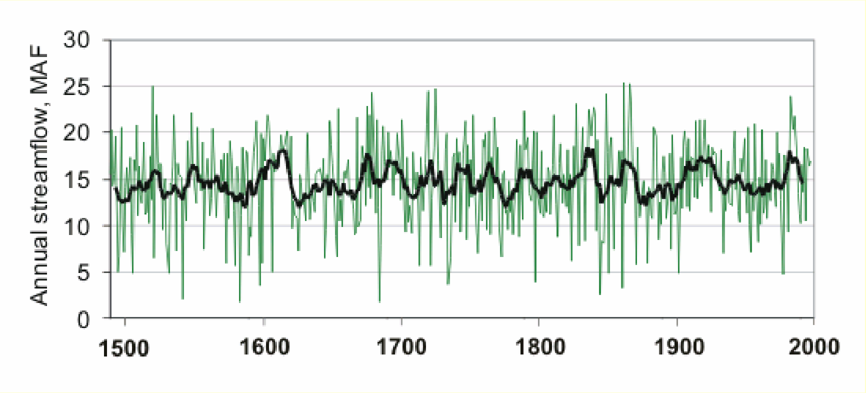
Workshop on the application of tree-ring data to water management



May 14, 2007 - Boulder, CO

Conveners: Connie Woodhouse, University of Arizona
and Jeff Lukas, University of Colorado

Sponsored by the Western Water Assessment

Western Water Assessment

Welcome and Logistics

Plan for day:

- Welcome, introductions, and some history
- Background on tree-ring data and methods
- Overview of application issues and challenges
- Presentations from participants and discussion
- Wrap-up and follow-up activities

Morning and afternoon breaks
Box lunches outside

Parking
Dinner

Who is here - Introductions

Acknowledgements

Workshop assistance:

WWA – Brad Udall, Christina Alvord

Partners and Collaborators:

Denver Water, Hydrosphere Resource Consultants, Northern Colorado Water Conservancy District, Rio Grande Water Conservation District, CA Dept Water Resources, US Bureau of Reclamation, US Geological Survey, City of Westminster, Wright Water Engineering

Funding for Research:

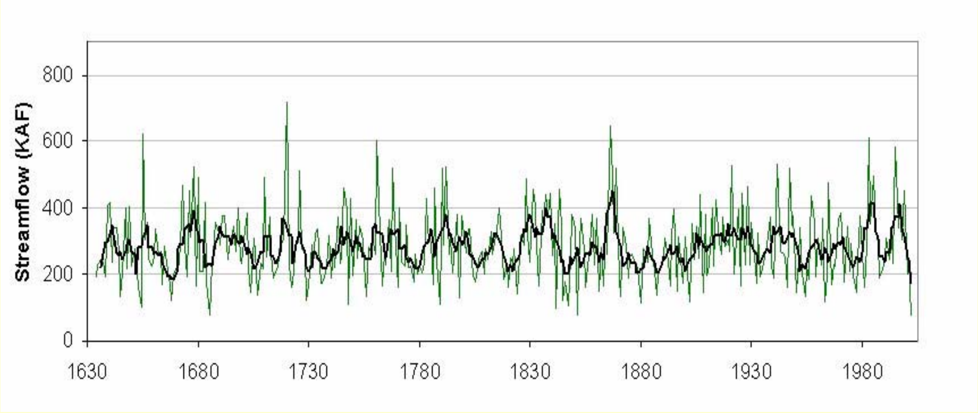
NOAA Office of Climate Programs: Western Water Assessment and Climate Change Data and Detection (GC02-046); Denver Water; USGS

Background and History

1998-99 - Connie develops annual flow reconstructions for Boulder Creek and Clear Creek

2002 - Connie and Robin Webb get NOAA grant to develop hydroclimatic reconstructions in partnership with water managers (TreeFlow project); Jeff is hired to help with the project - partners include Denver Water, NCWCD

2002-2006 - Development of 20 streamflow reconstructions for gages across Colorado (S. Platte, Upper Colorado, Arkansas, Rio Grande) in collaboration with partners



Background and History

2005 - *Planning Workshop to Develop Hydroclimatic Reconstructions for Decision Support in the Colorado River Basin* - Tucson - 30 climate and water scientists and 30 water managers

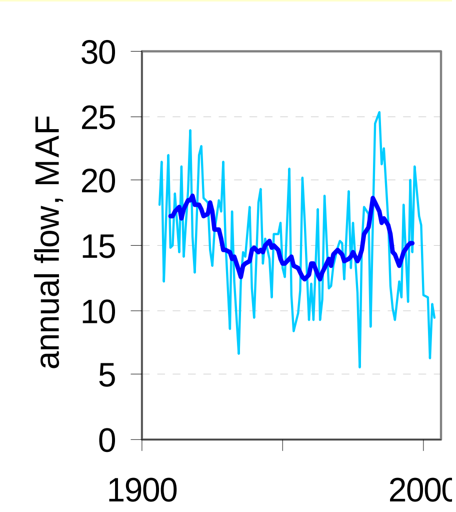
2006 - One-day technical workshops on streamflow reconstructions for water managers in Alamosa, Boulder, and Tucson

2006-2007 – New publications: *Updated Streamflow Reconstructions for the Upper Colorado River Basin,* NRC report on the Colorado River, including tree-ring reconstructions

2007 - More workshops, greater focus on applications, USBR EIS

So why use tree-ring data?

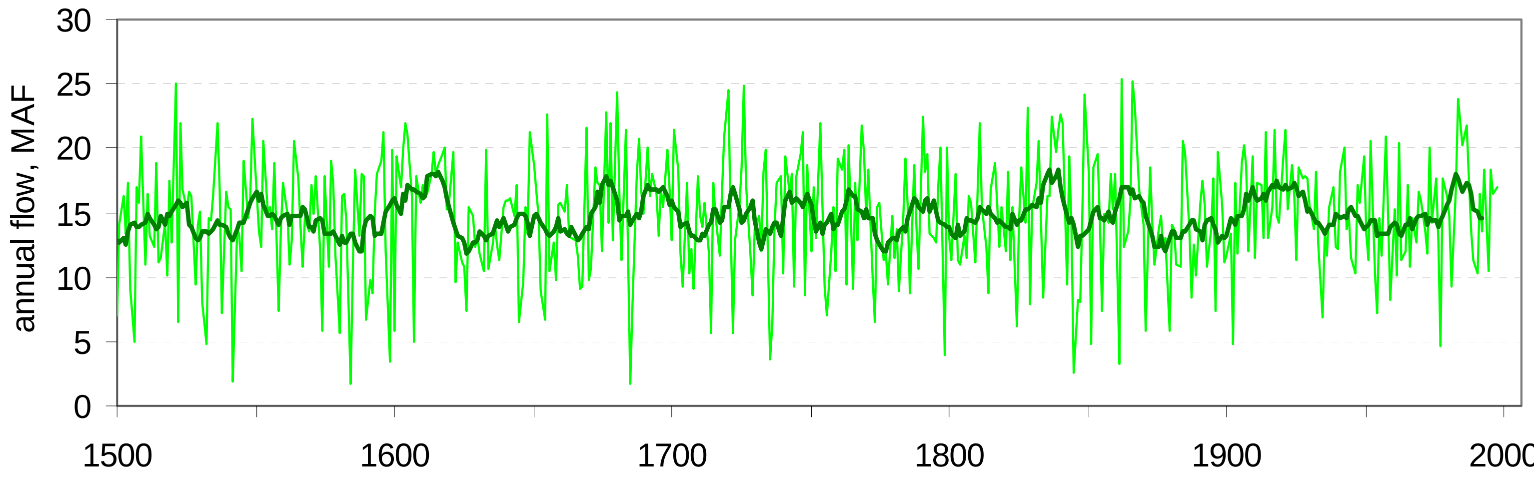
Extend the gaged hydrology by hundreds of years, to get a more complete picture of past hydrologic variability



Colorado at Lees Ferry

Gaged (natural flow) record

1906-2004

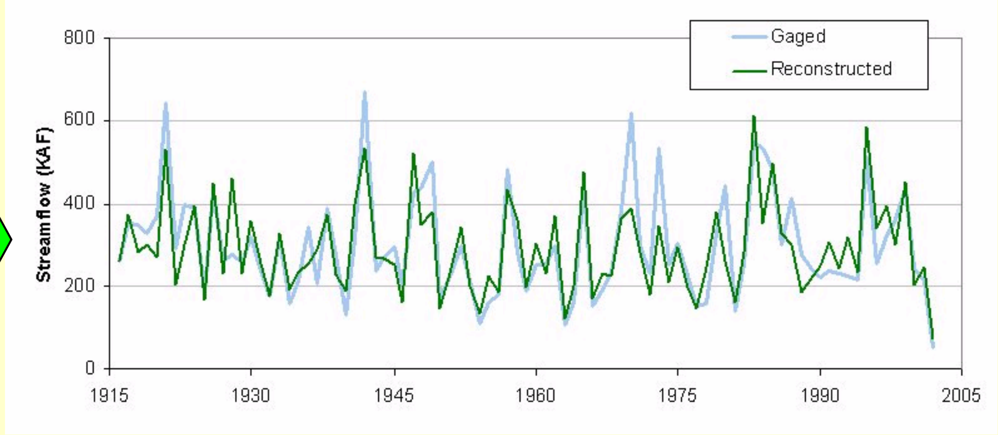


Tree-ring reconstruction

1490-1997

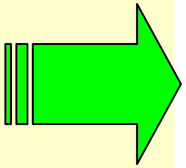
From Tree to Trace: How tree-ring reconstructions of streamflow are generated

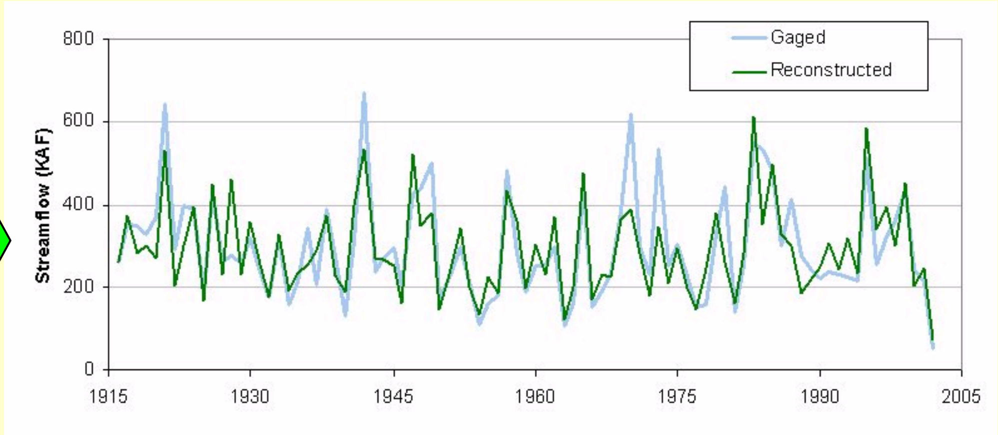
Lite Version - 75% fewer slides!

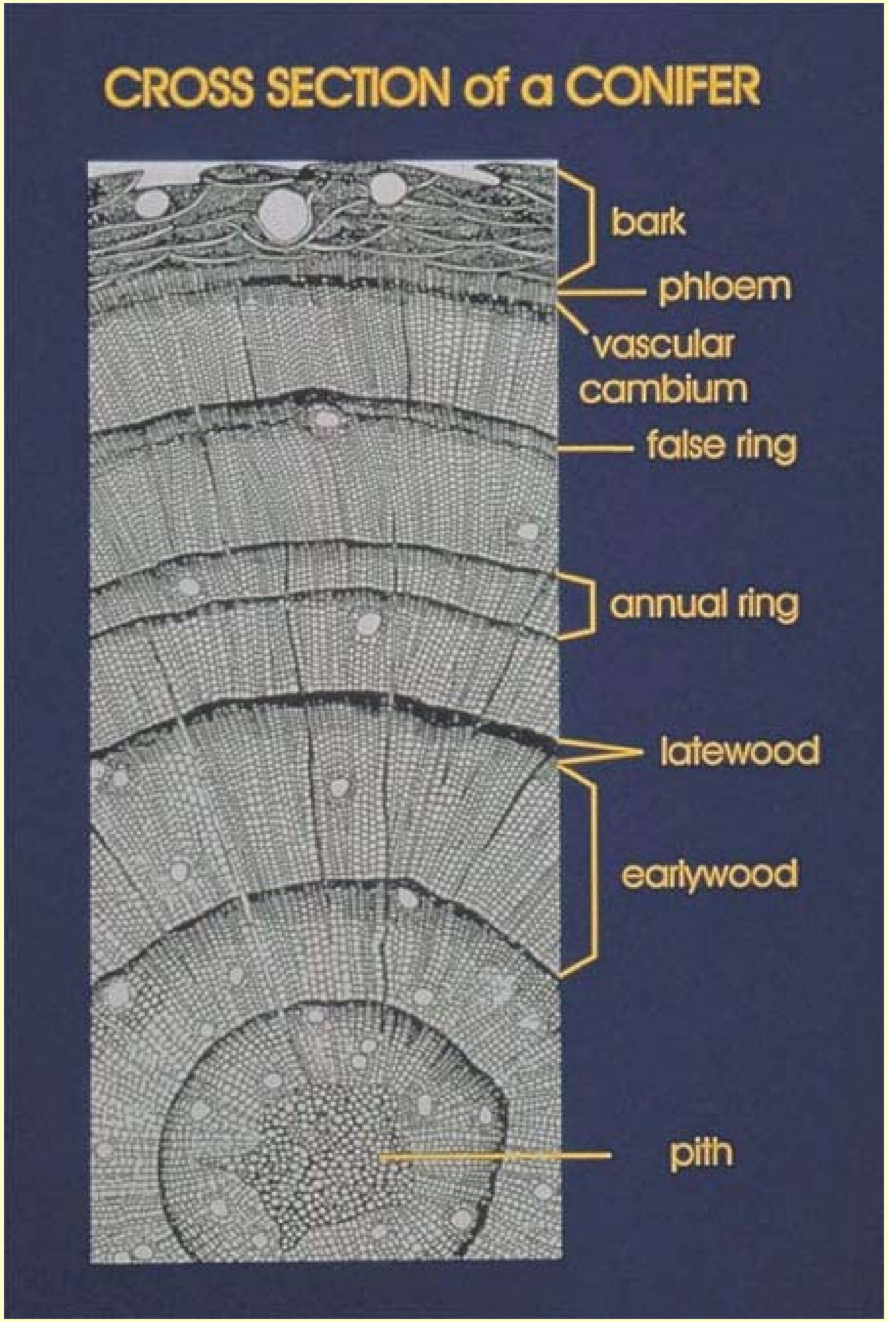


Part 1:

