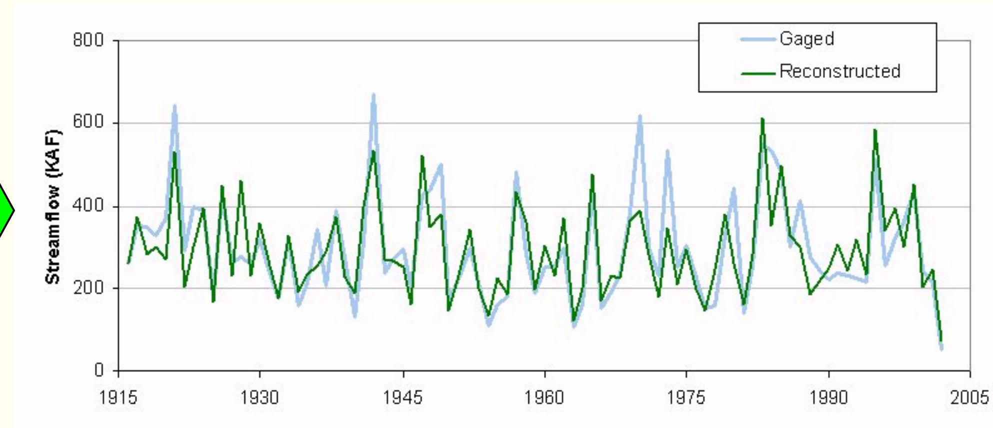
# Tree-ring-based streamflow reconstructions for the Rio Grande basin




**May 30, 2008 – NMSU Albuquerque Center**


Connie Woodhouse, University of Arizona
Jeff Lukas, University of Colorado


Western Water Assessment

NM STATE

CLIMAS
Climate Assessment for the Southwest

# Agenda

*Morning*

- Background and history of project
- How tree rings record climate information
- Building the tree-ring chronology
- Generating reconstructions of streamflow
- Information about reconstructions on the Web
- How reconstructions are being used in water management

*Afternoon*

- New reconstructions for the Rio Grande basin
- Visualizing climate and reconstruction data
- A new reconstruction approach for the Rio Grande
- Discussion of management issues and information needs for Rio Grande basin

*Please ask questions!*

# Acknowledgements


***PIs and Contributors for Rio Grande Project:***

*University of Arizona:* Connie Woodhouse, Gregg Garfin, Holly Hartmann, Ramzi Touchan, Dave Meko; *University of Colorado:* Jeff Lukas, Brad Udall; *New Mexico State University:* Deborah Bathke

***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

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NOAA Climate Program Office (Coping with Drought program, Regional Integrated Science Assessments: CLIMAS and Western Water Assessment)

Thanks to all who suggested people to invite to this workshop!

# About RISAs

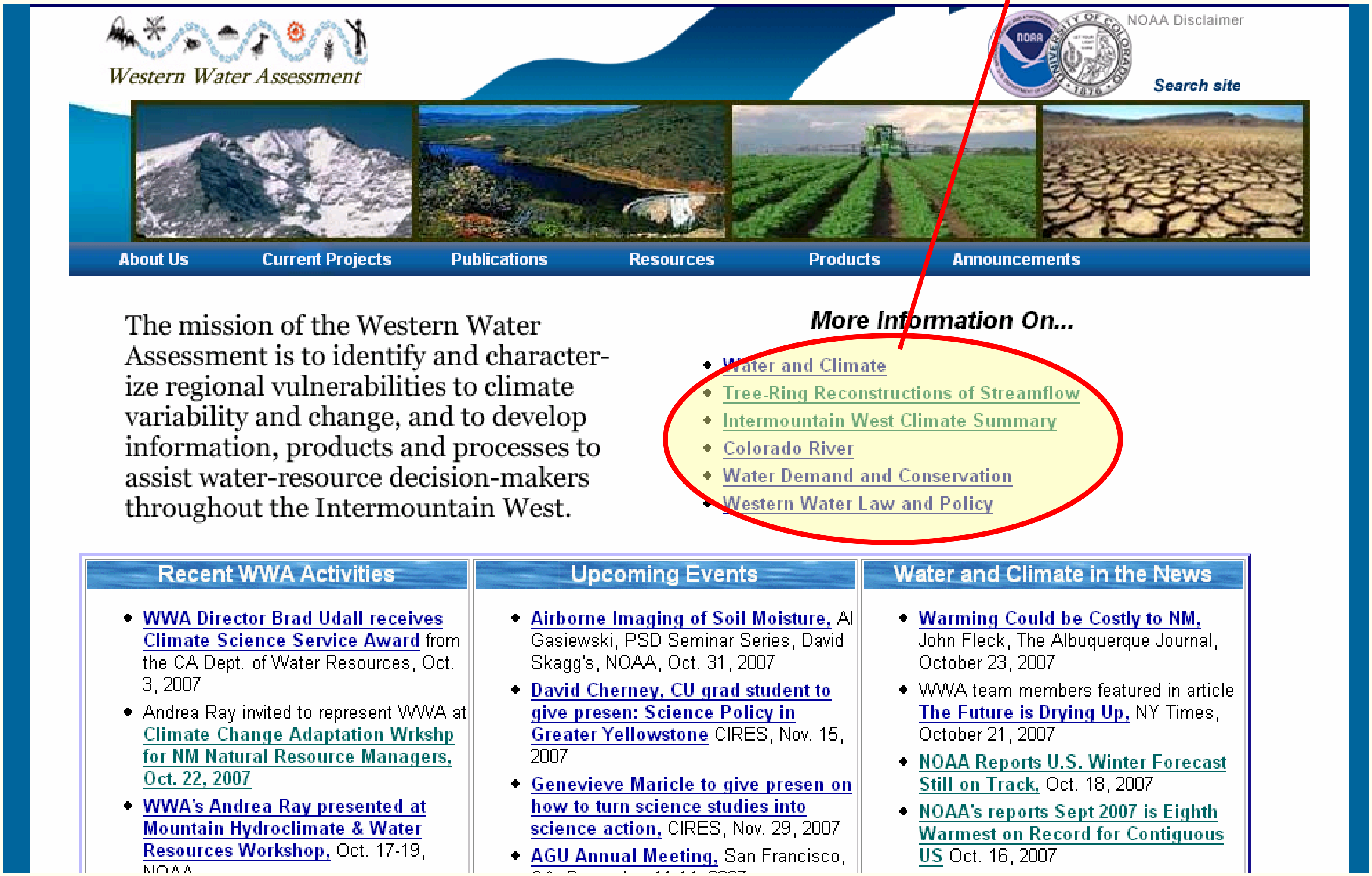
- RISAs (Regional Integrated Sciences & Assessments) are NOAA-funded programs that conduct climate-related research that supports decisionmaking at a regional level

- **Western Water Assessment** - CO, UT, WY
- **CLIMAS** (Climate Assessment for the Southwest) – AZ, NM

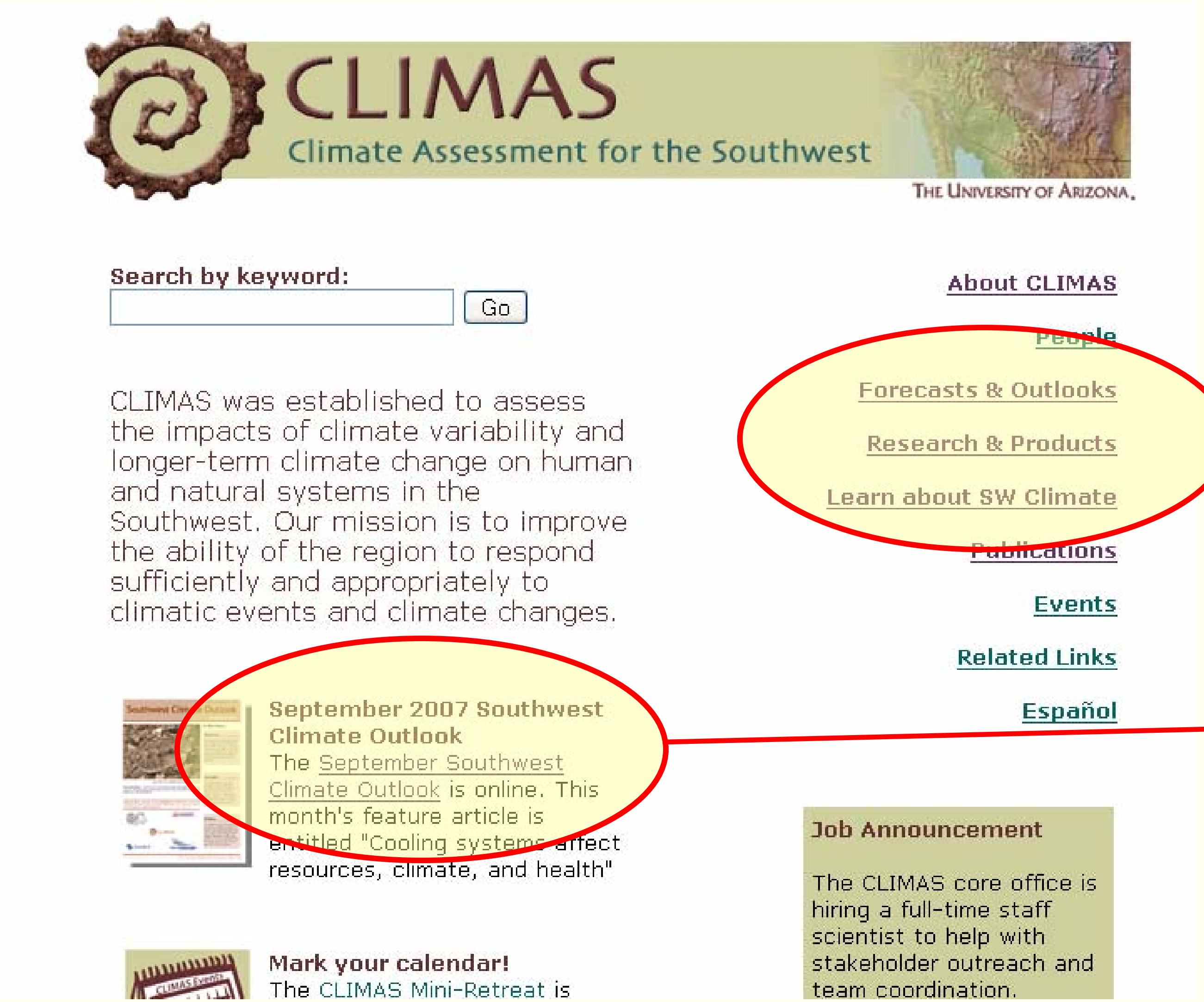
# Western Water Assessment

**http://wwa.colorado.edu**

Quick links to main projects and resources



# CLIMAS http://www.ispe.arizona.edu/climas/




Other projects and resources

Southwest Climate Outlook

# History behind this workshop

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

2007-2008 - More workshops, greater focus on applications

## **Cross-RISA project:**
## Tree-Ring Reconstructions of Hydroclimatic Variability in the Rio Grande Basin, New Mexico

*November 2007* - Workshop to introduce the use of tree-ring reconstructions of streamflow, and identify gages of interest

TODAY - Follow-up workshop - to deliver new reconstructions and tools, get feedback, and plan future collaborative work

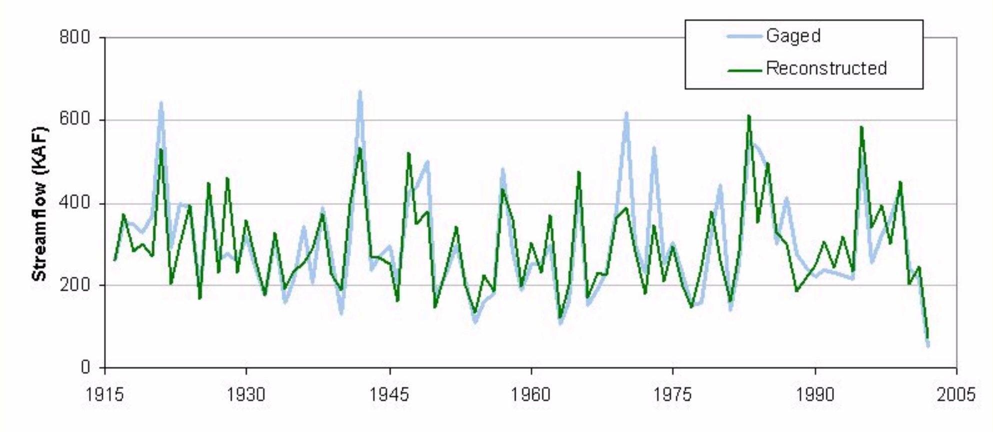
# Objectives for today (and beyond)

1) Morning - Describe how tree-ring reconstructions are developed and are being used
2) Afternoon – Show new work responding to the fall workshop, get further input on data products and applications

- We'll be a long-term partner in assisting with application of the data

# **Part 1:**

# Context and Background



# The conundrum of (water) management

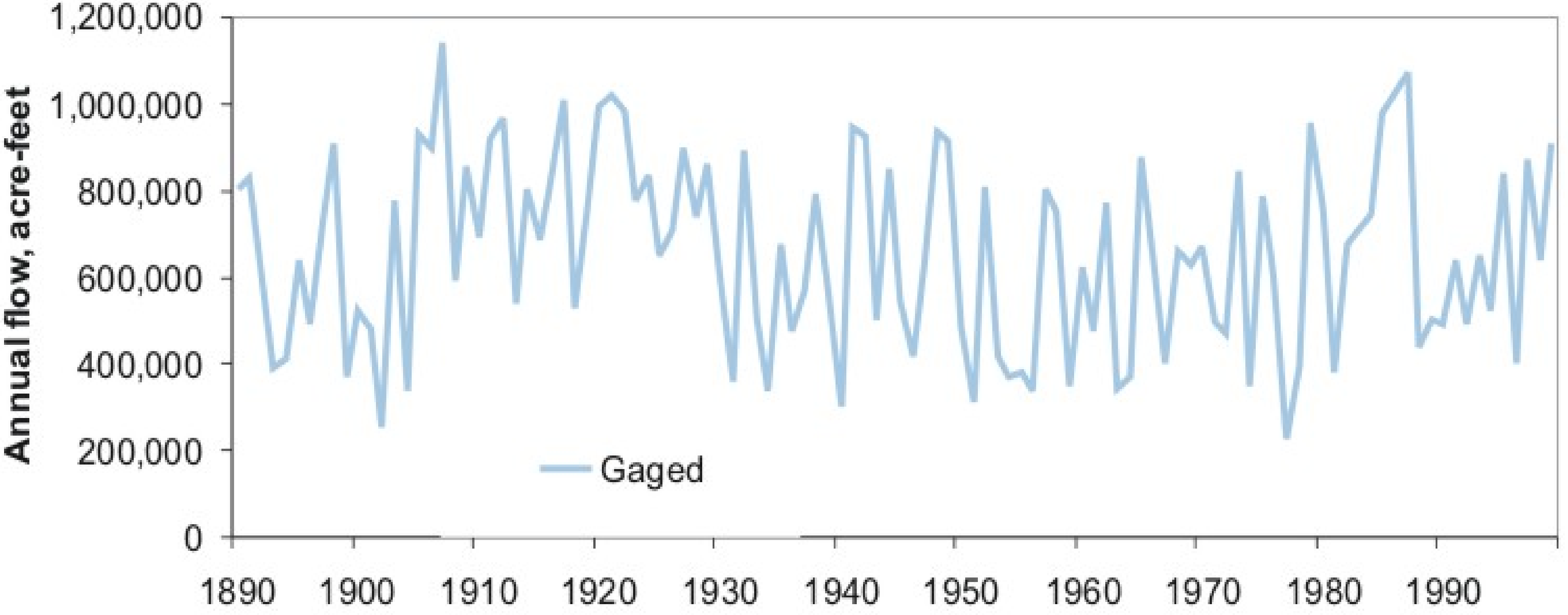
*We need to make decisions about the future, but we don’t know much about it.*

So how do we generally make decisions?

Based on past experience.

# Learning from experience in water management

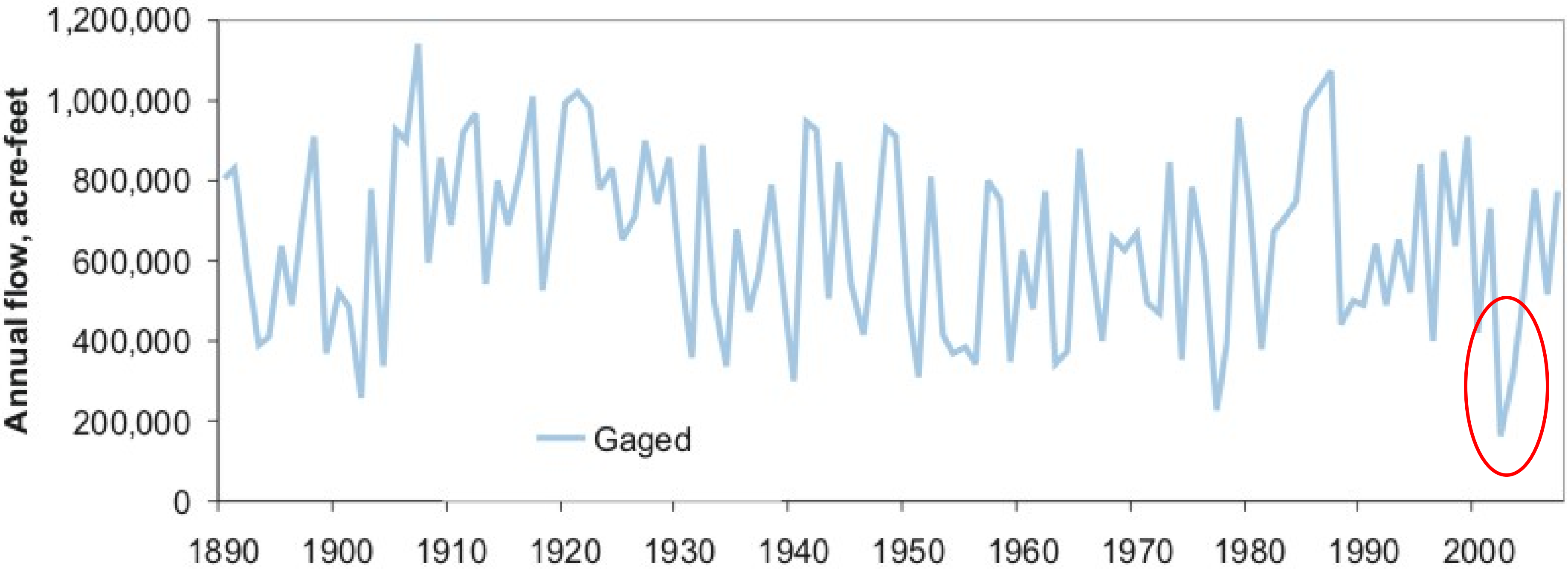
**Rio Grande near Del Norte, CO**
Gaged Annual Flow, 1890-1999




*110 years of experience – enough to fully describe the range of variability?*

# Learning from experience in water management

**Rio Grande near Del Norte, CO**
Gaged Annual Flow, 1890-2007




*2002 – Lowest water year flow*

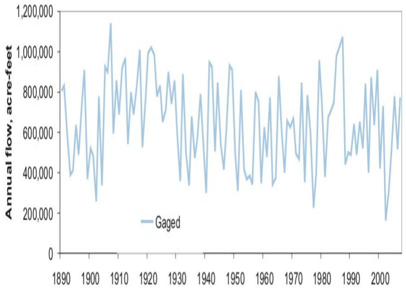
*2002-03 – Lowest 2-year mean flow*

*2002-04 – Lowest 3-year mean flow*

# Tree-ring reconstructions - a surrogate for experience

## Rio Grande near Del Norte, CO

Gaged record- 118 years

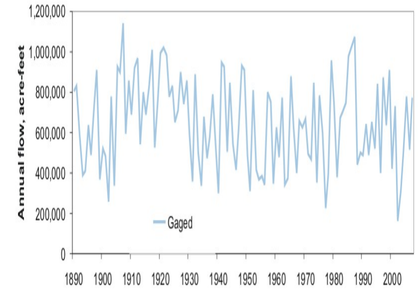


# Tree-ring reconstructions - a surrogate for experience

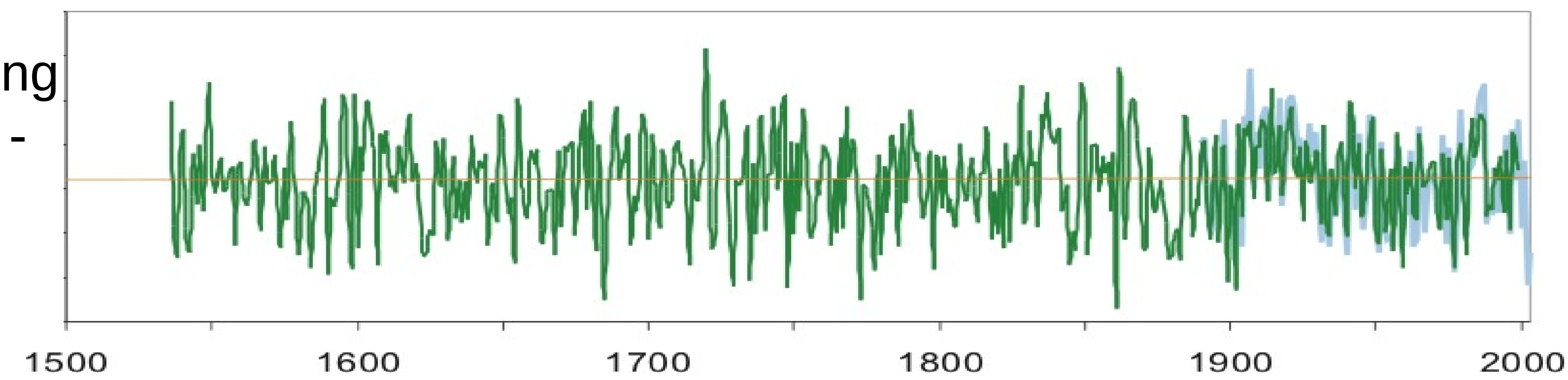
By extending the gaged hydrology by hundreds of years into the past, the reconstructions provide a more complete picture of hydrologic variability

## Rio Grande near Del Norte, CO

Gaged record- 118 years




Tree-ring record - 464 years



# Tree-ring reconstructions - a surrogate for experience

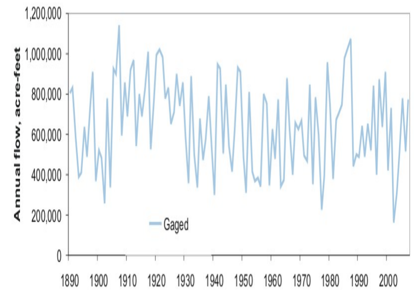
*Benefits:*

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

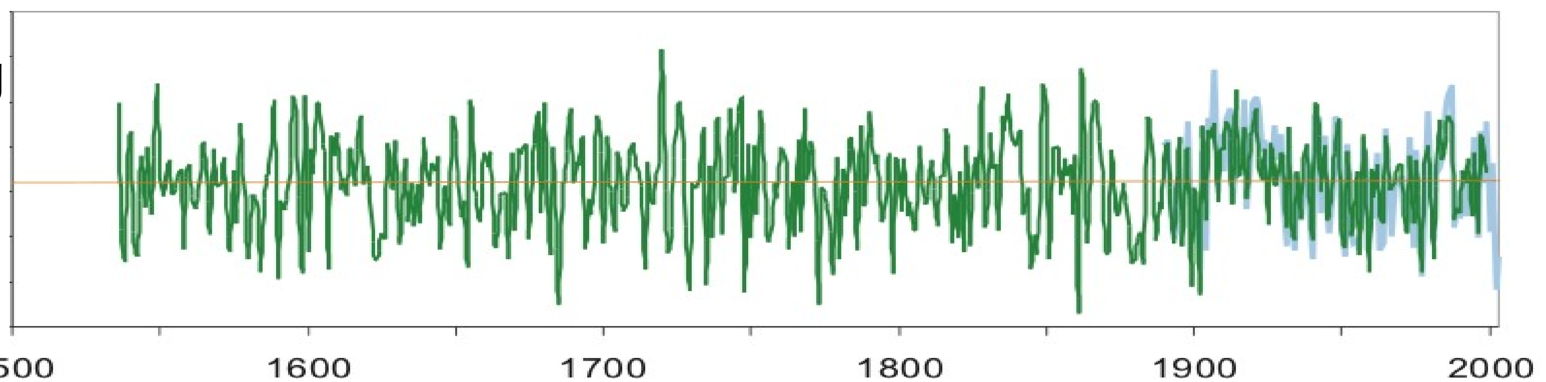
- Better assessment of *risk*

Rio Grande near Del Norte, CO

Gaged record- 118 years




Tree-ring record - 464 years



# Attributes of tree rings useful for climate and streamflow reconstruction

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

# Tree-ring science and streamflow reconstructions are not new

1900s - Douglass establishes tree-ring science; links tree growth and climate in Southwest

1930s - First studies relating tree growth to runoff in western US

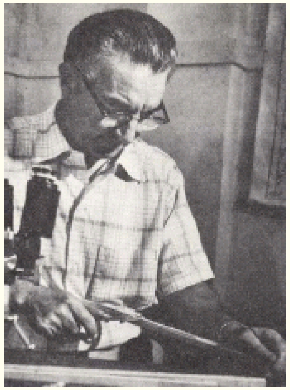
1940s - Schulman investigates history of Colorado River flow using tree rings

1960s - Fritts develops modern statistical methods for climate reconstruction

1976 - Stockton and Jacoby reconstruction of Lees Ferry streamflow

2000s - Many new flow reconstructions for western US

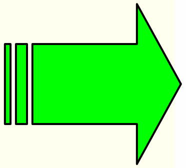
A.E. Douglass

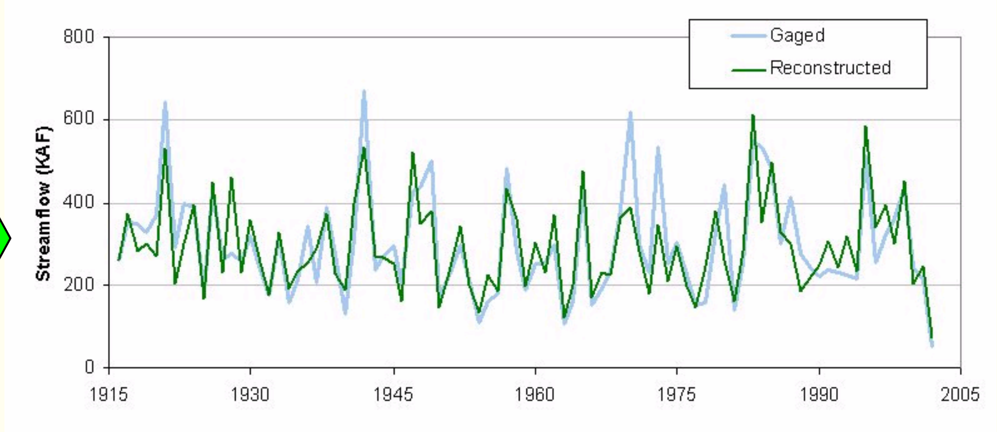


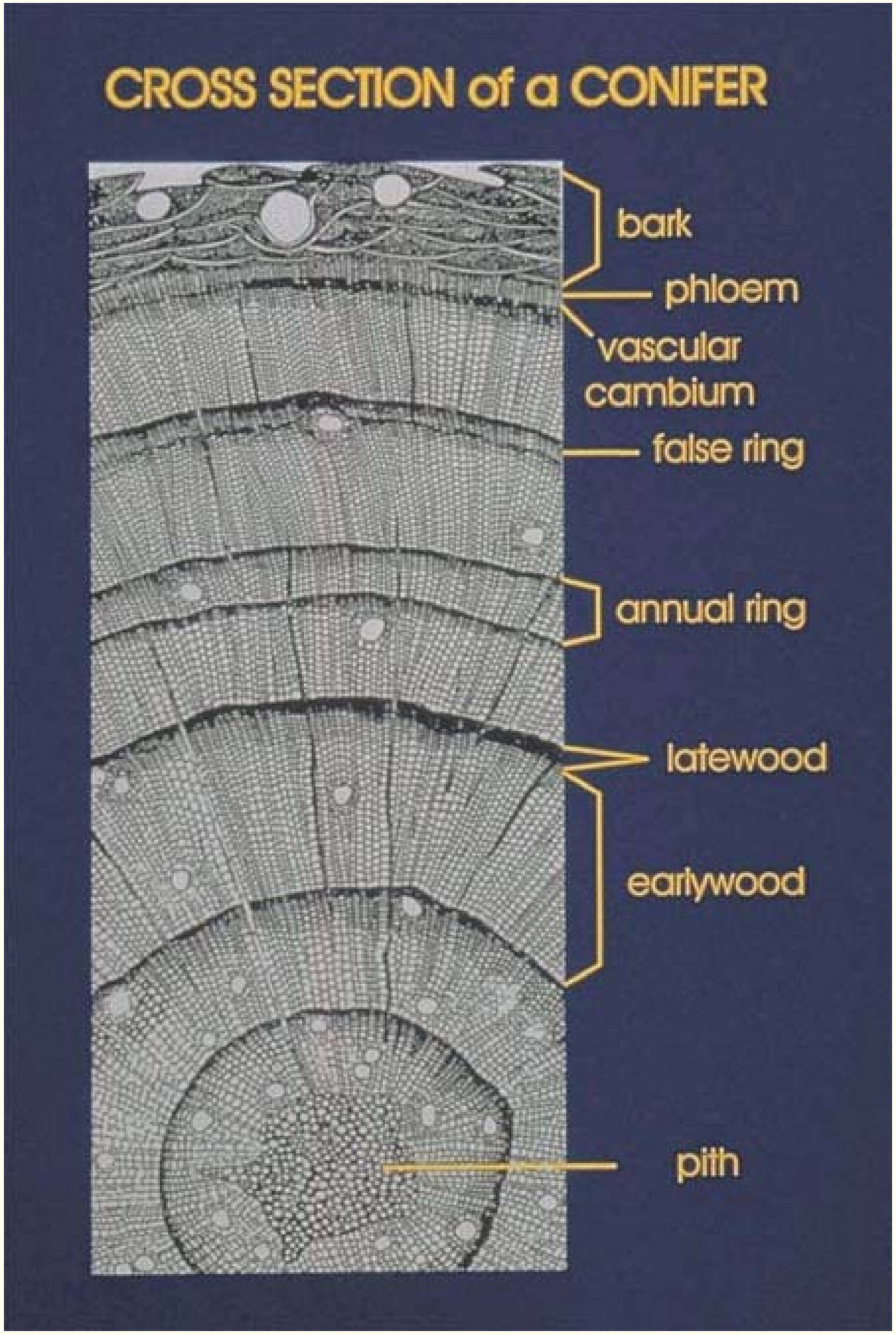
E. Schulman

# 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

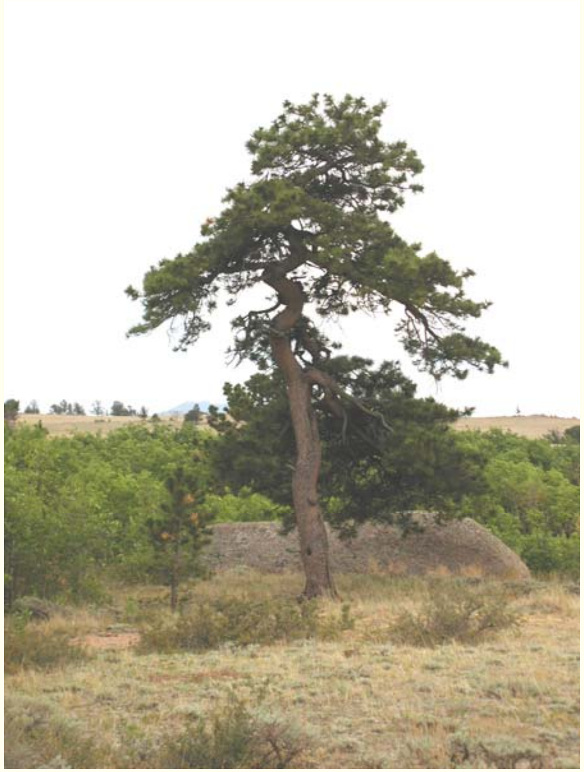
# Climate is the main limiting factor on tree growth in the intermountain West

