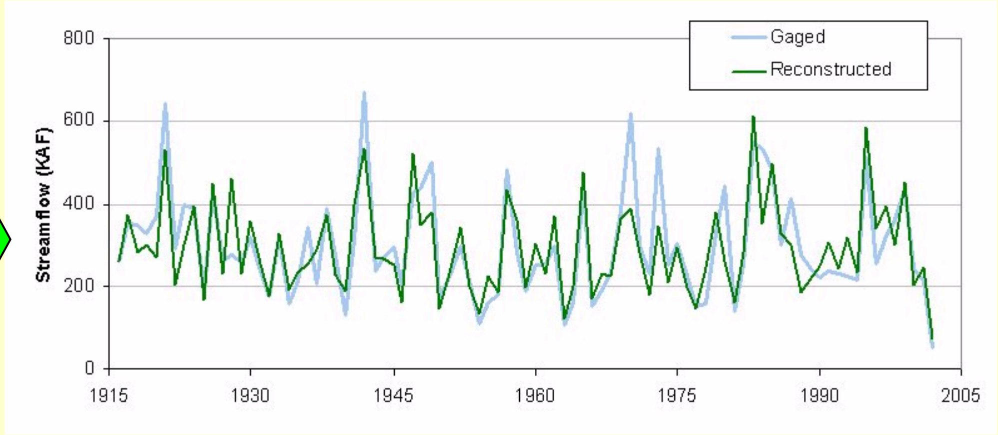
Tree-ring reconstructions of streamflow and their use in water management



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University of Colorado Boulder

Western Water Assessment

Outline

Introductions

- Context and background
- How tree rings record climate information
- Building a tree-ring chronology
- How streamflow reconstructions are generated

BREAK

- Reconstructions for the West, Colorado, and the San Juans
- How the reconstructions can be used in water management
- Relevance of the reconstructions in light of climate change

Please ask questions throughout

Acknowledgements

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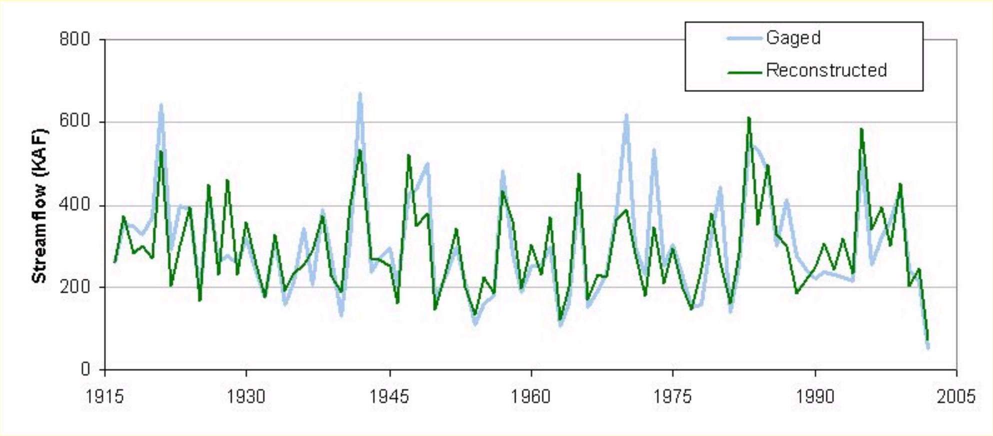
Part 1:

Context and Background



The conundrum of (water) management

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

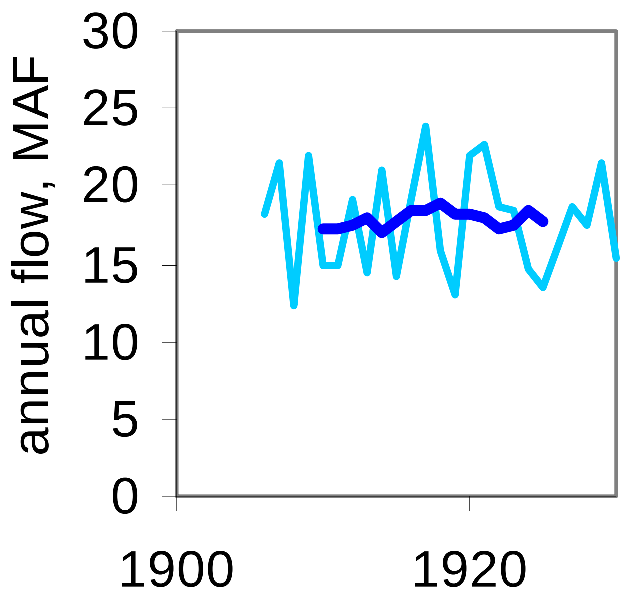
So how do we generally make decisions?

Based on past experience.

Learning from experience in water management

Colorado at Lees Ferry

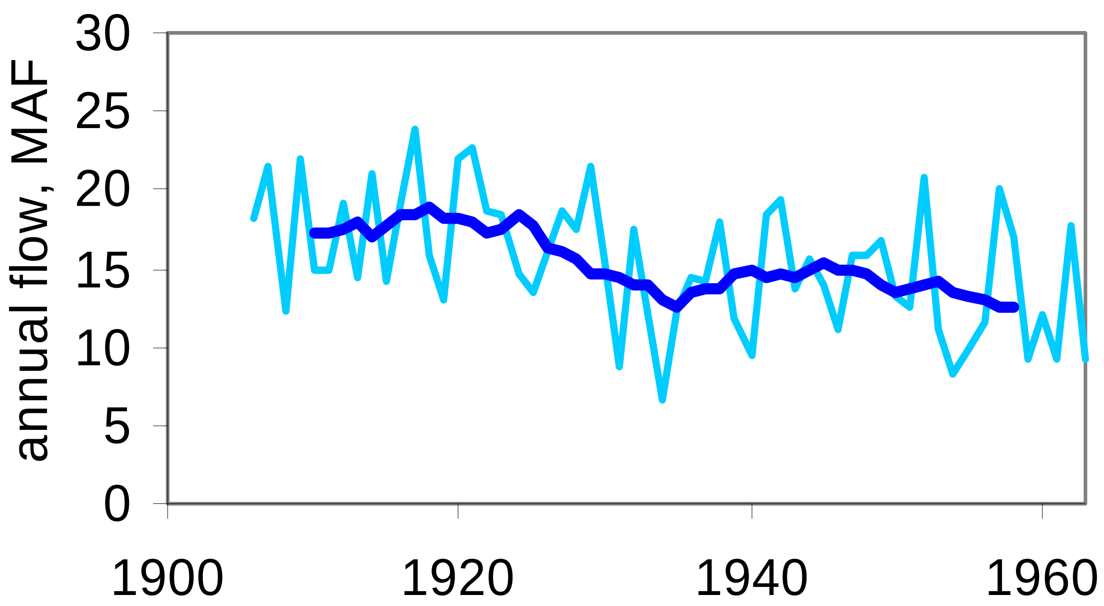
Gaged (natural flow) record, 1906-1930



Learning from experience in water management

Colorado at Lees Ferry

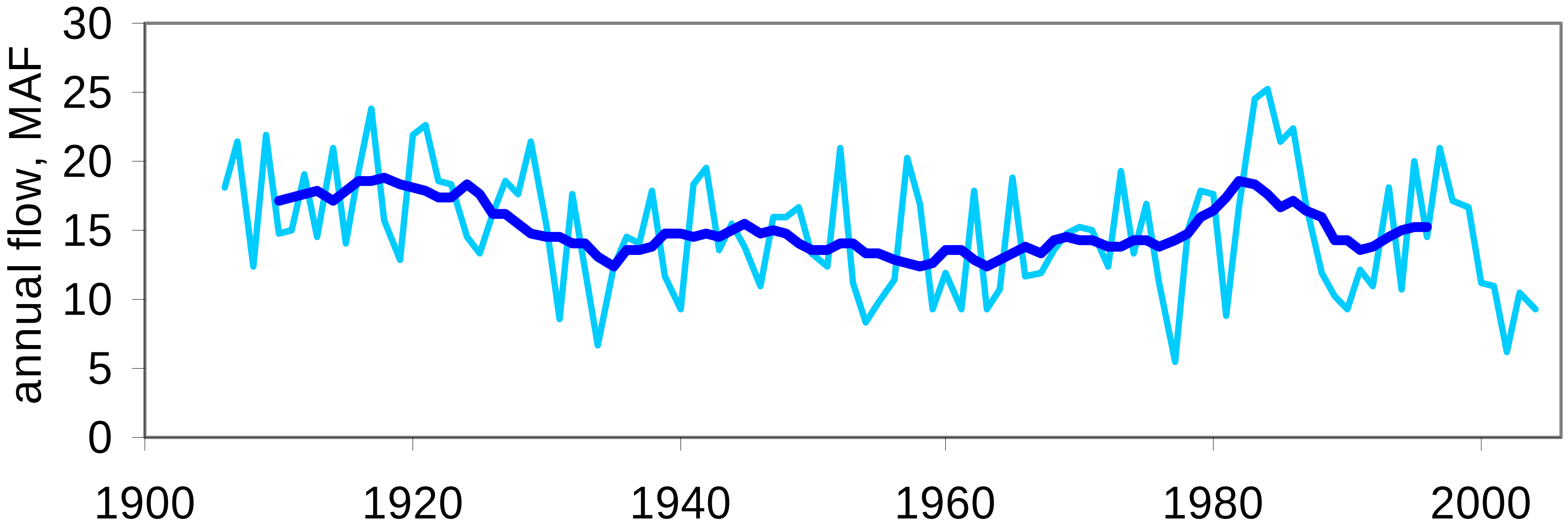
Gaged (natural flow) record, 1906-1963



Learning from experience in water management

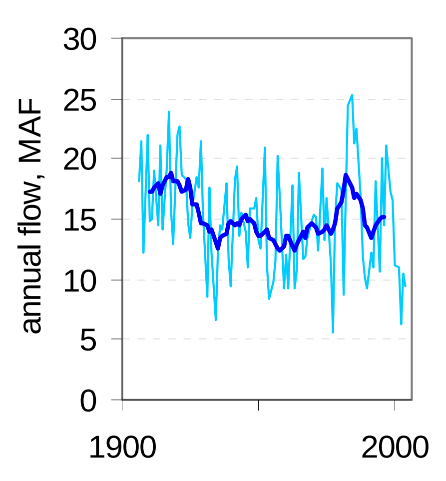
Colorado at Lees Ferry

Gaged (natural flow) record, 1906-2004



You can never have too much experience

Tree-ring reconstructions - a surrogate for experience



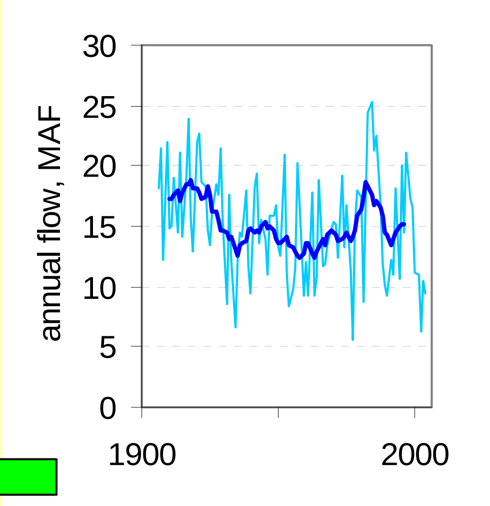
Colorado at Lees Ferry

Gaged (natural flow) record

1906-2004

Tree-ring reconstructions - a surrogate for experience

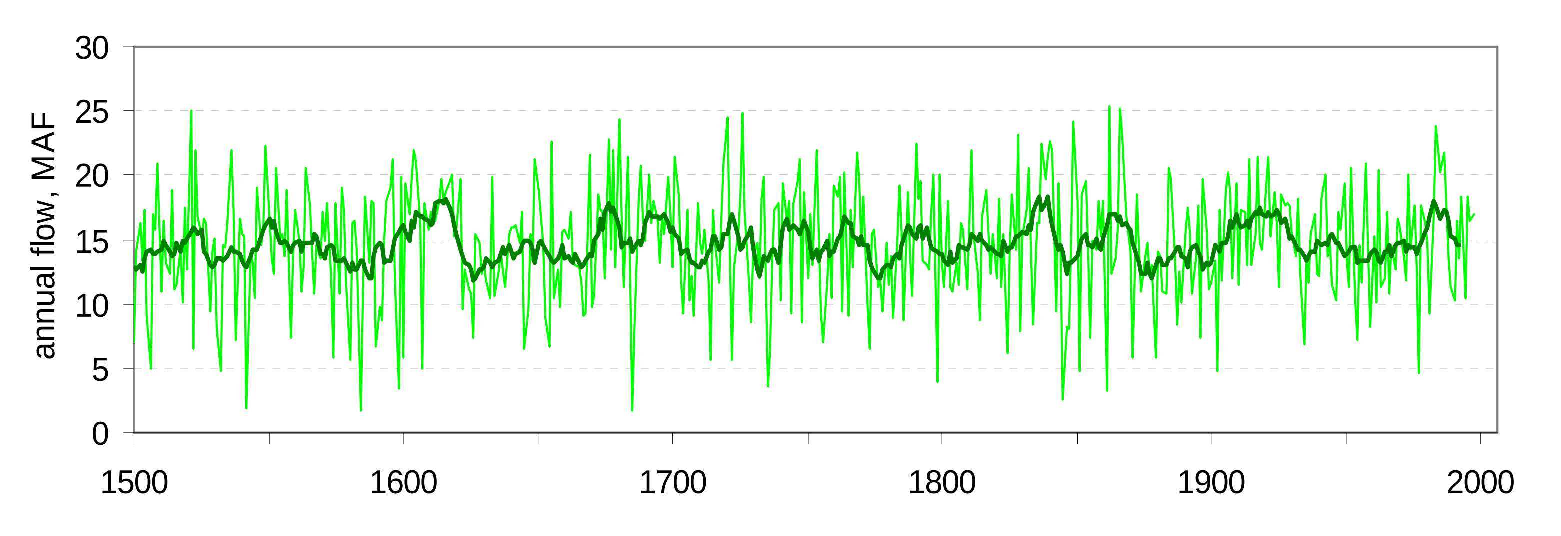
By extending the gaged hydrology by hundreds of years into the past, the reconstructions provide a more complete picture of hydrologic variability



Colorado at Lees Ferry

Gaged (natural flow) record

1906-2004



Tree-ring reconstruction

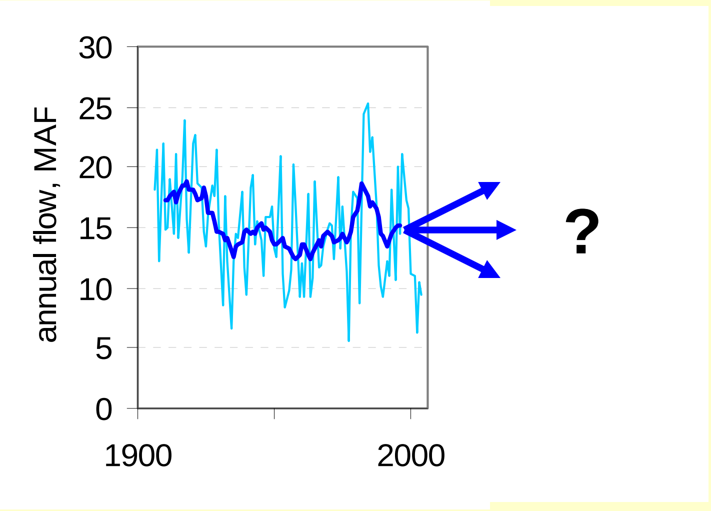
1490-1997

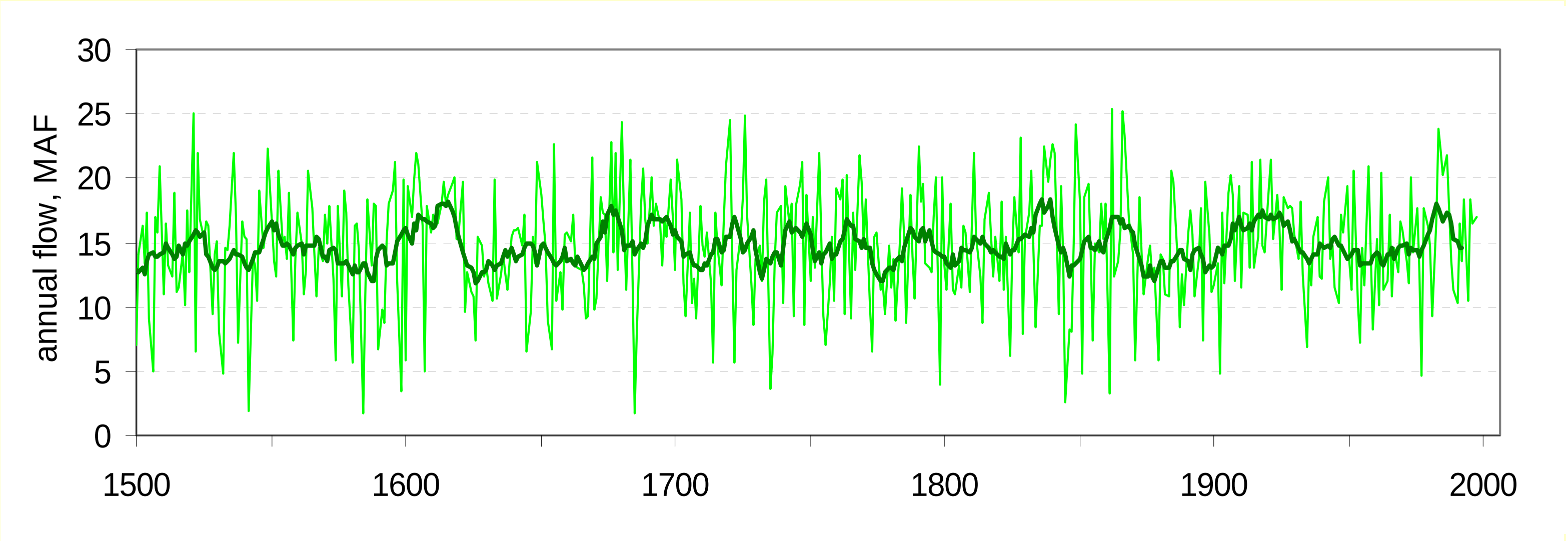
Tree-ring reconstructions - a surrogate for experience

Payoff:

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

- Better assessment of *risk*

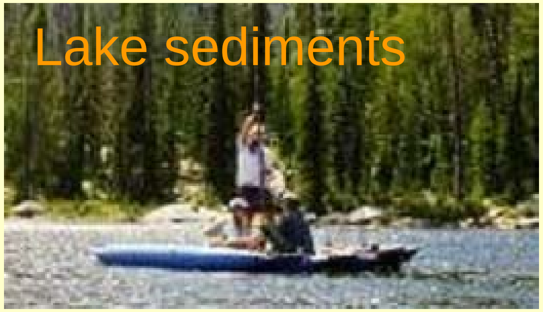


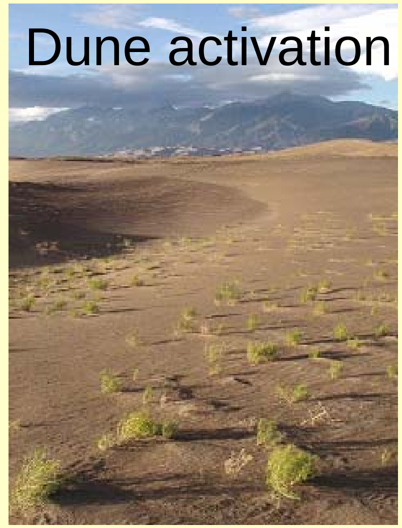


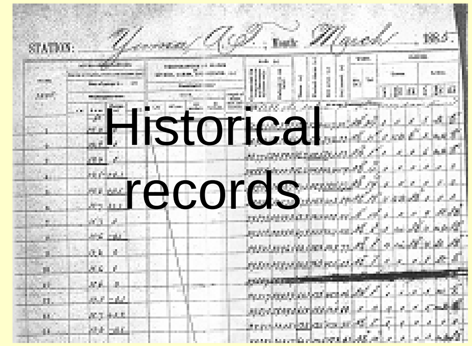
Tree-ring reconstruction

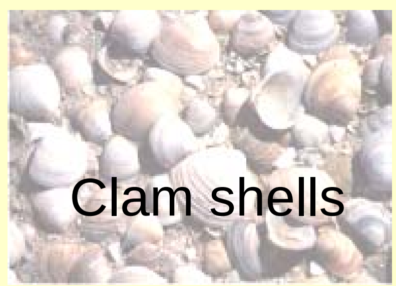
1490-1997

Paleoclimatology = records of pre-instrumental climate









Paleoclimatology reveals what has actually happened

Jonathan Overpeck

Key attributes of tree rings as a climate proxy

- 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

Dendrochronology

Dendroarchaeology

Dendroecology

Dendrogeomorphology

etc.

Dendroclimatology

The science that uses tree rings to study present climate and reconstruct past climate

Dendrohydrology

The science that uses tree rings to study changes in river flow, surface runoff, and lake levels

Key advances in dendrochronology, dendroclimatology, and dendrohydrology

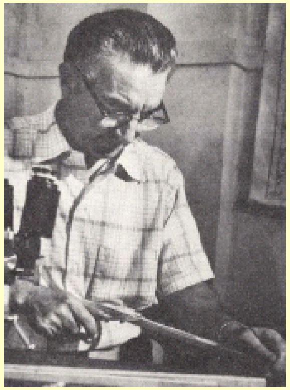
1905-1920 - Douglass establishes modern tree-ring science; links tree-growth and climate in Southwest

1930s - First studies relating tree growth to 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 in dendrochronology, dendroclimatology, and dendrohydrology

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

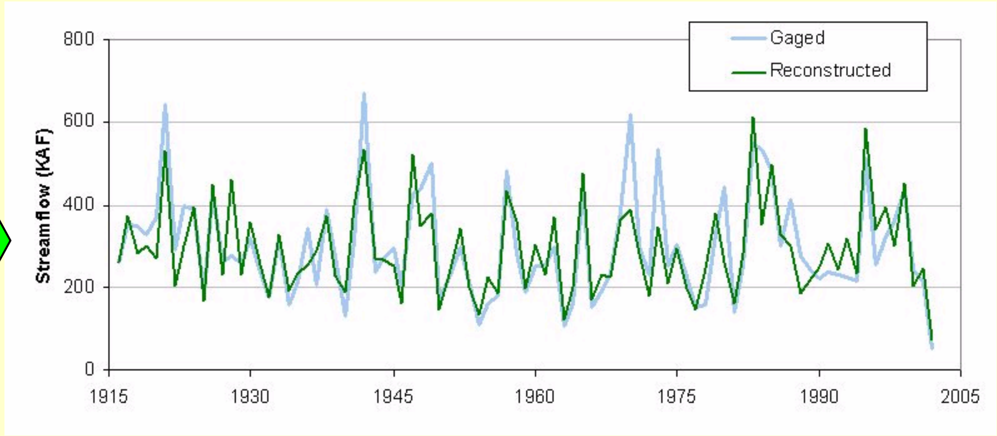
2006 - Woodhouse et al. reconstruction of Lees Ferry and other Colorado basin gages

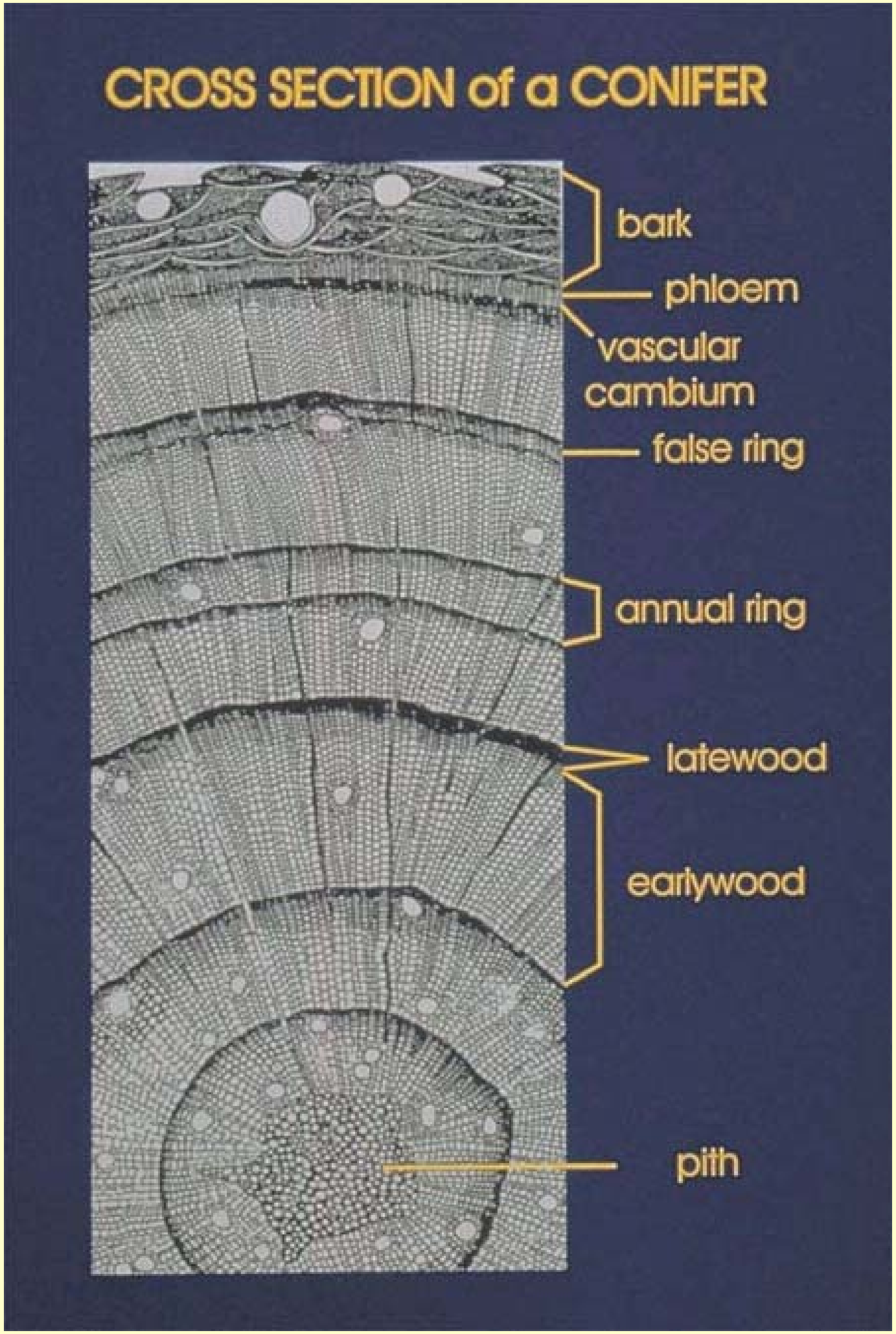
My little piece of this history

1998 - 2001	Fire history research in Black Hills, Front Range, San Juans
2000 -	80 new tree-ring collections across Colorado and the West for dendroclimatology and dendrohydrology
2002 -	Use of those collections to reconstruct streamflow in collaboration with water managers
2005 -	Workshops to explain the development and application of the tree-ring reconstructions

Part 2:

How tree rings record climate information





The formation of annual growth rings

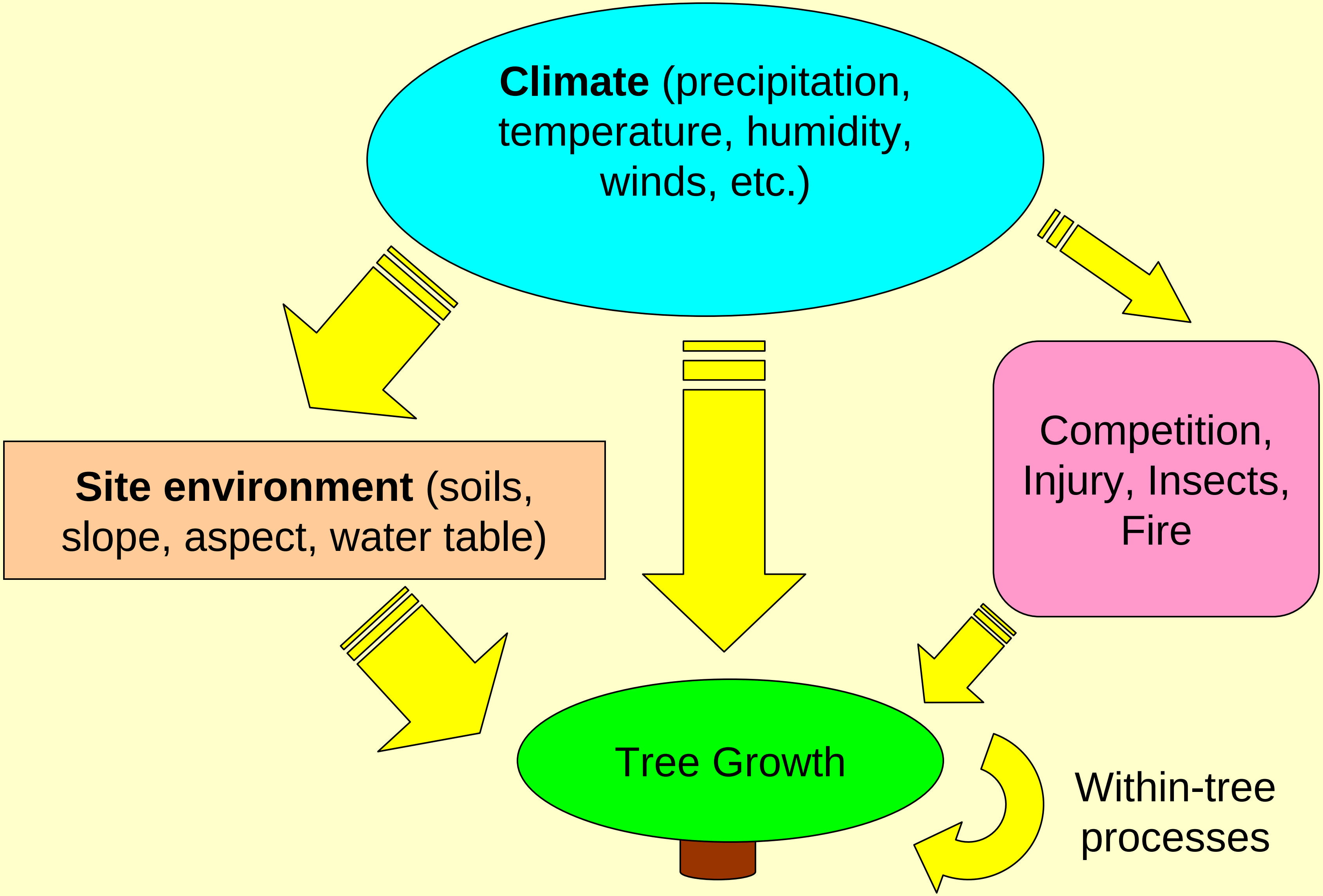
- New wood forms in the vascular cambium, underneath the bark
- Earlywood + latewood = growth ring
- In temperate climates, growth ring = *annual ring*
- Rings have varying widths when a limiting factor on growth varies in magnitude from year to year

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

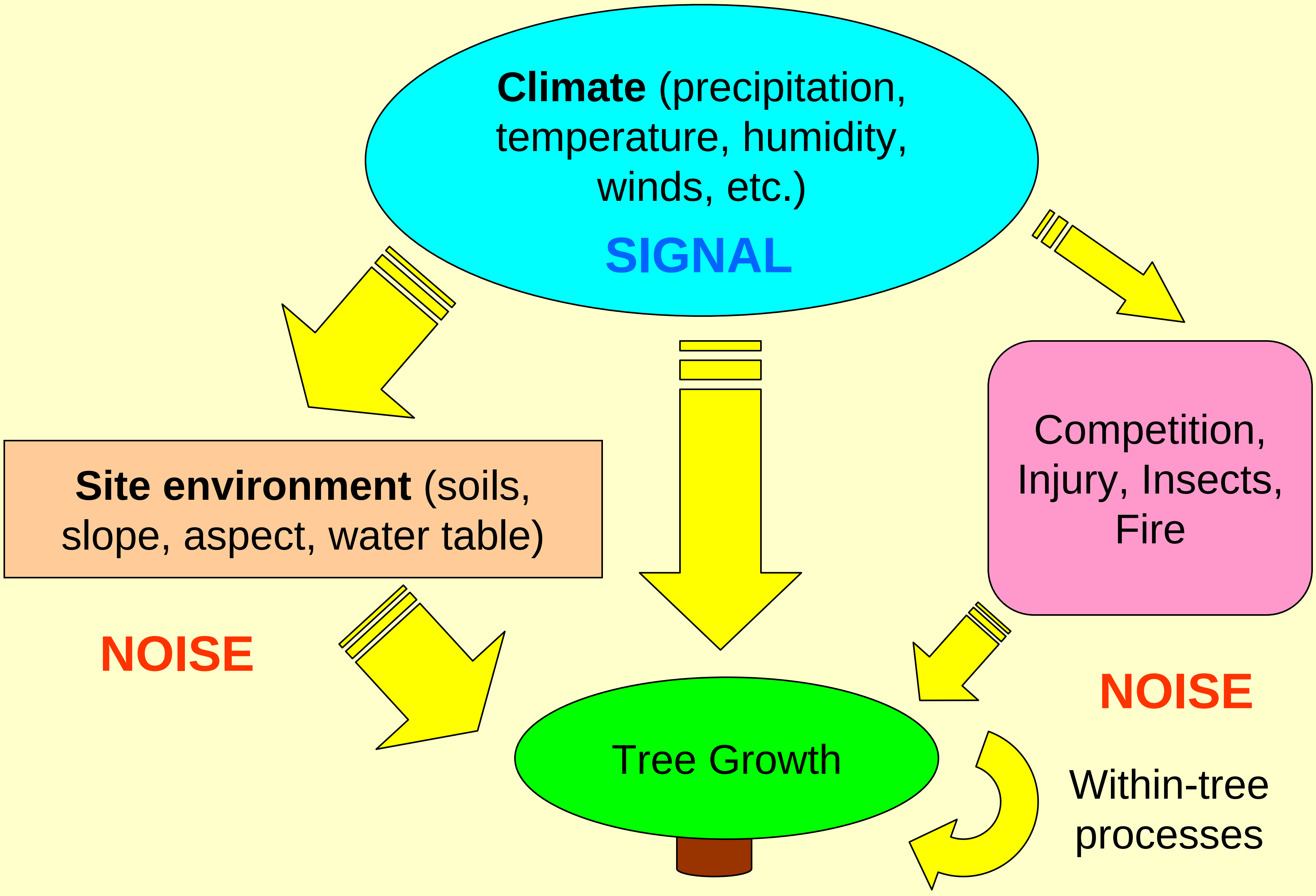
- At high elevations, growth is typically limited by summer warmth and length of the growing season

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

Climate is not the only *influence* on growth



The main goal is to increase Signal:Noise ratio



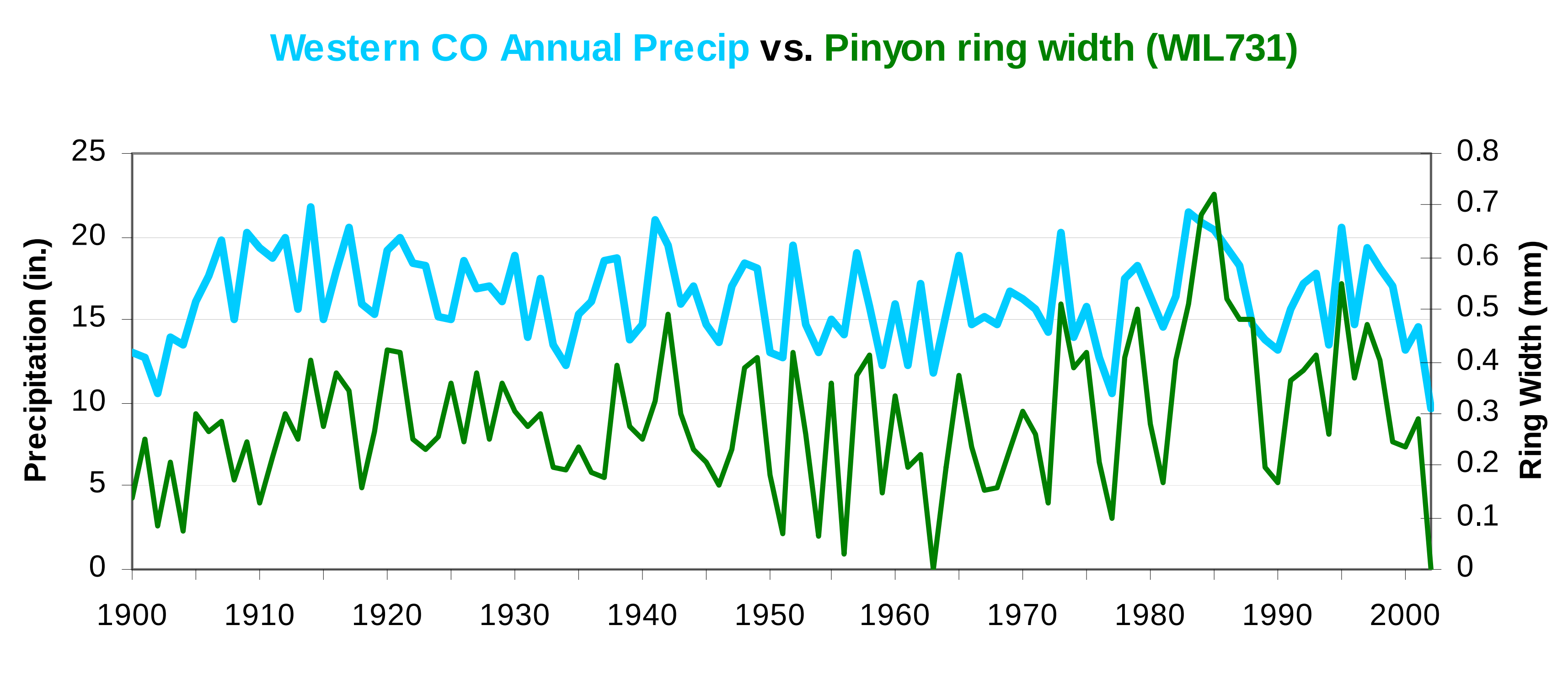
Moisture sensitivity

- “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)

Example of moisture signal as recorded by a single tree - western Colorado



- Here, the "raw" ring widths from one tree are closely correlated to the annual basin precipitation (r = 0.69)
- Our job is to *capture* and *enhance* the moisture signal, and reduce noise, through careful sampling 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

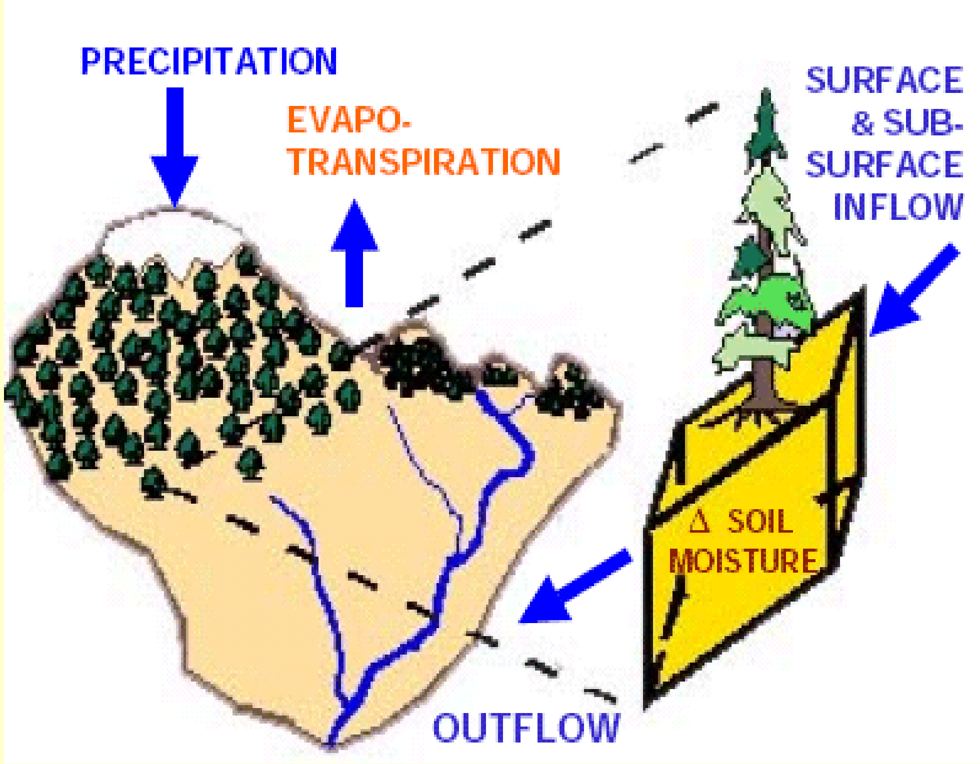


Image courtesy of D. Meko (U. AZ)