How Tree Rings Work







How annual growth rings form

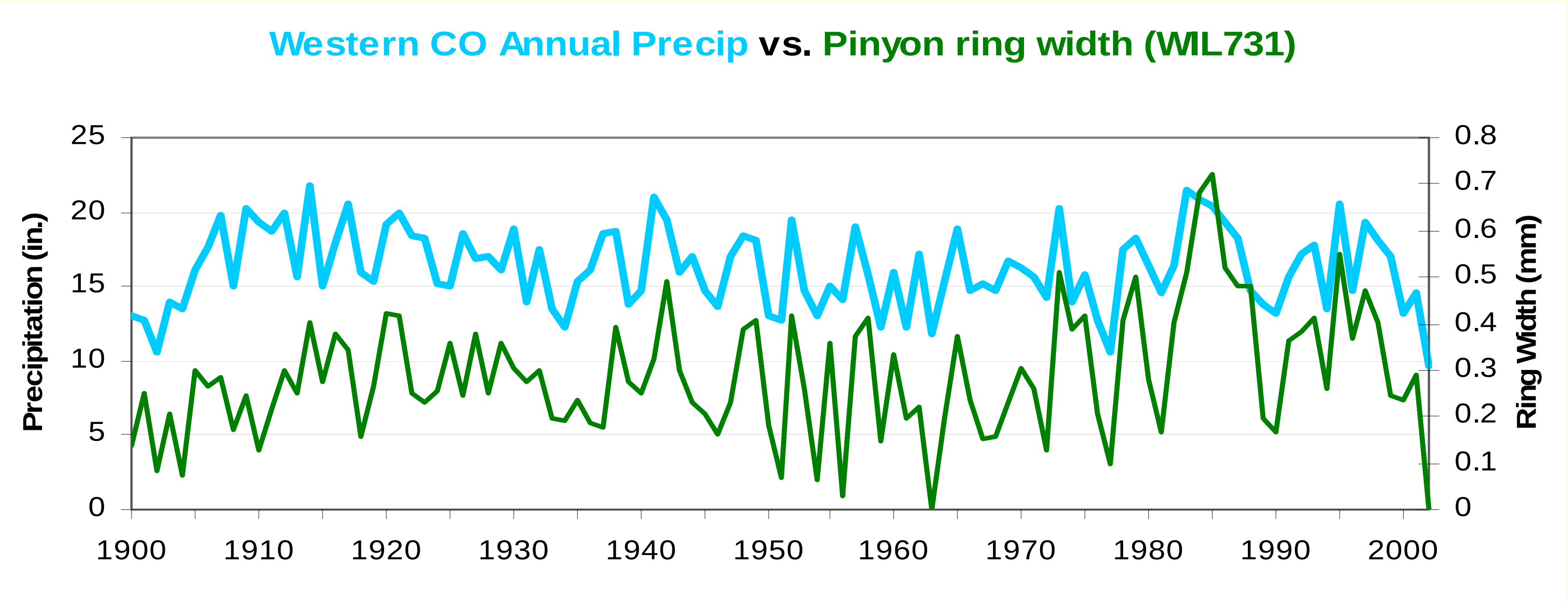
- New wood forms in the vascular cambium, underneath the bark
- Earlywood + latewood = growth ring
- In temperate climates, growth ring = *annual ring*
- Rings have varying widths when a limiting factor on growth varies in magnitude from year to year

Climate is typically the limiting factor for tree growth in the intermountain West

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

- At middle and lower elevations, growth is typically limited by **moisture availability** (precipitation - evapotranspiration)

The moisture signal recorded by trees in this region is particularly strong



- Here, the “raw” ring widths from one tree are closely correlated to the annual basin precipitation (r = 0.7)
- Our job is to *capture* and *enhance* the moisture signal, and reduce noise, through careful sampling and data processing
- Moisture signal can be used to reconstruct precip, PDSI, SWE, and streamflow

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

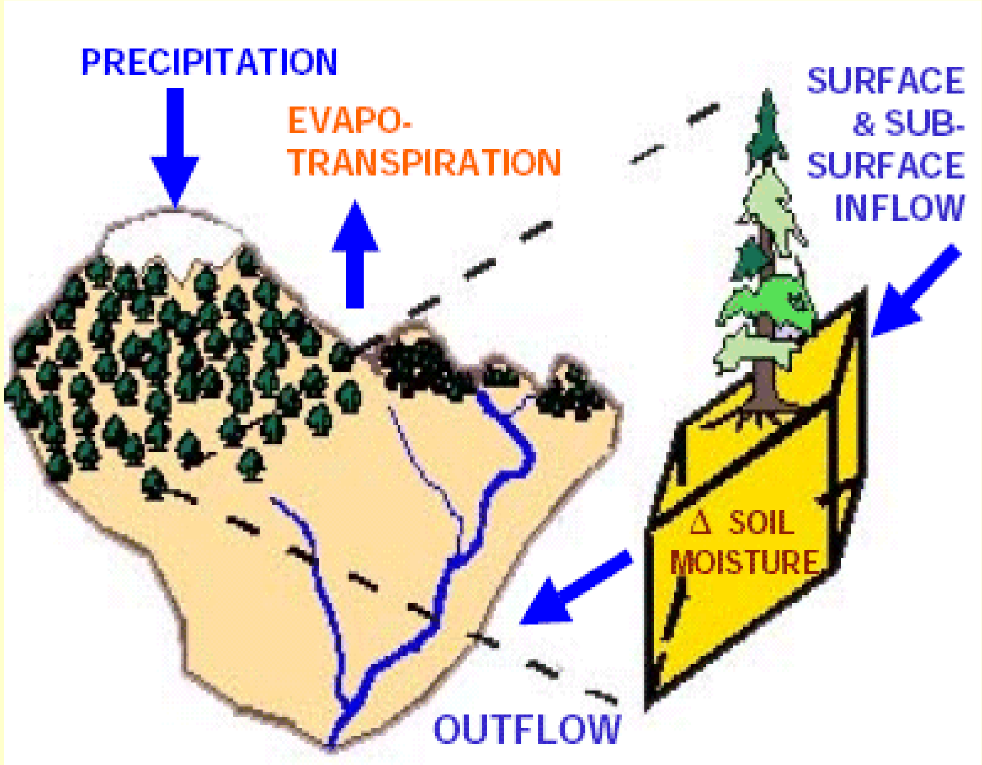
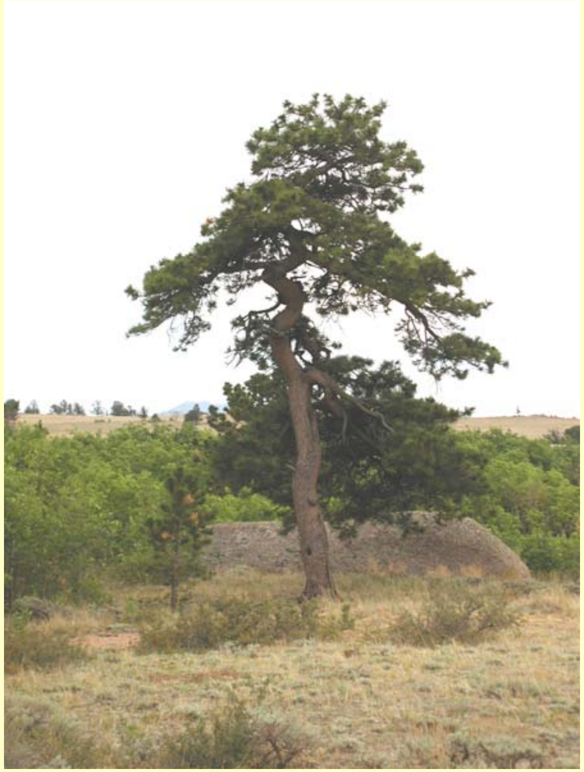


Image courtesy of D. Meko (U. AZ)

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

Douglas-fir

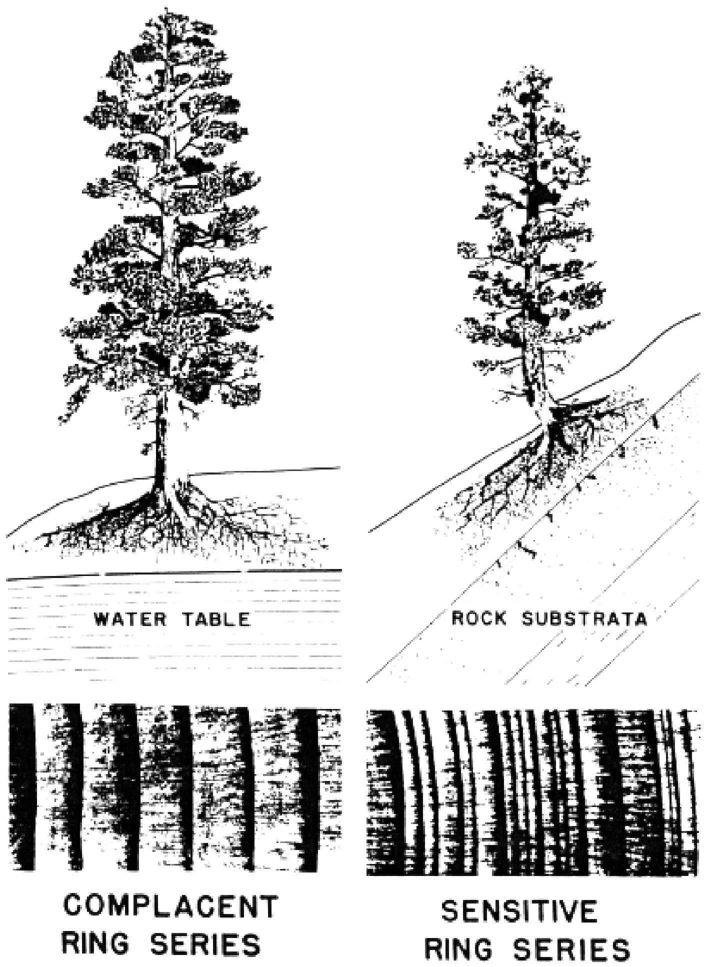
Pinyon Pine



Ponderosa Pine

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

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

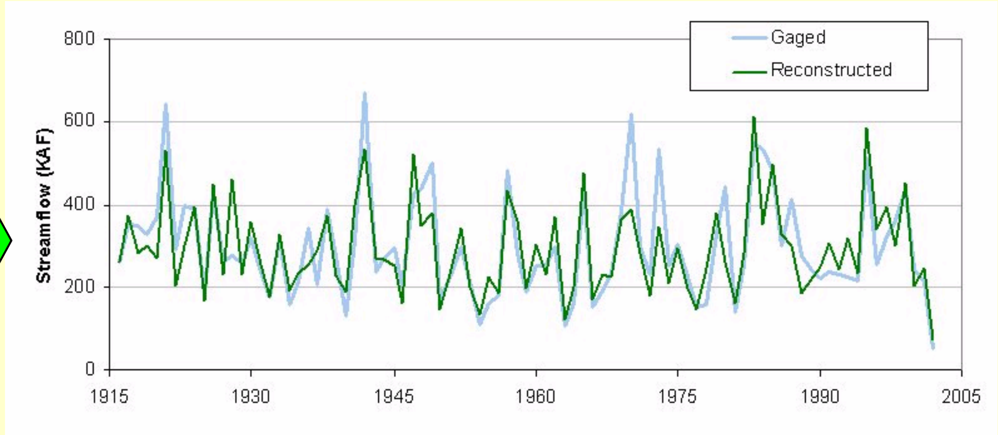


Fritts 1976

Green Mtn. Res, CO

Part 2:

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

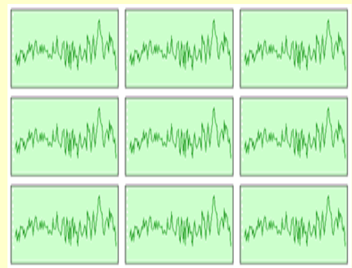
Multiple samples at a site

Crossdating

Measuring

Detrending

Series (of ring-width indices)



Quality Control

Compilation

Chronology (weighted average of all series)

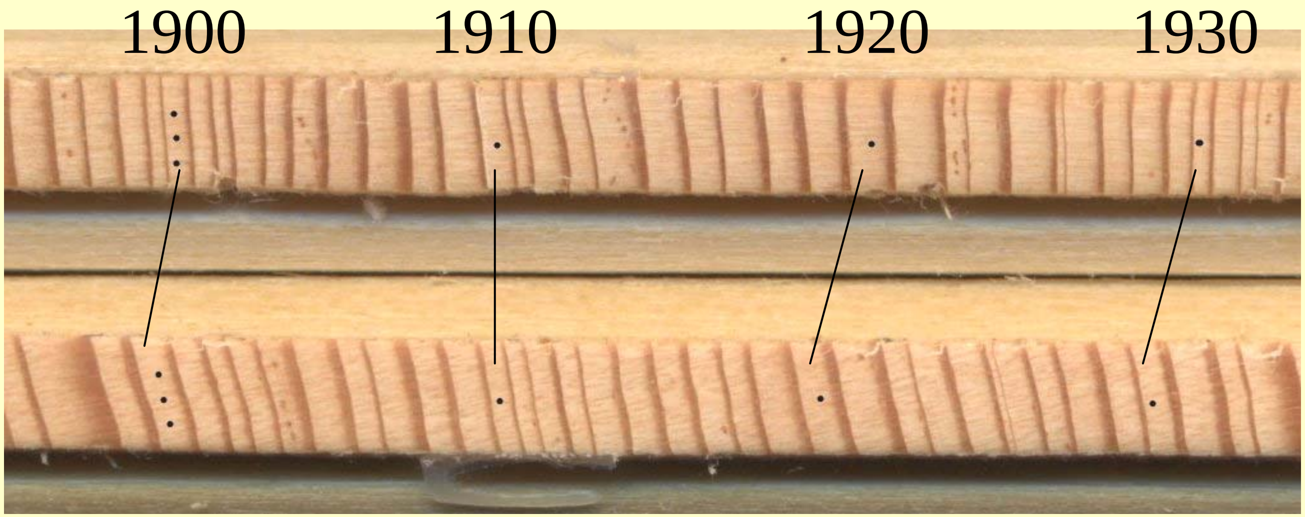
Sampling the trees

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

Crossdating the samples

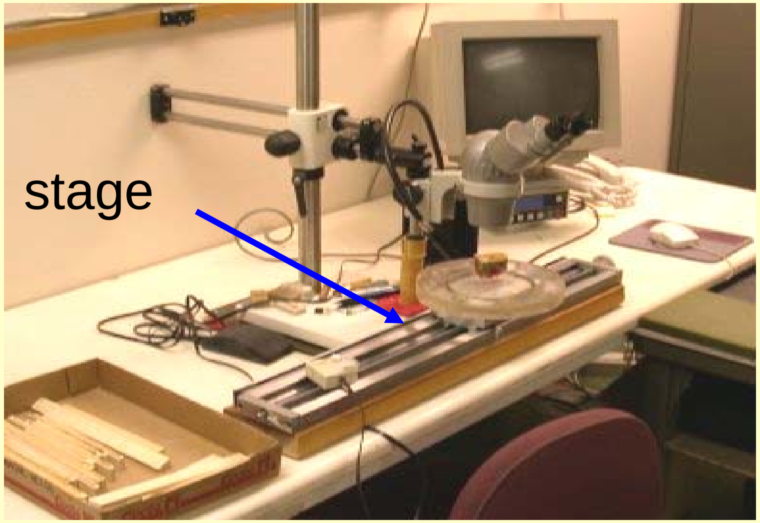
- Because of the common climate signal, the pattern of wide and narrow rings is highly replicated between trees at a site, and between nearby sites