- Near treeline, growth is more limited by summer warmth and length of the growing season

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

# Main moisture-sensitive species in the Southwest

**Douglas-fir**



**Ponderosa Pine**

**Pinyon Pine**

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

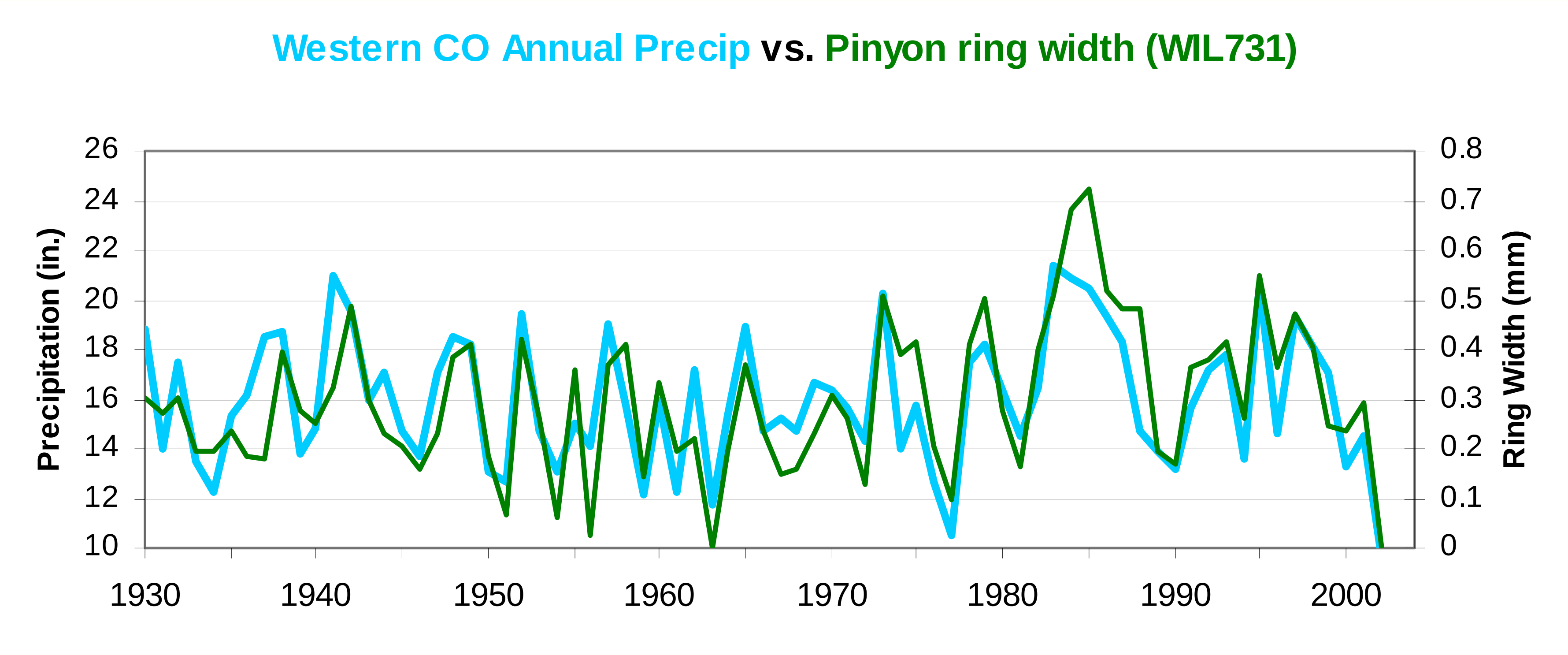
# Seasonality of moisture response

- Critical factor: soil moisture at start of growing season
- Tree growth in this region responds mainly to precipitation in fall/winter/spring prior to summer growing season, less so to what falls during the growing season itself
- So ring-width incorporates climate over roughly a year prior to the end of the growing season (~water year)

Douglas-fir, south San Juans, CO

**1977** - normal precip Jul-Sep - **1983**

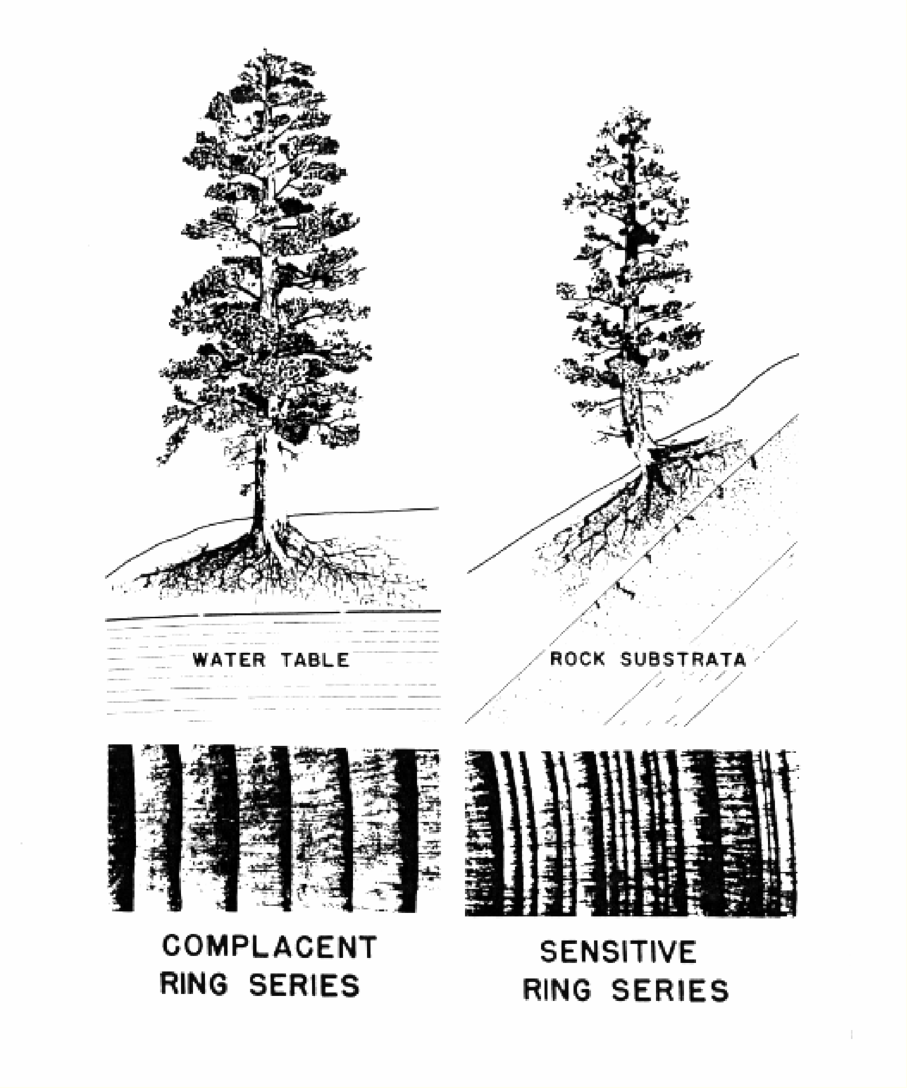
# The moisture signal recorded by trees in this region is particularly strong




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

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

# Stressful sites produce ring series with stronger signal




from *Fritts 1976*

## This moisture signal in tree rings can be a proxy for multiple moisture-related variables

- Annual or winter 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

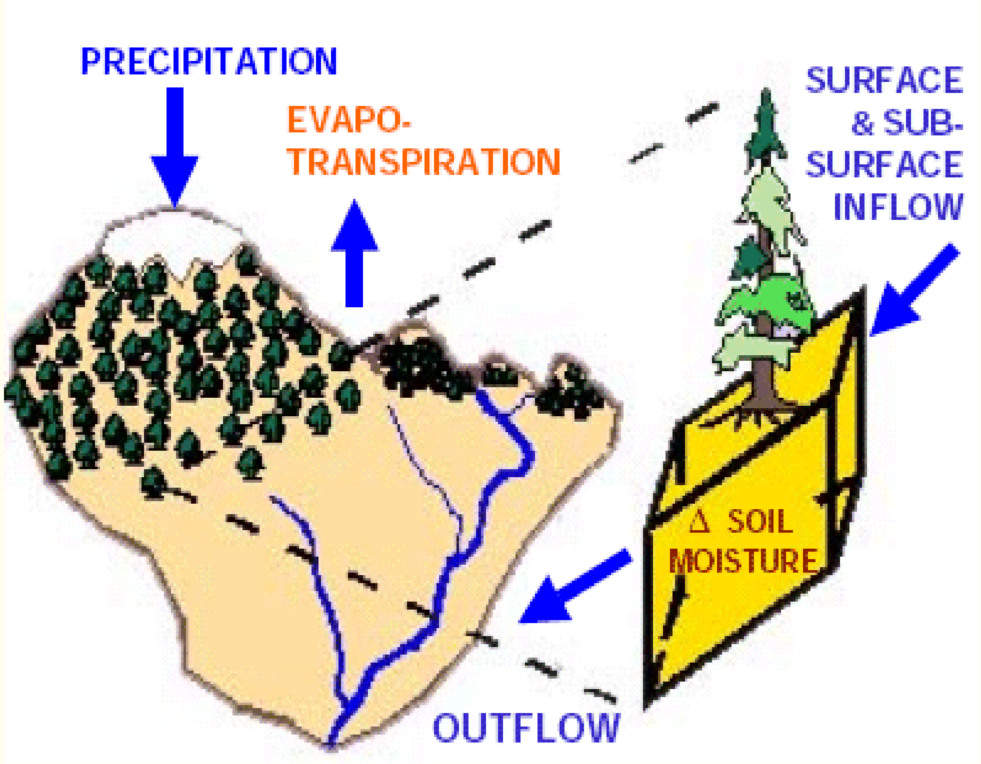
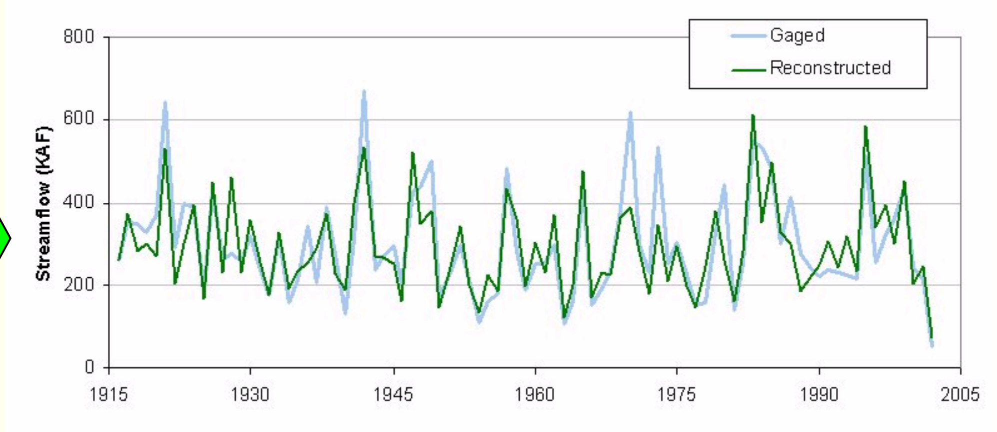



Image courtesy of D. Meko (U. AZ)

# Part 3:

## Building a tree-ring chronology




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

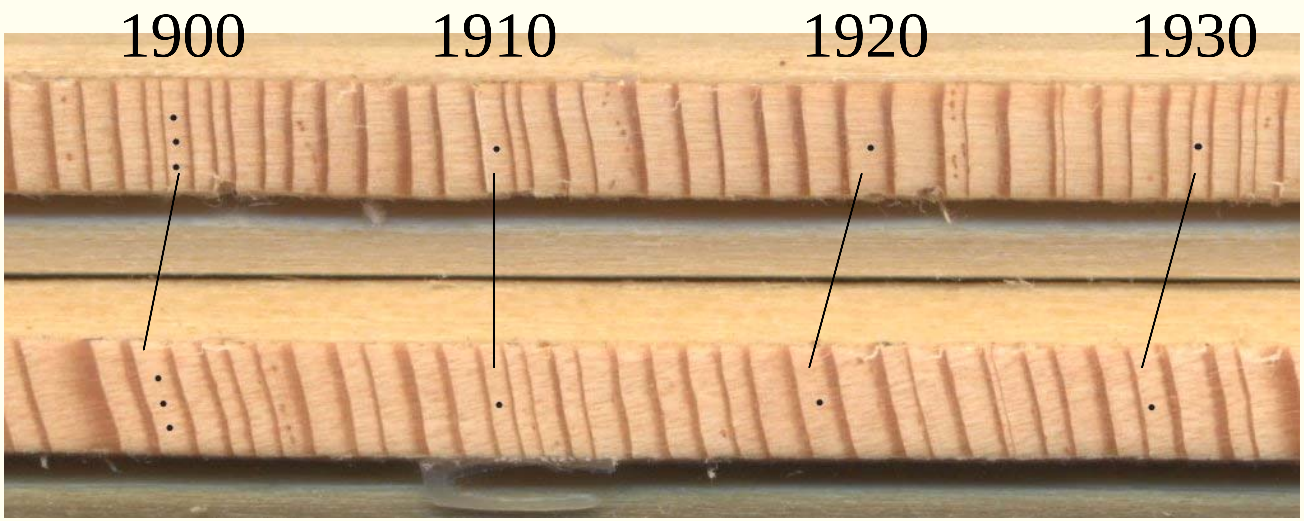
# Sampling the trees

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

# Crossdating the samples

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

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




Two Douglas-fir trees south of Boulder, CO

# Regional climate patterns = regional crossdating

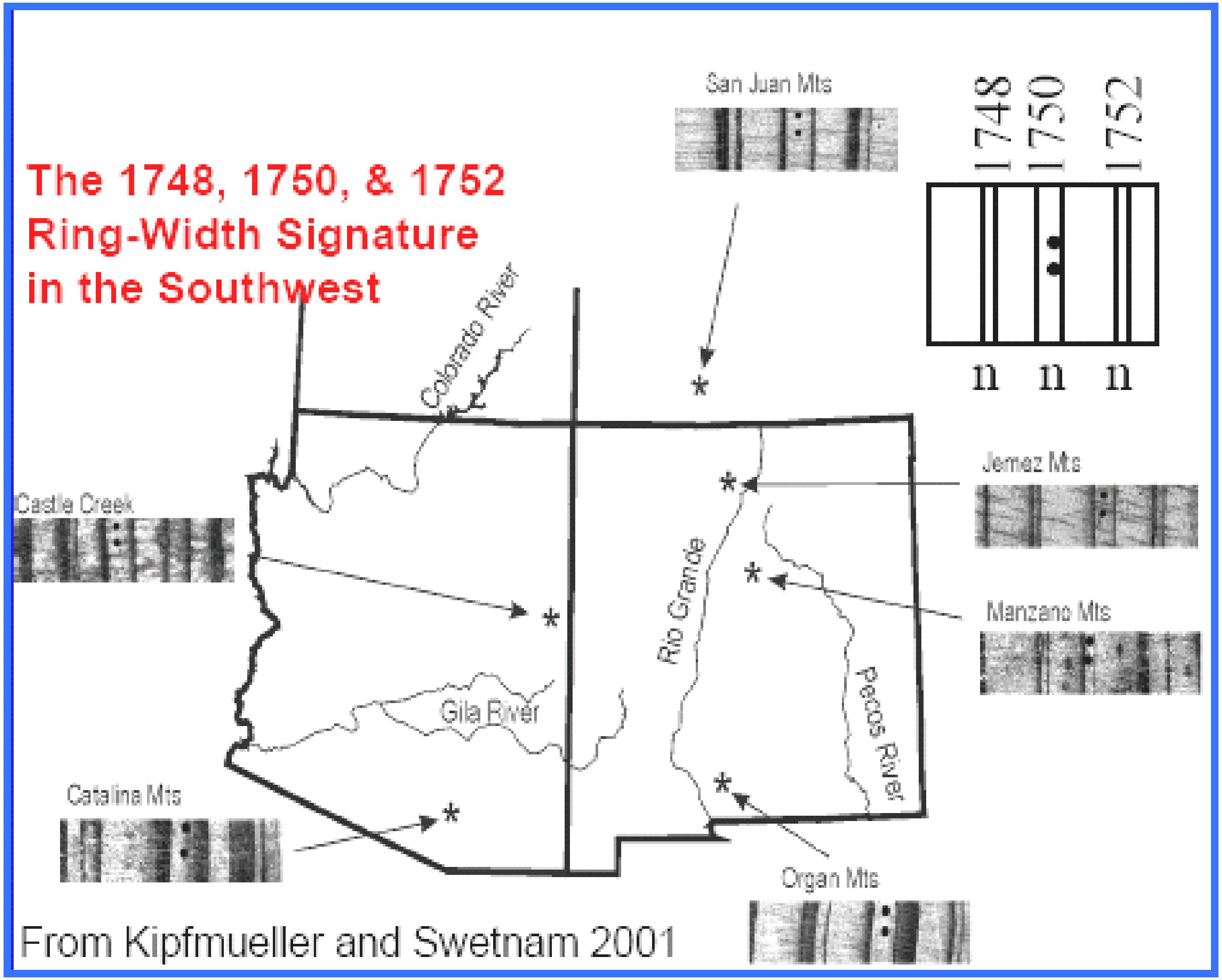



Image courtesy of K. Kipfmueller (U. MN) and T. Swetnam (U. AZ)

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

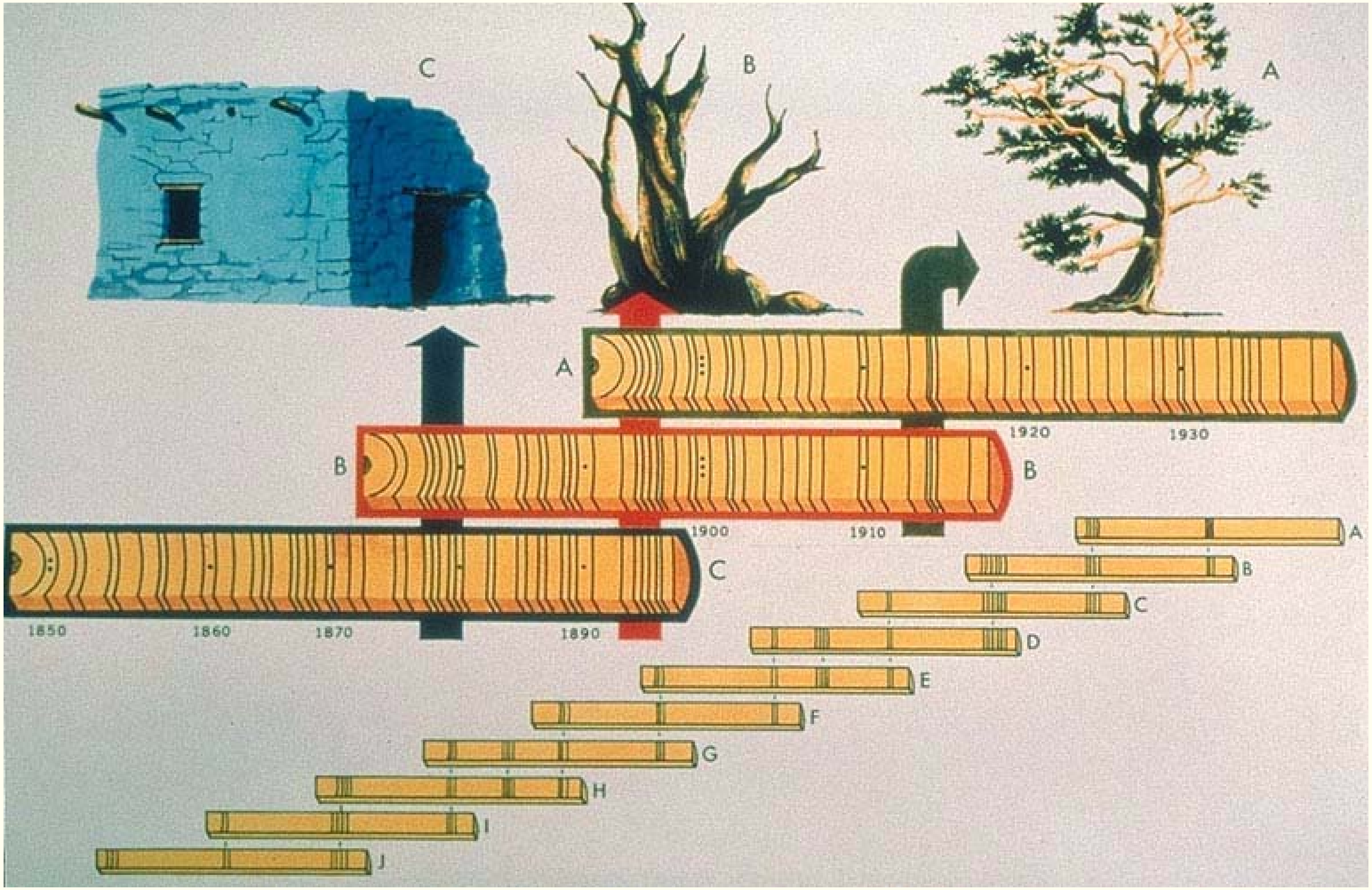
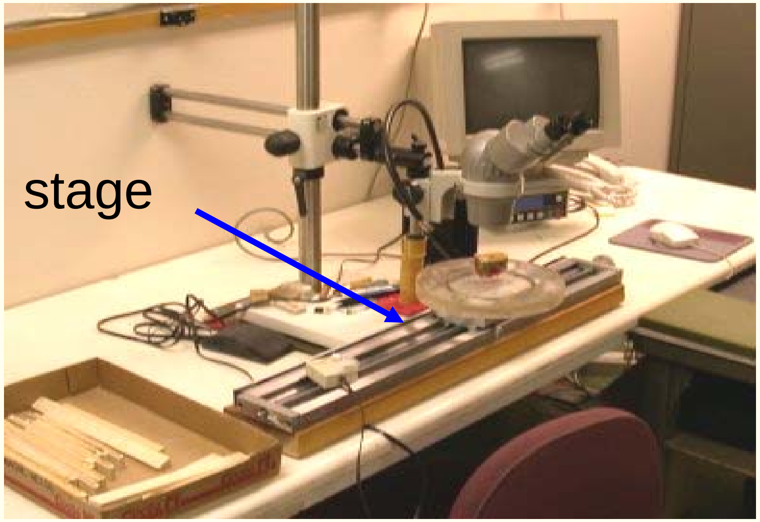
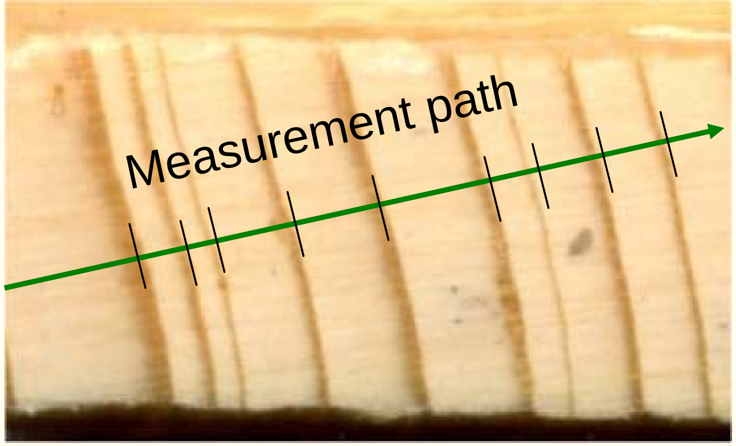



Image courtesy of LTRR (U. AZ)

# Measuring the samples

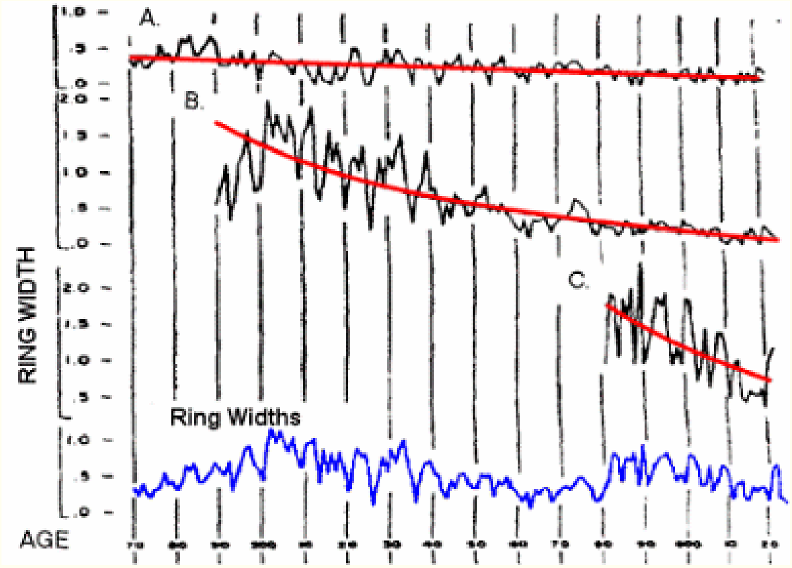



- Computer-assisted measurement system with sliding stage
  - captures position of core to nearest 0.001mm (1 micron)