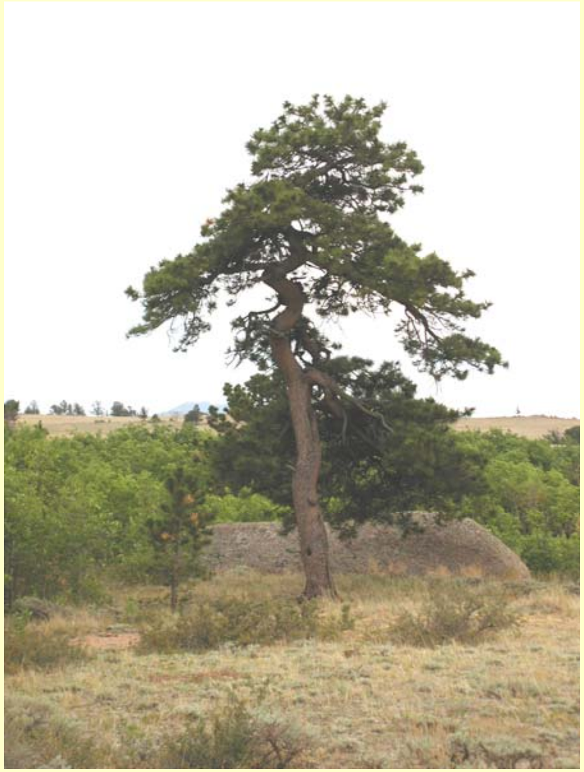
Principal moisture-sensitive species - CO, UT, AZ, NM

Douglas-fir

500-800 years

Pinyon Pine

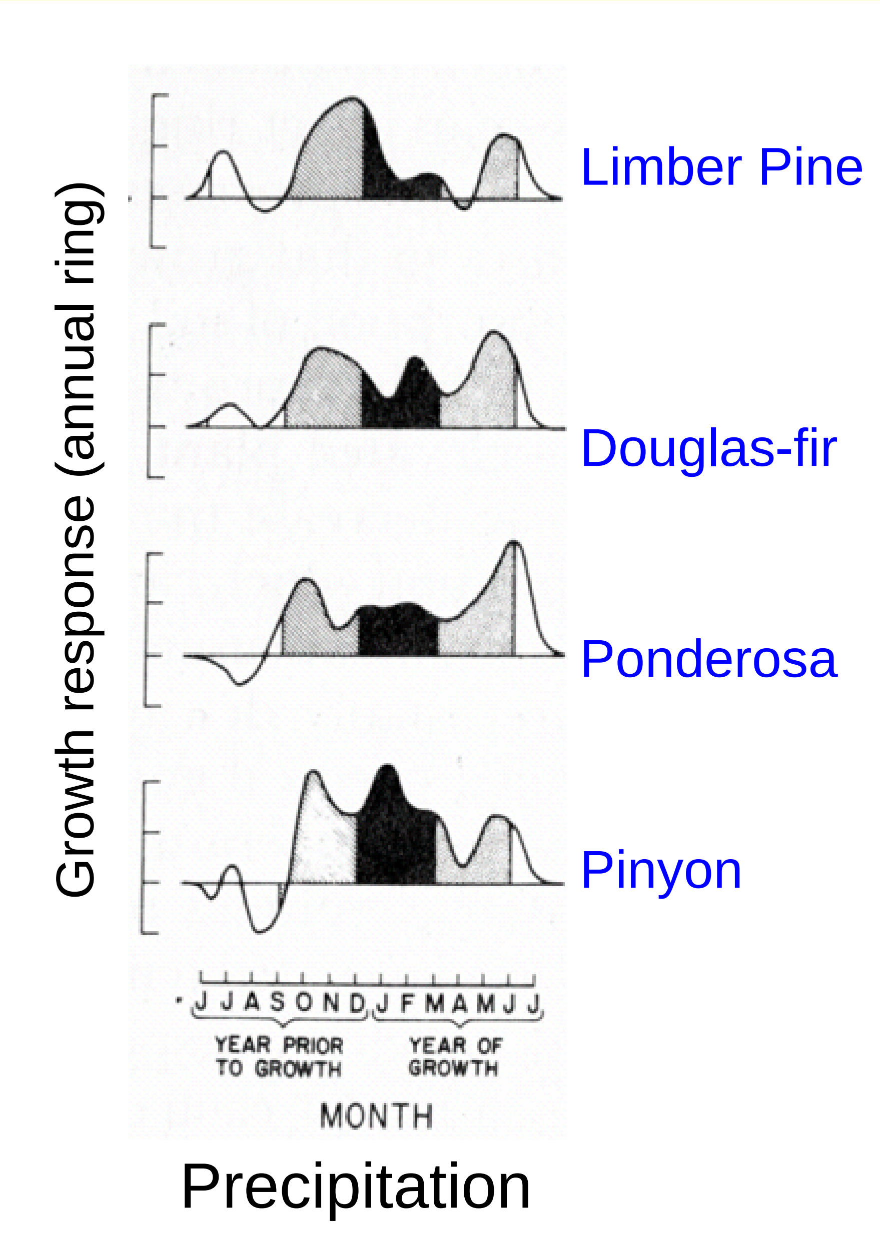
500-800 years



Ponderosa Pine

300-600 years

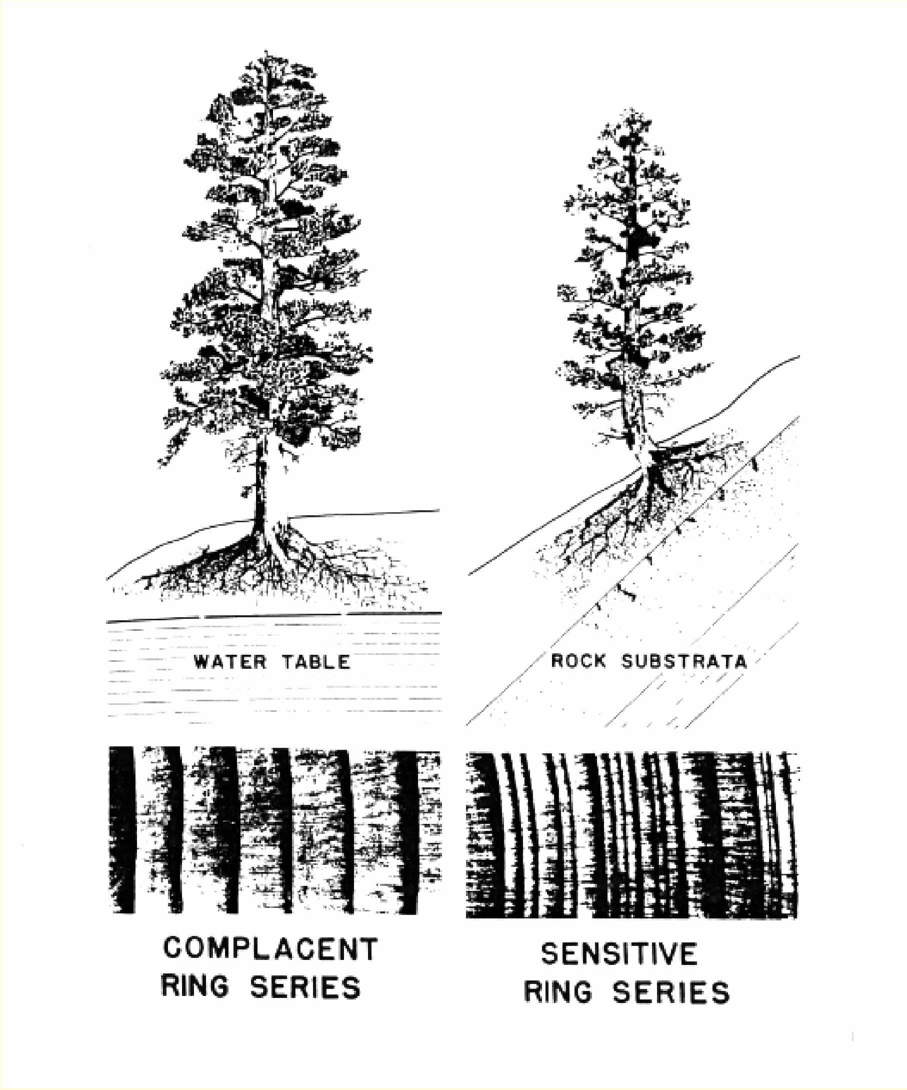
Seasonal climate responses by species - western US



- All species respond mainly to precipitation in fall/winter/spring prior to growing season
- Some variation in shape of the "response window"

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

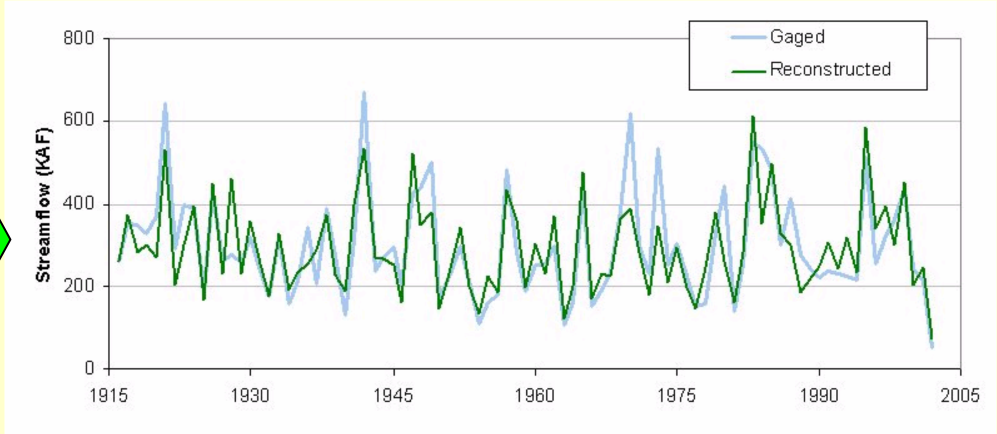
Gallery of stressful sites





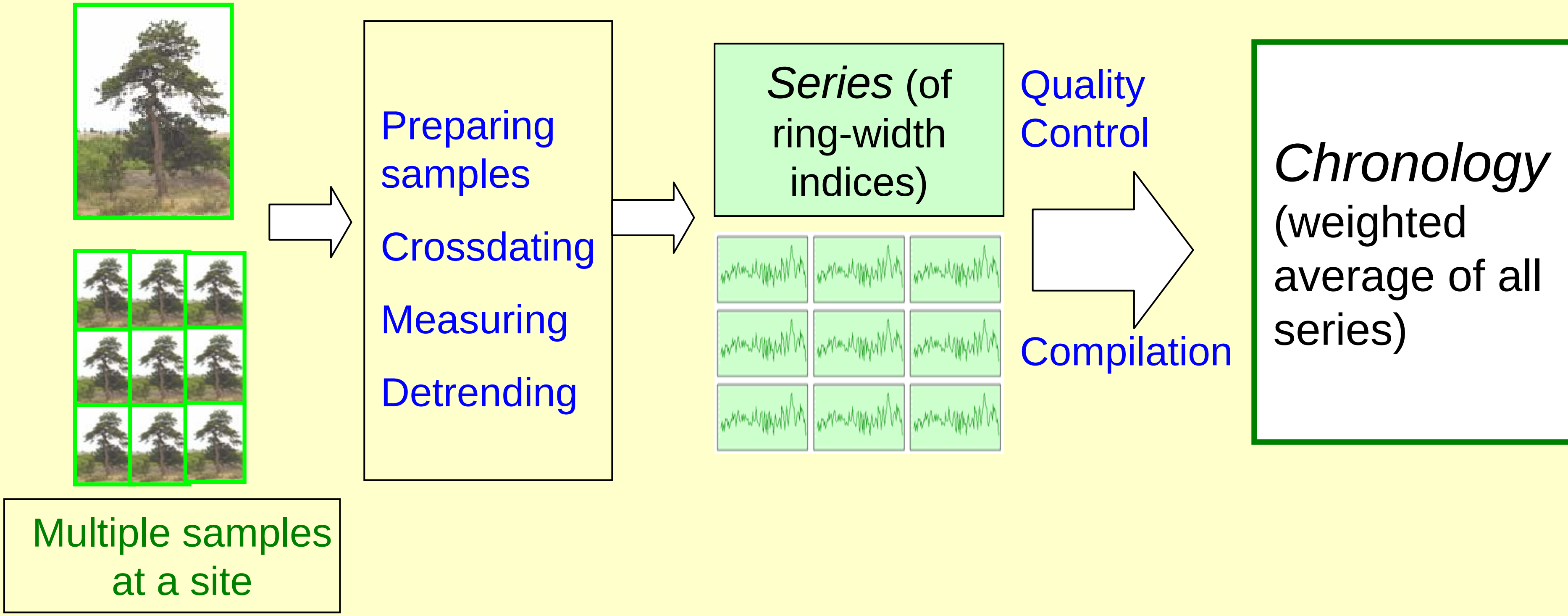
Part 3:

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

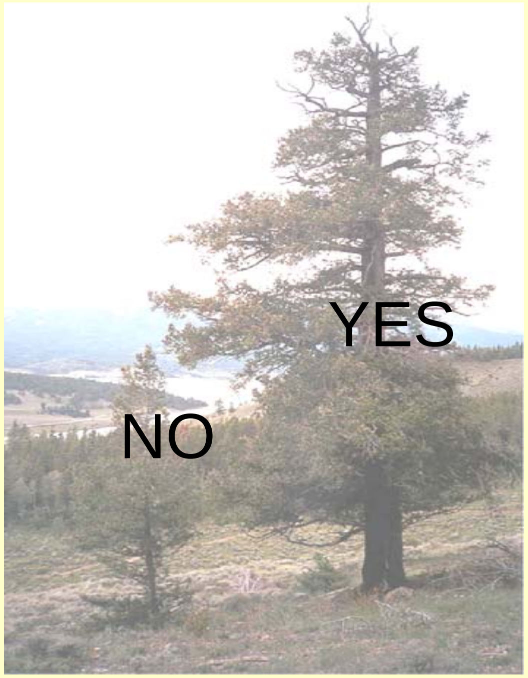


Sampling to develop a site chronology

- 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

Sampling dead trees ("remnant" wood)

- Increment borers can also be used to sample remnant wood (stumps, snags, logs)

- But it's often better to saw cross-sections

Sampling to develop a site chronology

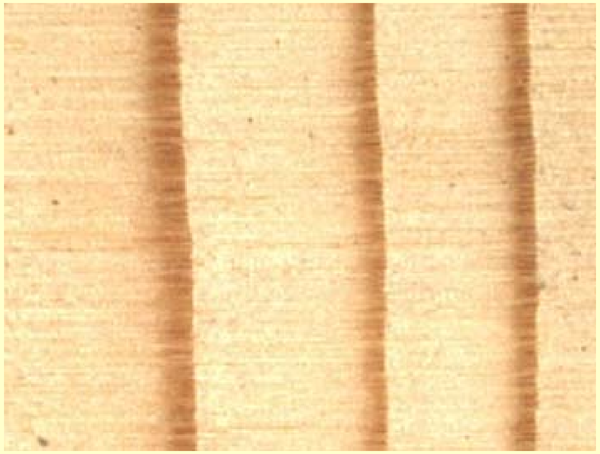
- Collect *two* cores (radii) from each tree, extending to the pith

- The two radii are from opposite sides of the tree
  - average out within-tree ring-width variability
  - facilitate identification of absent and micro rings

Schematic of coring for typical tree

Preparing the cores

- Cores are left to air dry for at least a few days, then glued to wooden core mounts
- Cores and sections are sanded with a belt sander, then hand-sanded to 1200-grit
- Individual cells (tracheids) must be clearly visible



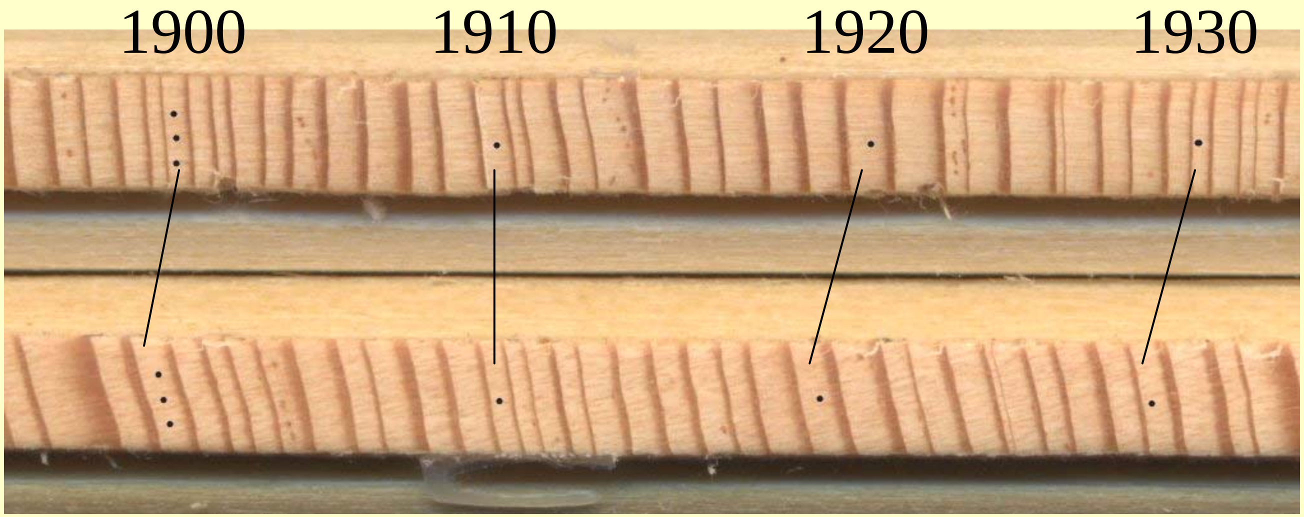
NO - can't see cells

OK - ready to crossdate

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

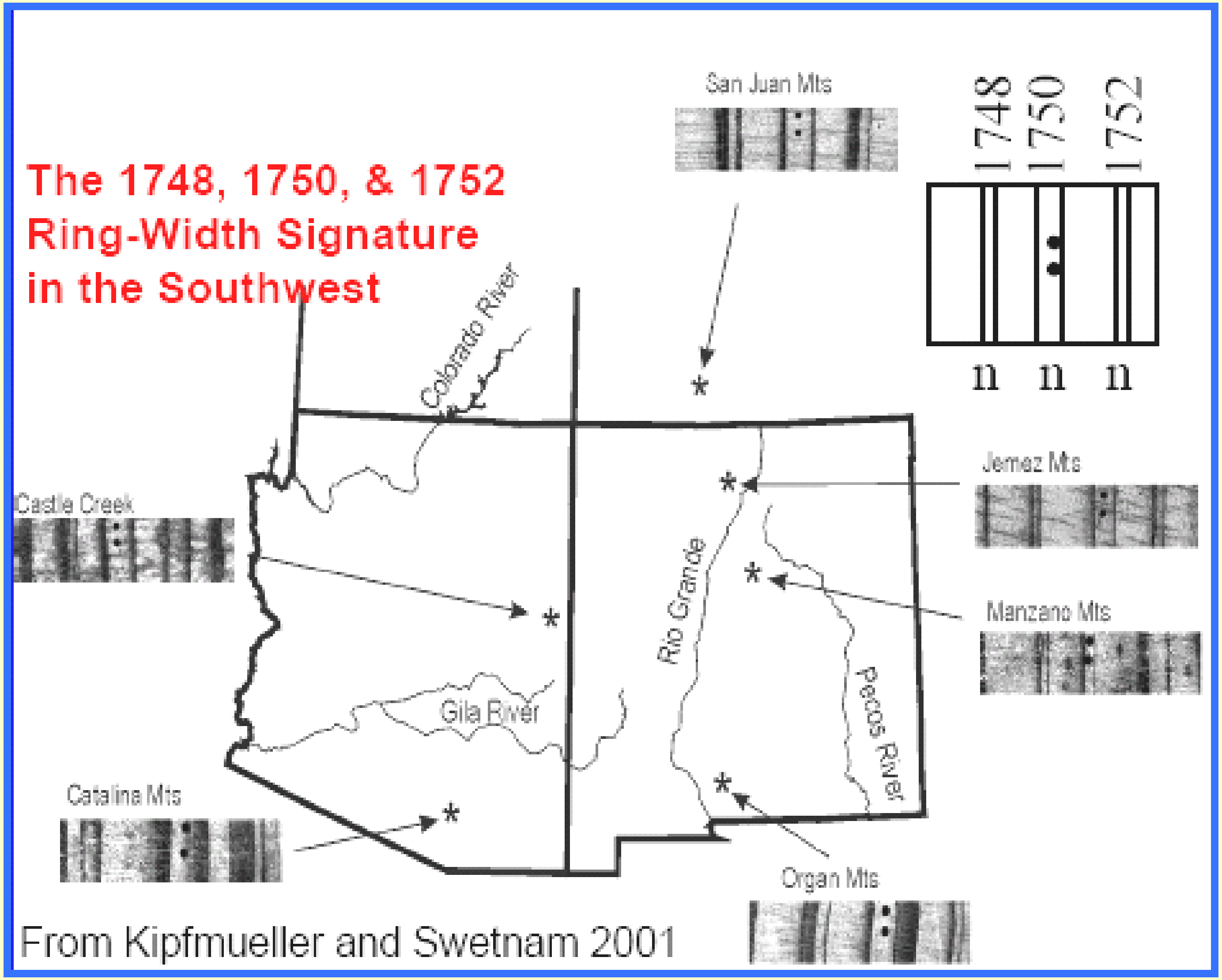


Image courtesy of K. Kipfmueller (U. MN) and T. Swetnam (U. AZ)

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

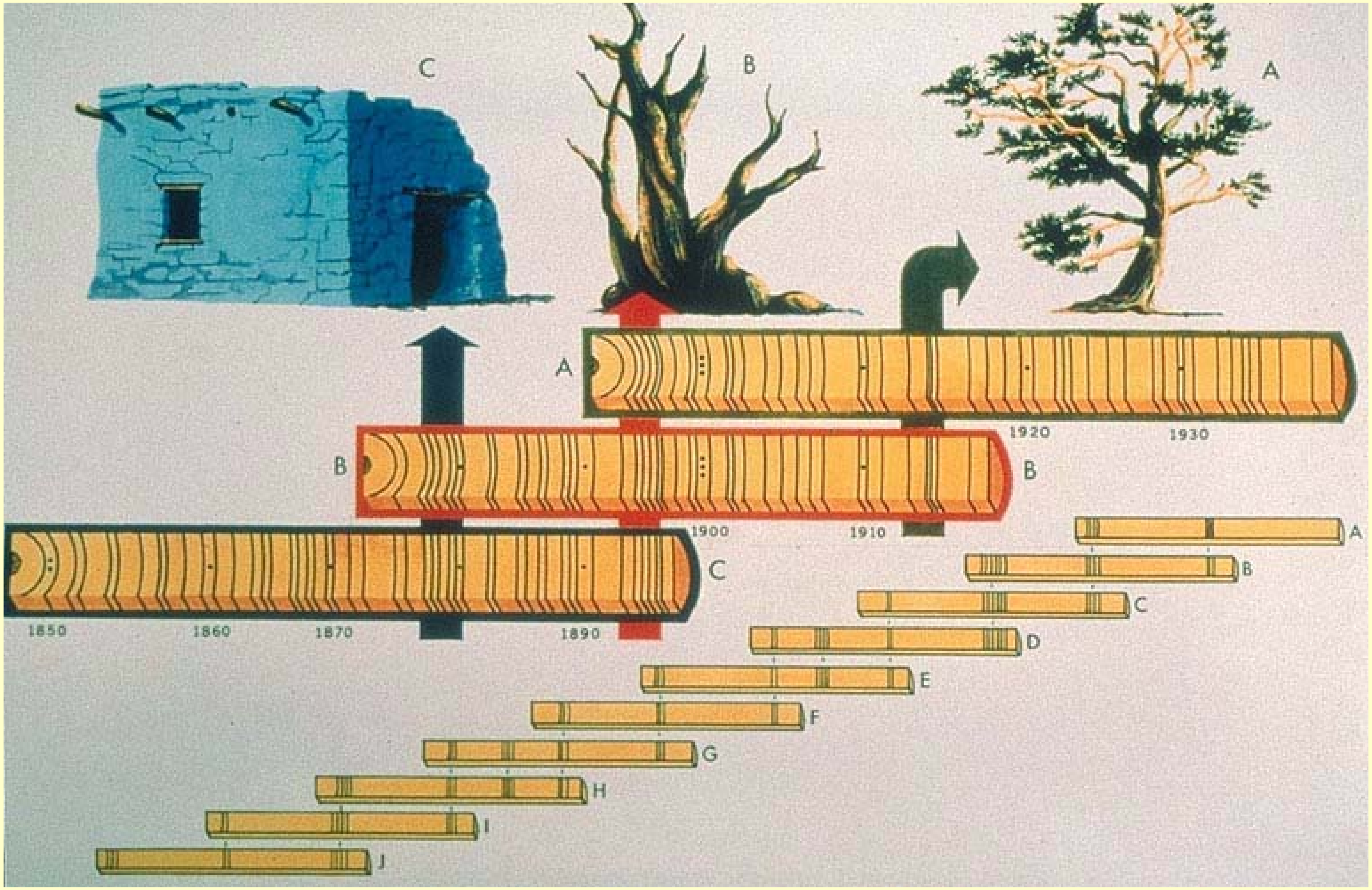
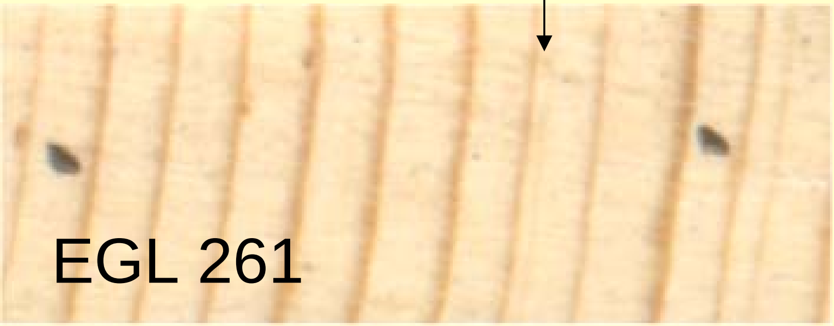
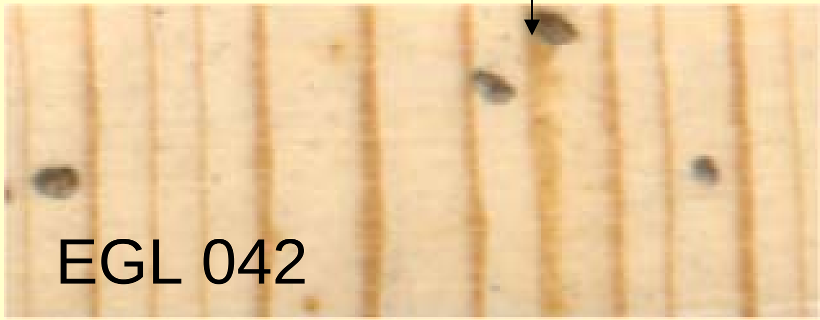


Image courtesy of LTRR (U. AZ)

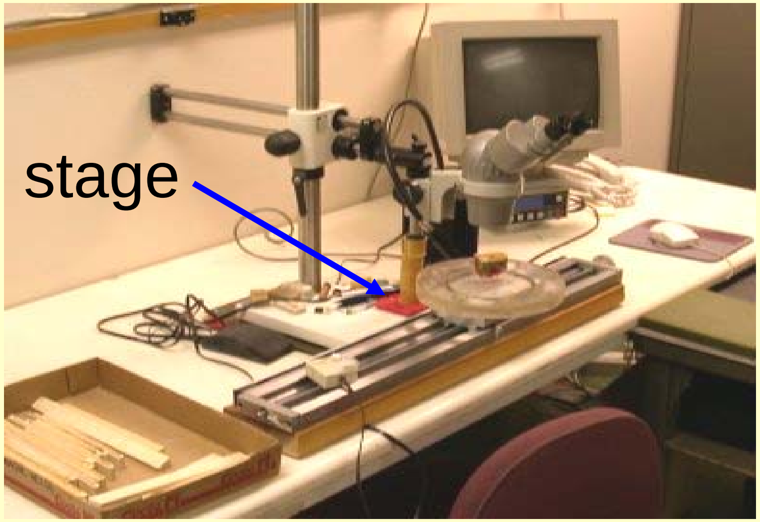
Cross-dating the samples

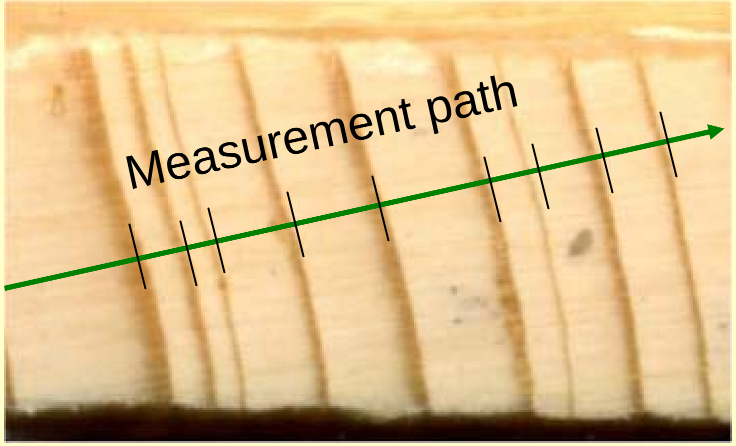
- Crossdating cores from living trees is usually straightforward, since the outside date is known
- Main challenge is inferring absent rings from pattern (mis)matches with other trees
  - frequency of absent rings ranges from 0 - 4% per site
  - cores with up to 10% absent rings can be crossdated





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

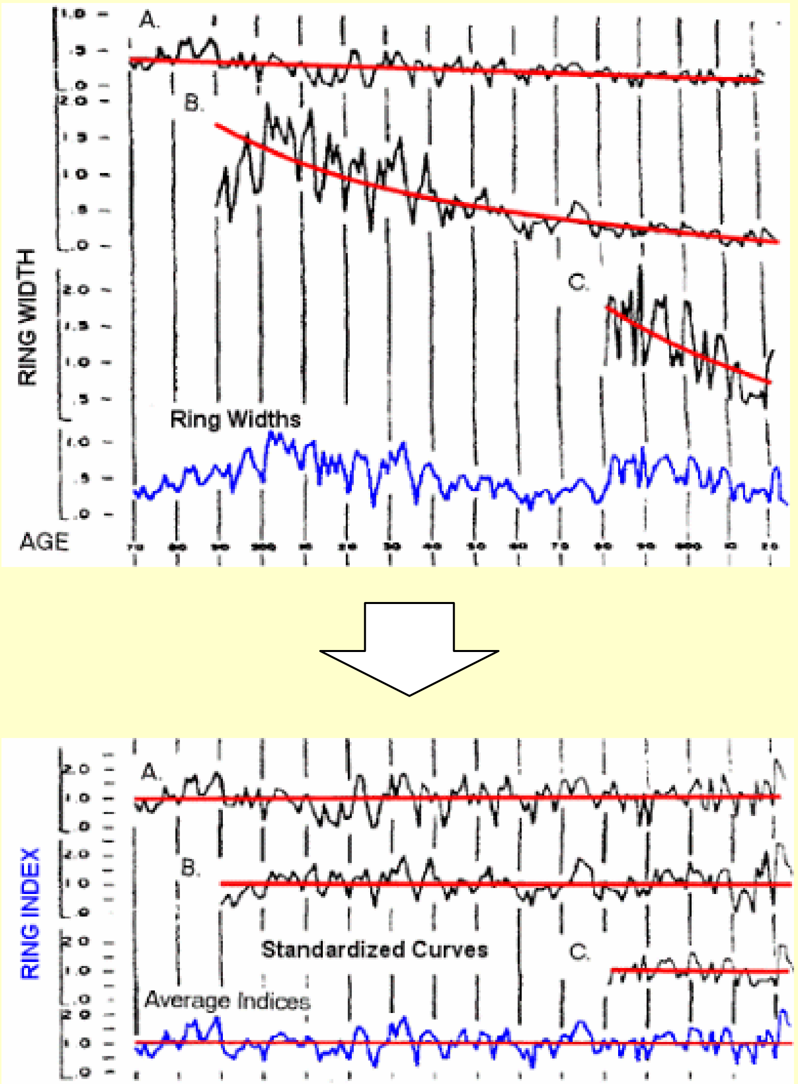
Using COFECHA for quality control

Seq	Series	Time_span		1725 1774	1750 1799	1775 1824	1800 1849	1825 1874	1850 1899	1875 1924	1900 1949	1925 1974	1950 1999
1	rpr051	1849	1920					.68	.78	.87			
2	rpr07	1854	1997						.83	.85	.89	.90	.86
3	rpr061	1745	1936	.23B	.26B	.26B	.18B	.48	.89	.93	.81		
4	rpr011	1860	1997						.65	.71	.83	.90	.86
5	rpr092	1864	1997						.70	.77	.71	.84	.88
6	rpr091	1878	1997							.74	.76	.87	.87
7	rpr061	1743	1997	.37B	.39B	.65B	.76	.81	.91	.92	.92	.90	.89
8	rpr081	1871	1997						.76	.78	.87	.80	.68
9	rpr052	1848	1997					.85	.85	.92	.89	.93	.93
10	rpr051	1848	1997					.88	.88	.91	.90	.92	.91

rpr061 1745 to 1936 192 years

[A] Segment	High	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	+0	+1	+2
1745 1794	-2	_	_	_	_	_	_	_	_	.88*	.14	.23	.12	_.03
1750 1799	-2	_	_	_	.05	_.10	_.06	.45	.09	.86*	.17	.26	.10	_.05
1775 1824	-2	_.15	_.21	_.40	_.14	_.28	.02	.40	.16	.80*	.27	.26	.10	_.18
1800 1849	-1	_.06	.03	_.22	_.41	_.15	.17	.01	.08	.10	.65*	.18	_.14	_.35

Detrending the measured series

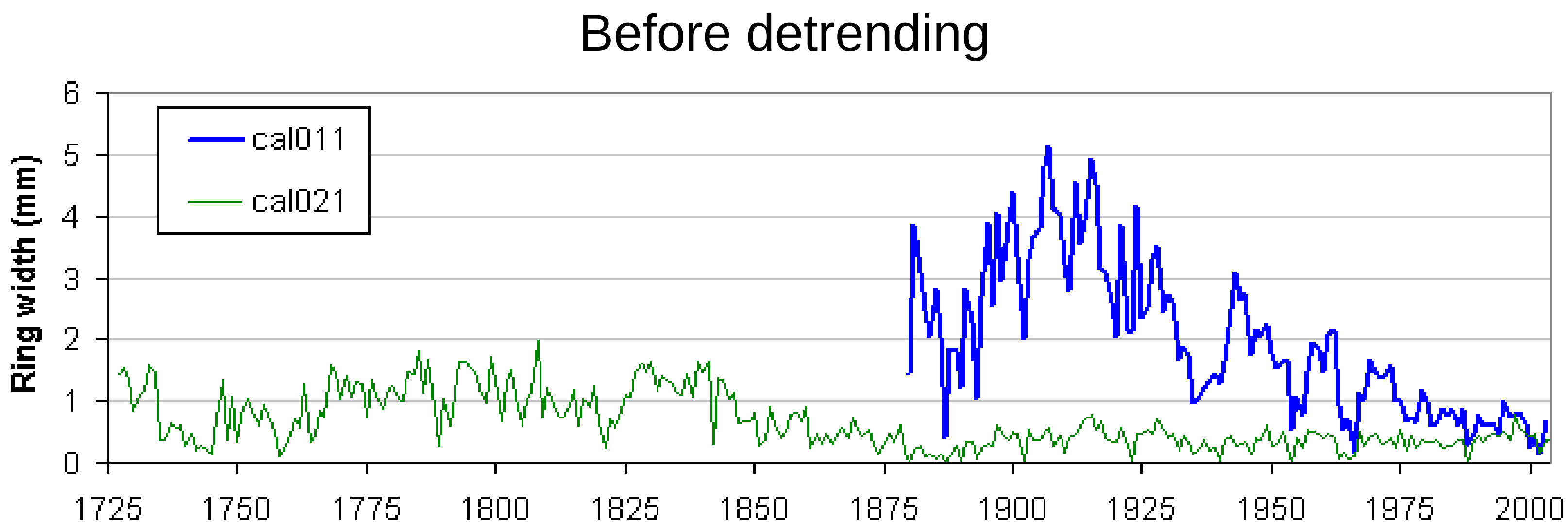


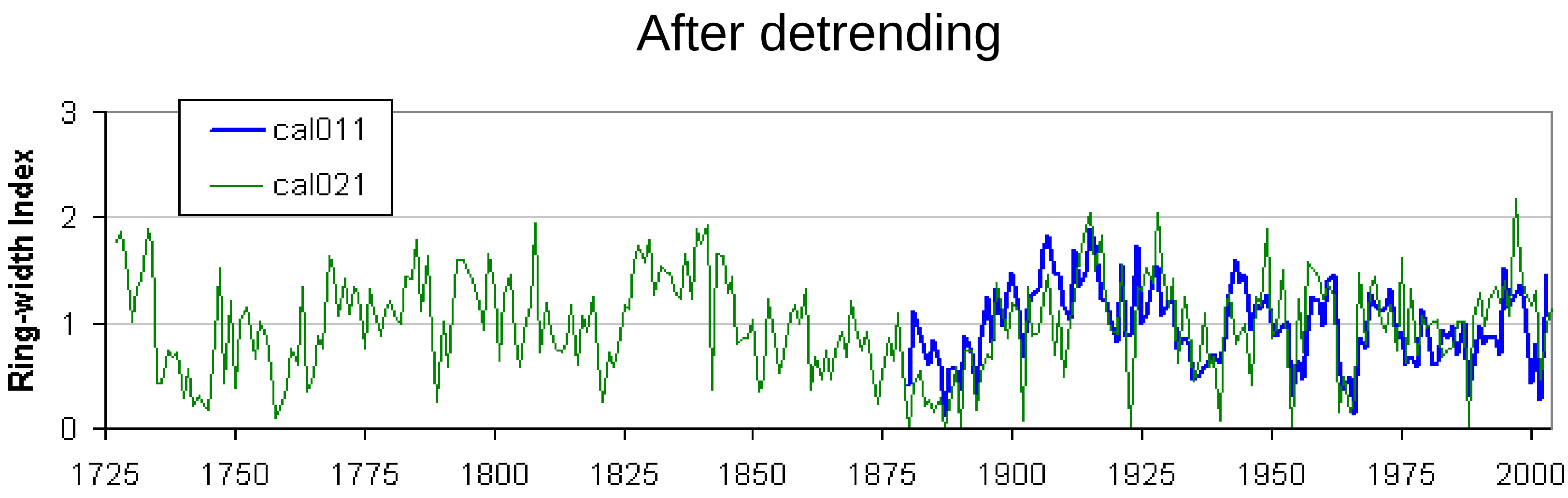
- Ring-width series typically have a declining trend with time due to tree geometry,
- These trends are low-frequency noise (i.e. non-climatic)

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

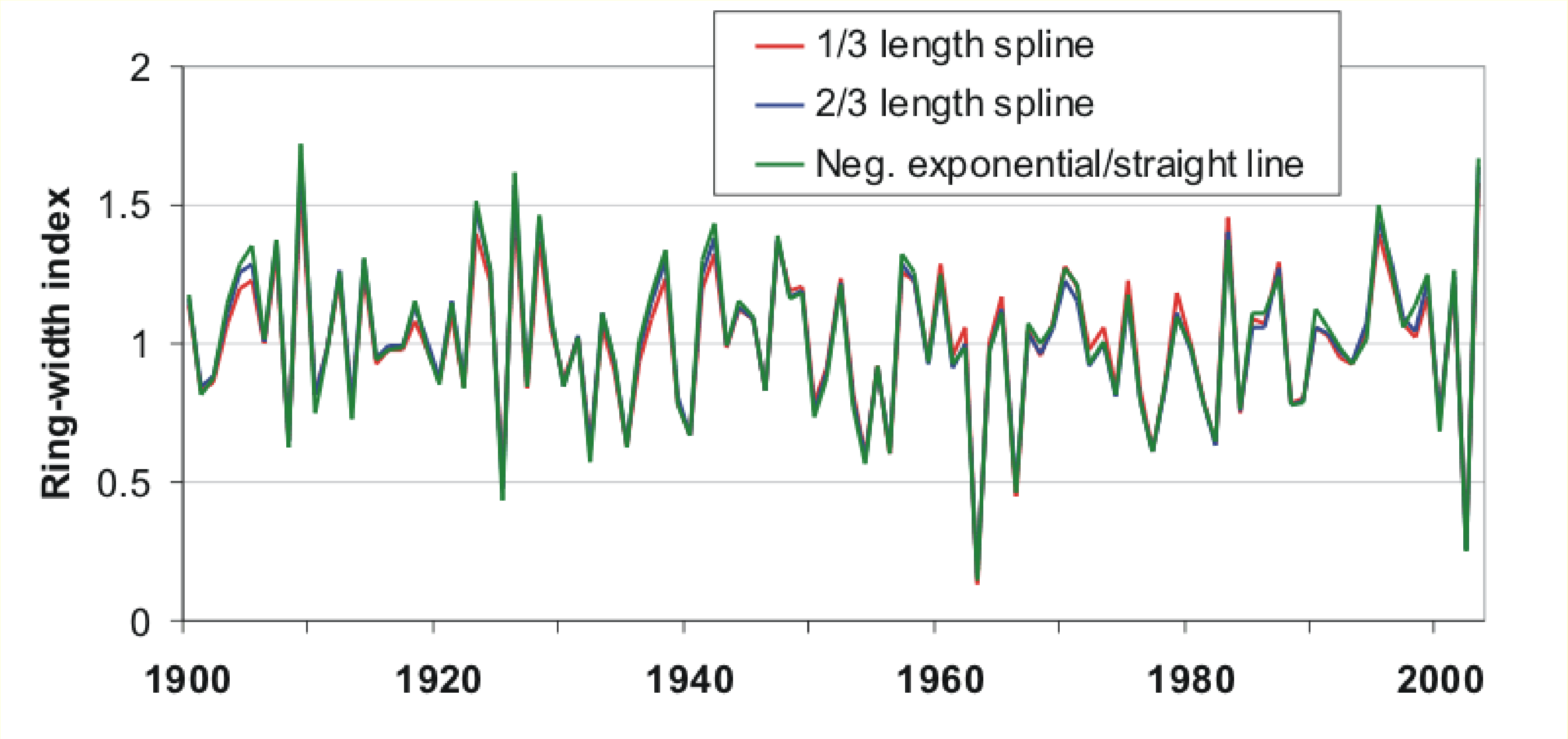
- These standardized curves are compiled into the site chronology