- This allows *crossdating:* the assignment of absolute dates to annual rings

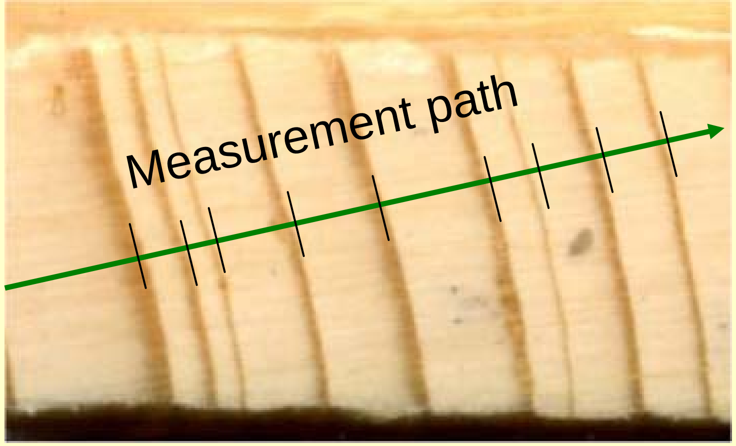


Two Douglas-fir trees south of Boulder, CO

Measuring the samples

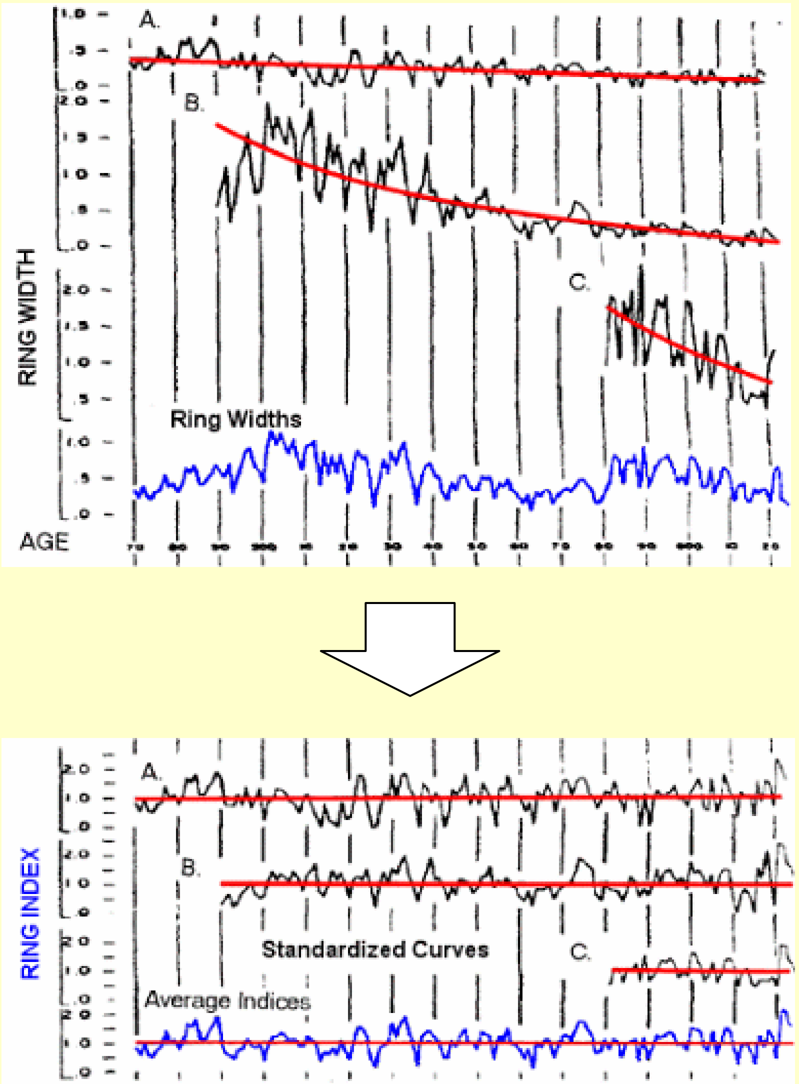


- Computer-assisted measurement system with sliding stage
  - captures position of core to nearest 0.001mm (1 micron)



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

Detrending the measured series

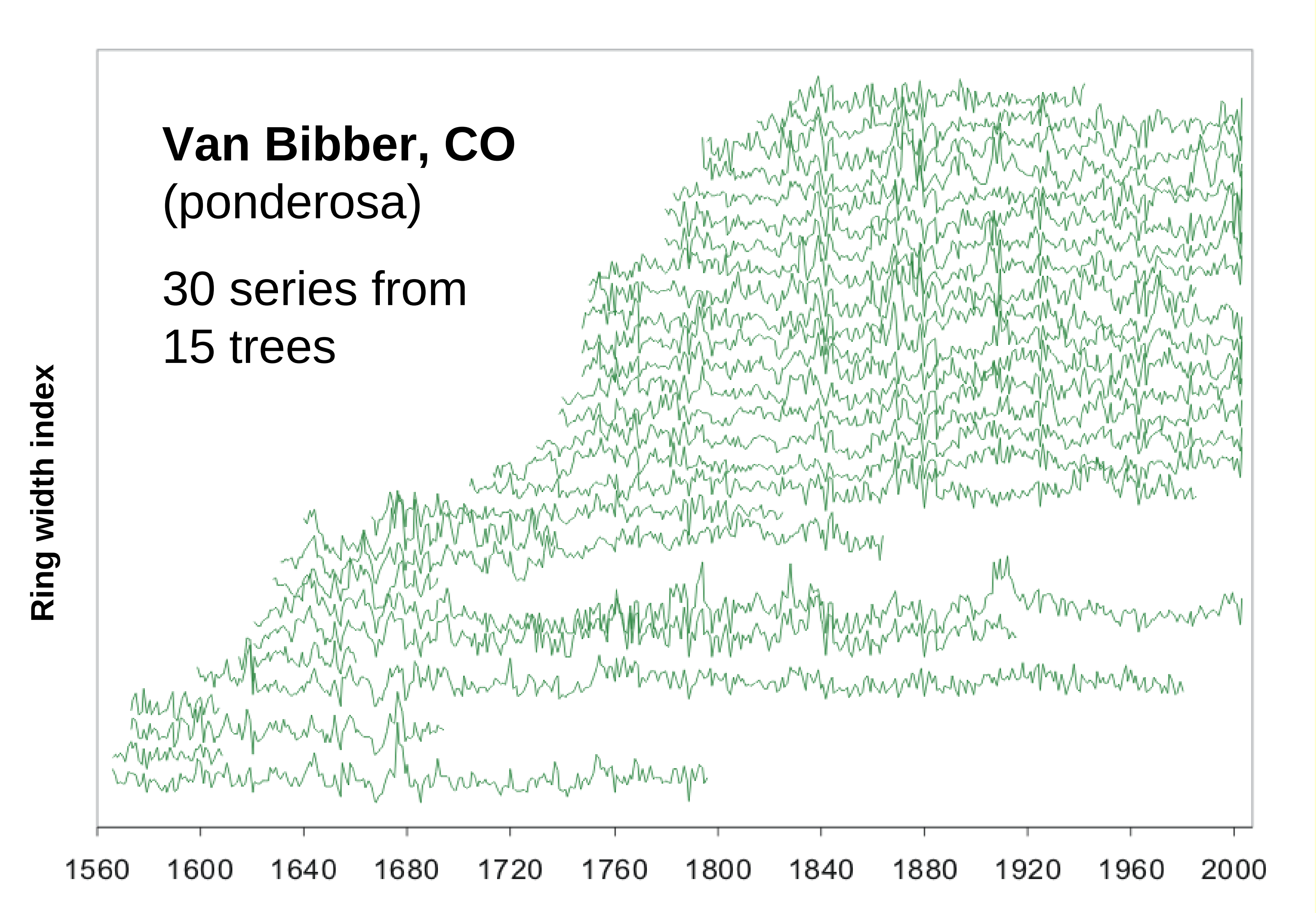


- Ring-width series typically have a declining trend with time because of tree geometry
- These are low-frequency *noise* (i.e. non-climatic)

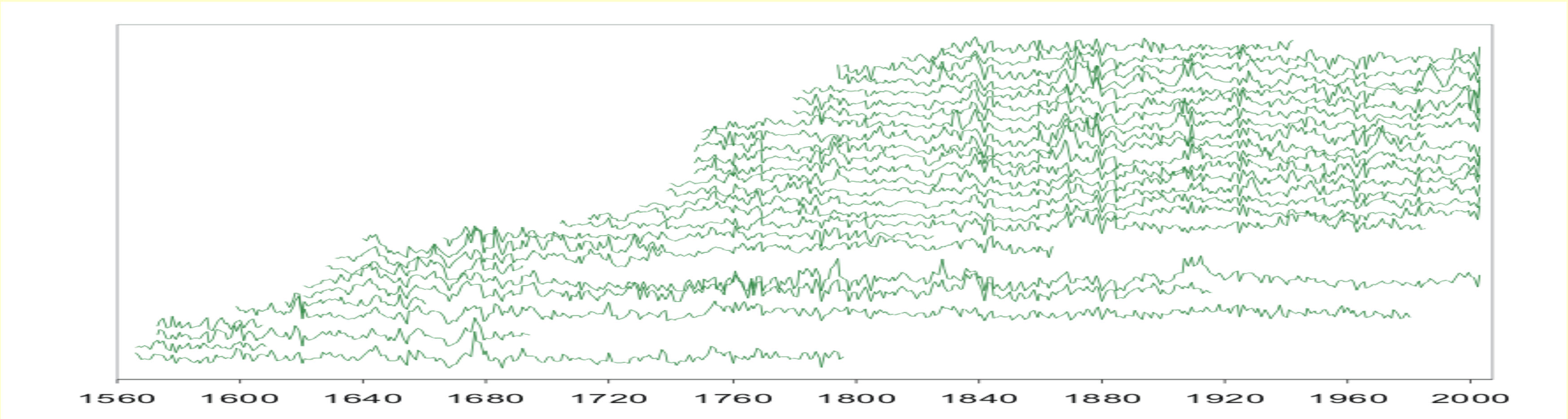
- Raw ring series are detrended with straight line, exponential curve, or spline

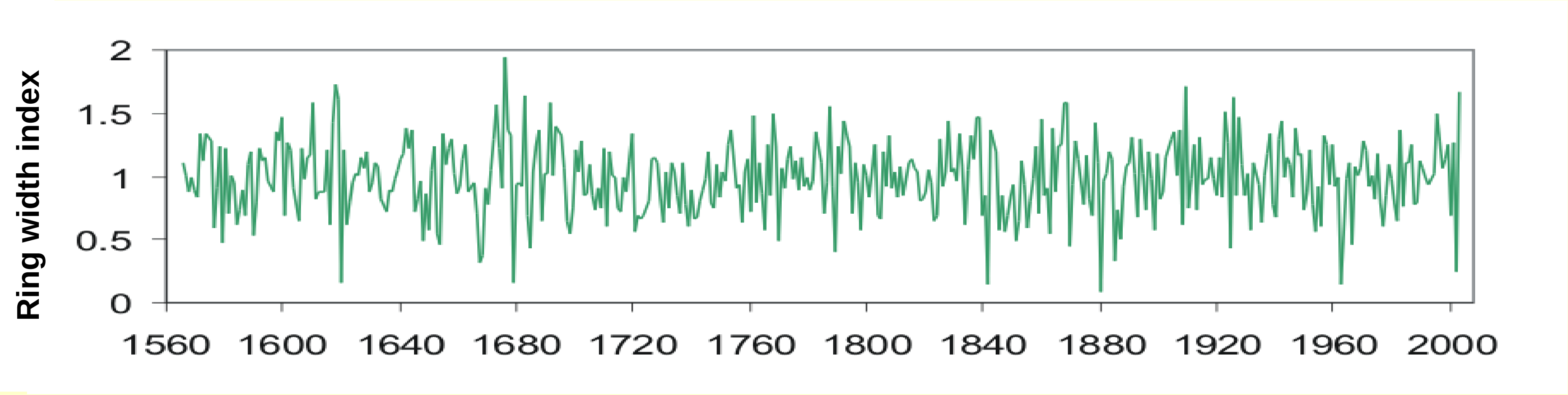
- These standardized series are compiled into the site chronology

By compiling the measurements from many trees...



