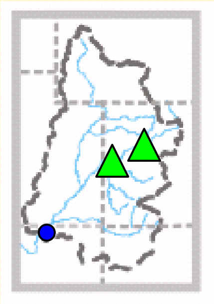
TRG

Variance Explained

55%



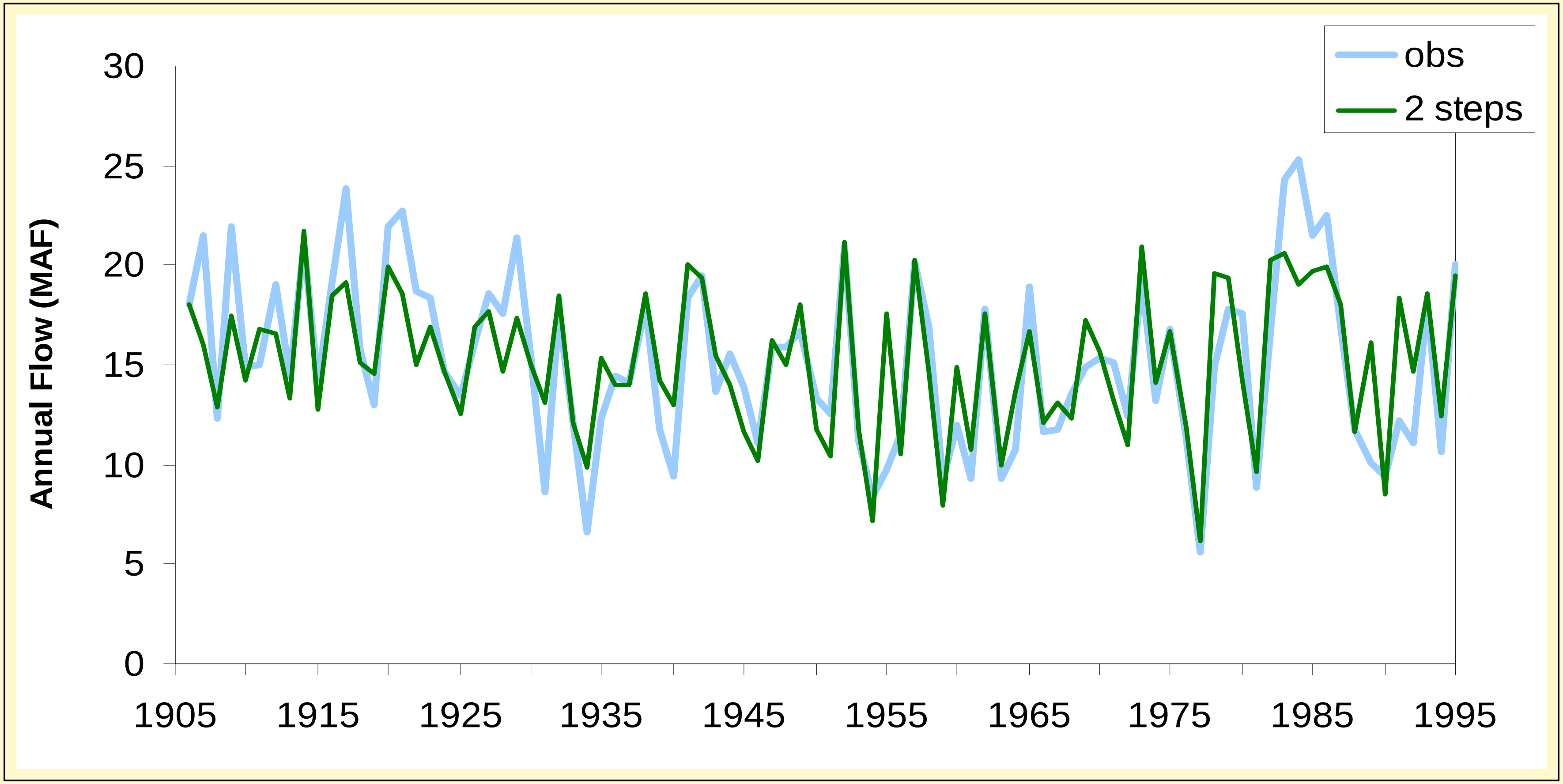
Colorado at Lees Ferry - forward stepwise regression



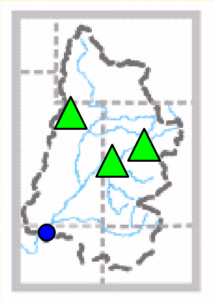
TRG + WIL

Variance Explained

67%



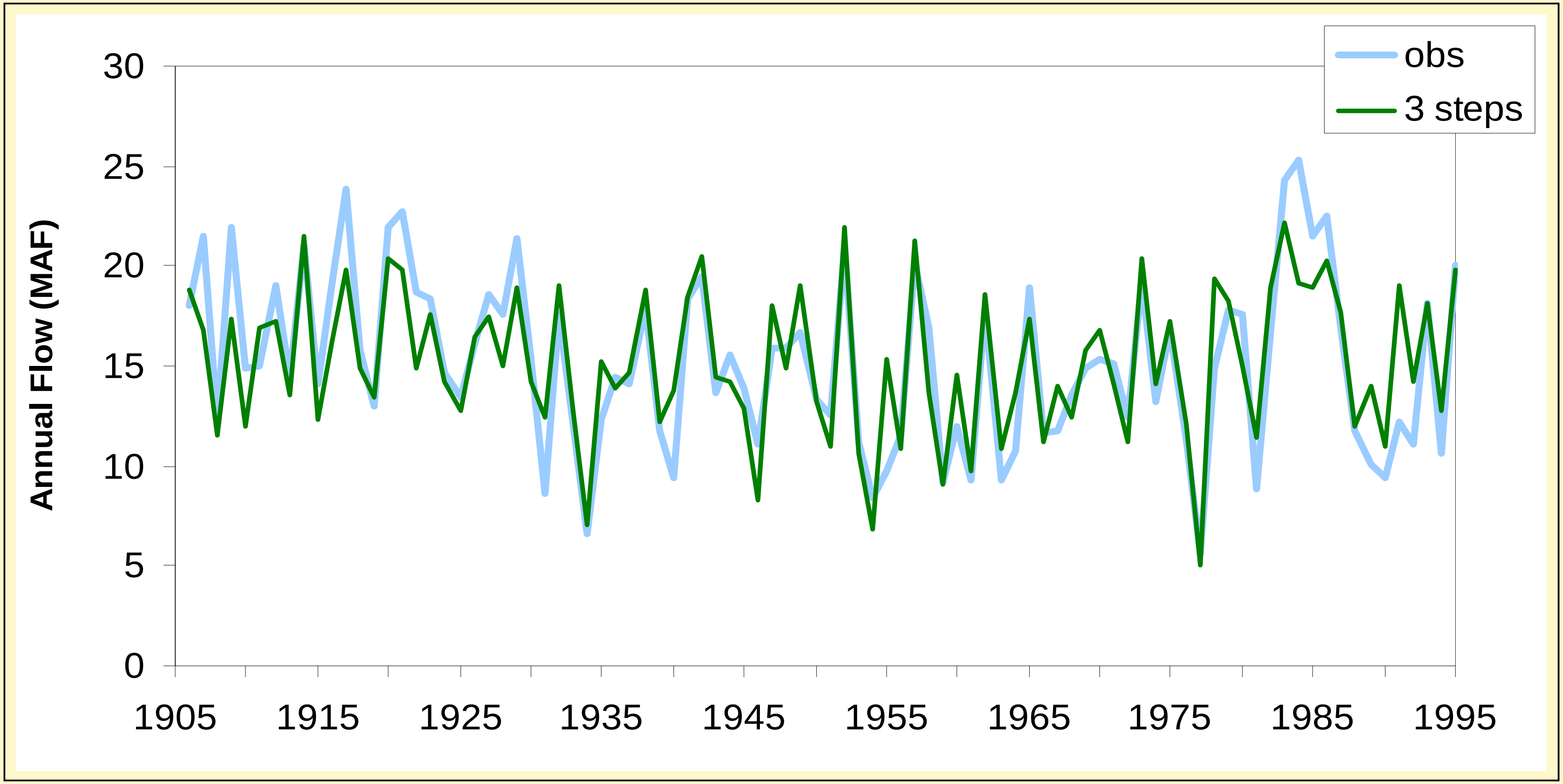
Colorado at Lees Ferry - forward stepwise regression



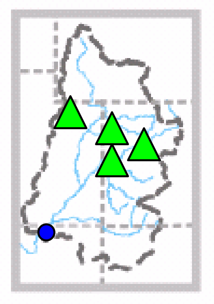
TRG + WIL + DJM

Variance Explained

72%



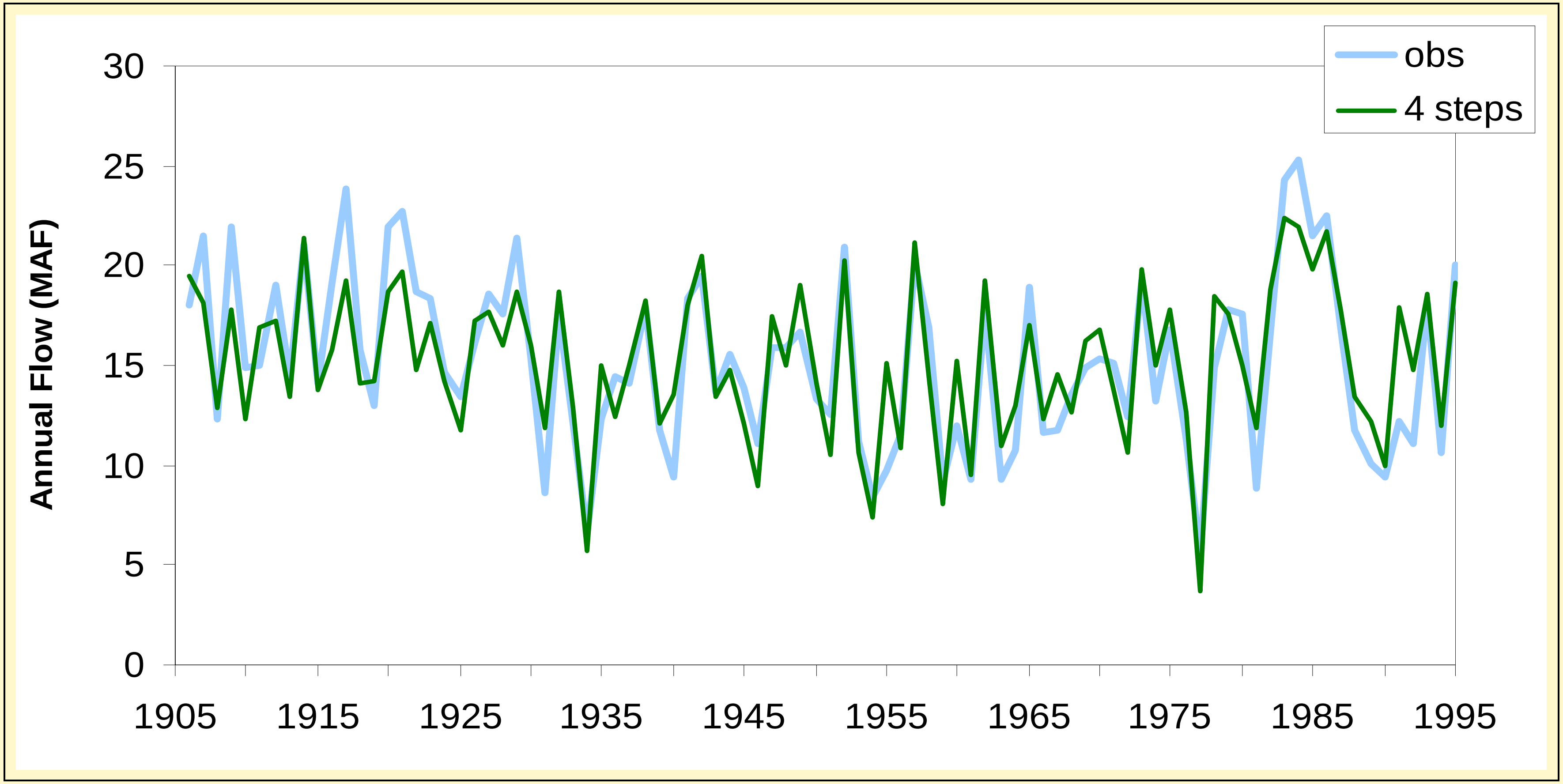
Colorado at Lees Ferry - forward stepwise regression



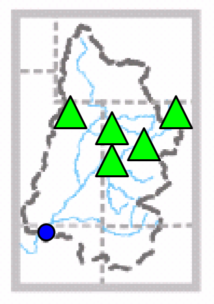
TRG + WIL + DJM + DOU

Variance Explained

75%



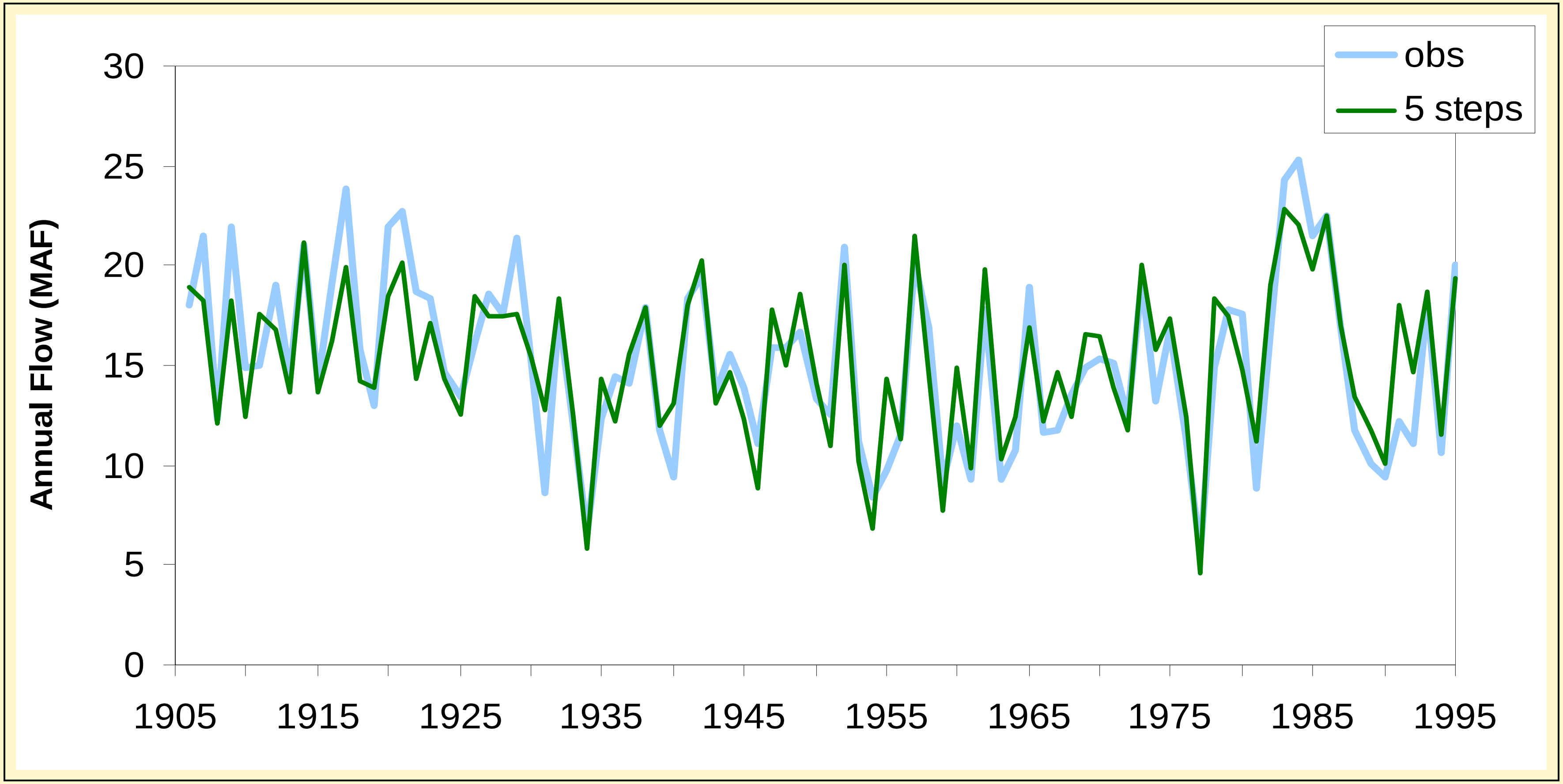
Colorado at Lees Ferry - forward stepwise regression



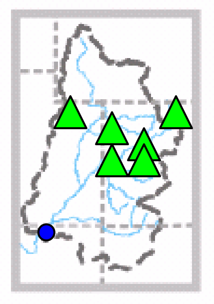
Variance Explained

77%

TRG + WIL + DJM + DOU + NPU



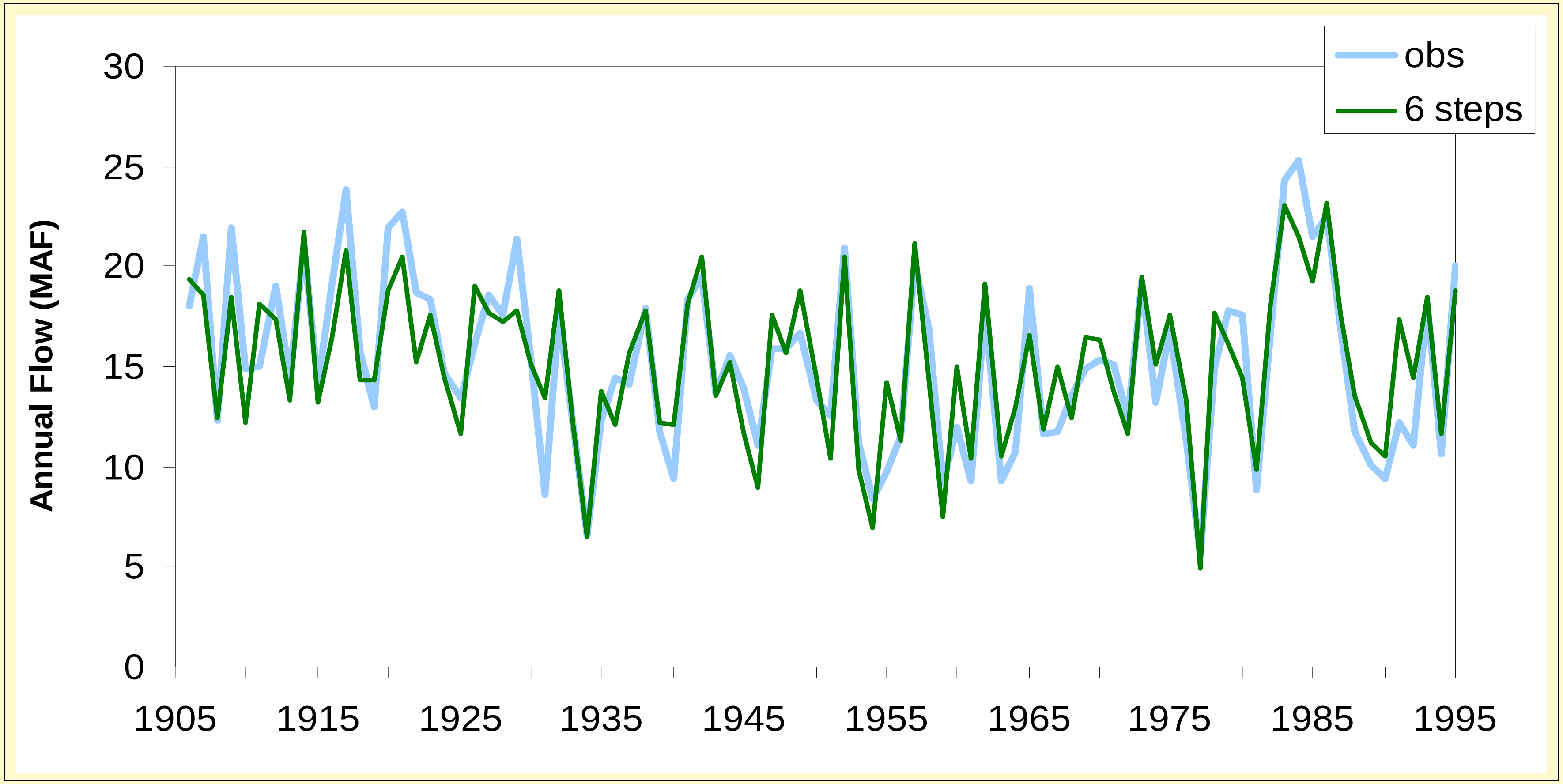
Colorado at Lees Ferry - forward stepwise regression



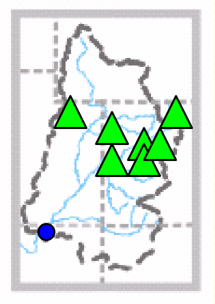
TRG + WIL + DJM + DOU + NPU + RED

Variance Explained

79%



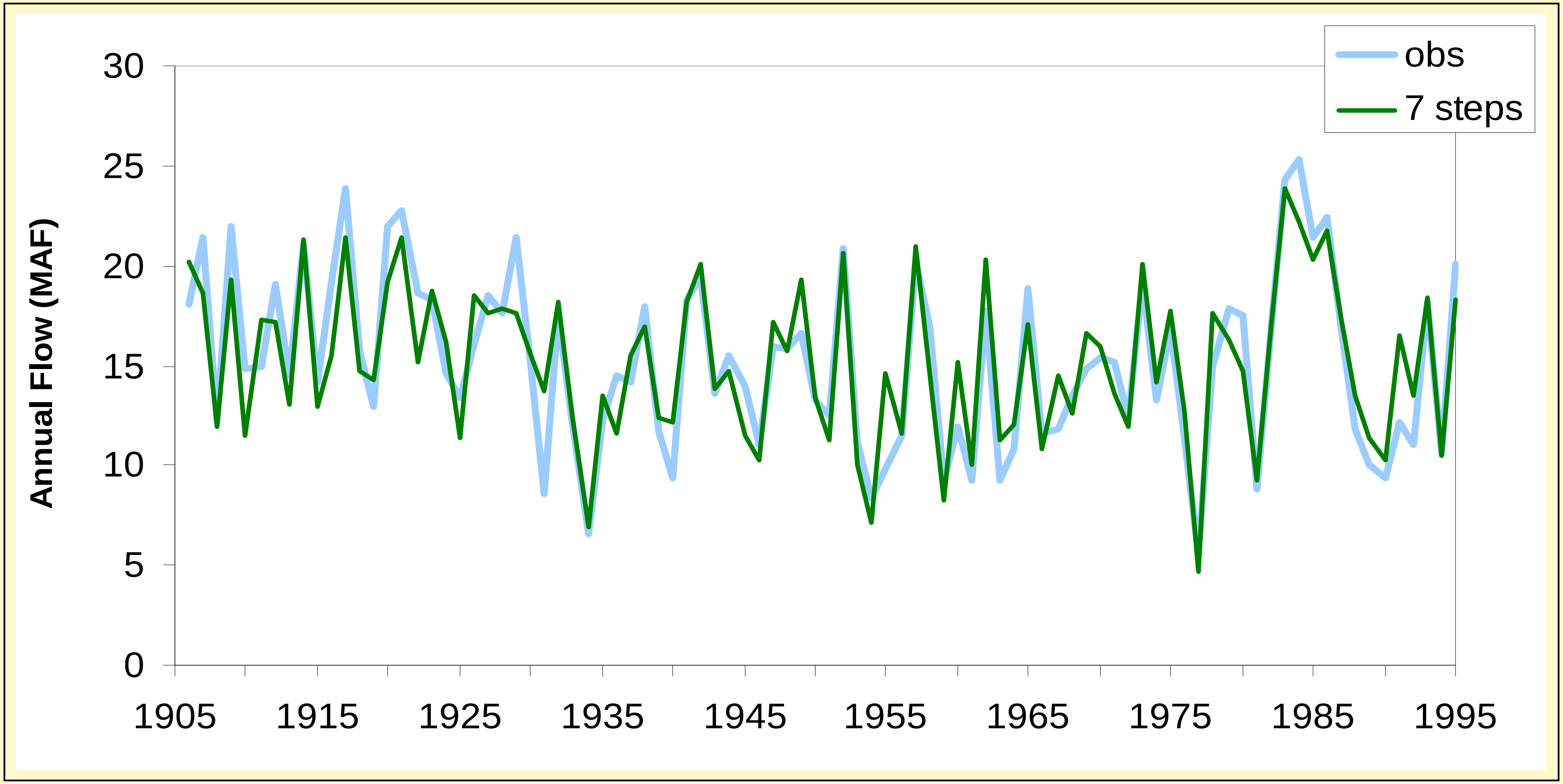
Colorado at Lees Ferry - forward stepwise regression



Variance Explained

81%

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



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?