Example of detrending - 2 trees, same site



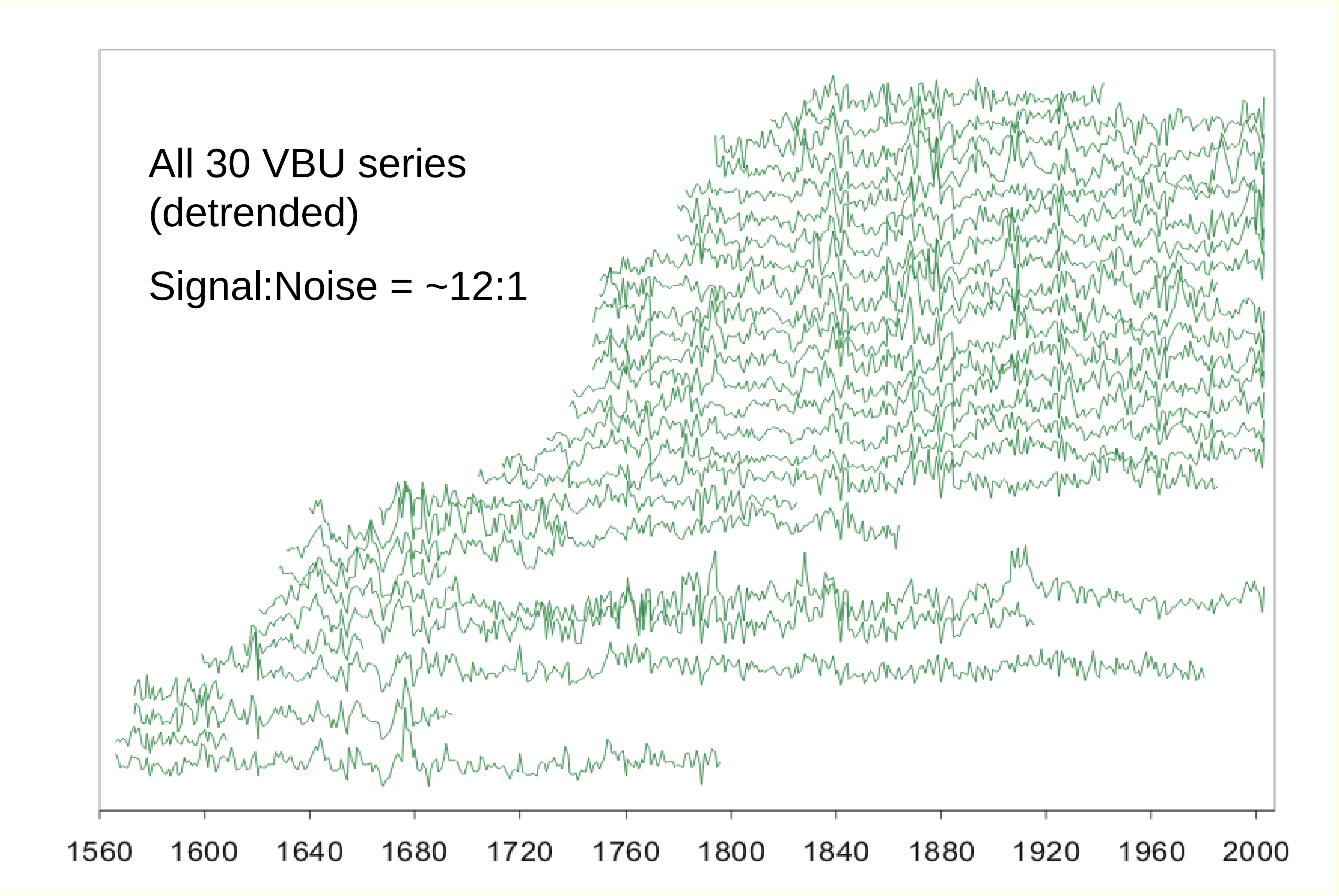


Effects of detrending choice - VBU chronology



- Choice of function(s) for detrending can affect final chronology, but the differences are usually not large

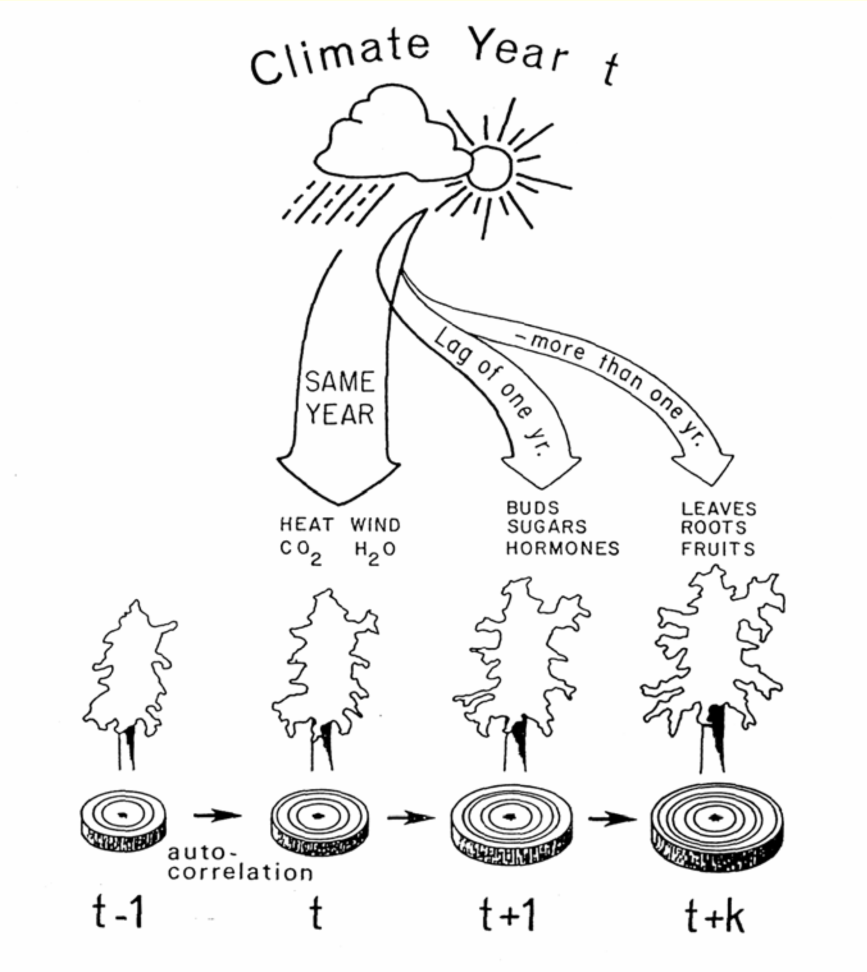
Coherence of signal among series at one site



Persistence in tree growth from year to year

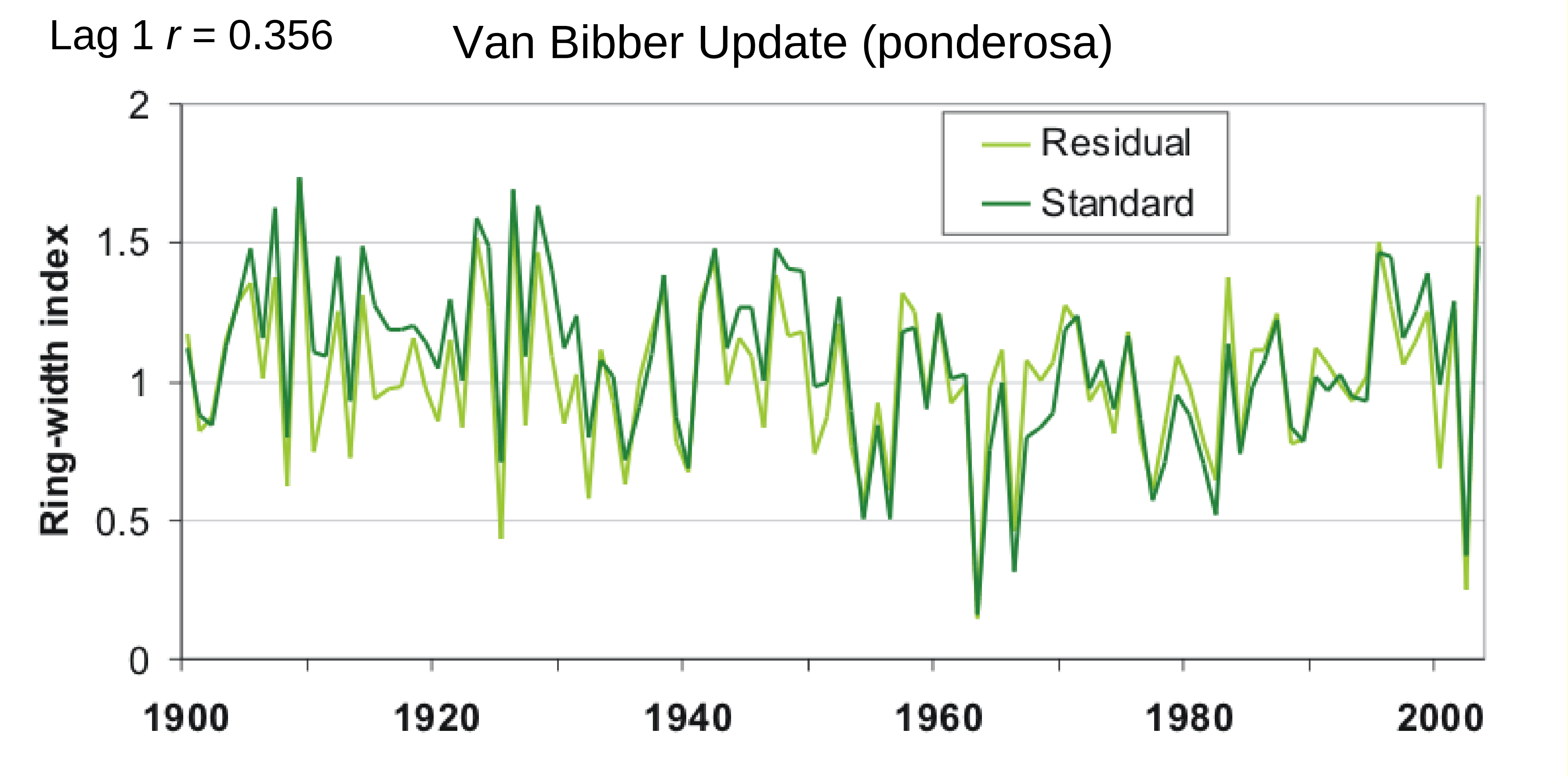
- The climate in a given year (t) can also influence growth in succeeding years (t+1, t+2, etc.) through storage of sugars and growth of needles

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

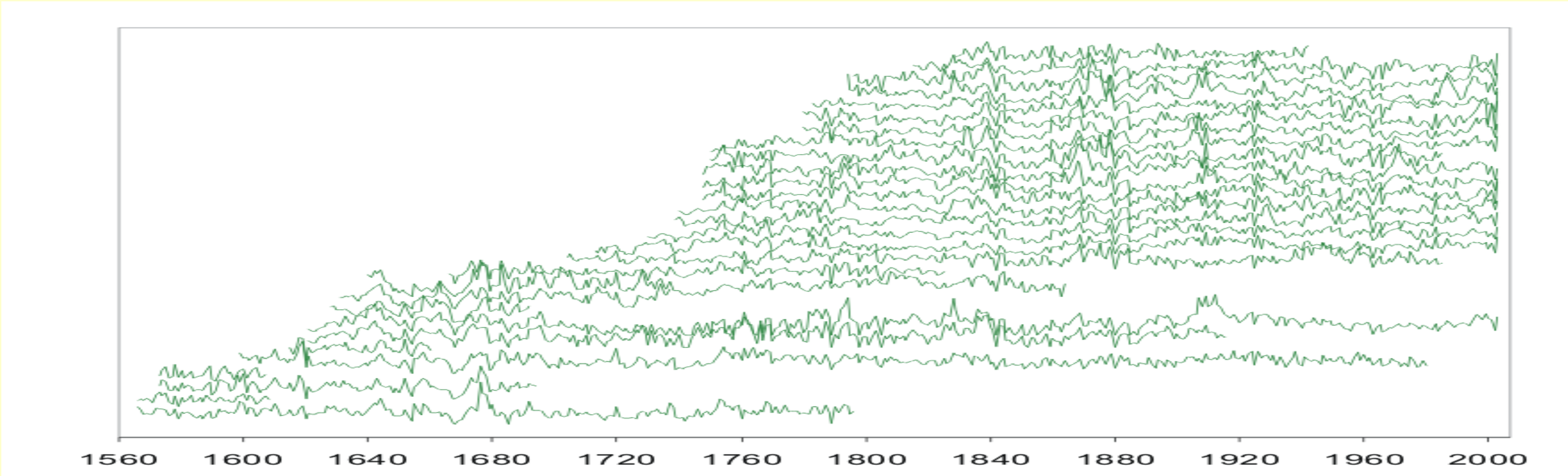


Persistence in the chronology can be retained or removed

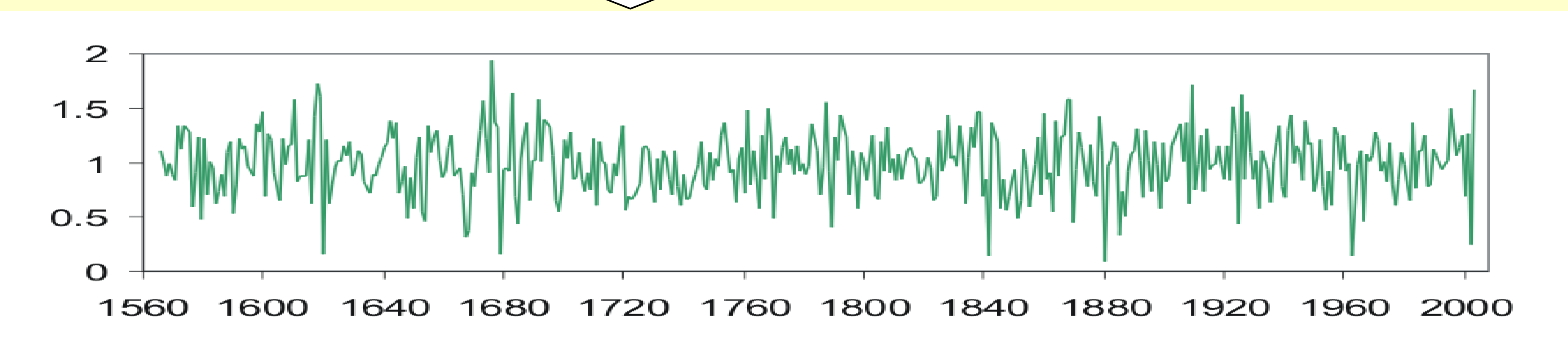
- *Standard chronology:* persistence in the series is retained
- *Residual chronology:* low order persistence is removed from each series before the chronology is compiled



Compiling the chronology

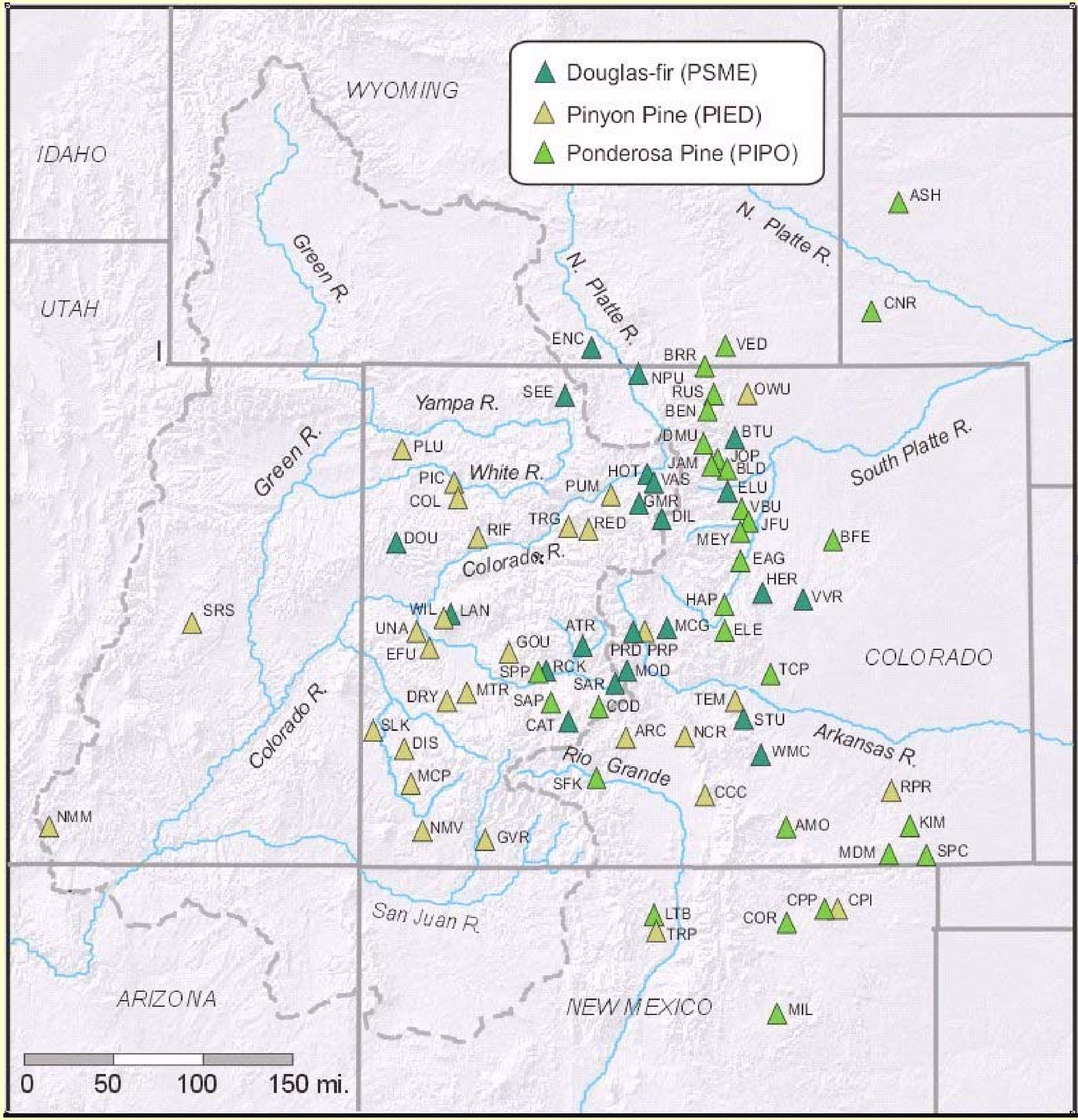


- The detrended series are robustly averaged, which reduces the effect of outliers

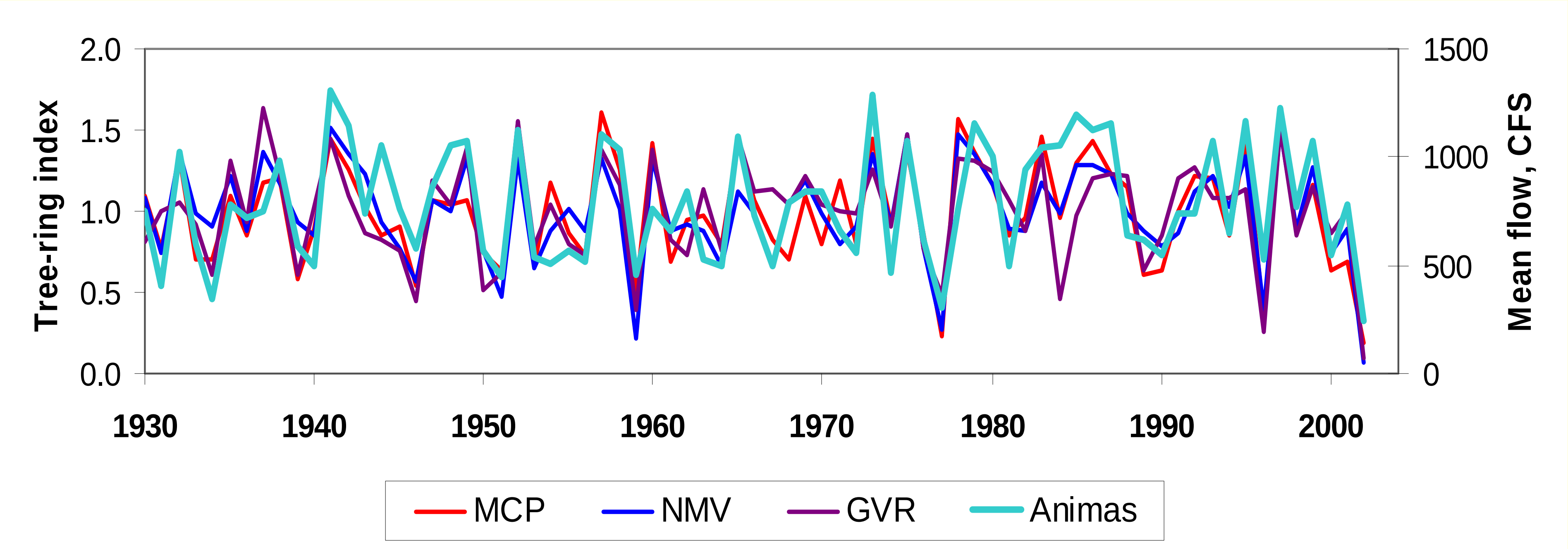


New moisture-sensitive chronologies in Colorado

- Average length: 550 years
- Strong relationships with annual precipitation and annual streamflow



Three pinyon chronologies near Durango vs. Animas at Durango gaged mean annual discharge



Correlations:

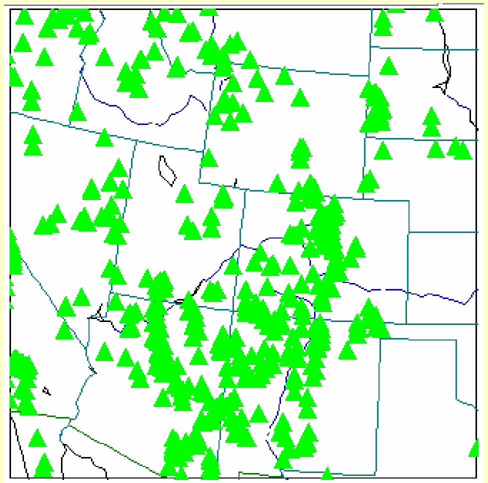
MCP-Animas: **0.79**

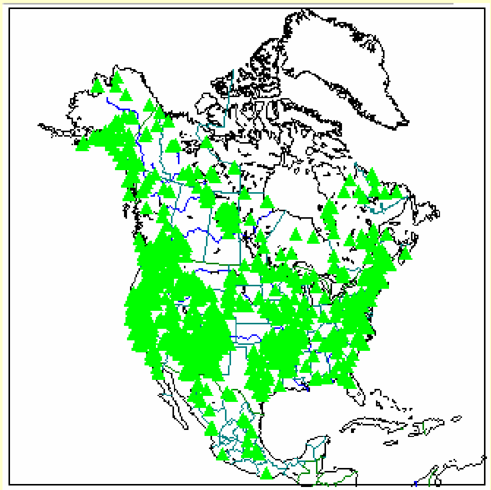
NMV-Animas: **0.78**

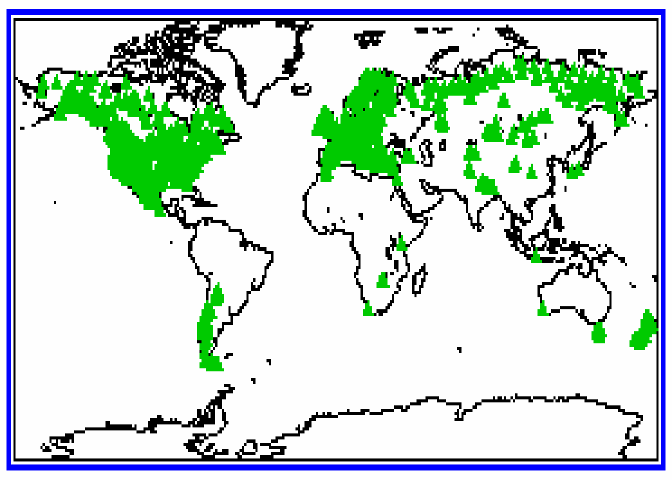
GVR-Animas: **0.62**

The larger world of tree-ring chronologies

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



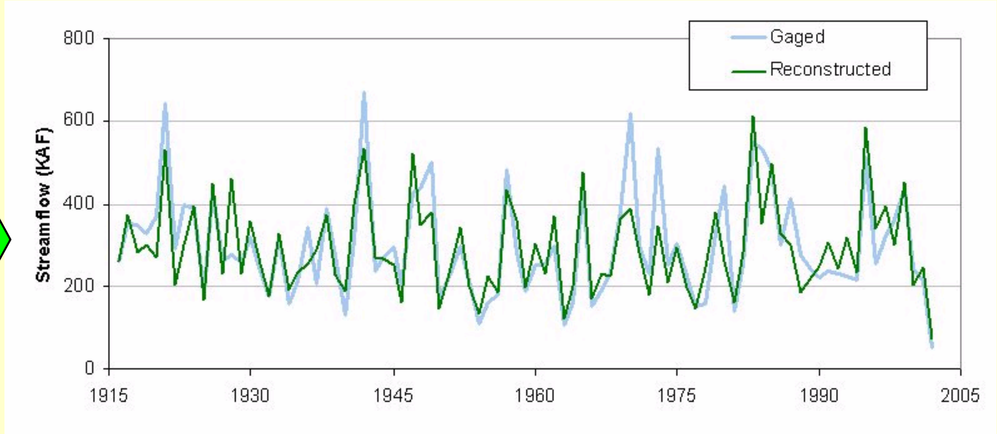




- 2500 chronologies contributed from all over the world
- Can be searched by moisture-sensitive species, location, years

Part 4:

Generating the streamflow reconstruction



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

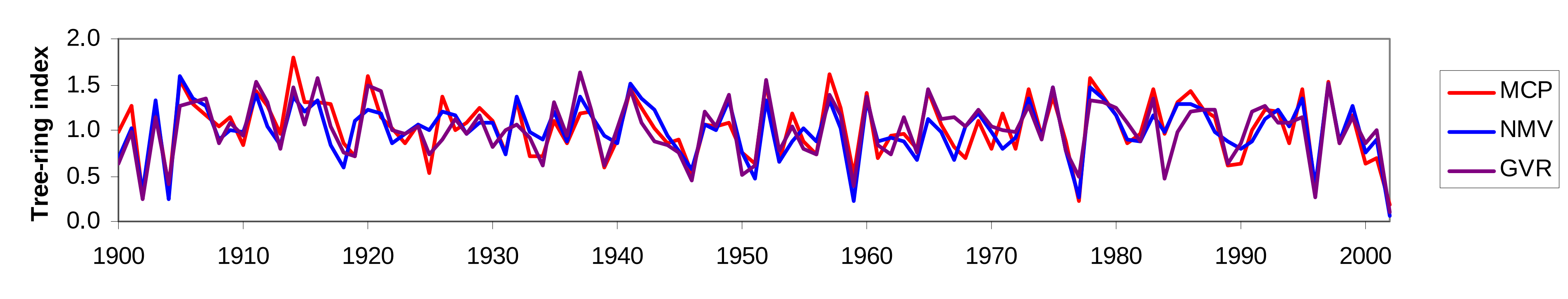
Assumptions behind the reconstruction methodology

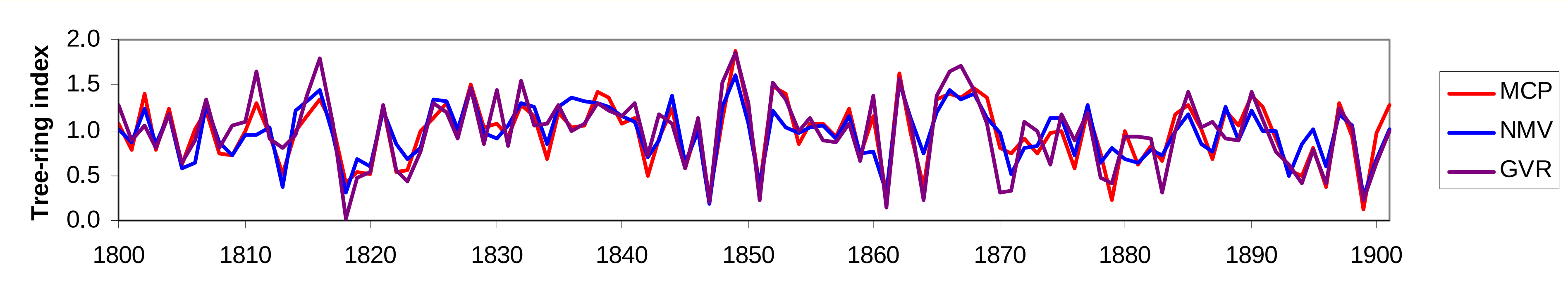
1) That the relationship between tree growth and streamflow has been stable over the past several centuries

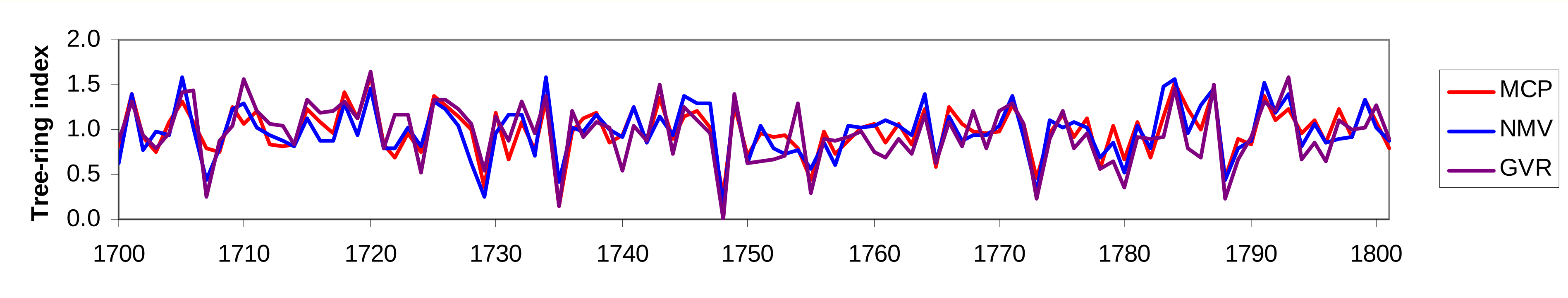
2) That the trees that do the best job of estimating the gaged flows will do the best job of estimating the pre-gaged-record flows

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

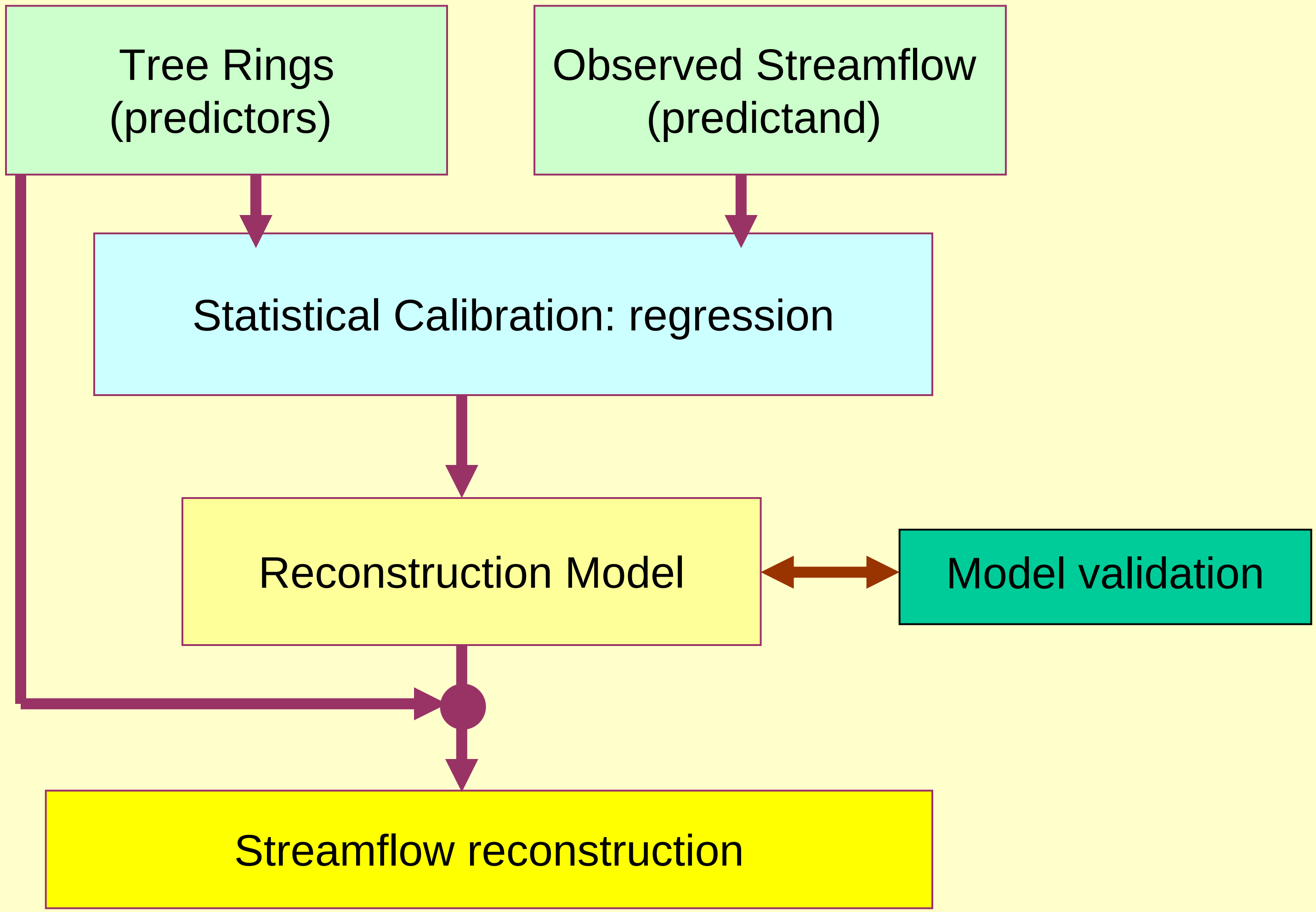
Three pinyon chronologies near Durango







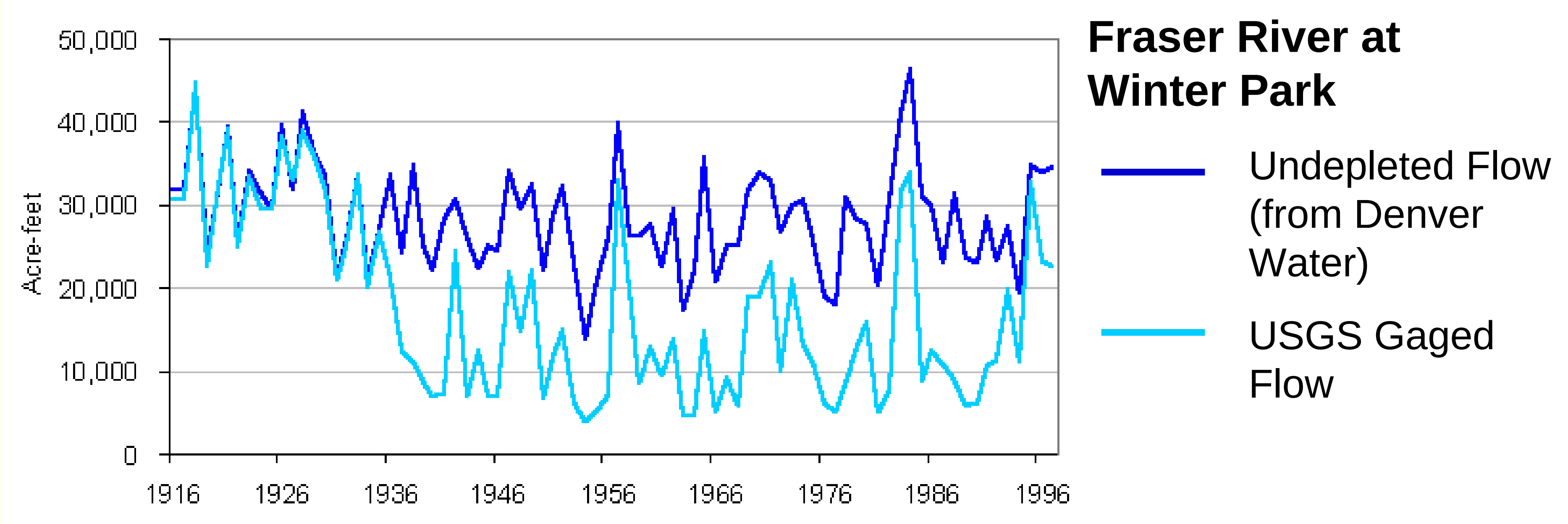
Overview of reconstruction methodology



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.