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

# Detrending the measured series



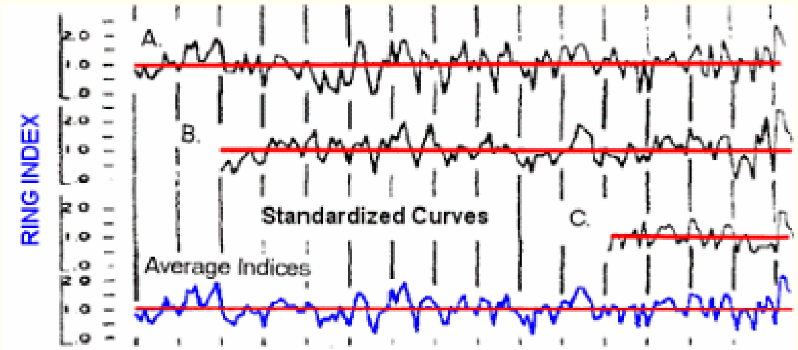



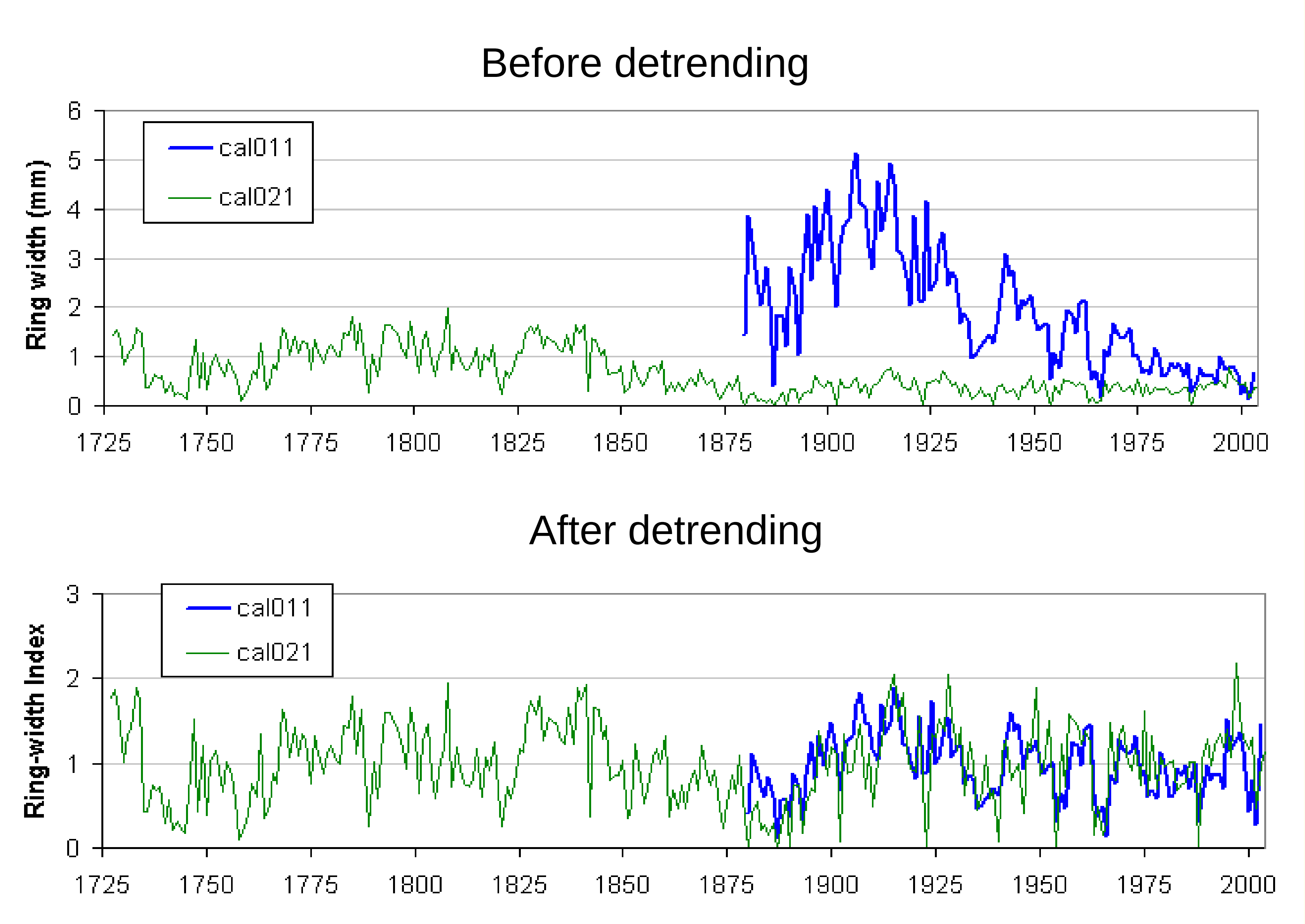

Image courtesy of LTRR (U. AZ)

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

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

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

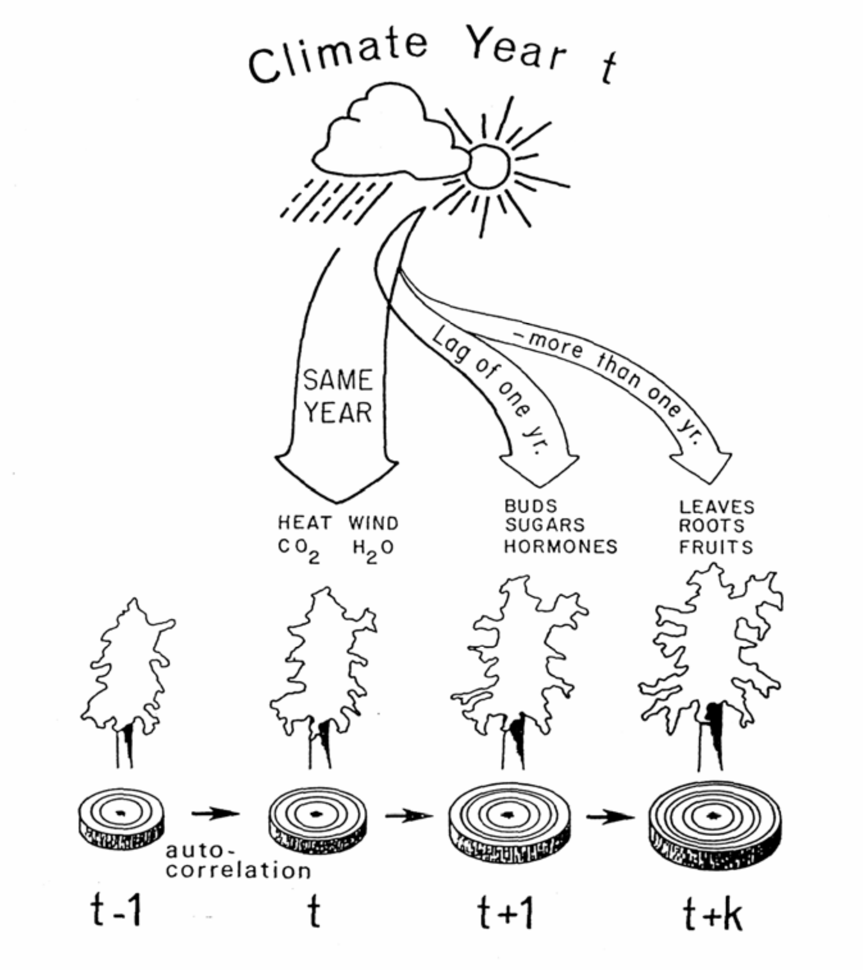
# Example of detrending - 2 trees, same site



# Persistence in tree growth from year to year

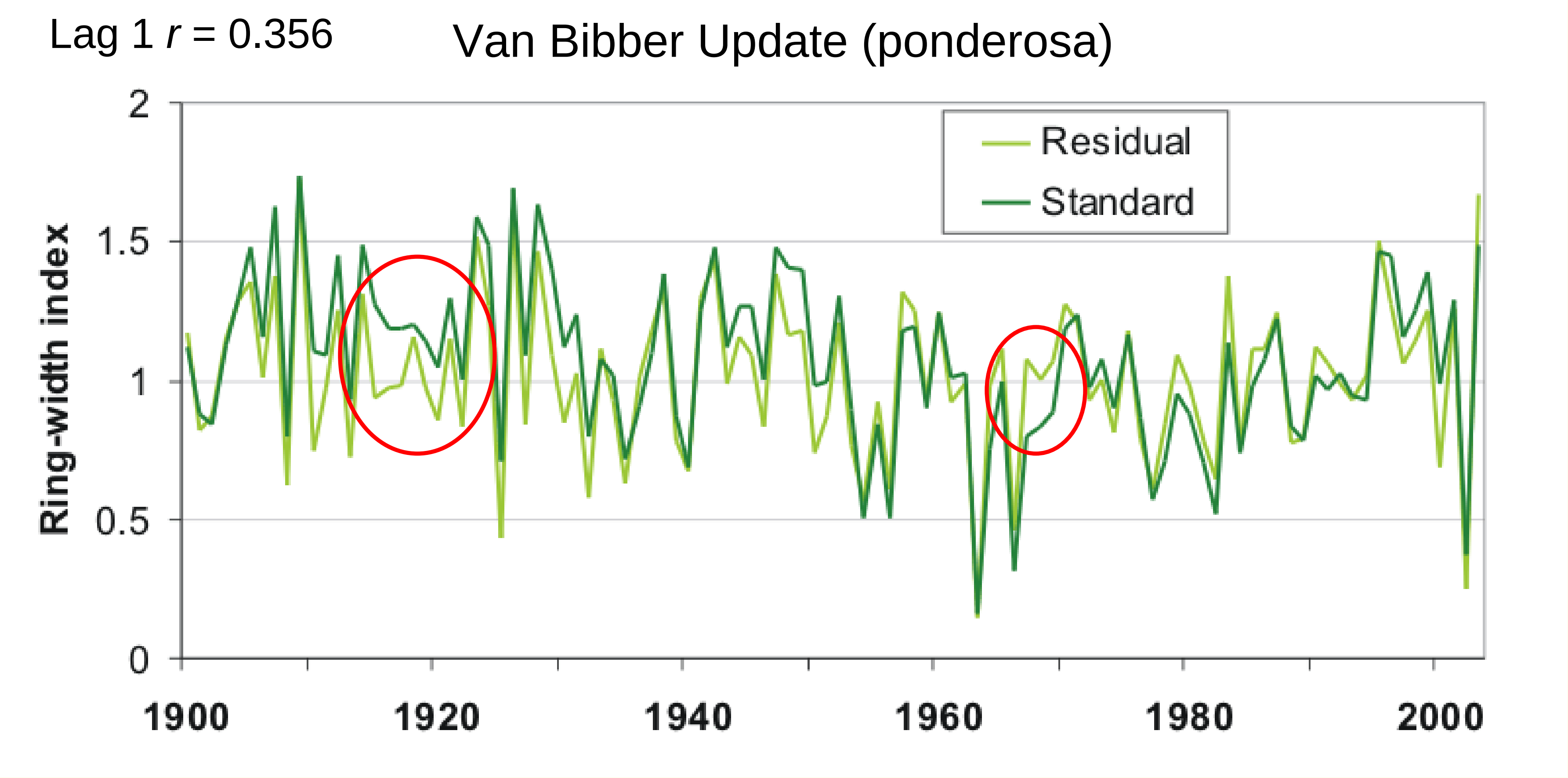
- The climate in a given year (t) can also influence growth in succeeding years (t+1, t+2, etc.) through storage of sugars and growth of needles

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

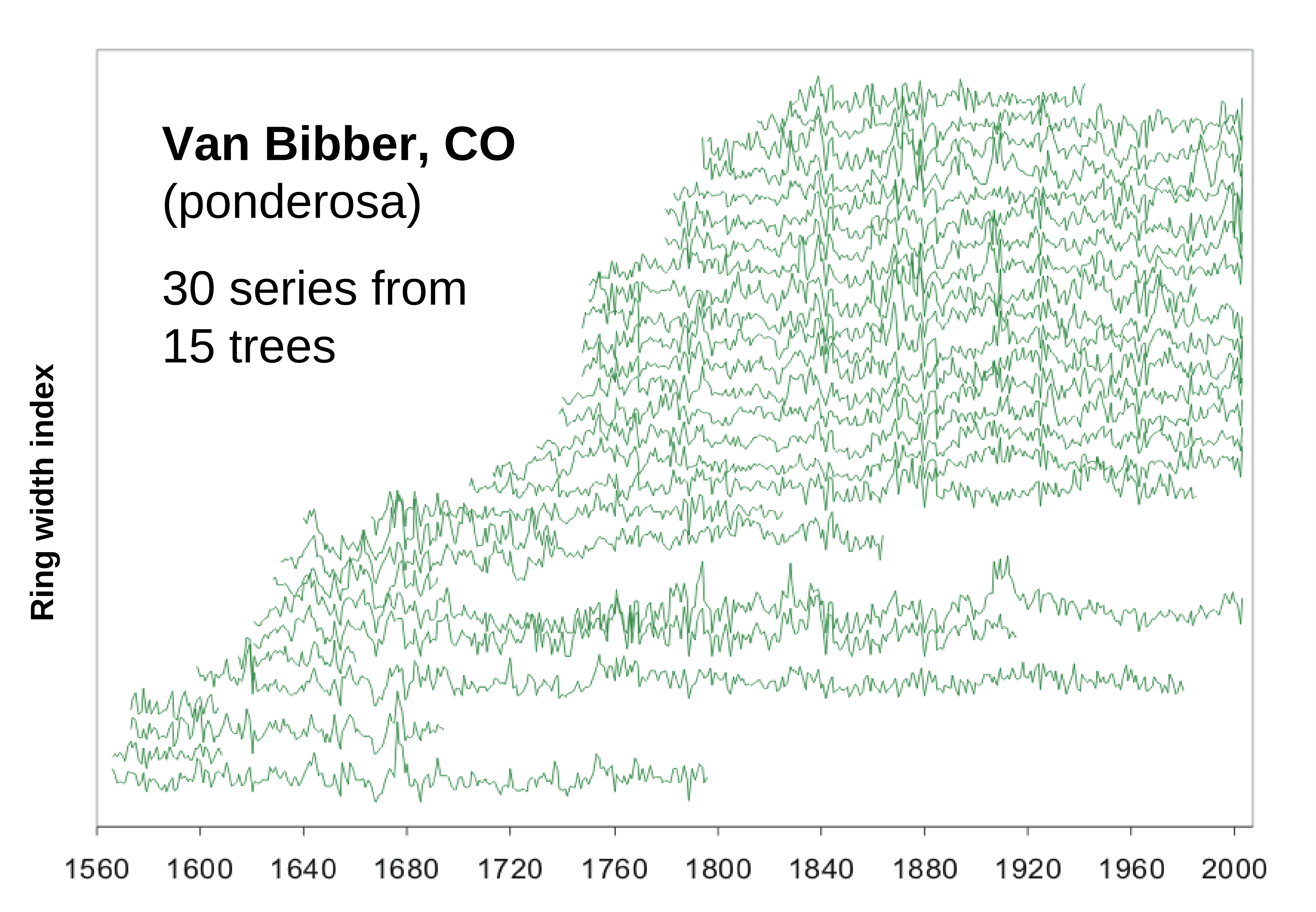


# Treatment of persistence in the ring series and chronology

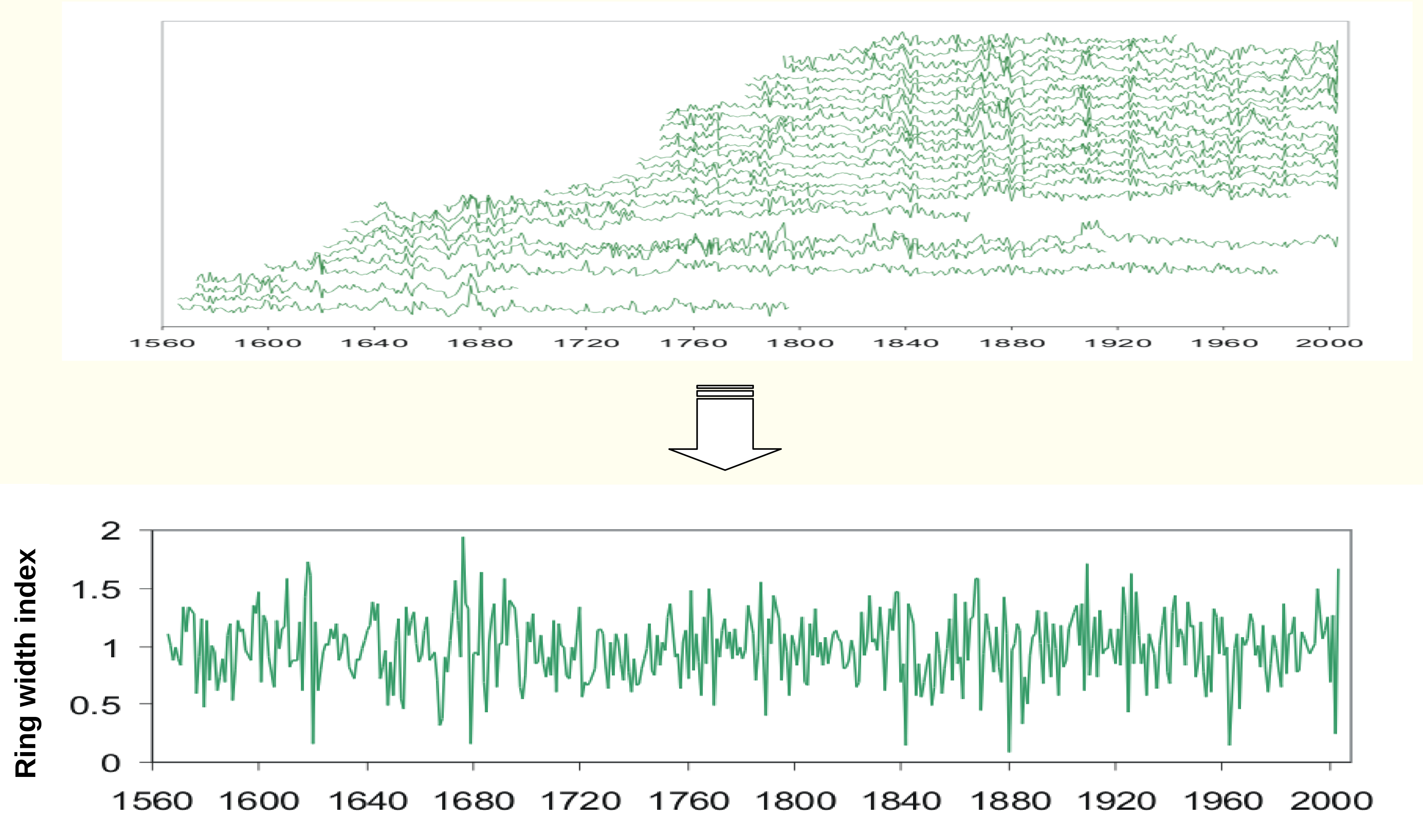
- *Standard chronology:* persistence in the series is retained
- *Residual chronology:* first-order persistence is removed from each series before the chronology is compiled



# By compiling the measurements from many trees...



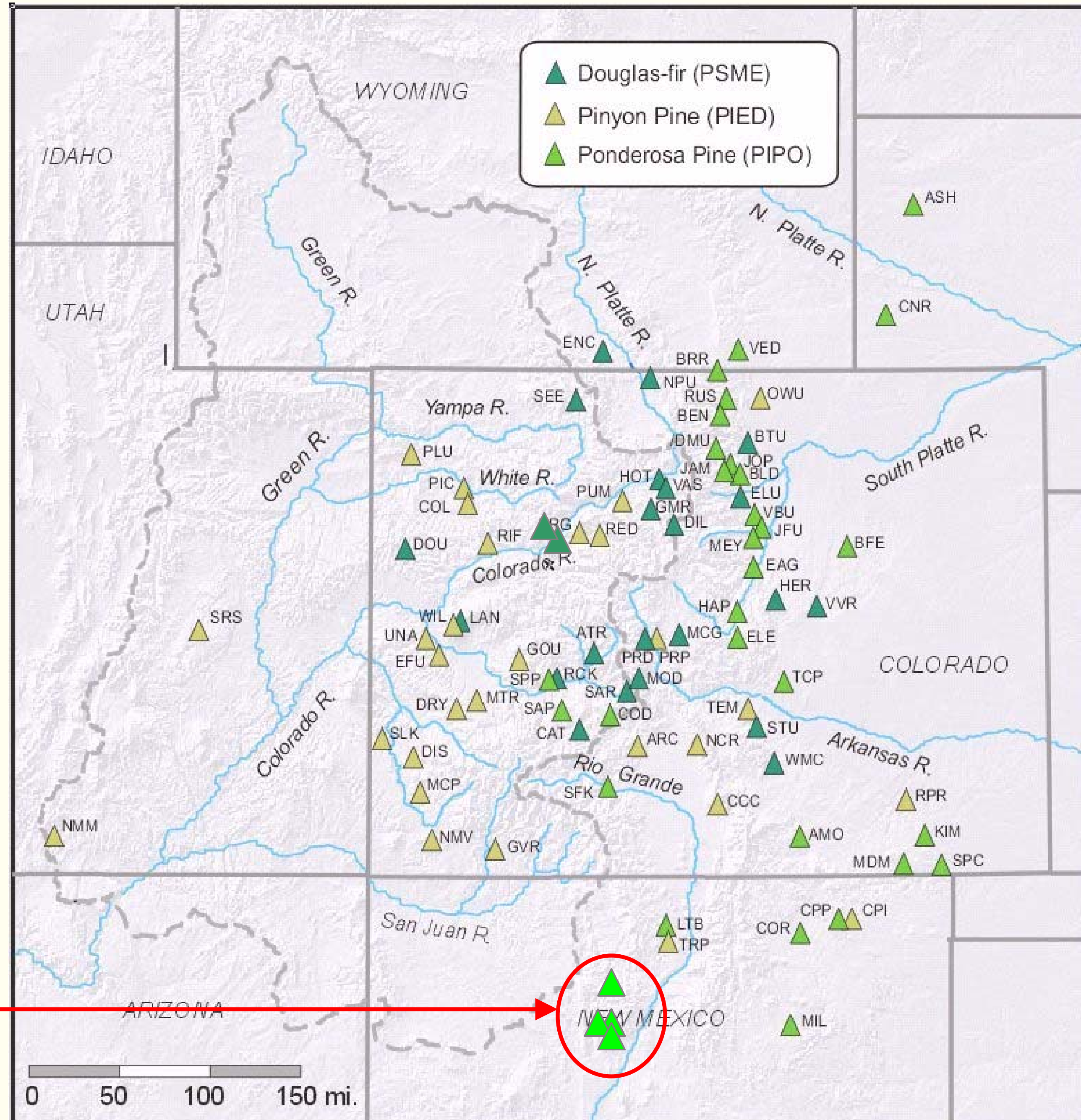
# …we enhance the common (climate) signal in the resulting site *chronology*



Moisture-sensitive chronologies developed 1999-2007 by CU-INSTAAR Dendro Lab

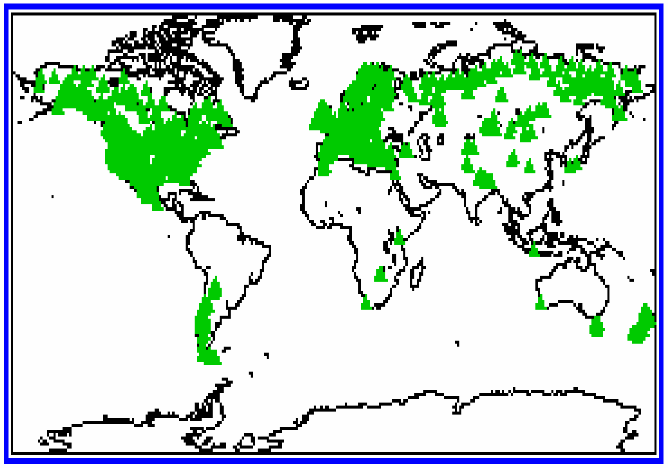
- Average length: 550 years
- High correlations with annual precipitation and annual streamflow

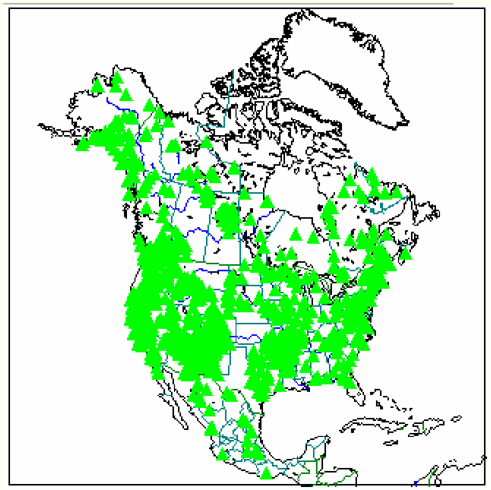
4 new chronologies 2007-08, Univ. of Arizona LTRR

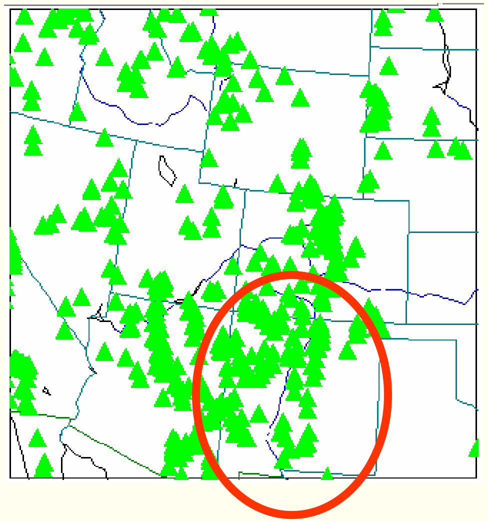


# The larger world of tree-ring chronologies

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



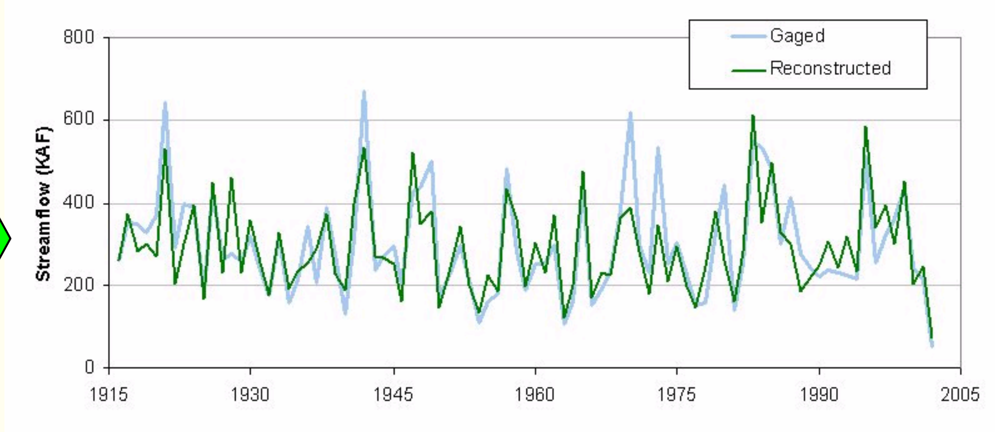




- 2500 chronologies contributed from all over the world
- 90 chronologies from New Mexico, nearly all are moisture-sensitive – but most collected in 1960s-1980s

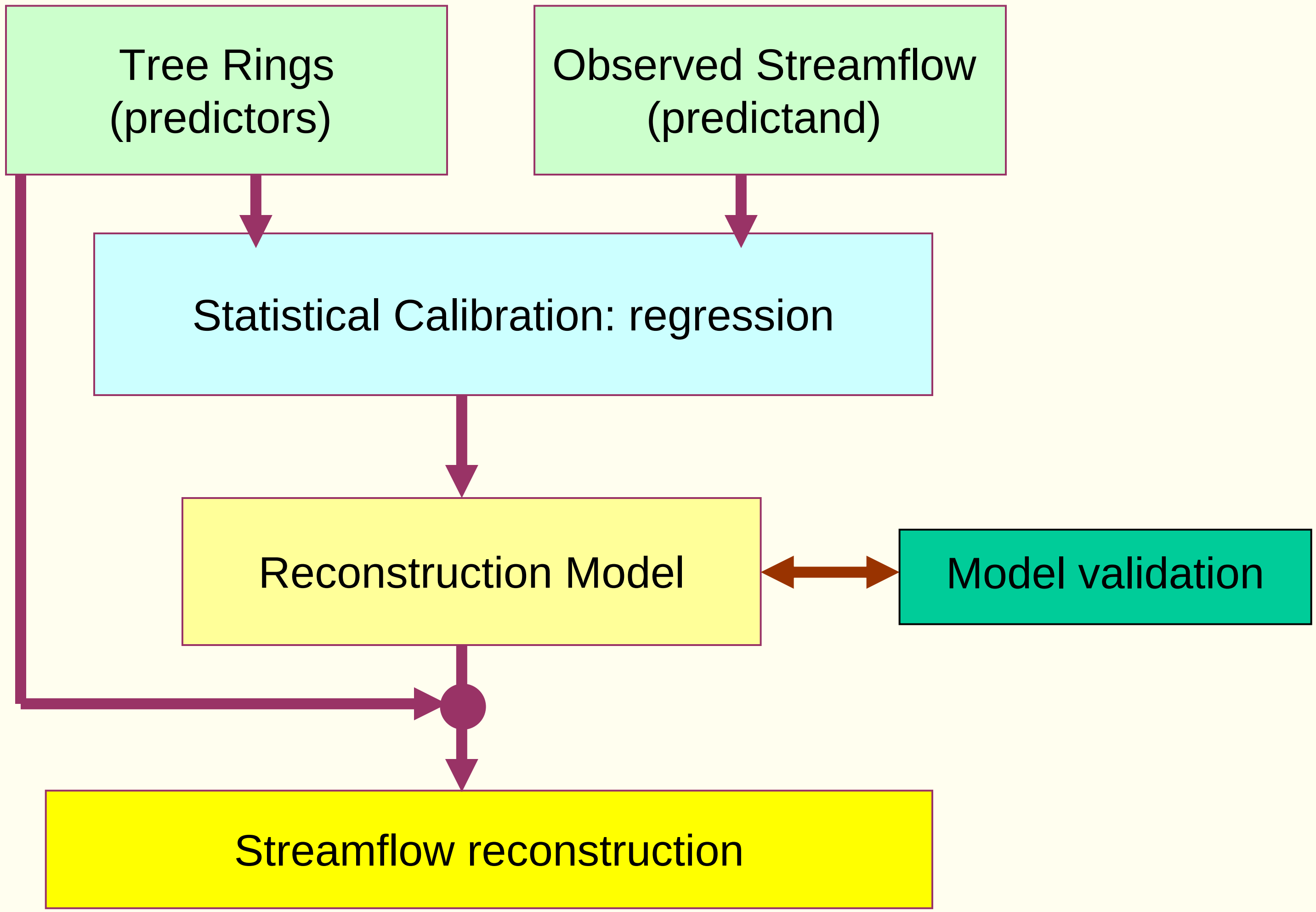
# Part 4:

## 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

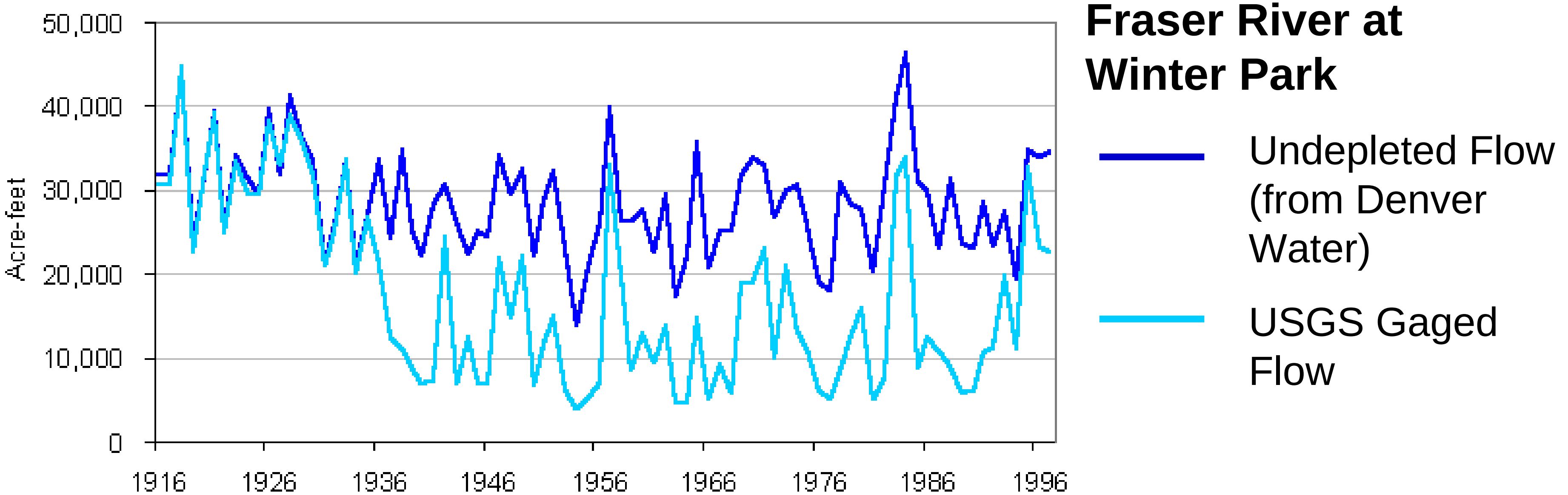
# Overview of reconstruction methodology




based on Meko (2005)

# Requirements for observed streamflow record

- **Length** – minimum 40 years for robust calibration with tree-ring data
- **Natural/undepleted record** – corrected for depletions, diversions, evaporation, etc. (*usually*)




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

# Requirements for tree-ring chronologies

- **Moisture sensitive species** - Douglas-fir, ponderosa pine, pinyon pine (limber & southwestern white pine)
- **Location** – from a region that is climatically linked to the gage of interest
  - *Because weather systems cross watershed divides, chronologies do not have to be in same basin as gage*
- **Years -**

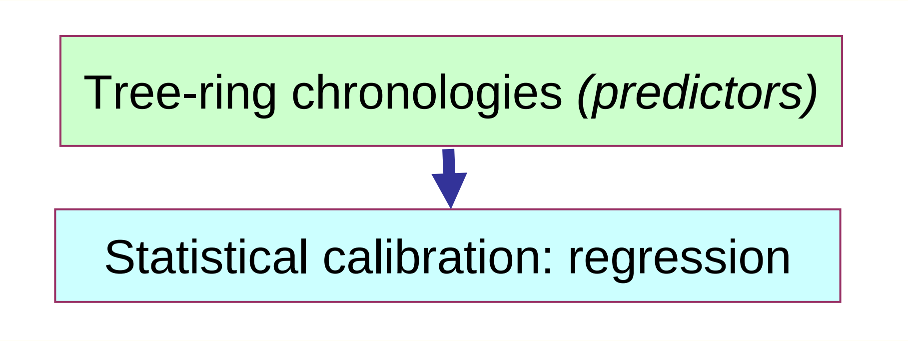
  **Last year** close to present for the longest calibration period possible

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

  - *reconstructions are limited by the shortest chronology unless time-varying subsets used*

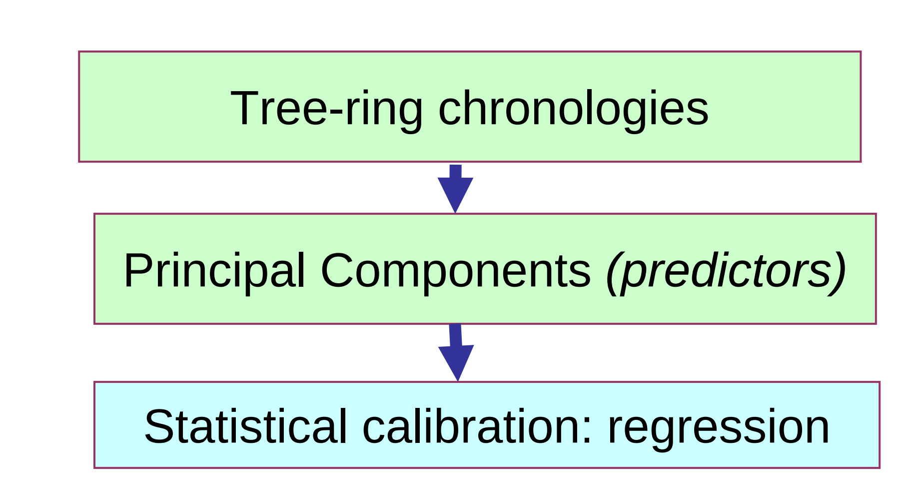
# Reconstruction modeling strategies

- **Individual chronologies** are used as predictors in a linear regression procedure




*OR*

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

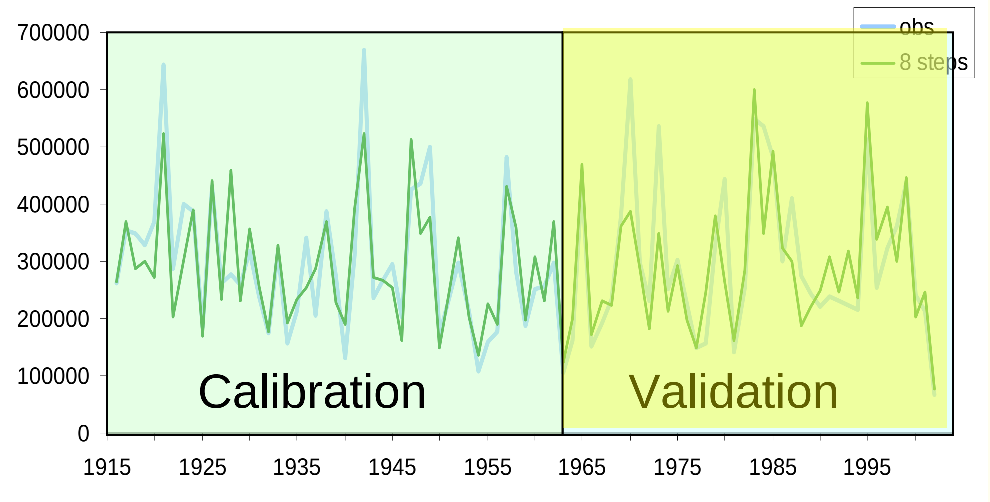



*These are the most common, but many other approaches are possible (e.g., quantile regression, neural networks, non-parametric methods)*

# Model validation strategy

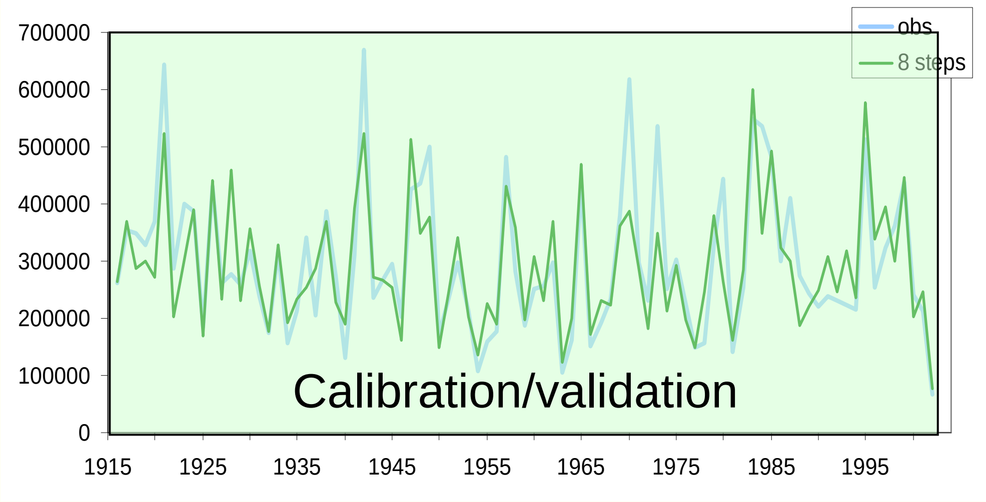
Goal: to calibrate model on a set of data, and validate the model on an independent set of data

Split-sample with truly independent calibration and validation periods

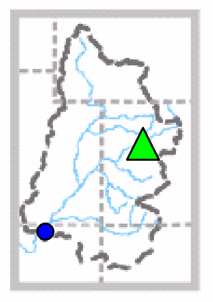



*OR*

Cross-validation ("leave-one-out") method – pseudo-independent validation



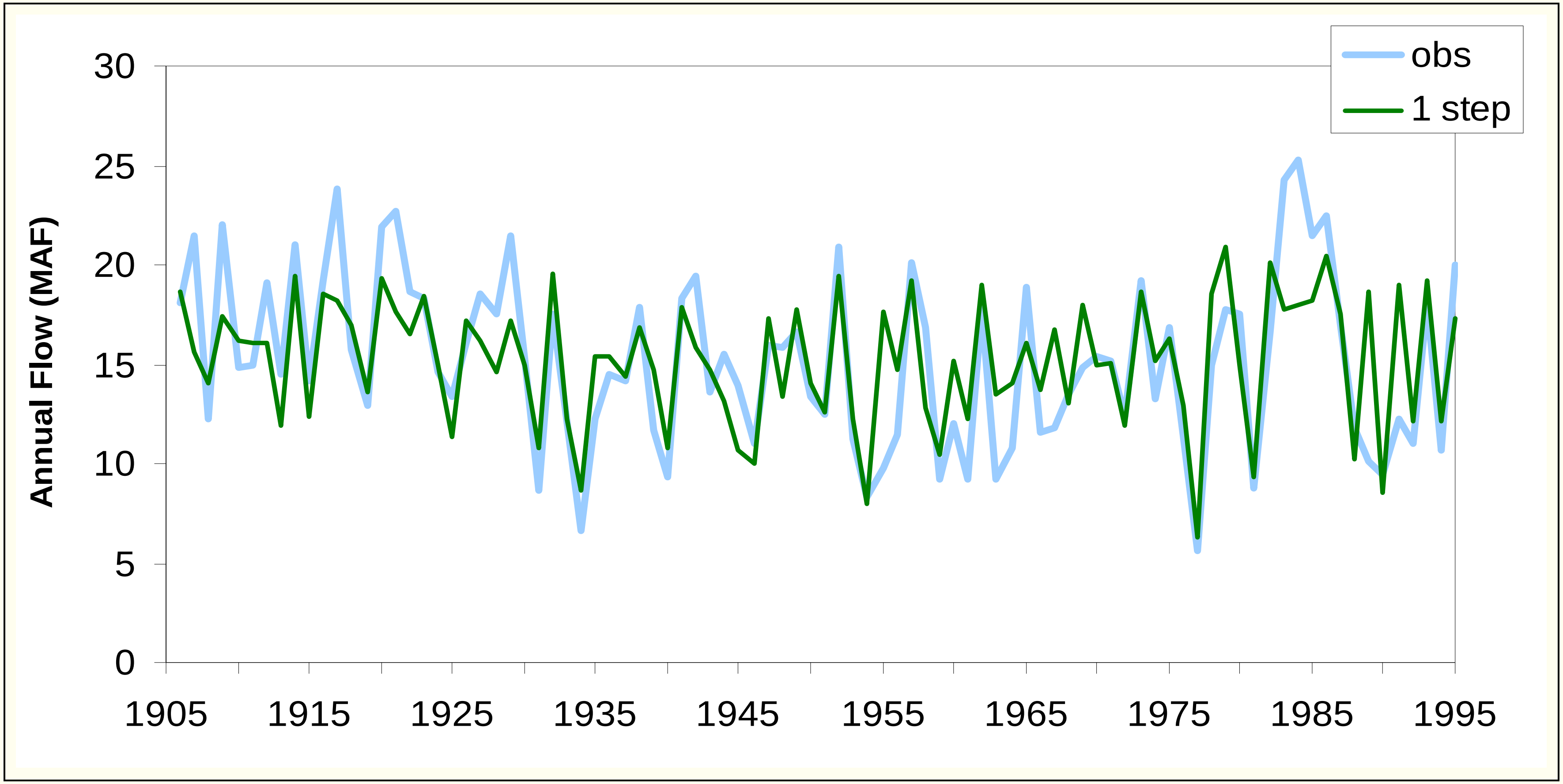
# Colorado at Lees Ferry - forward stepwise regression



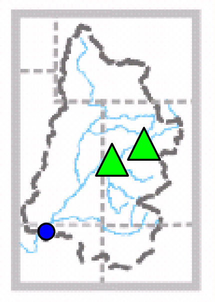
TRG

Variance Explained

**55%**



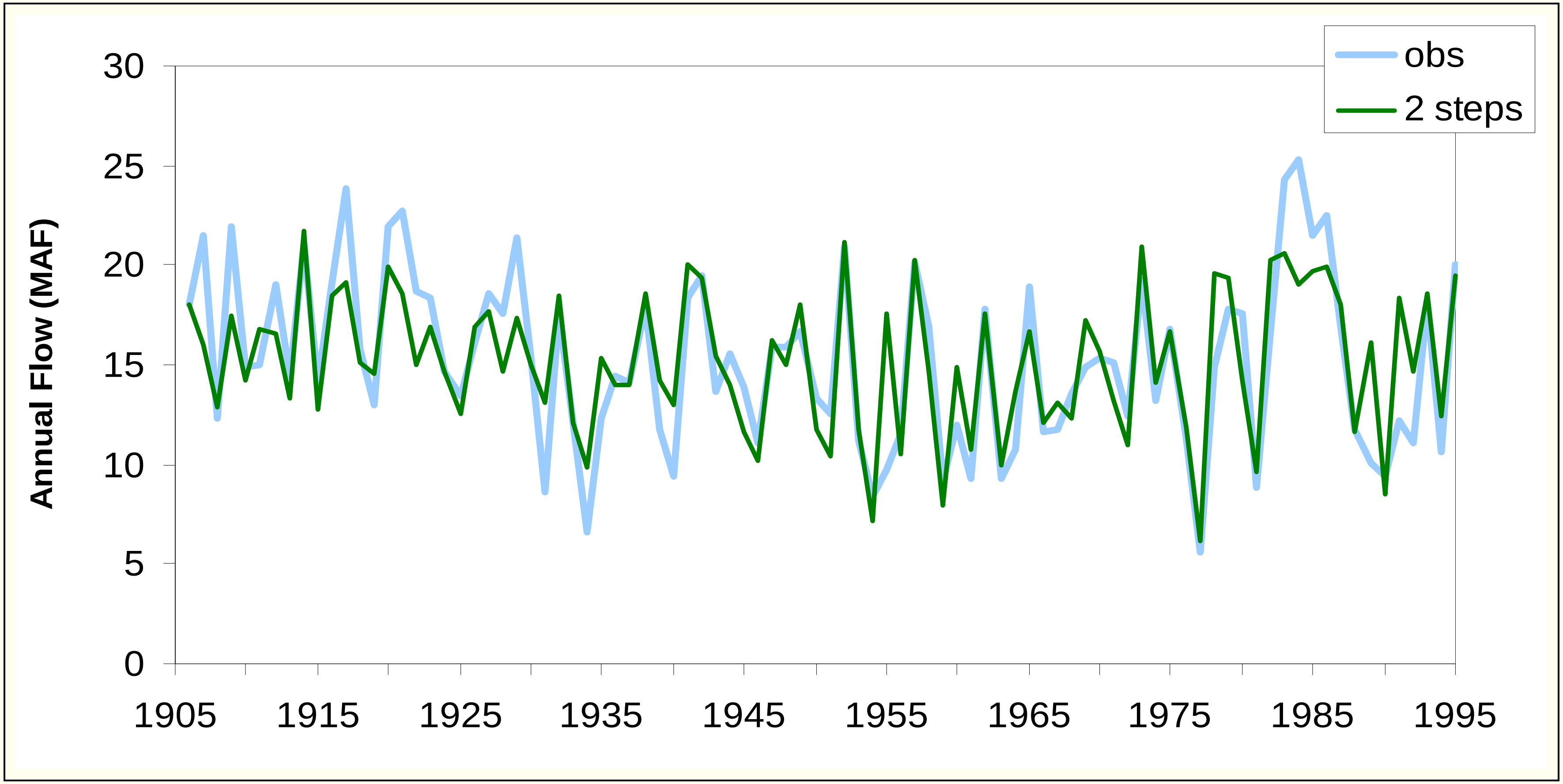
# Colorado at Lees Ferry - forward stepwise regression



TRG + WIL

Variance Explained

**67%**



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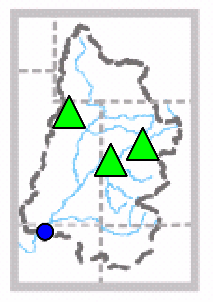
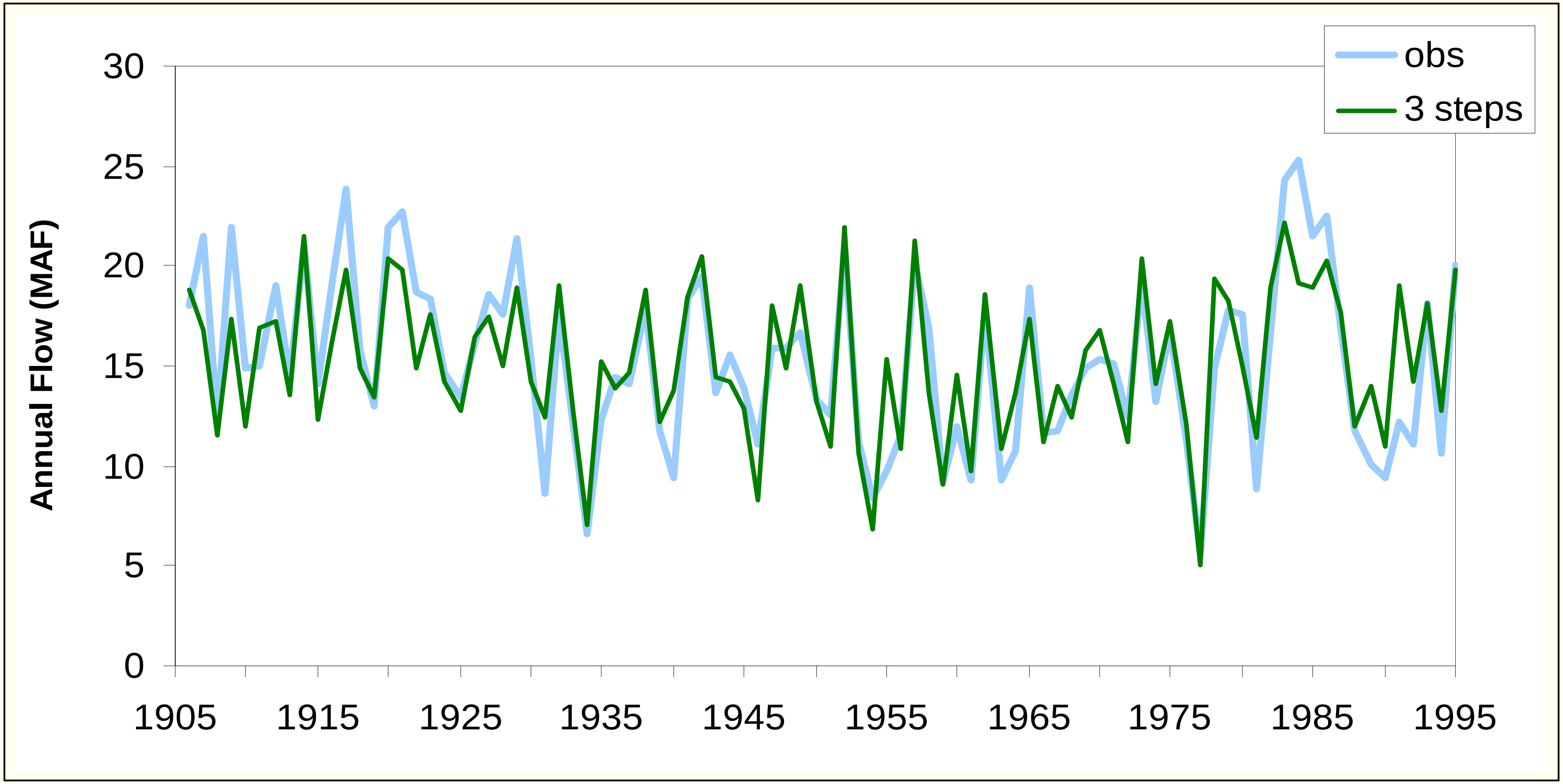


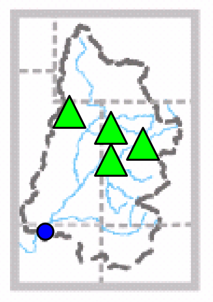
TRG + WIL + DJM

Variance Explained

**72%**



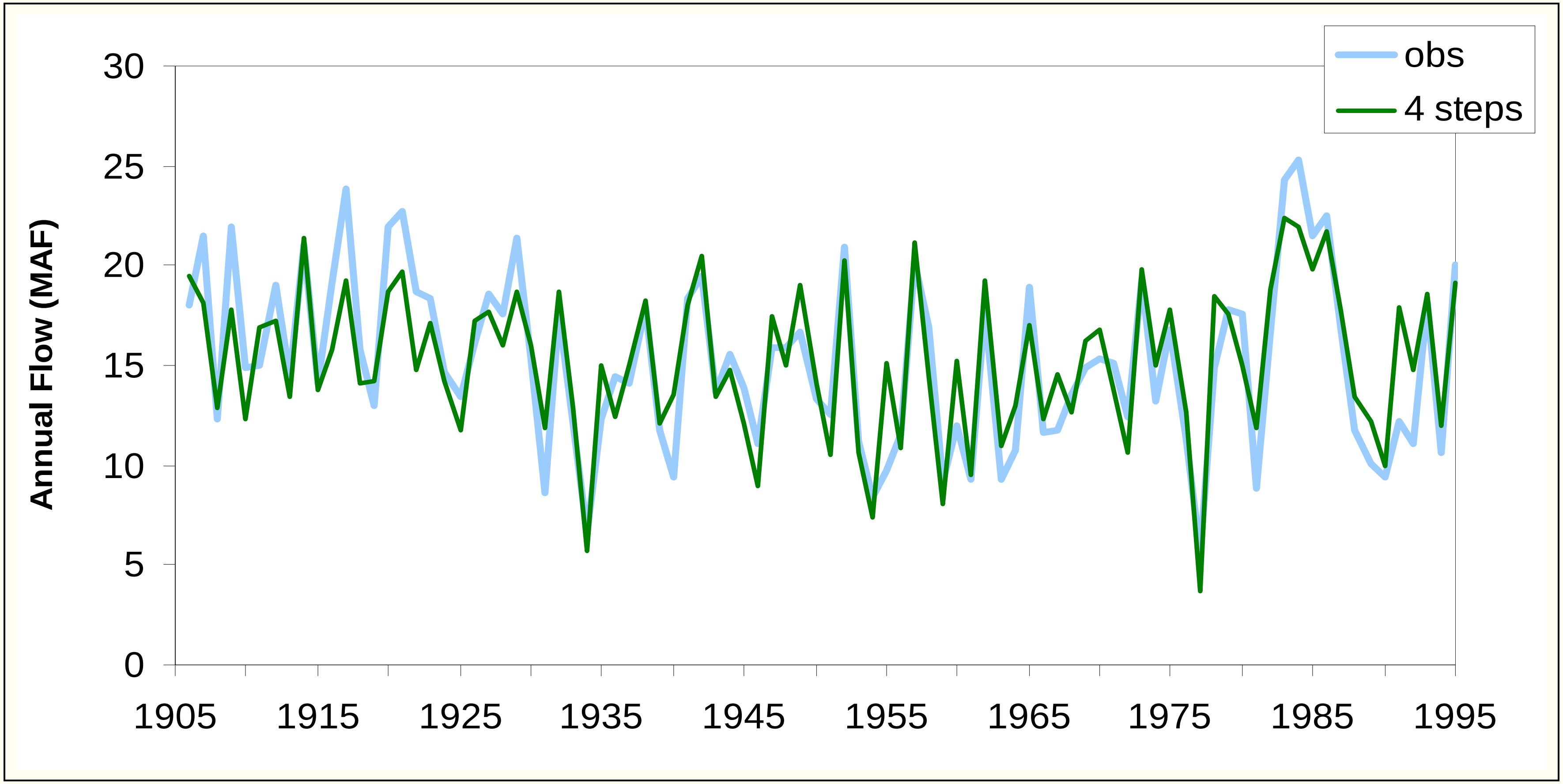
# Colorado at Lees Ferry - forward stepwise regression



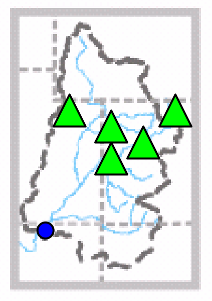
TRG + WIL + DJM + DOU

Variance Explained

**75%**



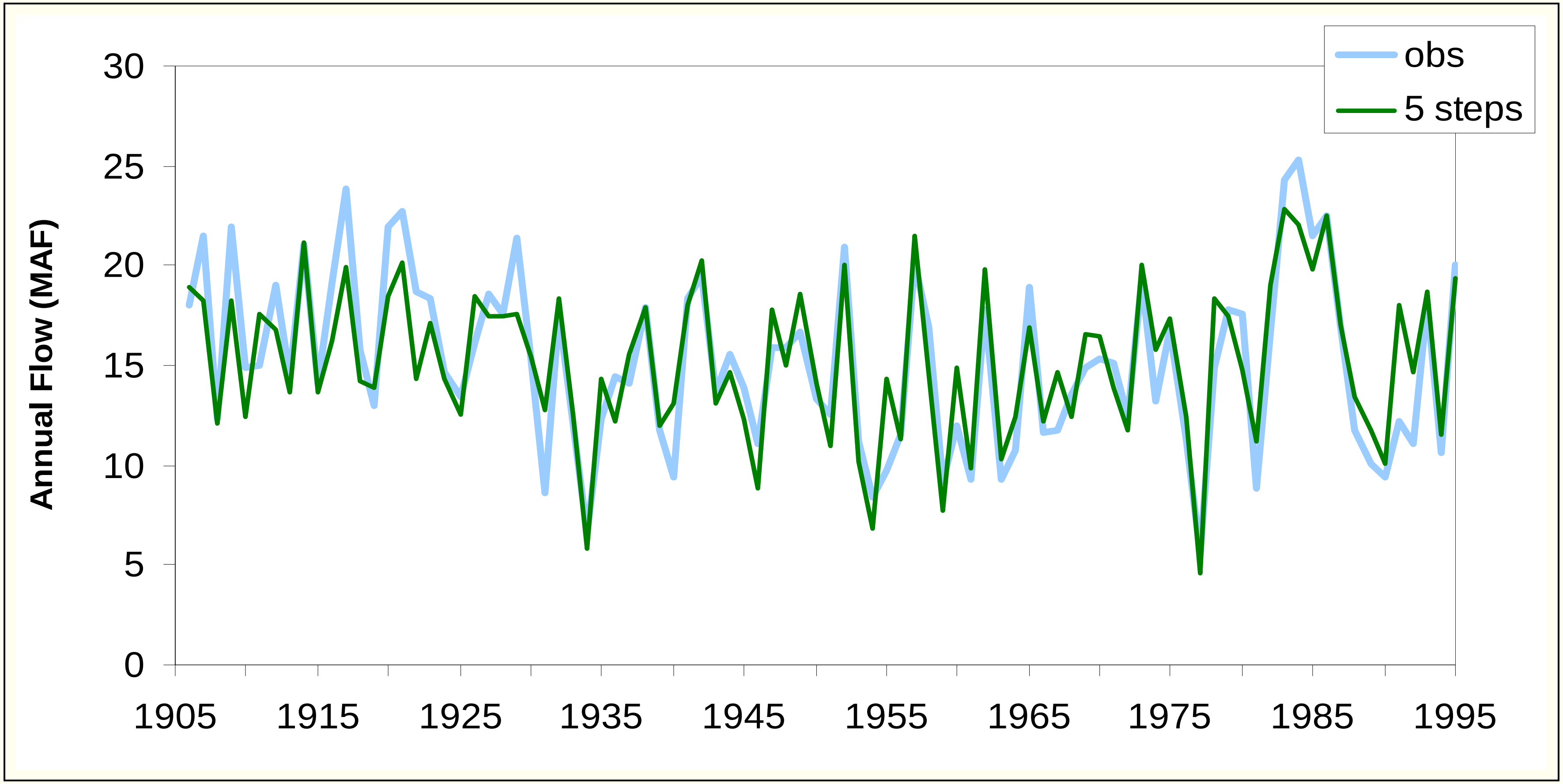
# Colorado at Lees Ferry - forward stepwise regression