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	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

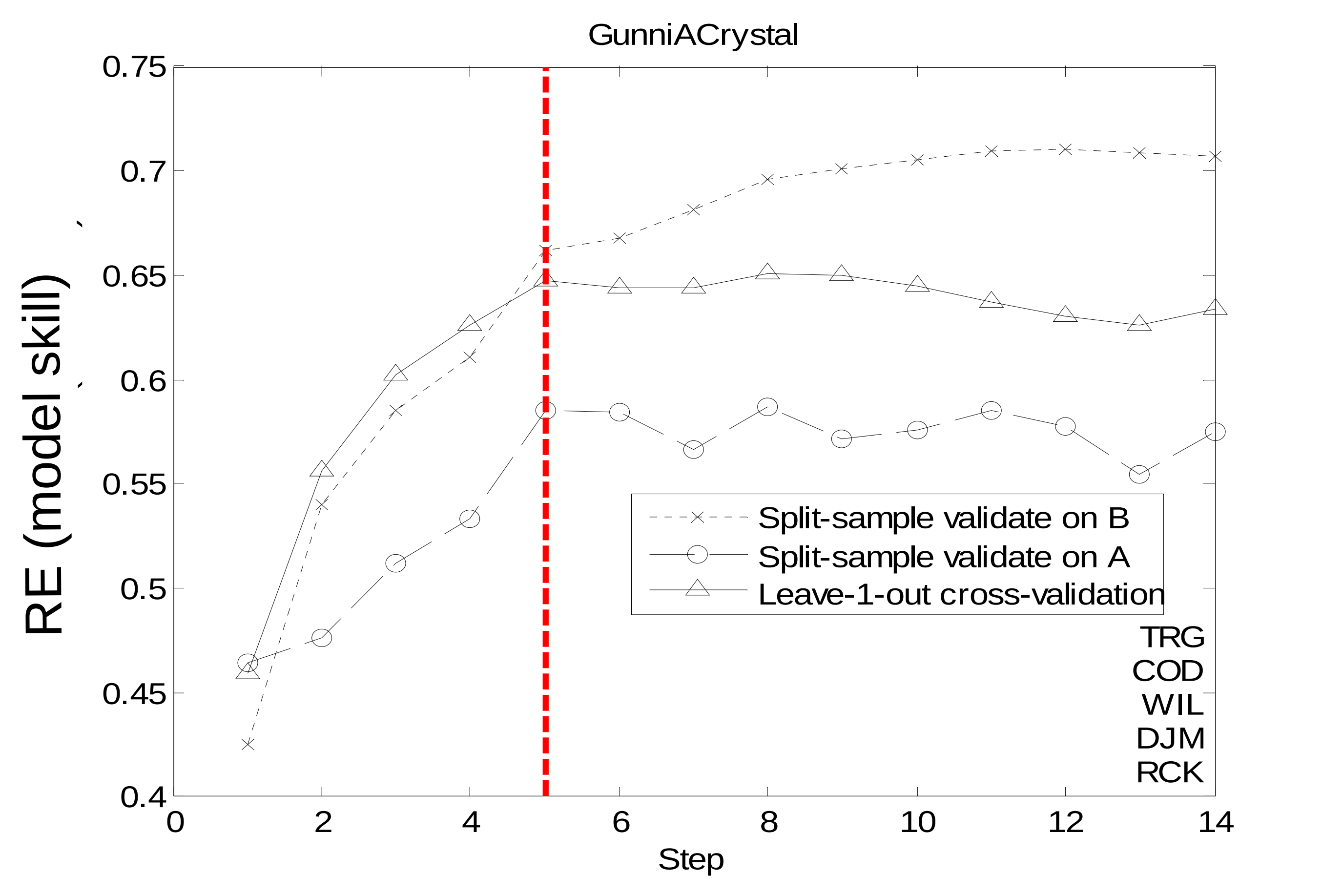
R2 and RE should be similar, and ideally above 0.50 - though much above 0.80 suggests overfitting

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

Prevention of overfitting

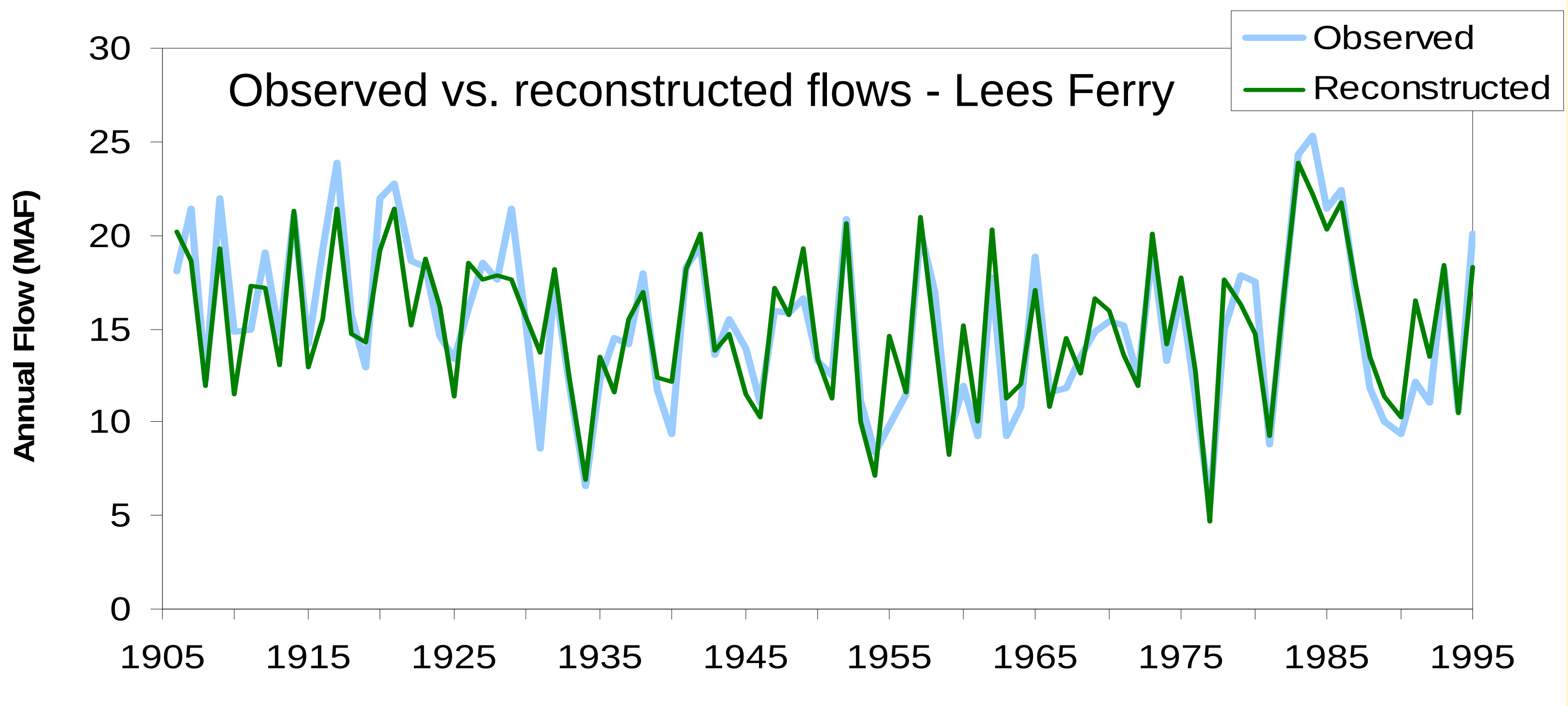
- An over-fit model is very highly tuned to the calibration period, but doesn't perform as well with data not in the calibration period (less predictive skill)
- In regression modeling, we can get fixated on R^2, but validation statistics like RE are a better measure of the quality of the model

Prevention of overfitting



- For this particular model (Gunnison R. at Crystal Res.), the validation RE is not improved appreciably with more than 5 predictors (red line)

How does the reconstruction compare to the gage record?

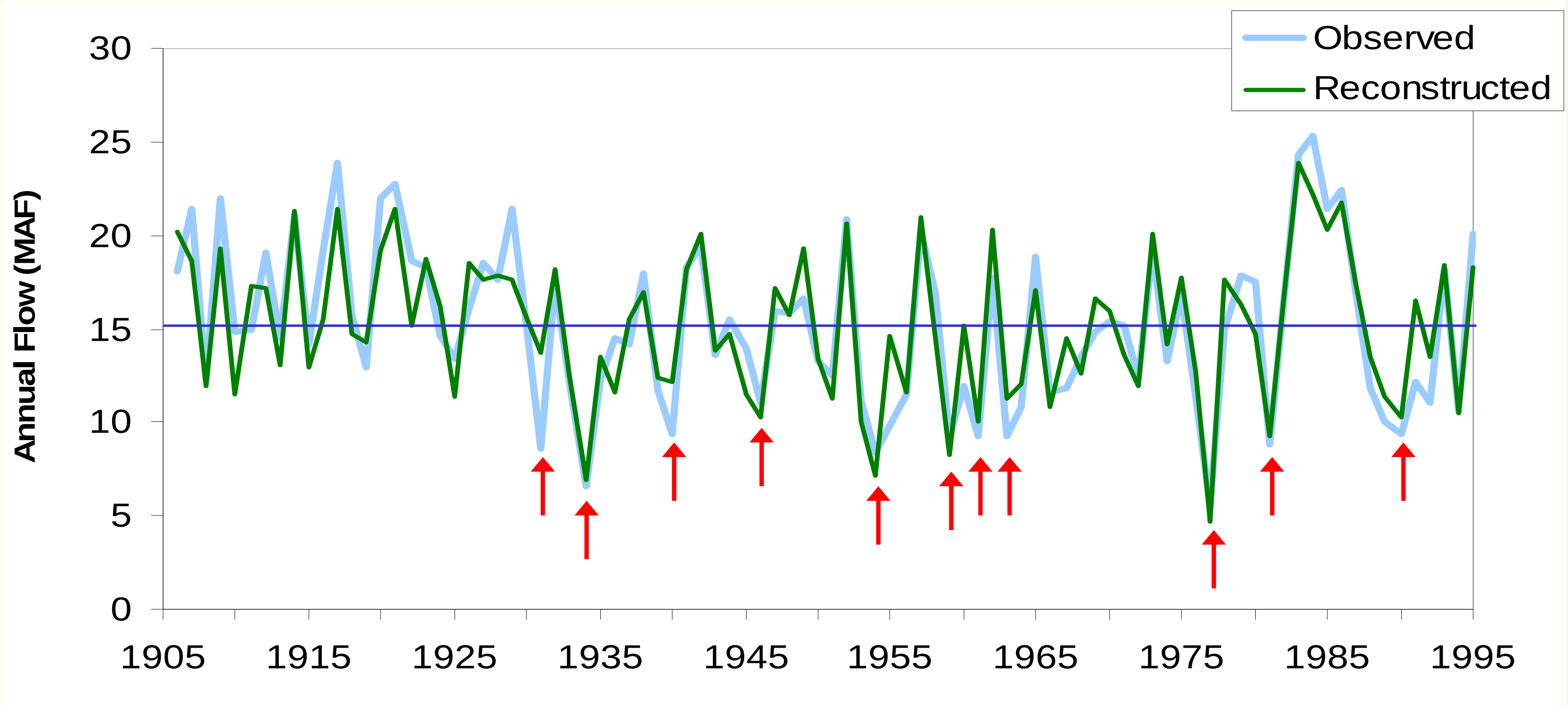


	Observed	Recon'd
Mean	15.22	15.22
Max	25.27	23.91
Min	5.57	4.71
StDev	4.32	3.88
Skew	0.16	-0.14
Kurtosis	-0.58	-0.37
AC1	0.25	0.04

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

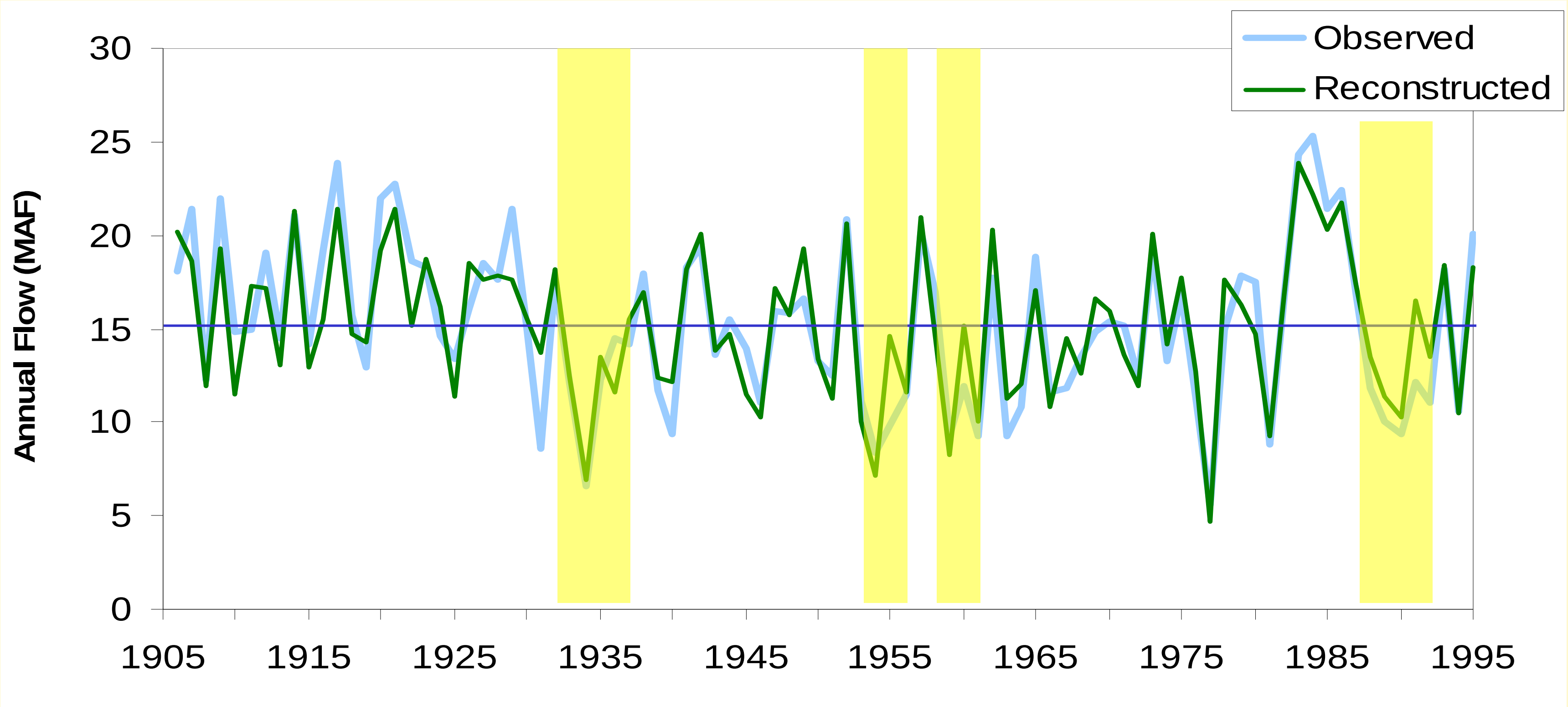
Also as expected, the standard deviation in the reconstruction is lower than in the gage record

Subjective assessment of model quality



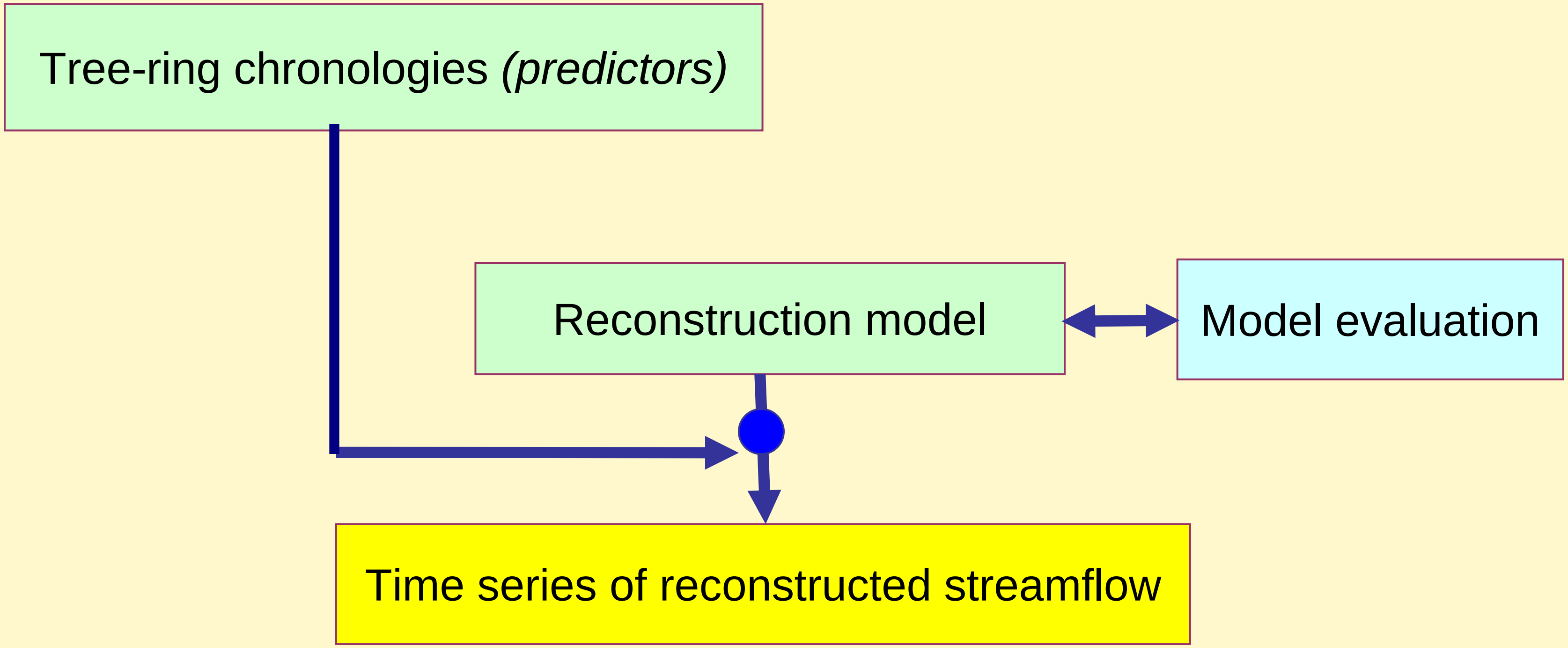
- Are severe drought years replicated well, or at least correctly classified as drought years?

Subjective assessment of model quality



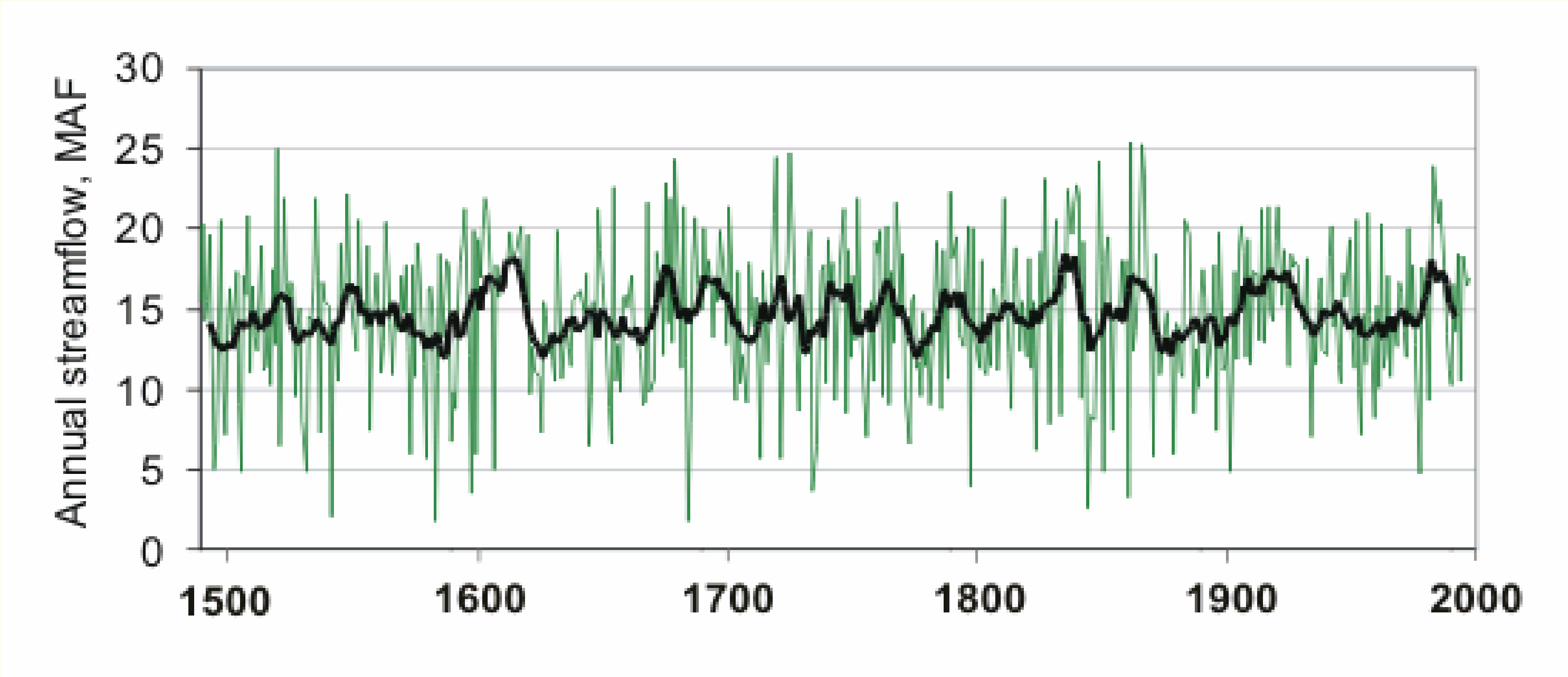
- Are the lengths and total deficits of multi-year droughts replicated reasonably well?

From model to full reconstruction



- When the regression model has been fully evaluated (residuals and validation statistics), then the model is applied to the full period of tree-ring data to generate the reconstruction

Full Colorado R. at Lees Ferry streamflow reconstruction, 1490-1997



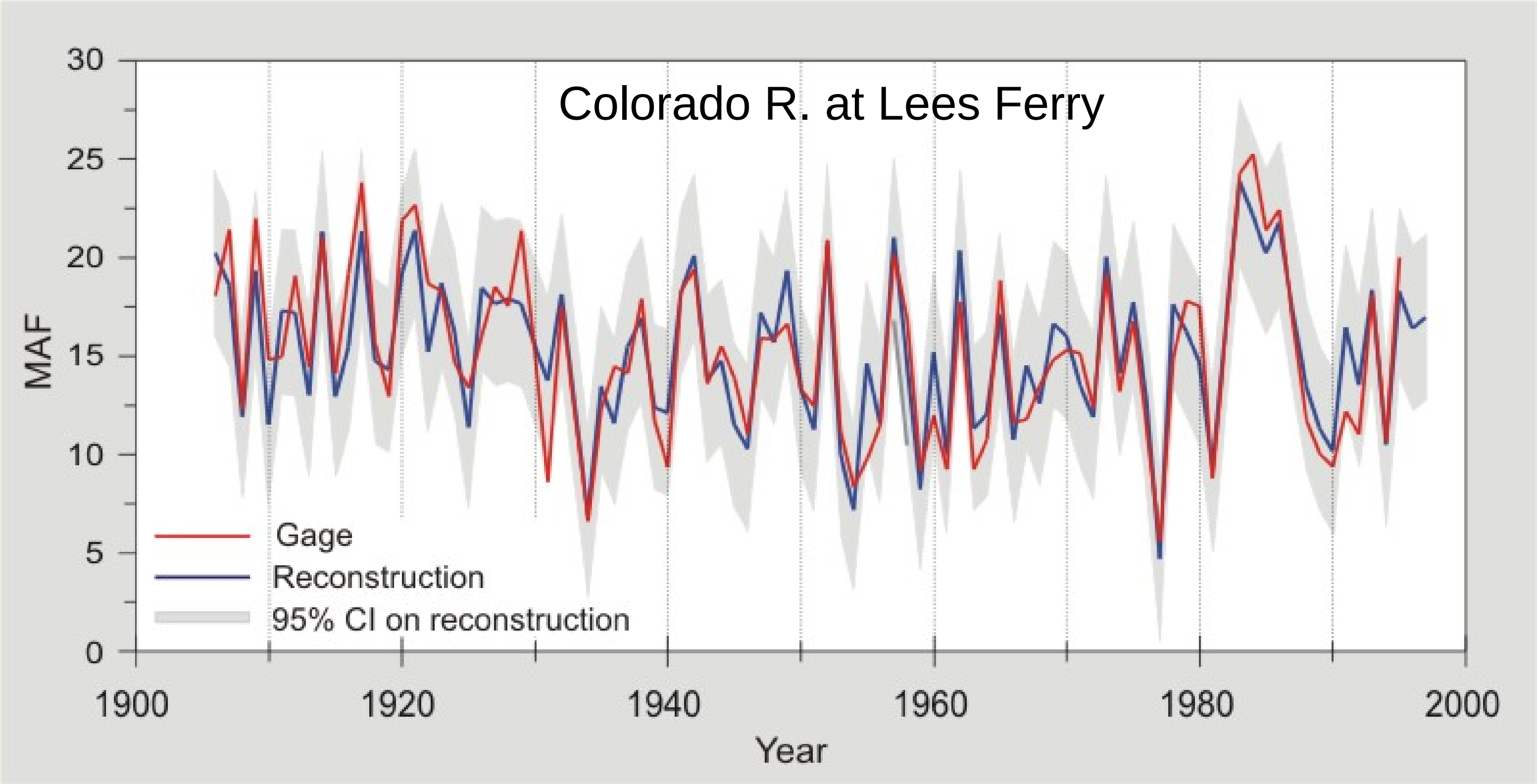
- Green = annual values; Black = 10-yr running mean
- Note both individual years and decadal periods with lower reconstructed flows than in the last century