About natural/undepleted flow records

- Record/estimates/models of depletions and diversions often inadequate, especially in early part of record
- The resulting uncertainties are added to typical errors in gage record (~5-10%)
- ***Our naïve view was:*** Flow record is “gold standard”, and where the tree-ring record varies from it, the trees are in error
- ***More realistic view:*** Flow record is a representation of actual flow, and discrepancies with tree-ring reconstruction *could* be due to errors in the flow record
- *The reconstruction can only be as good as the flow record on which it is calibrated*

Data selection - tree-ring chronologies

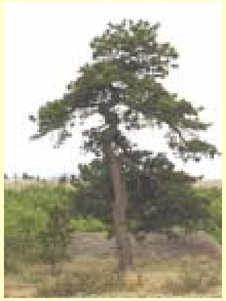
- **Moisture sensitive species** - in Colorado and Southwest: Douglas-fir, ponderosa pine, pinyon pine
- **Location** – from a region that is climatically linked to the gage of interest (more on this later)
- **Years -**

  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

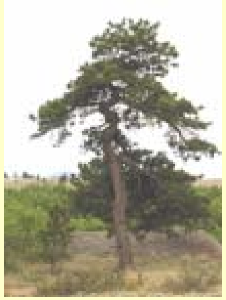
  - *reconstructions are limited by the shortest chronology*

ITRDB demo

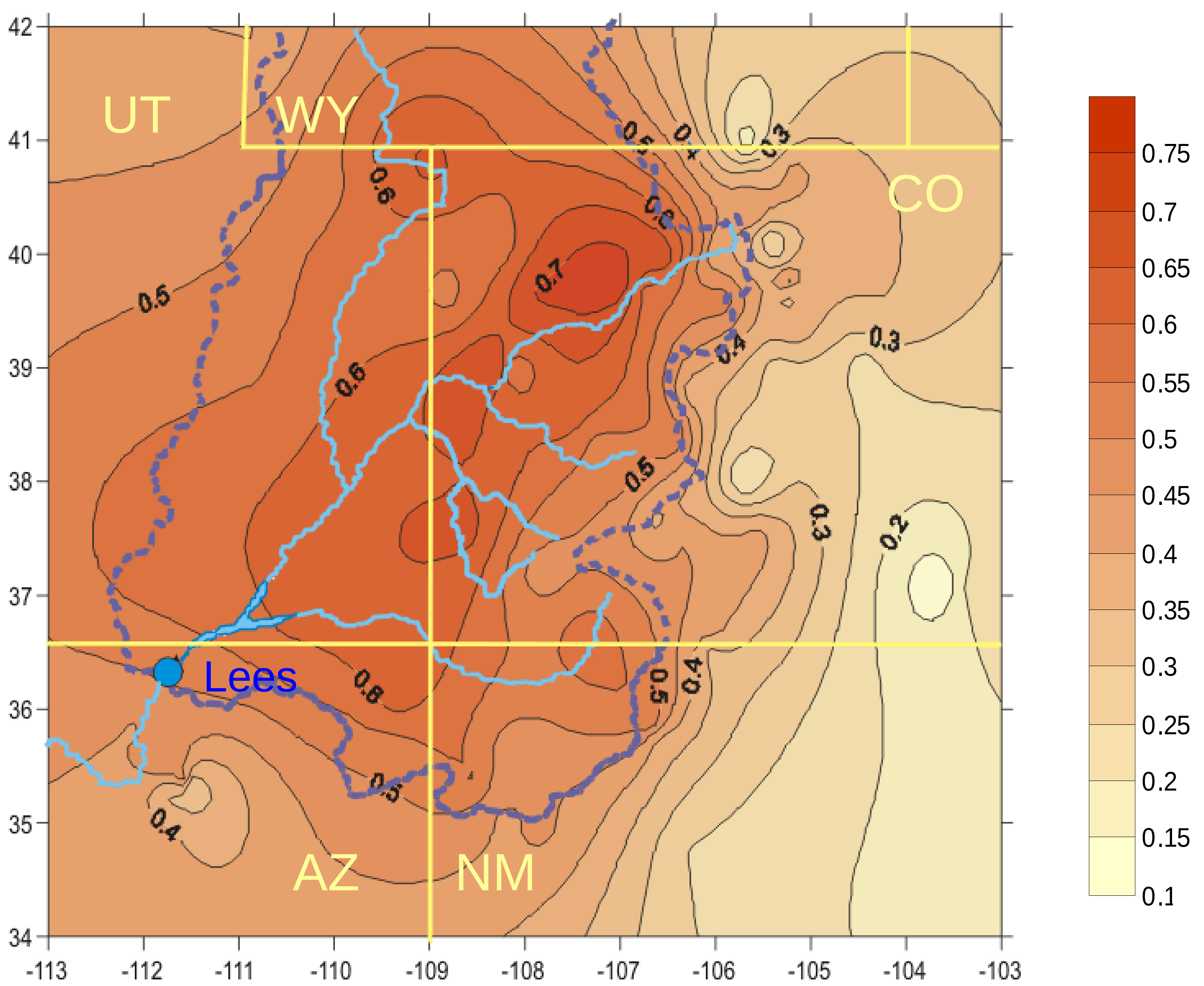


Physical linkage between tree growth and streamflow – regional climatology

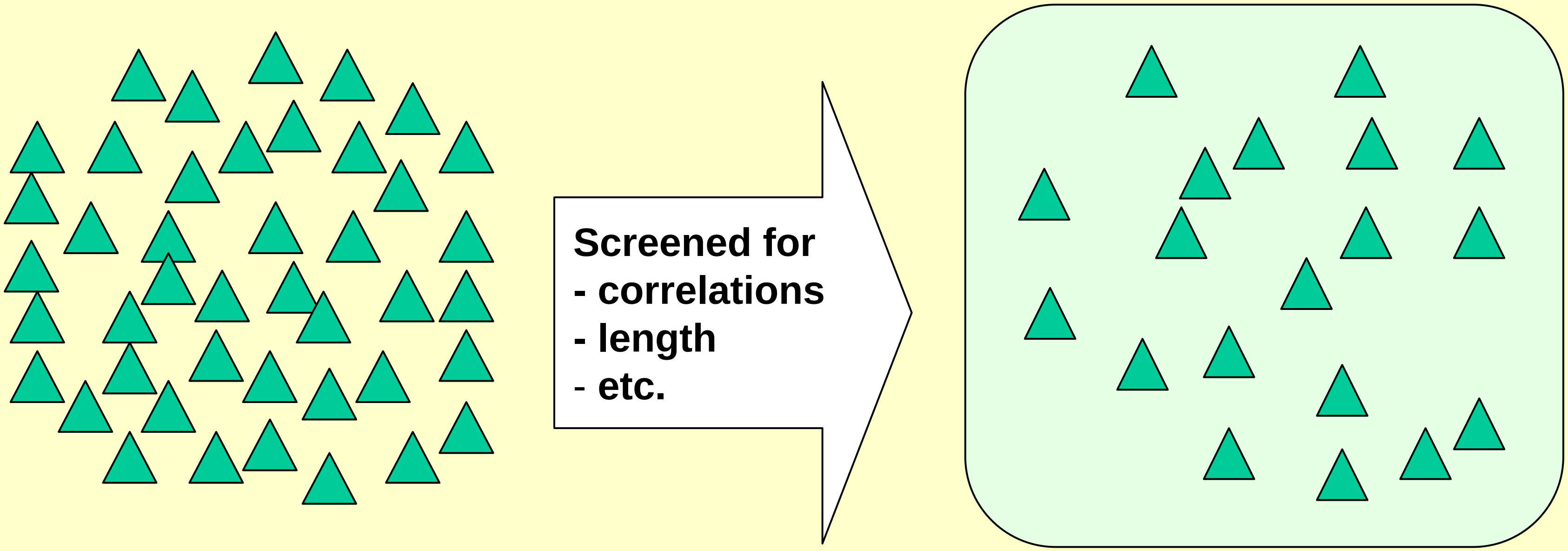
- Chronologies up to 300-400 miles from a gage may be significantly correlated because of a homogeneous climate across the region
- Because weather systems cross watershed divides, chronologies do not have to be in same basin as gage record
- At greater distances, any correlation could be due to *teleconnections*, which may not be stable over time



Correlations: Tree-ring chronologies - Lees Ferry streamflow



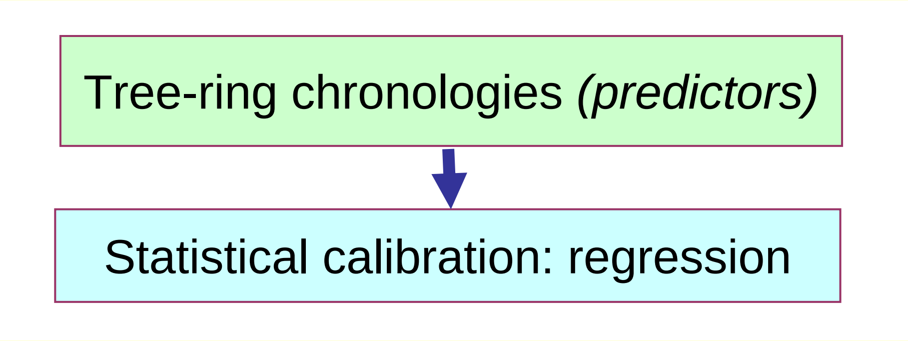
After *data selection and evaluation*, a pool of potential tree-ring predictors is generated



- 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

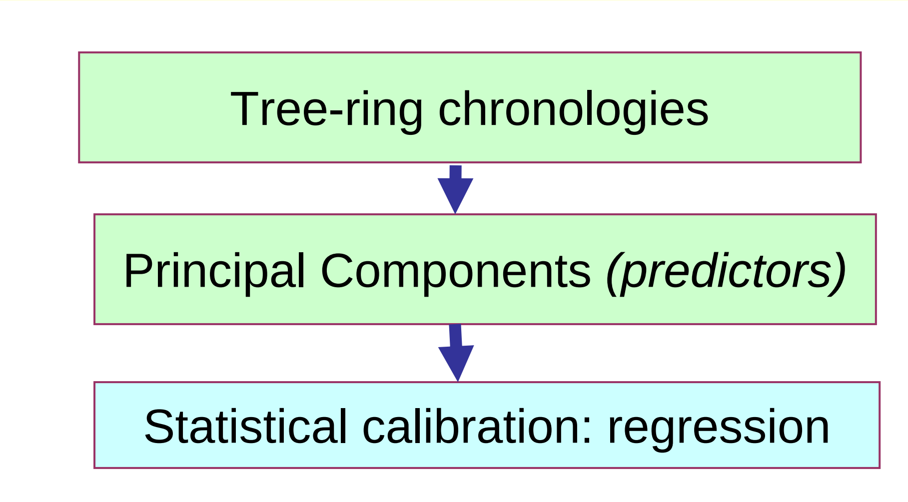
Reconstruction modeling strategies

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



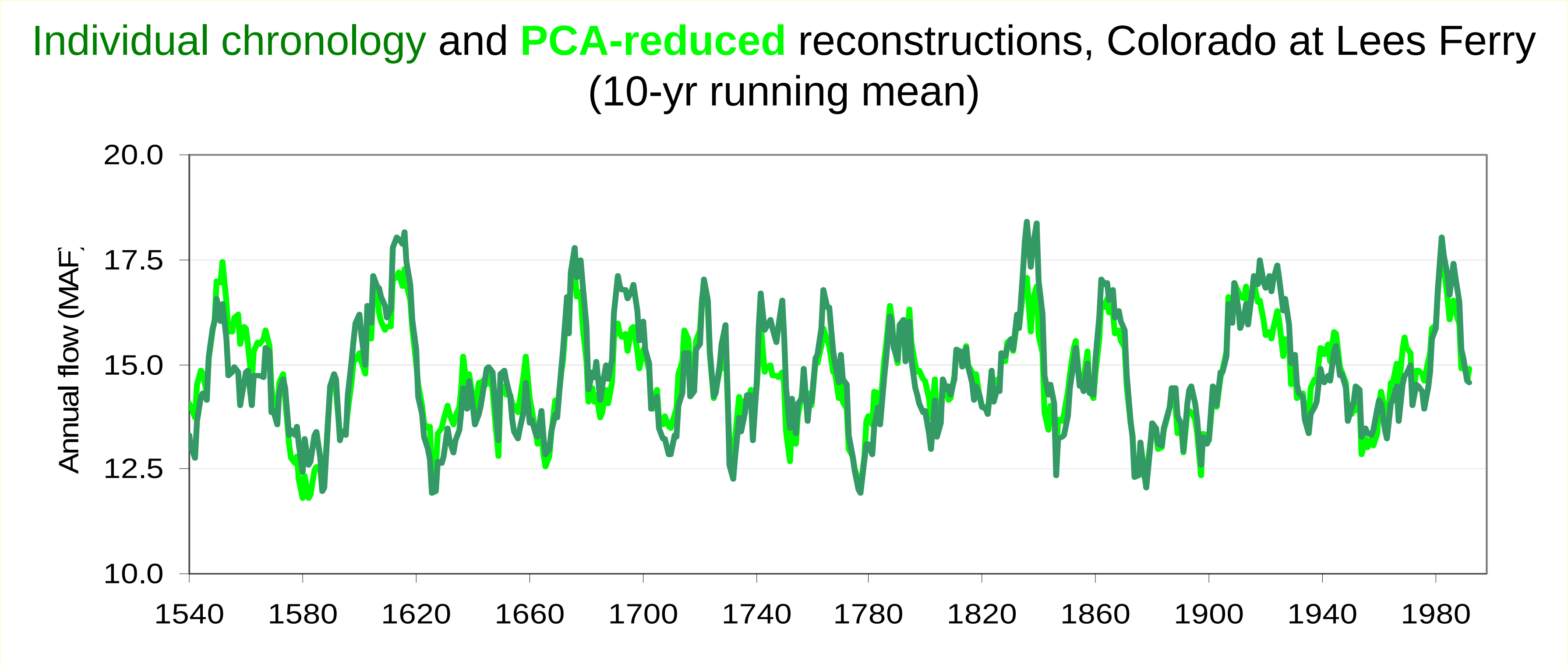
OR

- **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)

Reconstruction modeling strategies

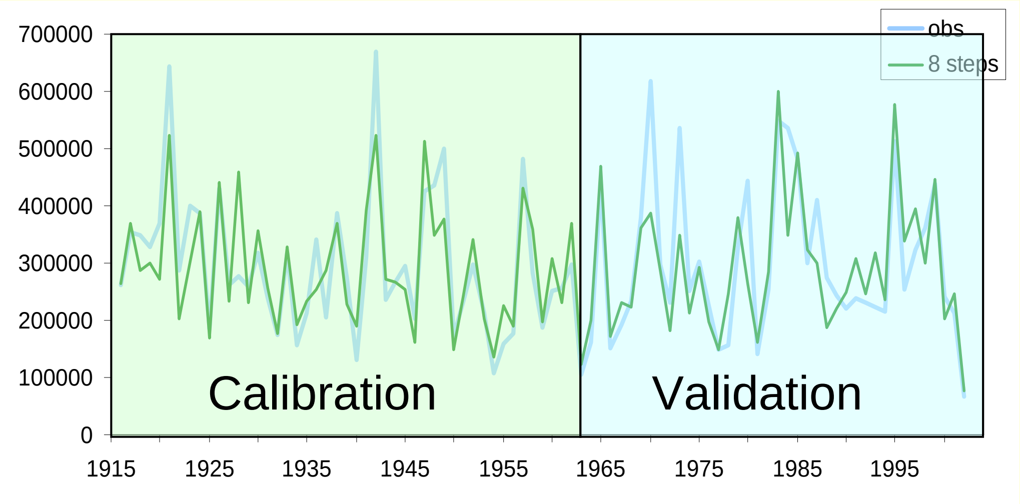


- The differences in final output between the two main strategies may not be very large, particularly if the primary predictor chronologies in the stepwise regression equation are dominant in the first few principal components

Model validation strategy

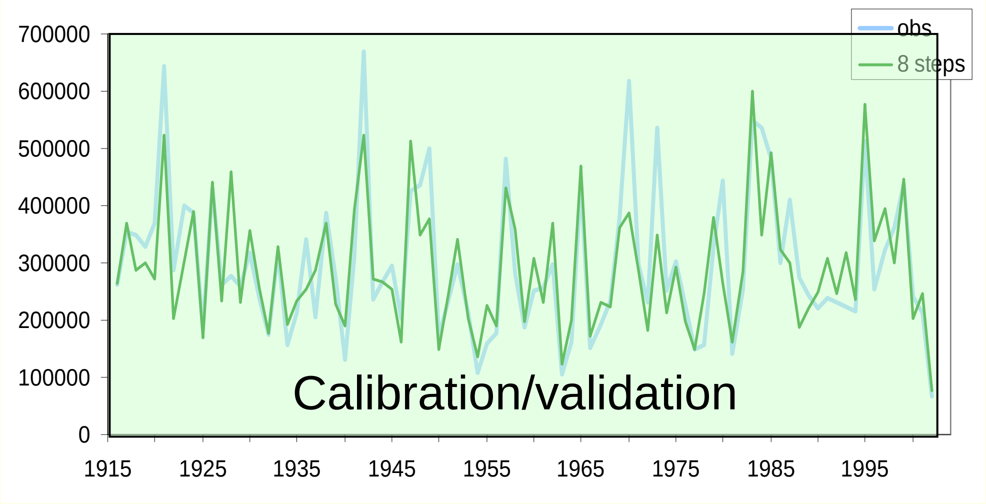
Goal: to calibrate model on a set of data, and validate the model on an independent set of data

Split-sample with independent calibration and validation periods



OR

Cross-validation (“leave-one-out”) method

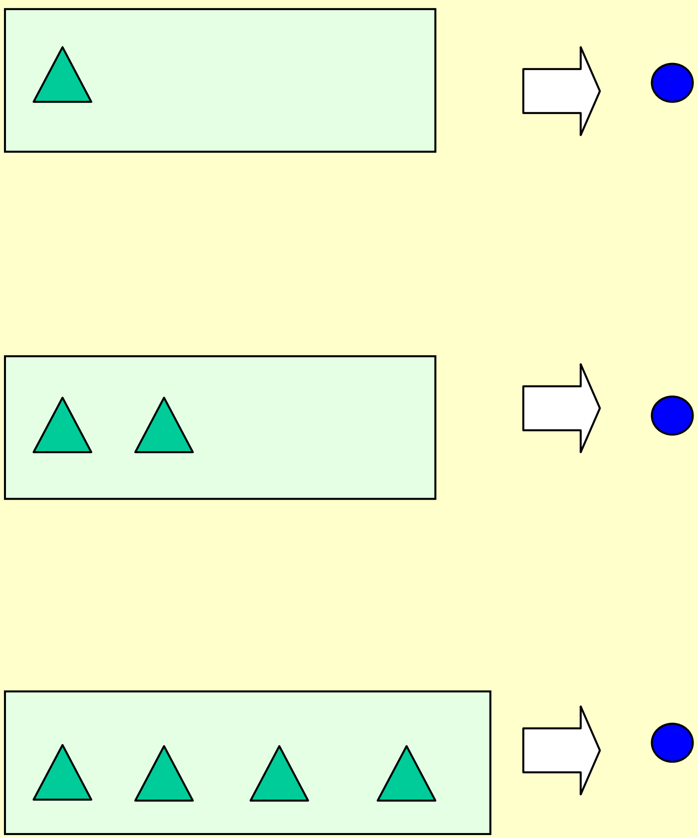


Model calibration: Forward stepwise regression

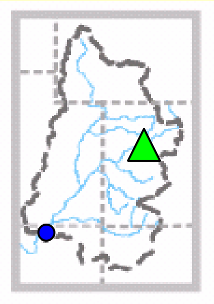
1) The chronology that explains the most variance in the flow record is selected as the first predictor in the regression

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



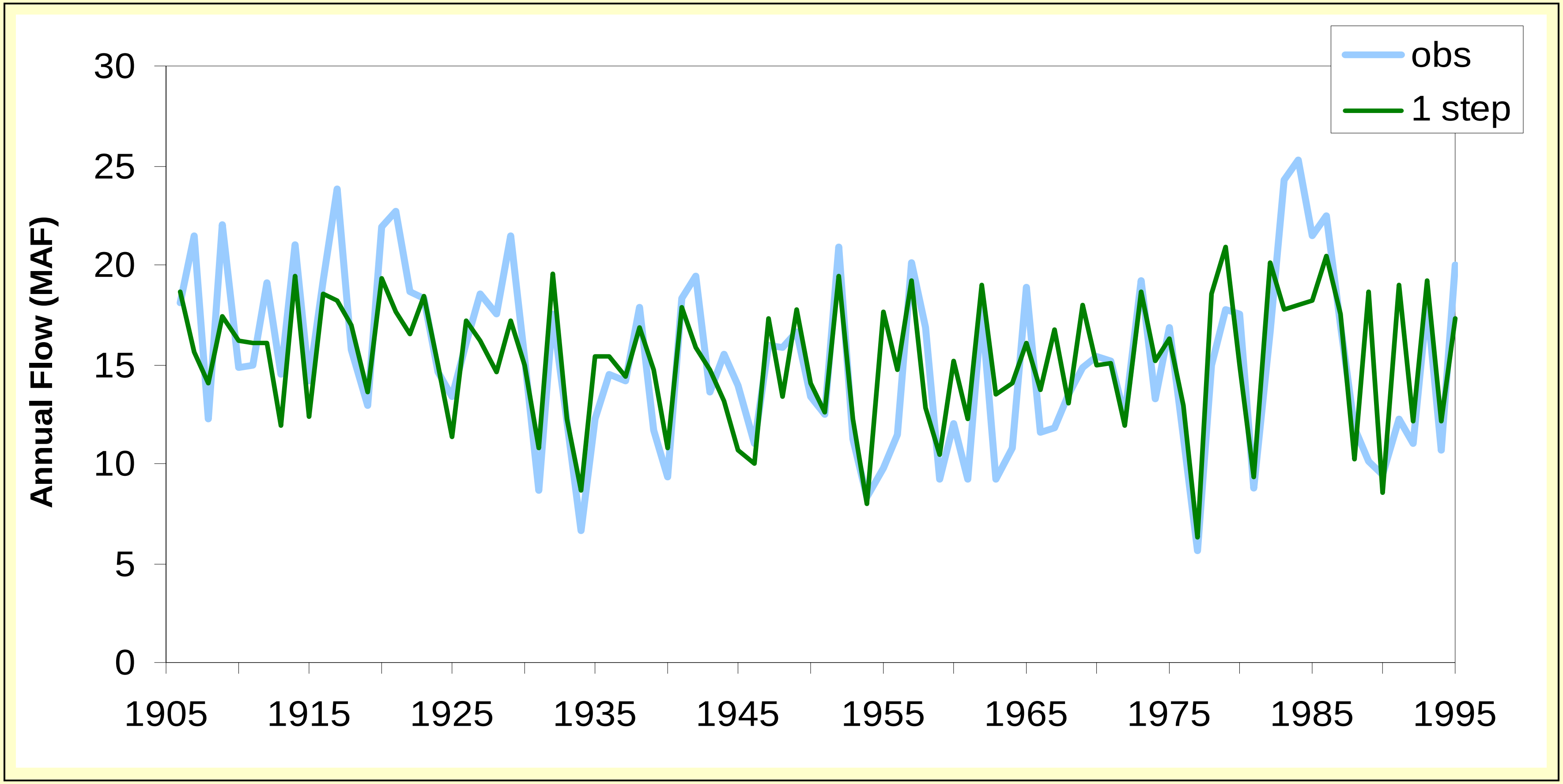
Colorado at Lees Ferry - forward stepwise regression



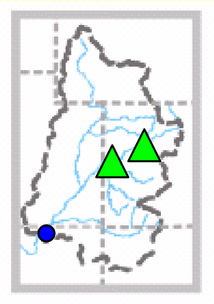
TRG

Variance Explained

55%



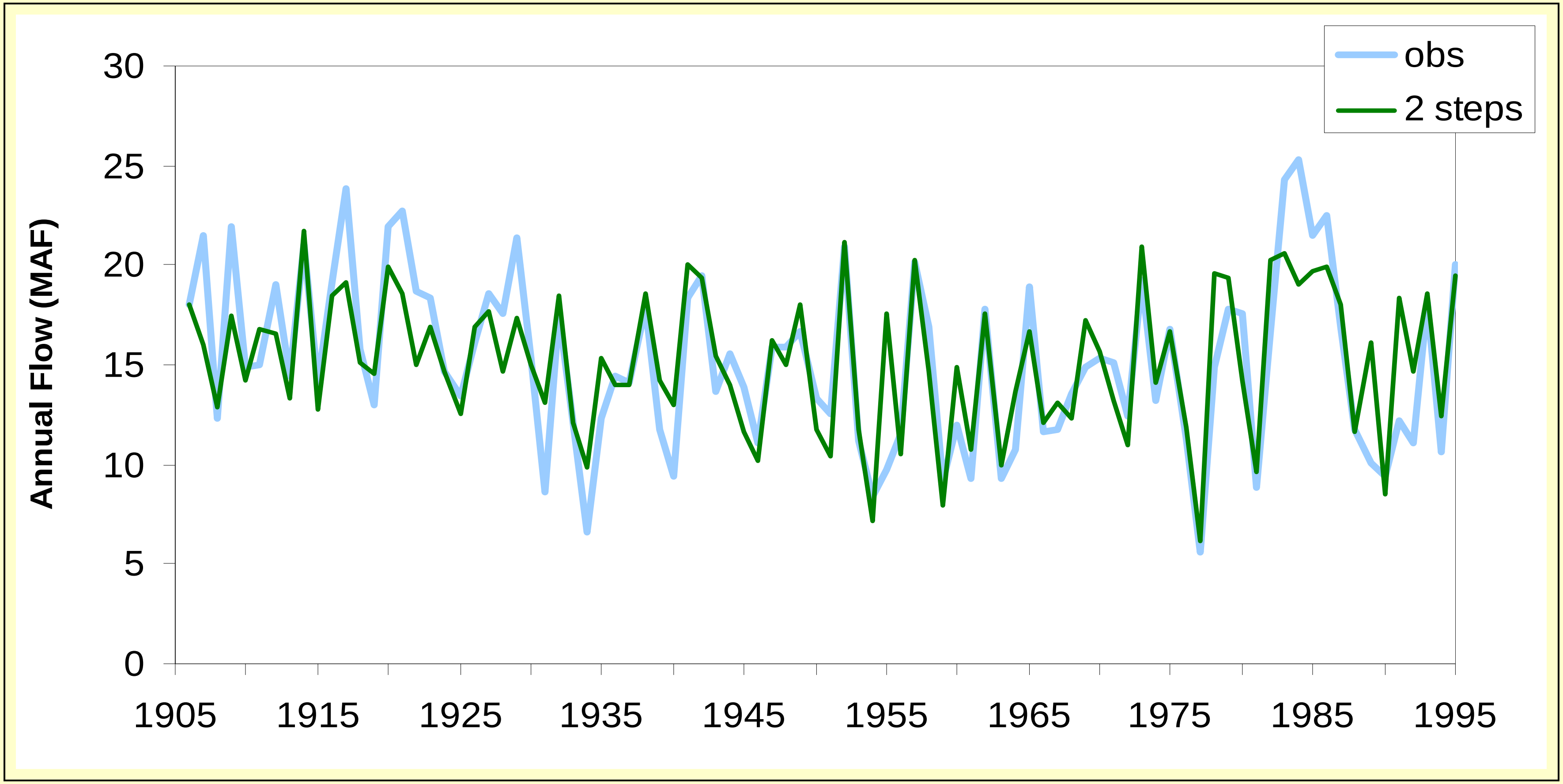
Colorado at Lees Ferry - forward stepwise regression



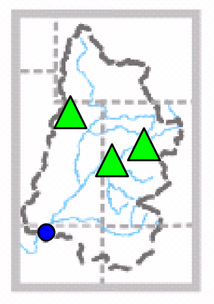
TRG + WIL

Variance Explained

67%



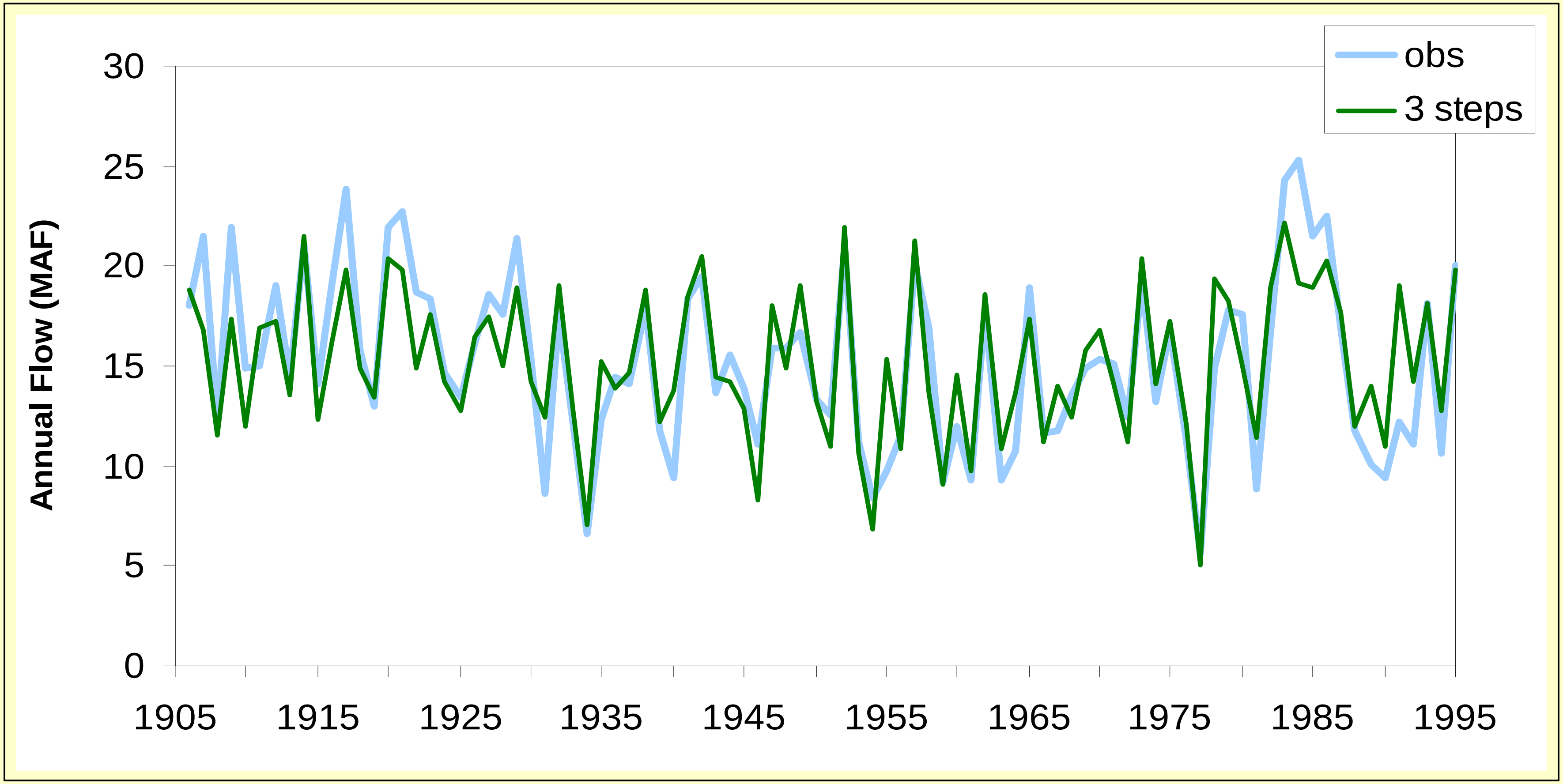
Colorado at Lees Ferry - forward stepwise regression



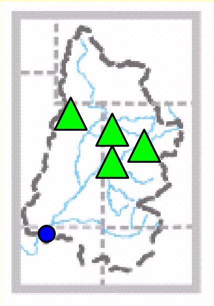
TRG + WIL + DJM

Variance Explained

72%



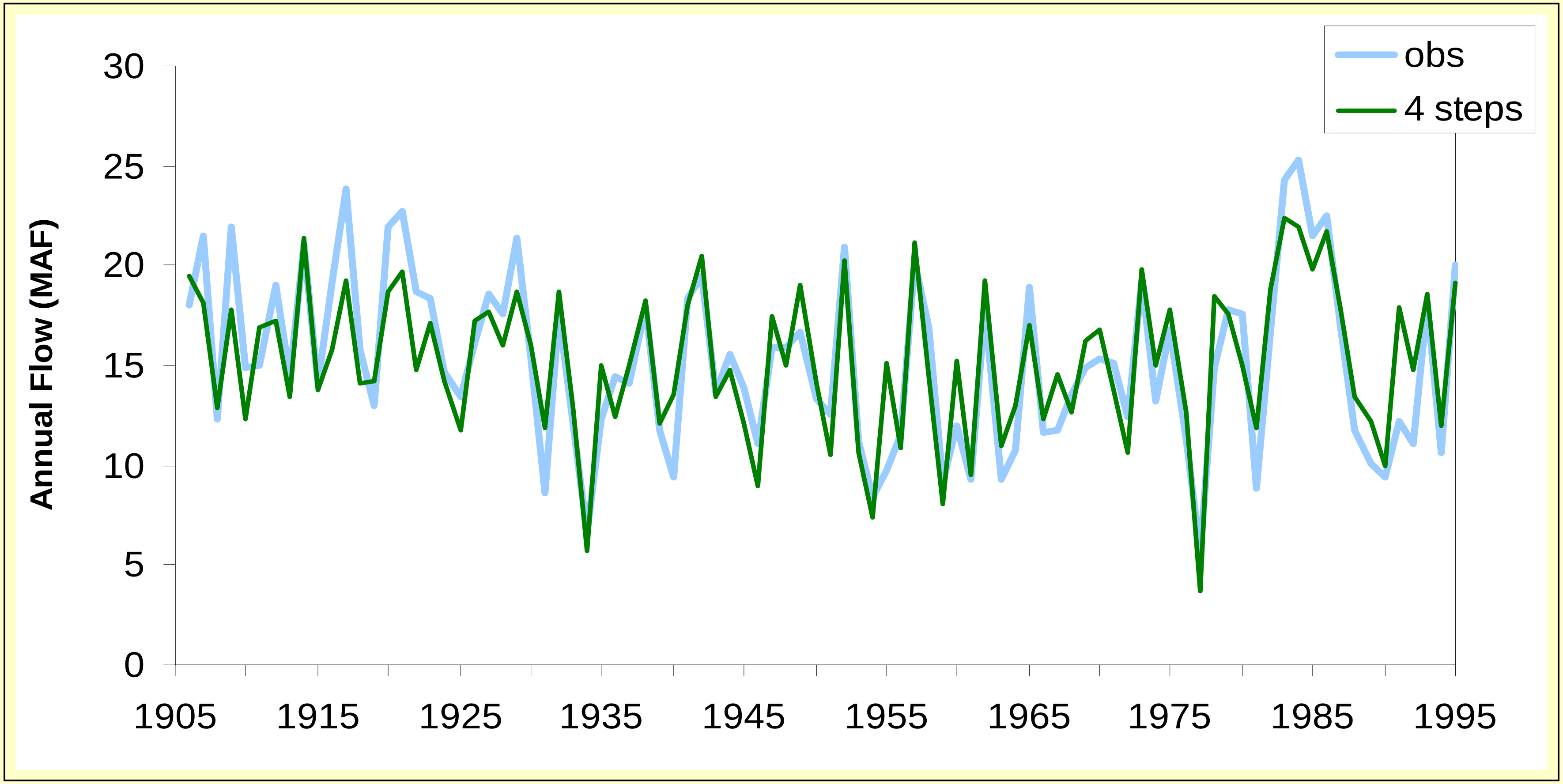
Colorado at Lees Ferry - forward stepwise regression



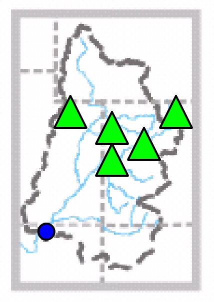
TRG + WIL + DJM + DOU

Variance Explained

75%



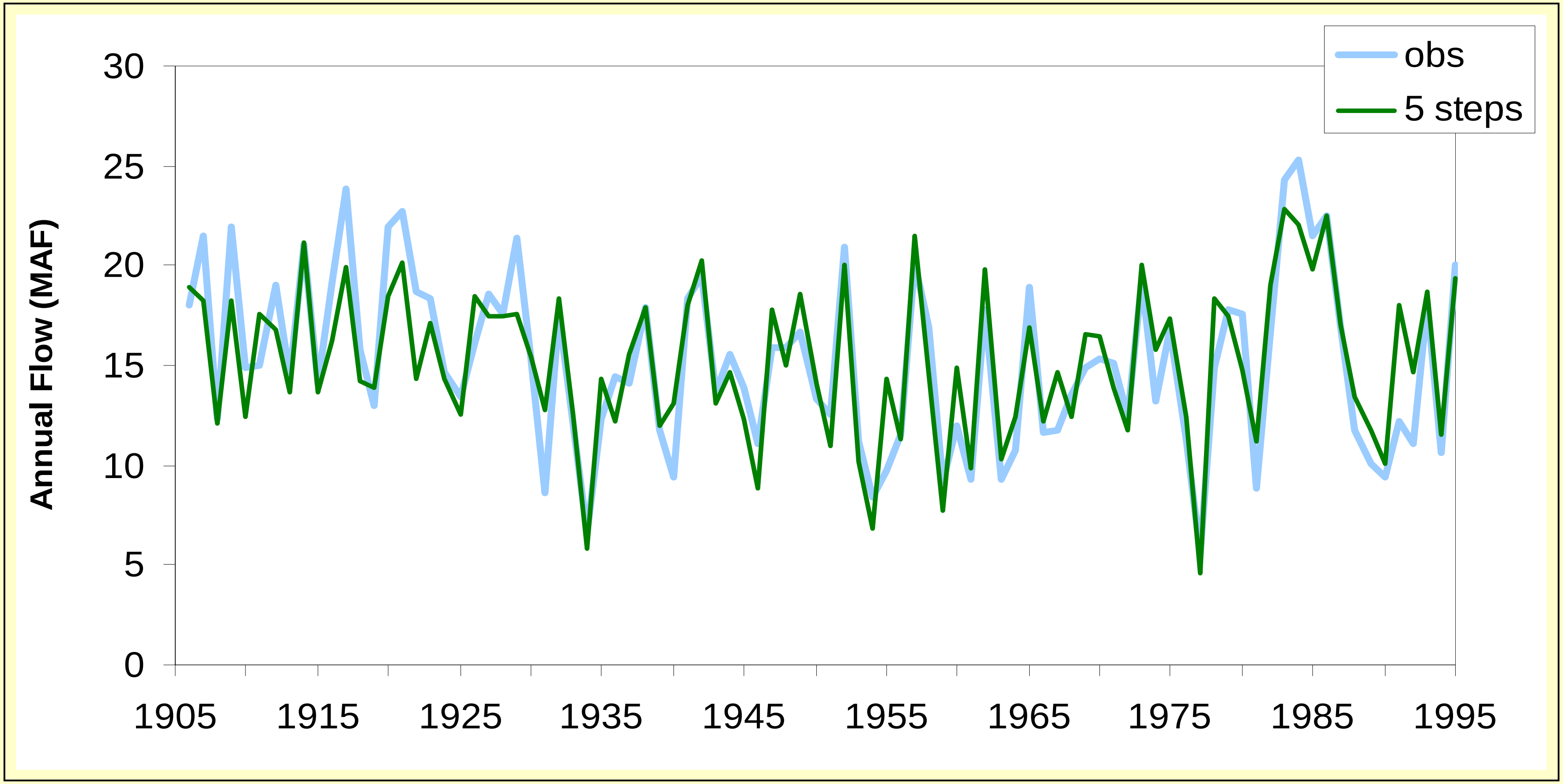
Colorado at Lees Ferry - forward stepwise regression



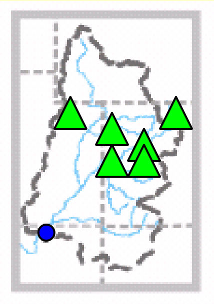
Variance Explained

77%

TRG + WIL + DJM + DOU + NPU



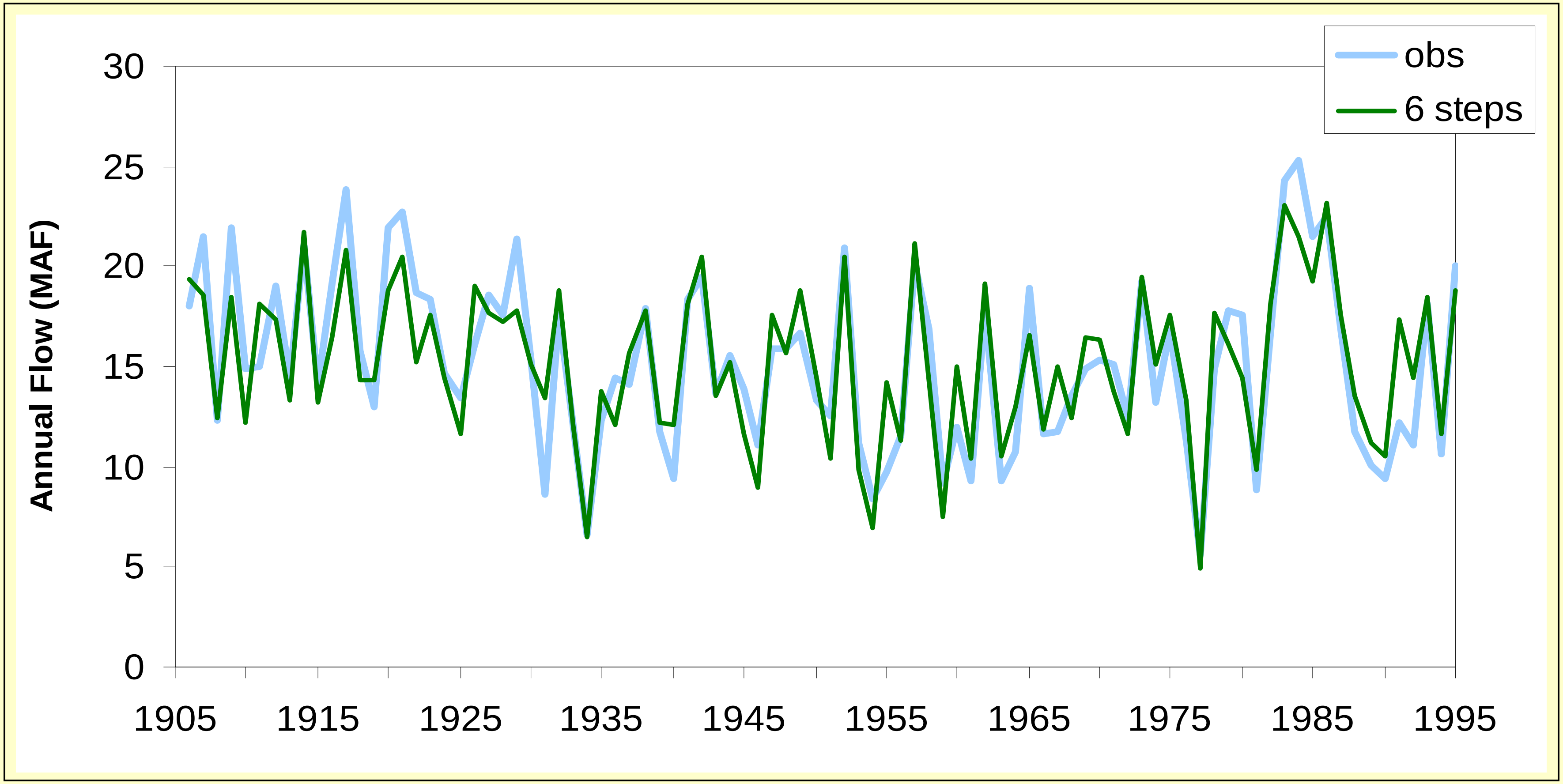
Colorado at Lees Ferry - forward stepwise regression



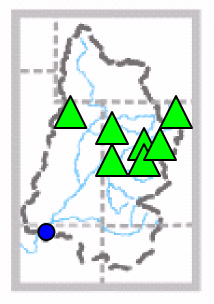
TRG + WIL + DJM + DOU + NPU + RED

Variance Explained

79%



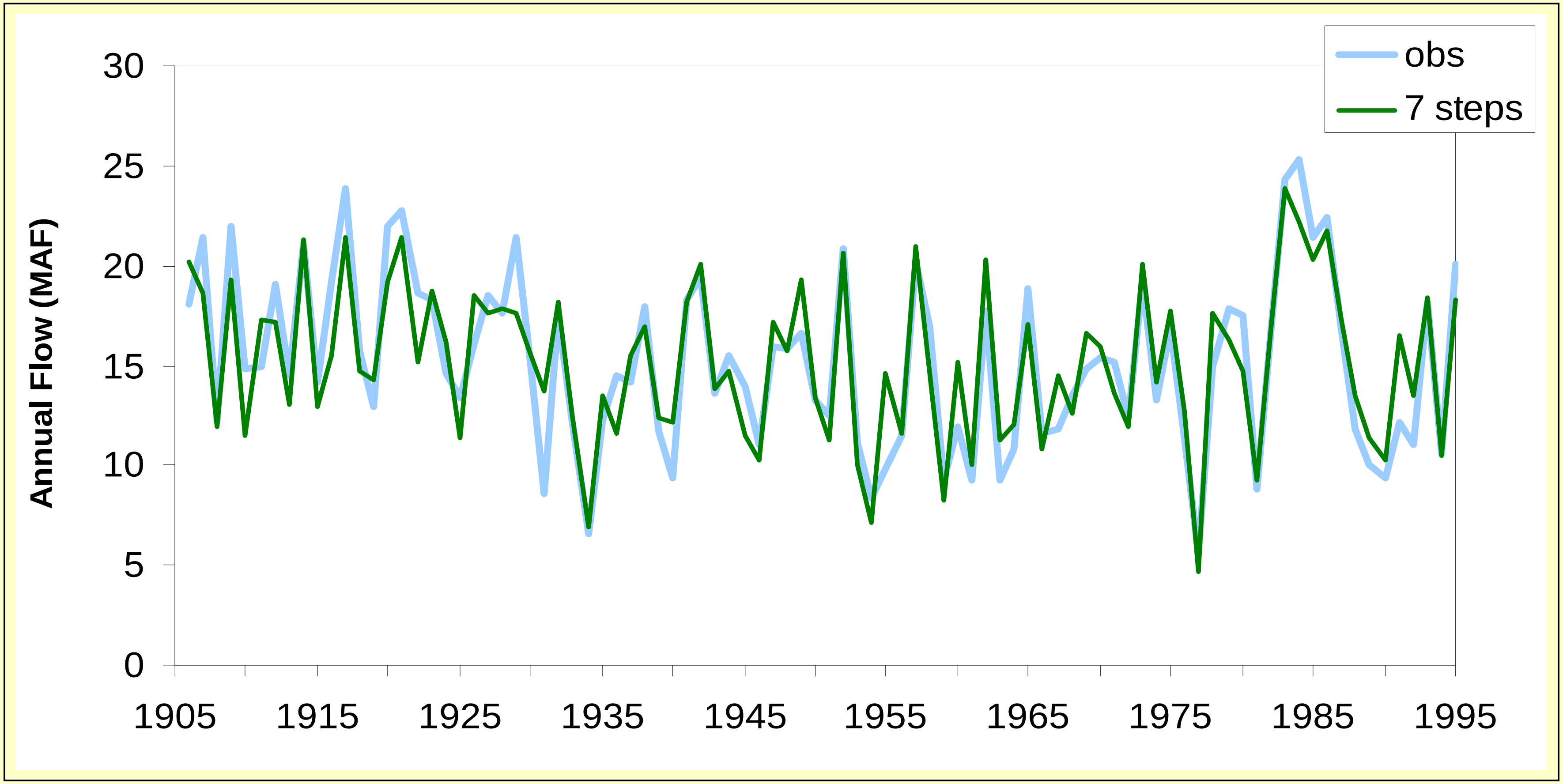
Colorado at Lees Ferry - forward stepwise regression



Variance Explained

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

81%



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?