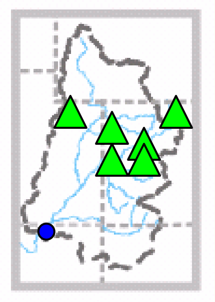
Variance Explained

**77%**

TRG + WIL + DJM + DOU + NPU



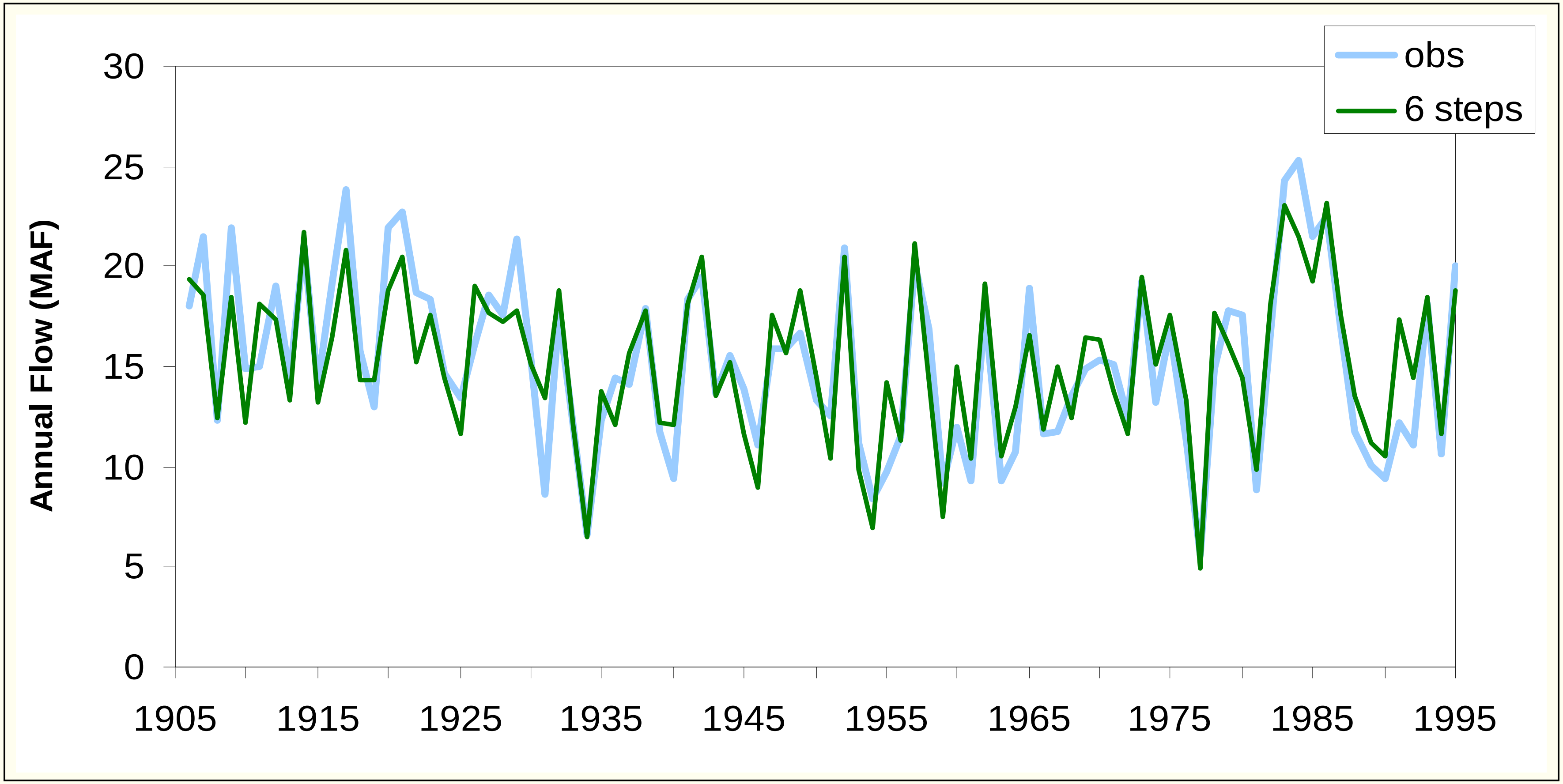
# Colorado at Lees Ferry - forward stepwise regression



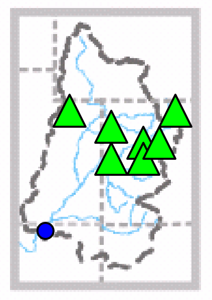
Variance Explained

TRG + WIL + DJM + DOU + NPU + RED

**79**%



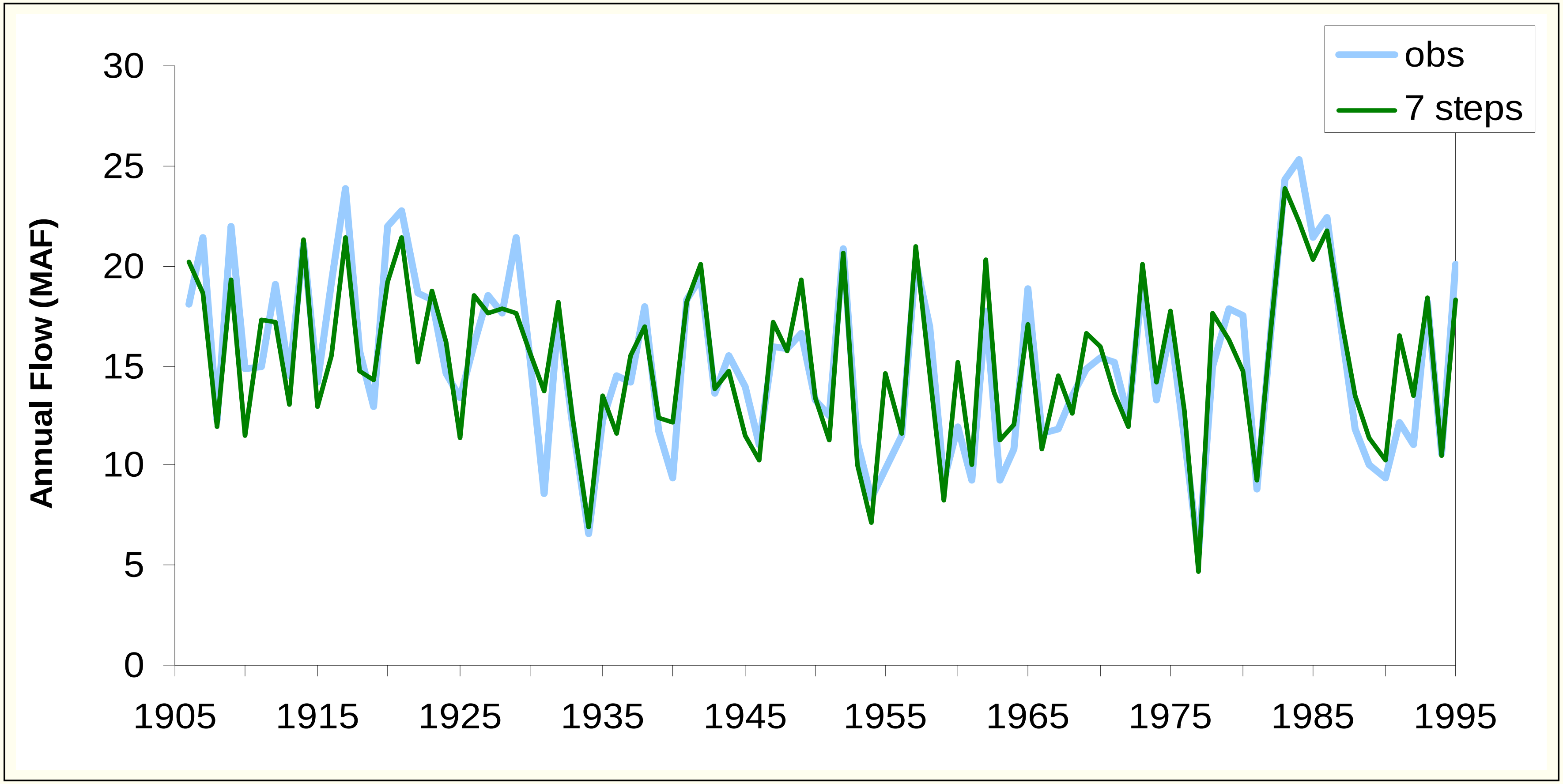
# Colorado at Lees Ferry - forward stepwise regression

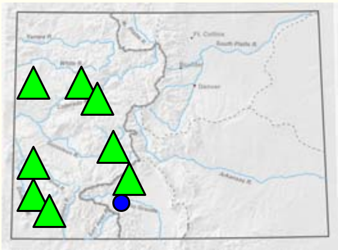


Variance Explained

**81**%

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



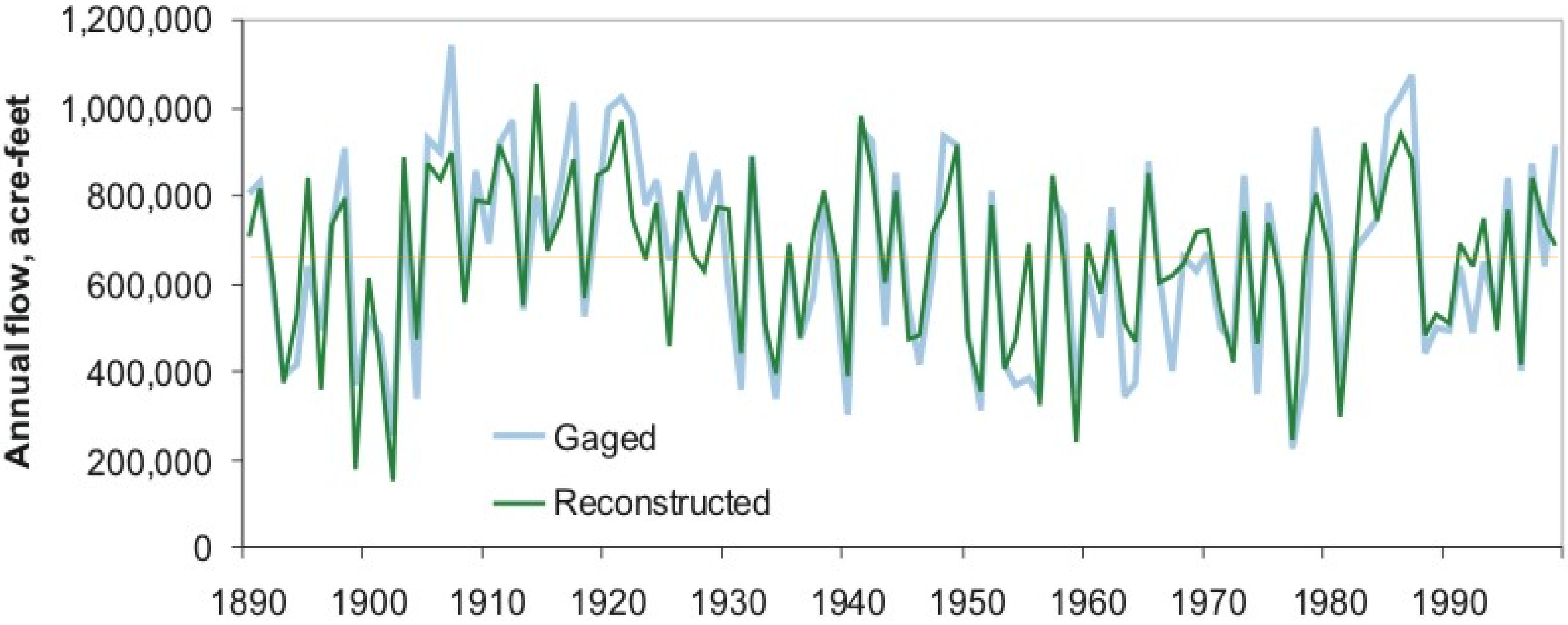


# Rio Grande near Del Norte, CO
## Forward stepwise regression

Variance Explained

**76**%

SLK + TRG + ARC + RED + CAT + DRY + MCP + DOU



# 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?

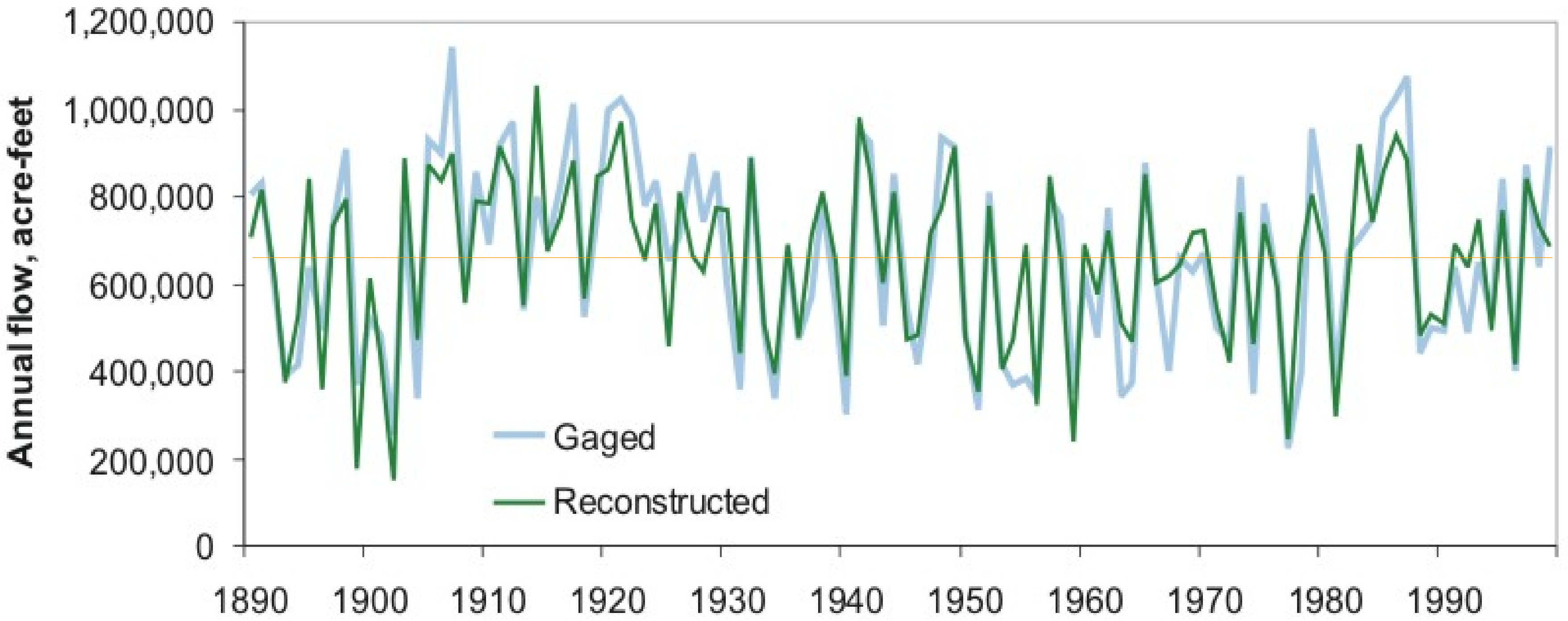
Validation statistics – based on withheld data or data generated in cross-validation process, compared to observed data

| | Calibration | Validation |
|---|---|---|
| **Gage** | **$R^2$** | **RE*** |
| **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 |
| Boulder Creek at Orodell | 0.65 | 0.60 |

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

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

# How does the reconstruction compare to the gage record?

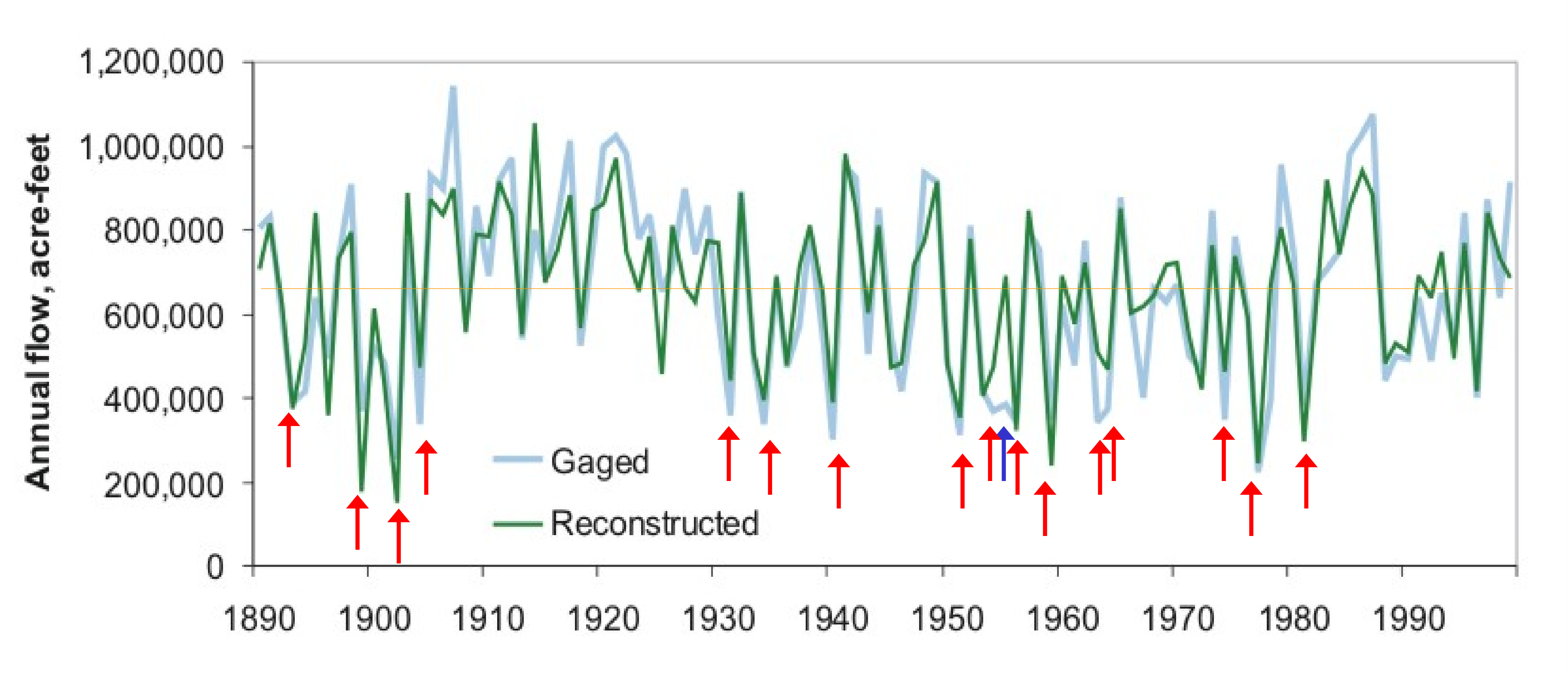



| | Observed | Recon'd |
|---|---|---|
| Mean | 656 KAF | 656 KAF |
| Std. Dev. | 190 KAF | 220 KAF |

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

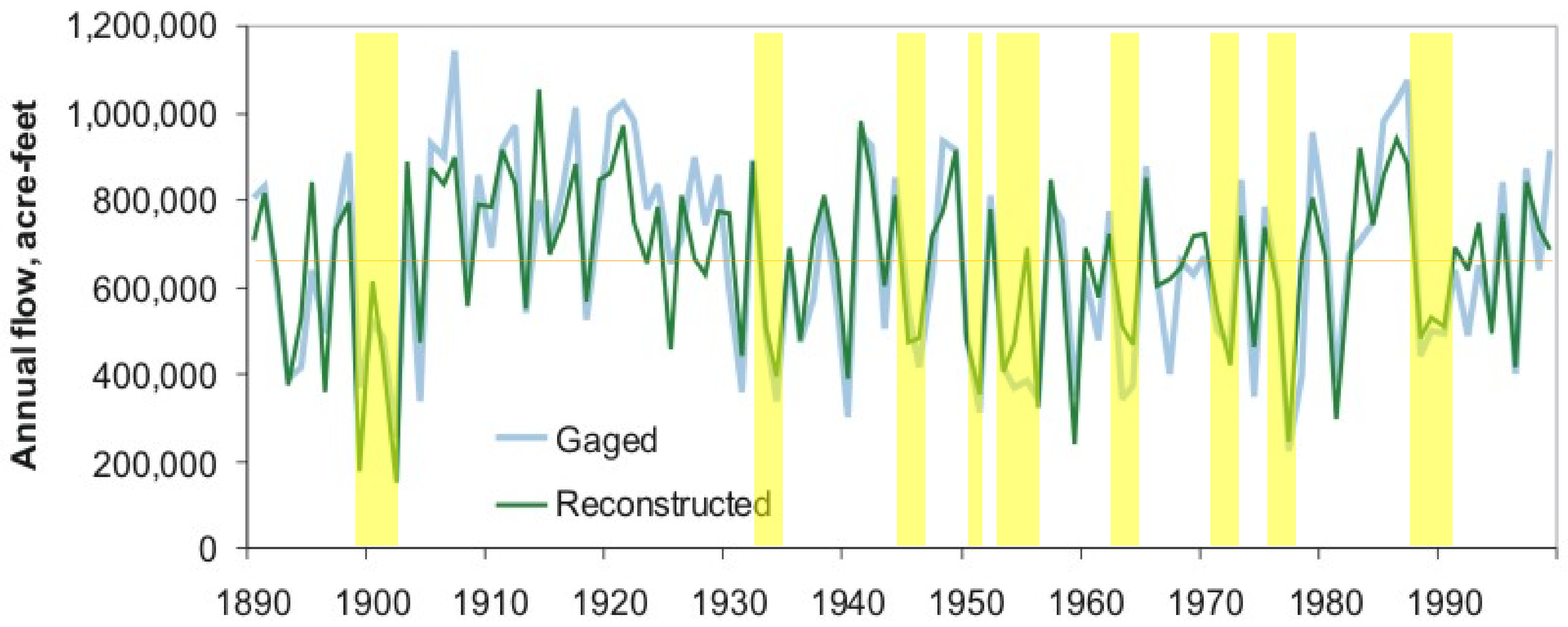
But the standard deviation of the reconstruction is lower than of the gage record – "side effect" of regression

# Subjective assessment of model quality



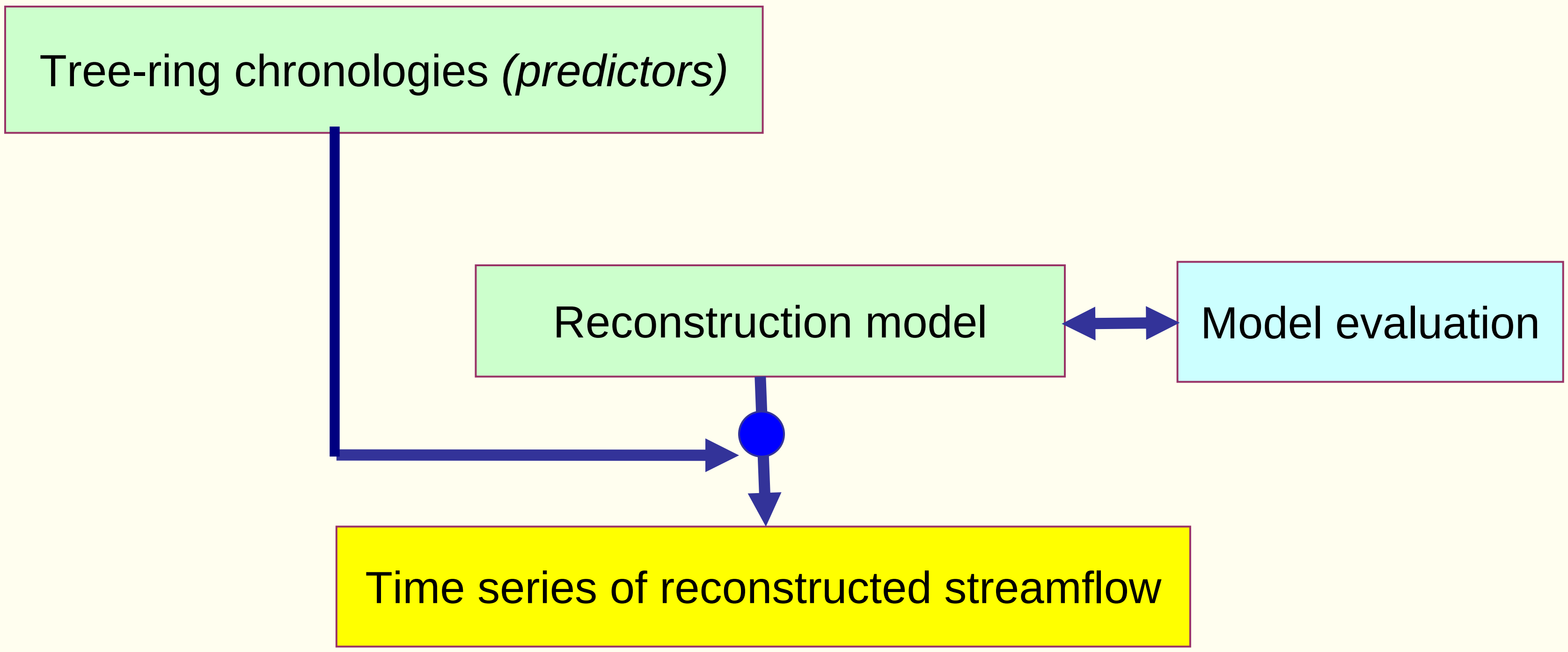

- Are severe drought years replicated well, or at least correctly classified as drought years?

# Subjective assessment of model quality



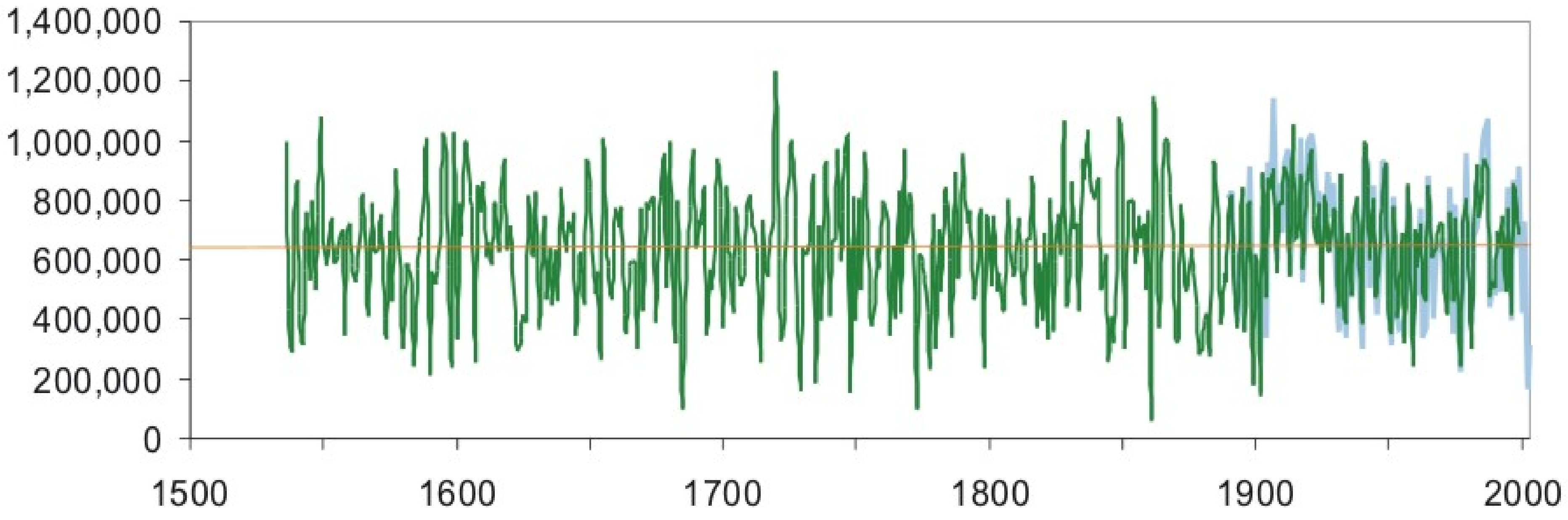

- Are the lengths and total deficits of multi-year droughts replicated reasonably well?