Uncertainty in the reconstructions 1 – errors

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

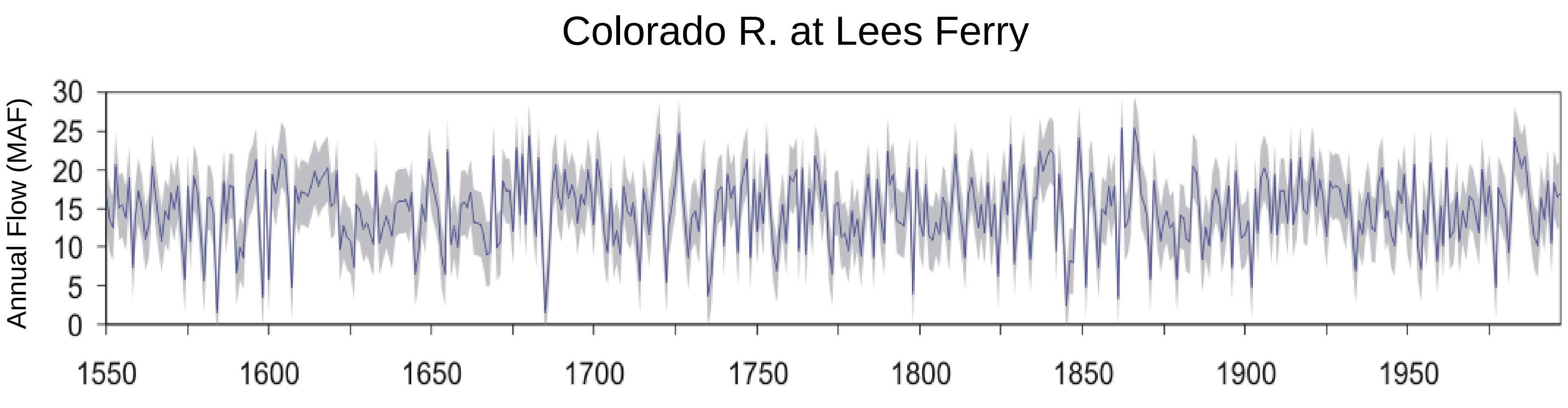
- The statistical uncertainty in the reconstruction model can be estimated from the validation errors (RMSE)

Using RMSE to generate confidence intervals for the model



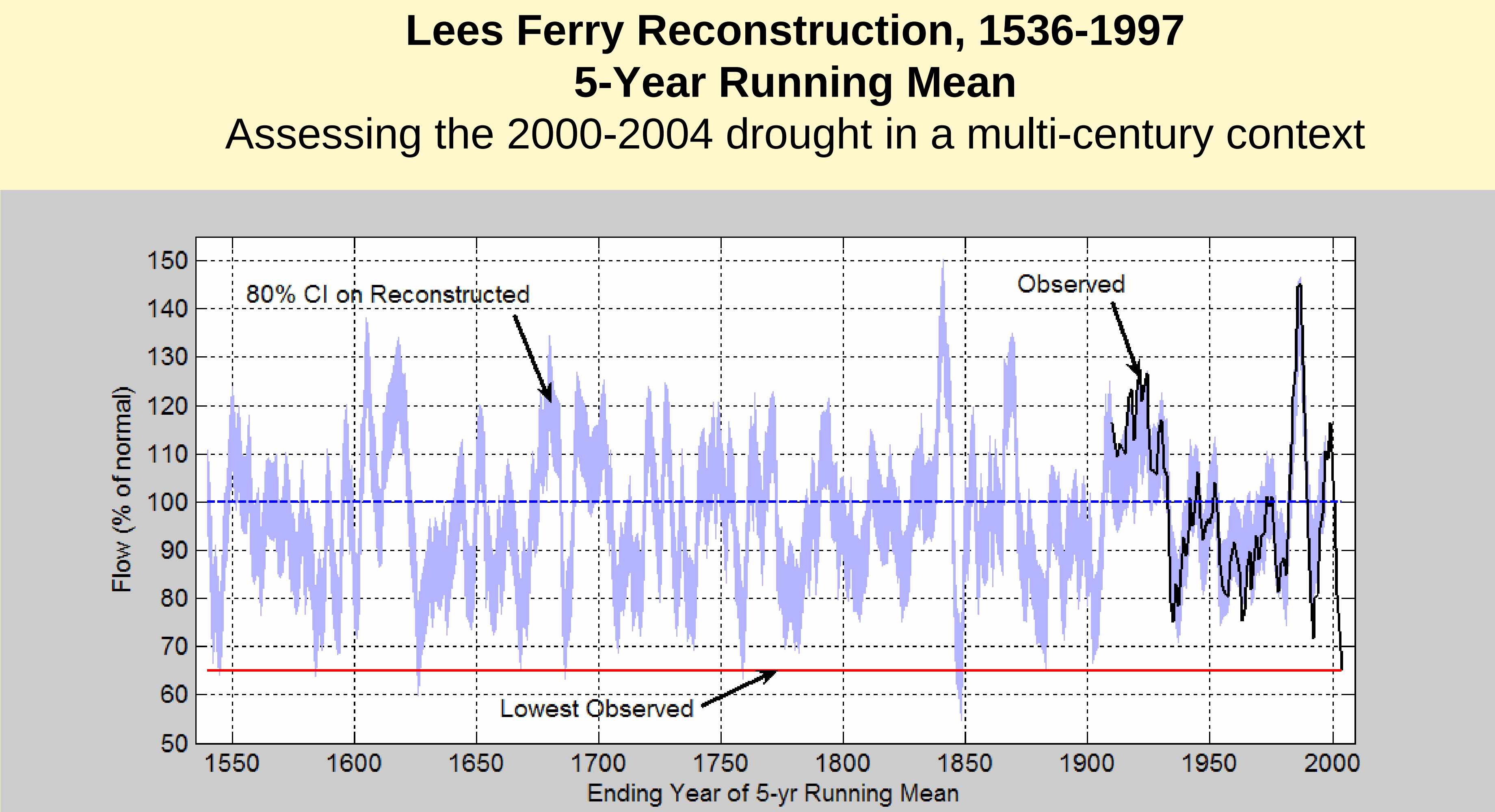
- Gray band = 95% confidence interval around reconstruction
- Indicates 95% probability that gaged flow falls within the gray band

Using RMSE to generate confidence intervals



- In applying these confidence intervals to the full reconstruction, we assume that the RMSE is representative of uncertainty throughout the reconstruction

Application of model uncertainty: using RMSE-derived confidence interval in drought analysis



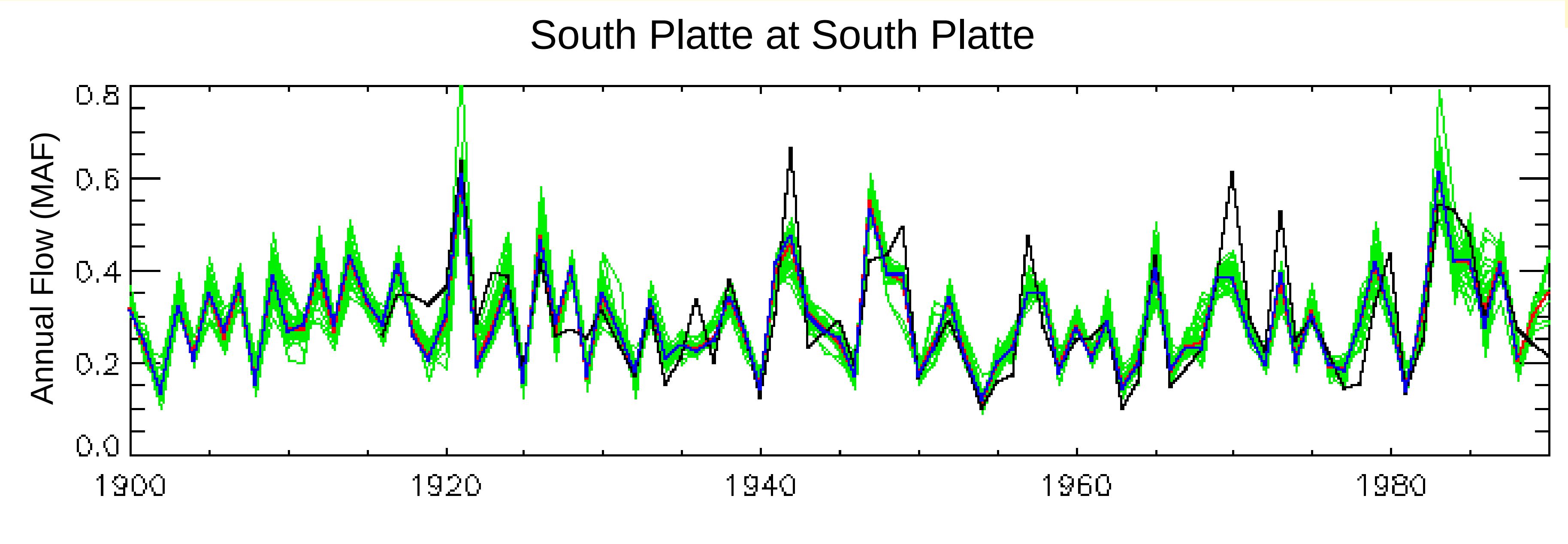
Data analysis: Dave Meko

Uncertainty in the reconstructions 2 – model sensitivity

- RMSE only summarizes the uncertainty associated with a specific model, which is the result of many choices in the treatment of the data and development of the model

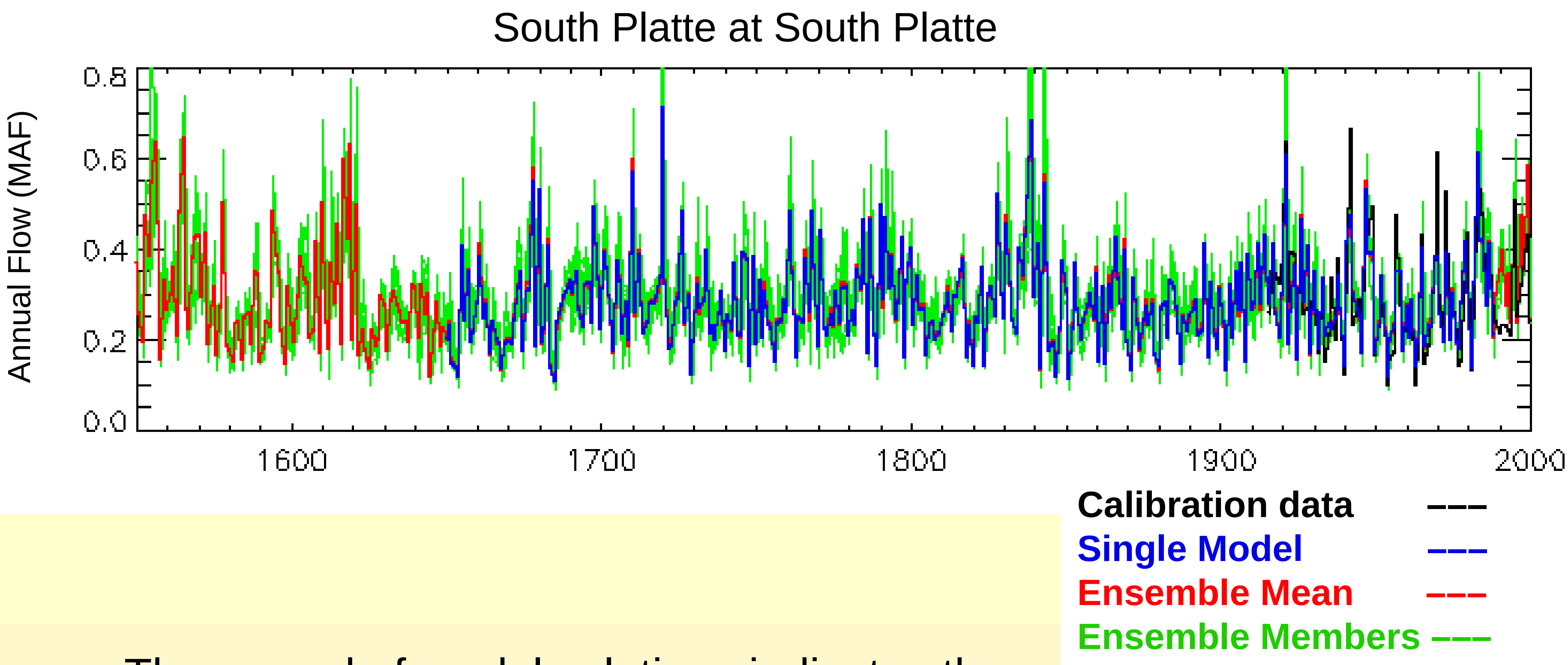
- The uncertainty associated with these data and modeling choices is *not* formally quantified, but sensitivity analyses can help assess their impacts (e.g., set of chronologies, gage data/years used, modeling approach, treatment of data).

Sensitivity to calibration period - ensemble method



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

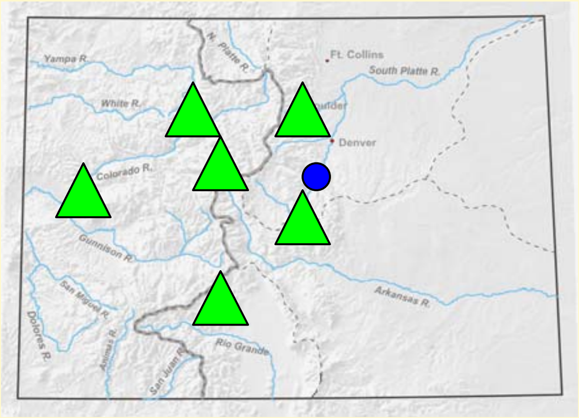
Sensitivity to calibration period - ensemble method



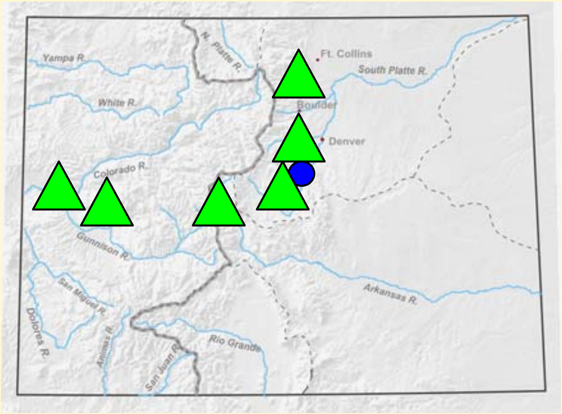
- The spread of model solutions indicates the sensitivity to the calibration period, given the same pool of predictors

Sensitivity to available predictors

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



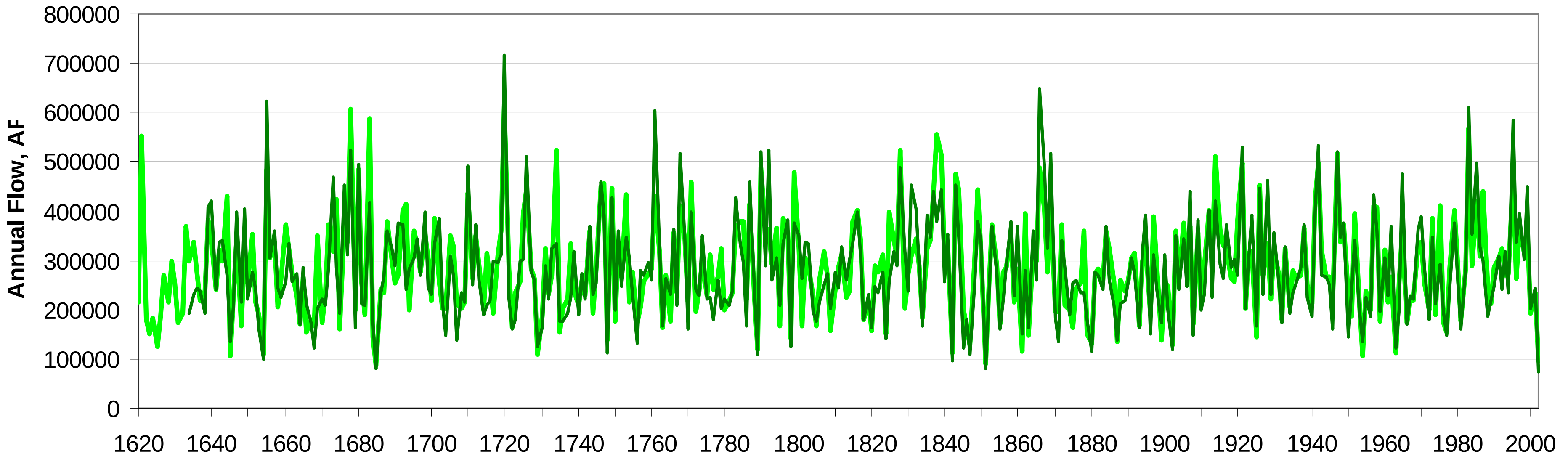
South Platte - First model



South Platte - Alternate model - predictors from first model excluded from pool

Sensitivity to available predictors - alternate models

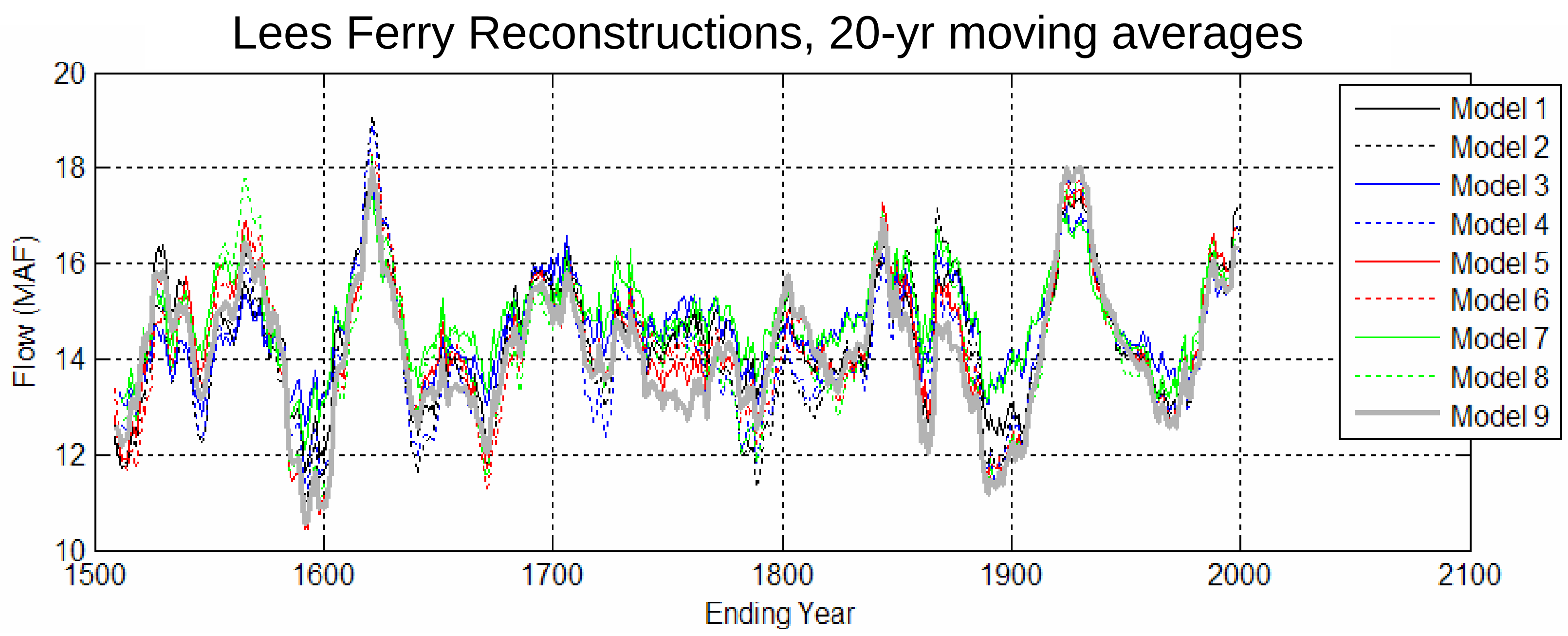
South Platte at South Platte, First Model and Alternate Model



- The two models correlate at r = 0.84 over their overlap period, 1634-2002
- In this case, completely independent sets of tree-ring data resulted in very similar reconstructions

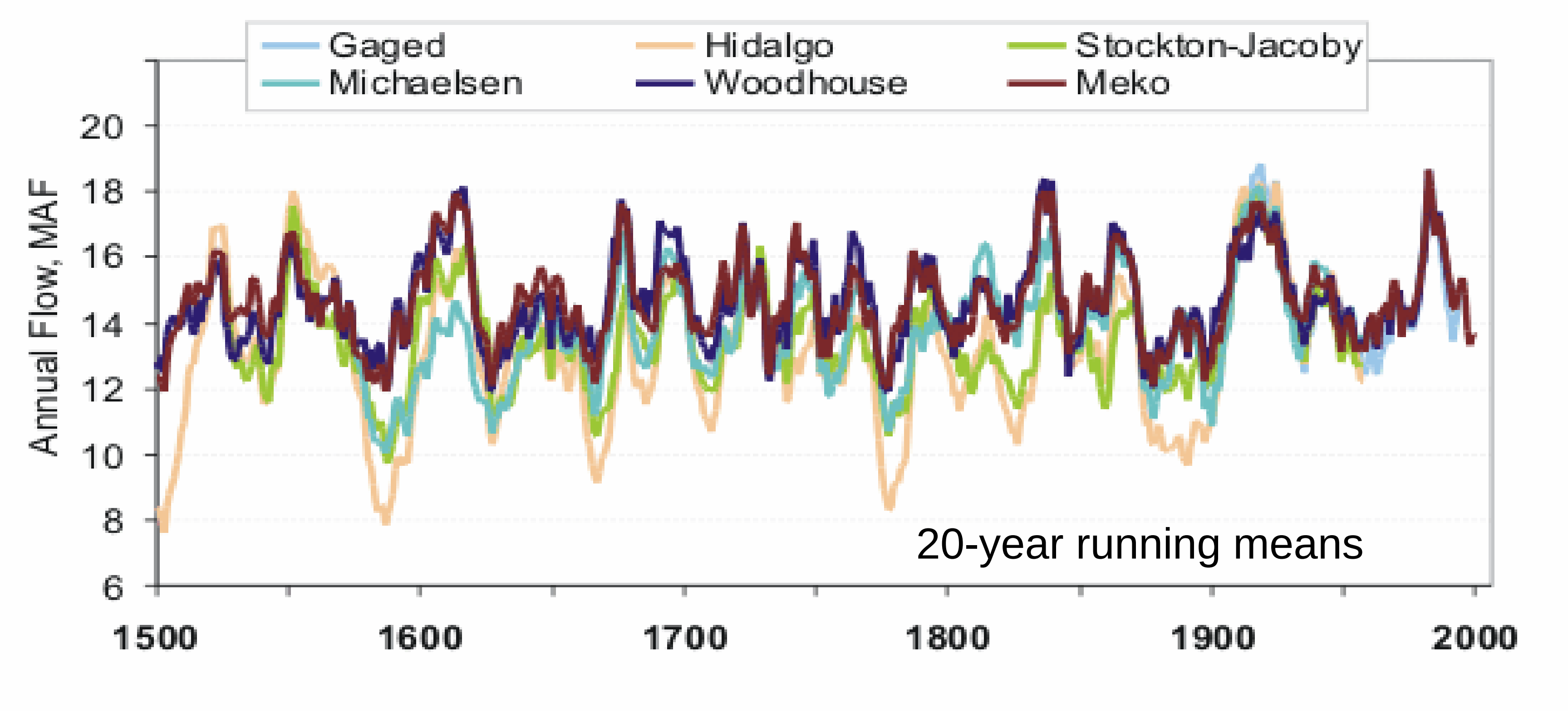
Sensitivity to other choices made in modeling process

Lees Ferry reconstructions (Woodhouse et a. 2006) from 9 different models that vary according to chronology persistence, pool of predictors, model choice