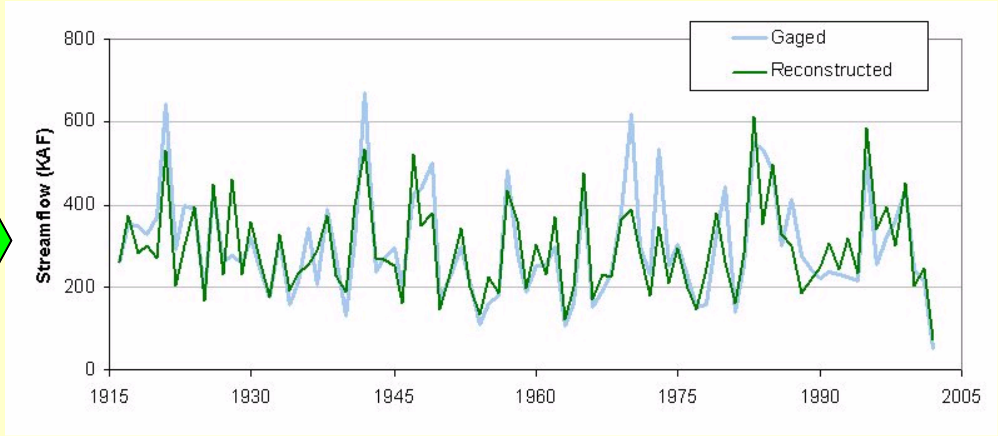
…we enhance the common (climate) signal in the resulting site *chronology*





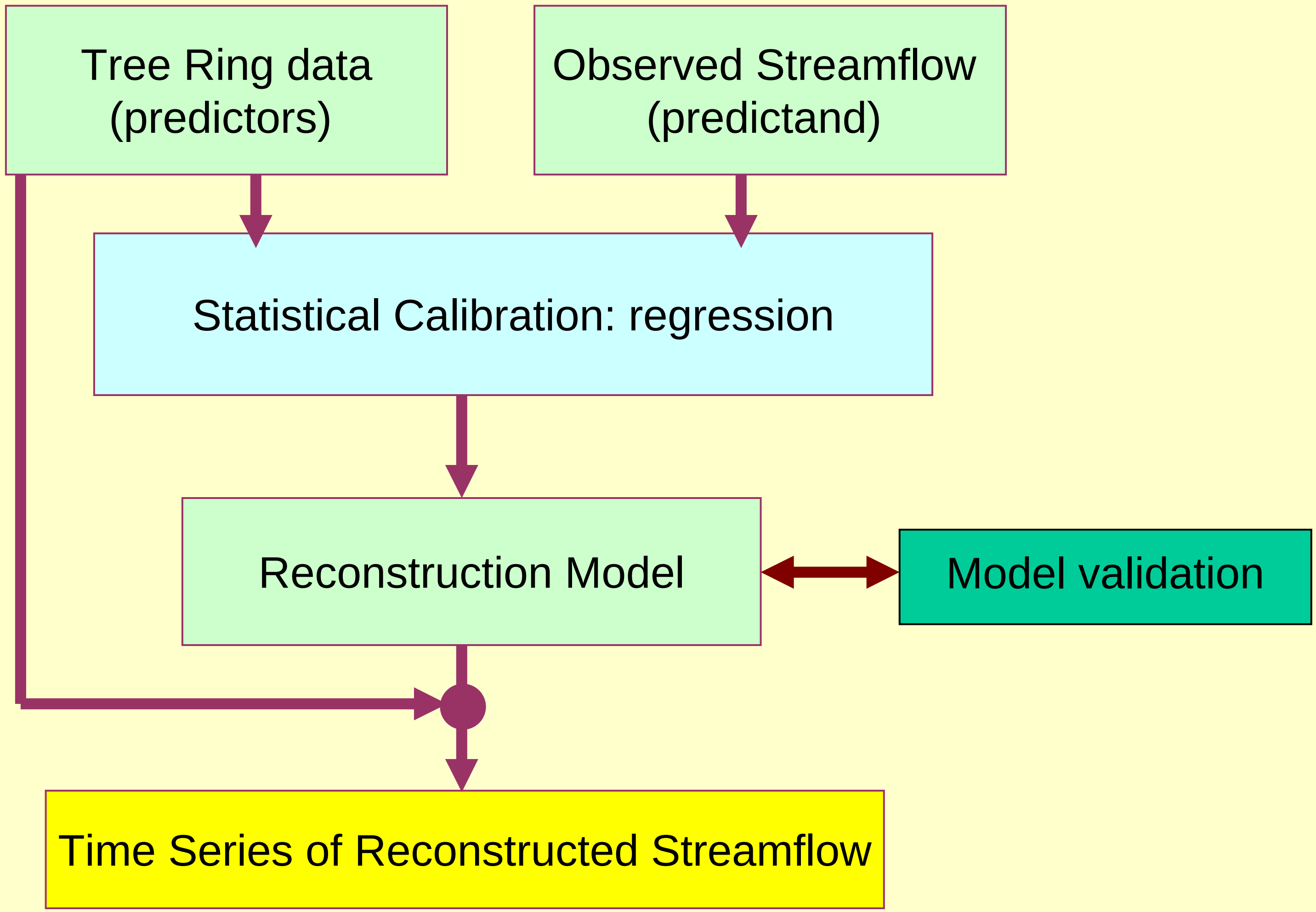
Part 3:

Generating the Reconstruction



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

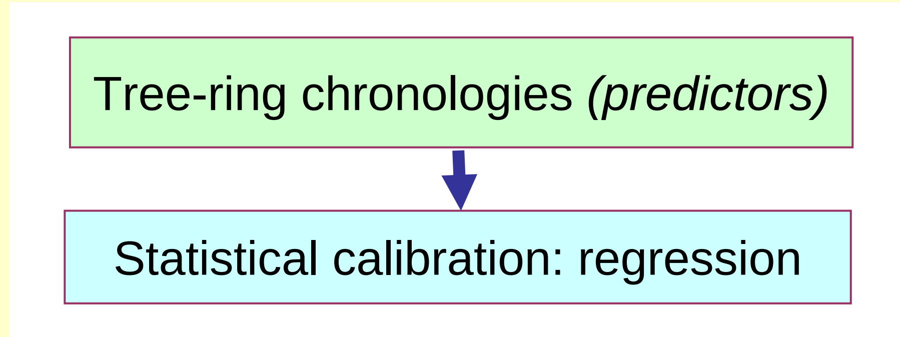
Overview of reconstruction methodology



based on Meko 2005

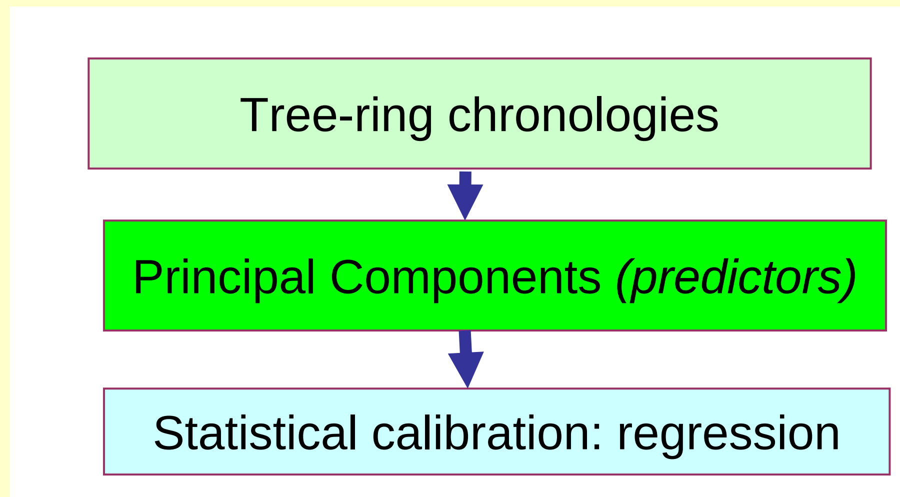
Reconstruction modeling strategies

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



OR

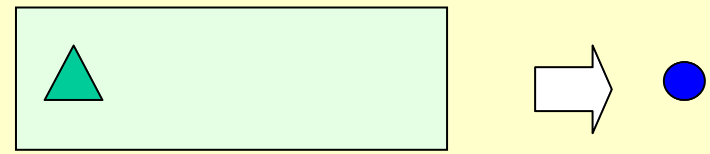
- **The set of chronologies is reduced** through Principal Components Analysis (PCA) and the components (representing modes of variability) are used as predictors in a regression



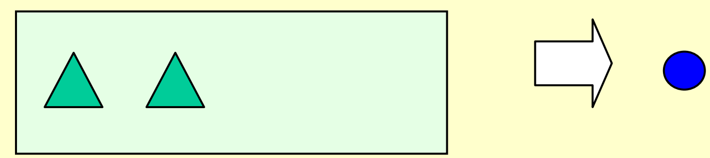
Many other approaches are possible (e.g., quantile regression, neural networks, non-parametric methods)

Model calibration: Forward stepwise regression

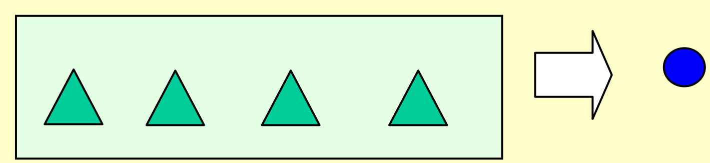
1) The chronology that explains the most variance in the flow record is selected as the first predictor in the regression



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



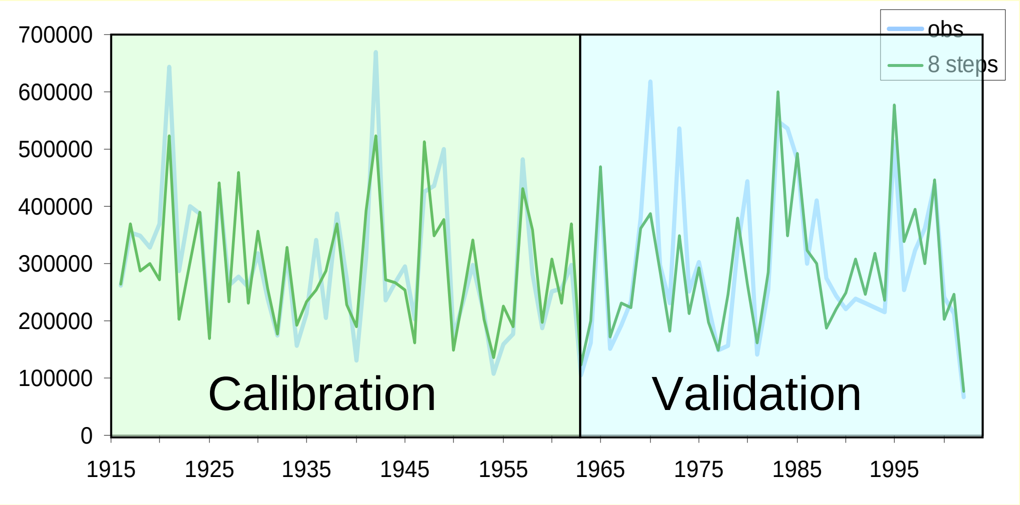
3) The process ends when no additional chronology significantly improves the fit of the regression to the flow record



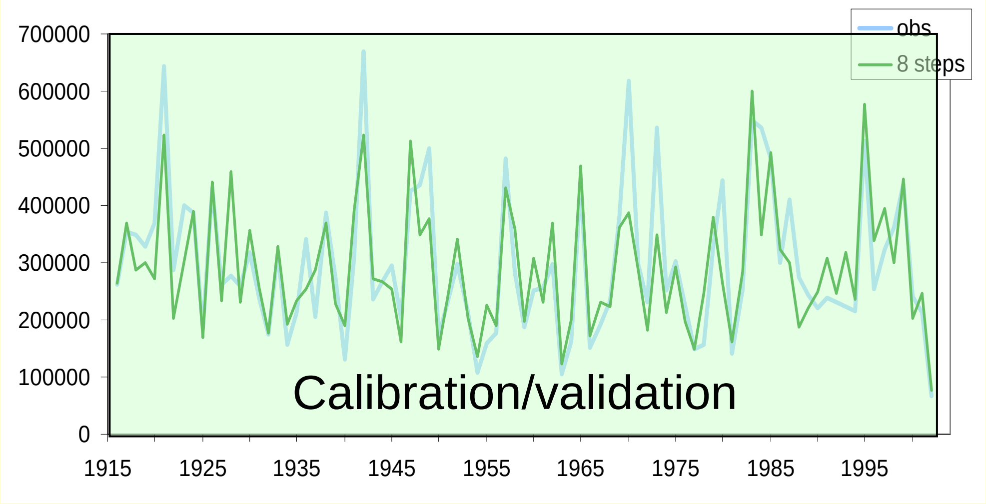
Model validation strategy

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

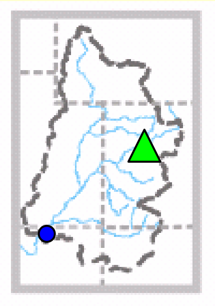
Split-sample with independent calibration and validation periods