Are regression assumptions satisfied?

Analysis of residuals

Residuals are assumed to have:

- NO significant trend with time
- NO significant changes in variance over time
- NO significant autocorrelation
- NO significant correlation with the model estimates
- NO significant correlation with individual predictors
- normal distribution

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

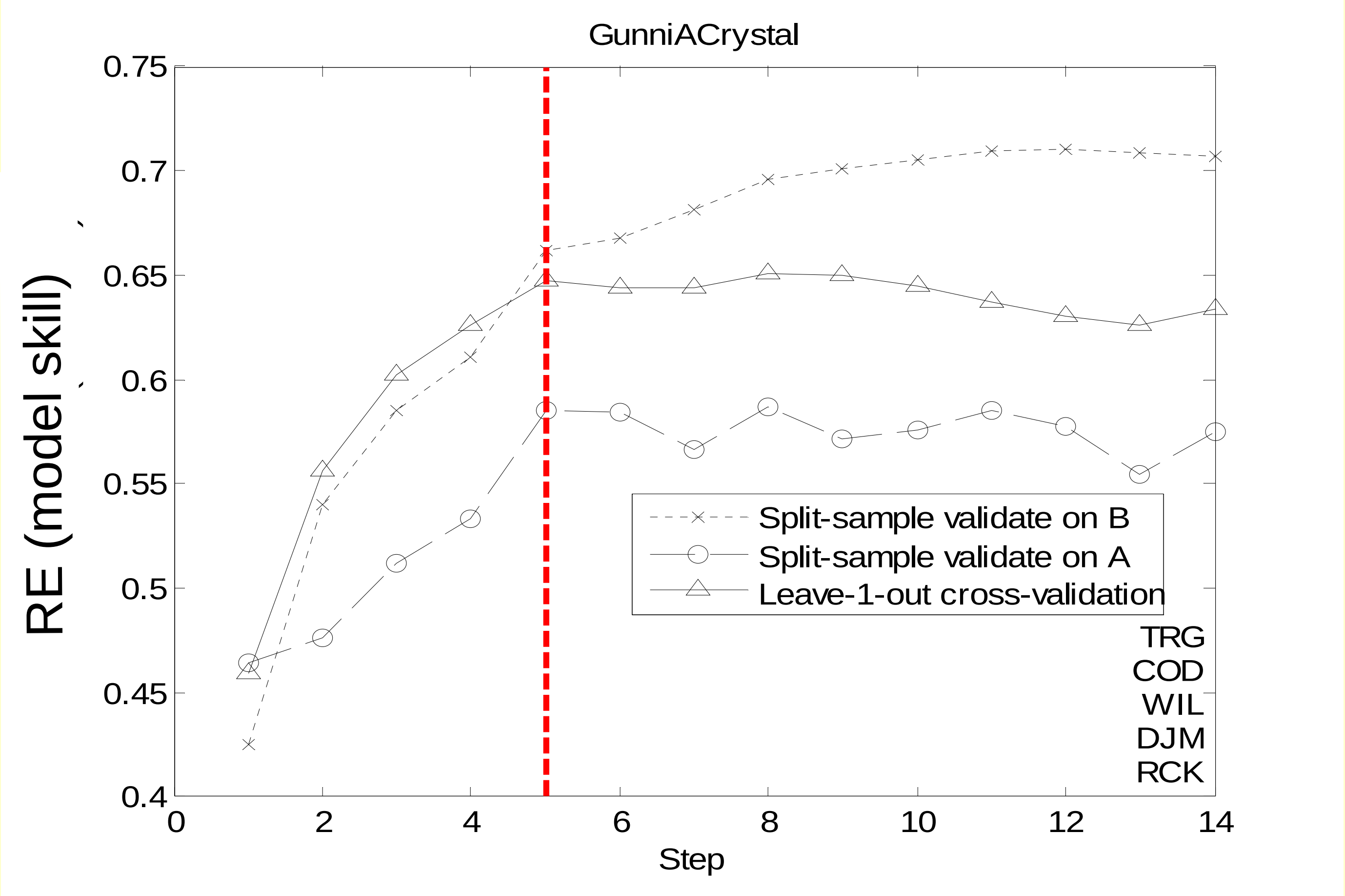
*RE is Reduction of Error statistic; tests model skill against “no knowledge”

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)

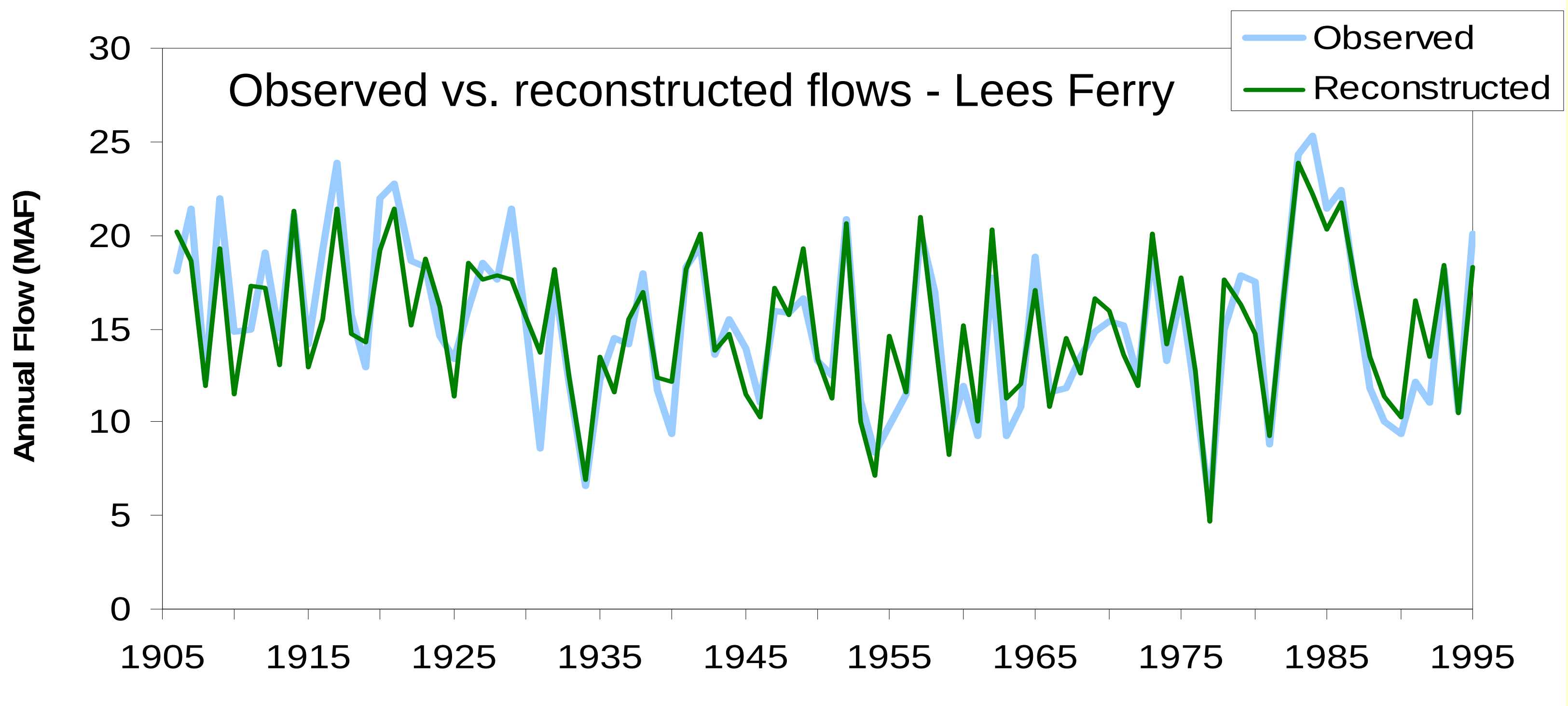
- In regression modeling, we can get fixated on R^2, but validation statistics like RE are a better measure of the quality of the model

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?

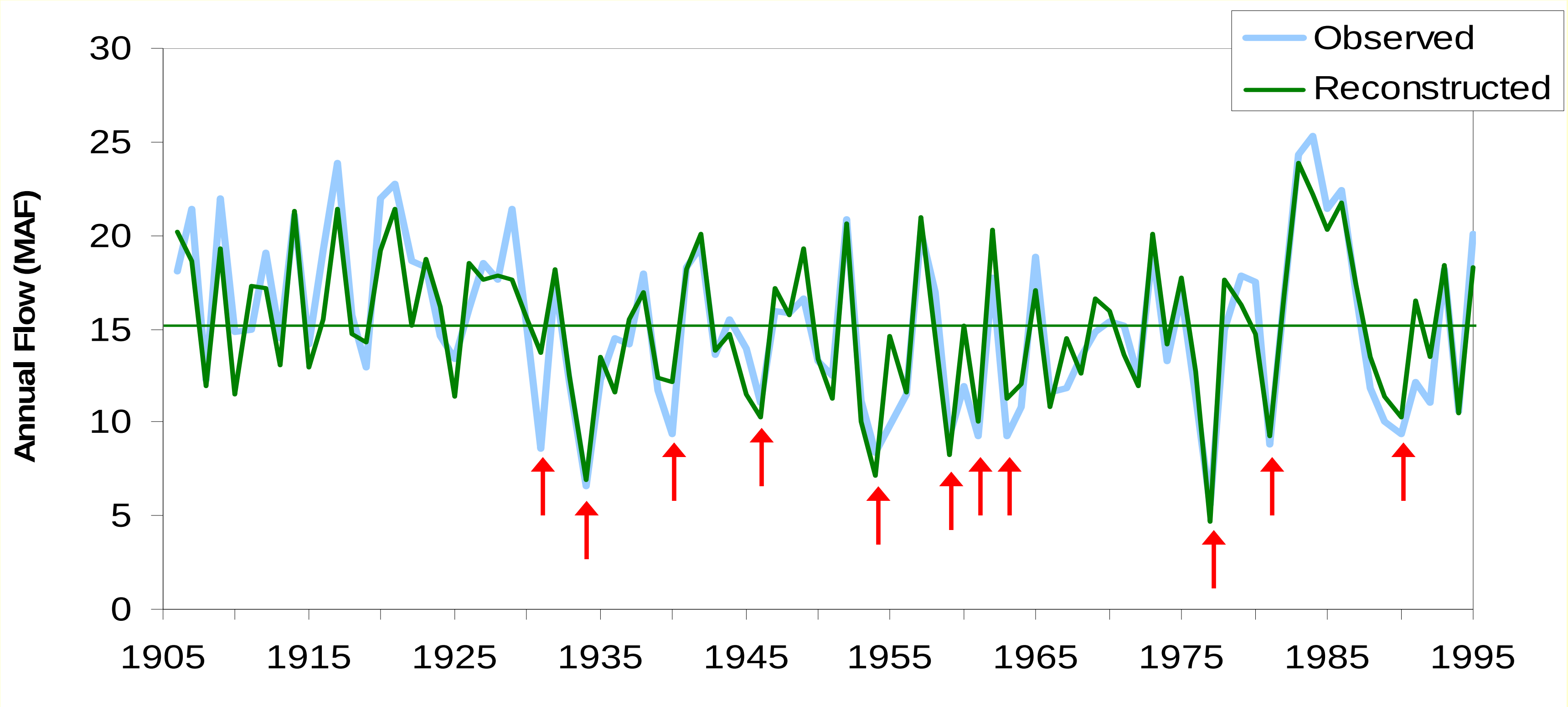


	Observed	Recon'd
Mean	15.22	15.22
Max	25.27	23.91
Min	5.57	4.71
StDev	4.32	3.88
Skew	0.16	-0.14
Kurtosis	-0.58	-0.37
AC1	0.25	0.04

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

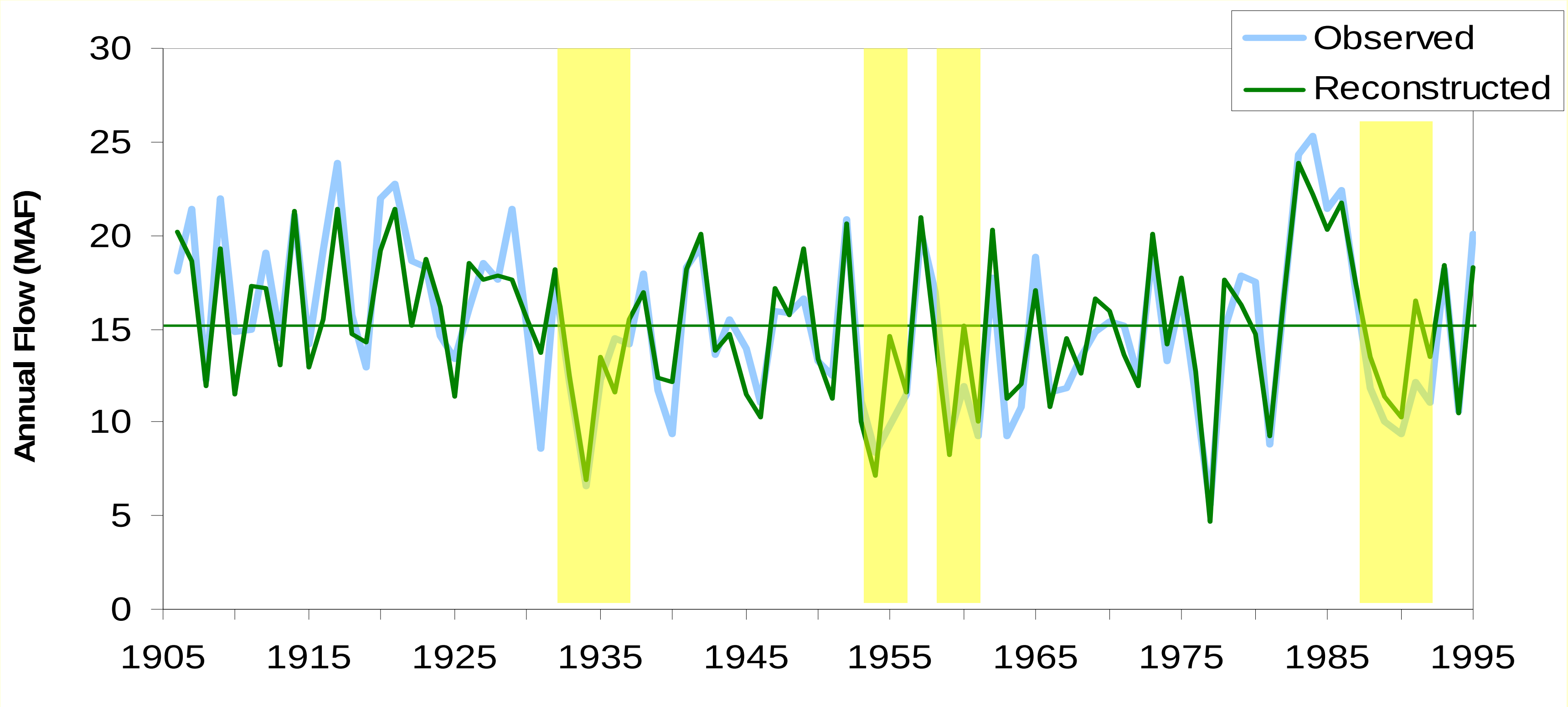
Also as expected, the standard deviation in the reconstruction is lower than in the gage record

Subjective assessment of model quality



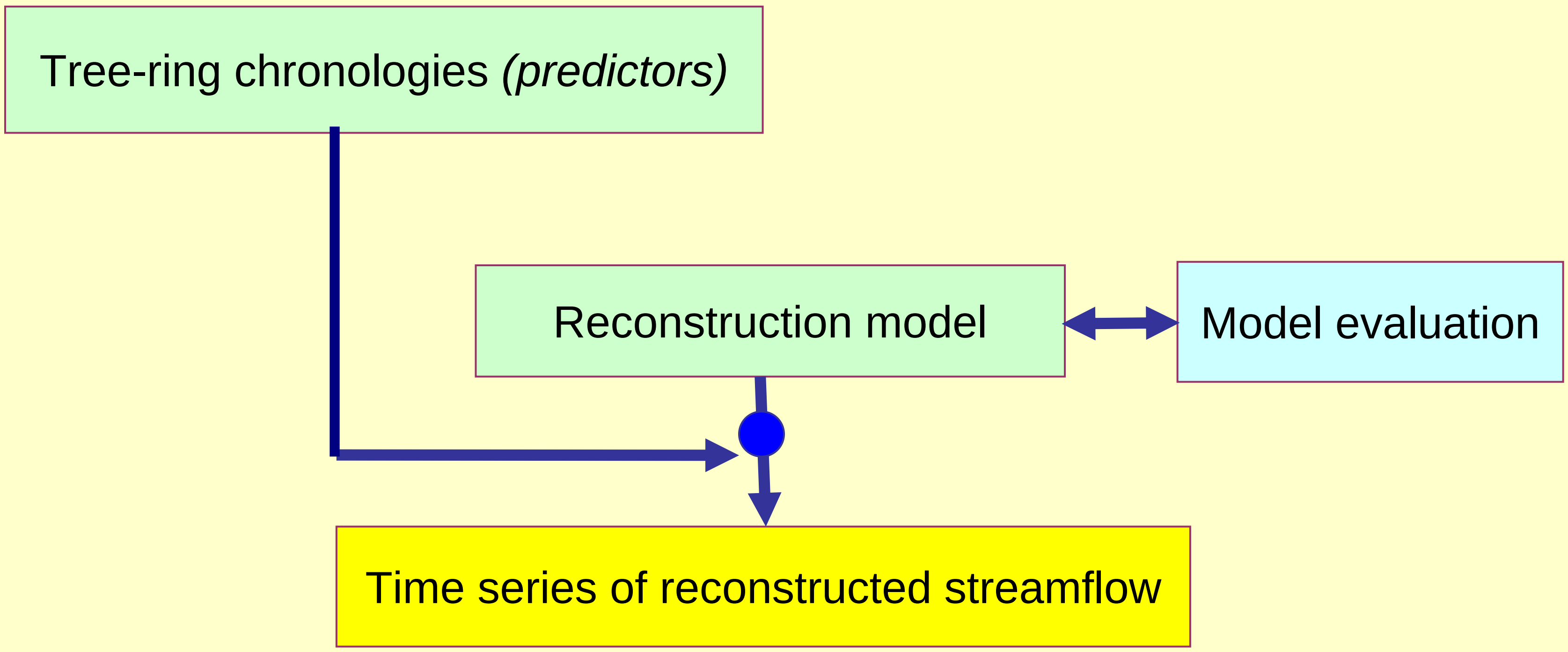
- Are severe drought years replicated well, or at least correctly classified as drought years?

Subjective assessment of model quality



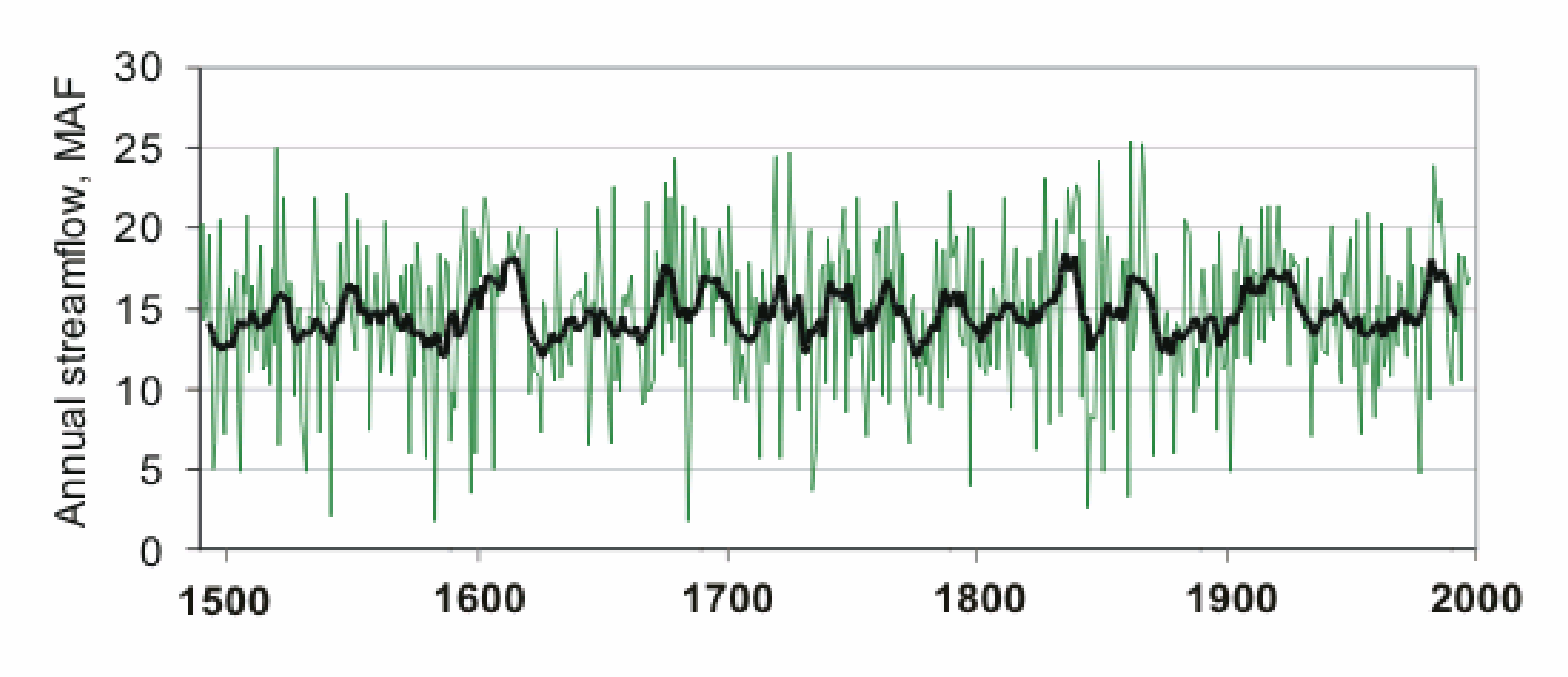
- Are the lengths and total deficits of multi-year droughts replicated reasonably well?

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

Uncertainty in the reconstructions

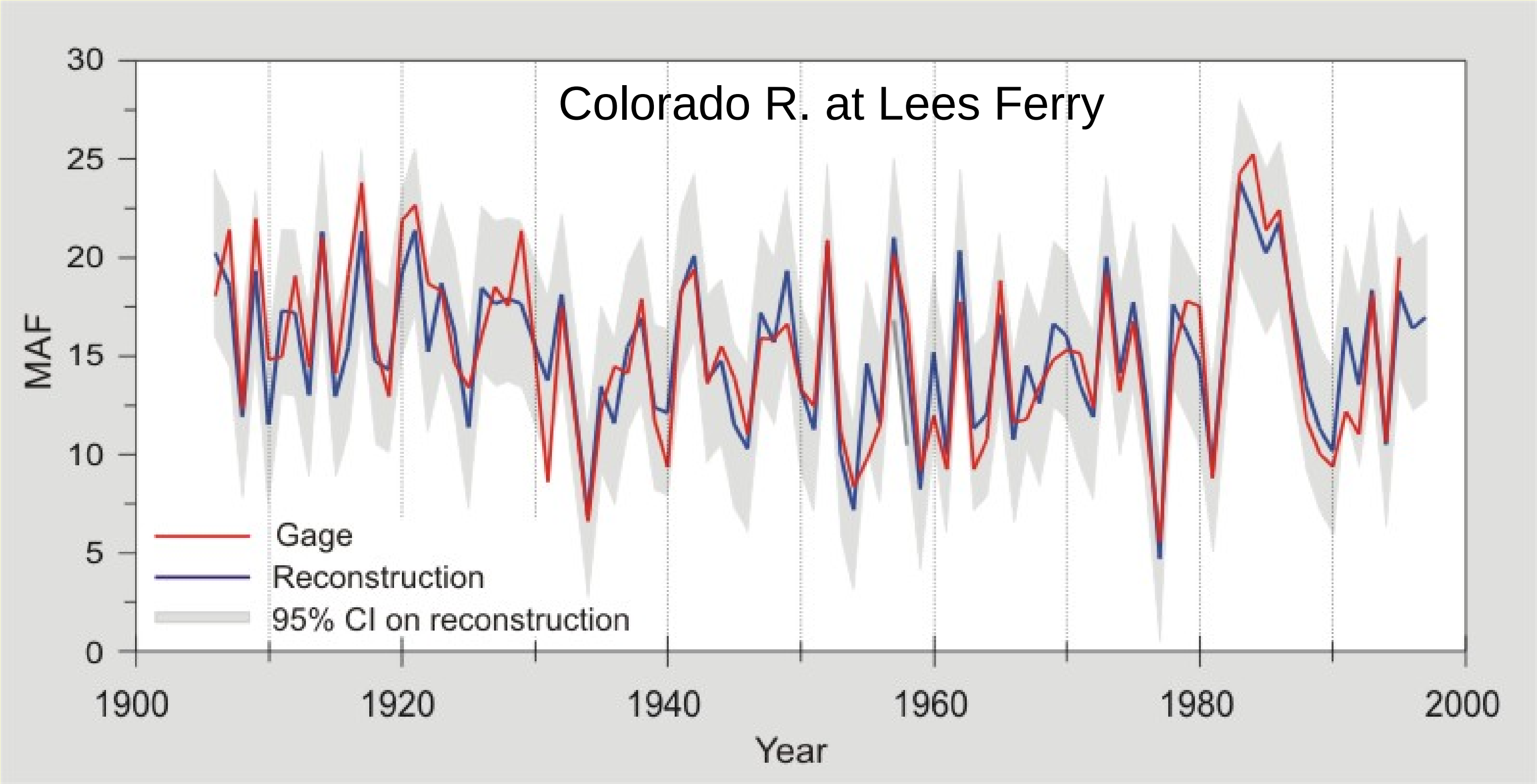
- Tree-ring data are imperfect recorders of climate and streamflow, so there will always be uncertainty in the reconstructed values

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

- 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

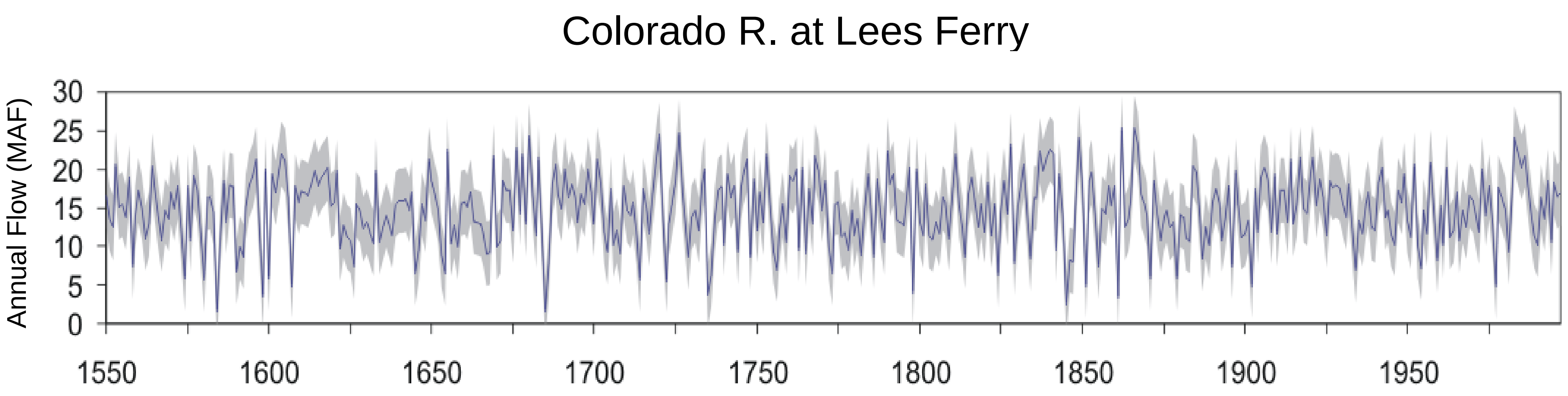
- The uncertainty associated with these data and modeling choices is not formally quantified but sensitivity analyses can help assess their impacts (e.g., set of chronologies, gage data/years used, modeling approach, treatment of data).

Using RMSE to generate confidence intervals for the model



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

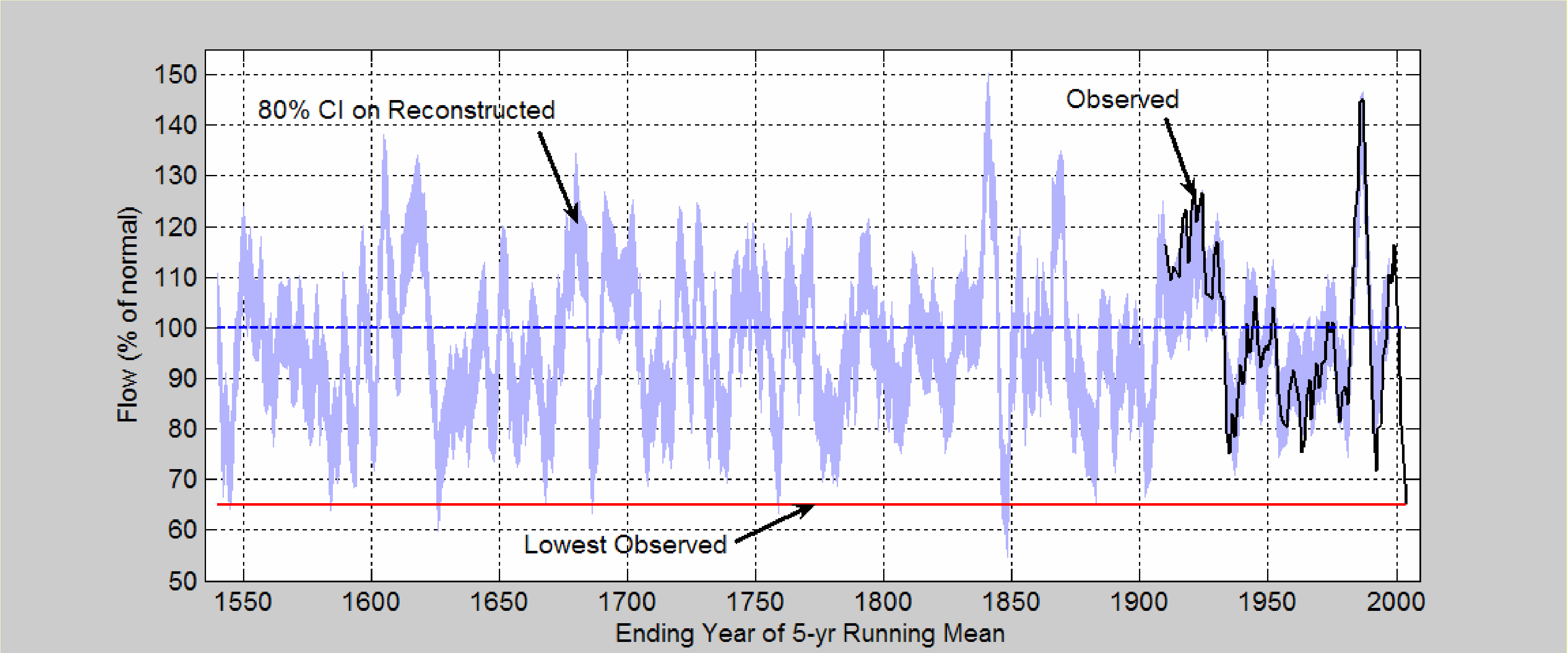
Using RMSE to generate confidence intervals



- 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

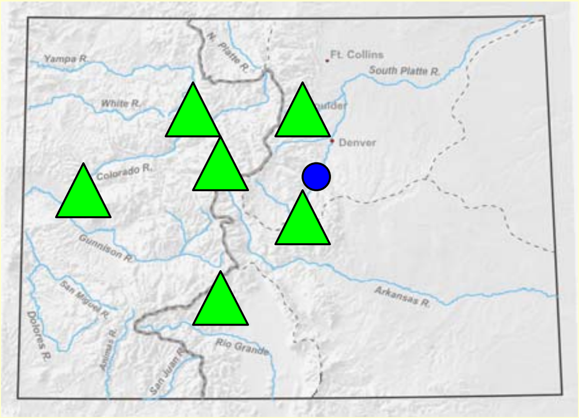
Lees Ferry Reconstruction, 1536-1997
5-Year Running Mean
Assessing the 2000-2004 drought in a multi-century context



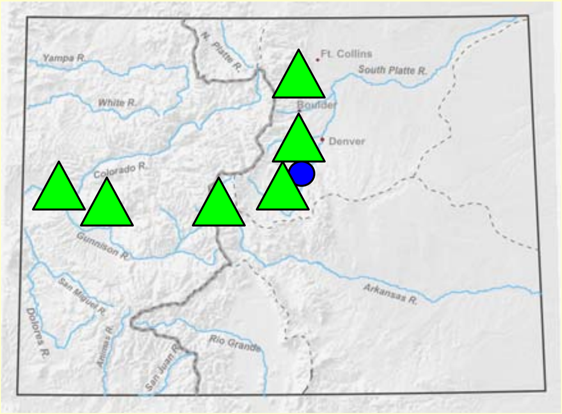
Data analysis: Dave Meko

Sensitivity to available predictors

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



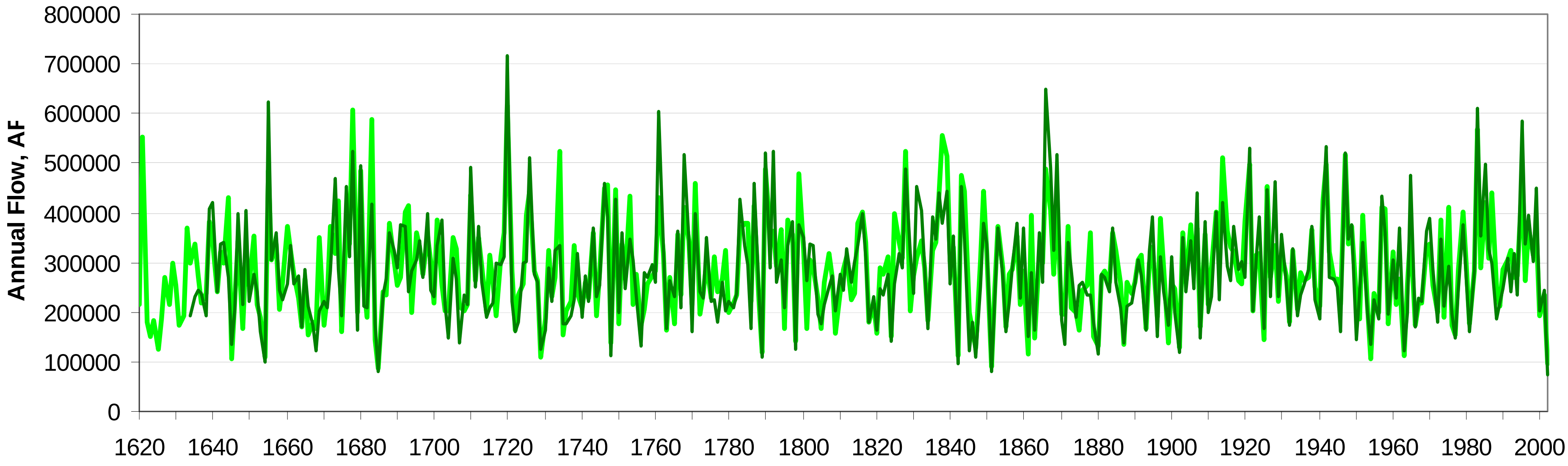
South Platte - First model



South Platte - Alternate model

Sensitivity to available predictors - alternate models

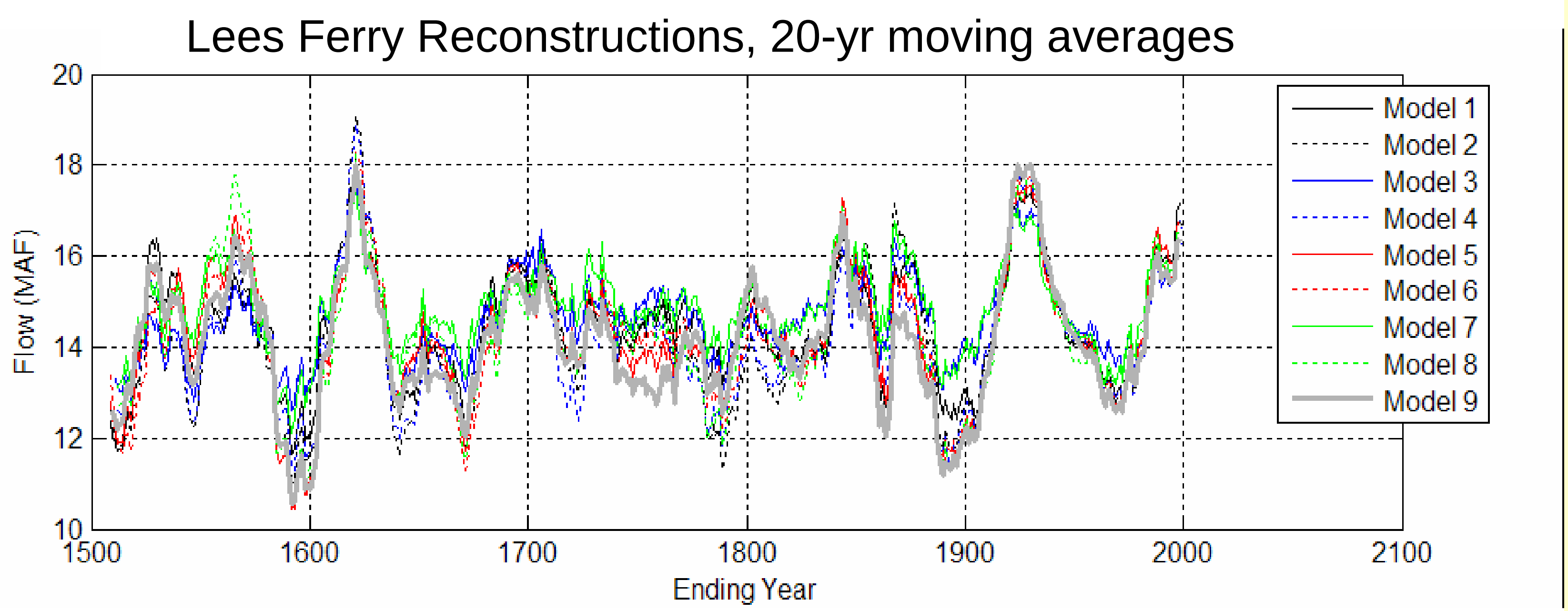
South Platte at South Platte, First Model and Alternate Model