Analysis from David Meko

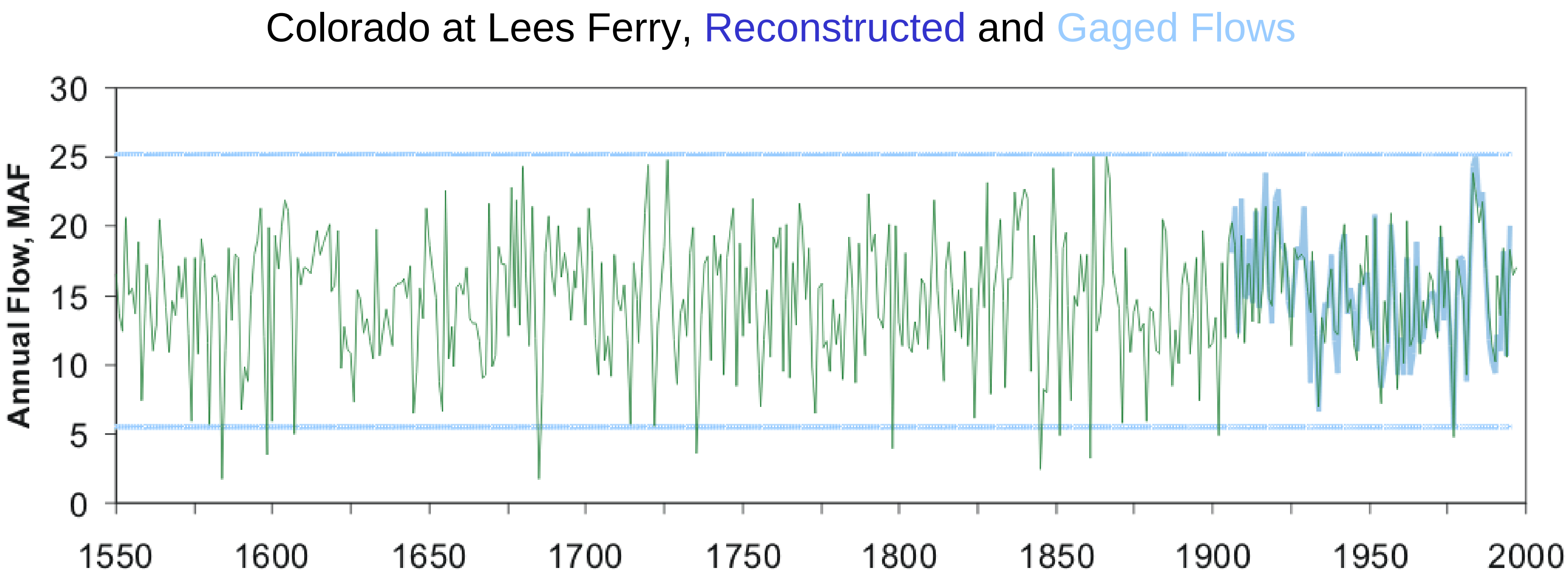
Sensitivity to just about everything – the “Lees Ferry 5”



Stockton-Jacoby (1976), Michaelson (1990), Hidalgo (2001)
– data through 1960s

Woodhouse (2006), Meko (2007)
– data through 1990s

Uncertainty related to extreme values



- Extremes of reconstructed flow not experienced in the calibration period often reflect tree-ring variations beyond the range of variations in the calibration period.
- These estimated extremes may be more uncertain than implied by RMSE

Uncertainty – final thoughts

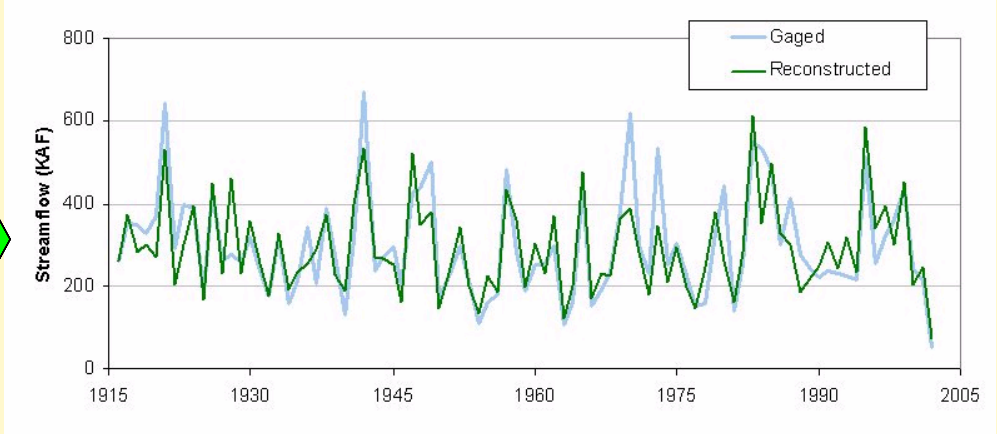
- RMSE is probably a reasonable measure of the magnitude of overall uncertainty in the reconstructions, but it should be recognized that it does not reflect all sources of uncertainty

- There is usually no one reconstruction that is the “right” one--though some may be better than others (as indicated by RE)

- A reconstruction is a *plausible estimate* of past streamflows

Part 4:

Reconstructions for the UCRB and the West



"One-stop shopping" for the western US

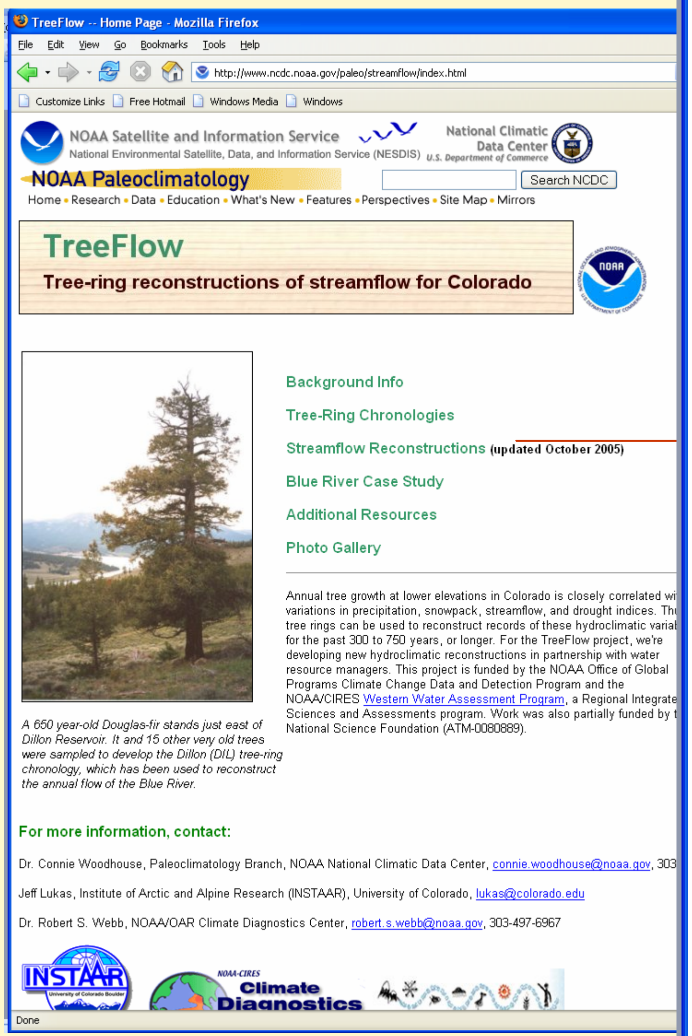
Tree-Ring Reconstructions of Streamflow for Water Management in the West

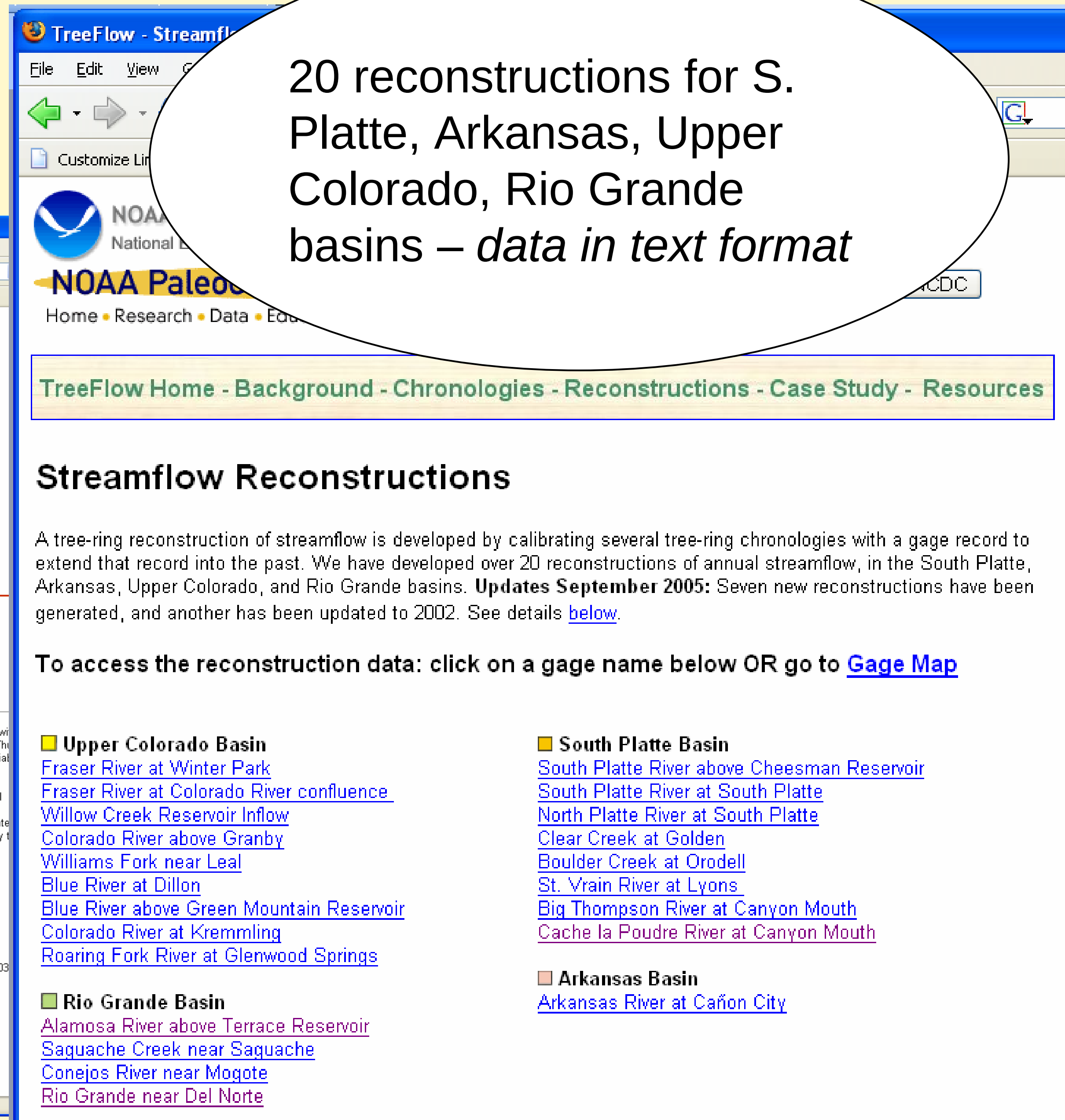
http://wwa.colorado.edu/resources/paleo/data.html

links to:

- TreeFlow for Colorado
- TreeFlow for California
- Woodhouse et al 2006 - Upper Colorado
- LTRR/Salt River Project - Lower Colorado
- NOAA World Data Center for Paleoclimatology

Colorado TreeFlow web site

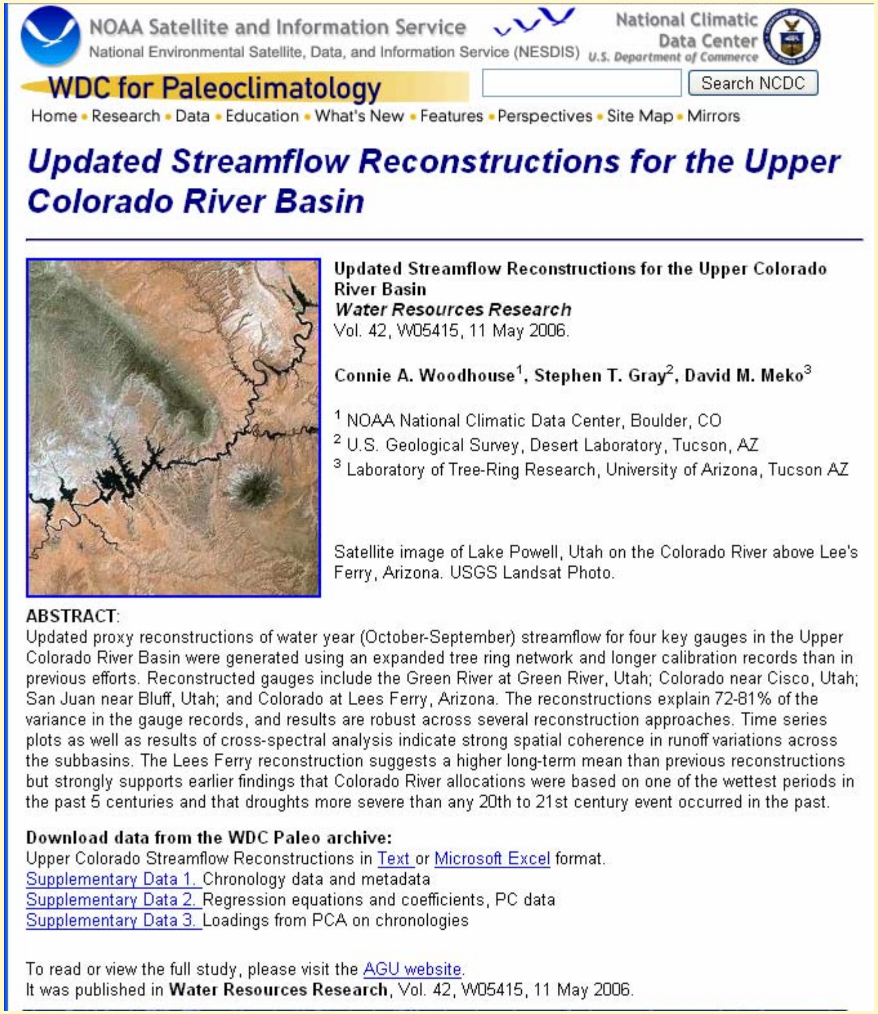




20 reconstructions for S. Platte, Arkansas, Upper Colorado, Rio Grande basins – *data in text format*

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

Woodhouse et al. 2006 - Upper Colorado River Basin



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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.

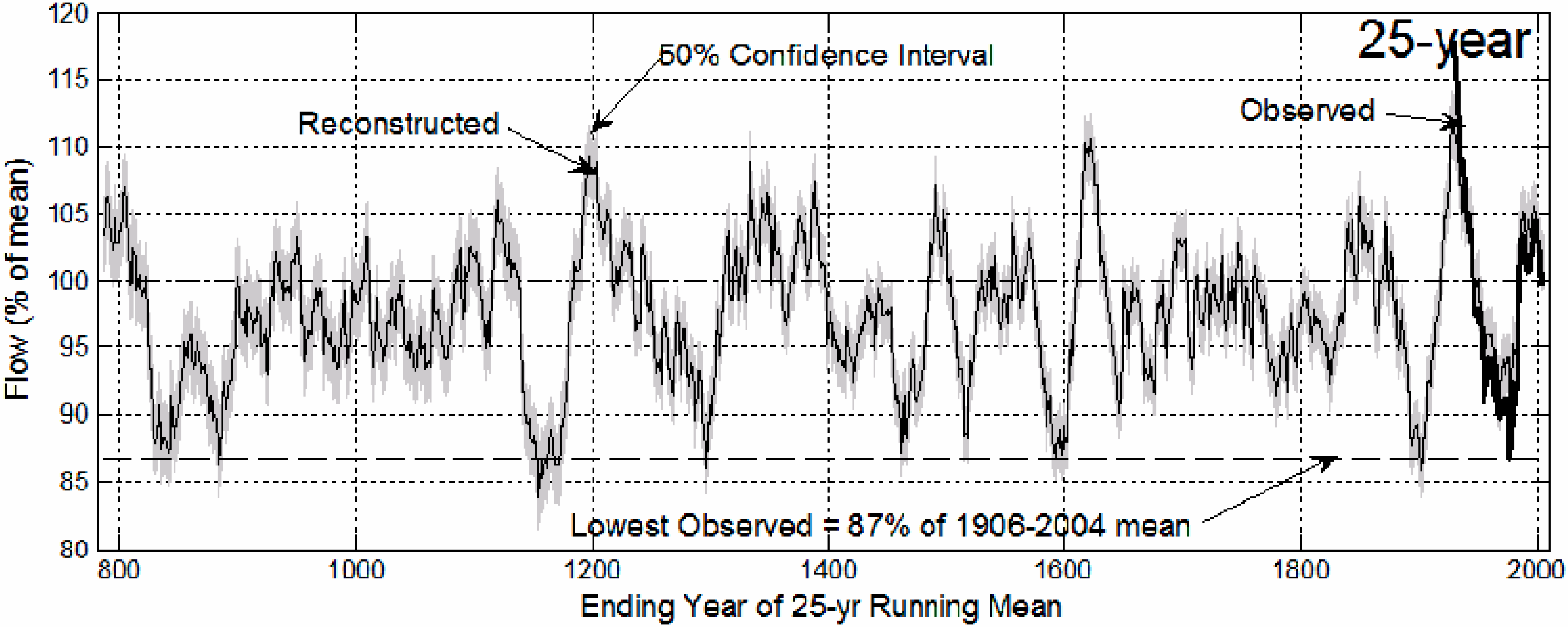
10 reconstructions for UCRB:

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

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

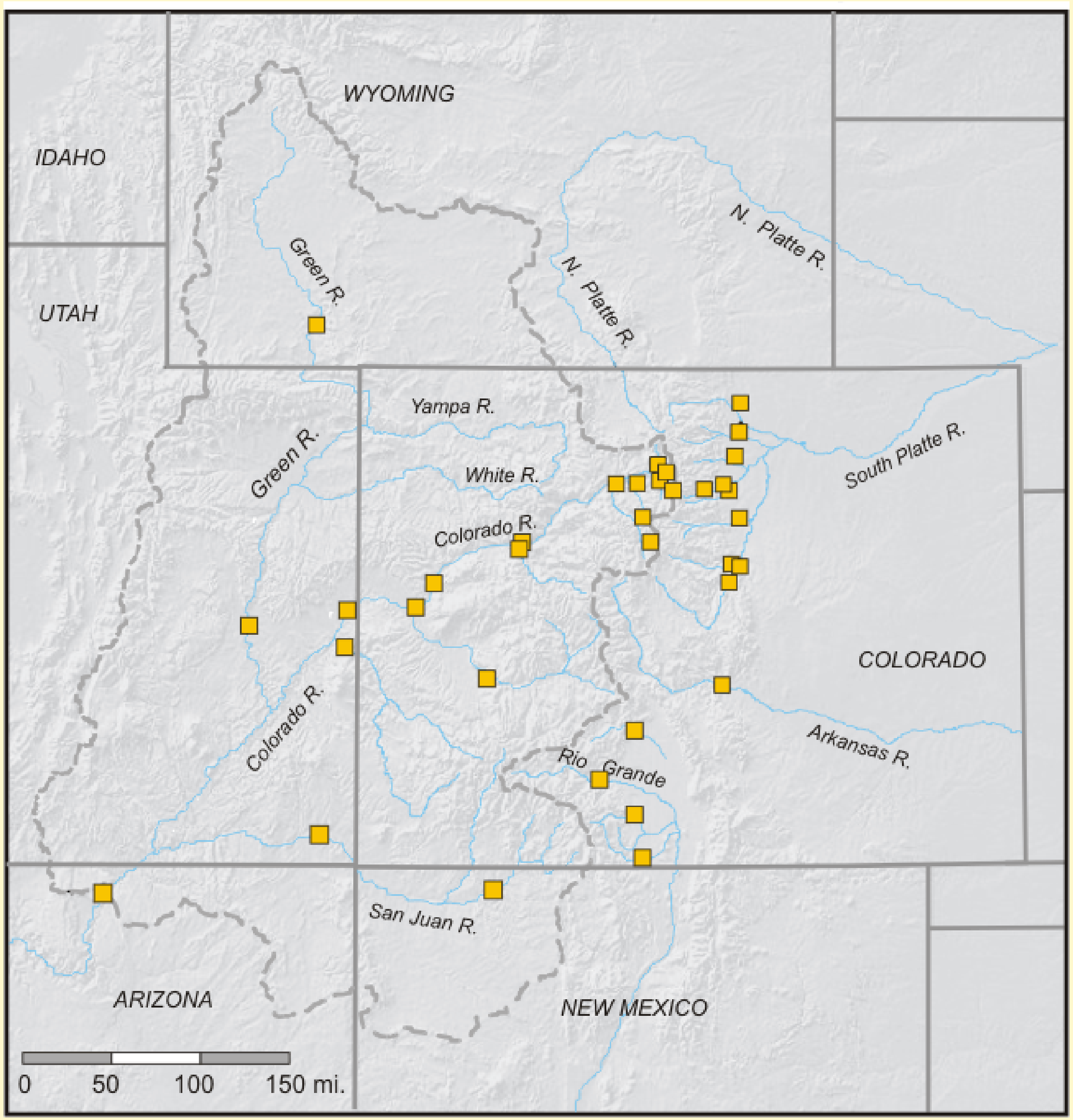


25-yr running means of reconstructed and observed annual flow of the Colorado River at Lees Ferry, expressed as percentage of the 1906-2004 observed mean.

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

Streamflow reconstructions (■) in Colorado and the upper Colorado River basin

- The reconstructions explain 60-81% of the variance in the gaged records
- All are 350-700 years long except new Lees Ferry (1244 yrs)



LTRR/Salt River Project - Lower Colorado Basin

Synchronous Extreme Streamflows, Upper Colorado and Salt-Verde Basins

- Salt + Verde + Tonto
- Gila at head of Safford Valley
- Salt + Tonto
- Verde

A Collaborative Project between The University of Arizona's
Laboratory of Tree-Ring Research &
The Salt River Project

http://fpnew.ccit.arizona.edu/kkh/ srp.htm, see full report

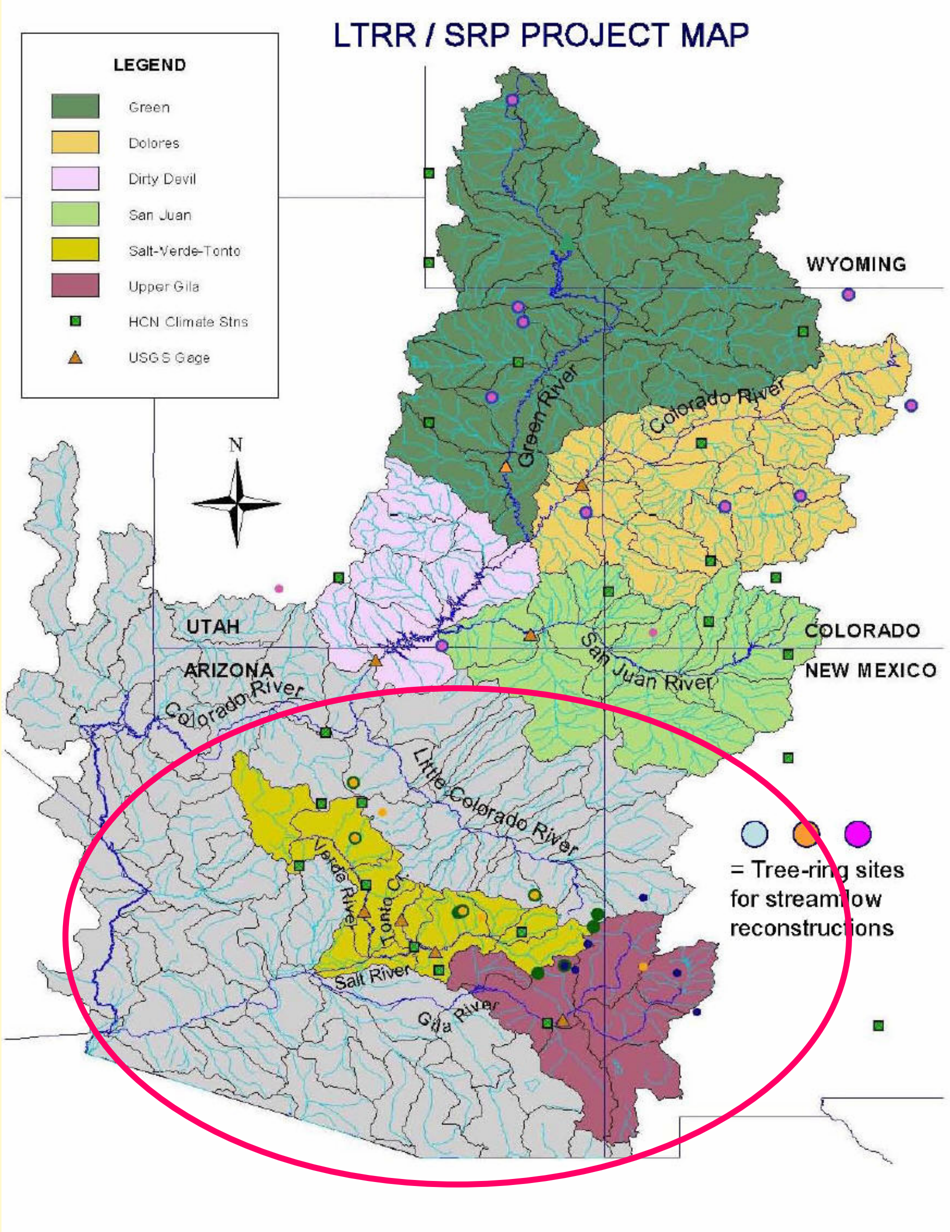
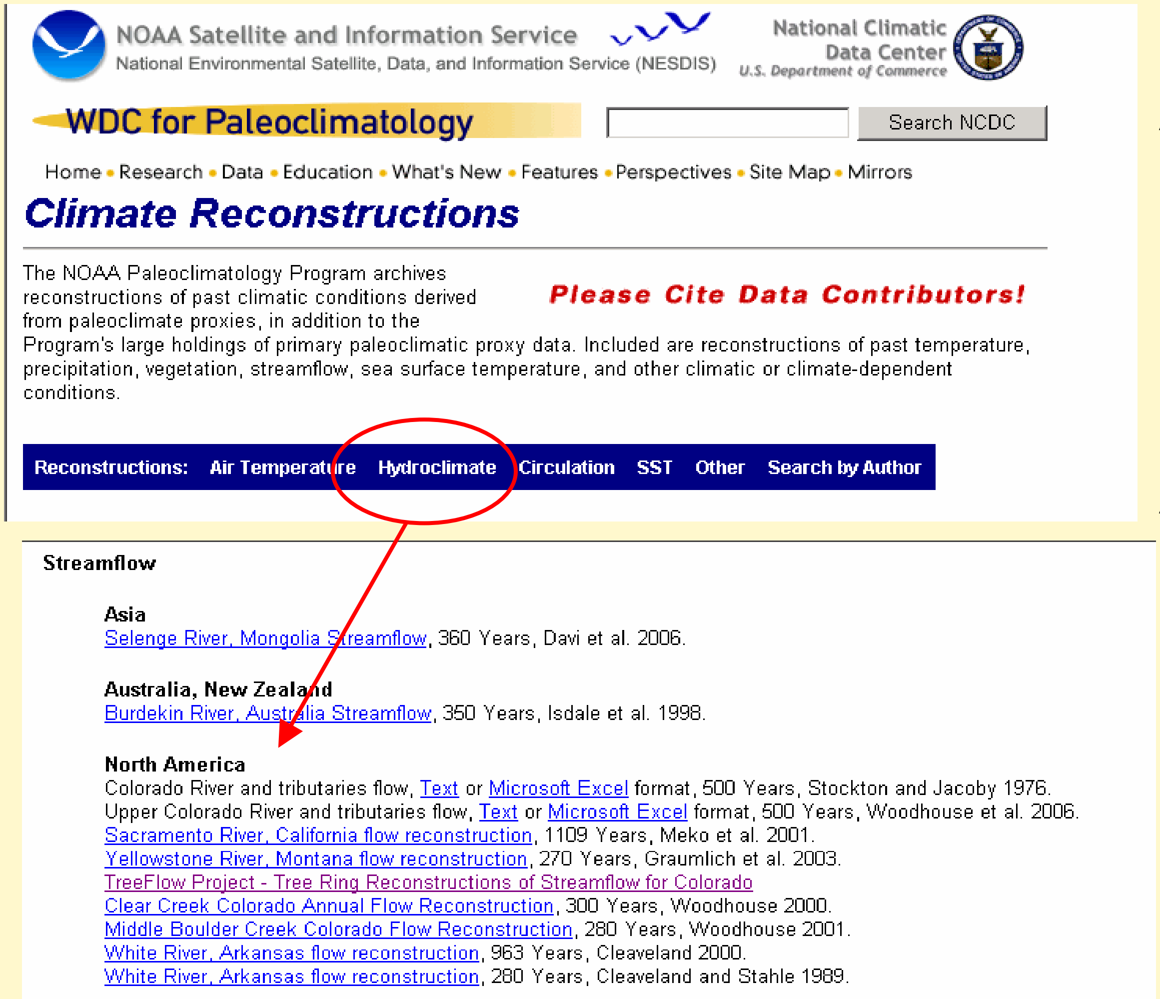