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



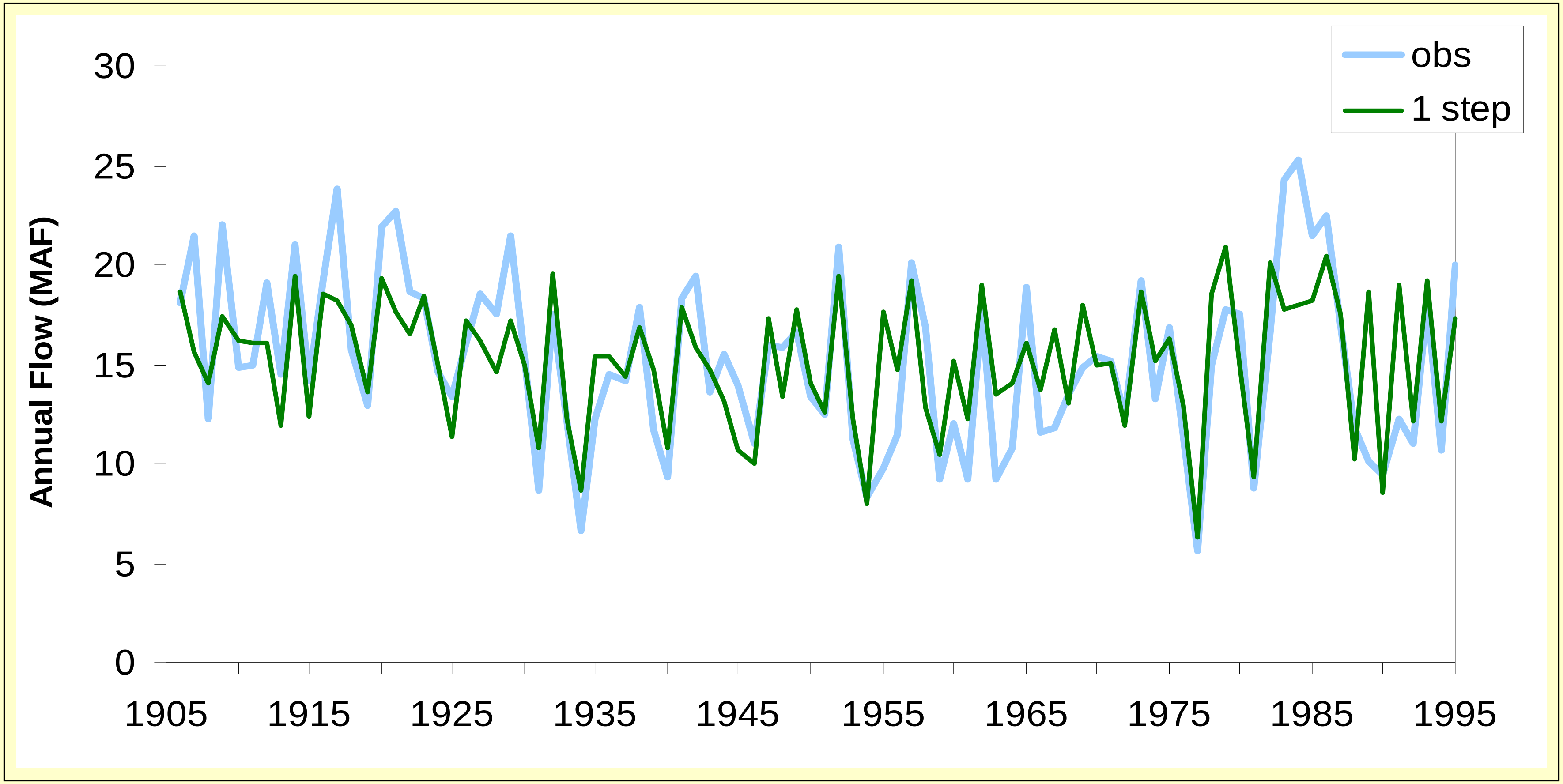
Colorado at Lees Ferry - forward stepwise regression



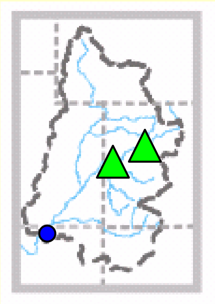
TRG

Variance Explained

55%



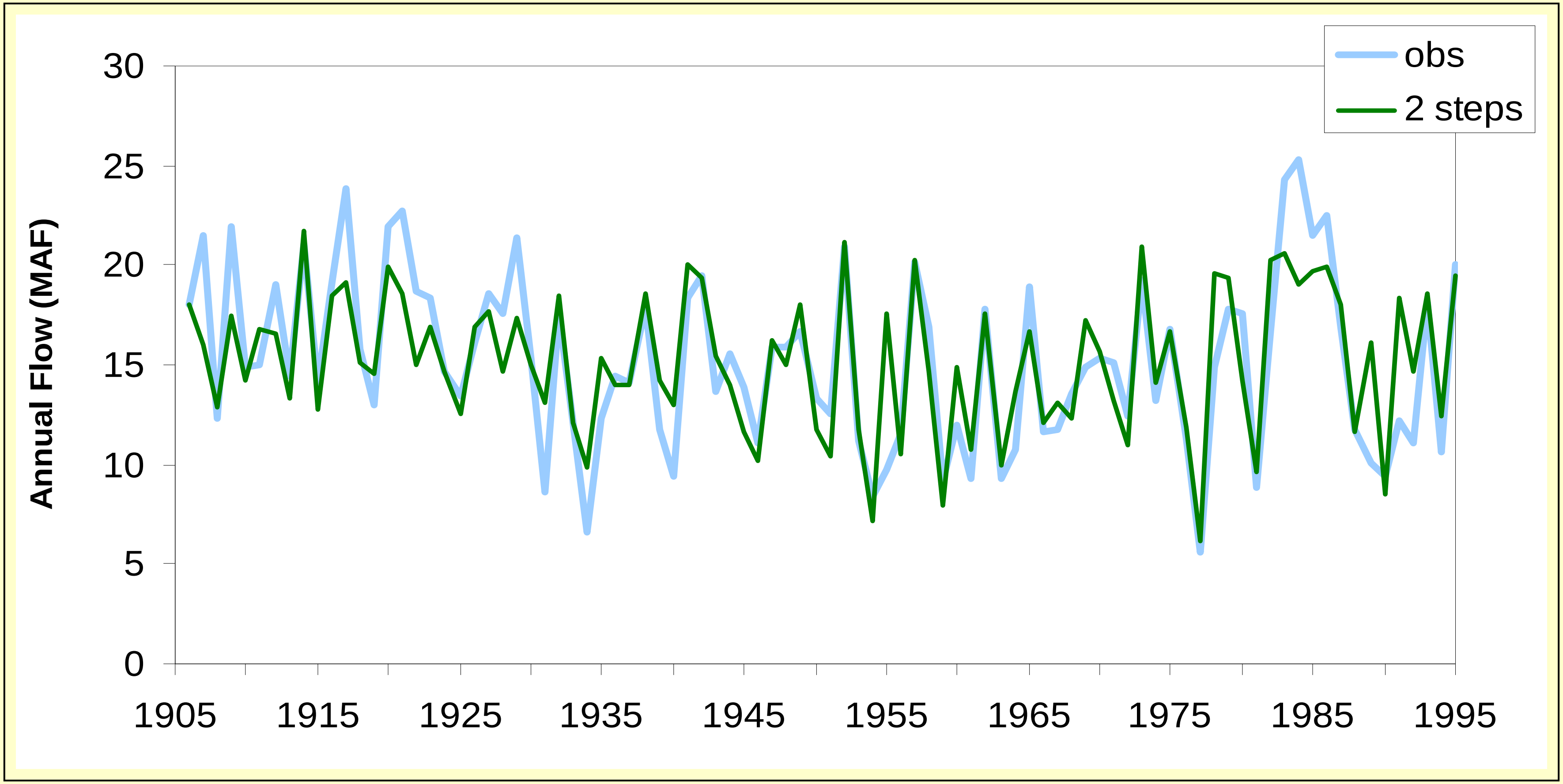
Colorado at Lees Ferry - forward stepwise regression



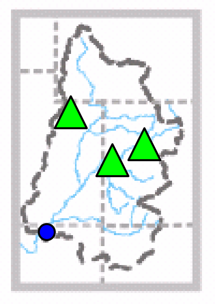
TRG + WIL

Variance Explained

67%



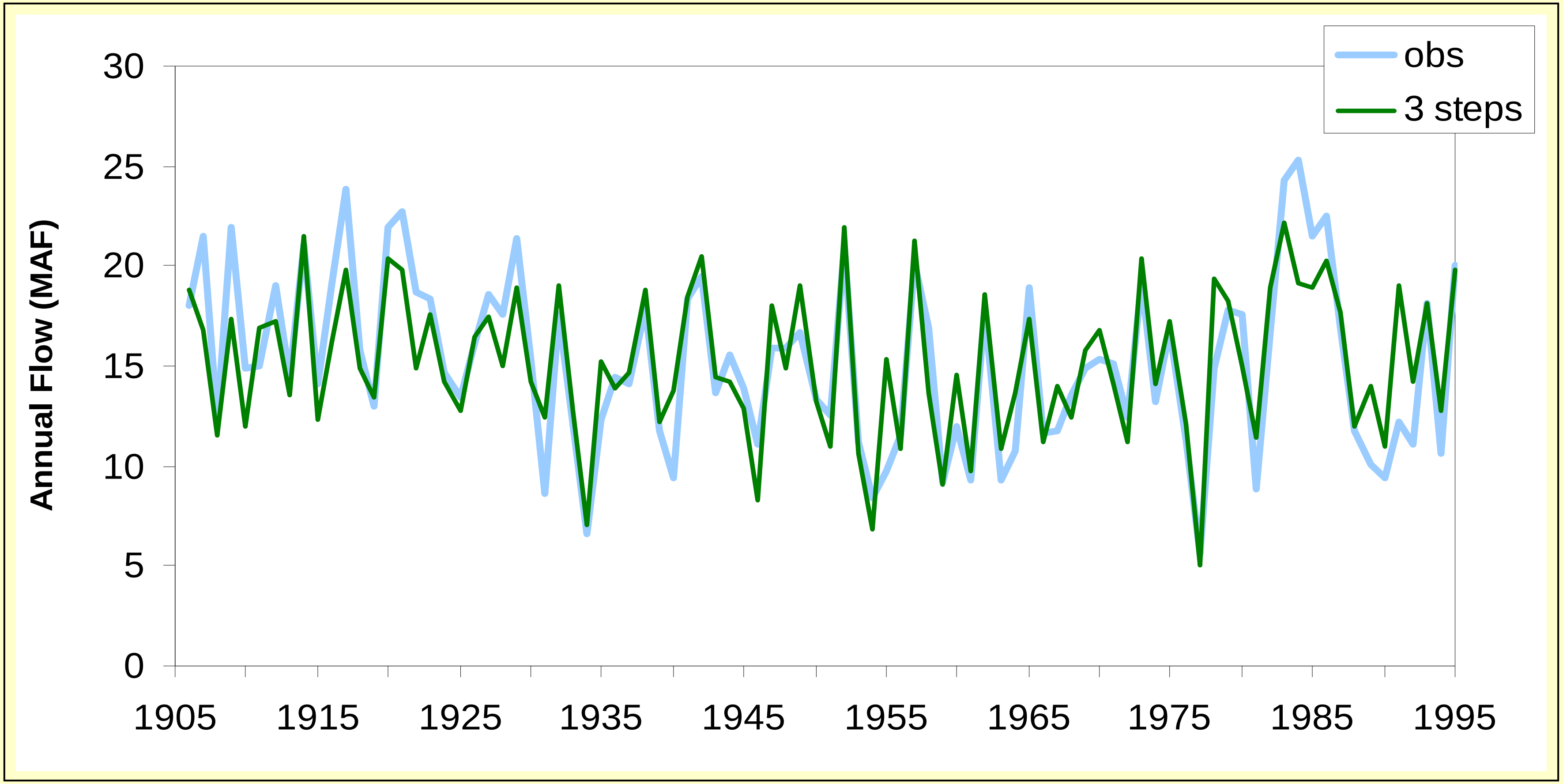
Colorado at Lees Ferry - forward stepwise regression



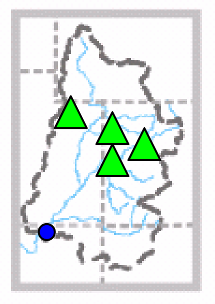
TRG + WIL + DJM

Variance Explained

72%



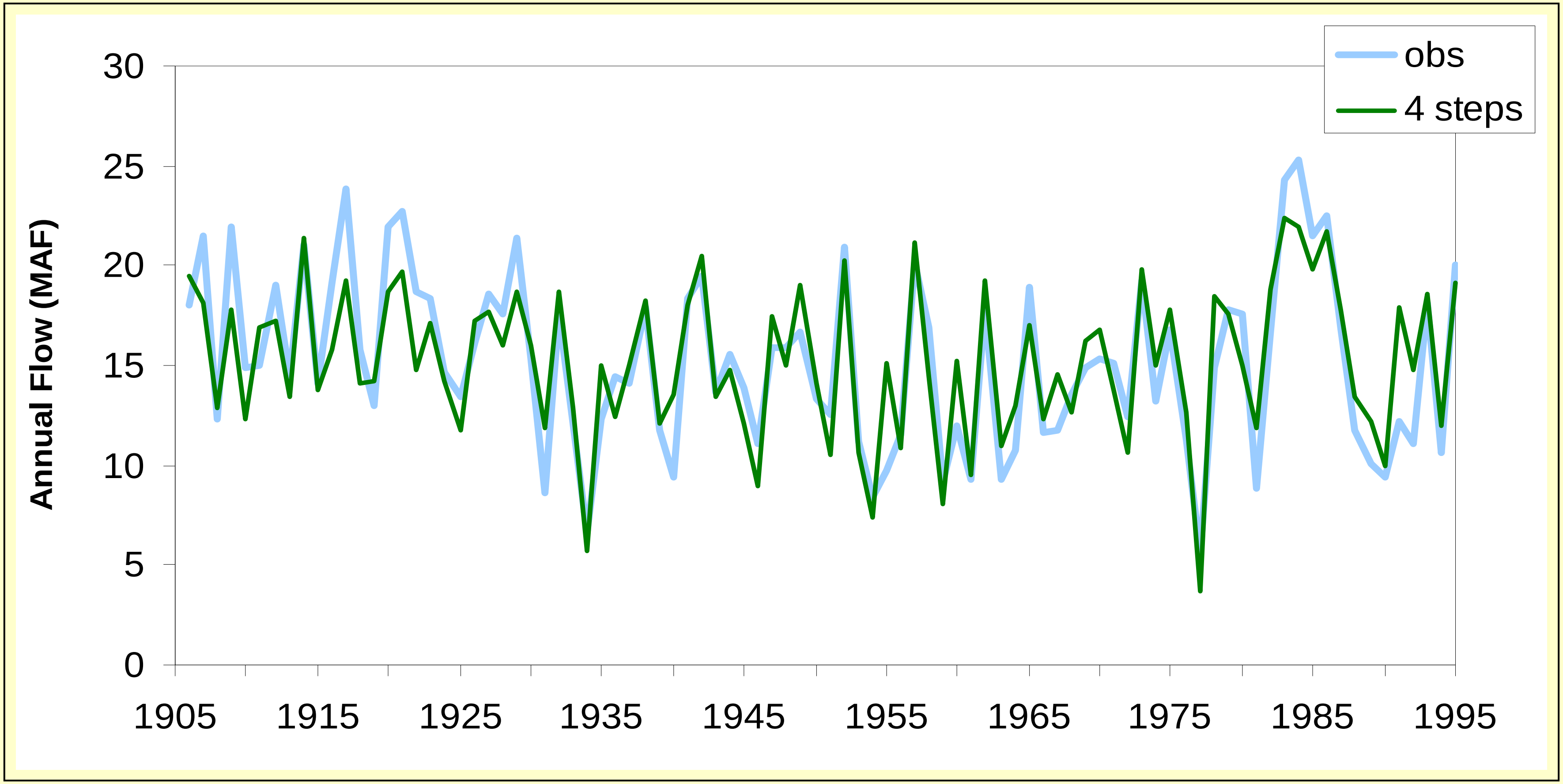
Colorado at Lees Ferry - forward stepwise regression