# 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 reconstruction of Rio Grande annual streamflow, 1536-1999



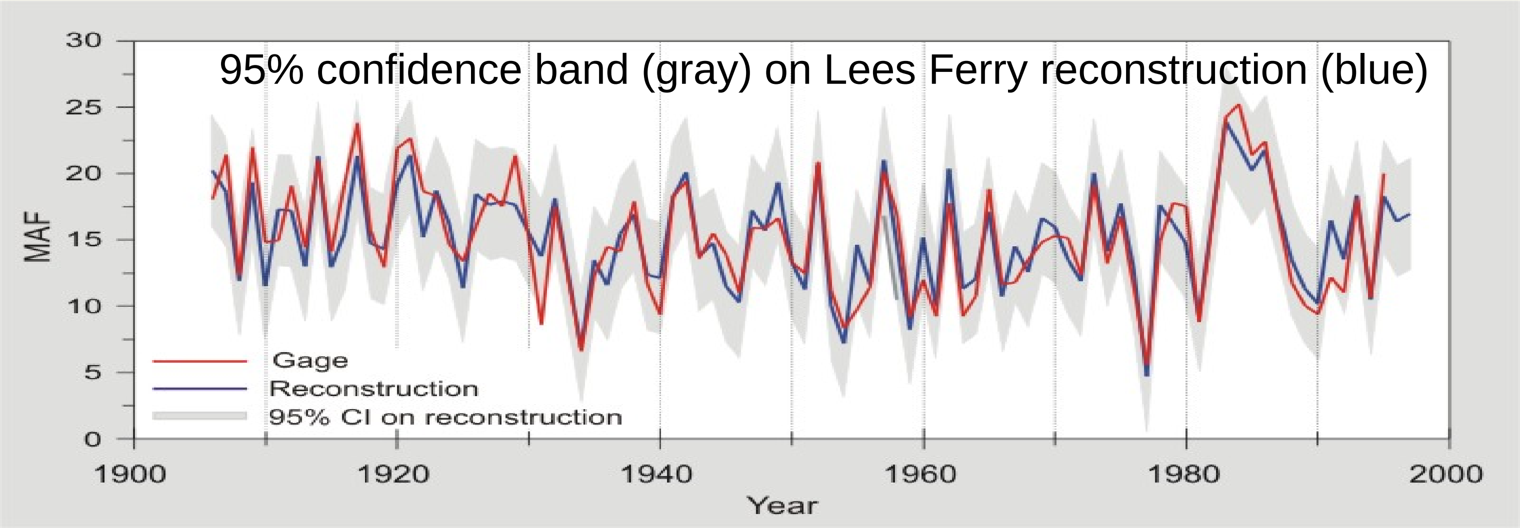

- Generally, greater year-to-year variability in reconstructed flows before 1900
- Also, more extreme high and low flows before 1900

# Uncertainty in the reconstructions – errors

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

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

- Then RMSE can be used to generate confidence intervals (50%, 80%, 95%, etc.) for display and probabilistic analyses



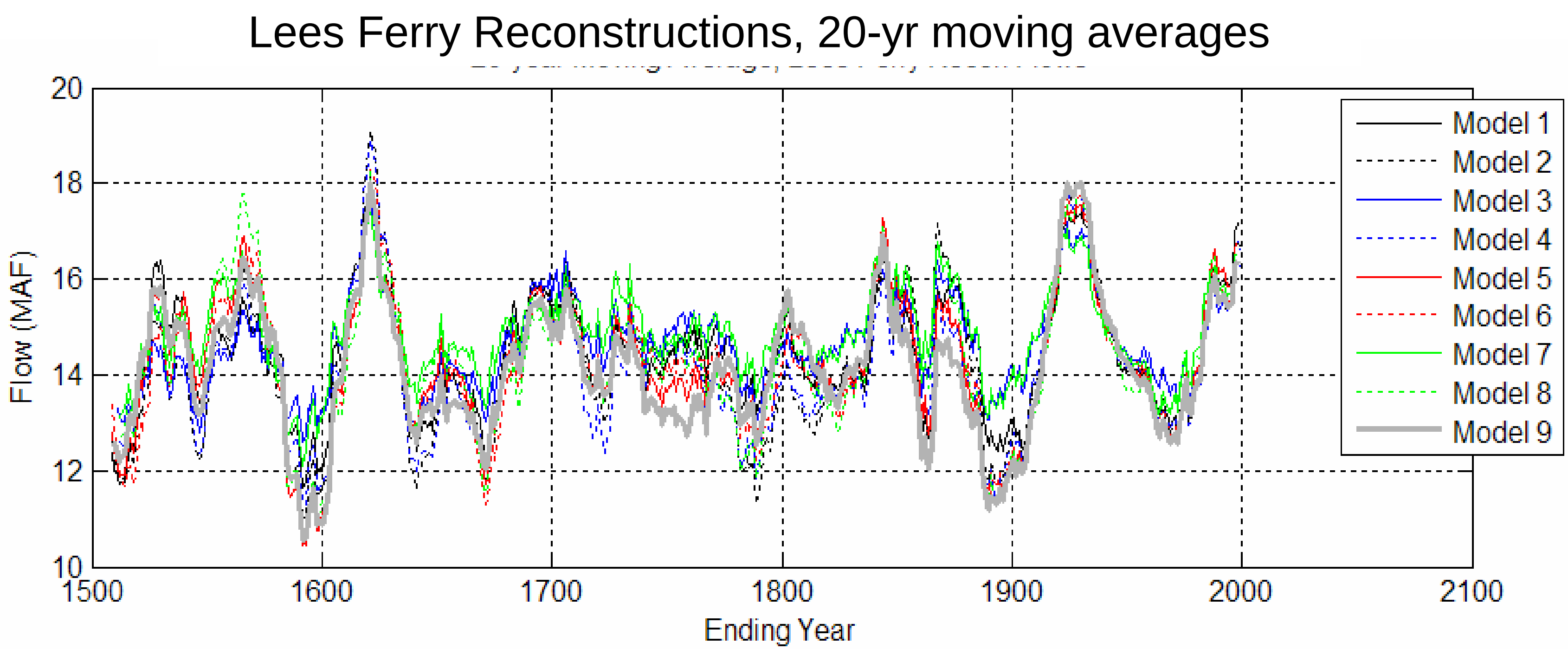
# Uncertainty in the reconstructions – model sensitivity

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

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

# Sensitivity to several choices made in modeling process

Lees Ferry reconstructions from 9 different models that vary according to data treatment, chronologies used, model choice



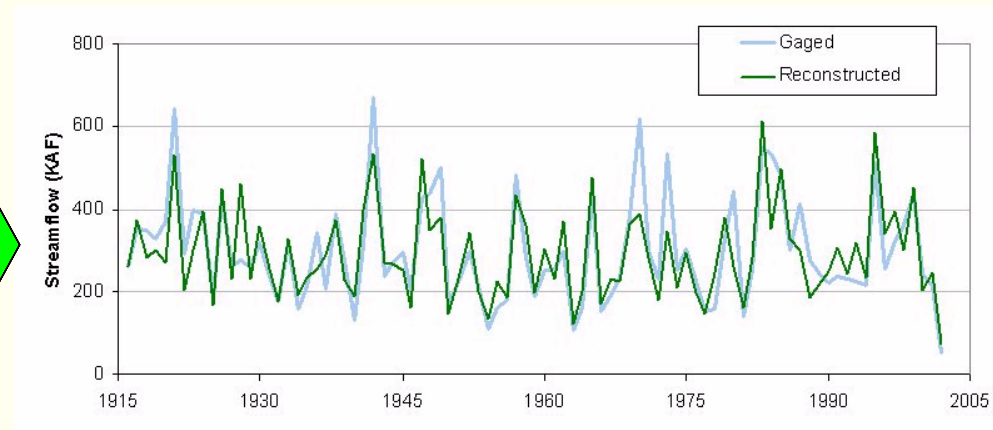

Analysis from D. Meko

# Uncertainty – final thoughts

- RMSE is probably a reasonable measure of the magnitude of overall uncertainty in the reconstructions, but it should be recognized that it does not reflect all sources of uncertainty
- There is no one reconstruction that is the “right” one--though some may be better than others (as indicated by RE, and length of calibration period)
- A reconstruction is a *best estimate* of past streamflows, and each annual point represents the central tendency of a range of plausible values, given the uncertainty

# Part 5:

## Streamflow and climate reconstructions for the Southwest



# One-stop resource for the western US

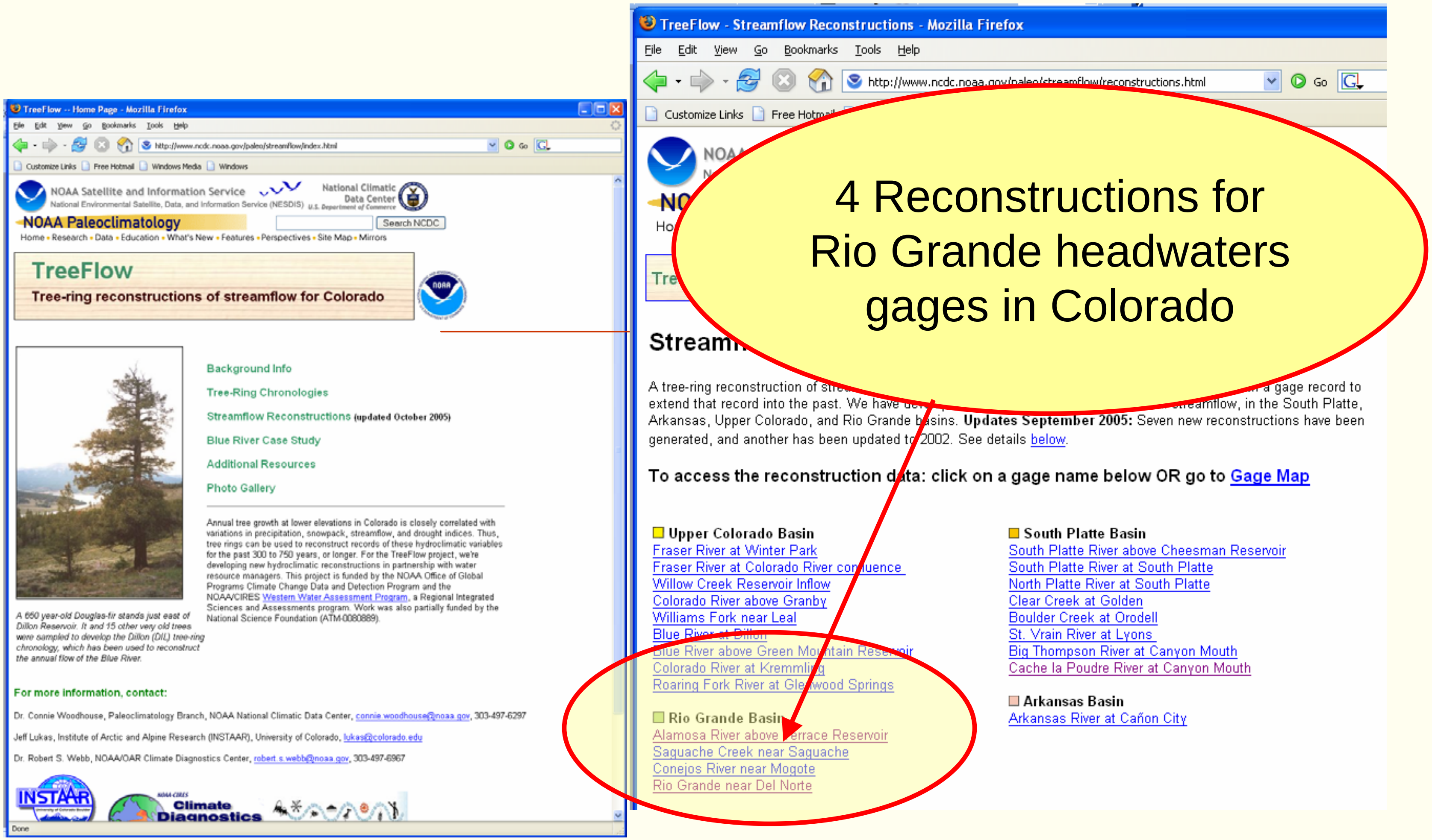

**Tree-Ring Reconstructions of Streamflow for Water Management in the West**

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

- Introduction to streamflow reconstructions
- Other workshops we've held, including presentations
- Applications of reconstructions to resource management
- Links to data: streamflow and precipitation reconstructions for the West
- Colorado River Streamflow: A Paleo Perspective
- *new Rio Grande TreeFlow page*

# Links to data: **Colorado TreeFlow (streamflow reconstructions)**

Developed by Woodhouse and Lukas, 2002-2005




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

# Links to data: **Woodhouse et al. 2006 - Upper Colorado River Basin streamflow**

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

WDC for Paleoclimatology

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## *Updated Streamflow Reconstructions for the Upper Colorado River Basin*

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

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

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

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

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

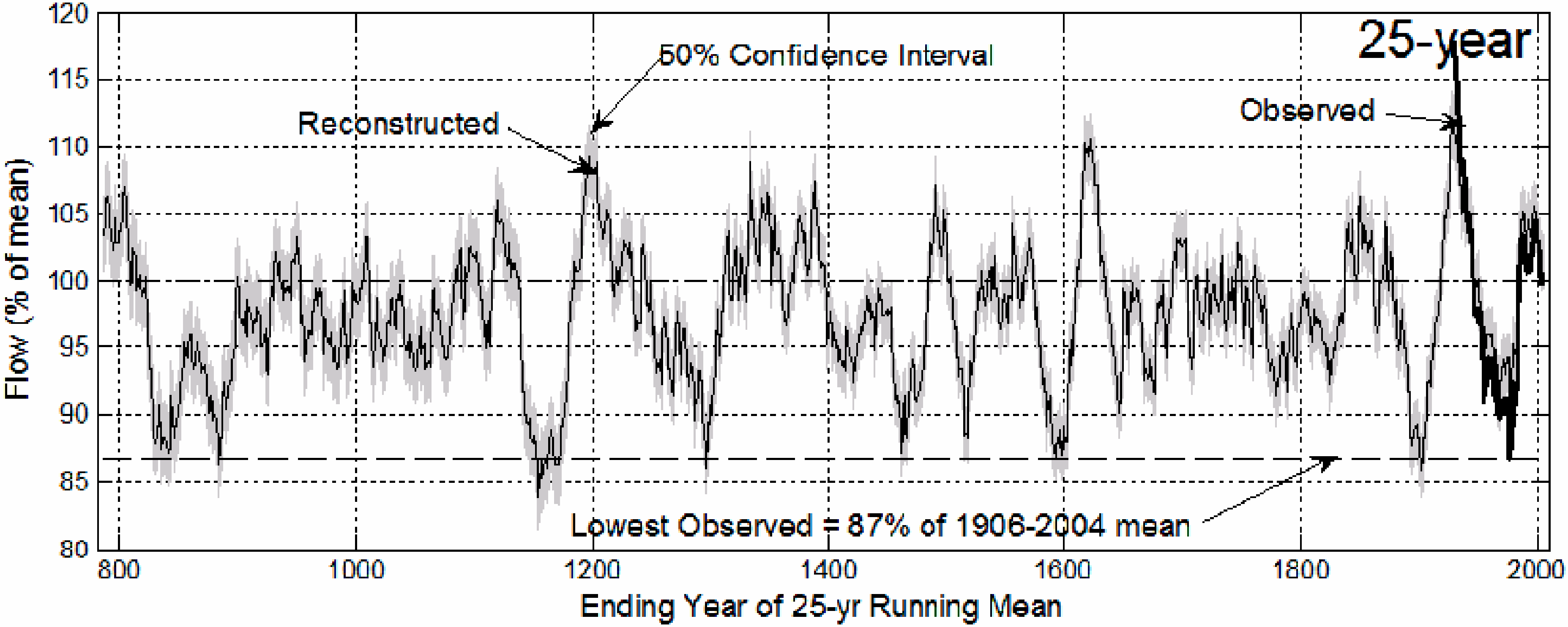
**Download data from the WDC Paleo archive:**
Upper Colorado Streamflow Reconstructions in Text or Microsoft Excel format.
Supplementary Data 1. Chronology data and metadata
Supplementary Data 2. Regression equations and coefficients, PC data
Supplementary Data 3. Loadings from PCA on chronologies

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

- 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**

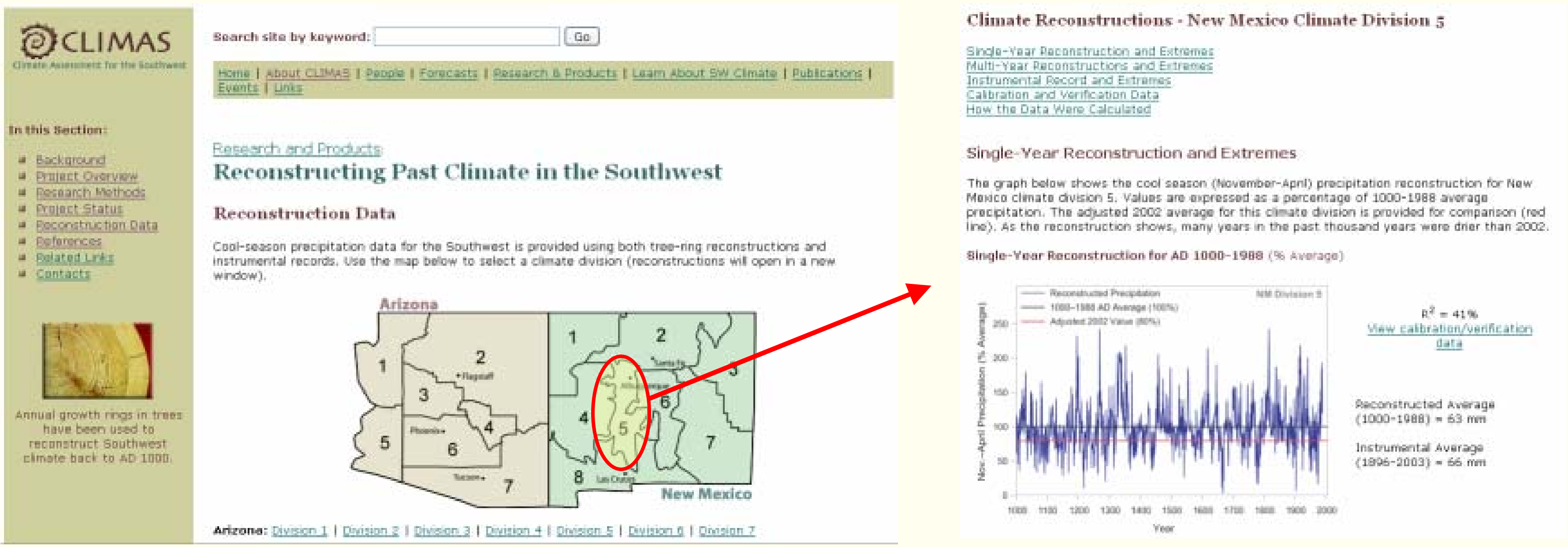
# Links to data: Reconstruction of Colorado River at Lees Ferry, AD 762 - 2005




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*

# Links to data: **Ni et al. 2002 – Southwest US (AZ/NM) November-April precipitation**




• 1000-year reconstructions of cool-season precipitation for each climate division in Arizona and New Mexico

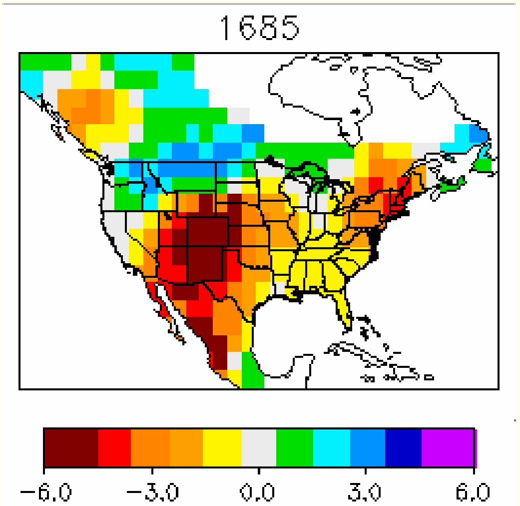
**http://www.ncdc.noaa.gov/paleo/pubs/woodhouse2006/woodhouse2006.html**

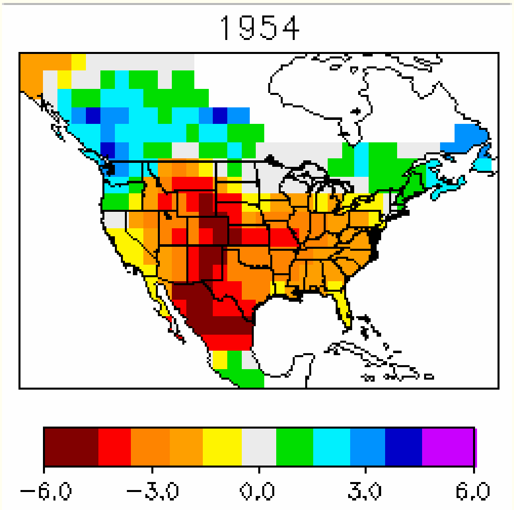
# Links to data: **North America gridded summer PDSI reconstructions – Cook et al.**

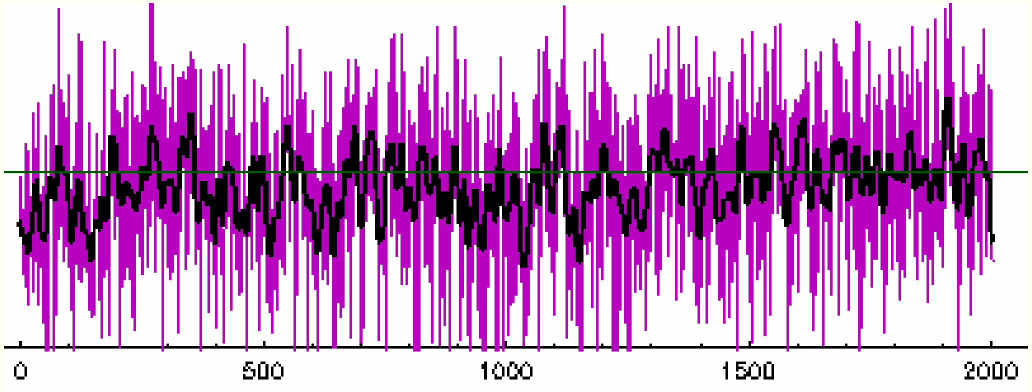
Reconstructions for each of 286 points on 2.5-degree grid

Products:

- Maps of PDSI over much of N. America for a given year
- PDSI time-series for each gridpoint (6 gridpoints in NM + so. CO)



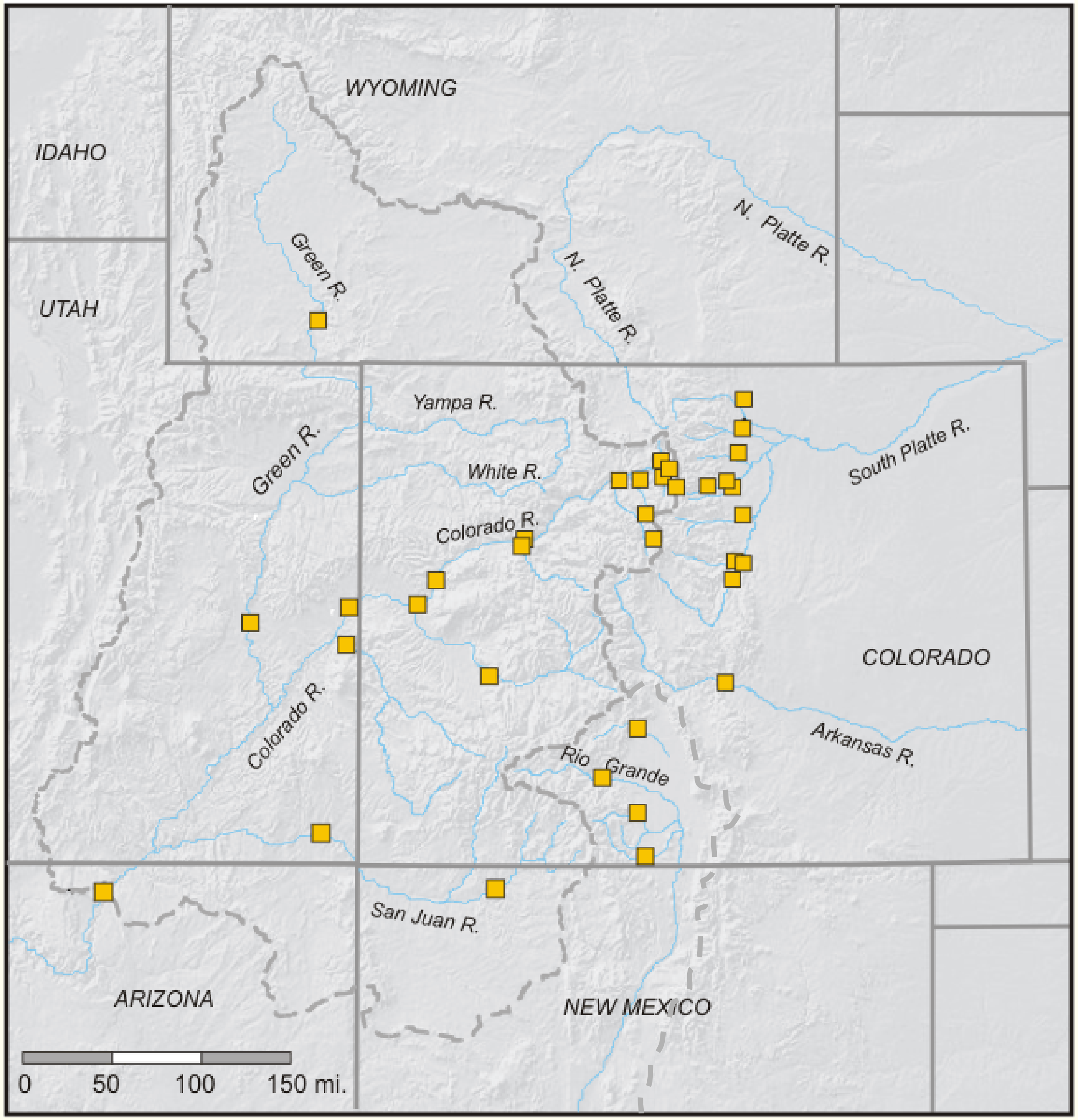
# Now over 30 streamflow reconstructions for the region

Forthcoming:

- Rio Grande and Canadian (this afternoon)

- Animas at Durango

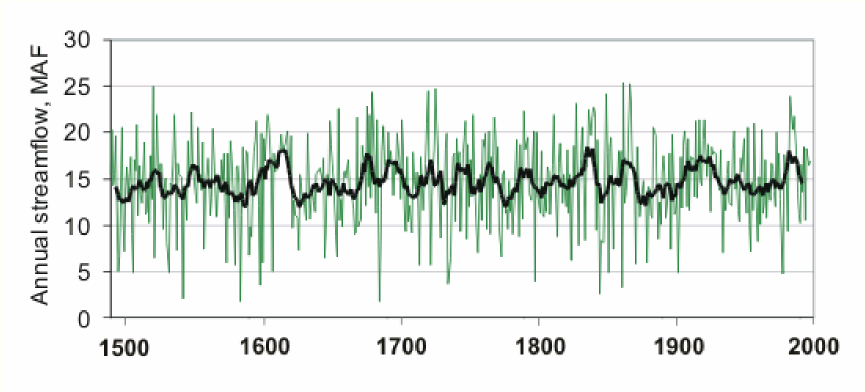
- Upper Green (U. Wyo.)




Gage reconstructions

# Part 6:

## How reconstructions of streamflow can be used in water management




Reconstruction data

?

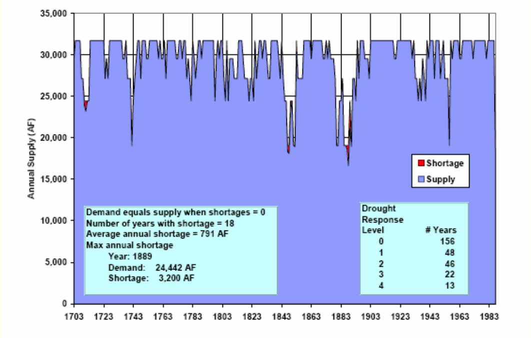



Figure 5. Demands & Supplies: 15% Reduced Flow Hydrology, Current Trends Scenario (demand = 31,700 AF/year).

Policy analysis

## How are streamflow reconstructions being used by water providers and other decision makers?

Applications can be considered in a 4-tiered context:

- Information is ***consulted***; looked up or received in a briefing (awareness)
- After it is consulted, it is ***considered*** in management (how to use?)
- Some form of the information is ***incorporated*** into operations (modeling challenges)
- Information is used in the ***communication of risk***, and ultimately may play a part in decision making (who makes the decisions and upon what are they based?)