Image courtesy of K. Hirschboeck and D. Meko (U. AZ)

NOAA – National Climatic Data Center
World Data Center for Paleoclimatology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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

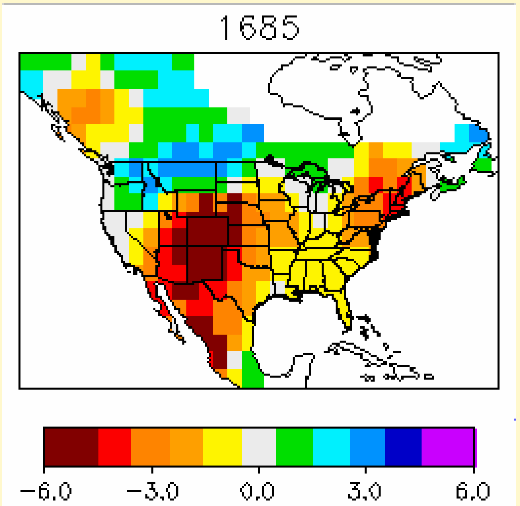
North America gridded summer PDSI reconstructions – Cook et al.

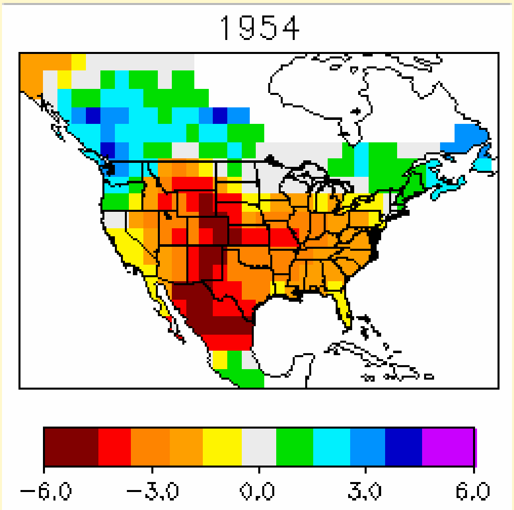
Reconstructions for

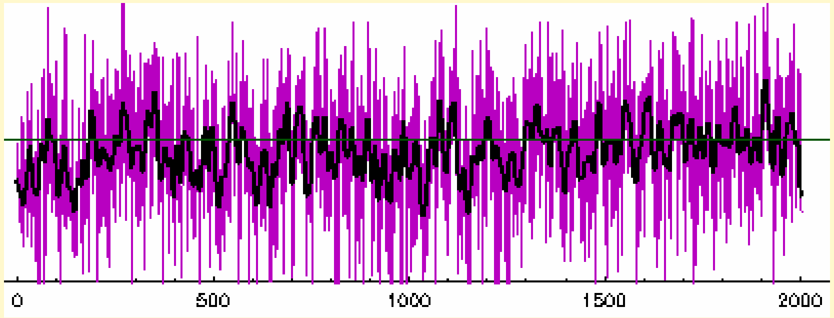
each of 286 points on
2.5-degree grid

Products:

- Maps of PDSI over much of N. America for a given year
- PDSI time-series for each gridpoint
- *Reconstruction quality varies greatly with region and over time*

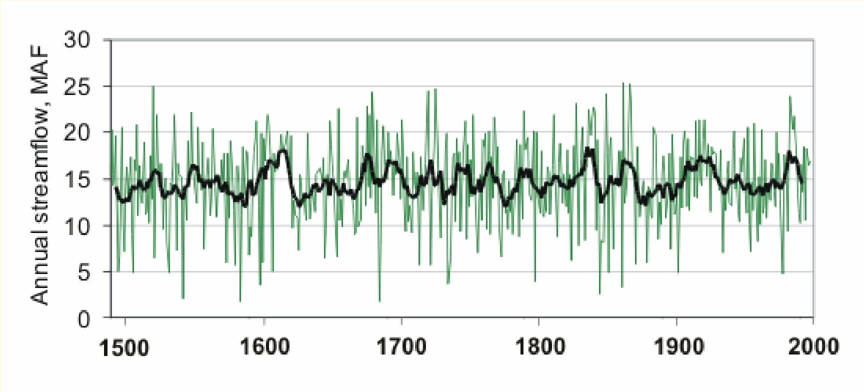






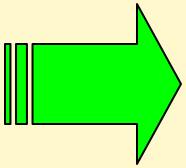
Part 5:

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



Reconstruction data

?



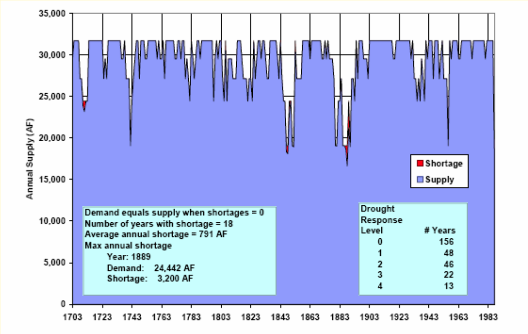


Figure 5. Demands & Supplies: 15% Reduced Flow Hydrology, Current Trends Scenario (demand = 31,700 AF/year).

Policy analysis

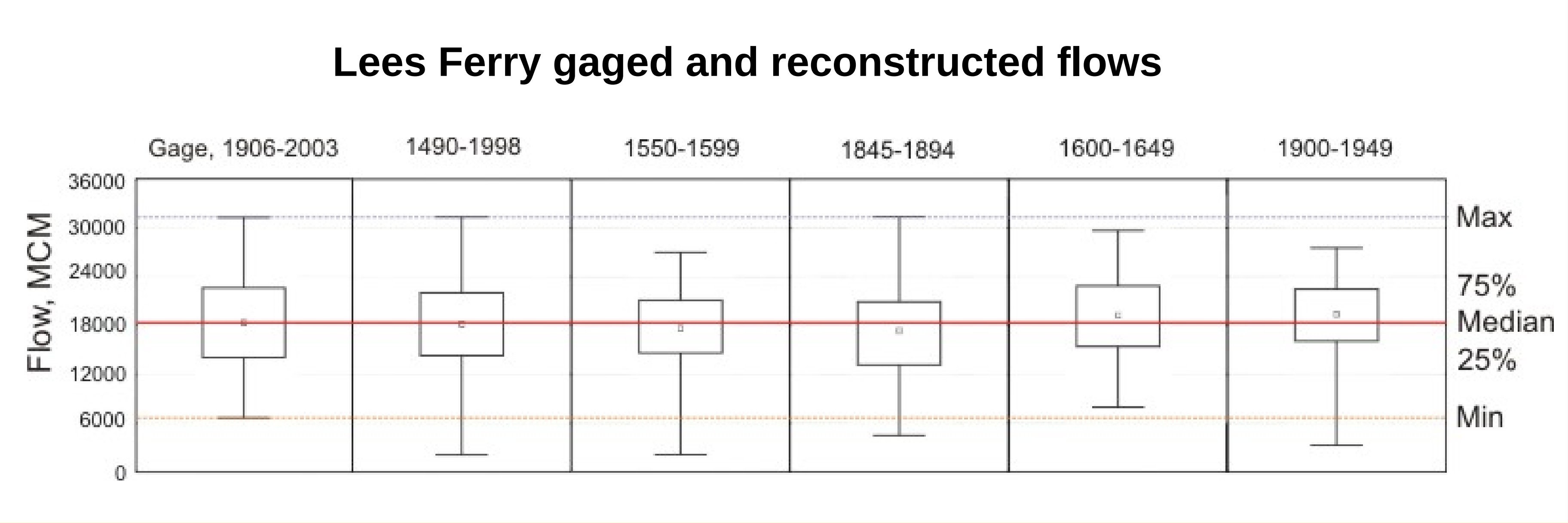
Using the reconstructions - two degrees of difficulty

- 1) Provide long-term context for the gage record
  - *can be qualitative or quantitative*

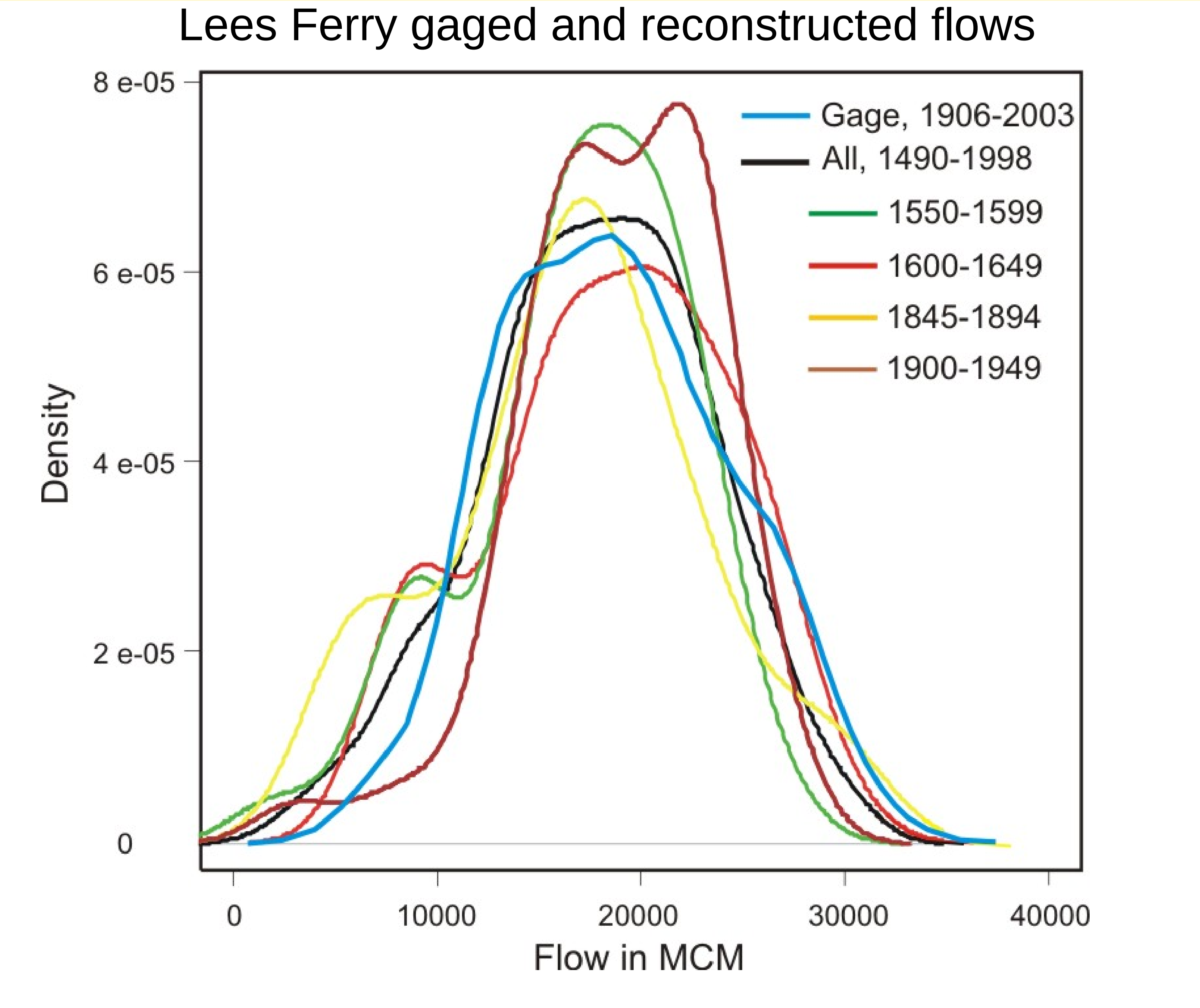
- 2) Input into a system model to assess management scenarios
  - *requires further processing of the reconstruction data*
  - *leads to more effective communication of risk*

1) Providing long-term context for the gage record

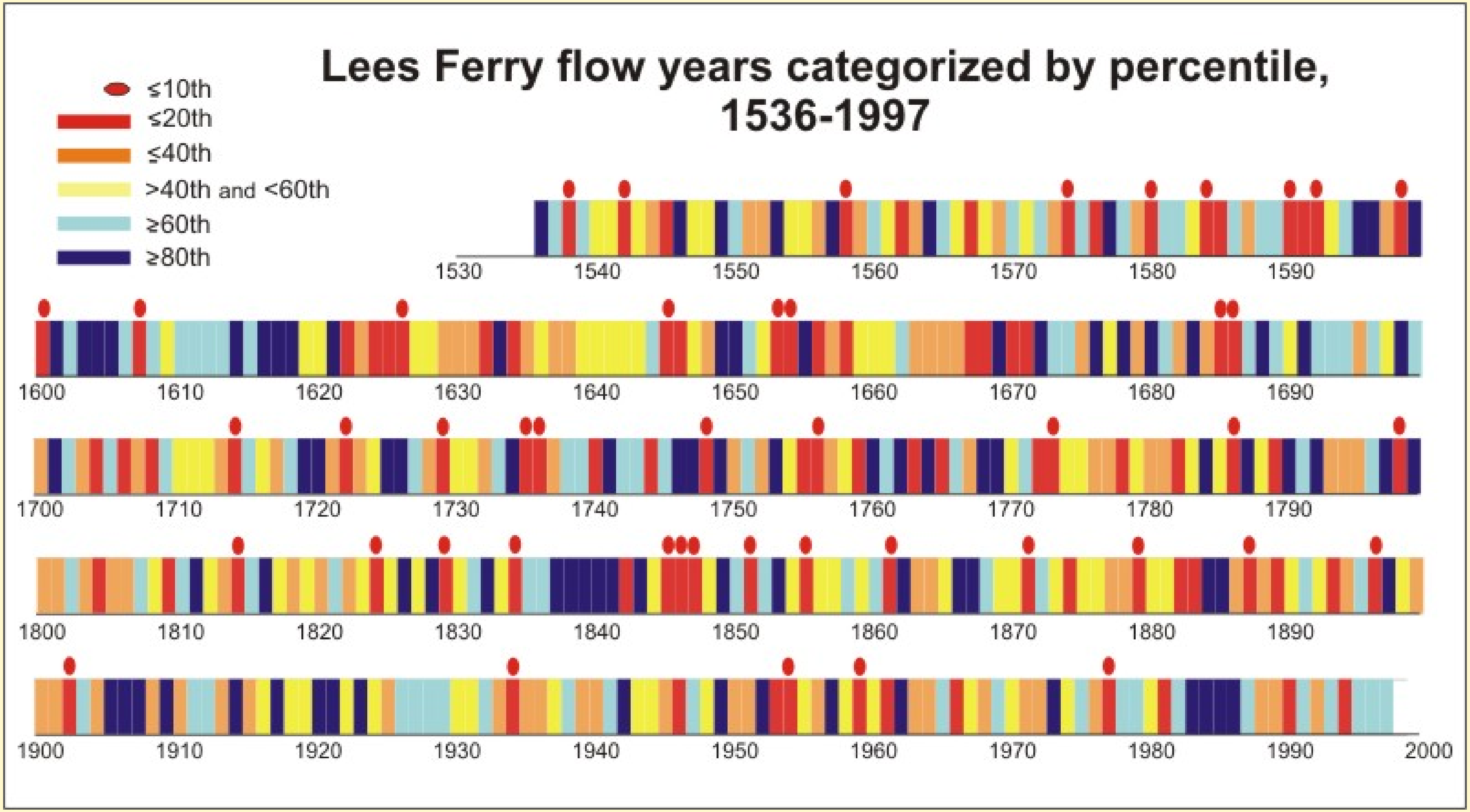
Box and whiskers plots can be used to compare the distributions of flows between the gage and reconstructed flow records



Probability density functions (PDFs) show more subtle differences in the distributions

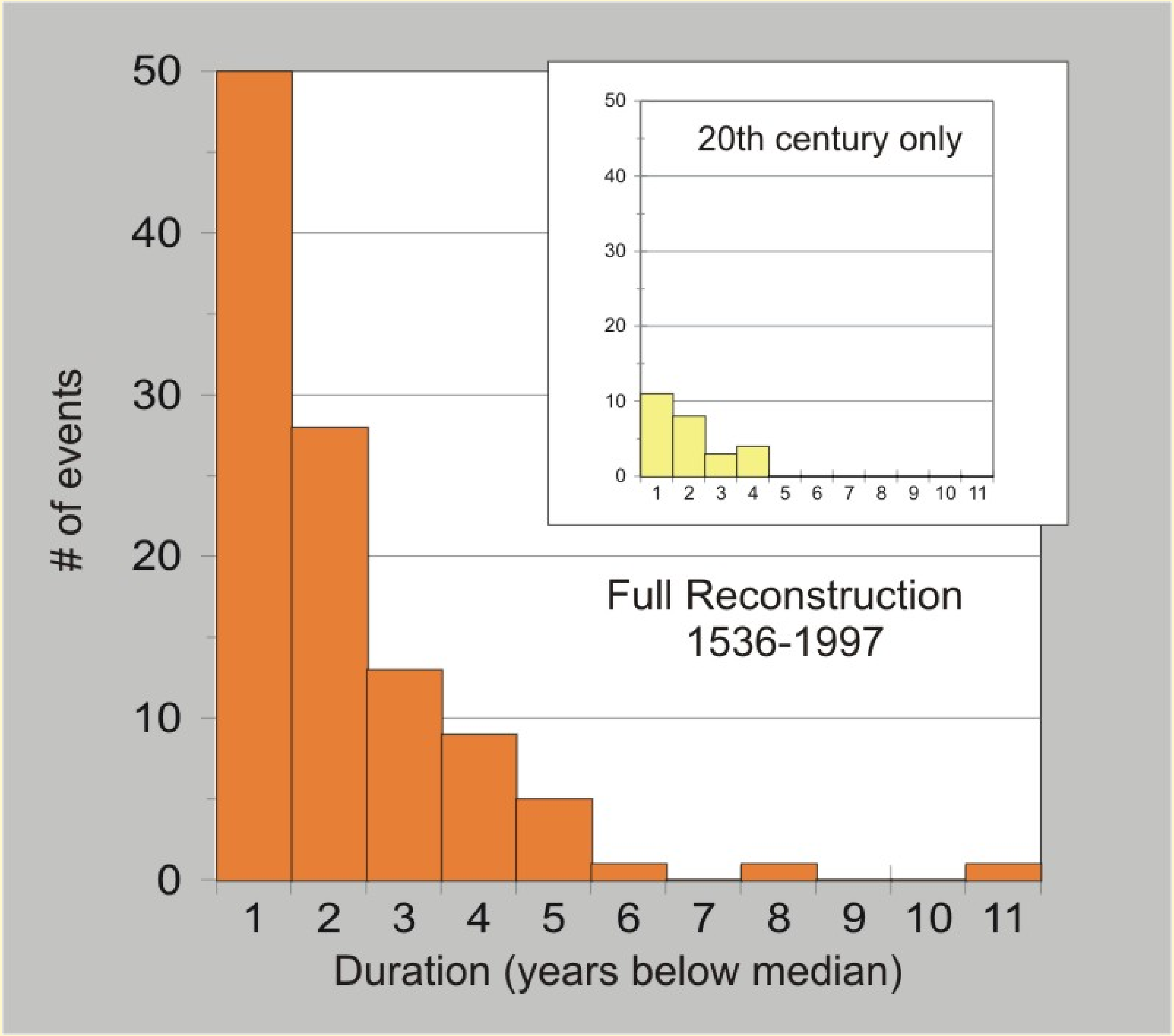


The temporal distribution or sequences of high and low flow years can also be examined



- Extreme events are not evenly distributed over time

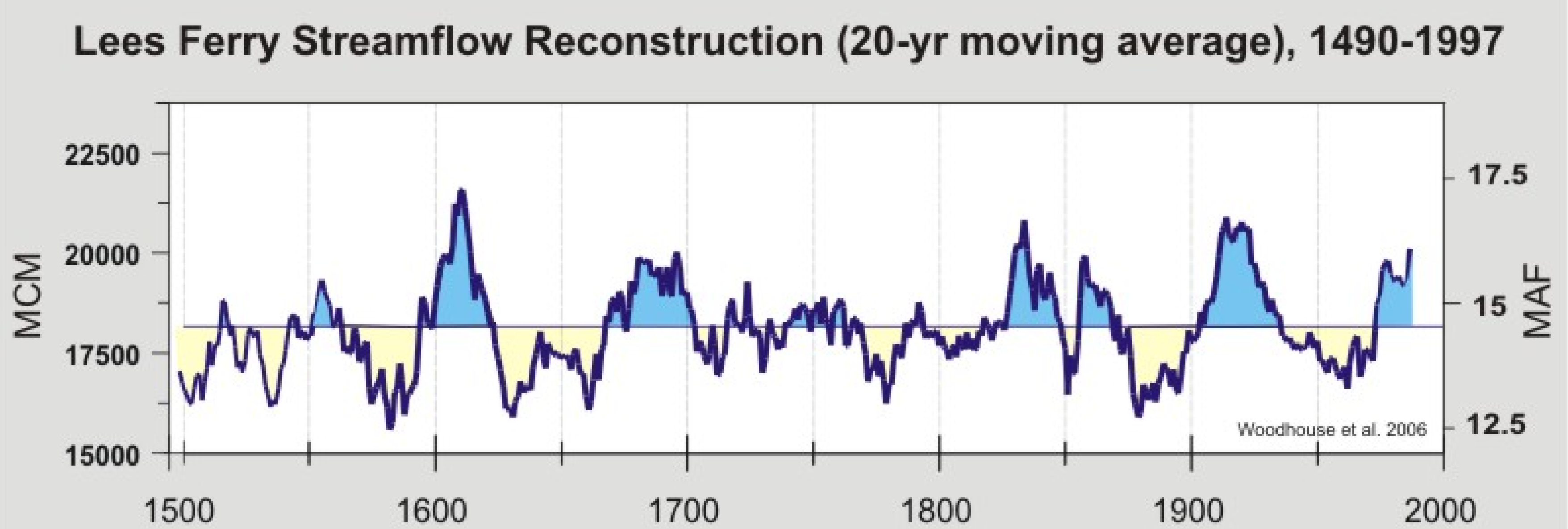
Reconstructed Lees Ferry Streamflow, 1536-1997
Drought Duration and Frequency of Drought Events



Here, drought is defined as one or more consecutive years below the long-term median.

The 20th century represents only a subset of the droughts in the full reconstruction period

A 20-year moving average shows clear decadal-scale variability The climatological community is currently addressing the question: What drives this variability?