- 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

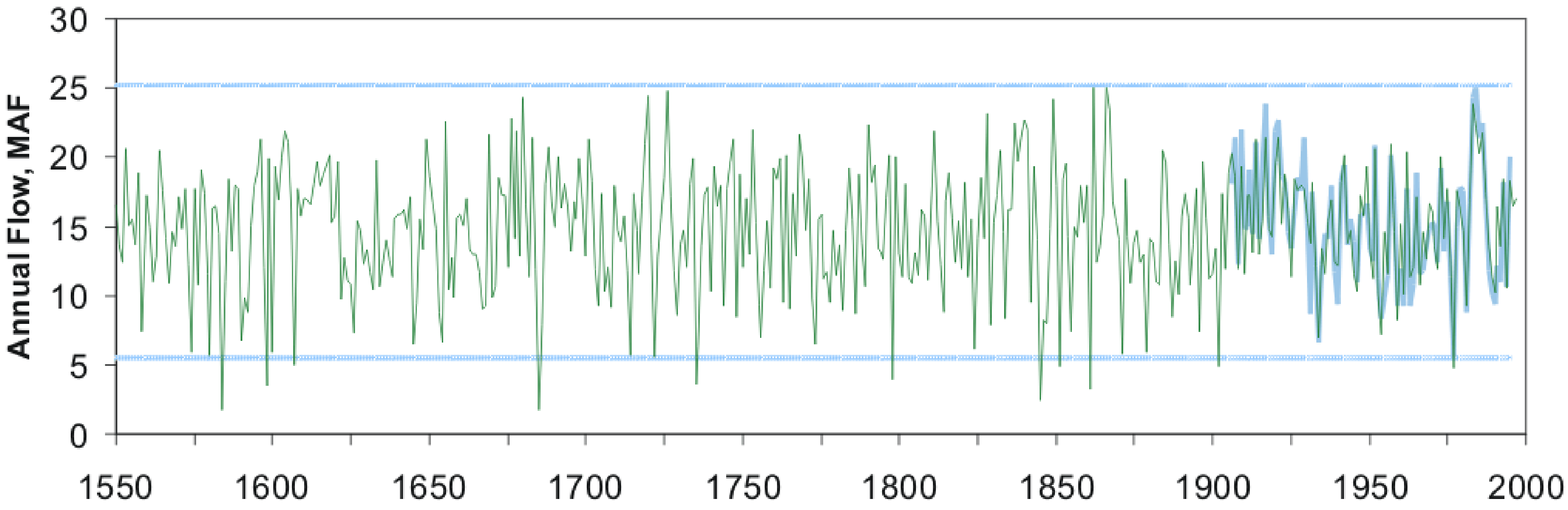
Lees Ferry reconstructions from 9 different models that vary according to chronology persistence, pool of predictors, model choice



Analysis from D. Meko

Uncertainty related to extreme values

Colorado at Lees Ferry, Reconstructed and Gaged Flows



- 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 estimates may be more uncertain than implied by the RMSE

Uncertainty in perspective

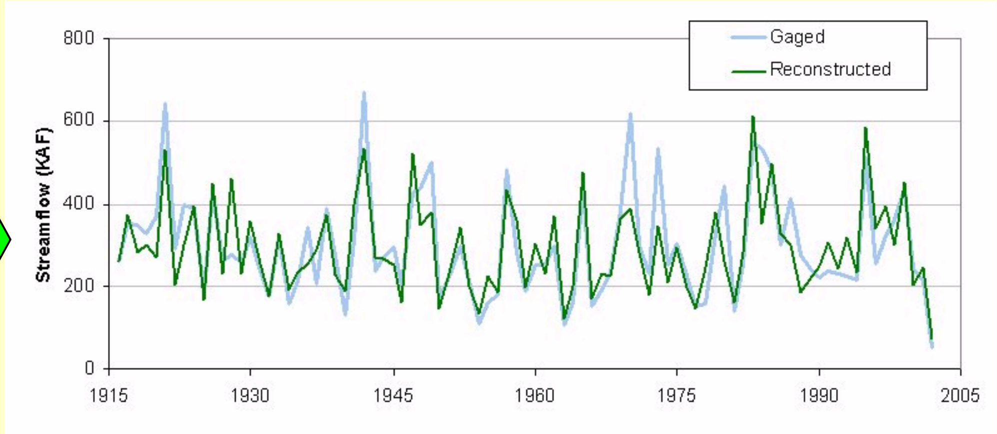
- RMSE is probably a reasonable measure of the magnitude of overall uncertainty in the reconstructions, but it should be recognized that it does not reflect all sources of uncertainty

- 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 West, Colorado, and the San Juans



Where to get them, what they look like

“One-stop shopping” for the western US

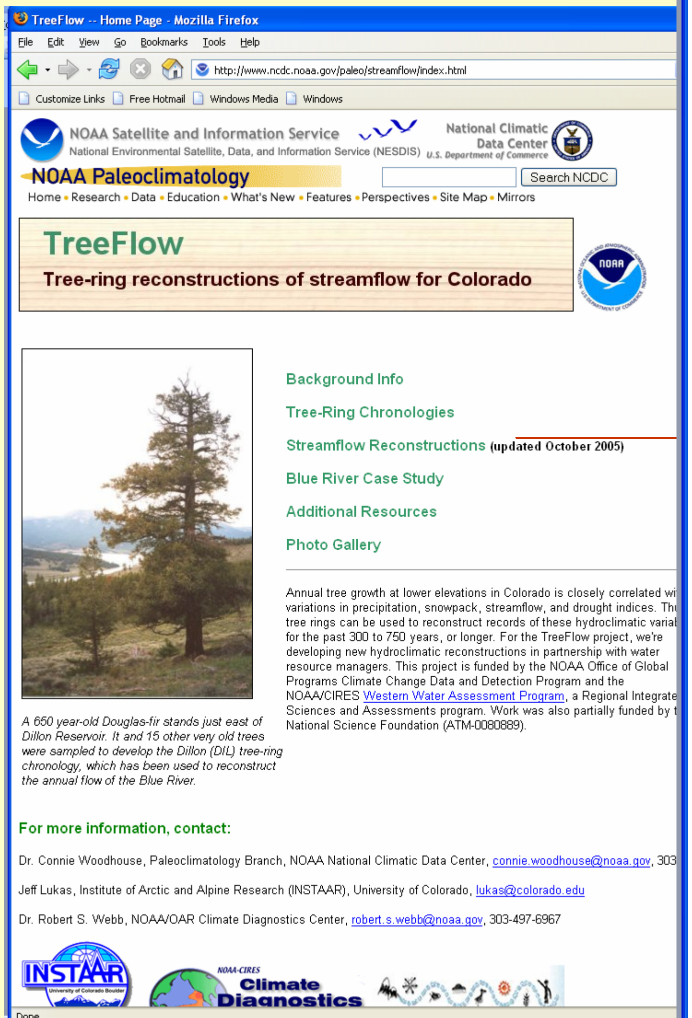
Tree-Ring Reconstructions of Streamflow for Water Management in the West

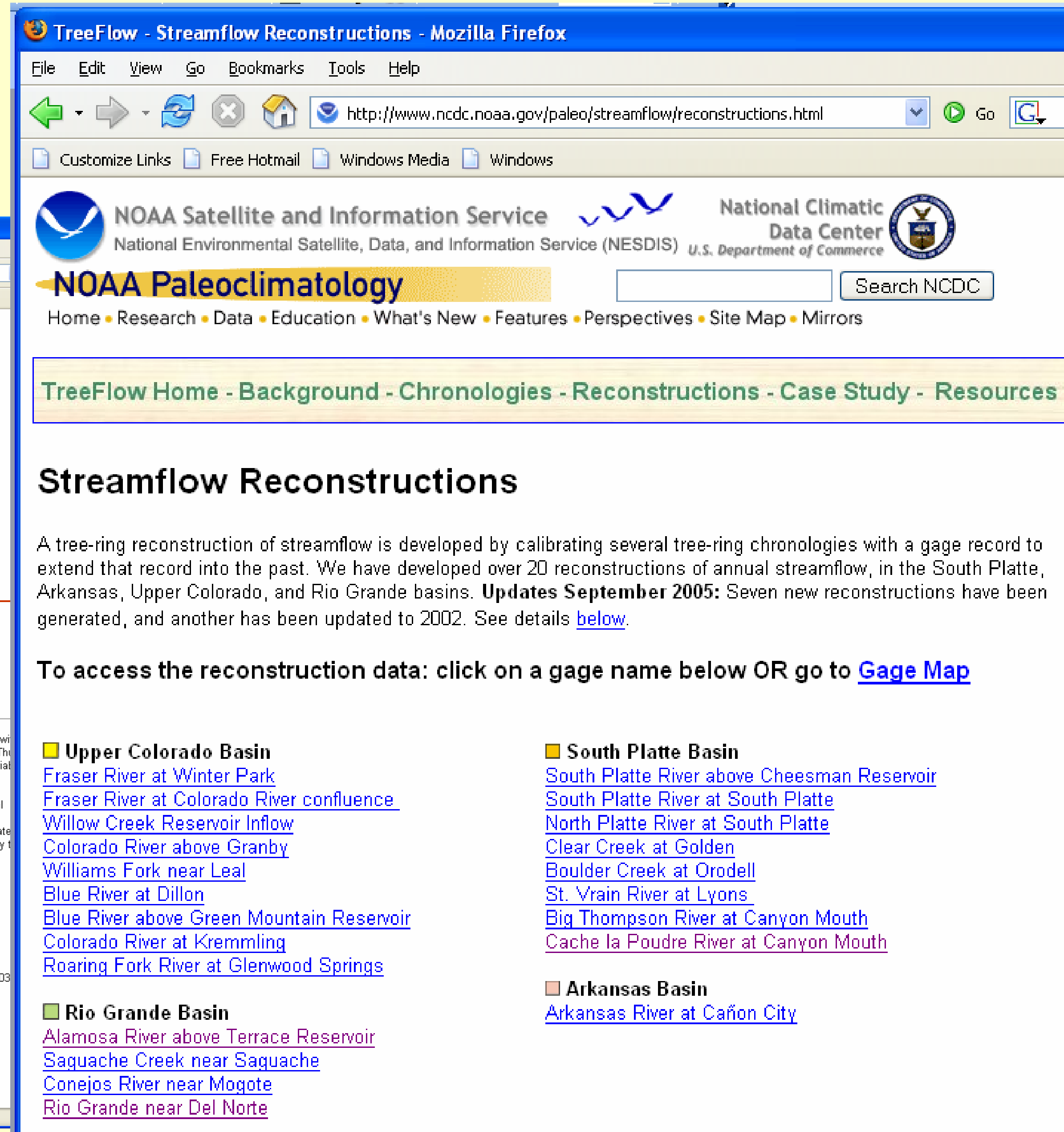
http://wwa.colorado.edu/resources/paleo/data.html

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





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

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**

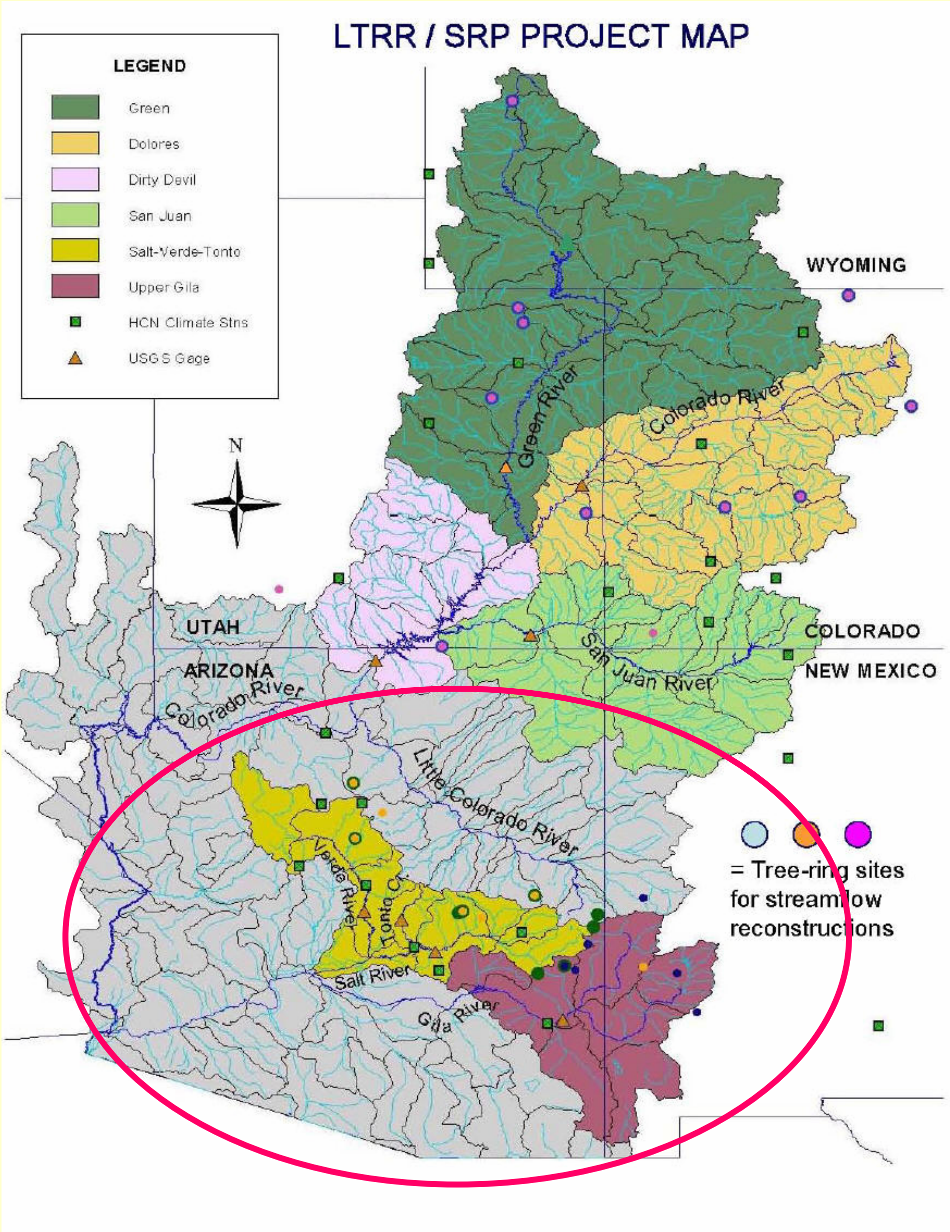
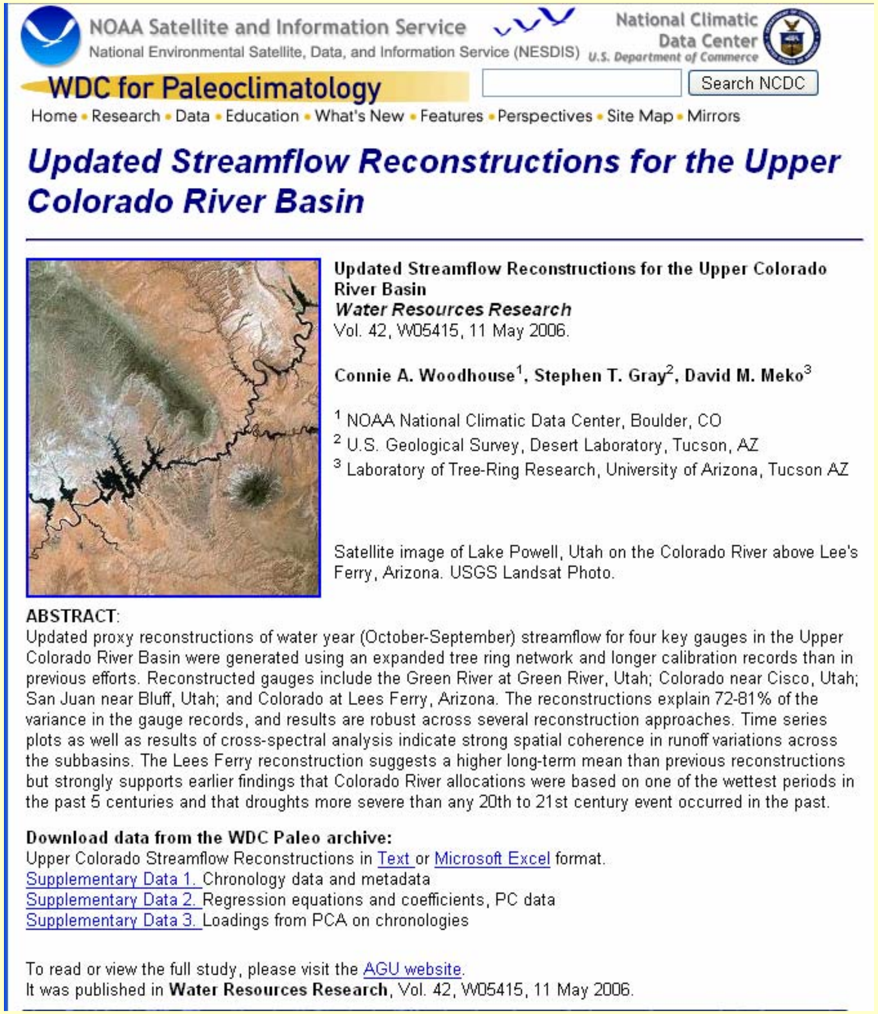


Image courtesy of K. Hirschboeck and D. Meko (U. AZ)

Woodhouse et al. 2006 Upper Colorado River Basin


NOAA Satellite and Information Service
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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.

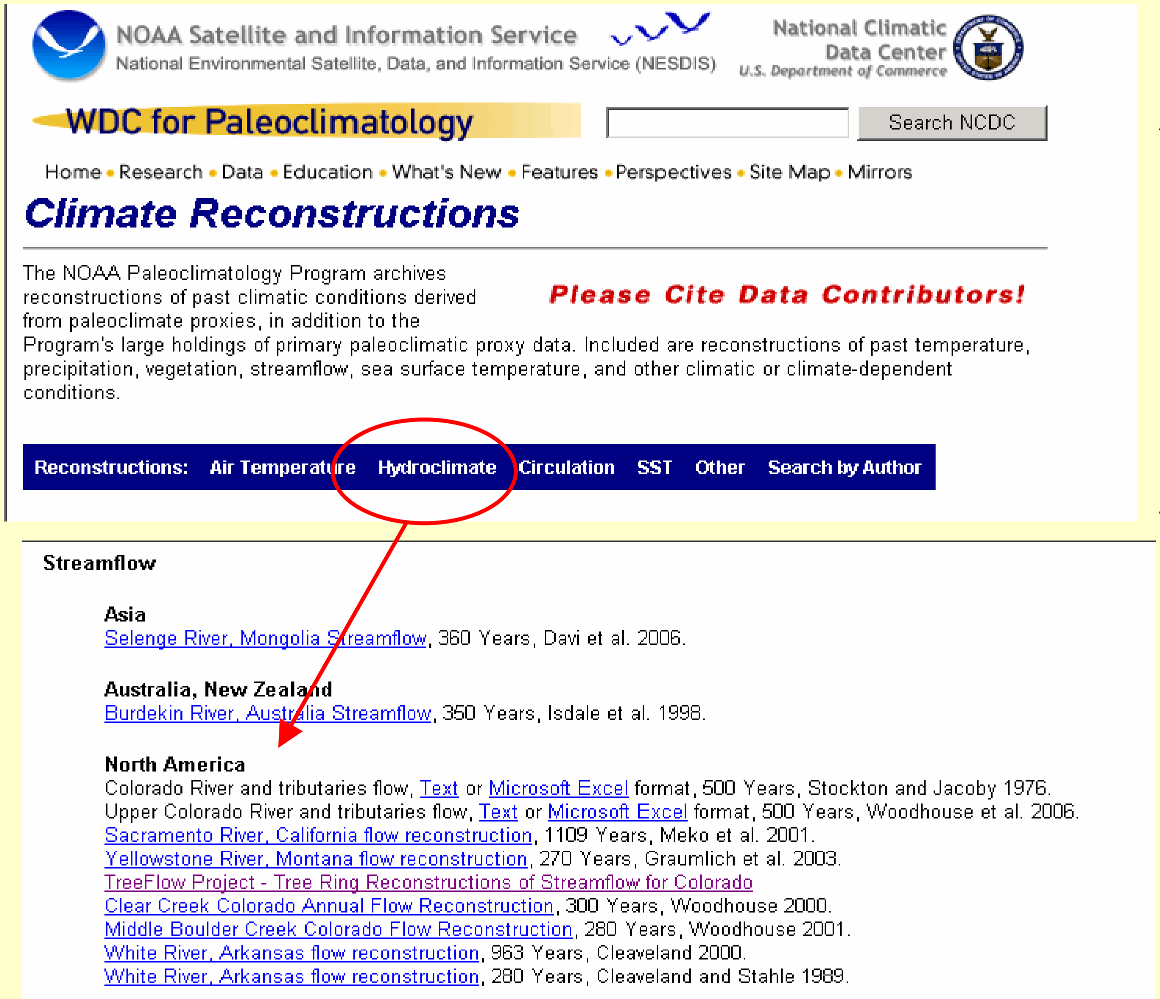
Download data from the WDC Paleo archive:
Upper Colorado Streamflow Reconstructions in Text or Microsoft Excel format.
Supplementary Data 1. Chronology data and metadata
Supplementary Data 2. Regression equations and coefficients, PC data
Supplementary Data 3. Loadings from PCA on chronologies

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.

- 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

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

NOAA – National Climatic Data Center
World Data Center for Paleoclimatology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U.S. Department of Commerce

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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

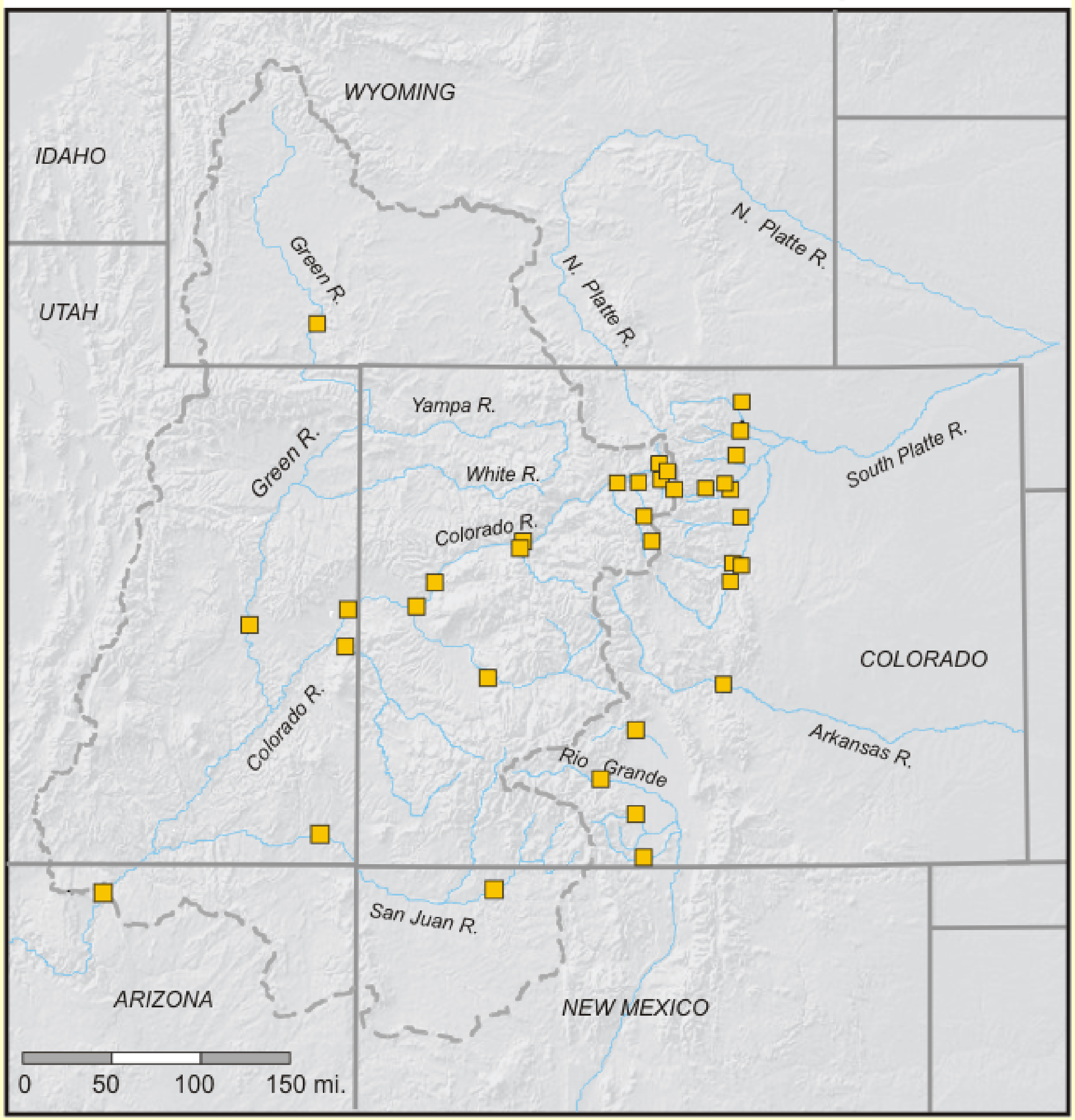
Also:

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

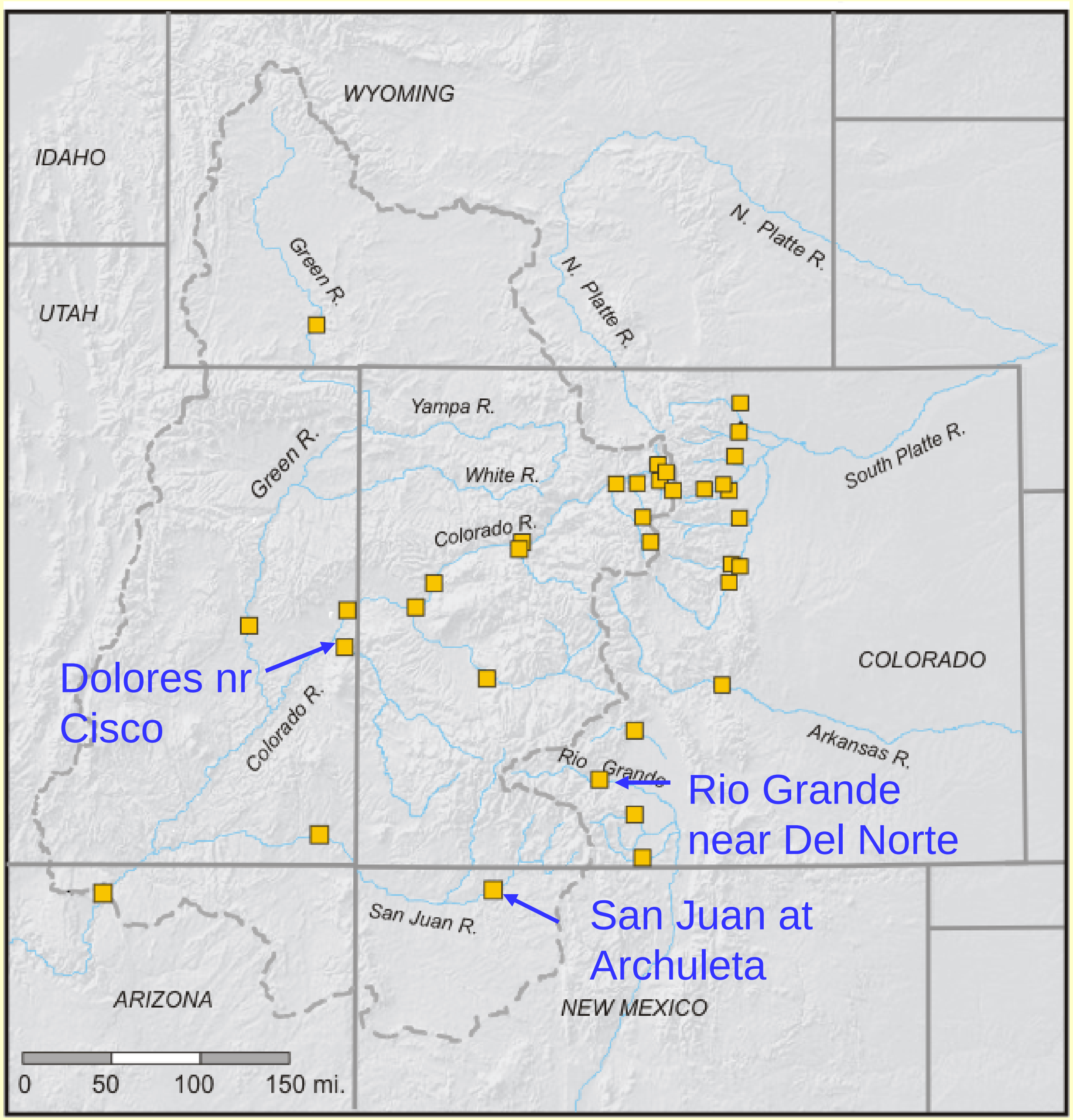
http://www.ncdc.noaa.gov/paleo/recons.html

Reconstructions (■) in Colorado and the upper Colorado River basin

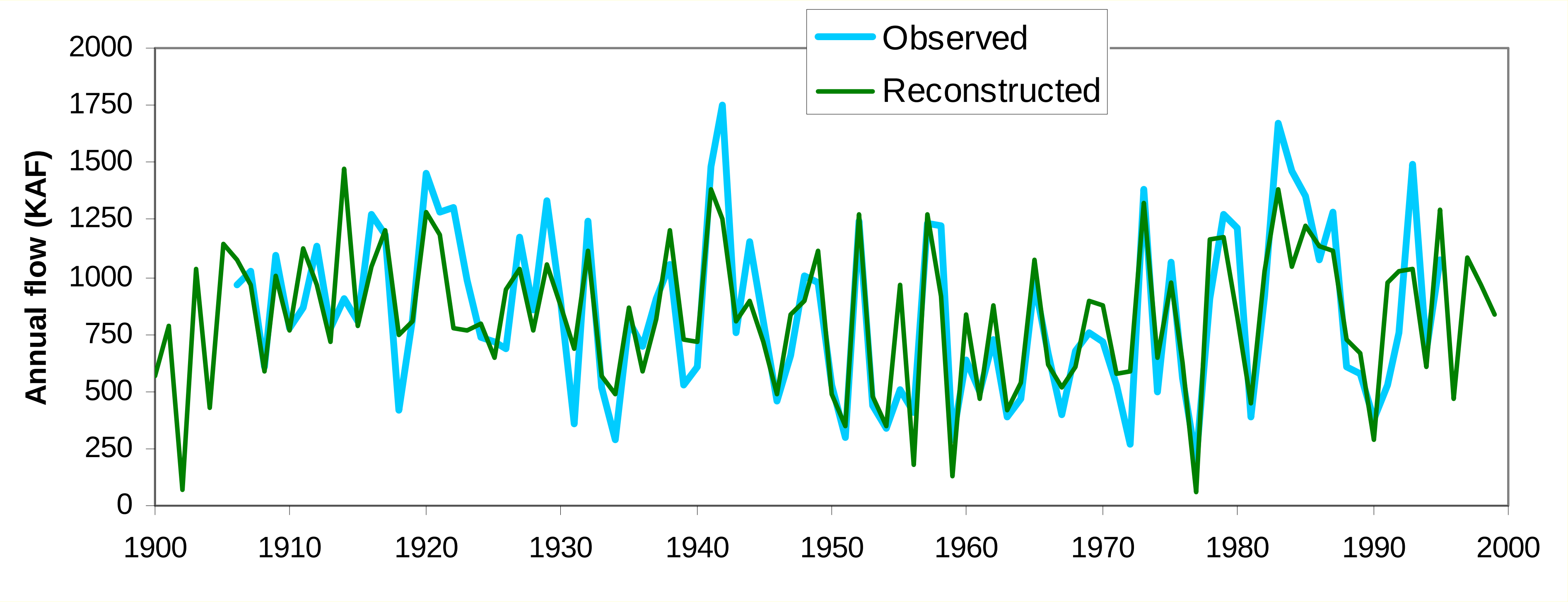
- Over 30 reconstructions, representing nearly all of the streamflow leaving Colorado
- Developed by Woodhouse and others 2001-2006



Streamflow reconstructions for the San Juans

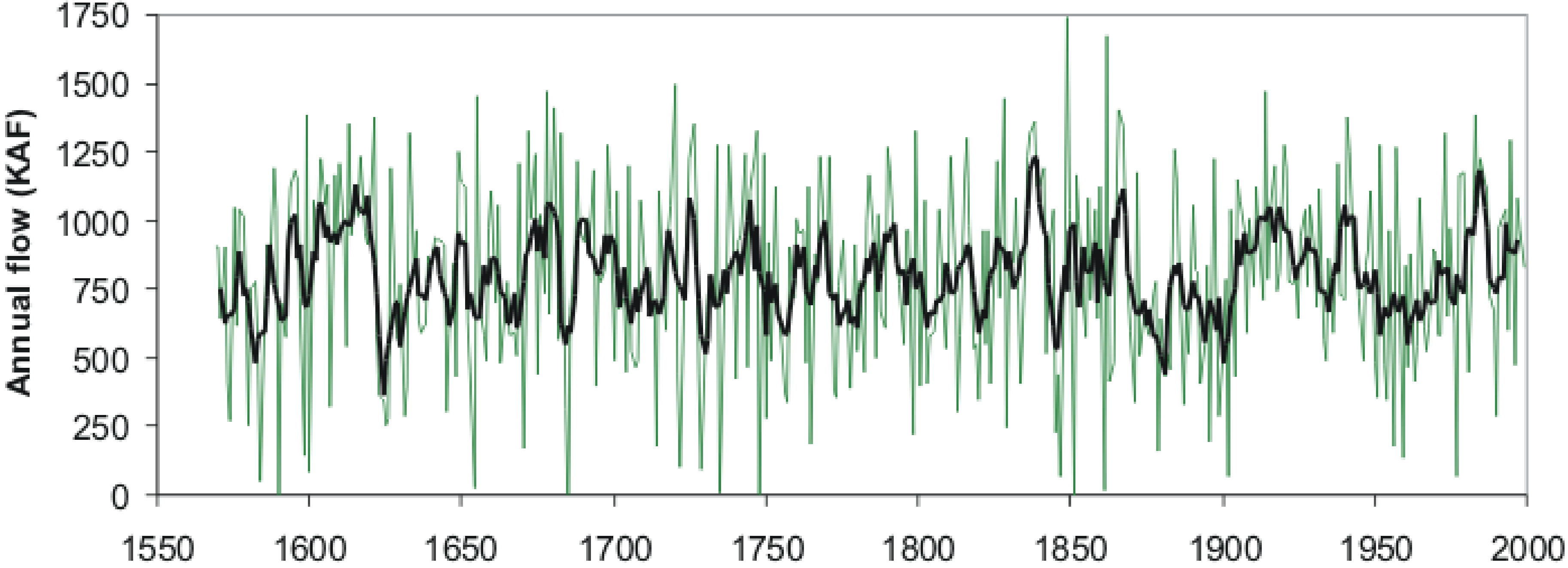


Dolores near Cisco - calibration



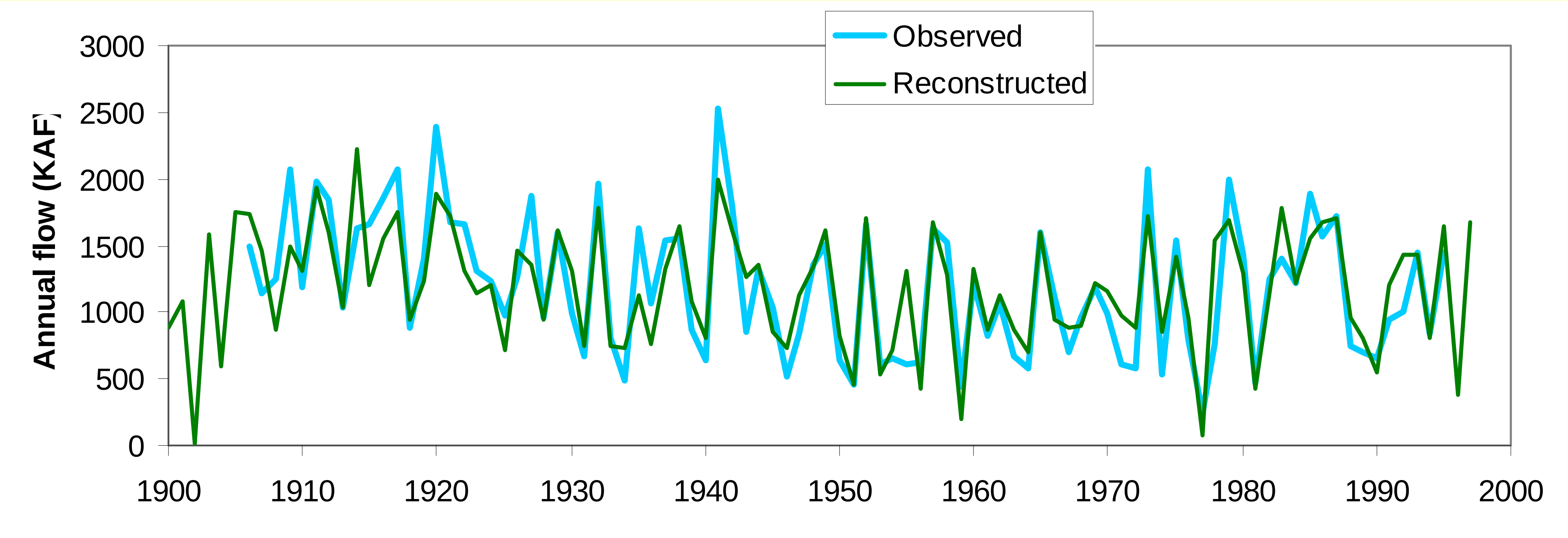
- Observed (natural flow) record from USBR
- Calibration from 1906-1995
- R2 = 0.69
- 1977: observed 195 KAF, reconstructed 63 KAF
- 2002: observed 269 KAF

Dolores near Cisco - reconstruction 1569-1999



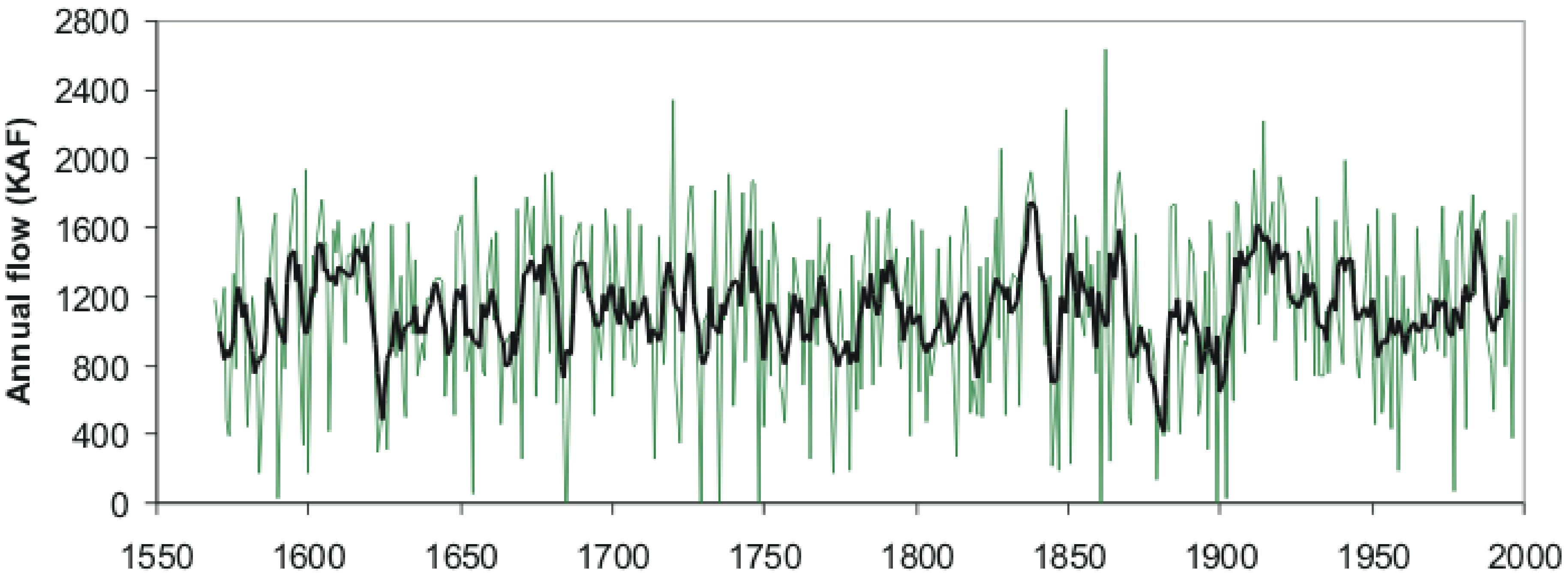
- Annual flows in green, 5-yr running mean in black
- 7 years w/ reconstructed flows below 1977 (63 KAF)
- 1622-1626: 5-yr running mean 368 KAF
- 1959-1963: 5-yr mean 509 KAF observed, 546 KAF reconstructed
- 2000-2004: 5-yr mean 454 KAF observed

San Juan at Archuleta - calibration



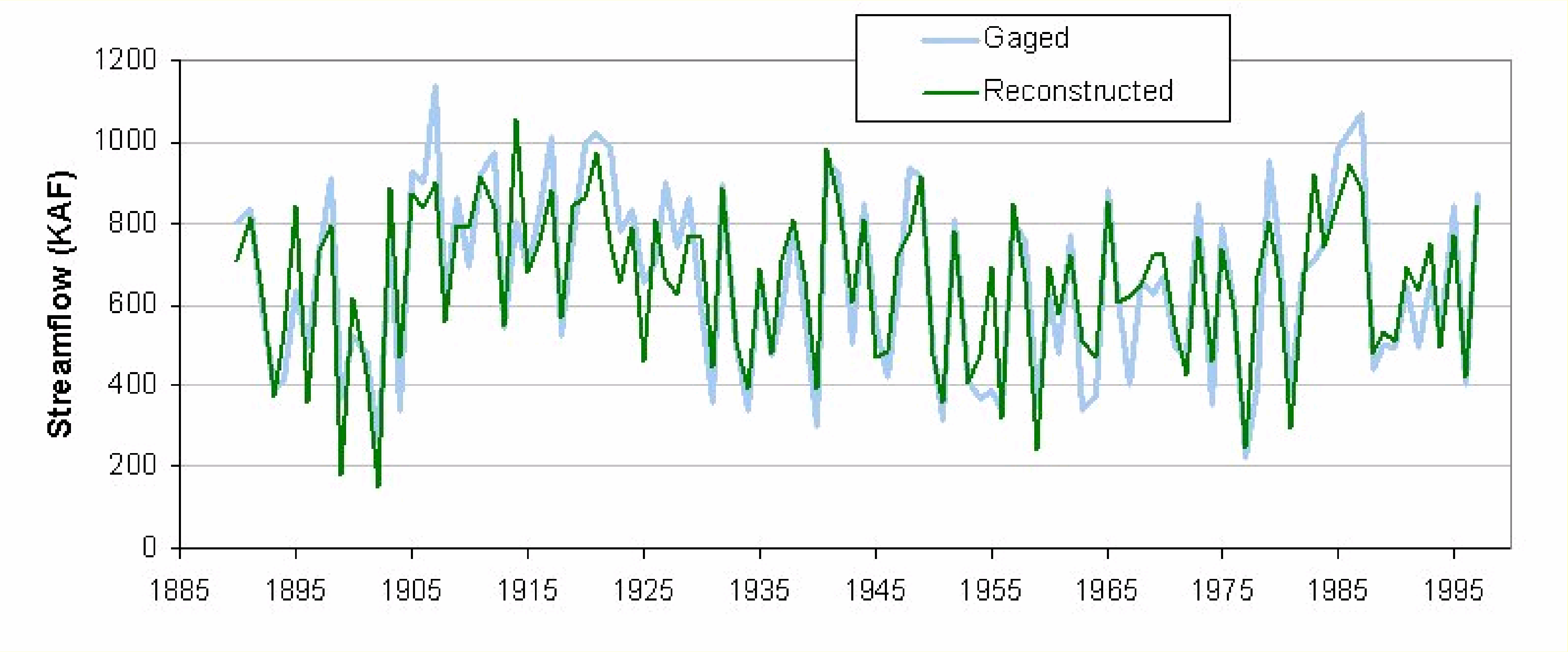
- Observed (natural flow) record from USBR
- Calibration from 1906-1995
- R2 = 0.72
- 1977: observed 249 KAF, reconstructed 70 KAF
- 2002: observed -23 KAF (?)