From Ray (2004)

• Information is ***consulted***; looked up or received in a briefing

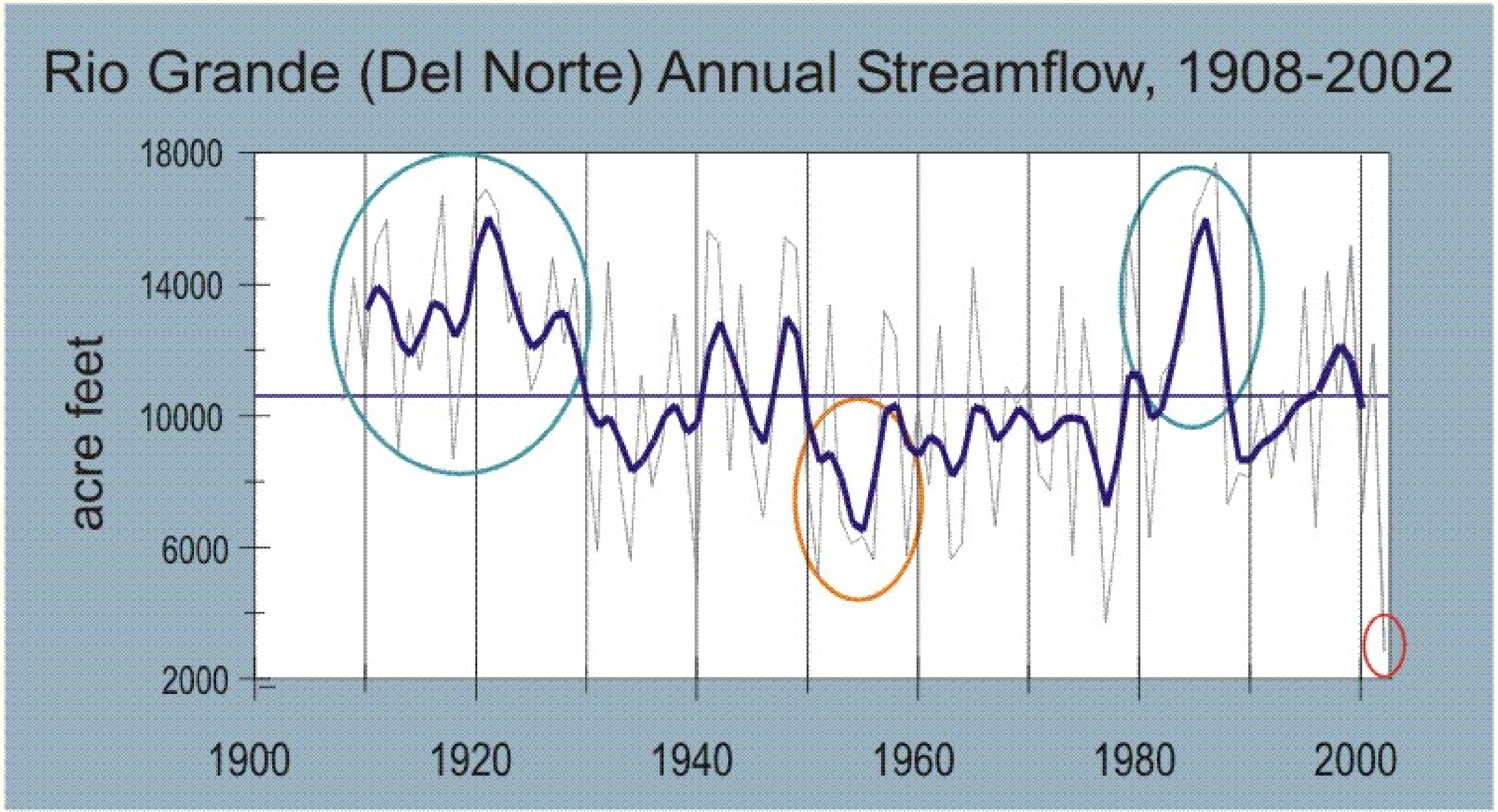
**Technical workshop for water resource professionals**

Boulder, Durango, Alamosa CO, Tucson, Albuquerque, Cheyenne, Salt Lake City

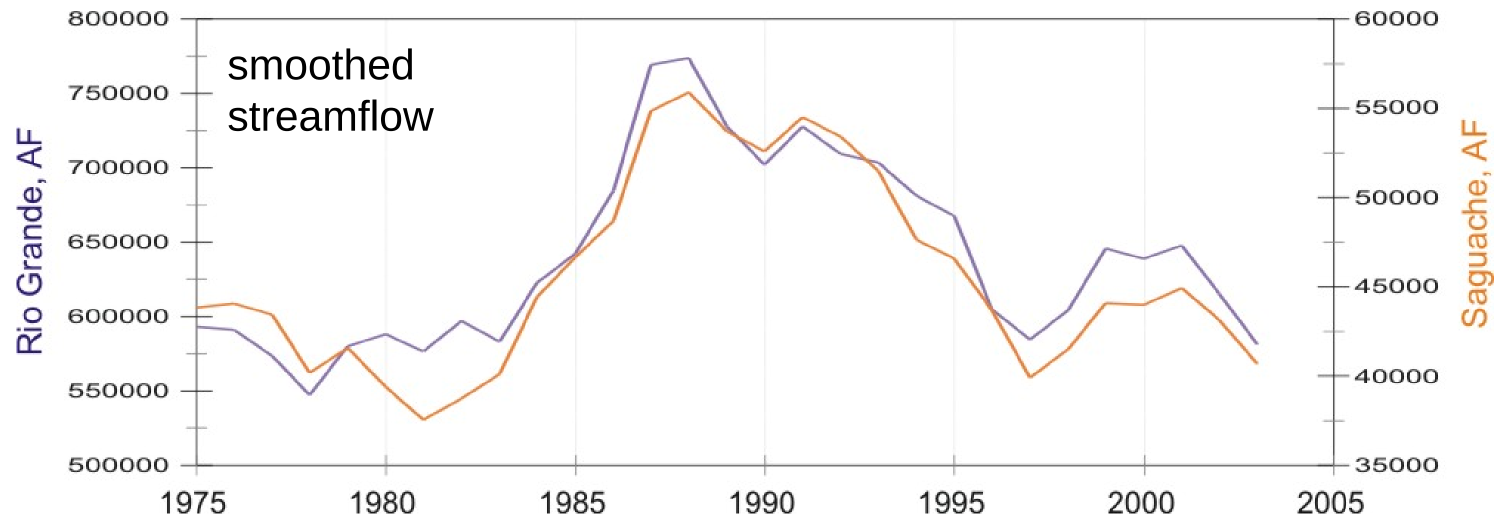
• After it is consulted, it is ***considered*** in management.

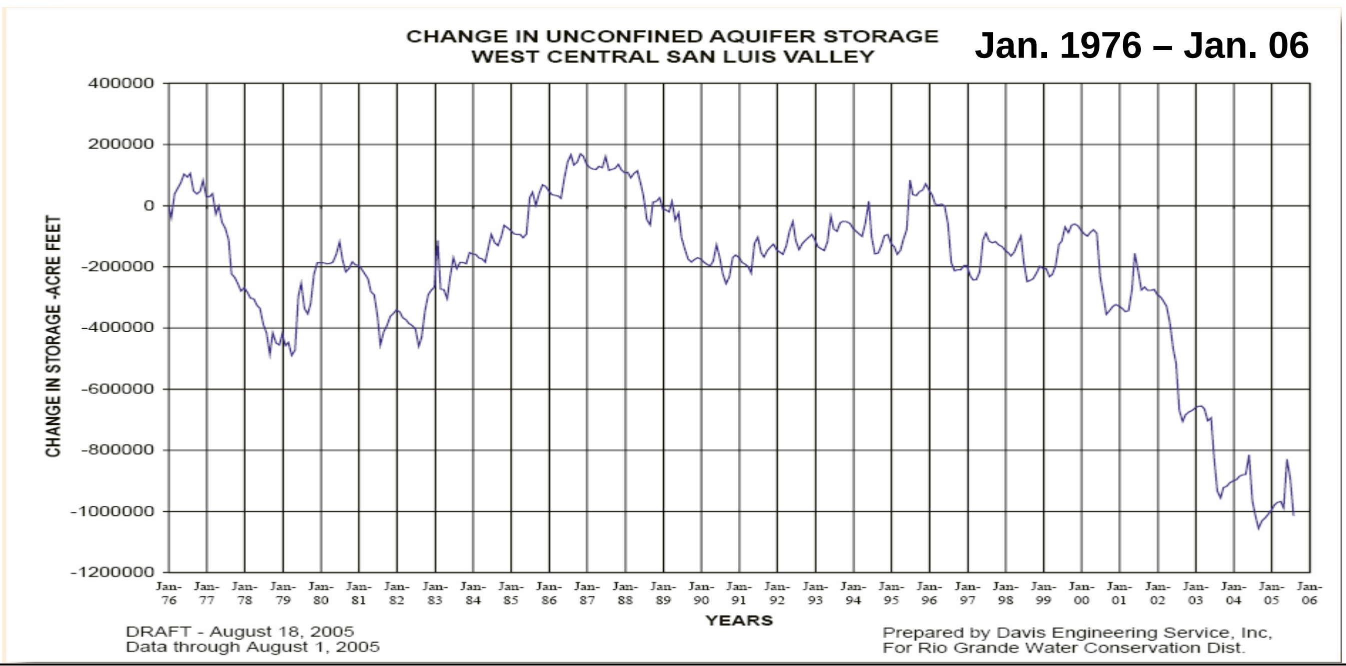
**Rio Grande Water Conservation District: Are the wet periods experienced in the 20th century record the "normal" state?**

What is the character of long-term, low-frequency variations in water supply that affect aquifer levels?

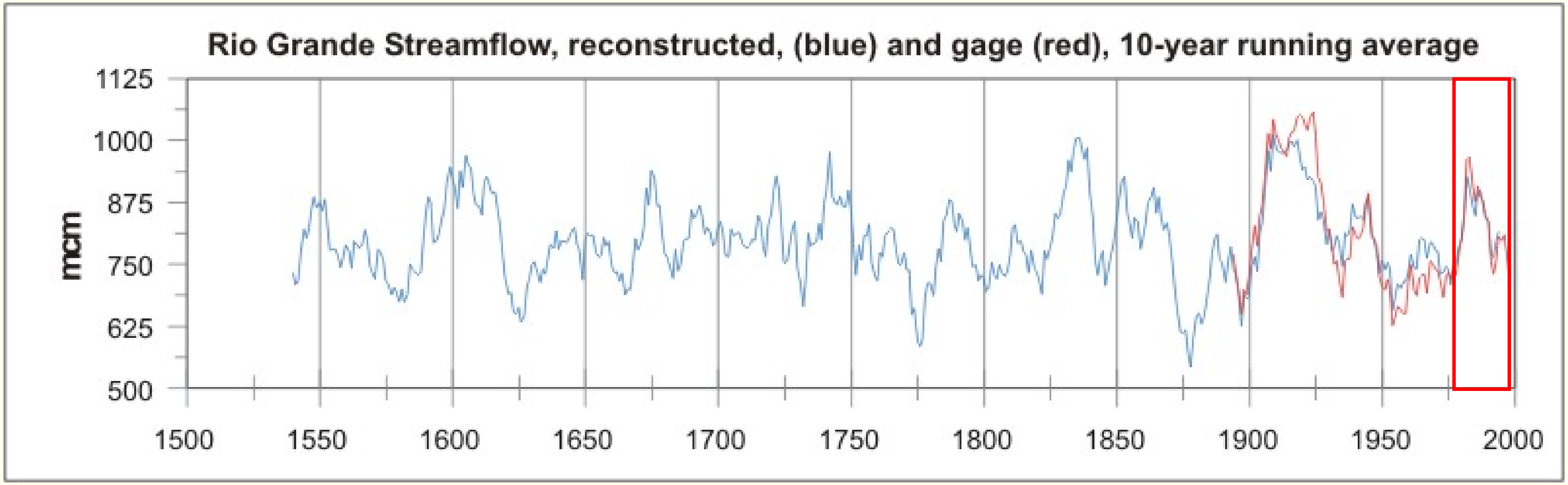



# Comparison of Annual Flow and Changes in Unconfined Aquifer Storage, 1976-2003



# Reconstructed Rio Grande Streamflow, 1536-1999




**Comparing the short period of instrumental record with the long-term record from the tree-ring data:**

**Implications for long-term groundwater management?**

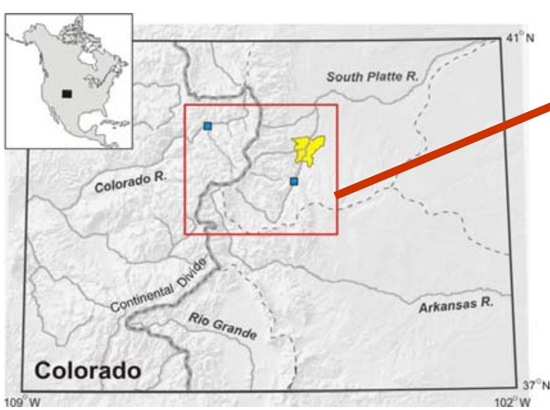
• Some form of the information is ***incorporated*** into operations.

# Denver Water

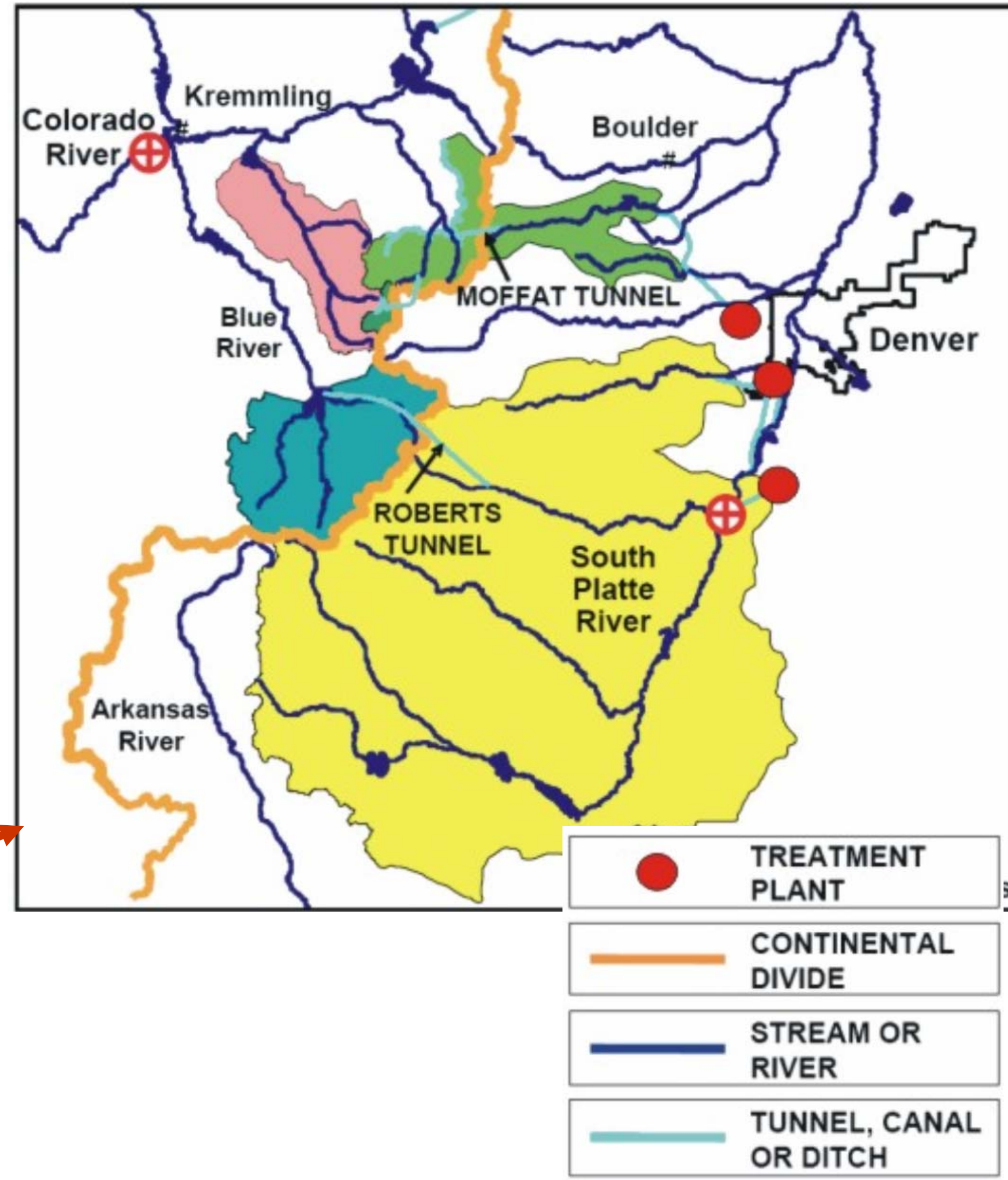
Denver Water uses a water system model called the Platte and Colorado Simulation Model (PACSM)

PACSM is an integrated system of computer programs that simulate streamflows, reservoir operations and water supply in the South Platte and Colorado River basins.

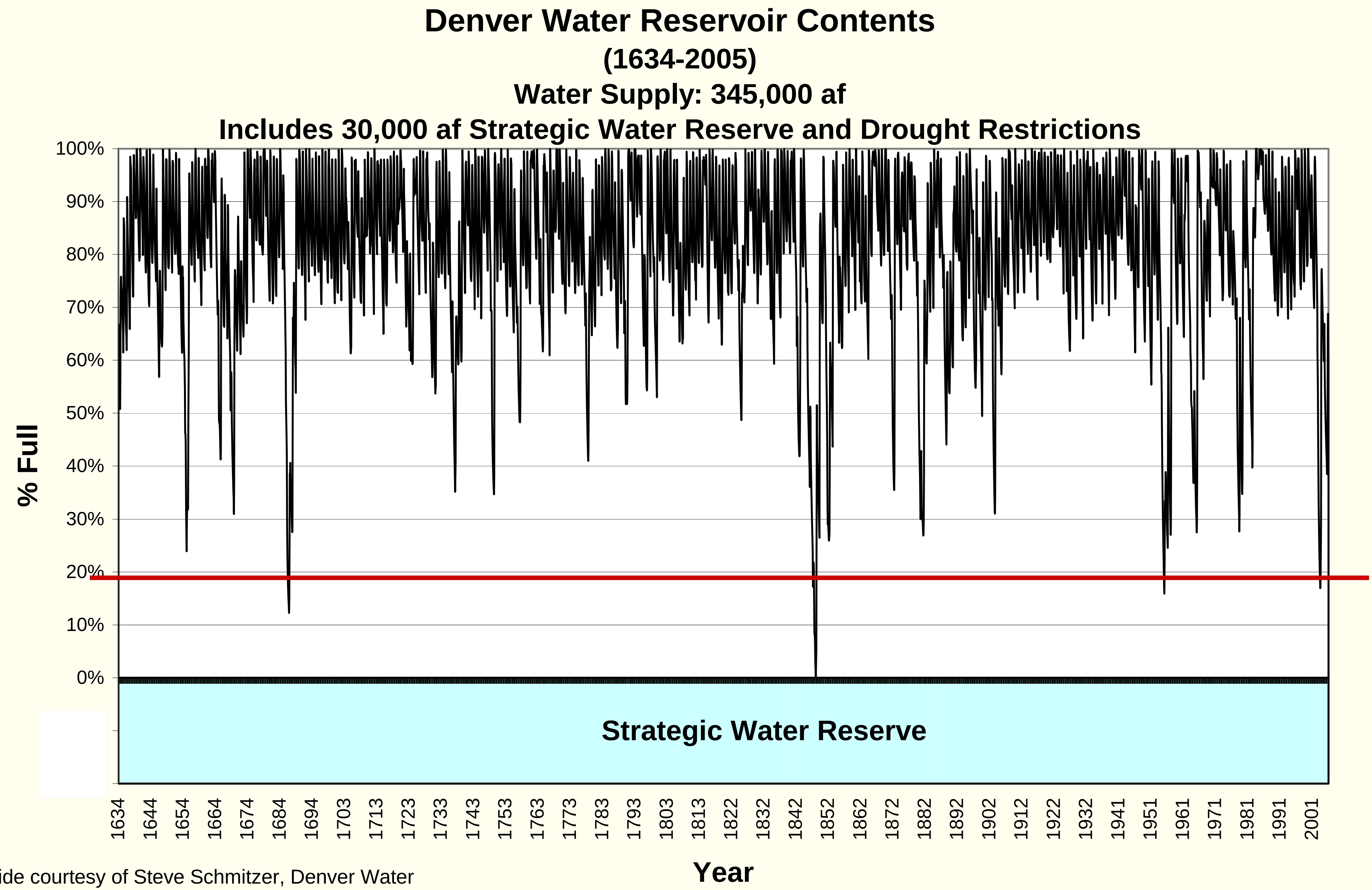
Hydrologic Period: 1947 – 1991
Daily data, 450 locations




**Denver Water Collection System**



# Tree-Ring Reconstructions Integrated into Denver Water System Model




Slide courtesy of Steve Schmitzer, Denver Water

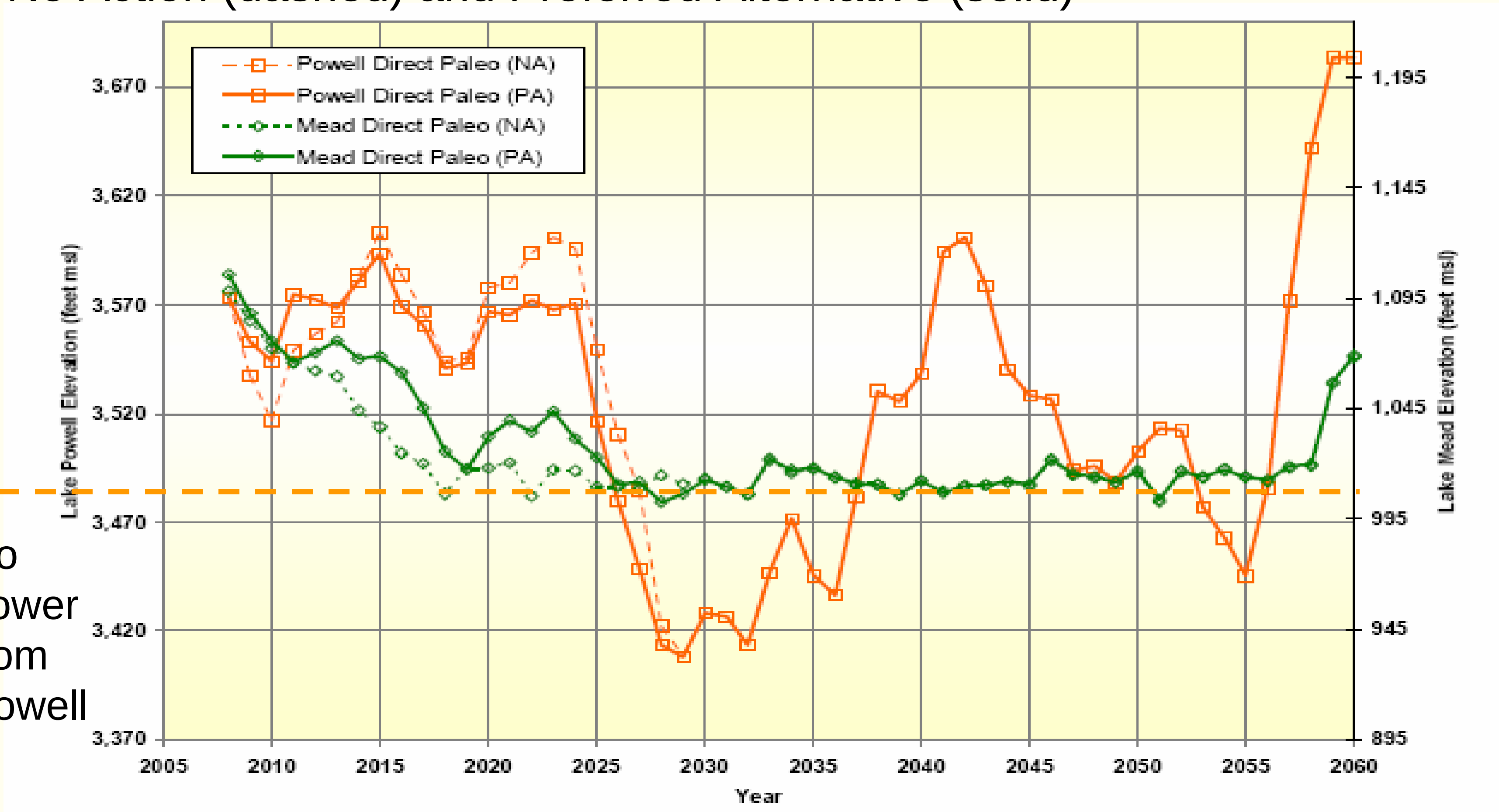
• Information is used in the ***communication of risk***, and ultimately may play a part in decision making

# Model output from Reclamation "Shortage" EIS, 2007

*Hydrology based on Meko et al. Lees Ferry reconstruction, yrs 1130-1182*

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

No Action (dashed) and Preferred Alternative (solid)




No power from Powell

US Bureau of Reclamation

• Information is used in the ***communication of risk***, and ultimately may play a part in decision making

## Worst case scenarios for drought planning:

### An example from the City of Chandler (AZ)

• What should be the basis for a worst case scenario for drought?

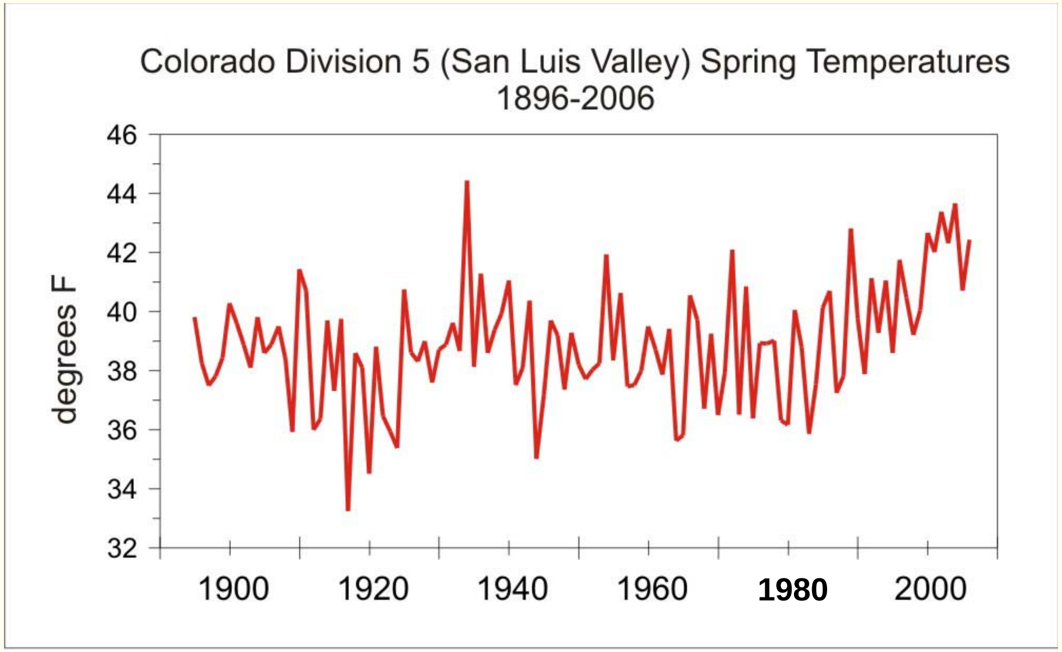
• One suggestion was to use the driest year on record, 2003, for 10 or 20 consecutive years.

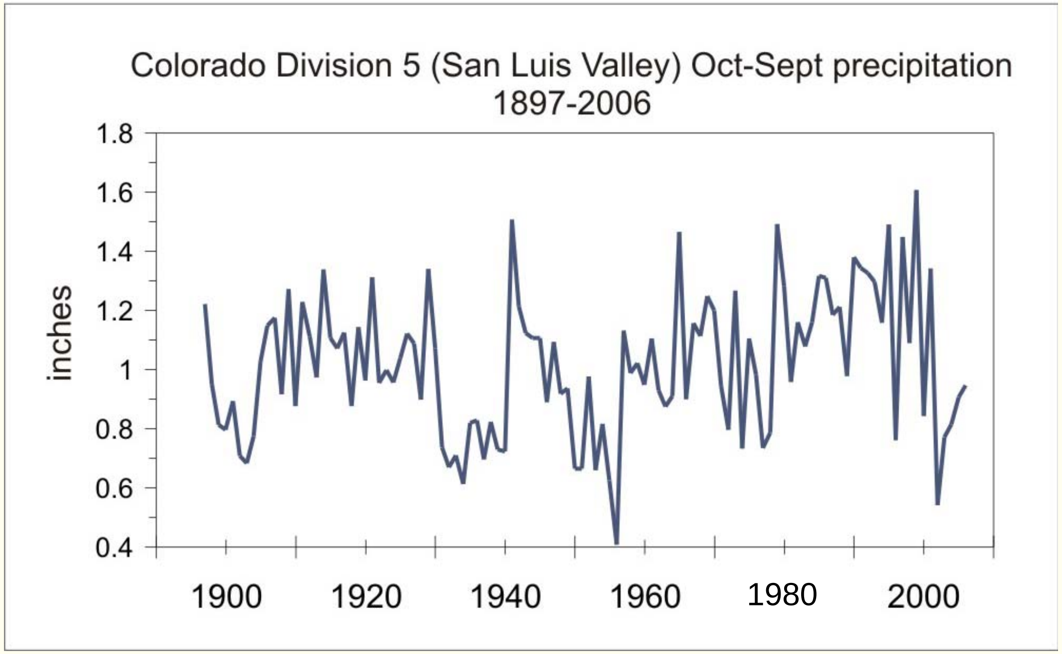
• After considering reconstructions of Colorado River basin streamflow, this seemed improbable

• Instead, a scenario of 10 dry years out of 25 years is being considered as being more realistic

• Although the City is not actually incorporating the streamflow reconstructions into a water supply model, they have found the tree-ring data valuable for decision making regarding drought.