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)

2) Reconstructions as input into models, to assess management scenarios

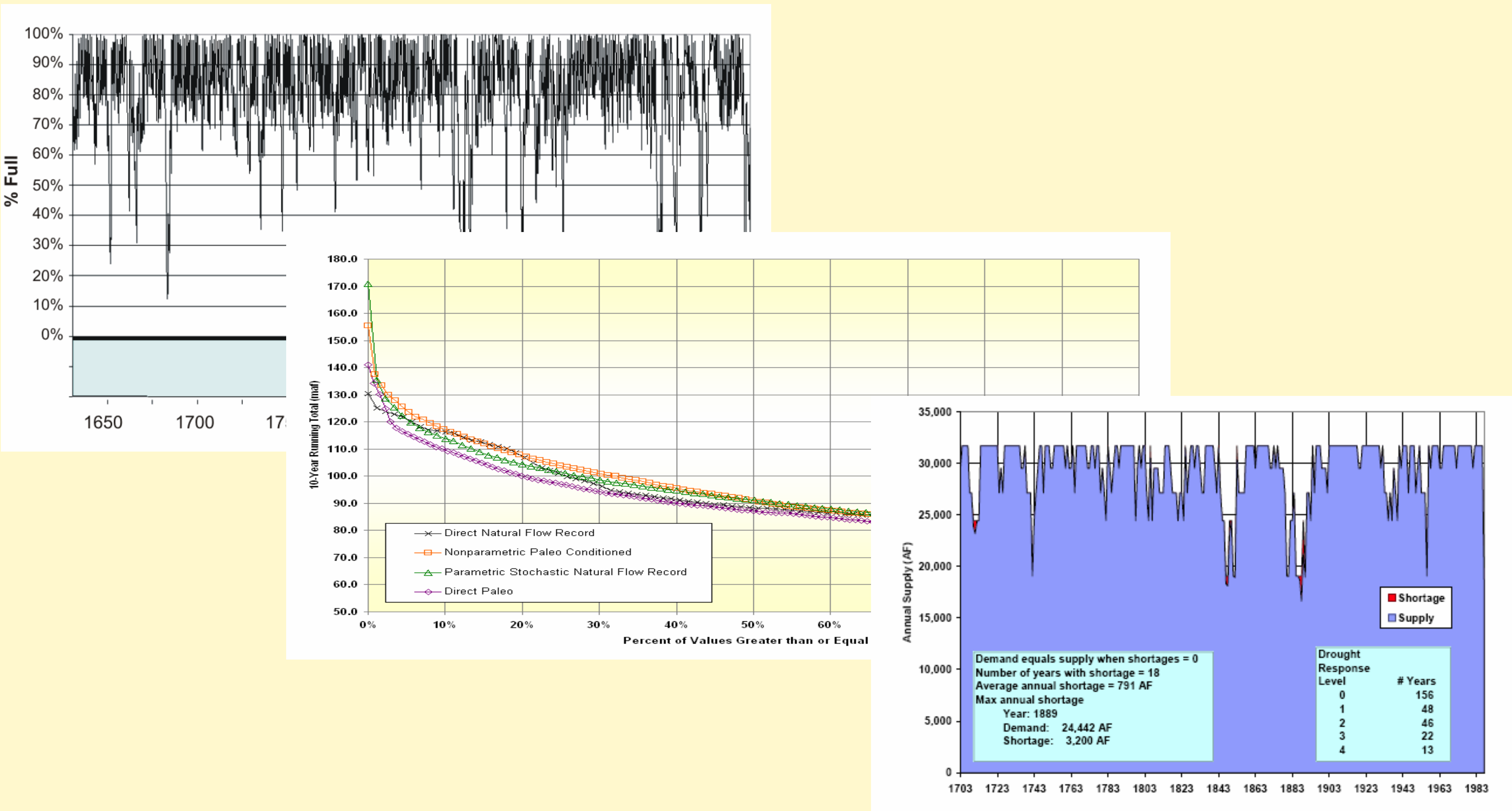
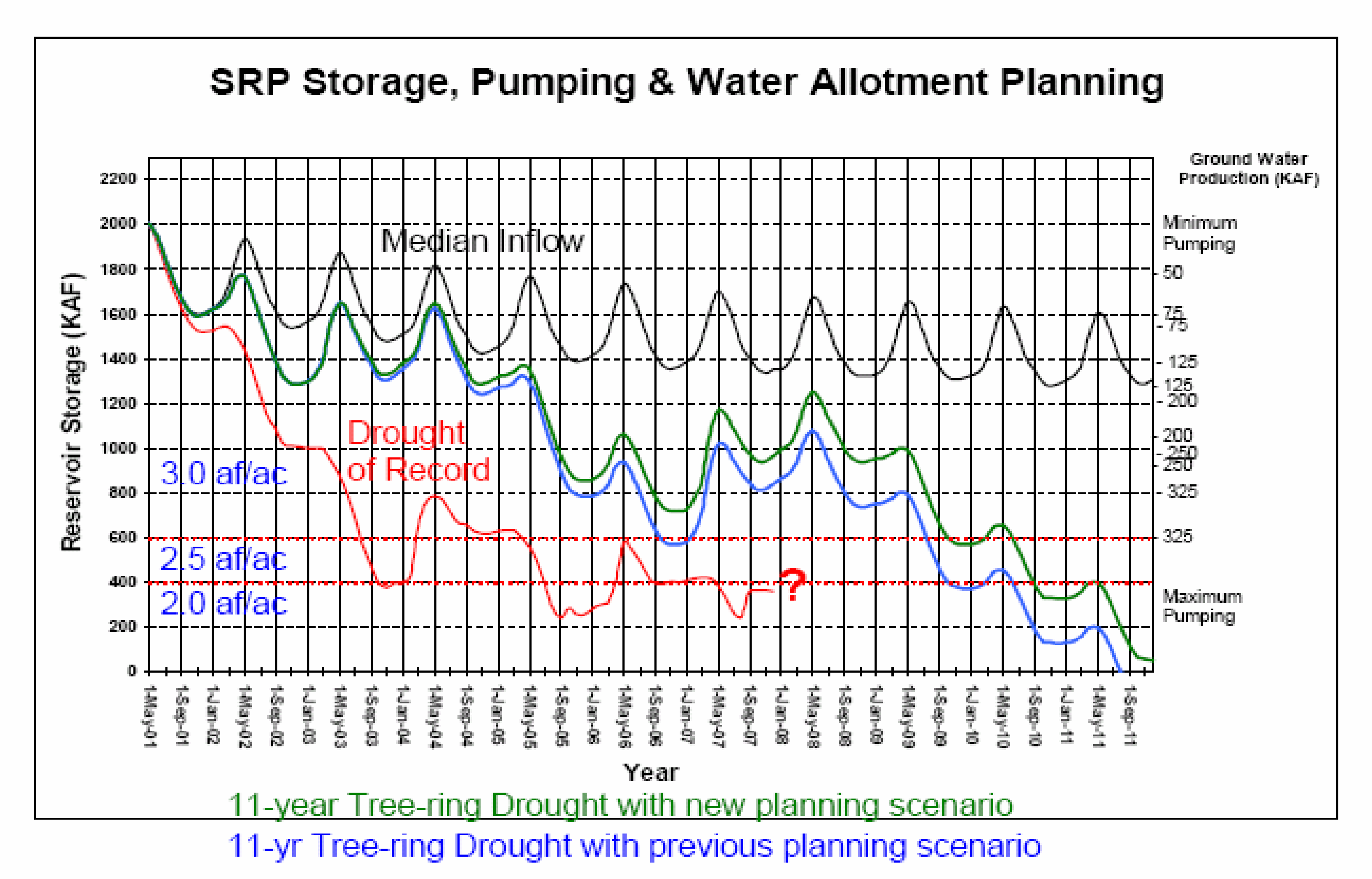


Figure 5. Demands & Supplies: 15% Reduced Flow Hydrology, Current Trends Scenario (demand = 31,700 AF/year).

Salt River Project, AZ - test of allotment/pumping strategy

- SRP recognized that the 1950s design drought (6 years) was shorter than the worst expected future droughts
- An 11-year reconstructed drought in the Salt-Verde-Tonto basin (1575-1585) was used to test SRP’s current allotment and pumping strategy
- Simple model, using annual inflows, was used

Salt River Project, AZ - test of allotment/pumping strategy



- The 11-year drought reduced reservoir storage to zero in year 11 (blue)
- A slight change in the allotment/pumping scenario increased it above zero (green)

Denver Water - water supply yield analyses

Challenge:

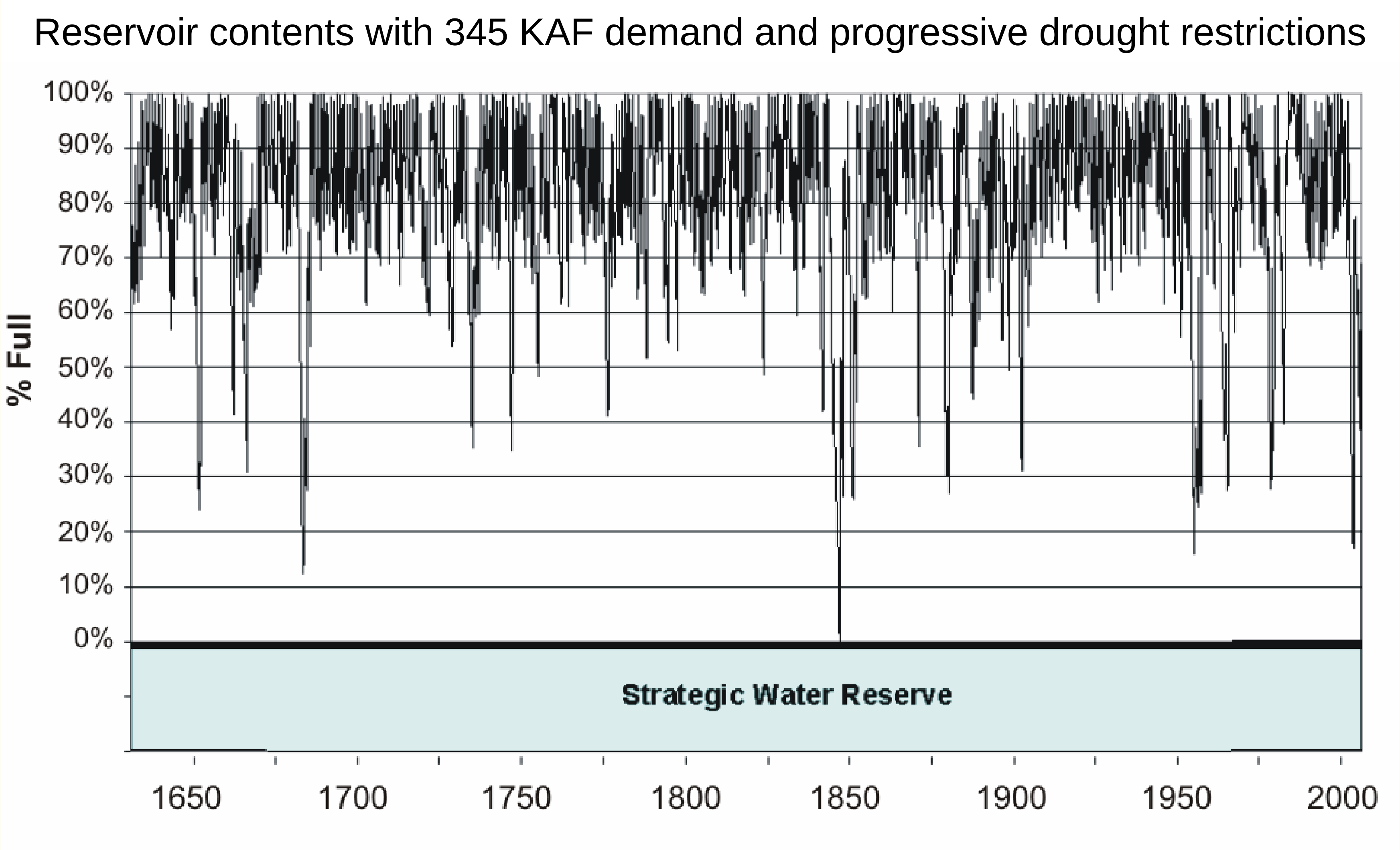
Denver Water's Platte and Colorado Simulation Model (PACSM) requires daily model input from 450 locations

Solution:

An "analogue year" approach

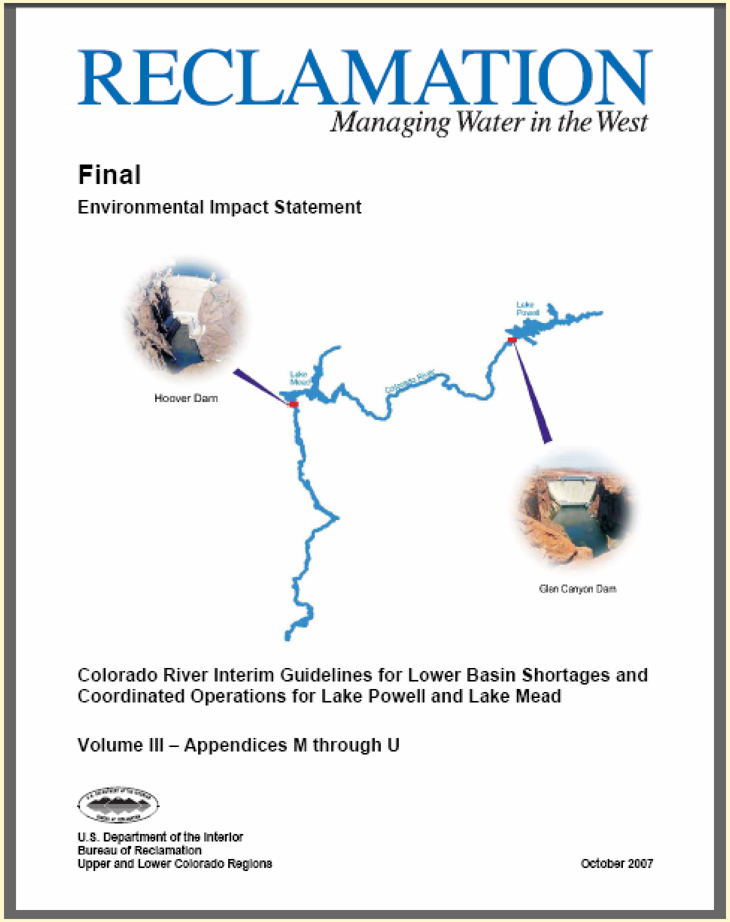
- Match each year in the reconstructed flows with one of the 45 model years (1947-1991) with known hydrology (e.g., 1654 is matched with 1963), and use that year's hydrology.
- Years with more extreme wet/dry values are scaled accordingly
- Data are assembled as new sequences of model years
- PACSM is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

Reclamation - analyses for Colorado River Shortage EIS



Appendix N

Analyses of Hydrologic Variability Sensitivity

"…performed to evaluate the potential effects to the hydrologic resources of alternative hydrologic inflow sequences."

Jim Prairie, Reclamation

Reclamation - analyses for Shortage EIS

Challenges:

1) Skepticism of reconstructed flow magnitudes, more trust in reconstructed system states

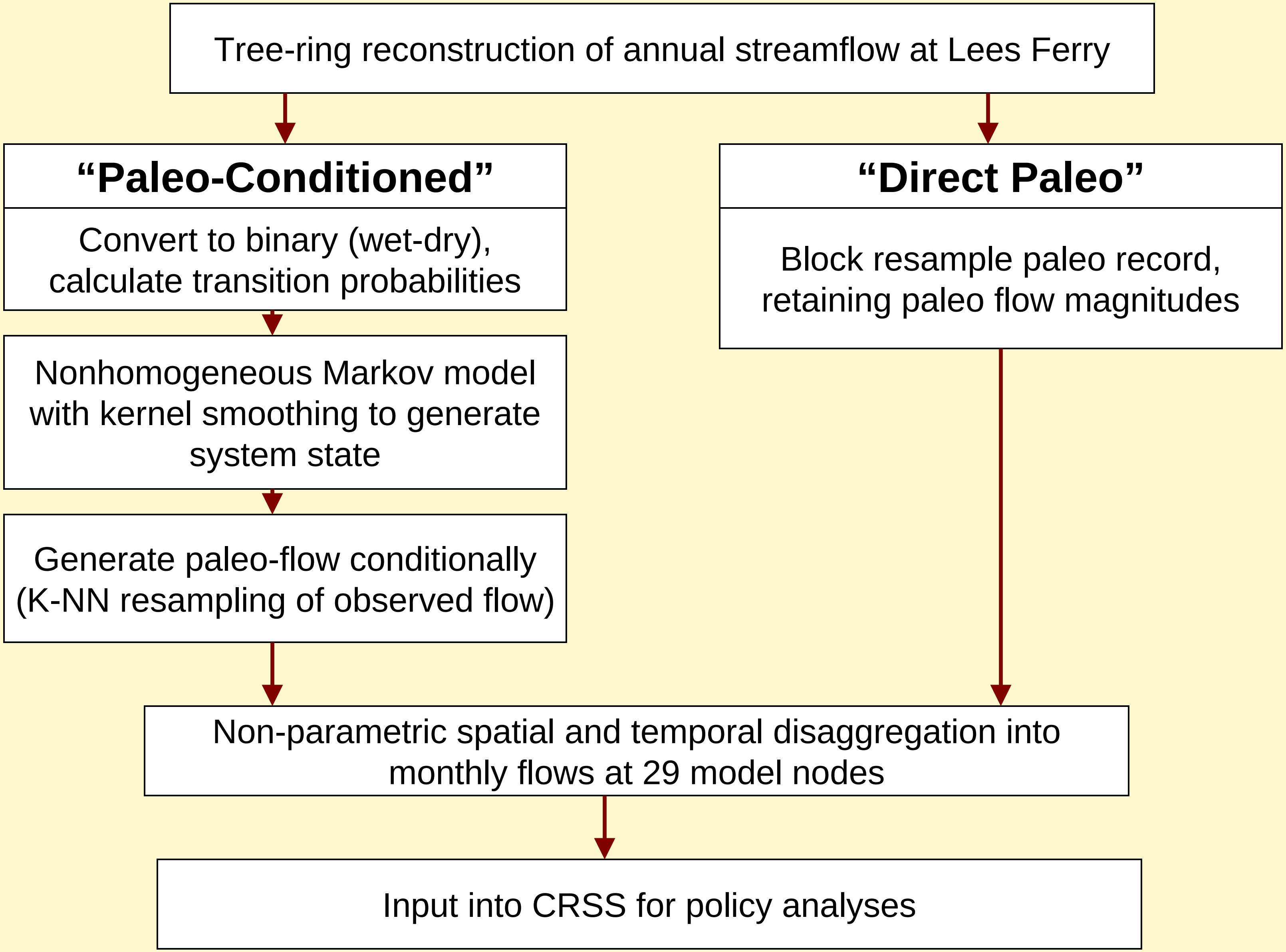
2) CRSS model requires monthly inputs at 29 model nodes

Solutions:

1) 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

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

Flowchart of paleohydrologic analyses



Adapted from Jim Prairie, Reclamation

Advantages of paleo-conditioned hydrology

- Combines strengths of
  - Reconstructed paleo streamflows: system state
  - Observed streamflows: flow magnitudes
- Develops a rich variety of streamflow sequences
  - Generates sequences not in the observed record
  - Generates drought and surplus characteristics of paleo period
- Transition Probability Matrix provides flexibility
  - Use TPM to mimic climate signal (e.g., PDO)
  - Generate drier or wetter than average flows

Disadvantages

- Precludes generation of single-year flows more extreme than those in the observed record
- Reinforces perceptual bias against paleo-magnitude information

Adapted from Jim Prairie, Reclamation

Hydrologic sensitivity runs in CRSS

4 hydrologic inflow scenarios

1) ISM - Observed flow (1906-2004)

- **99 traces**

2) Direct Paleo flow (1490-1997) (Woodhouse et al., 2006)

- **508 traces**

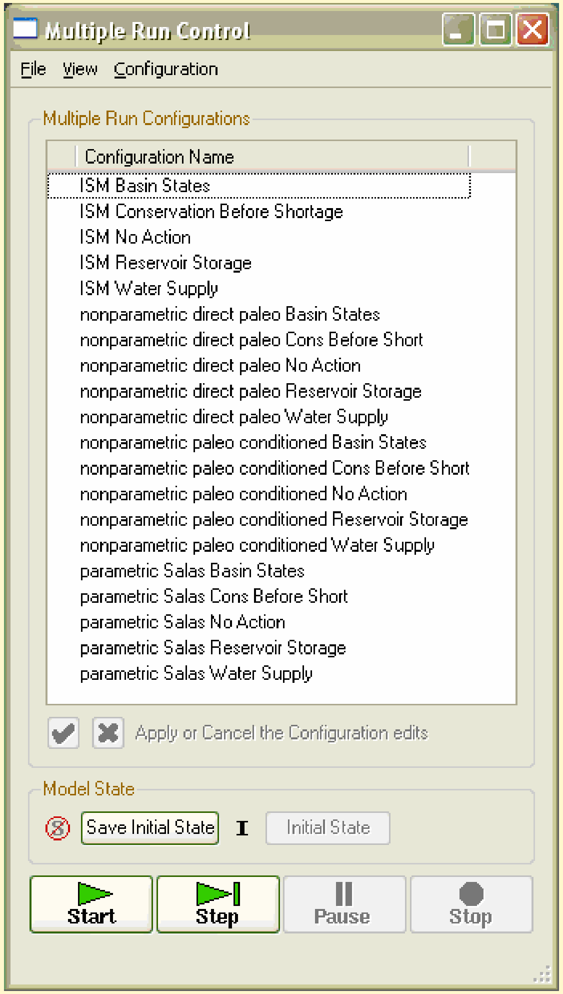
3) Paleo-conditioned (Prairie, 2006)

- **125 traces**

4) Parametric stochastic (Lee et al., 2006)