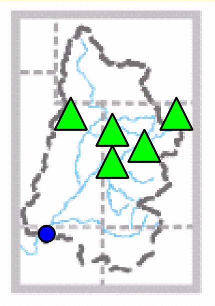
Variance Explained

TRG + WIL + DJM + DOU

75%



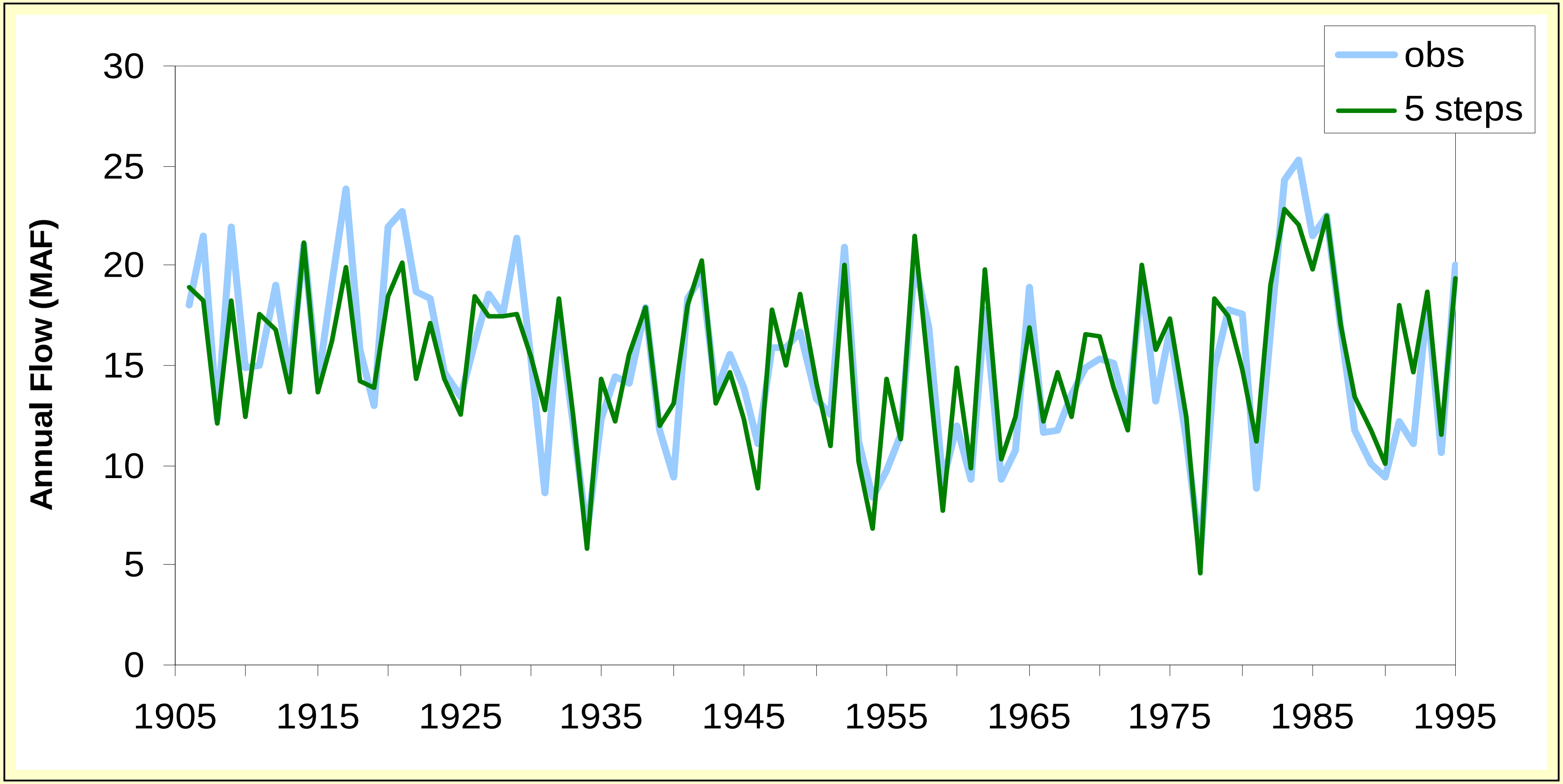
Colorado at Lees Ferry - forward stepwise regression



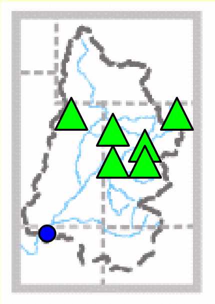
TRG + WIL + DJM + DOU + NPU

Variance Explained

77%



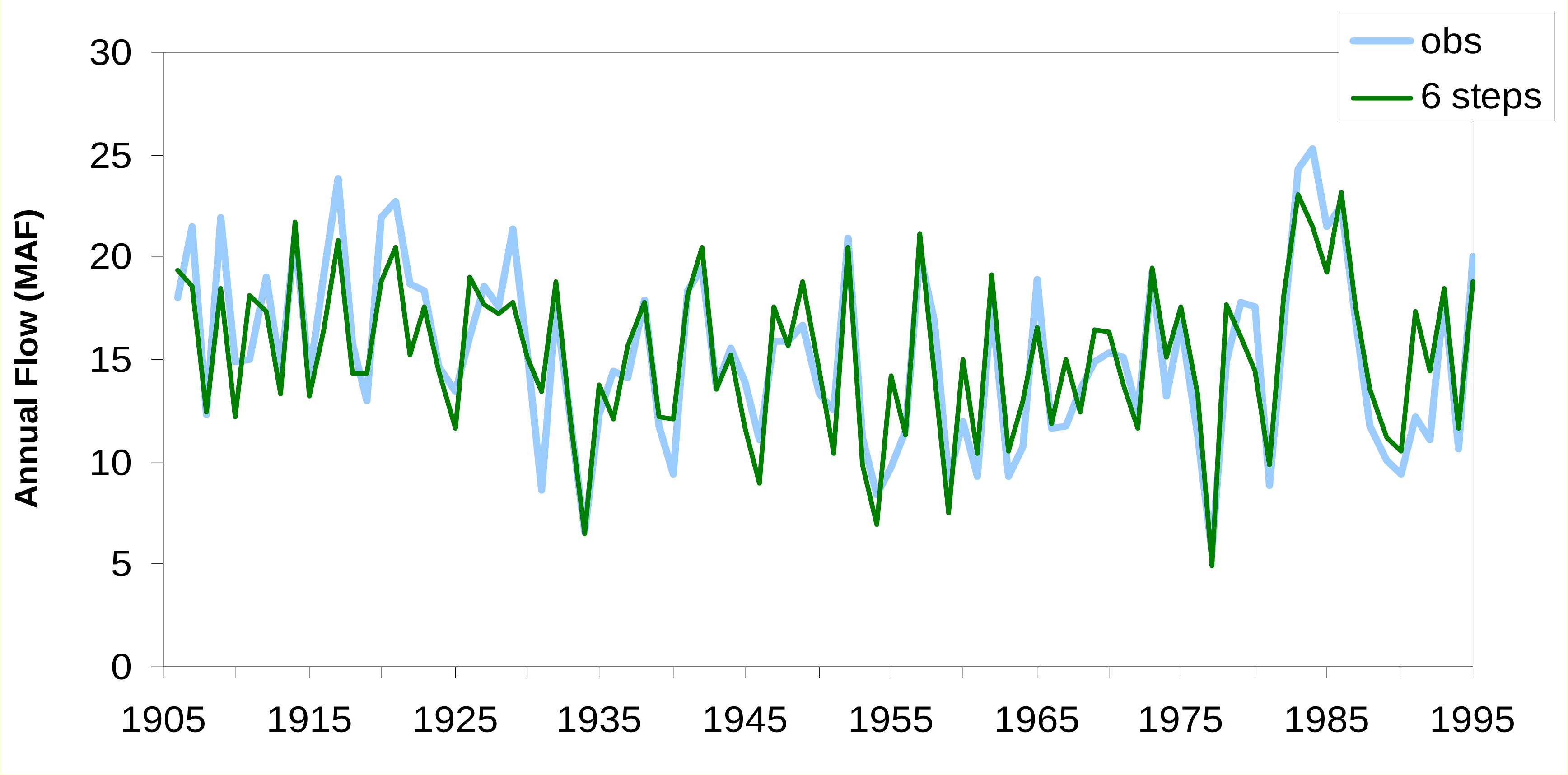
Colorado at Lees Ferry - forward stepwise regression



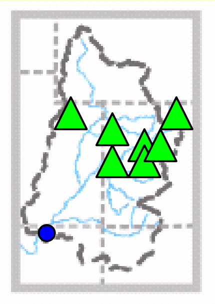
TRG + WIL + DJM + DOU + NPU + RED

Variance Explained

79%



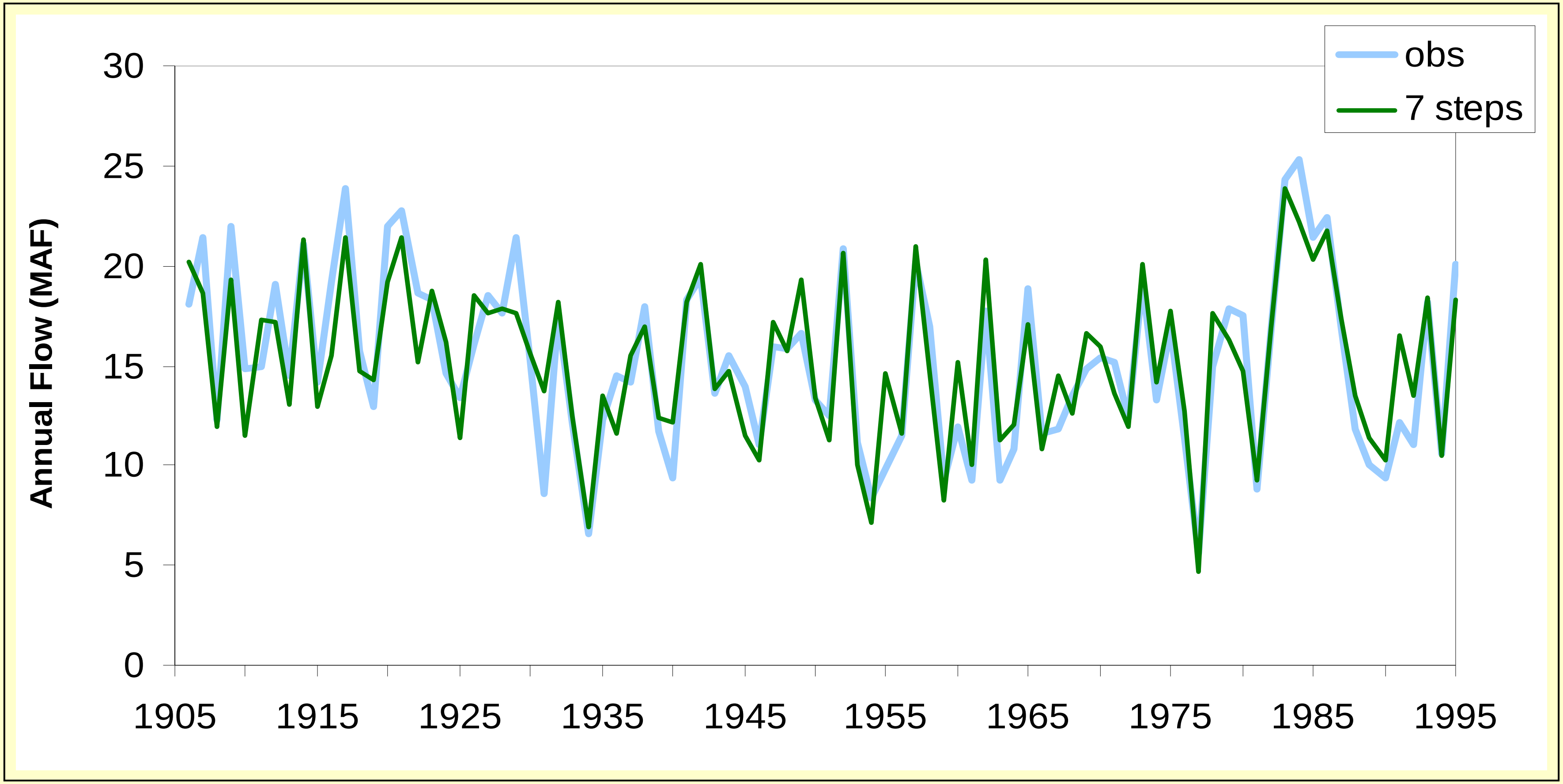
Colorado at Lees Ferry - forward stepwise regression



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?