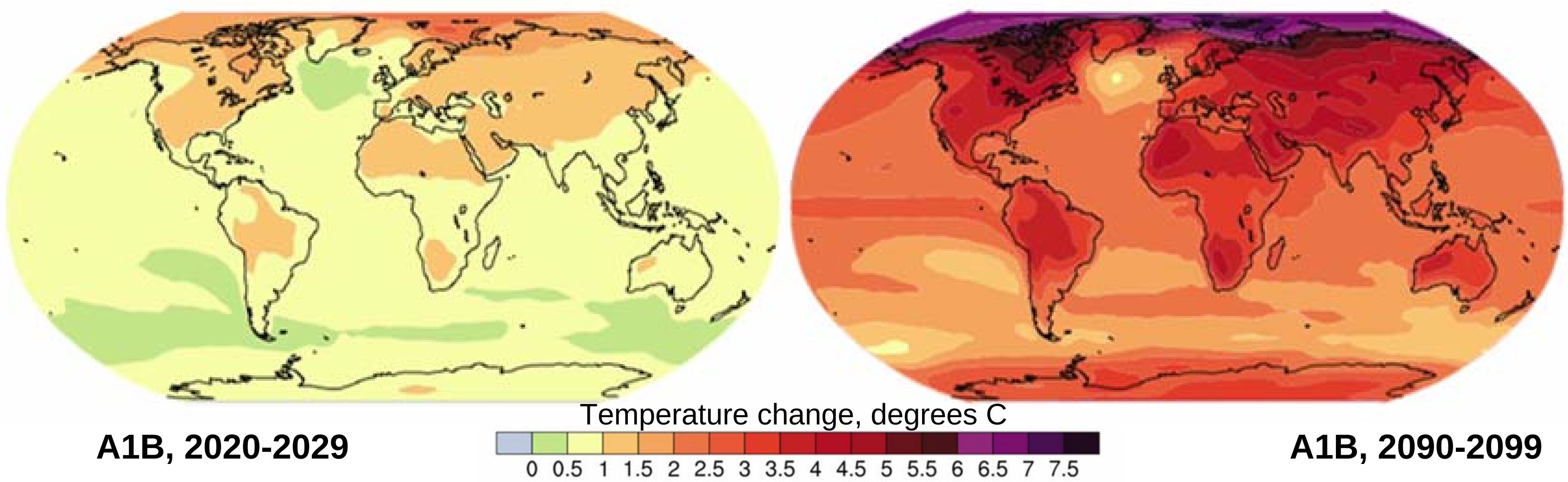
# How relevant is the past to current and future conditions?



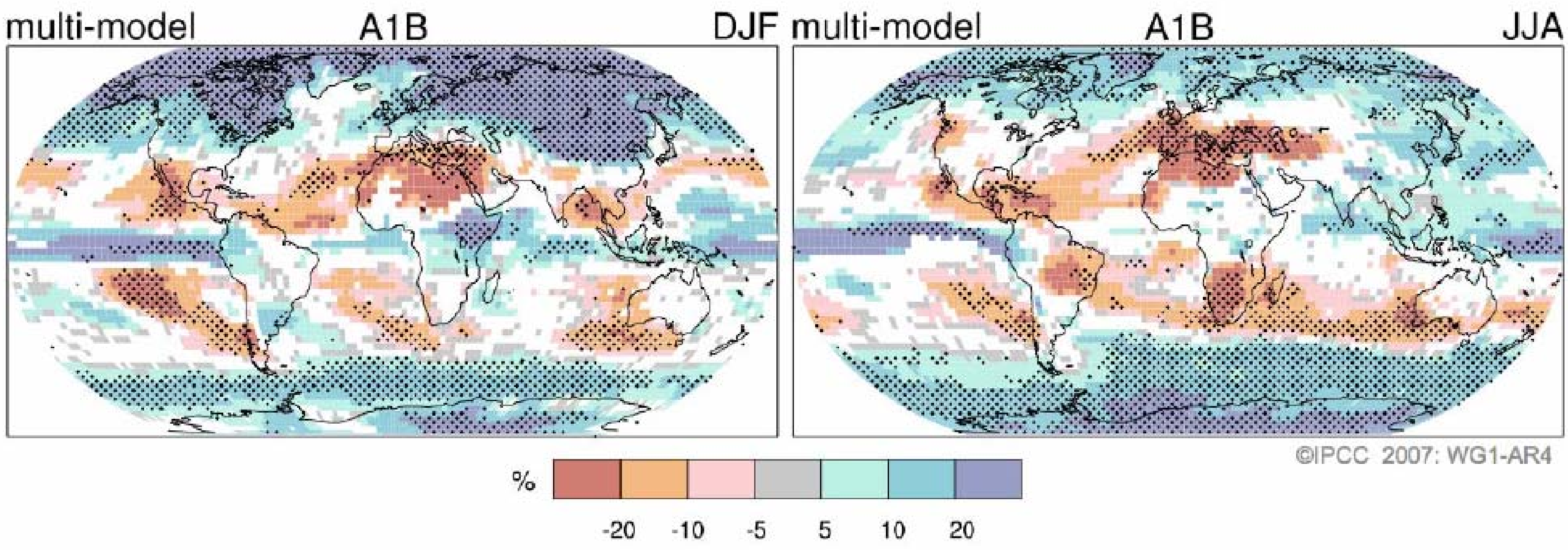

Spring temperatures in the Upper Rio Grande (Colorado) basin have risen, particularly since the 1970s, but clear trends in precipitation are not evident

# Projected Patterns of Temperature Changes



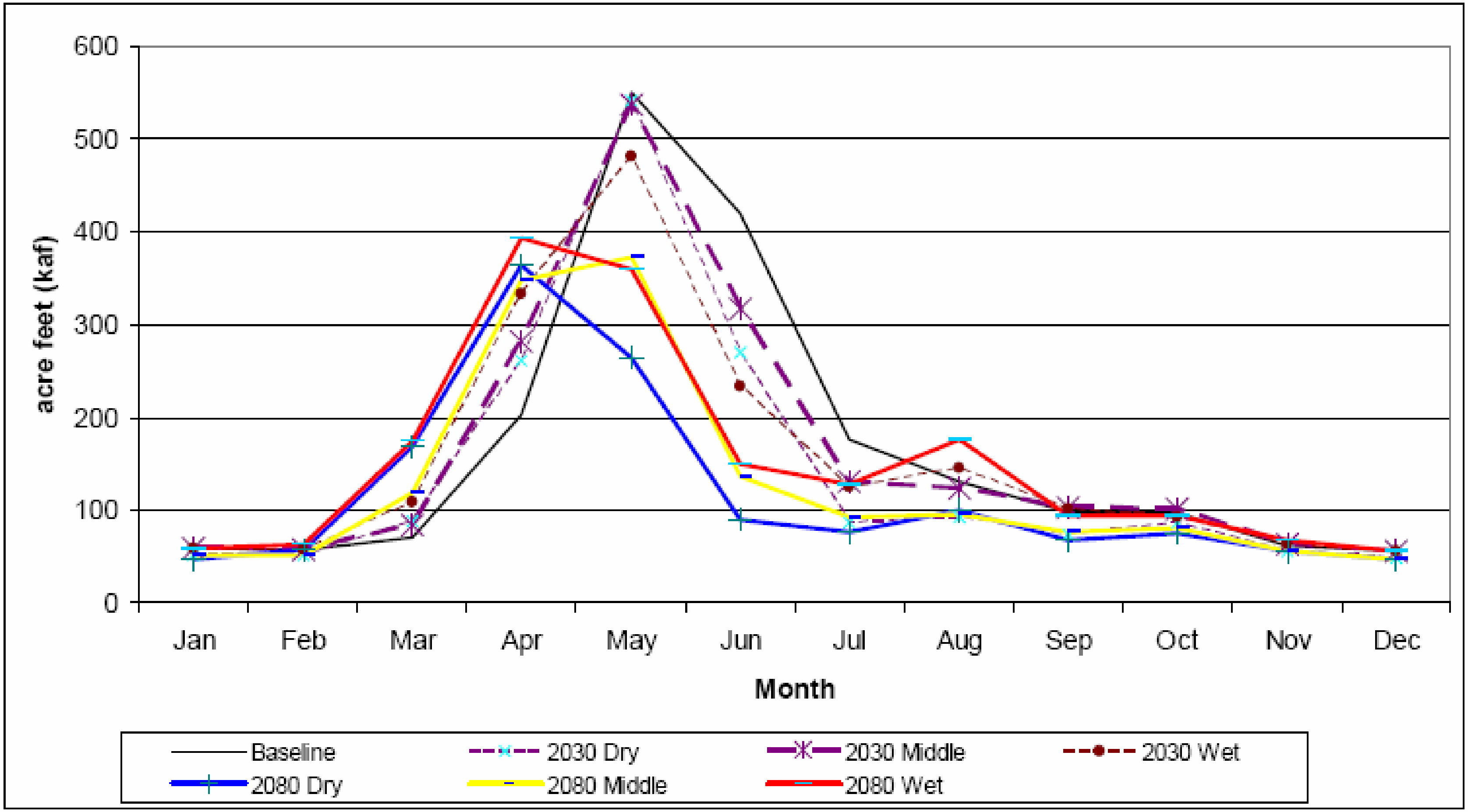

**A1B, 2020-2029** **A1B, 2090-2099**

# Projected Patterns of Precipitation Changes



# Down-scaled projections for the Rio Grande basin

Average monthly streamflow for Rio Grande and tributaries for 3 climate change models, the A1B scenario, for 2030 and 2080




From: Hurd and Coonrod (July 2007) *Climate Change Impacts on New Mexico's Water Resources, http://agecon.nmsu.edu/bhurd/hurdhome/index.htm*

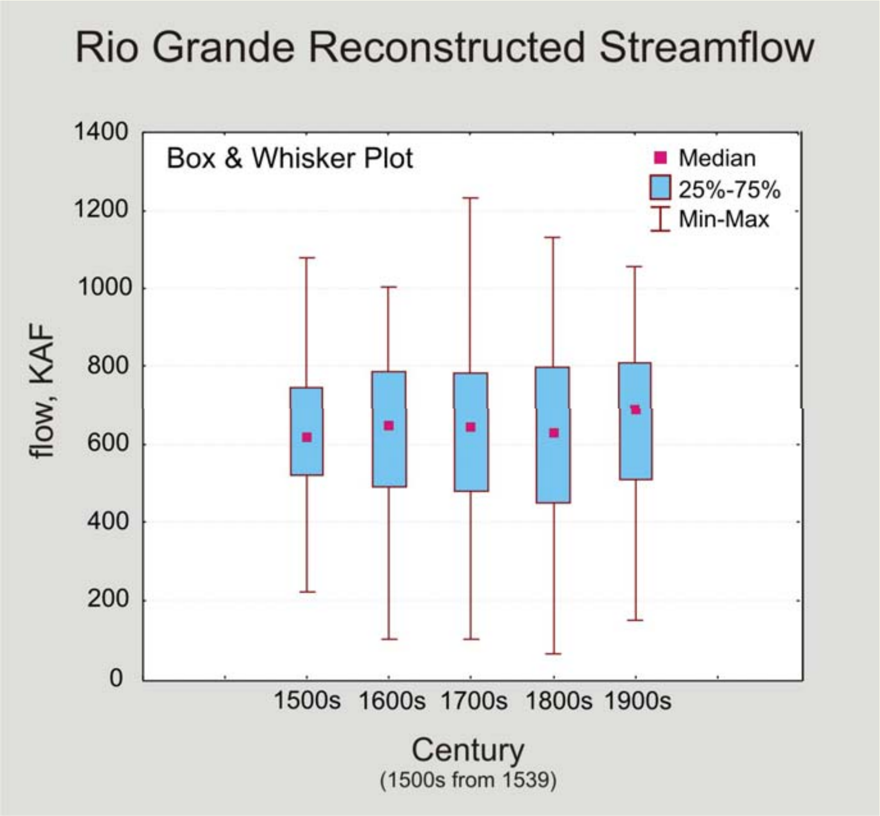
**With regard to future climate, two things are quite likely:**

- increasing temperatures
- decreasing water supply as a result of warmer temperatures and earlier snowmelt

Paleoclimatic records provide a broader range of variability, including droughts, than the instrumental records.

There is no reason to think we will experience a smaller range of natural variability in the future.

Consequently paleohydrologic records, in combination with temperature projections, may be useful for assessing future climate scenarios.

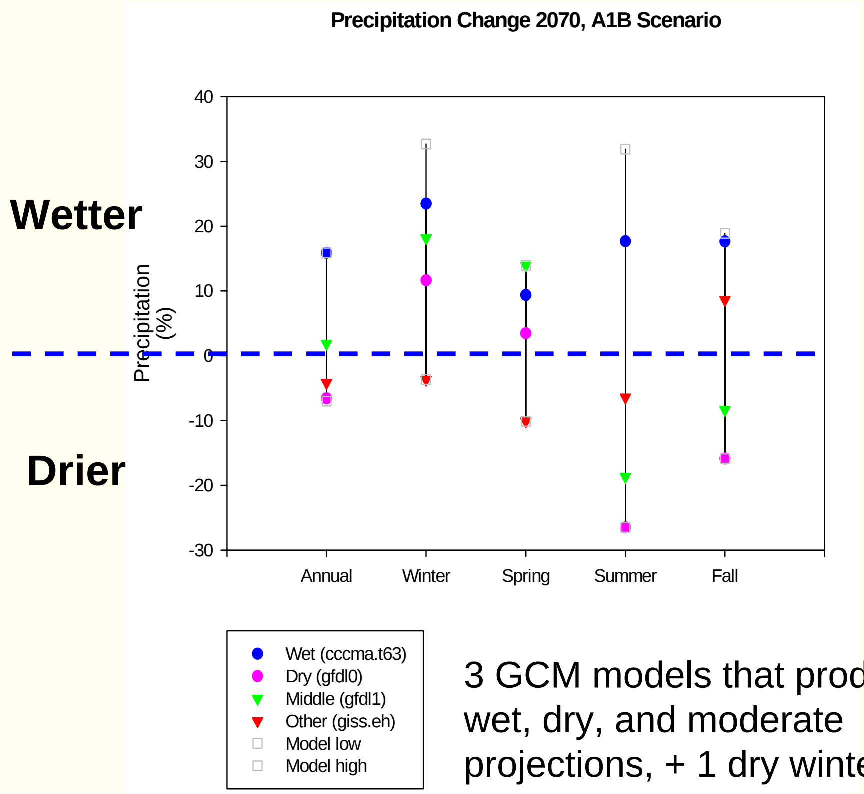


# Approach: Stratus and AMEC Consultants for the City of Boulder, CO

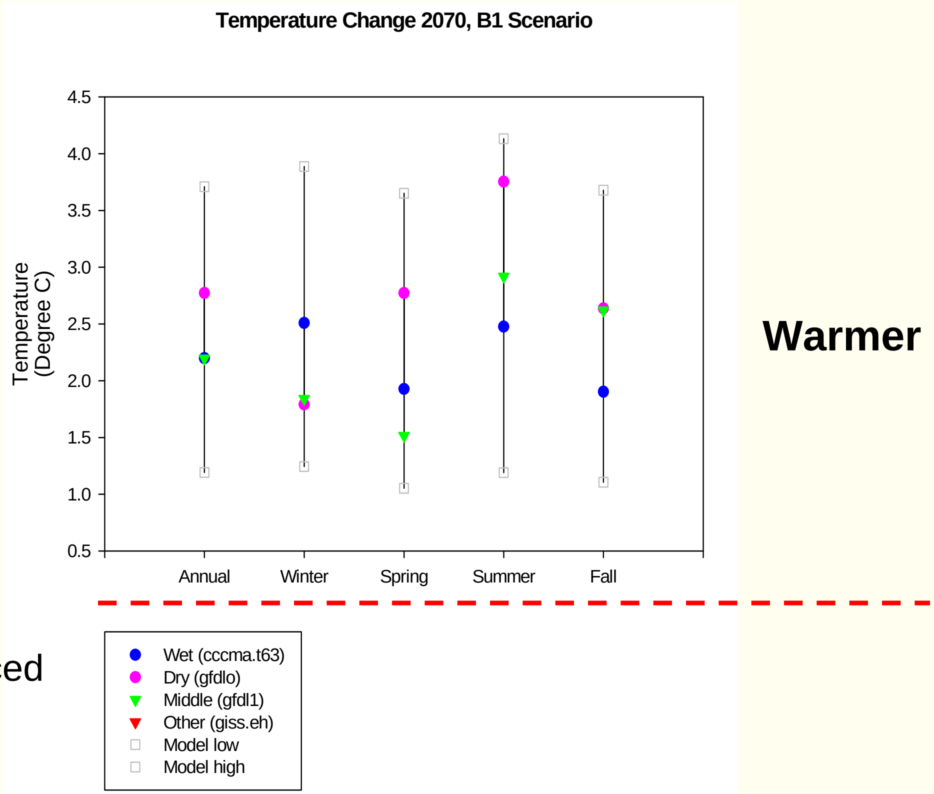
- Looked at A1, A1b, and B1 scenarios for two 20-yr times slices centered on 2030 and 2070

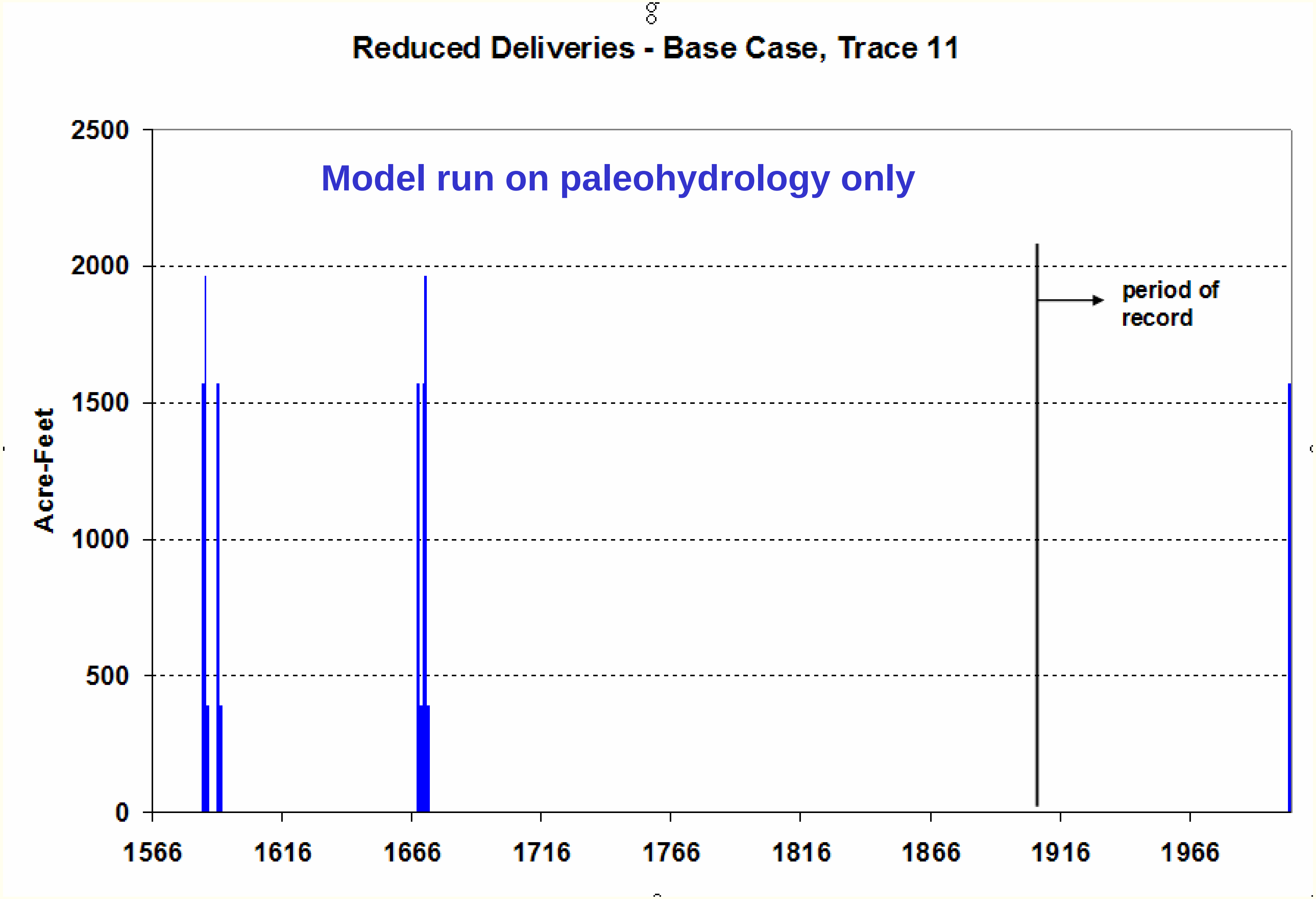
- Used an analogue method to develop monthly temperature and precipitation inputs for a hydrologic model, with sequences based on the 437-yr reconstruction, and with climate change from GCMs imposed.

- Results were projected impacts on City of Boulder supply and demand.




3 GCM models that produced wet, dry, and moderate projections, + 1 dry winter



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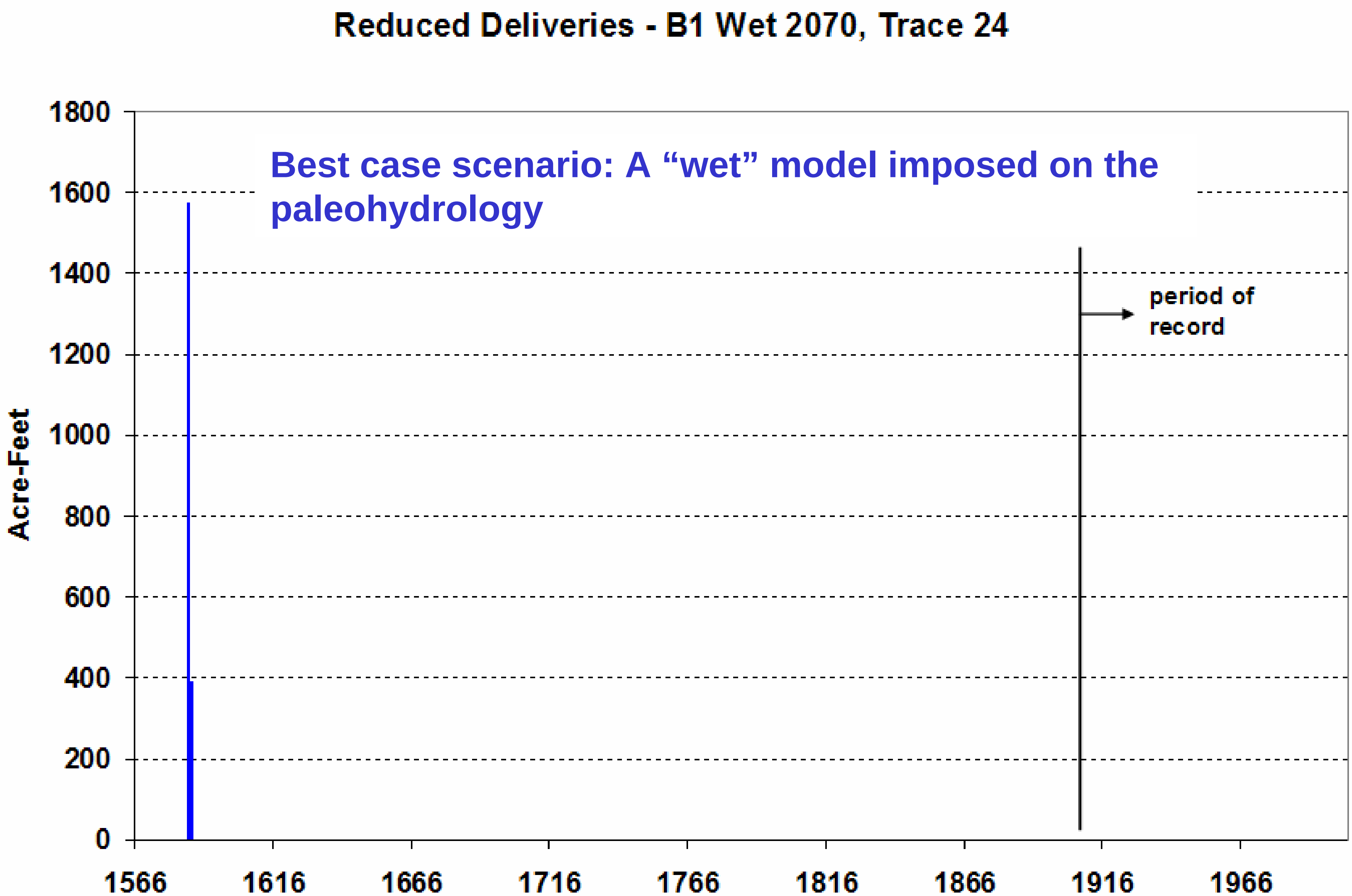
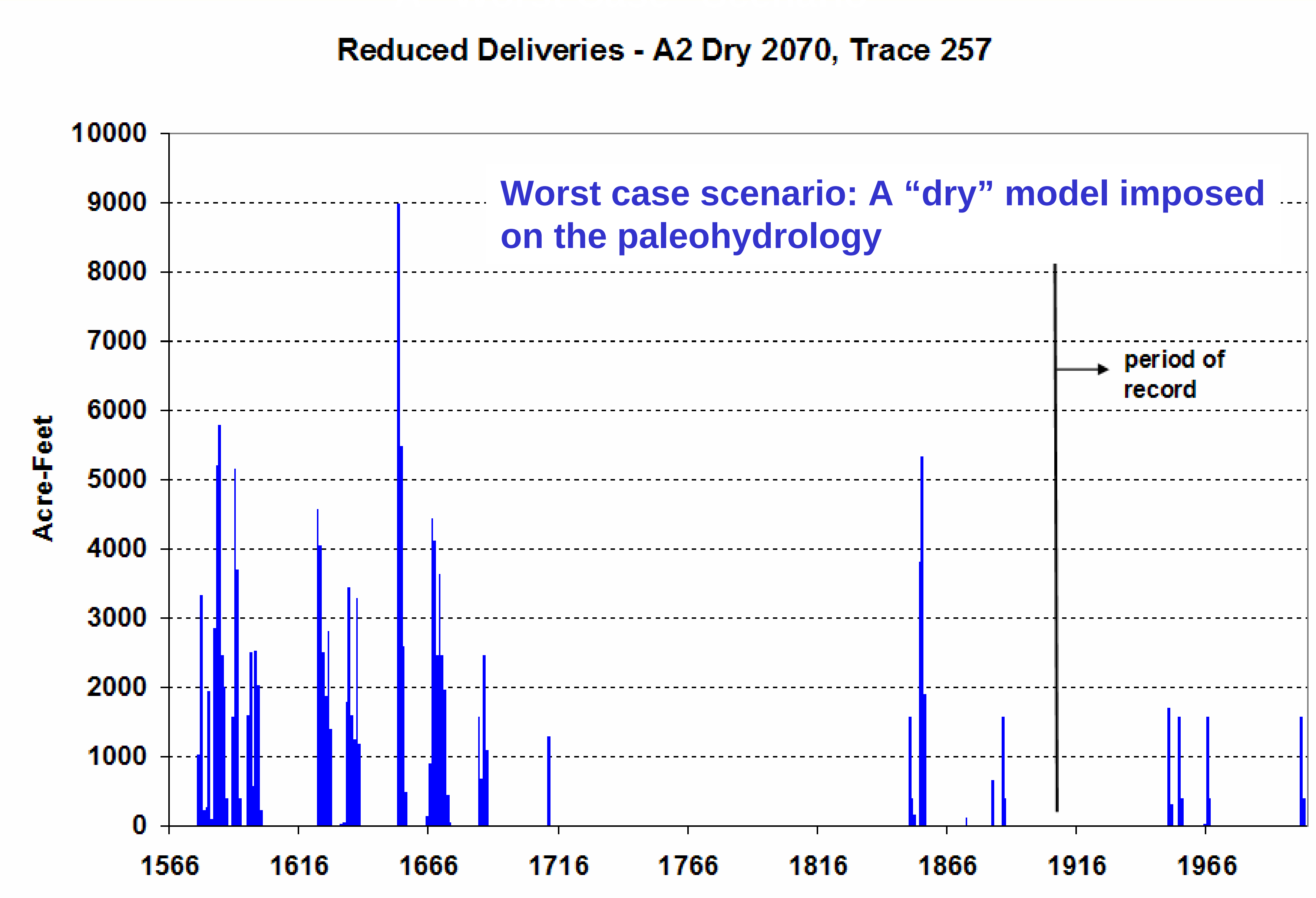
Best case scenario: A “wet” model imposed on the paleohydrology



# A “Worst Case” Scenario

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