San Juan at Archuleta - reconstruction 1569-1999



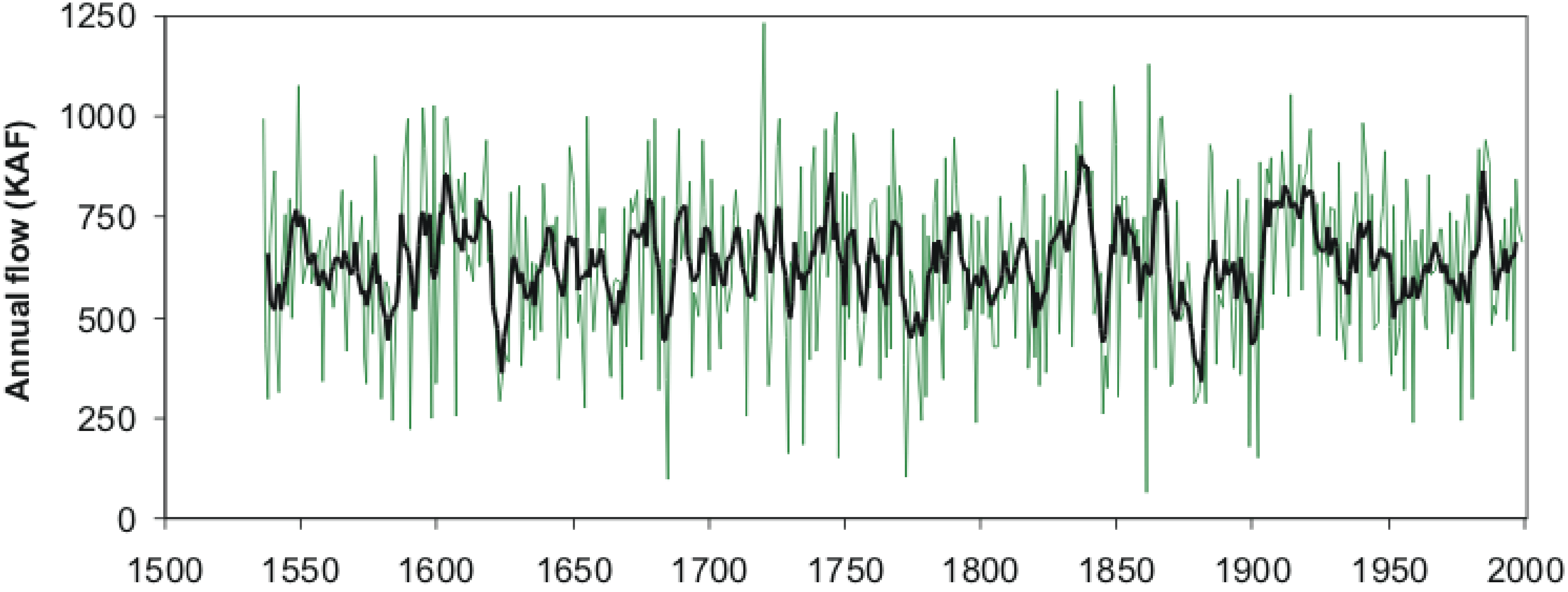
- Annual flows in green, 5-yr running mean in black
- 10 years w/ reconstructed flows below 1977 (70 KAF)
- 1879-1883: 5-yr running mean 423 KAF
- 1959-1963: 5-yr mean 840 KAF observed, 876 KAF reconstructed
- 2000-2004: 5-yr mean 459 KAF observed

Rio Grande near Del Norte - calibration



- Observed (undepleted flow) record from CO State Engineer
- Calibration from 1890-1997
- $R2 = 0.76$; $RE = 0.72$
- 1902: observed 255 KAF, reconstructed 152 KAF
- 2002: observed 164 KAF

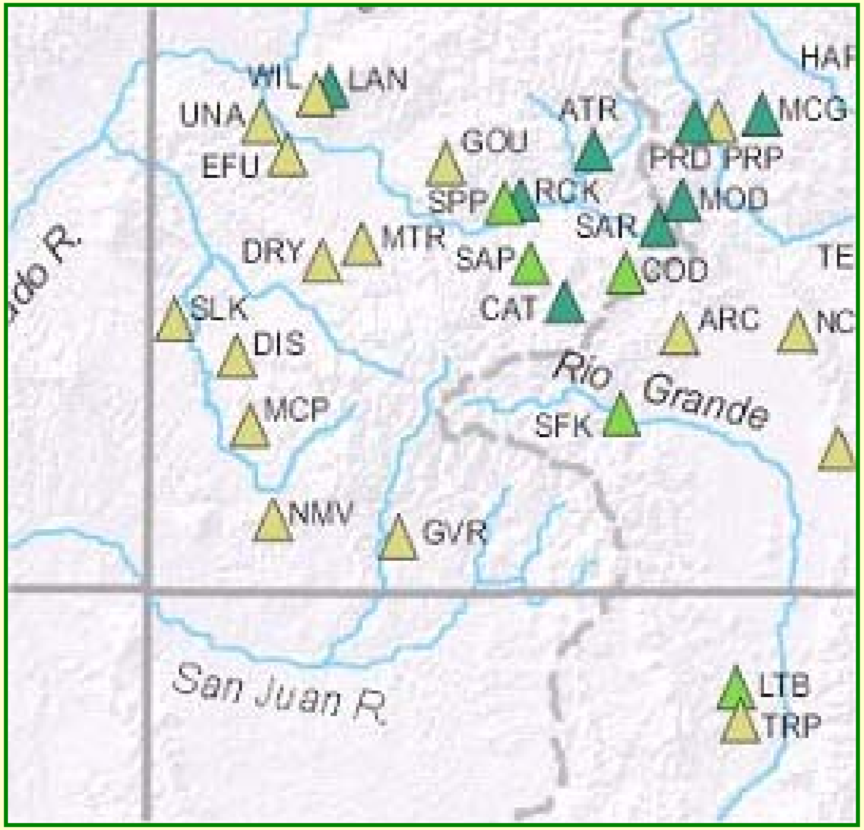
Rio Grande near Del Norte - reconstruction



- Annual flows in green, 5-yr running mean in black
- 5 years w/ reconstructed flows below 1902 (152 KAF)
- 1879-1883: 5-yr running mean 339 KAF
- 1959-1963: 5-yr mean 462 KAF observed, 525 KAF reconstructed

Potential future reconstructions for San Juans

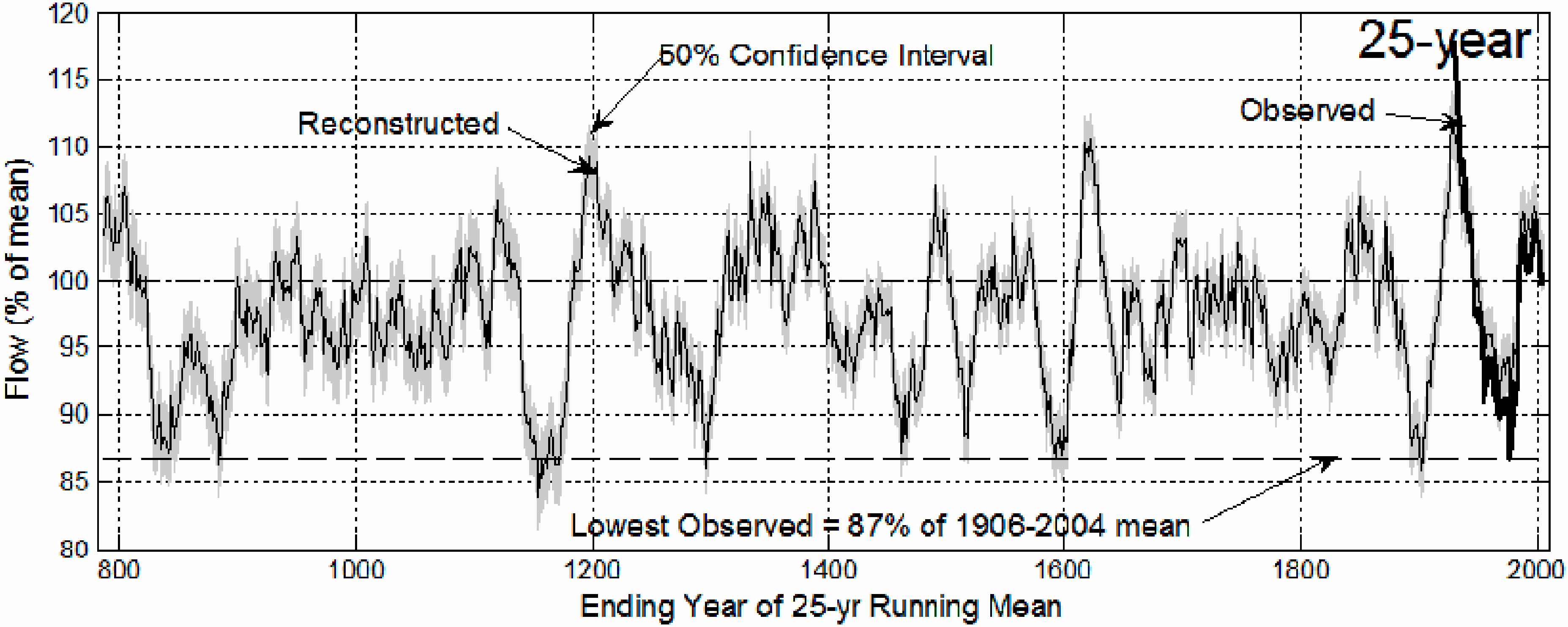
- Good distribution of tree-ring chronologies across the San Juans
- Potential to reconstruct any gage with >50 years of record
- Preliminary reconstruction of Piedra at Arboles shows smaller basins can be well-estimated
- Could include 2002 in calibration of new reconstructions



Using “remnant wood” to reconstruct >1000 yrs

Douglas-Fir on Grand Mesa dated from 926-1770

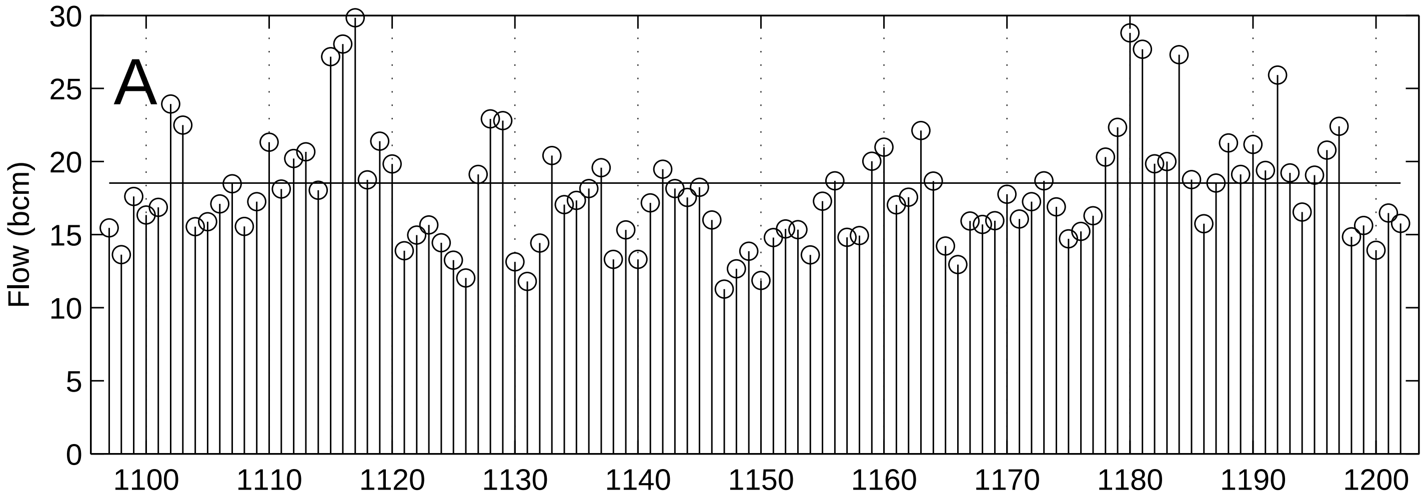
Reconstruction of Colorado River at Lees Ferry, AD 762 - 2005



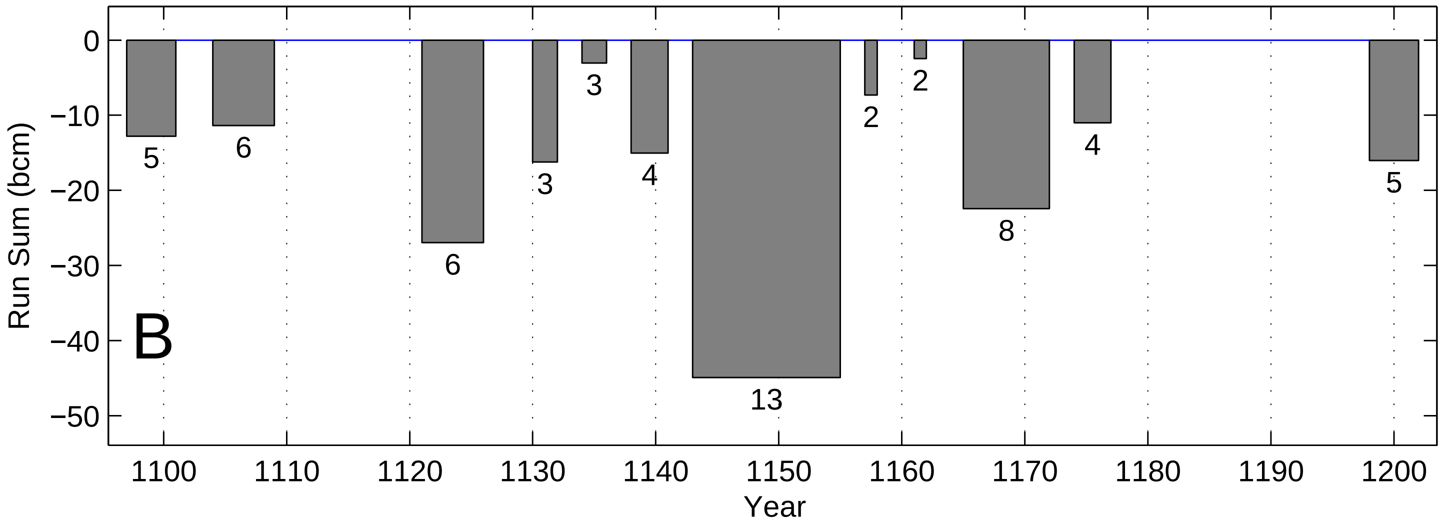
25-yr running means of reconstructed and observed annual flow of the Colorado River at Lees Ferry, expressed as percentage of the 1906-2004 observed mean.

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

Year-by-year details of 1100-1200: (a) flows and (b) runs below the observed mean

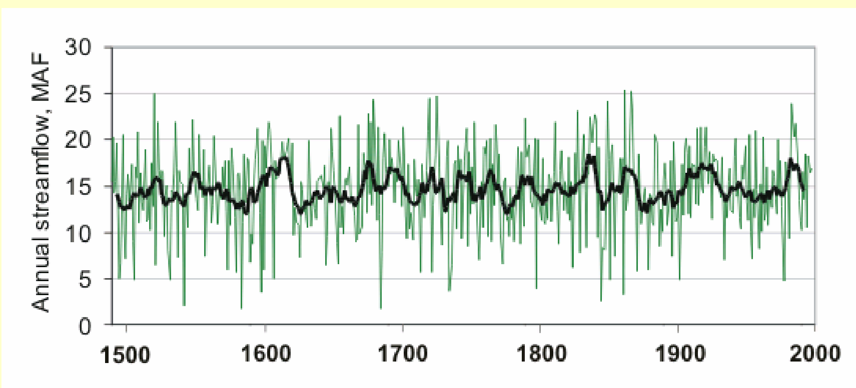


In 57-year period, only 9 years above observed mean (15 MAF)



Part 5:

How the reconstructions can be used in water management



Reconstruction data

?

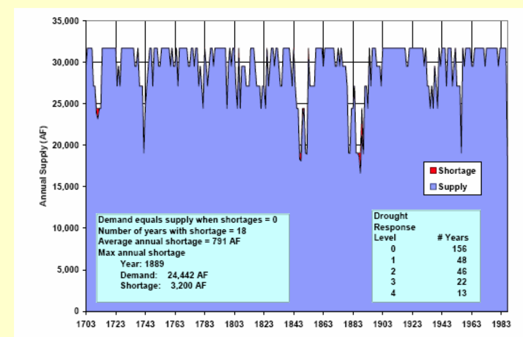


Figure 5. Demands & Supplies: 15% Reduced Flow Hydrology, Current Trends Scenario (demand = 31,700 AF/year).

Policy analysis

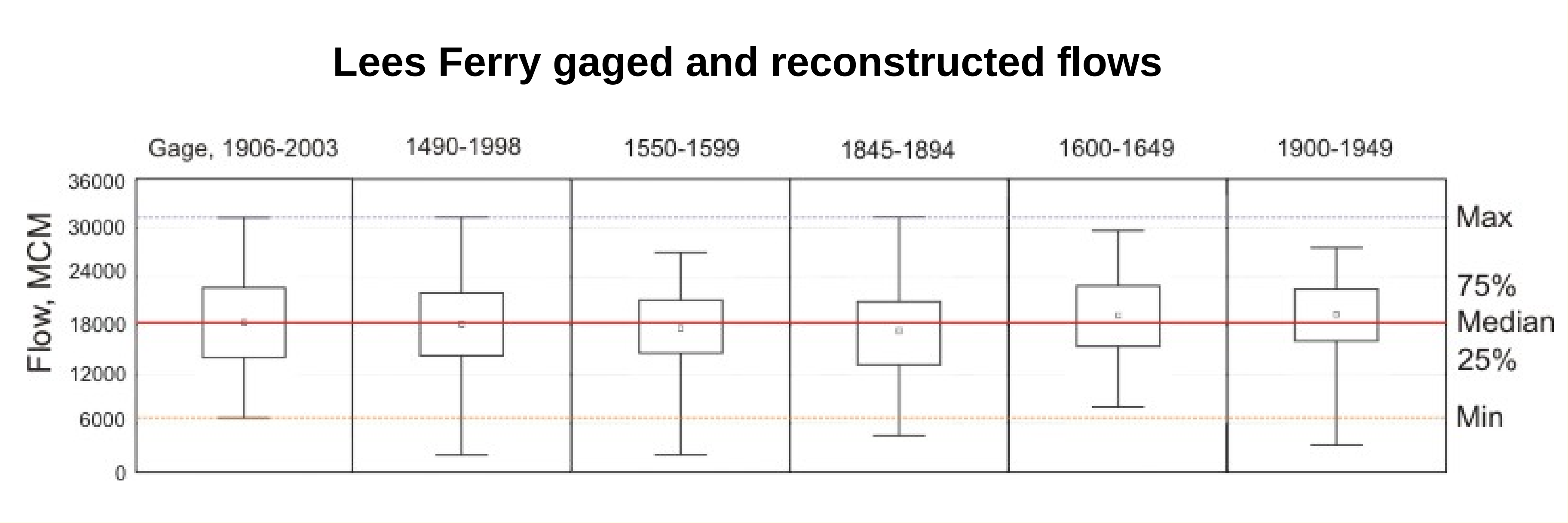
Using the reconstructions - two degrees of difficulty

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

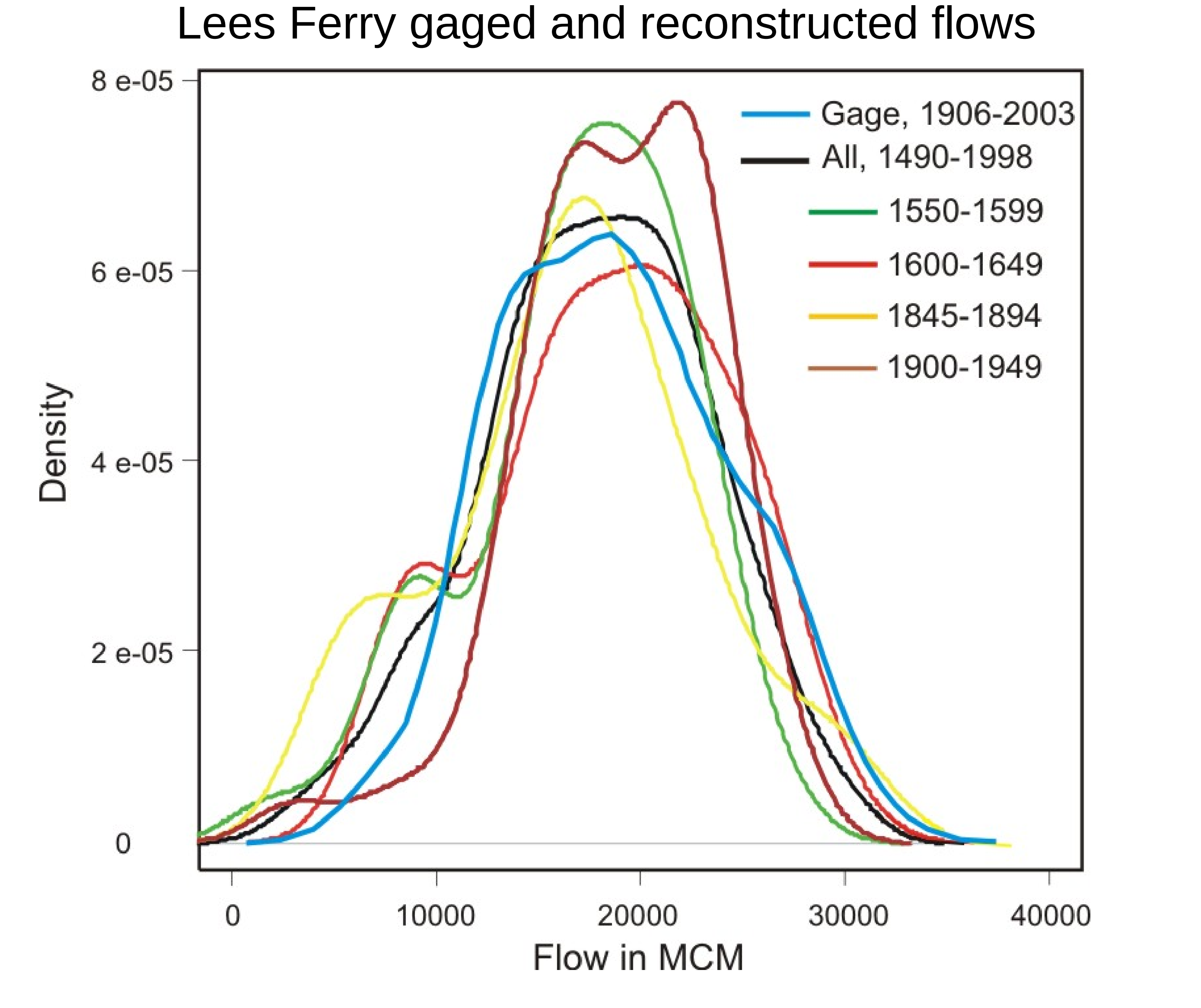
- 2) Input into a system model to assess management scenarios
  - *requires further processing of the reconstruction data*
  - *leads to more effective communication of risk*

1) Providing long-term context for the gage record

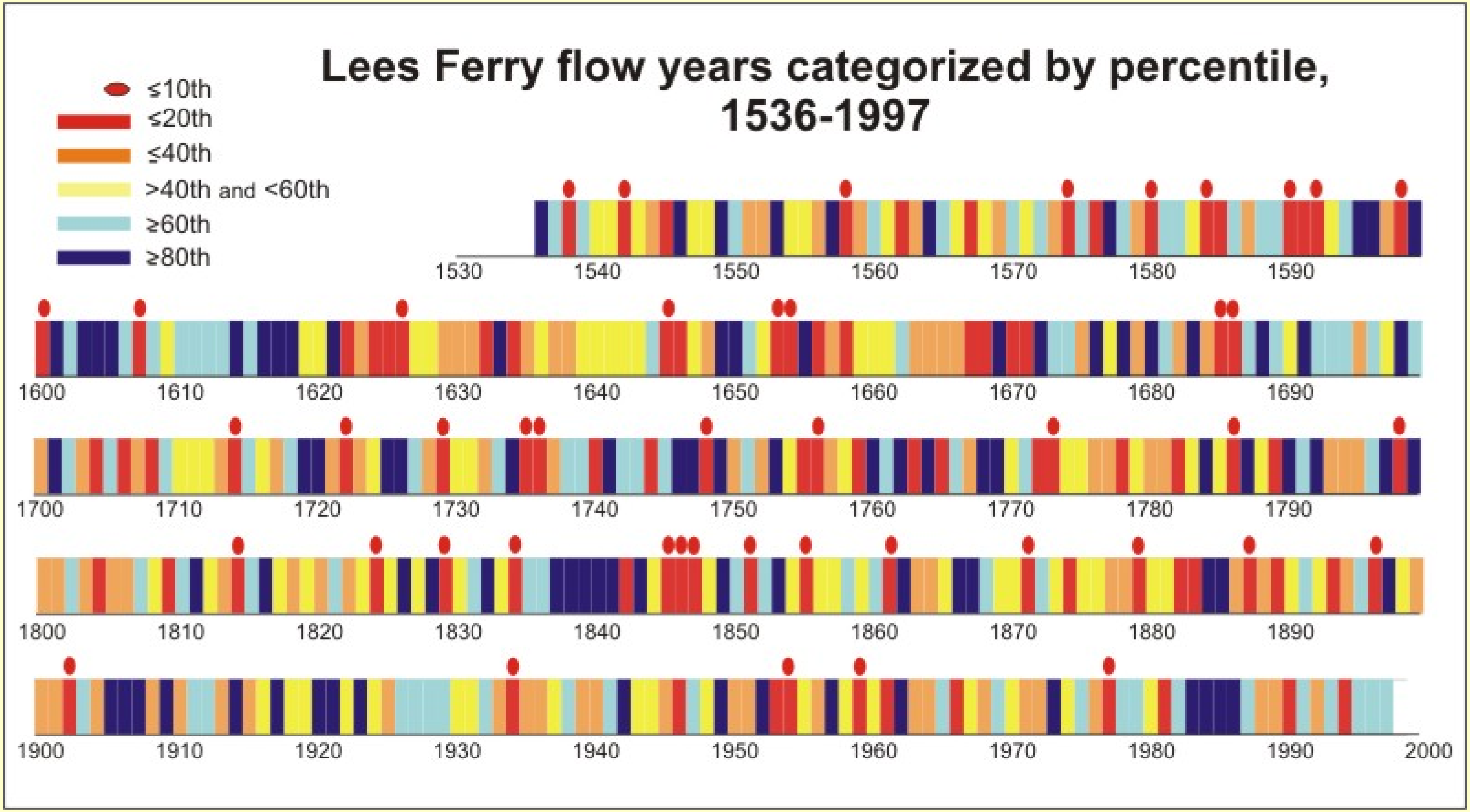
Box and whiskers plots can be used to compare the distributions of flows between the gage and reconstructed flow records



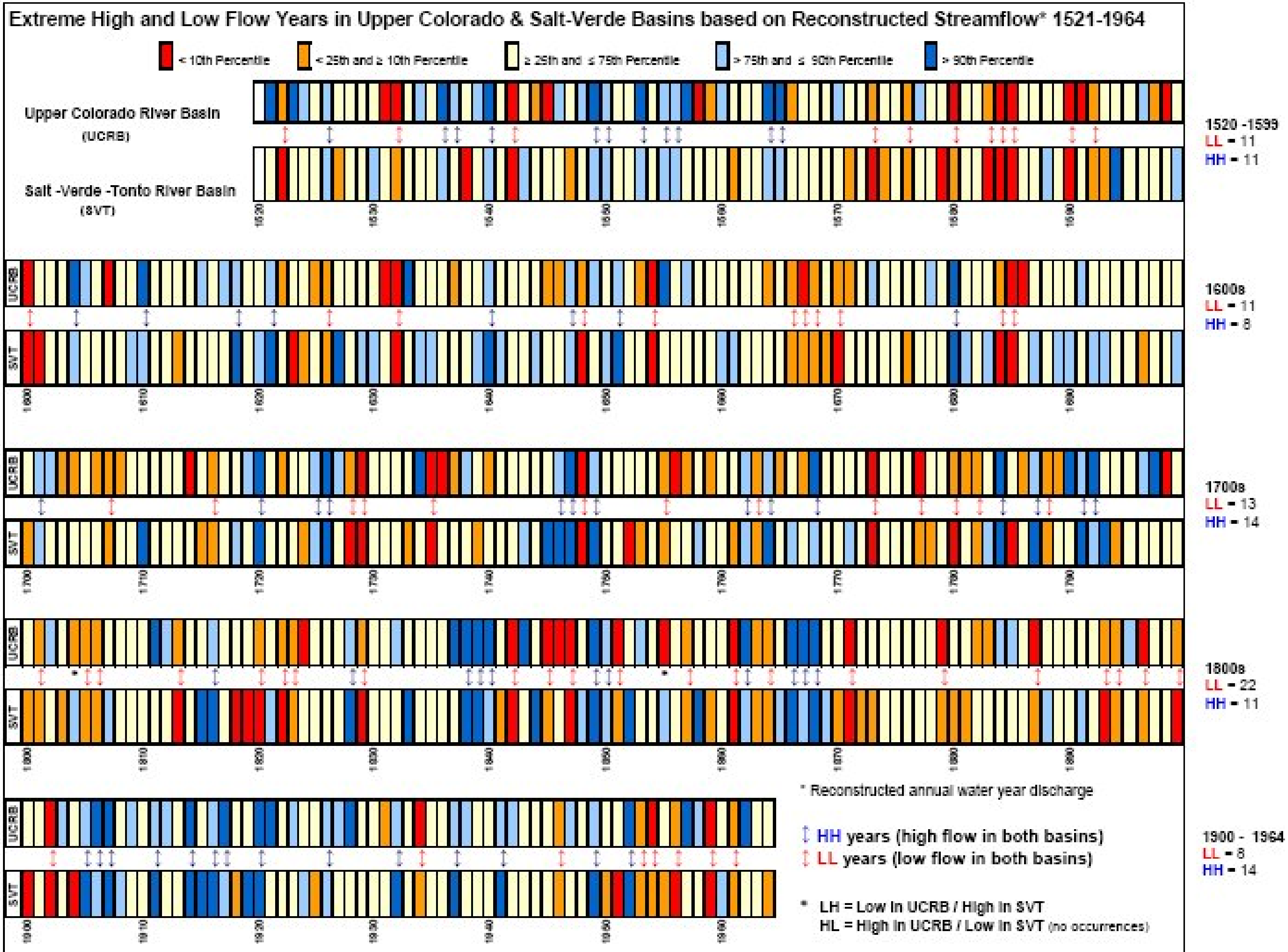
Probability density functions (PDFs) show more subtle differences in the distributions



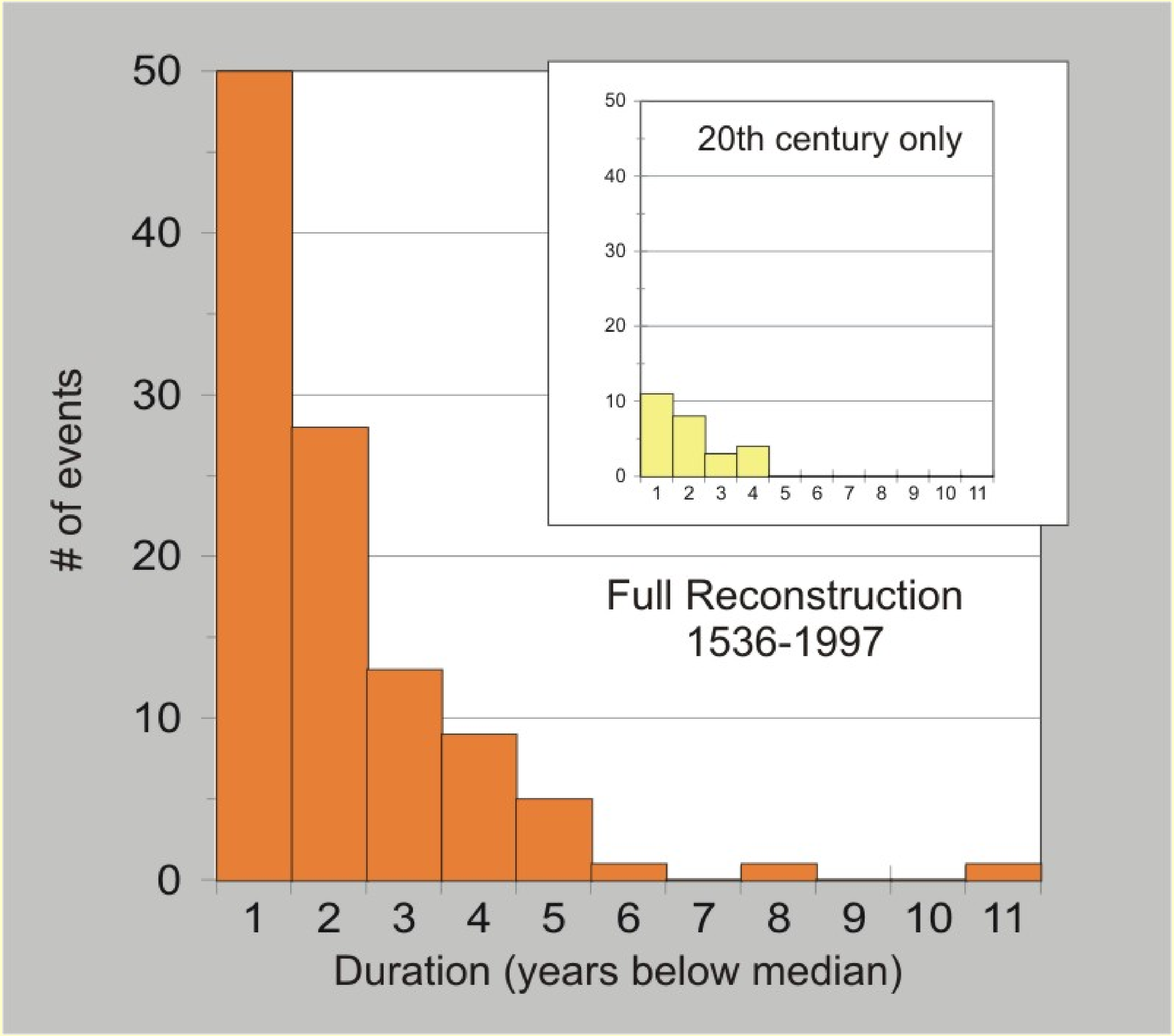
The temporal distribution or sequences of high and low flow years can also be examined



- Extreme events are not evenly distributed over time


Extreme High and Low Flow Years in Upper Colorado & Salt-Verde Basins based on Reconstructed Streamflow* 1521-1964
< 10th Percentile
< 25th and ≥ 10th Percentile
≥ 25th and ≤ 75th Percentile
> 75th and ≤ 90th Percentile
> 90th Percentile
Upper Colorado River Basin
(UCRB)
Salt -Verde -Tonto River Basin
(SVT)
1520 -1599
LL = 11
HH = 11
UCRB
SVT
1600s
LL = 11
HH = 8
1700s
LL = 13
HH = 14
1800s
LL = 22
HH = 11
1900 - 1964
LL = 8
HH = 14
* Reconstructed annual water year discharge
HH years (high flow in both basins)
LL years (low flow in both basins)
* LH = Low in UCRB / High in SVT
HL = High in UCRB / Low in SVT (no occurrences)

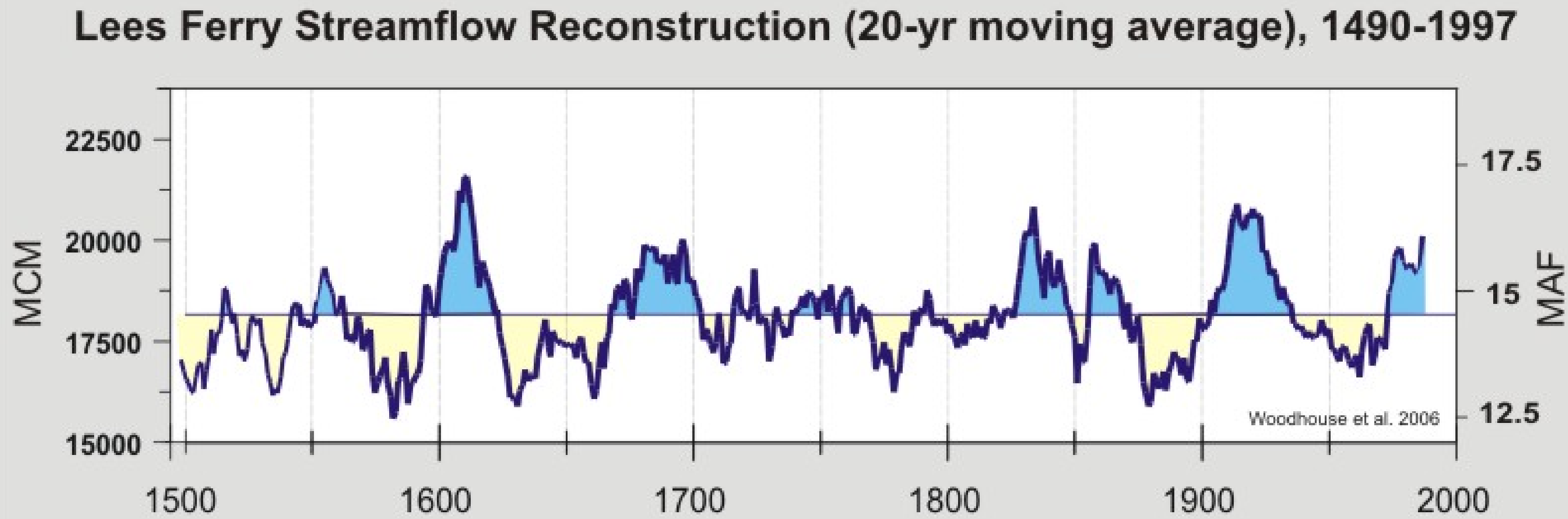
Reconstructed Lees Ferry Streamflow, 1536-1997
Drought Duration and Frequency of Drought Events



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

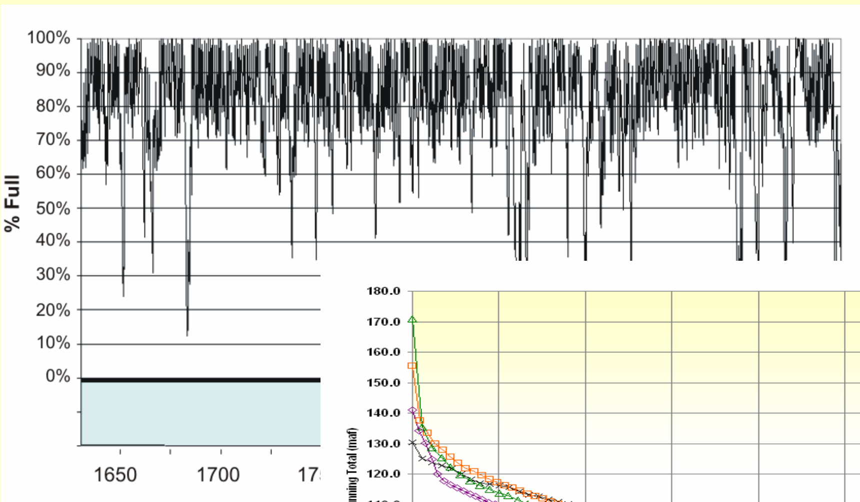
The 20th century represents only a subset of the droughts in the full reconstruction period

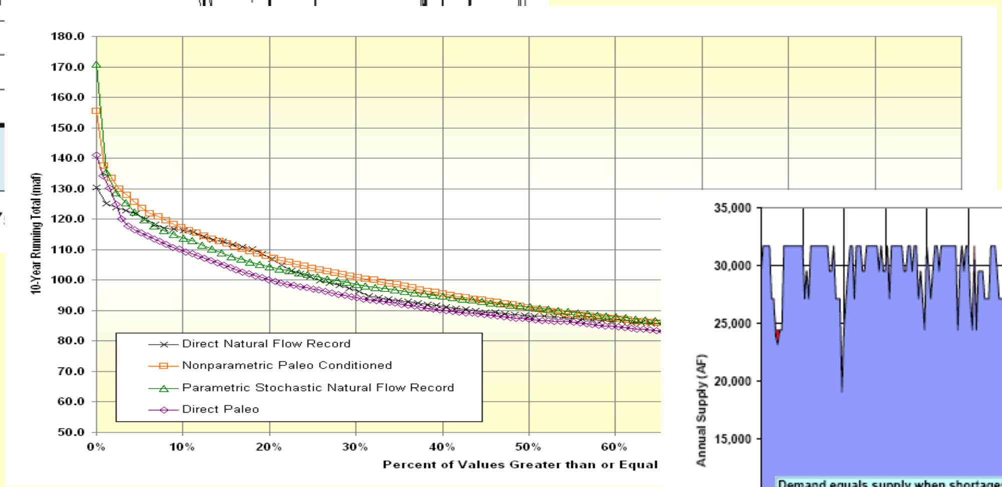
A 20-year moving average shows clear decadal-scale variability
The climatological community is currently addressing the question: What drives this variability?