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

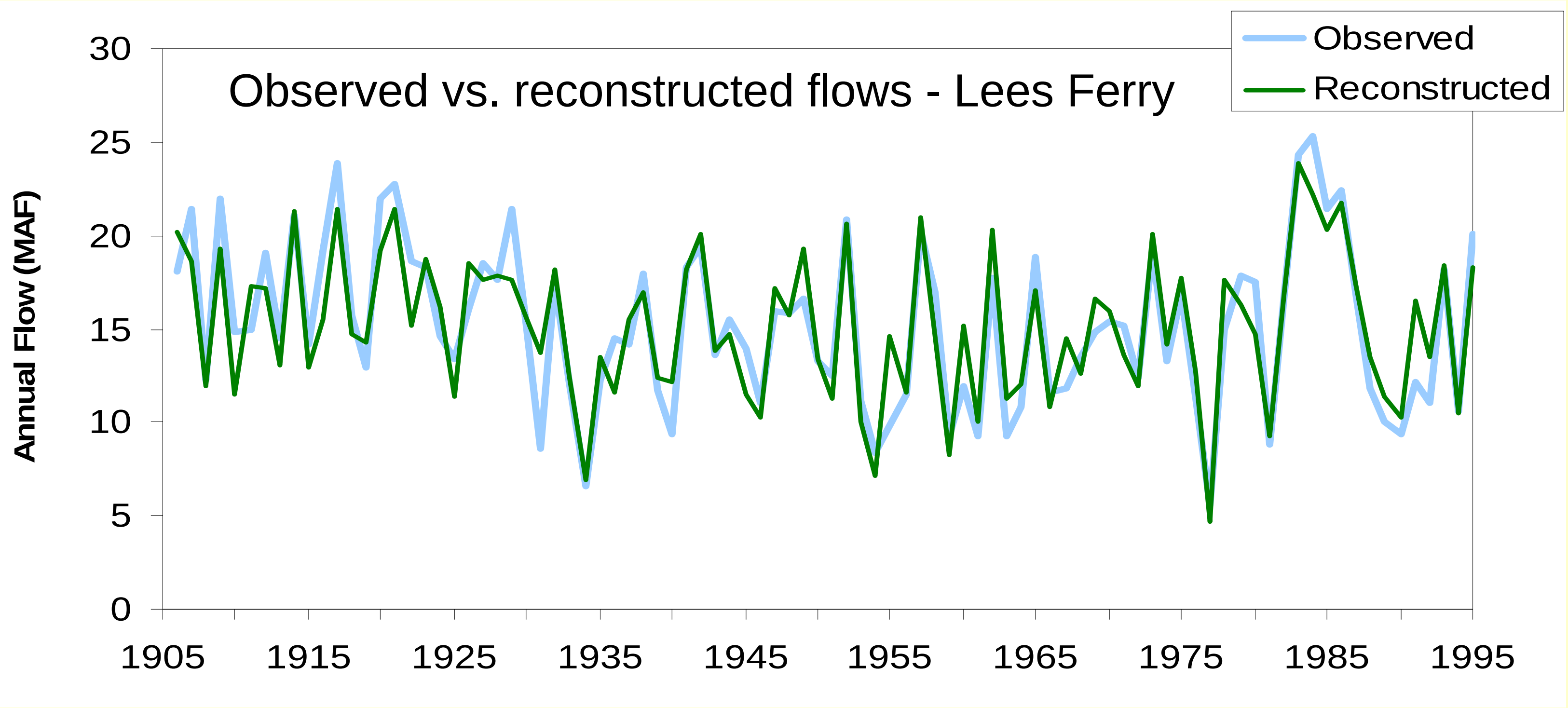
Validation statistics – based on withheld data or data generated in cross-validation process, compared to observed data

	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”

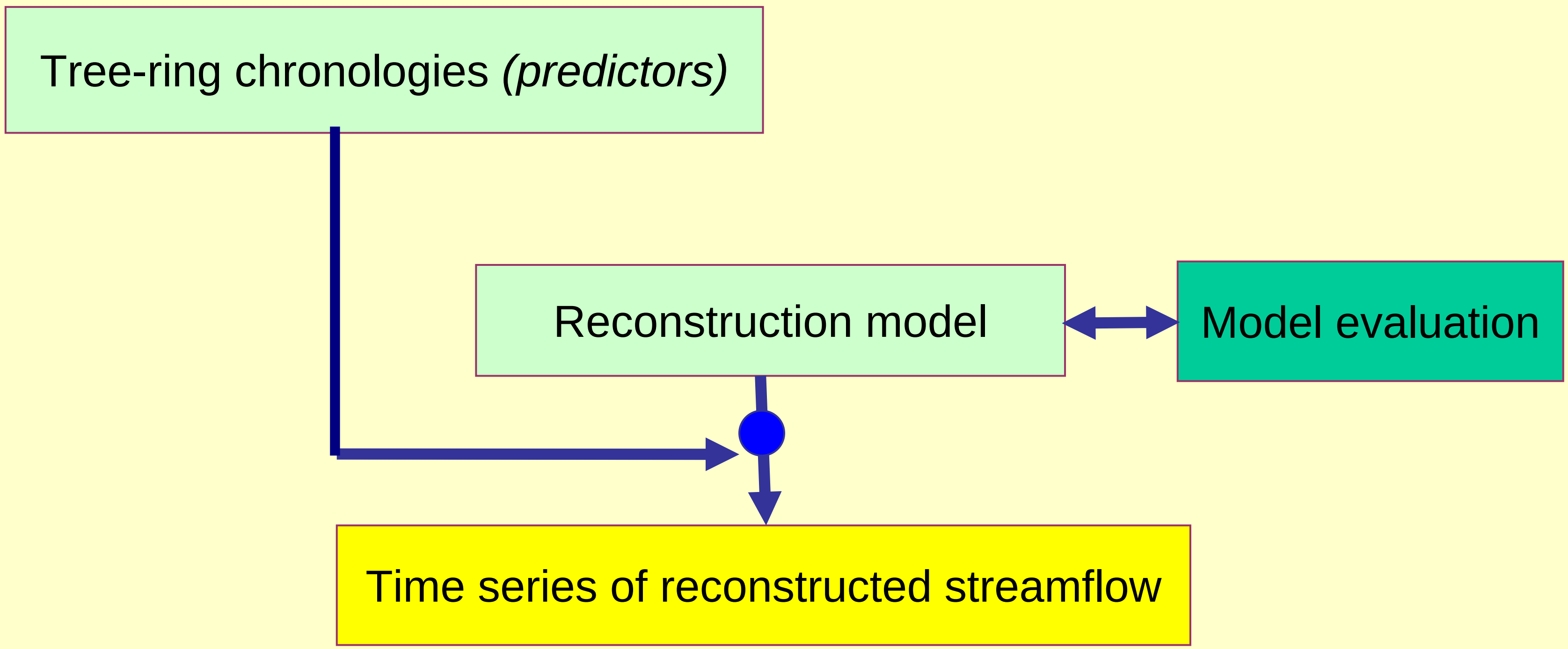
How does the reconstruction compare to the gage record?



	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

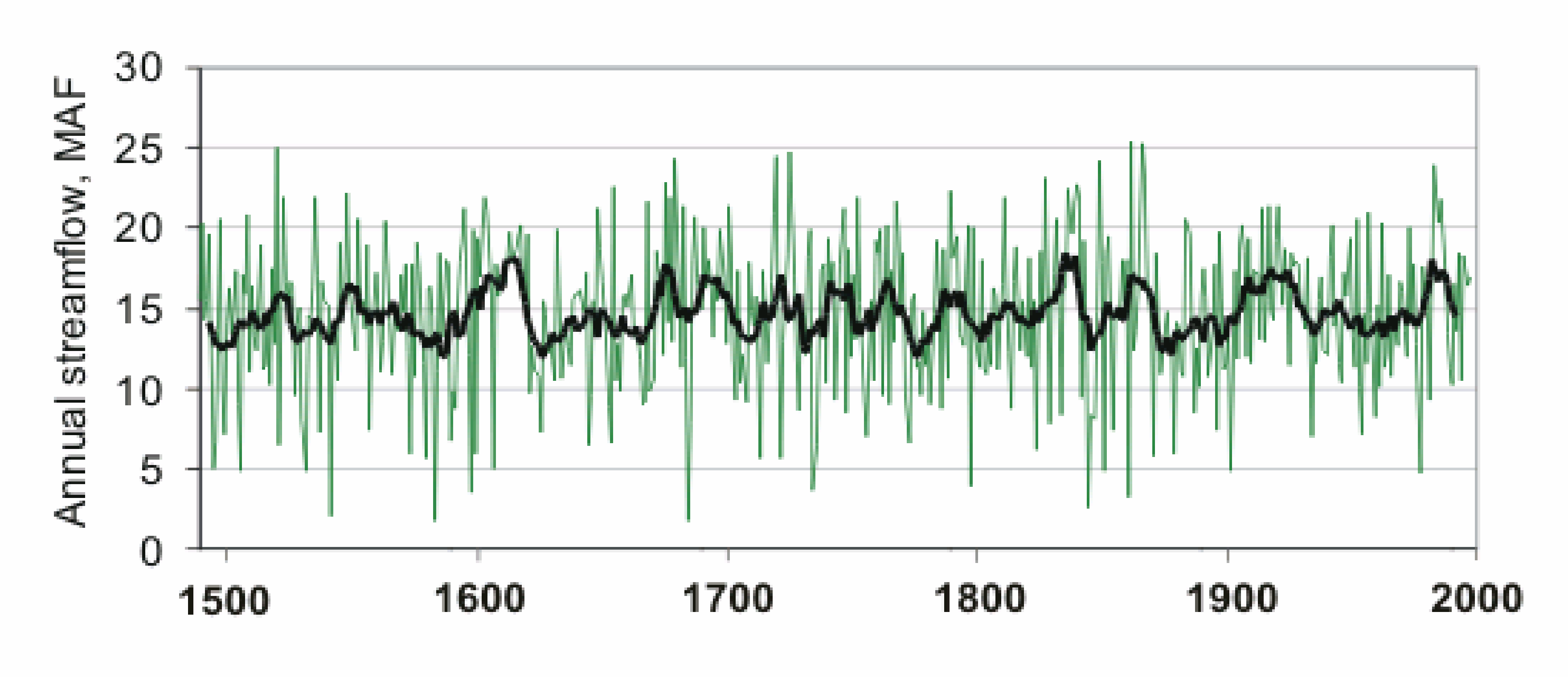
The means are the same, as expected from the the linear regression. Also as expected, the standard deviation in the reconstruction is lower than in the gage record, but in this reconstruction, the lowest flow value is slightly underestimated.

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

Colorado R. at Lees Ferry Streamflow reconstruction, 1490-1997



- Green = annual values
- Black = 10-yr running mean

Uncertainty in the reconstructions

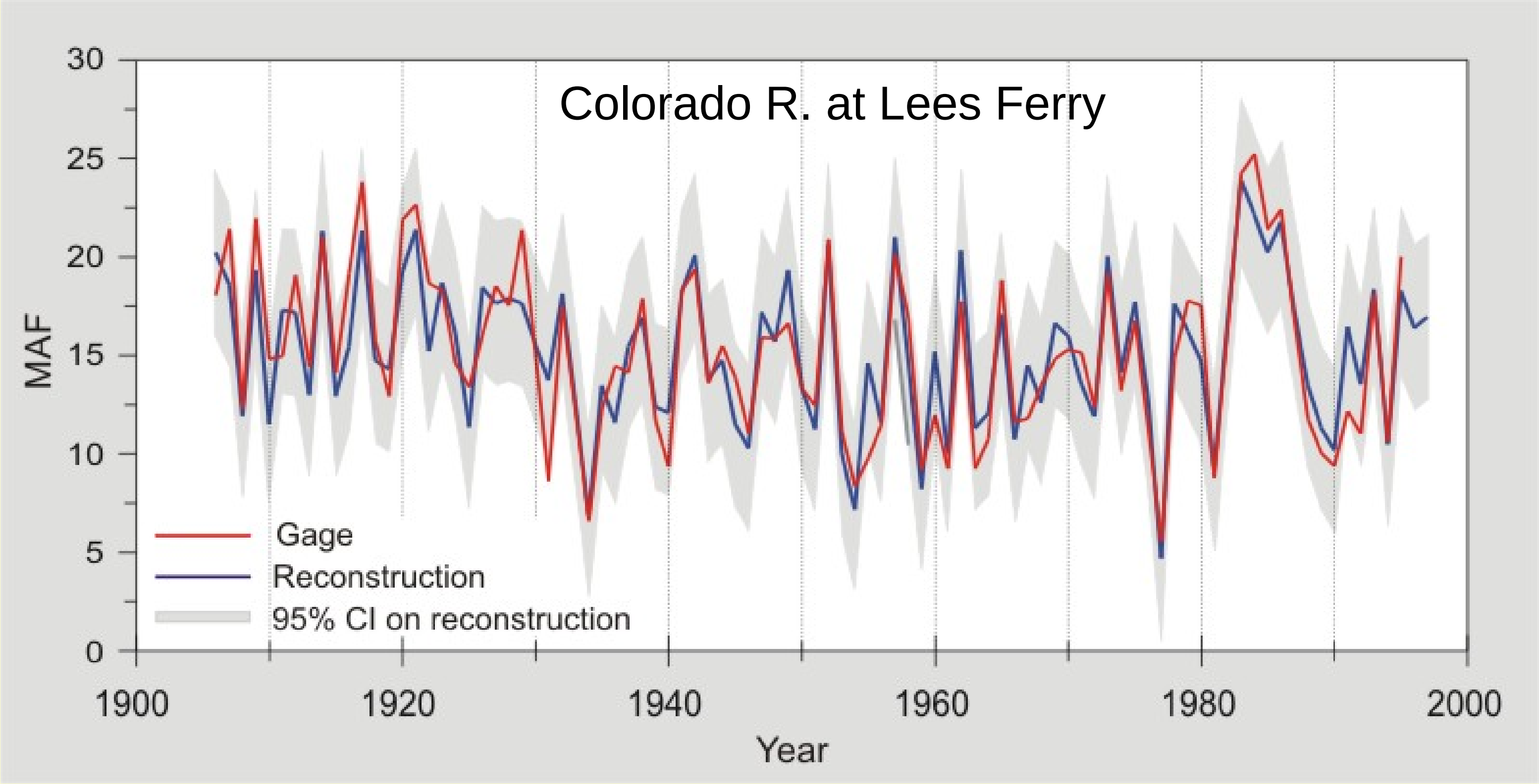
- Tree-ring data are imperfect recorders of climate and streamflow, so there will always be uncertainty in the reconstructed values

- 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 (*more on this later*).