- **100 traces**

- All 4 inflow scenarios were run for each management alternative

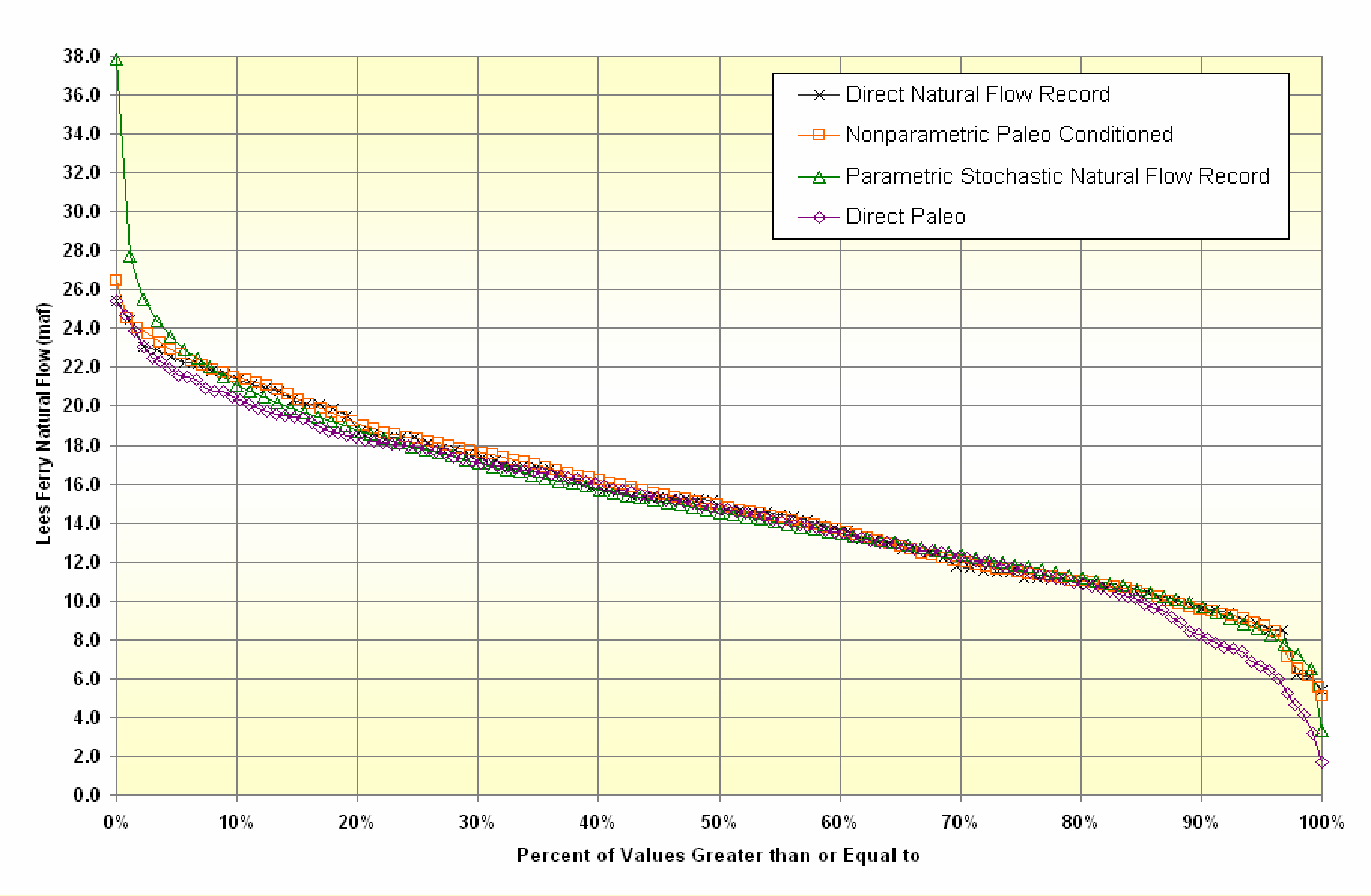


Adapted from Jim Prairie, Reclamation

CRSS output from Appendix N

Annual Natural Flow at Lees Ferry

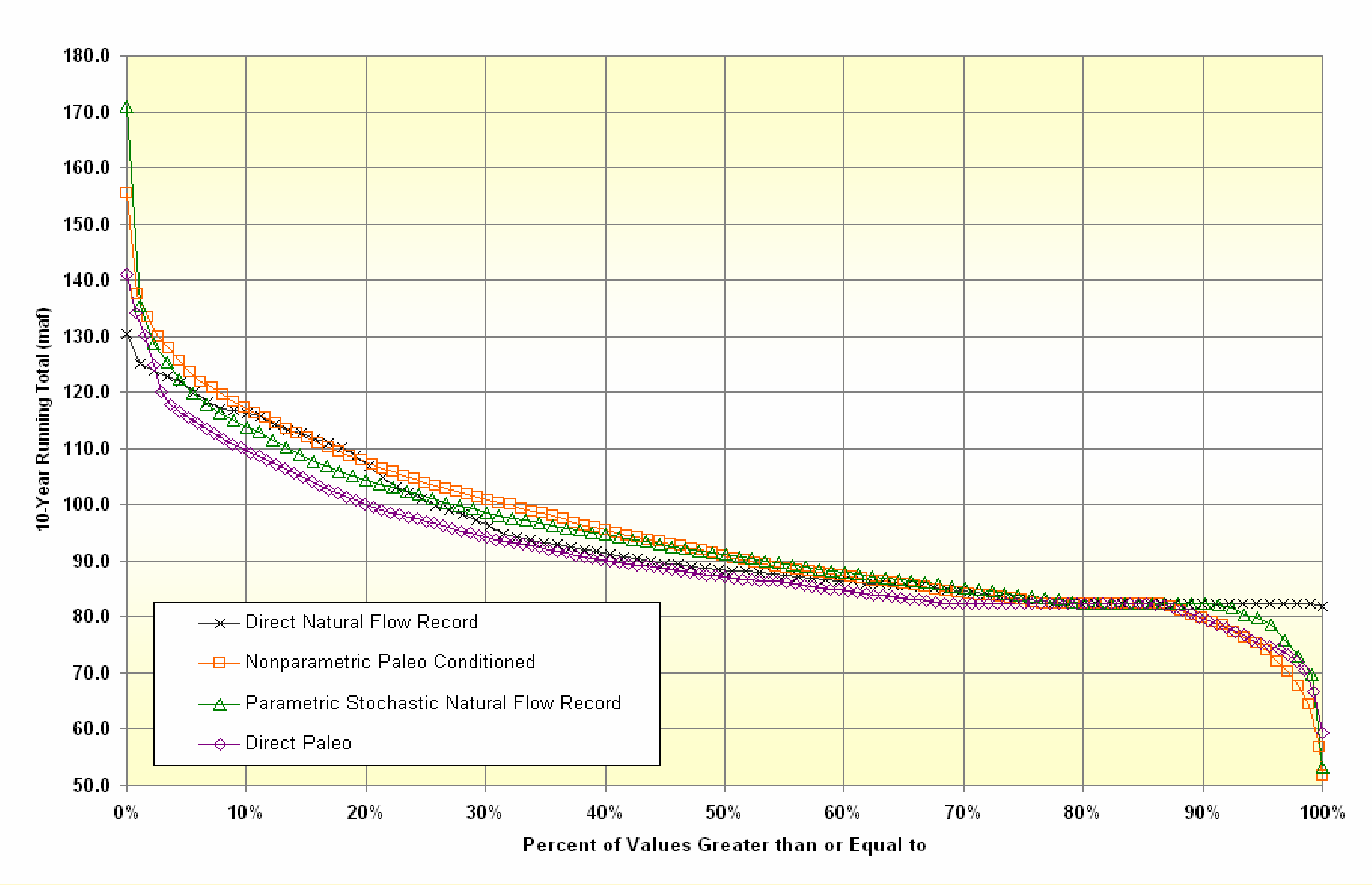
No Action Alternative, *Years 2008-2060*



CRSS output from Appendix N

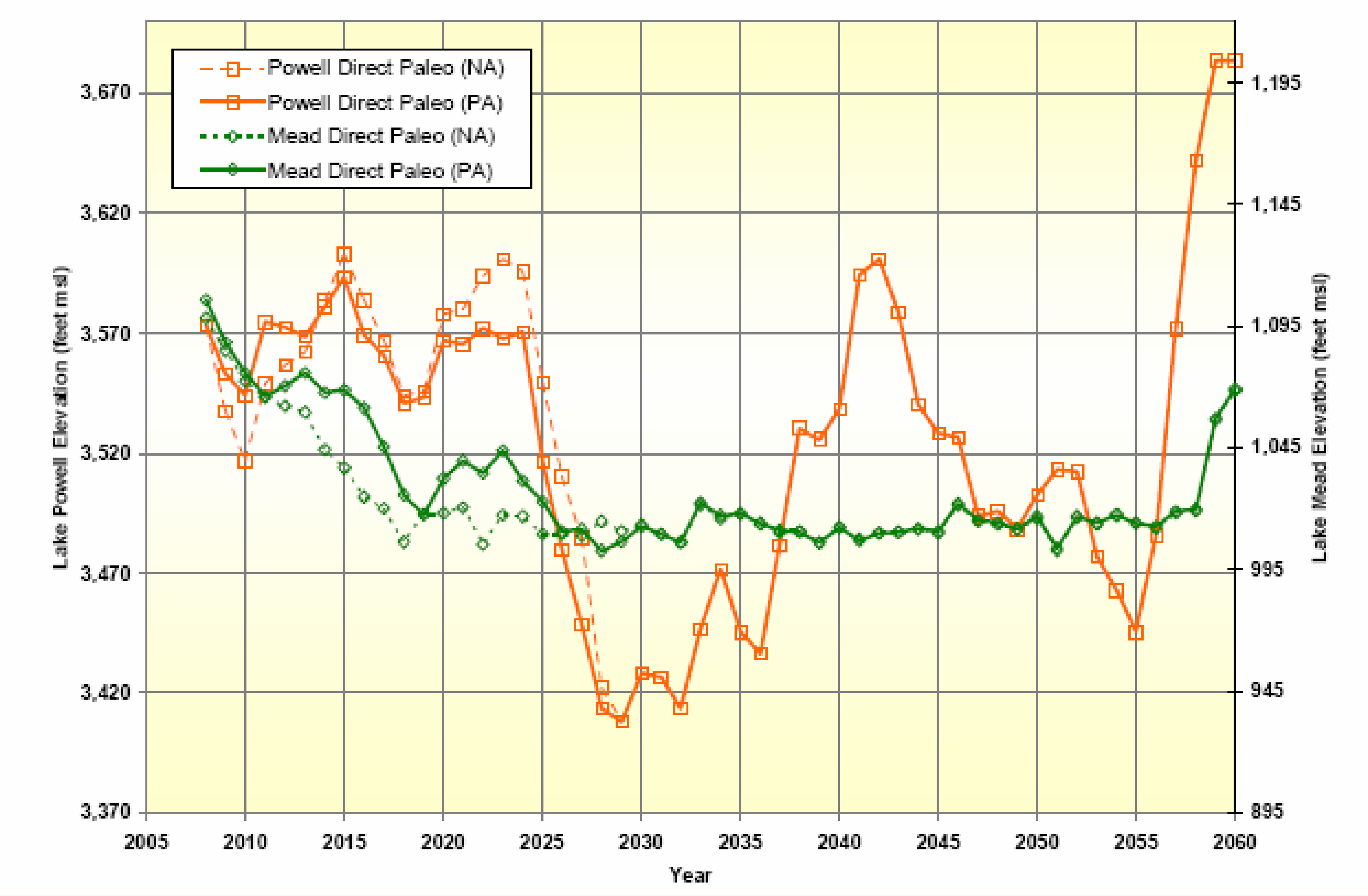
Glen Canyon 10-Year Release Volume

No Action Alternative, *Years 2008-2060*



CRSS output from Appendix N

Powell (orange) and Mead (green) year-end elevations
No Action (dashed) and Preferred Alternative (solid), ***Years 2008-2060***
Direct Paleo based on Meko et al., yrs 1130-1182

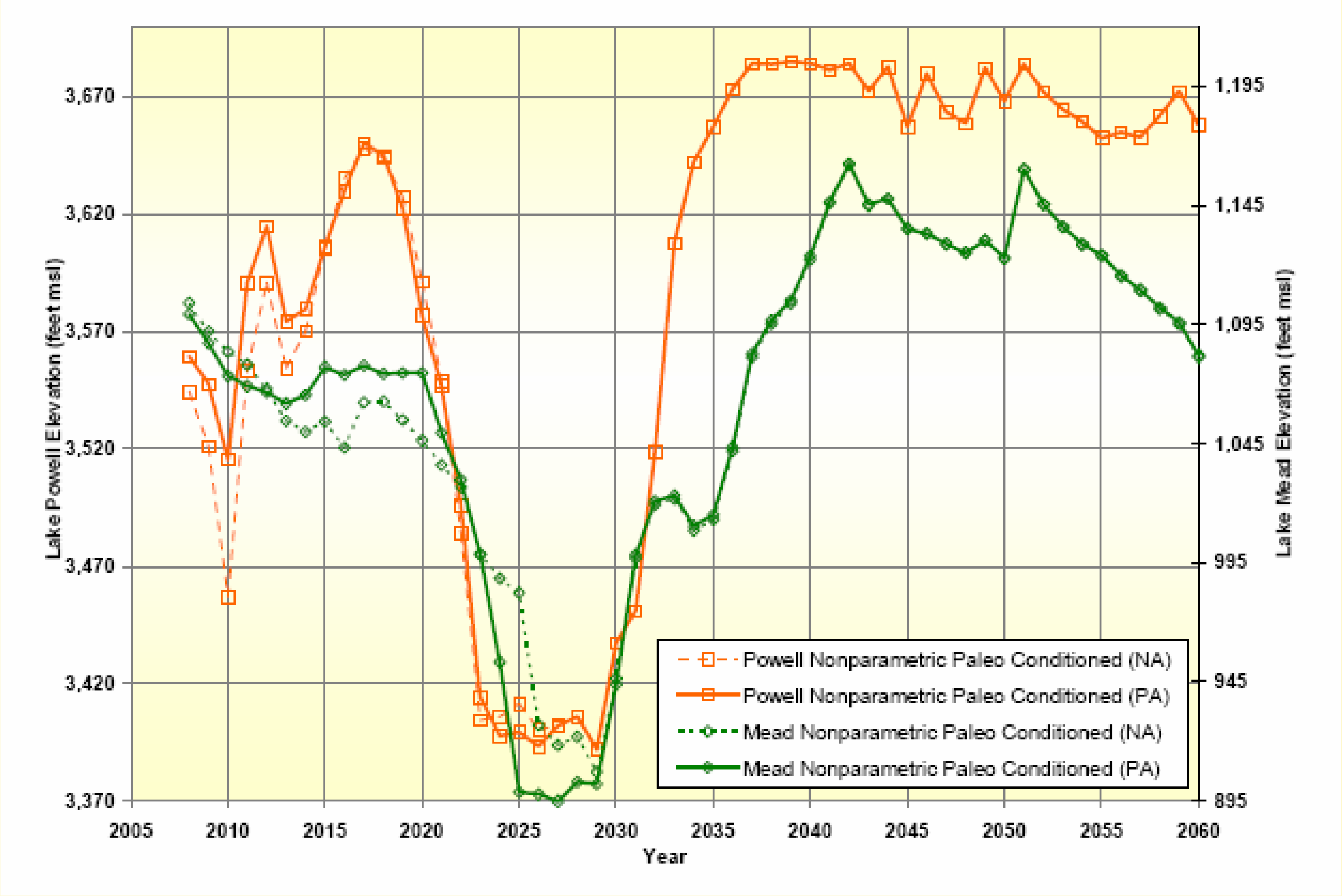


CRSS output from Appendix N

Powell (orange) and Mead (green) year-end elevations

No Action (dashed) and Preferred Alternative (solid), ***Years 2008-2060***

Paleo-conditioned based on Meko et al., run 50 (worst-case)

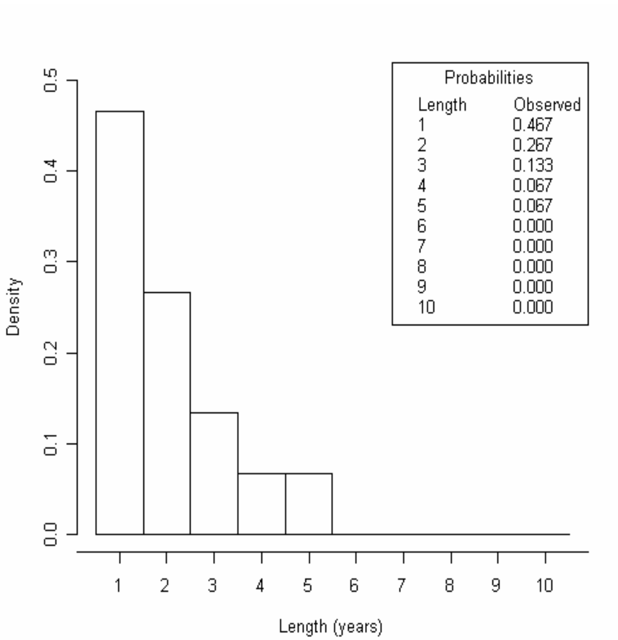


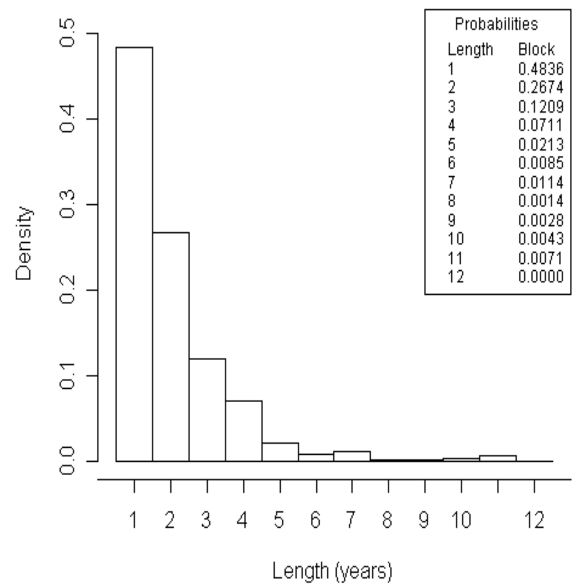
Reclamation – analyses for Gunnison Basin EIS

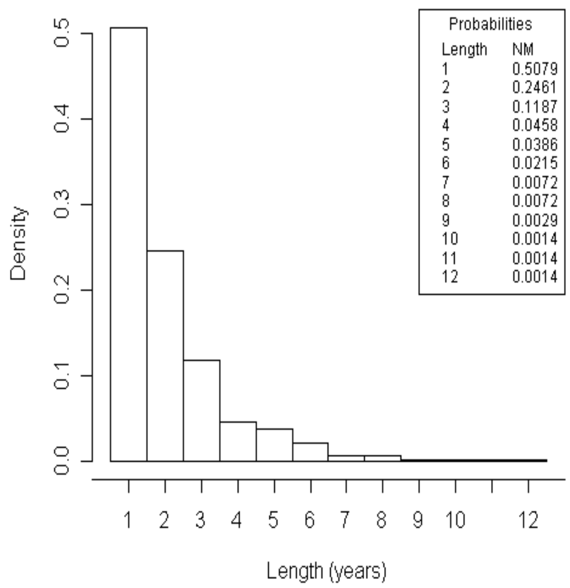
- Observed hydrology: 1937-1997
- Tree-ring reconstruction: 1569-1997 (Woodhouse et al. 2006)
- Paleo-conditioning technique used, with two variants, to generate alternative hydrologies:
    - Non-homogeneous Markov Chain – transition probabilities used to generate binary sequences
    - Block sampling – 30 year binary blocks resampled from paleo record
- Analyses completed, but won't be included in EIS

Reclamation – analyses for Gunnison Basin EIS

PDF - Drought Length







Observed	Paleo – Block	Paleo - NHMC
max - 5 yrs	max – 11 yrs	max – 12 yrs

Adapted from Ken Nowak, CU and Jim Prairie, Reclamation

OK, so paleo provides a bigger window on past hydrology, but what about the future?

GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L22708, doi:10.1029/2007GL031764, 2007

Click Here for Full Article

Warming may create substantial water supply shortages in the Colorado River basin

Gregory J. McCabe[1] and David M. Wolock[2]

Received 21 August 2007; revised 19 October 2007; accepted 25 October 2007; published 27 November 2007.

[1] The high demand for water, the recent multiyear drought (1999–2007), and projections of global warming have raised questions about the long-term sustainability of water supply in the southwestern United States. In this study, the potential effects of specific levels of atmospheric warming on water-year streamflow in the Colorado River basin are evaluated using a water-balance model, and the results are analyzed within the context of a multi-century tree-ring reconstruction (1490–1998) of streamflow for the basin. The results indicate that if future warming occurs in the basin and is not accompanied by increased precipitation, then the basin is likely to experience periods of water supply shortages more severe than those inferred from the long-term historical tree-ring reconstruction. Furthermore, the modeling results suggest that future warming would increase the likelihood of failure to meet the water allocation requirements of the Colorado River Compact.

substantially since the Compact was written [*Diaz and Anderson*, 1995].

[4] The long-term sustainability of the water-supply system in the Colorado River basin will be affected by the future levels of natural flows that replenish the reservoirs. One approach to defining future expectations of flow is to "reconstruct" historical long-term flow estimates from tree rings [*Woodhouse et al.*, 2006]. This long-term historical context provides an indication of flow conditions that have occurred in the past and may occur in the future. A contrasting approach to predicting future flow conditions in the Colorado River basin is based on climate model simulations. *Christensen and Lettenmaier* [2006], for example, report 8% to 11% reductions in UCRB runoff by the end of the 21st century.

[5] The objective of this study is to evaluate the sensitivity of UCRB water supply to global warming by using a

Anthropogenic warming will likely impact future hydrology in the UCRB

- Precipitation change uncertain *(increase? decrease?)*
- Temperature increase very likely (already being observed regionally and in most locations)
  - increase in evapotranspiration
  - decrease in soil moisture
  - decreased snowpack accumulation (more precip. falls as rain)
  - increased sublimation from snowpack
  - earlier meltout of snowpack
- *Likely effects on hydrology: lower flows, earlier peak flows*
- Precipitation change could either (partly) mitigate these effects or make things worse

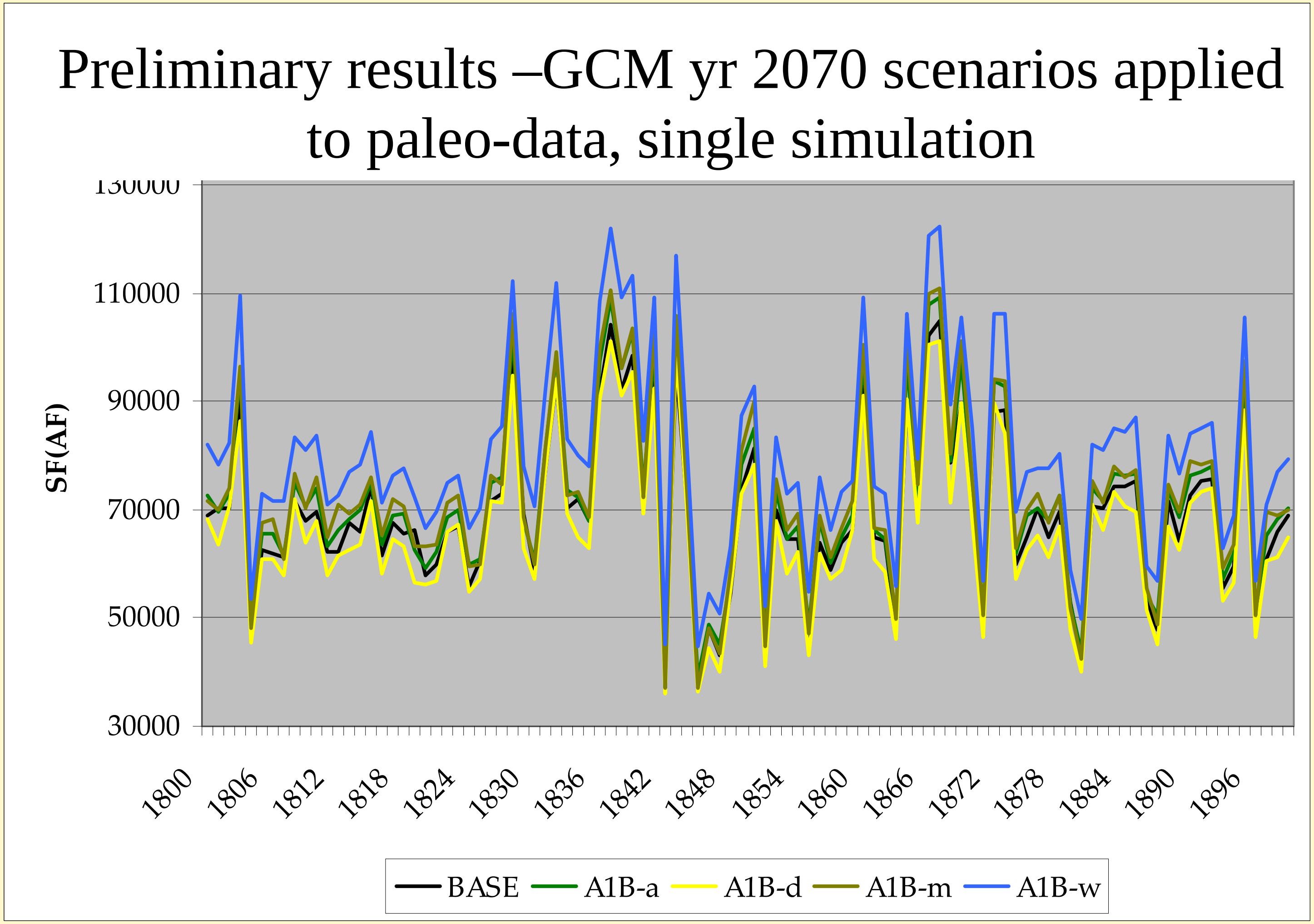
So how can the past (tree-ring data) be made relevant to planning for future climate/hydrology?

- Natural modes of variability will continue to operate, alongside human-forced warming trends (though the former may be altered to some degree by warming)
- The greater variability seen in the paleohydrologic records, compared to gaged 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

Integration of tree-ring flow reconstruction with climate change scenarios - City of Boulder (with CU and Stratus Consulting)

- Monthly temps & precip, and observed streamflow (1953-2002) are resampled to pair the paleo streamflows for 1566-2002 with corresponding monthly temperature and precipitation
- Effectively disaggregates the annual paleo streamflows into estimated climatic variables (monthly precipitation and temperature) so that those variables can be manipulated independently
- Then the simulated monthly temperature and precipitation are input into a snowmelt-runoff (SRM) and water-balance (WATBAL) model to produce modeled Boulder Creek flows
- Then changes in temperature and precipitation forecasted from climate models are combined with the paleodata to produce simulations of past hydrology under plausible future climate conditions
- Allows water managers to assess the joint risks of climate variability and climate change
- *Southwest Hydrology*, Jan/Feb 2007

Integration of tree-ring flow reconstruction with climate change scenarios - City of Boulder (with CU and Stratus Consulting)



McCabe and Wolock 2007 – Delta-Q approach

- Two warming scenarios:
  - 0.86 degree C, same observed increase in the UCRB in the 20th century
  - 2.0 degree C,warmer scenario consistent with model projections.
- Applied these to observed monthly temps in UCRB from 1901-2000, and ran a water-balance model (Wolock and McCabe 1999, calibrated against 1906-2004 Lees Ferry natural flows), with these modified climate inputs
- Results: average decrease in 1901-2000 annual streamflow of 8% for the 0.86-degree scenario, and 17% for the 2.0-degree scenario.
- Then applied these modeled reductions in streamflow to the driest 100-year period (1573-1672) in the Woodhouse et al. (2006). Lees Ferry flow reconstruction (1490-1997)
- This yielded 100-year mean flows of 12.2 MAF for the 0.86-degree scenario and 11.0 MAF for the 2.0-degree scenario, compared to 13.3 MAF for the unmodified 1573-1672 reconstructed flows, and 15.2 MAF for the modeled 1901-2000 flows.

Reclamation – New research project

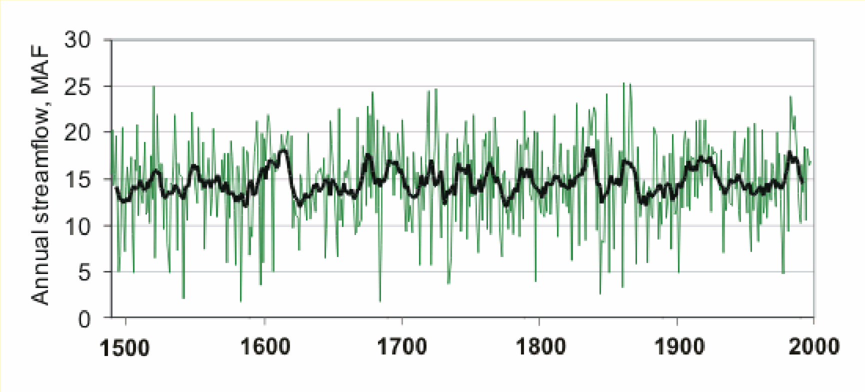
Development and Comparison of Long-Term Planning Hydrologies using Alternate Climate Information Sets (Brekke et al.)