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 - specific examples





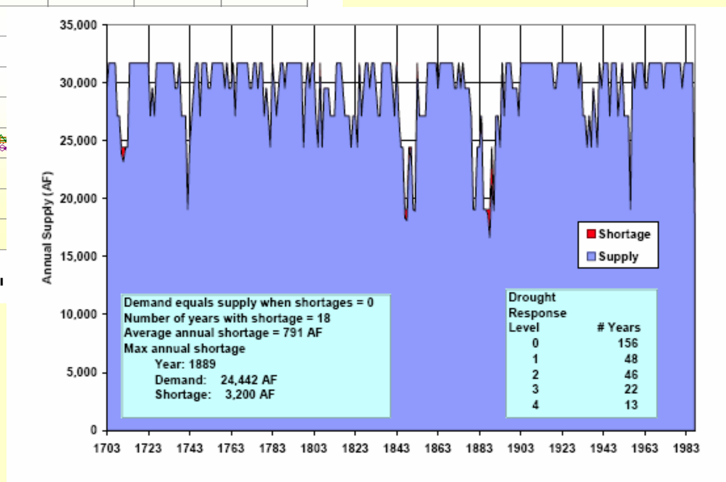


Figure 5. Demands & Supplies: 15% Reduced Flow Hydrology, Current Trends Scenario (demand = 31,700 AF/year).

Denver Water - water supply yield analyses

Challenge:

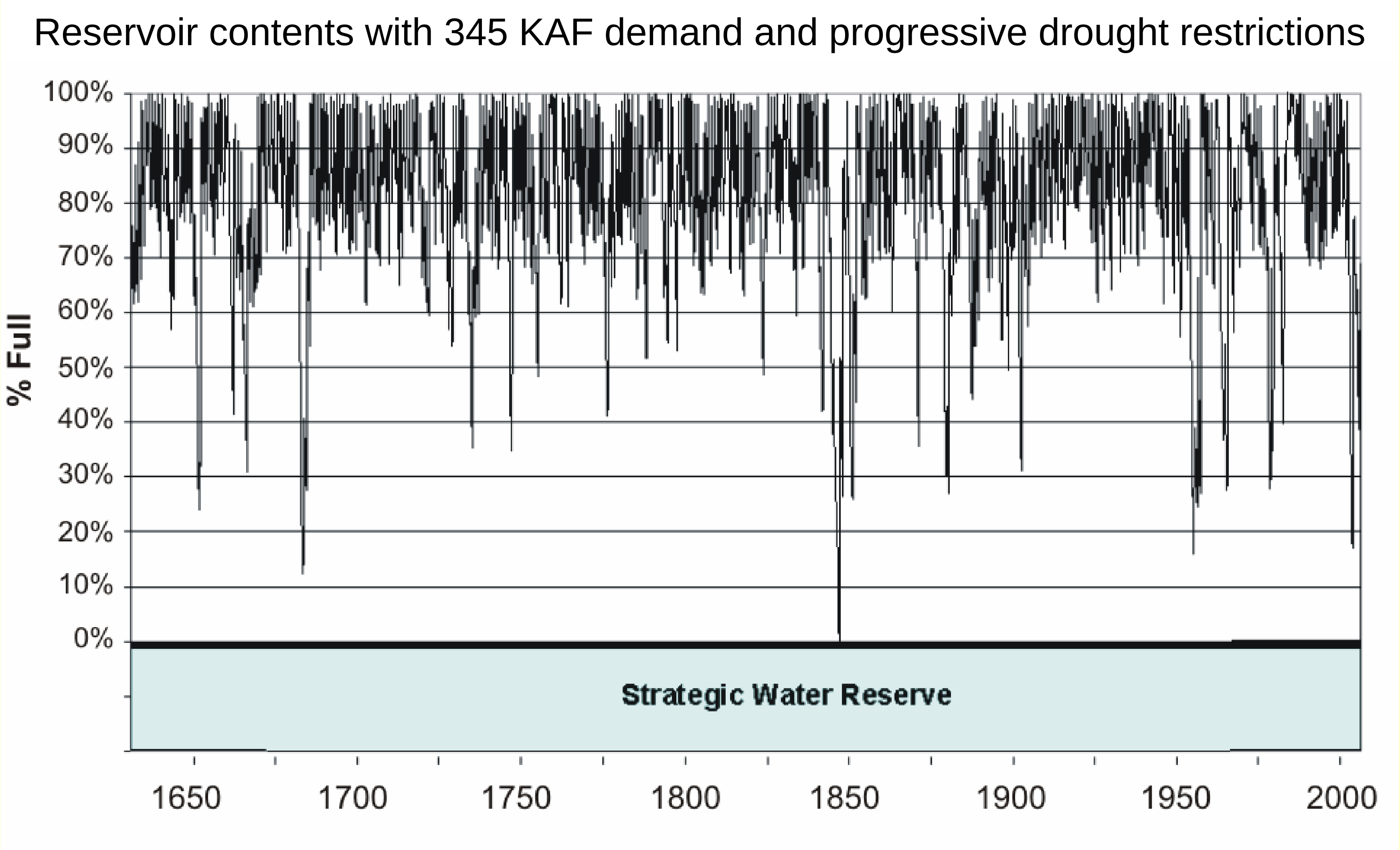
Denver Water's Platte and Colorado Simulation Model (PACSM) requires daily model input from 450 locations

Solution:

An "analogue year" approach

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

Denver Water - water supply yield analyses



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

US Bureau of Reclamation - analyses for “Shortage EIS”

Challenges:

1) CRSS model requires monthly inputs at 29 model nodes

2) Distrust of extreme reconstructed flow values, need to conservatively incorporate new data

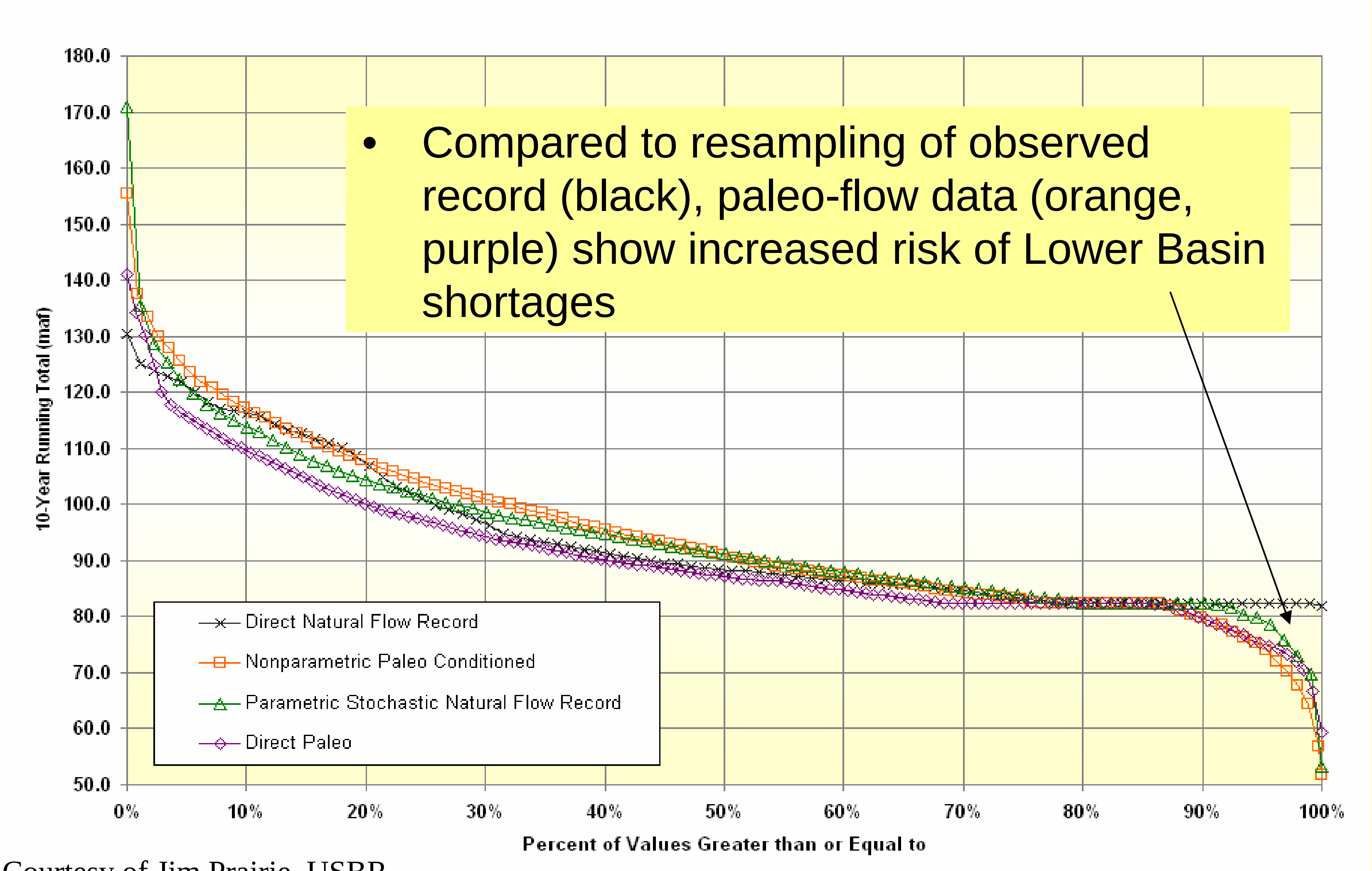
Solutions:

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

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

US Bureau of Reclamation - analyses for "Shortage EIS"

Glen Canyon 10-Year Release Volume
No Action Alternative, *Years 2008-2060*



Courtesy of Jim Prairie, USBR

City of Boulder - water supply yield analyses

Challenges:

1) Incorporate reconstruction uncertainty into modeling

2) Represent potential effects of climate change on hydrology

3) Represent uncertainty in future demand

Solutions:

1) Noise added to reconstruction to represent uncertainty; multiple model runs

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

3) Different demand scenarios (4)

City of Boulder - water supply yield analyses

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

Shortages modeled during 3 paleo-droughts

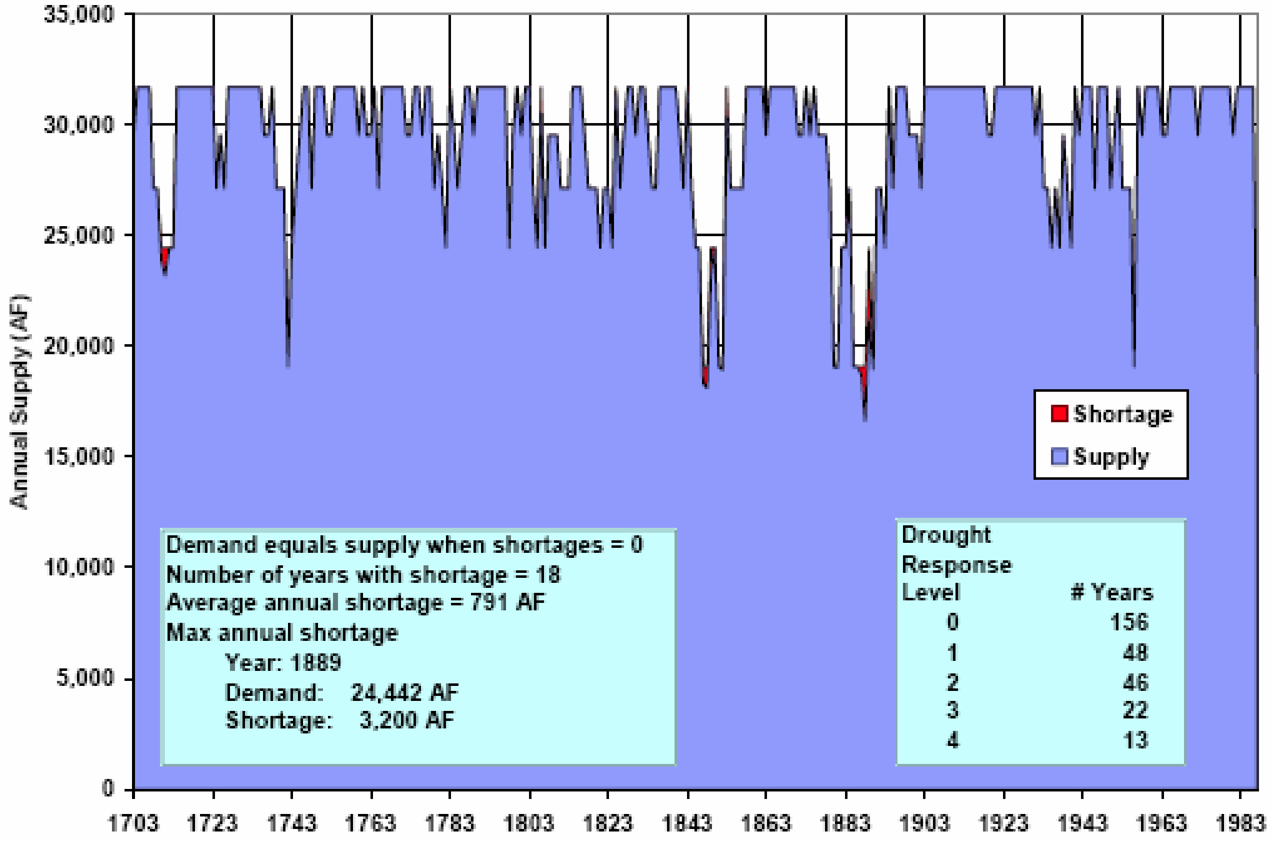
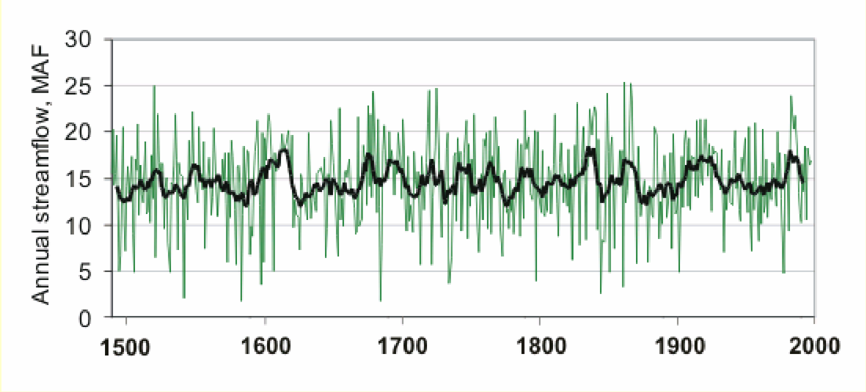


Figure 5. Demands & Supplies: 15% Reduced Flow Hydrology, Current Trends Scenario (demand = 31,700 AF/year).

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

Part 6:

What is the relevance of the reconstructions in light of climate change?



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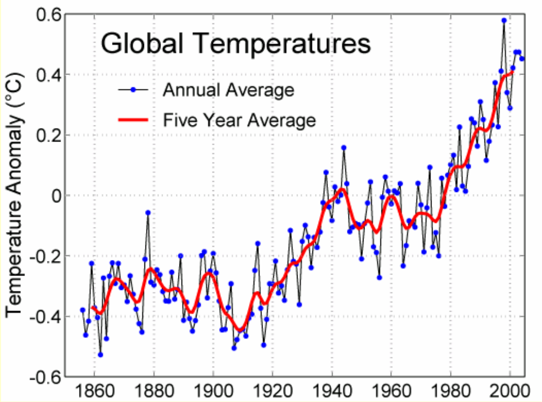
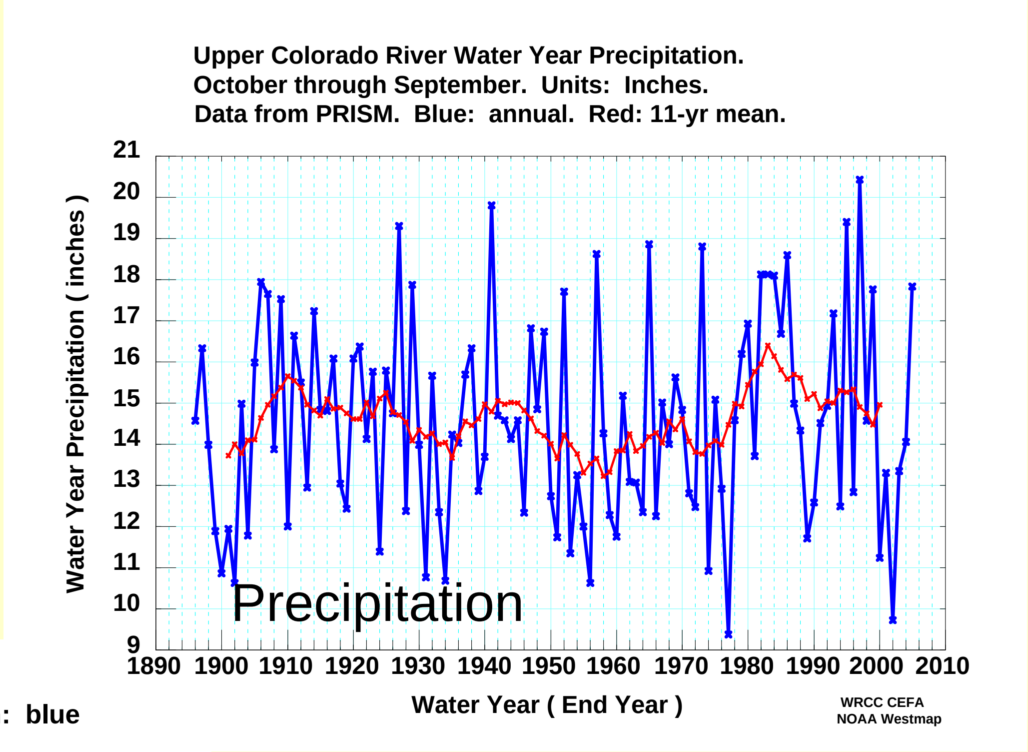
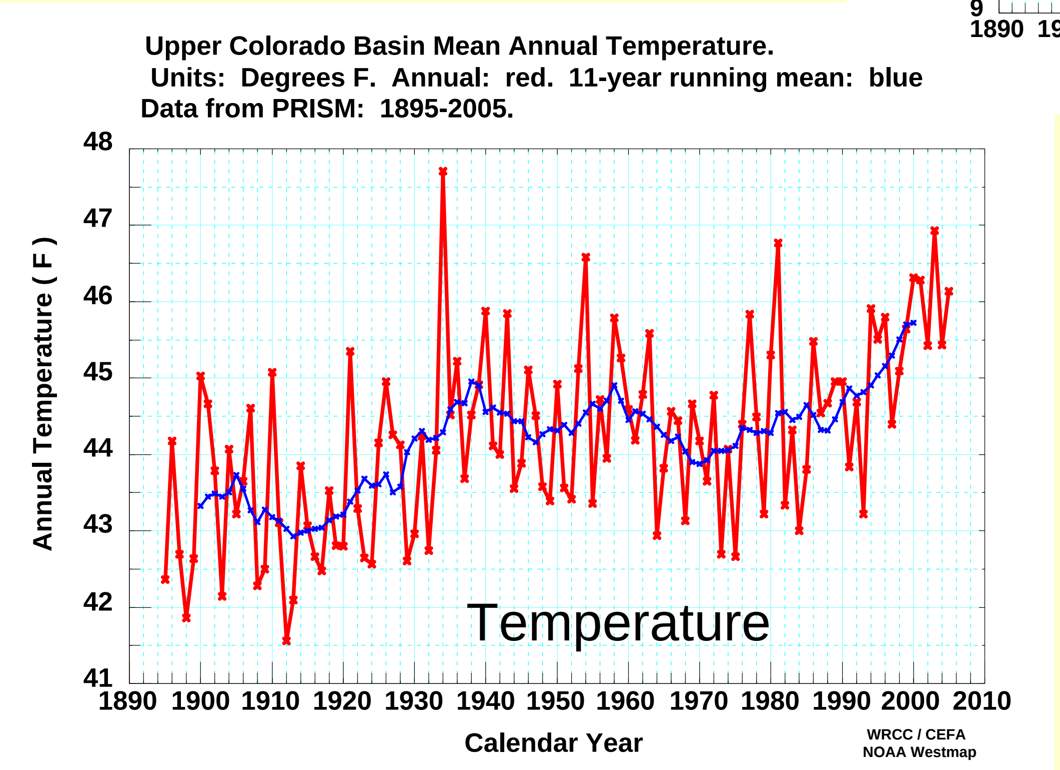


Observed trends in the Upper Colorado River Basin (UCRB)

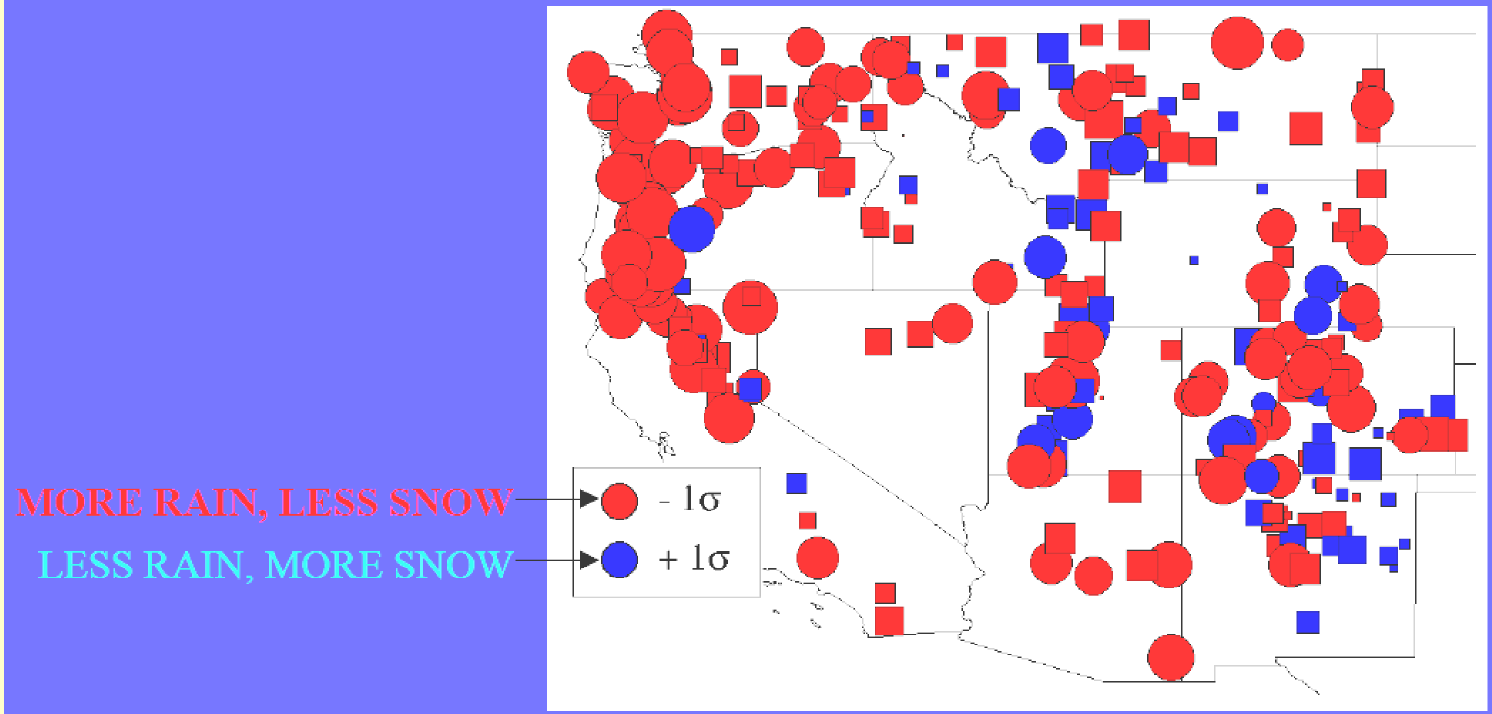




Annual temperatures have risen over the past 110 years, but clear trends in precipitation are not evident

The change in temperature is having an impact on regional snowpack, even without changes in precipitation.

Shift from Snowfall to Rainfall



Trends in ratio of winter (Nov-Mar) snowfall water equivalent (SFE) to total winter precipitation (rain *plus* snow) for the period WY1949-2004. Circles represent significant ($p<0.05$) trends, squares represent less significant trends.

Knowles et al. 2005, AGU

Projections of Future Climate in the upper Colorado River Basin

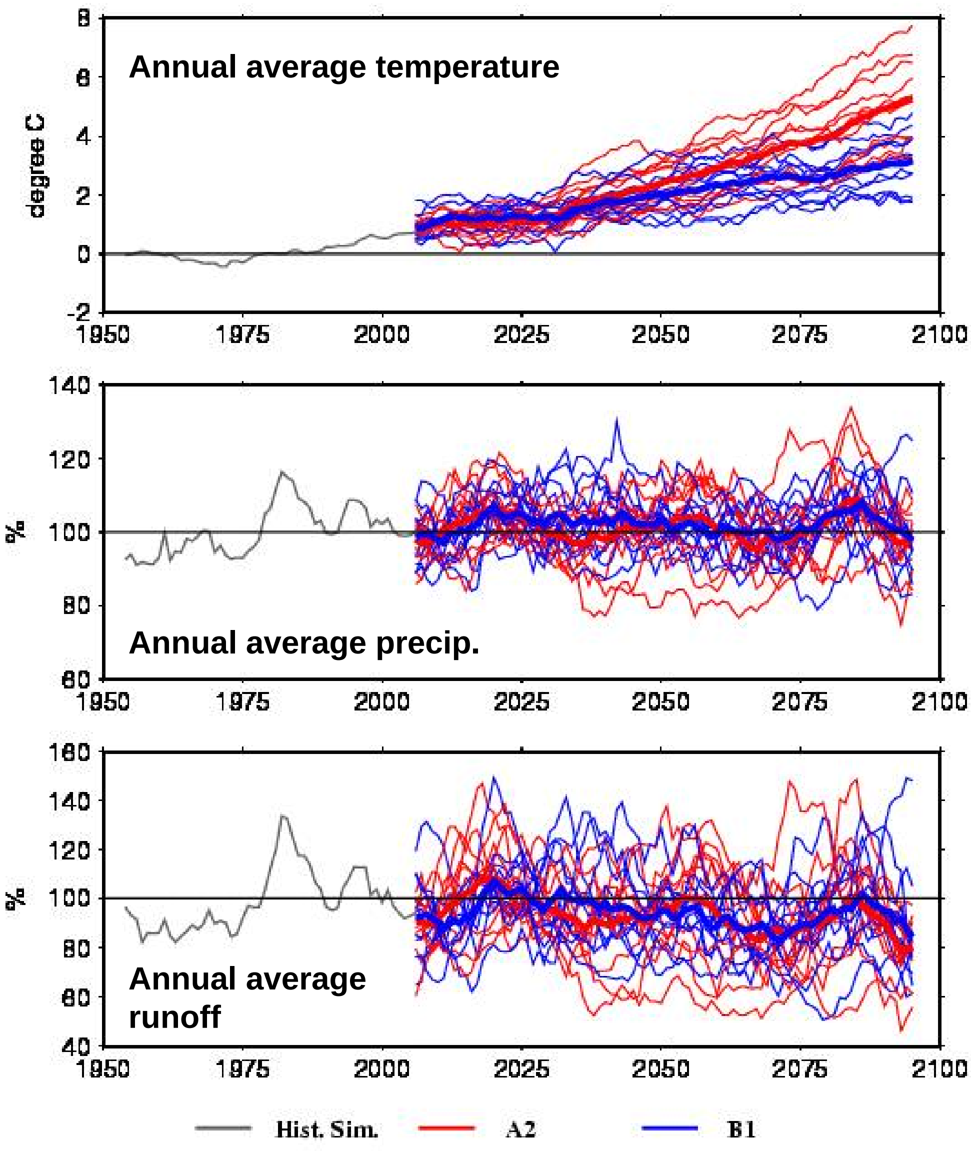
Observed and projected conditions for the Colorado River Basin above Lees Ferry, using 11 models and 2 scenarios downscaled to the Colorado River basin (upper two panels) and used to drive the VIC macroscale hydrology model (lower panel)

- temperature increase consistent among models

- no model consensus on precipitation

- large spread in runoff projections but mostly down

9-year running means expressed as departures from 1950-1999 means



Preliminary data from Christensen and Lettenmaier

Climate change will likely impact future hydrology

- Precipitation change uncertain *(increase? decrease?)*

- Temperature increase very likely (already being observed 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
- Because of their length, tree-ring data are best-suited to assess and understand multidecadal scale variability and its causes
- The greater variability seen in the paleohydrologic records may 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

Wrapping things up...

The take-home messages

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 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

The take-home messages

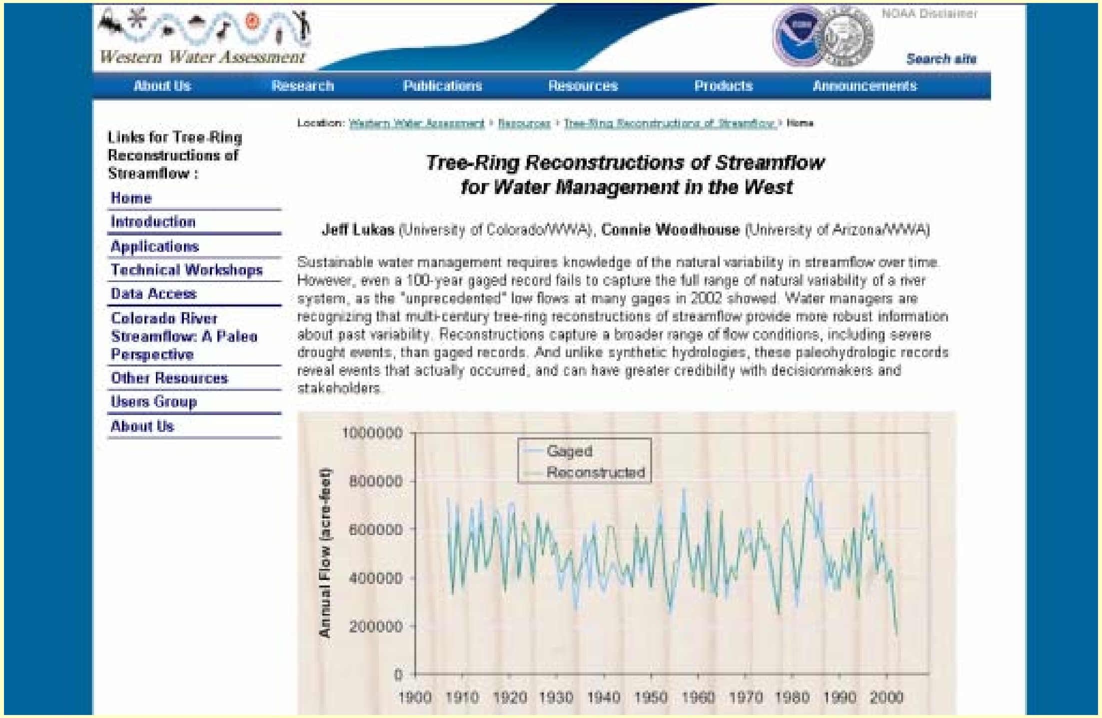
5) There are several annual flow reconstructions available for the San Juan region, and more could be readily generated

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

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

8) Climate change will impact future hydrology, but past experience will still be relevant

WWA Tree-Ring Reconstructions Webpages



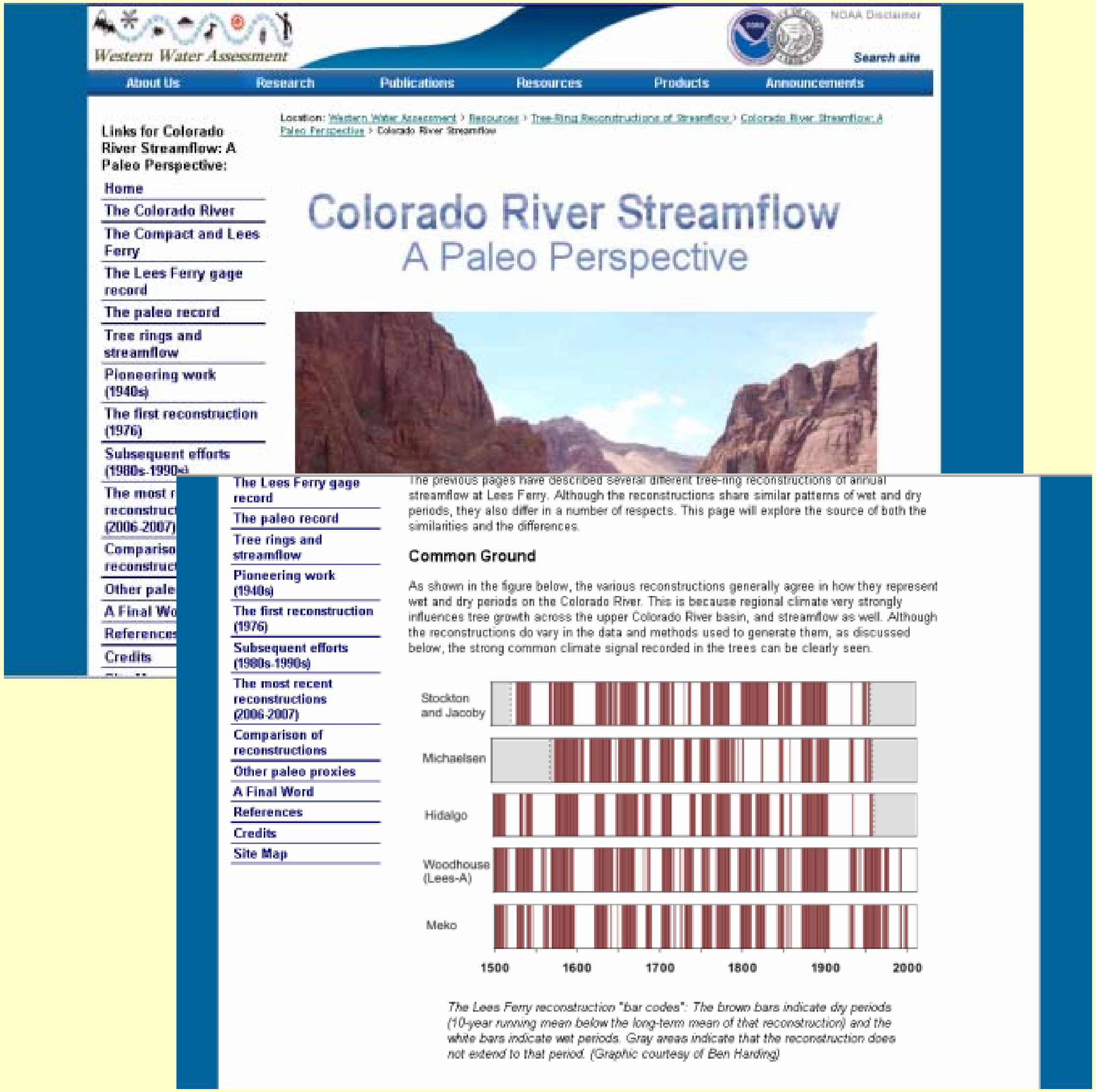
http://wwa.colorado.edu/resources/paleo/

- 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?

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

- Monthly temperatures, monthly precipitation, and gaged streamflow from instrumental record (1953-2002) are resampled to match 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 will be 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