Using RMSE to generate confidence intervals for the model



- 2 x RMSE approximates the 95% confidence intervals around the reconstruction
- So the CIs should encompass ~95% of the gage values

Where to find reconstruction data

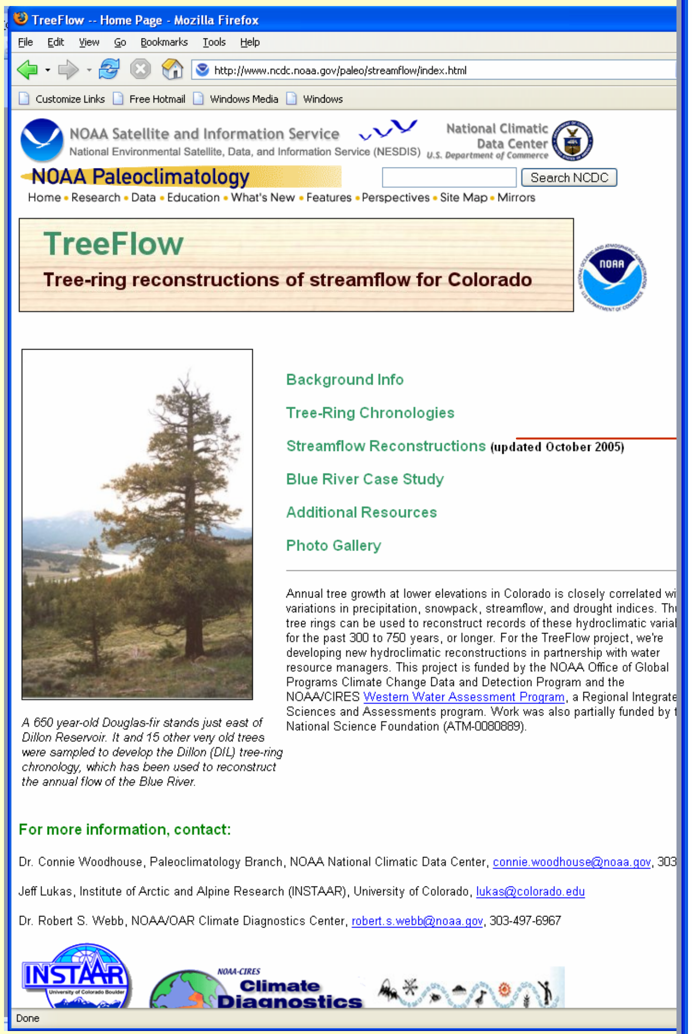
Tree-Ring Reconstructions of Streamflow for Water Management in the West

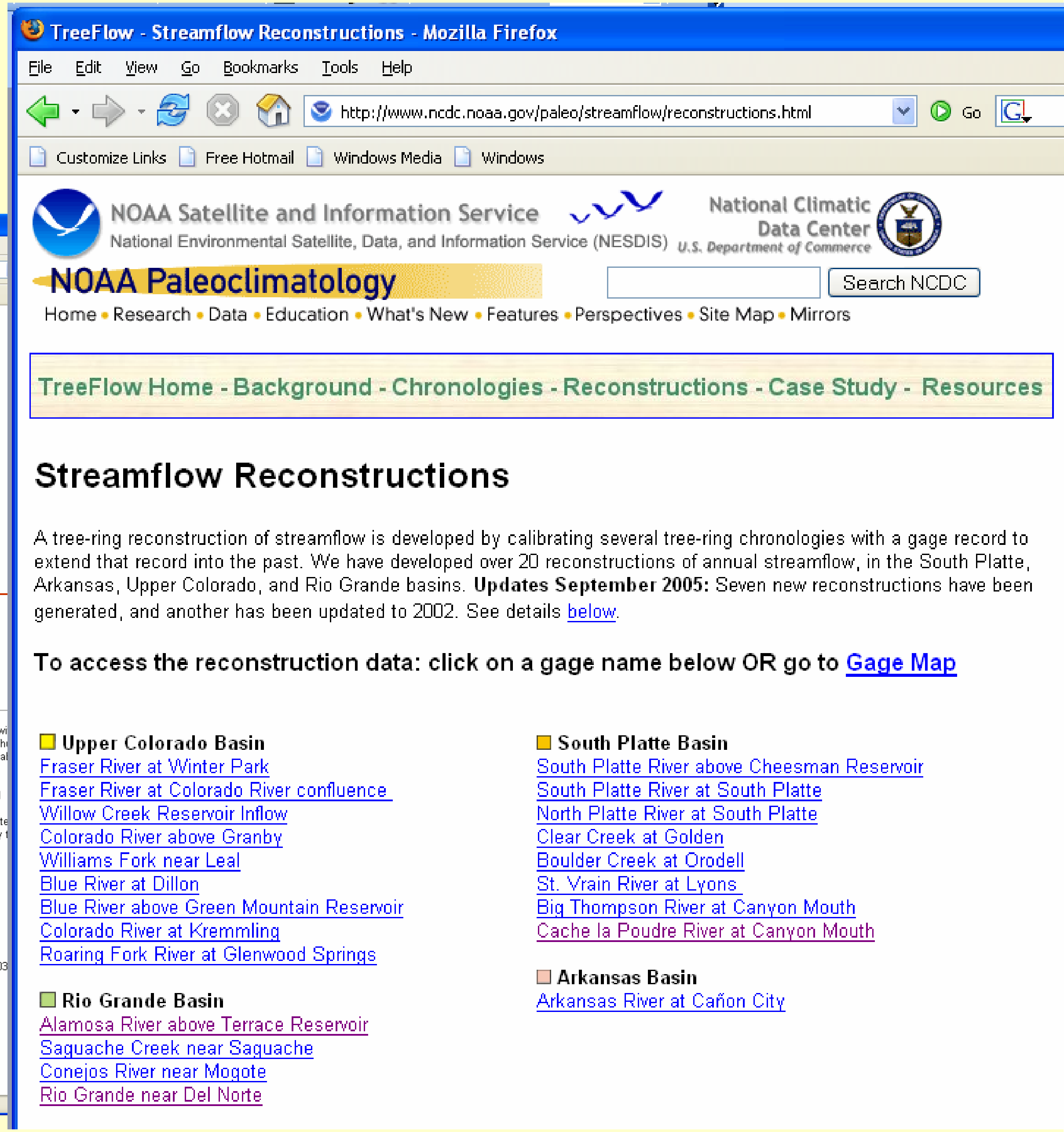
http://wwa.colorado.edu/resources/paleo/data.html

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**

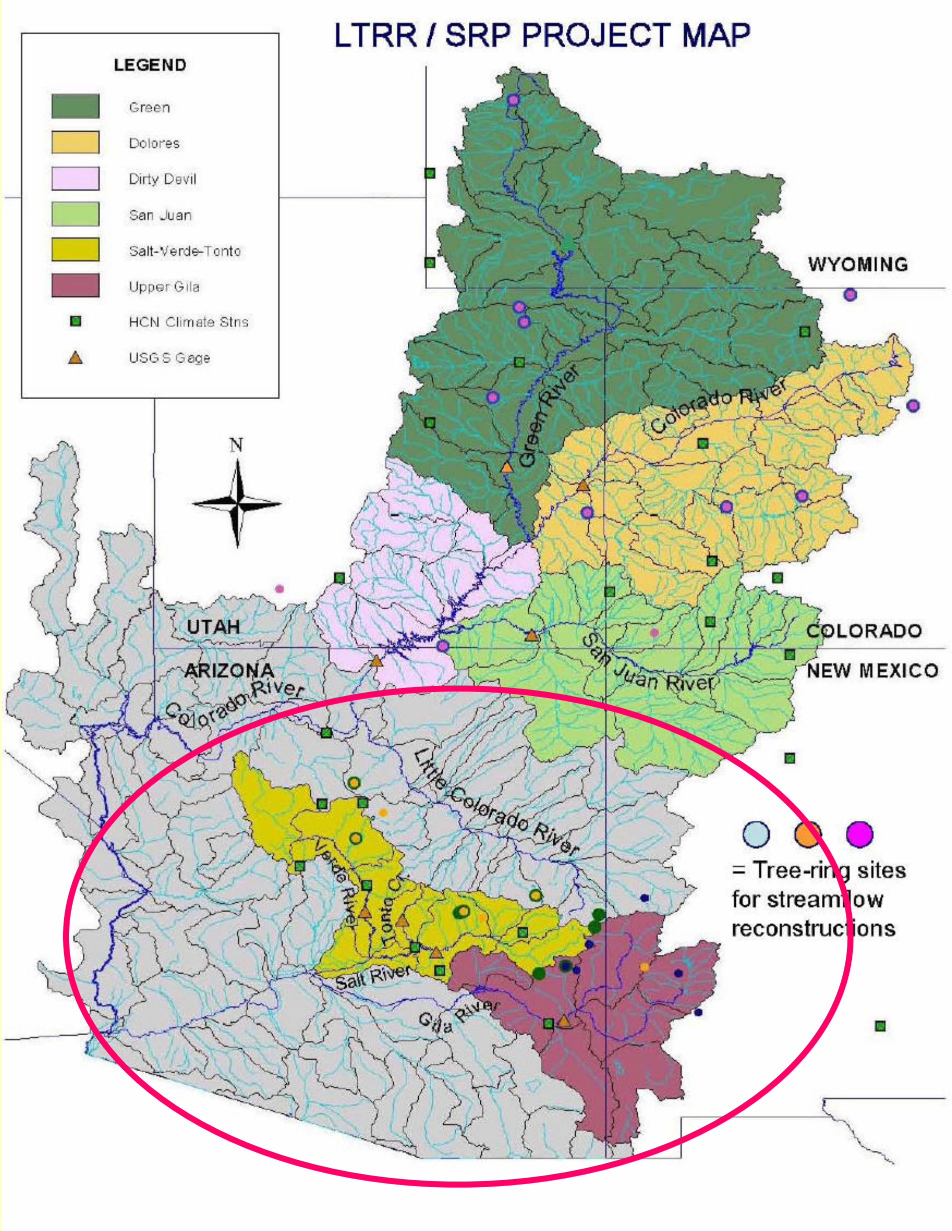


Image courtesy of K. Hirschboeck and D. Meko (U. AZ)

Woodhouse et al. 2006 Upper Colorado River Basin

NOAA Satellite and Information Service
National Environmental Satellite, Data, and Information Service (NESDIS)
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Updated Streamflow Reconstructions for the Upper Colorado River Basin

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Water Resources Research
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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

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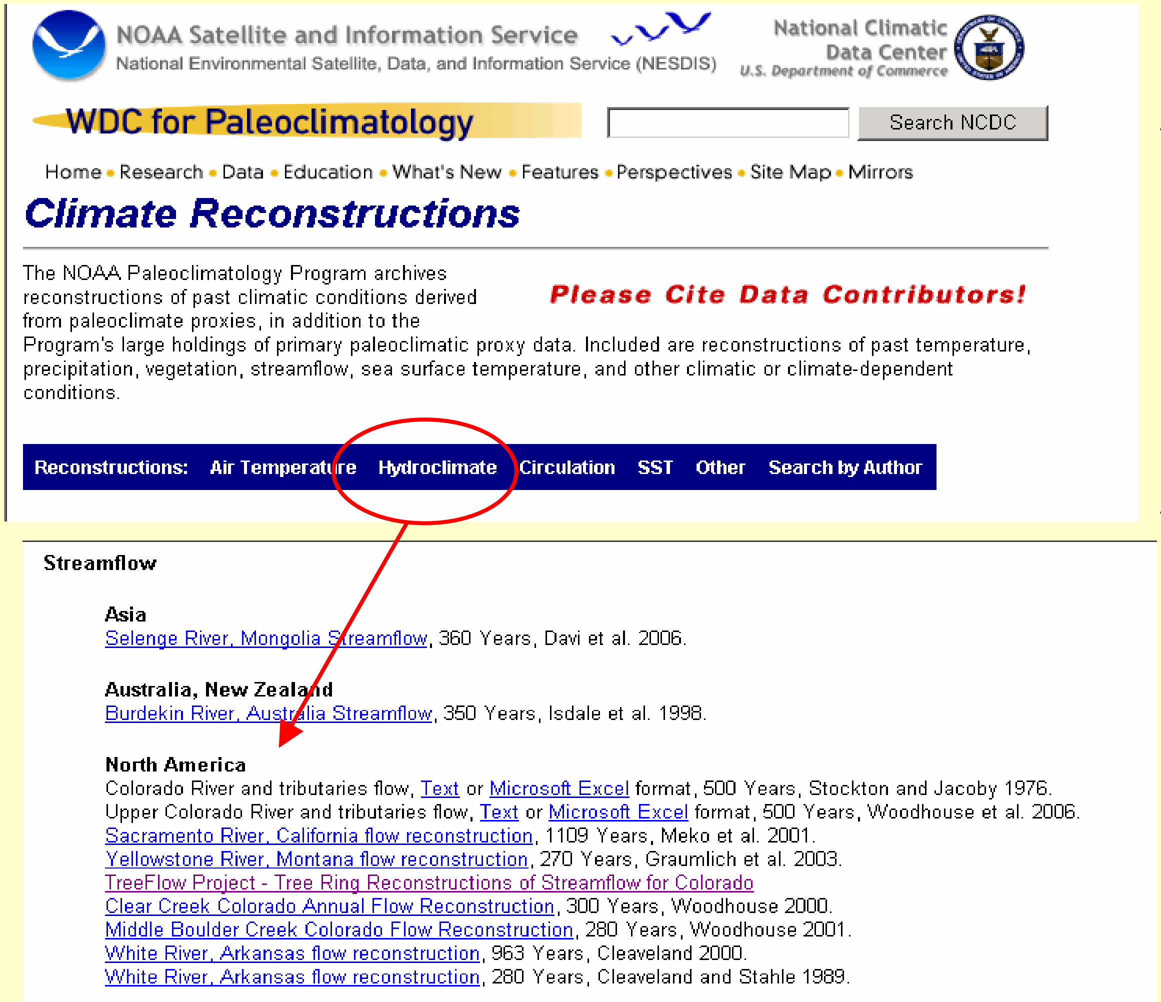

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Climate Reconstructions

Please Cite Data Contributors!

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.

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

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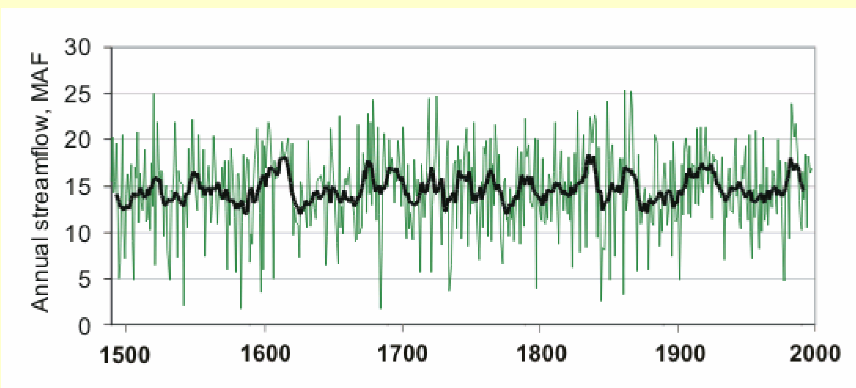
The application of tree-ring data to water management



Reconstruction data

?

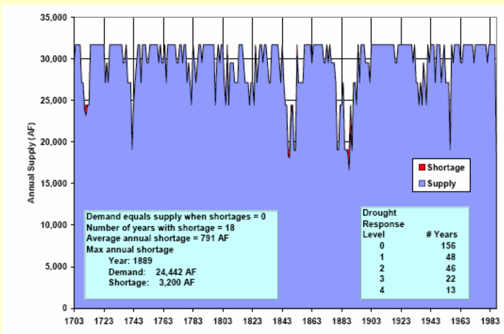


Figure 5. Demands & Supplies: 15% Reduced Flow Hydrology, Current Trends Scenario (demand = 31,700 AF/year).

Policy analysis