- How do planning hydrologies vary when developed using alternative climate information sets (e.g., blends of instrument record, paleoclimate data, climate projections)?
  - Null: Observed
  - Alt 1: Observed + Paleo-conditioning
  - Alt 2: Observed + future-period GCM
  - Alt 3: Observed + transient GCM
  - Alt 4: Observed + transient GCM + Paleo

- Test basins: Gunnison, Upper Missouri

Part 6:

Forthcoming data, applications, and resources for the UCRB and beyond



Forthcoming tree-ring data and reconstructions

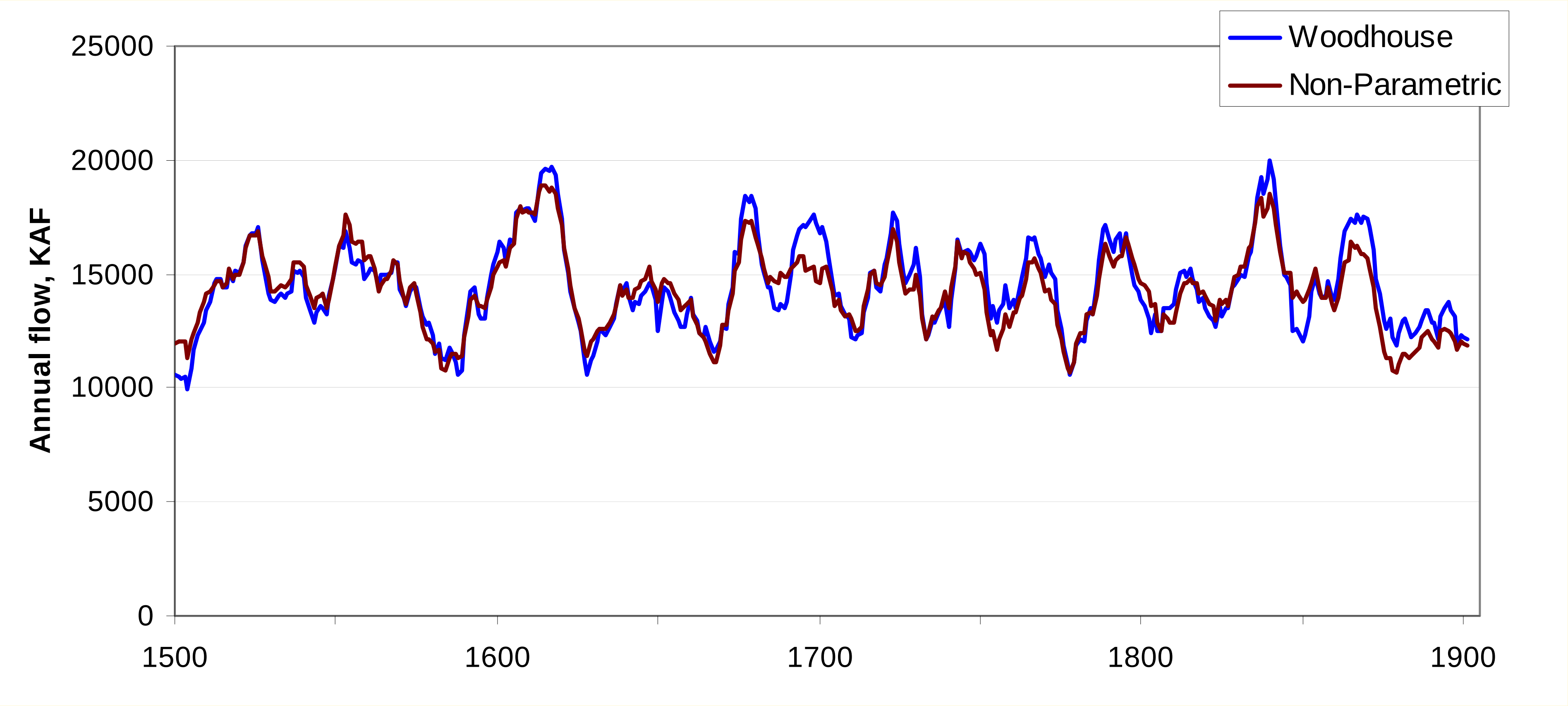
- Green River basin – work by Glenn Tootle and Steve Gray (UWyo) to collect new chronologies and improve Green River reconstructions
- Rio Grande basin – new chronologies by UAZ Fall 2007, new reconstructions spring 2008 for mainstem and tribs
- Western Colorado – continuing collection of remnant material for >1000 yr chronologies (and upper Colorado reconstructions?)
- North America – new version of gridded PDSI reconstructions to be released in 2008

Forthcoming new reconstruction approach

- *Non-Parametric Paleo Project* - AMEC/Hydrosphere, funded by Reclamation and Western Water Assessment
- Test case: Colorado River at Lees Ferry
  - Pool of chronologies very similar to Woodhouse et al. (2006)
  - PCA used to extract PCs from tree-ring network over entire time span (1490-2005)
  - Based on first 2 PCs, for each year in paleo period (1490-1905), calculate 10 nearest neighbors in observed period (1906-2005)
  - Using KNN, conditionally resample observed flows from these neighbor-years to populate each paleo-year with a flow

Forthcoming new reconstruction approach

Preliminary Non-P model vs. Woodhouse et al. 2006, 10-yr running means, 1500-1900



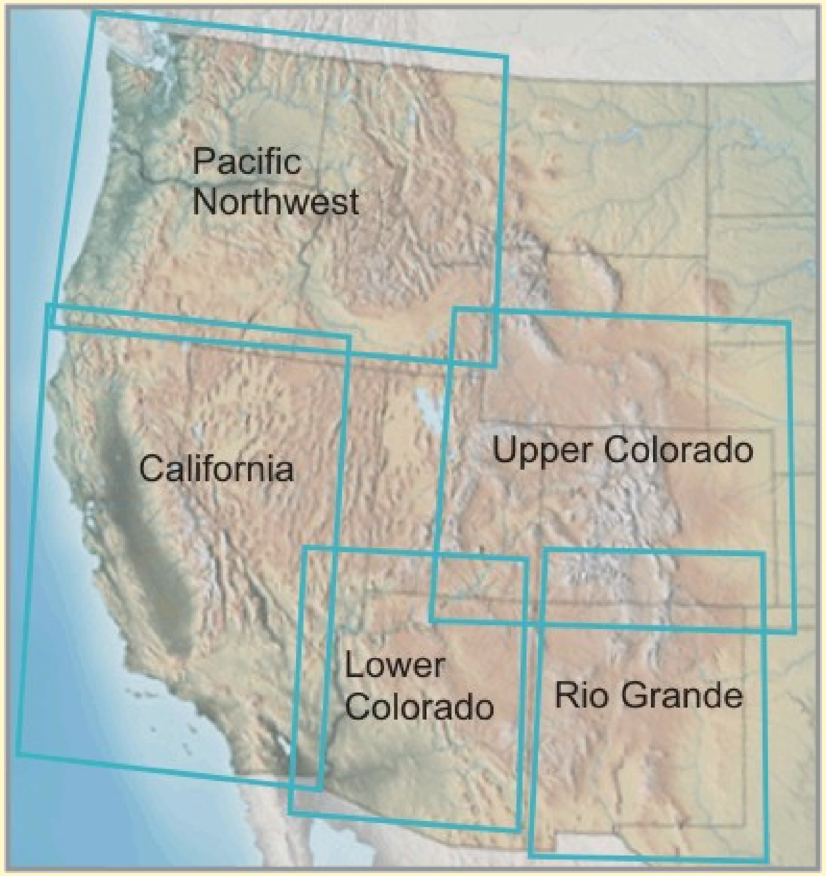
Data courtesy of Subhrendu Gangopadhyay, AMEC

Forthcoming application - Colorado River Water Availability Study, State of Colorado

- The question: “How much water from the Colorado River Basin System is available to meet Colorado’s current and future water needs?”
- Work to begin in June 2008
- Task 6 is the development of “Alternative Historical Hydrologies” from tree-ring data to run as input into CDSS

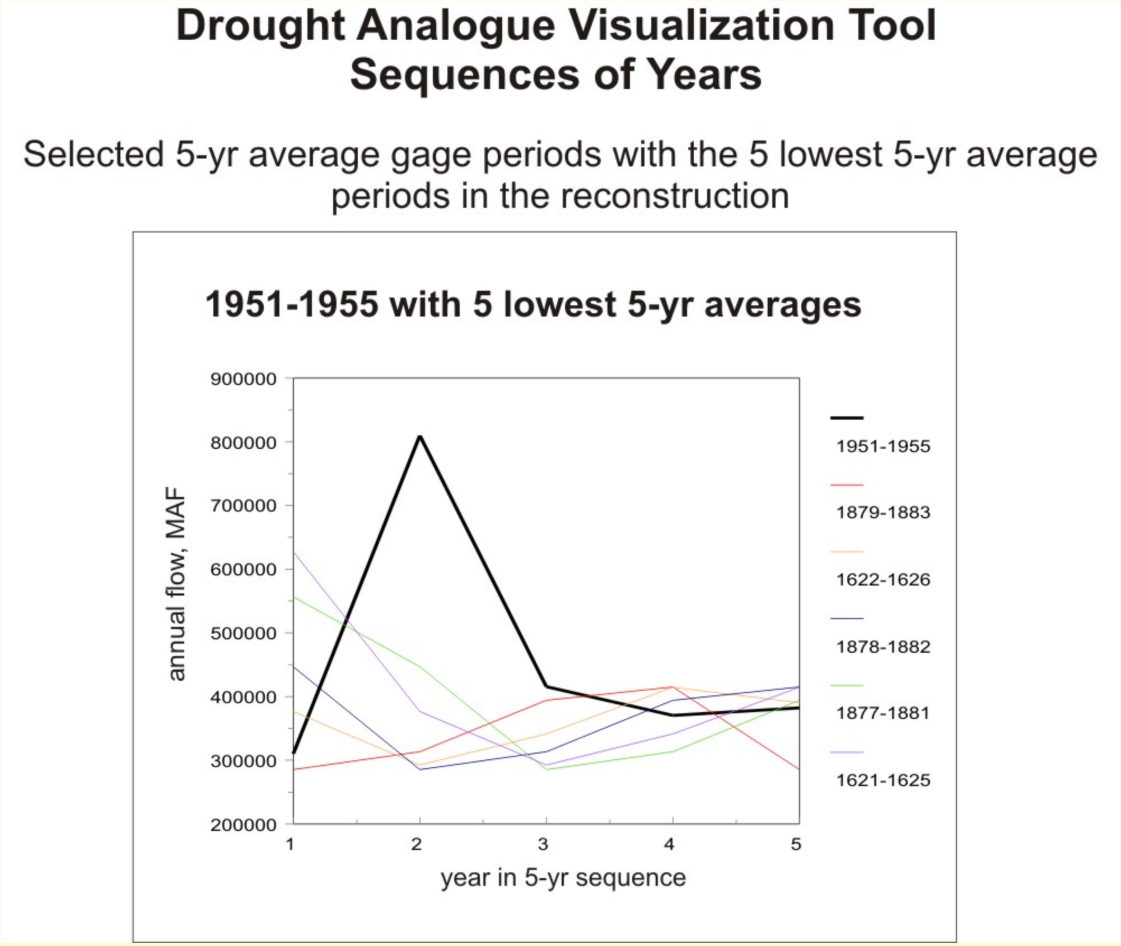
Forthcoming resources – New WWA webpages

- New TreeFlow web pages at Western Water Assessment in summer 2008
- Organization of content by basin/region



Forthcoming resources – visualization tools

- Rio Grande prototype on web in late spring 2008
- Various ways to put observed record in paleo context



Forthcoming resources – technical workshops

- Albuquerque – May 30
- Durango, CO – June 13

- Las Vegas – Fall 2008?
- So. California – Fall 2008?

- Any suggestions?

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

6) Many flow and climate reconstructions are available for the UCRB, and local, state, and federal entities are using them in analyses for planning and management

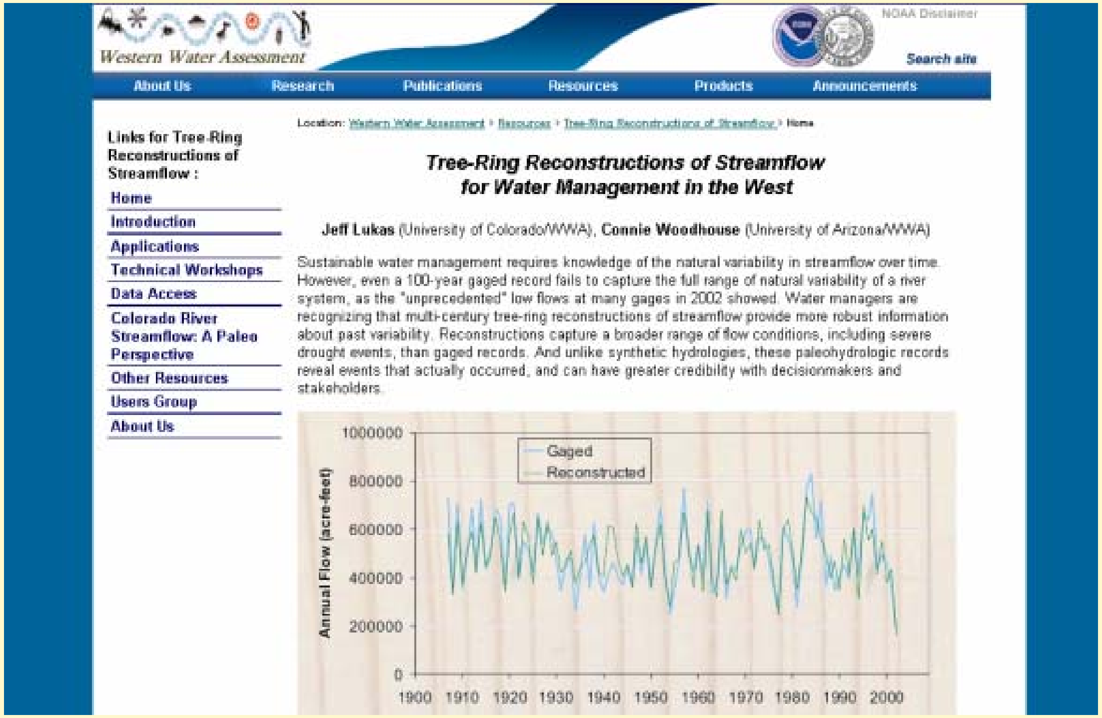
7) There are different levels of complexity in applying the reconstructions to water management; what is required to effectively assess and communicate risk?

8) Reconstructions can used alone or in combination with climate change projections to help prepare potential future variability

Open Discussion:

Where to go next with paleohydrology in the UCRB and the West?

WWA Tree-Ring Reconstructions Webpages



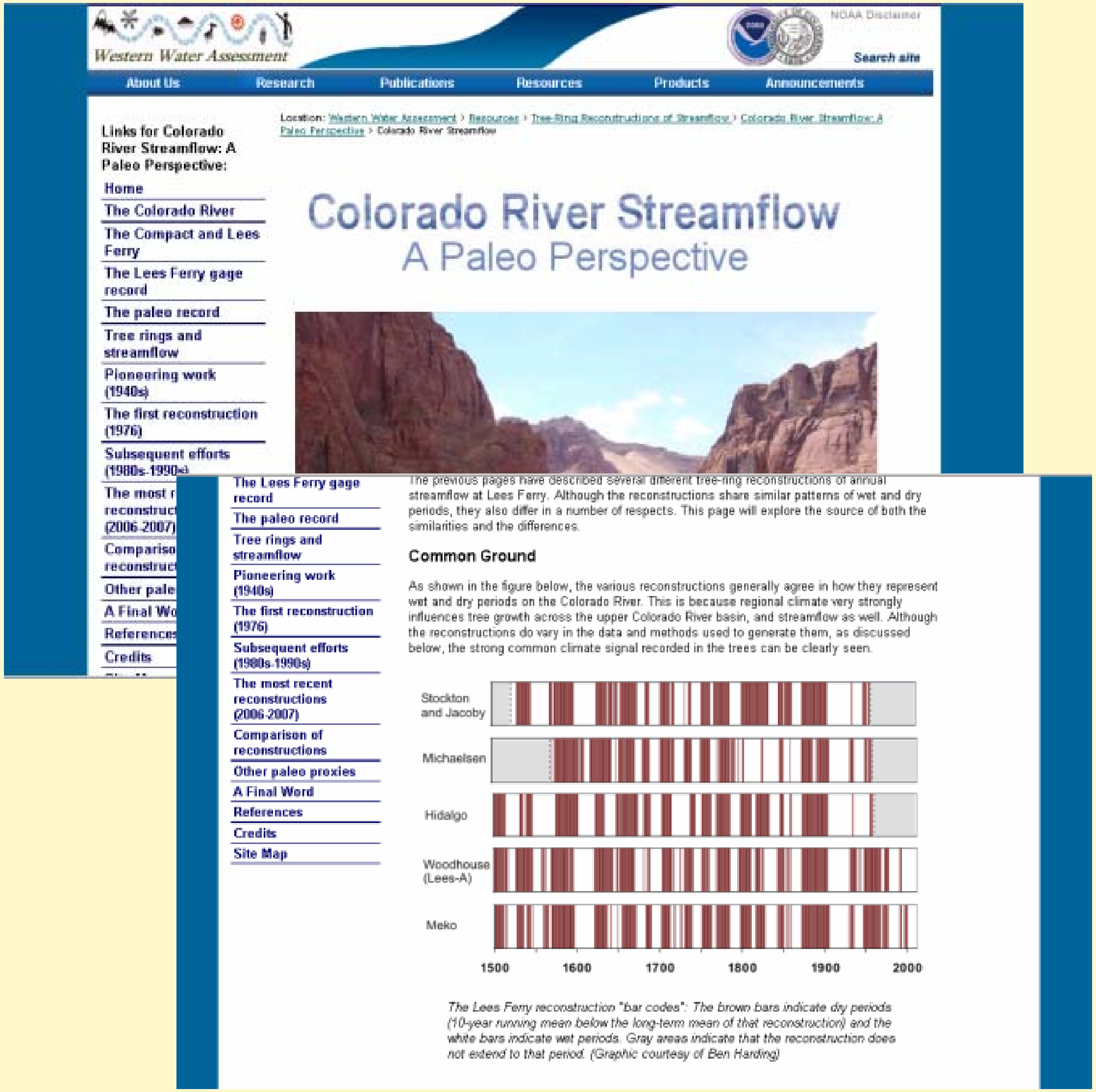
http://wwa.colorado.edu/resources/paleo/

- Technical Workshops
- Descriptions of applications
- Access to data
- Resources
- Colorado River Streamflow: A Paleo Perspective
- Users group

Technical Workshops page

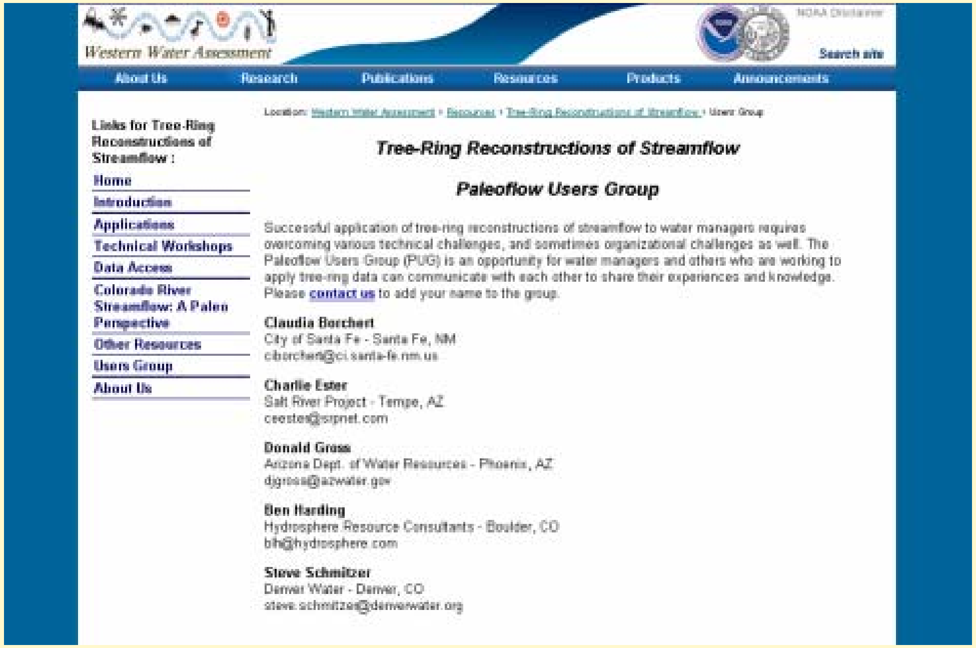
- Access to workshop presentations
- *Presentations from this workshop to be posted soon*

Colorado River Streamflow: A Paleo Perspective



- Background on the river and its management
- Description of all tree-ring studies of the Colorado
- Comparison of 6 reconstructions

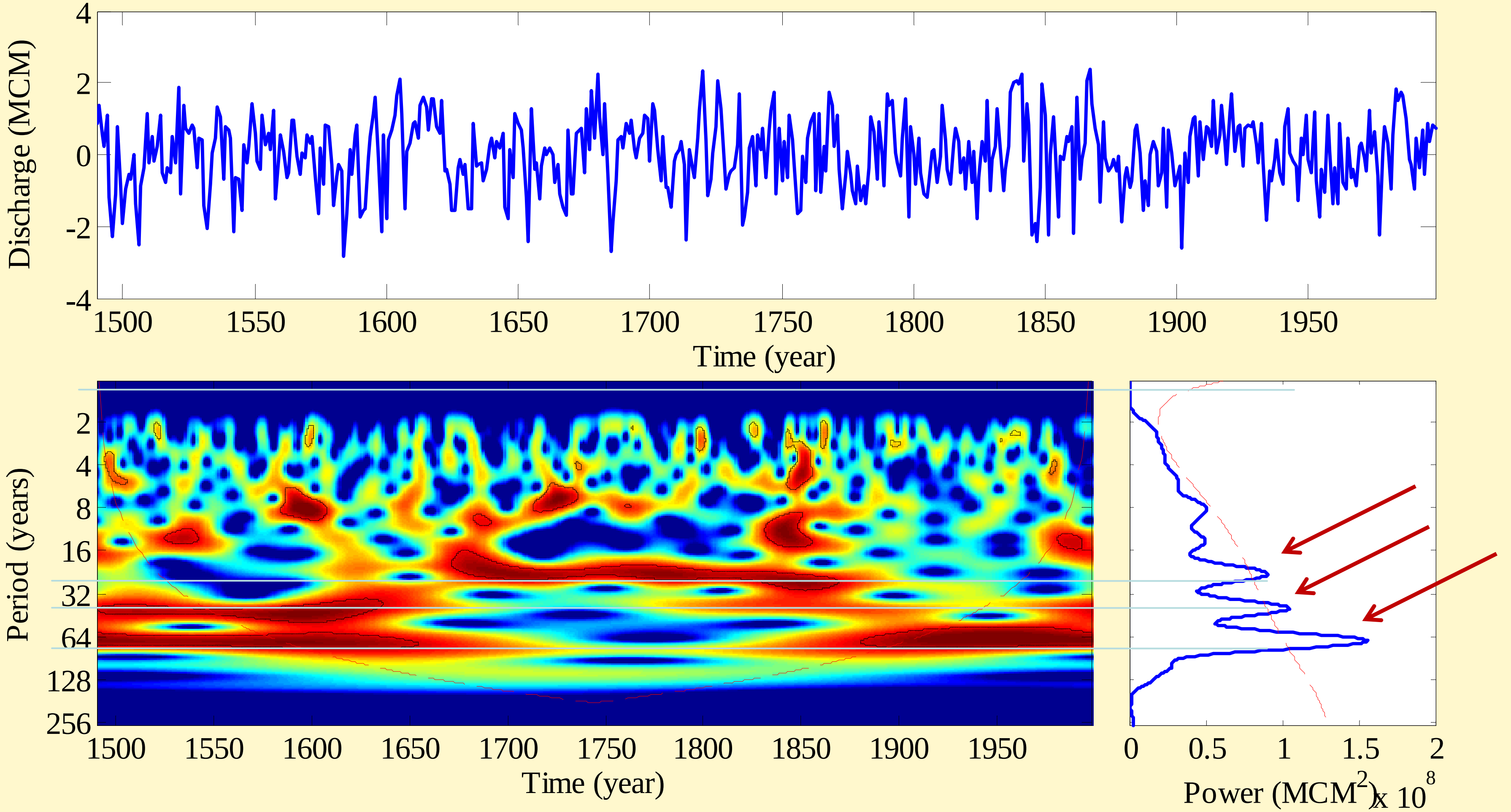
Paleoflow Users Group



- List of water practitioners using tree-ring data
- Next step: listserv?

Forthcoming application - Using reconstructed climate variability to model possible future variability – Lall et al.

Lees Ferry streamflow, reconstruction, wavelet, and global wavelet



Using reconstructed climate variability to model possible future variability