New Streamflow Reconstructions for the Upper Colorado River Basin: Placing Recent Droughts into a Centuries-Long Context

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This article is a summary of a paper published in May 2006 in Water Resources Research, "Updated streamflow reconstructions for the Upper Colorado River Basin." The paper's authors are Connie Woodhouse of the NOAA/NCDC, who is a participant in the Western Water Assessment, Stephen Gray, formerly of USGS, now the Wyoming State Climatologist, and David Meko, of the University of Arizona and who is a participant in the Climate Assessment of the Southwest.

Over the past several decades, scientists have developed reconstructions of annual streamflow for centuries prior to the streamflow gage record using data from tree rings. These reconstructions are useful for assessing a broader range of hydrologic variability than contained in the gage records (Figure 1a). The Colorado River at Lees Ferry was the first tree-ring based quantitative reconstruction of streamflow (Stockton and Jacoby, 1976). Lees Ferry is the gage that reflects flows for the Upper Colorado River basin under the 1922 Colorado Compact. The Stockton and Jacoby reconstruction of the annual flows from 1520 to 1961 contained several important findings, including that the highest sustained flows in the entire record occurred in the first part of the 20th century, the period upon which the Colorado River Compact of 1922 was negotiated, while the most persistent and severe drought occurred in the late 16th century.

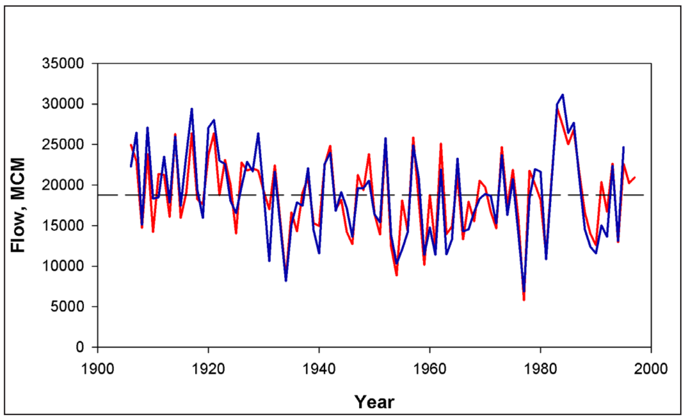

Figure 1a. Comparison of observed and reconstructed streamflow, Lees Ferry gauge (blue line) and Lees-A reconstruction (red line), 1906-1997 (gauge to 1995). Figures 1-3 are reproduced from WGM (2006), see the article for details.

In a paper published in May 2006, Woodhouse and co-authors (2006) updated the Stockton and Jacoby reconstruction at Lees Ferry using an expanded tree-ring network and a longer gage record for the calibration of the reconstruction. They also developed streamflow reconstructions for three key gages in the Upper Colorado River basin: the Green River at Green River, Utah; Colorado near Cisco, Utah; and San Juan near Bluff, Utah (Figure 1b). The reconstructions explain 72-81% of the variance in the gage records, and results are relatively stable across several reconstruction methodologies. The new reconstruction of Lees Ferry flows suggests a slightly higher long-term mean than Stockton and Jacoby's, but confirms the earlier findings that Colorado River allocations were based on one of the wettest periods in the past five centuries, while droughts more severe than any 20th-21st century event have occurred in the past. In addition, five-year droughts similar to the drought of 2000-2004 (in terms of average flow) appear to have occurred as many an eight times in the past five centuries. Analyses indicate similar patterns of runoff variations across the Green, Colorado main stem and San Juan sub-basins, indicating that drought tends to occur across the entire upper basin.

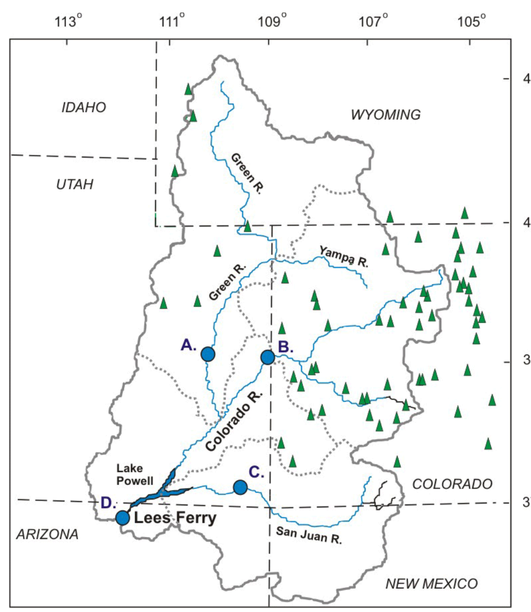

Figure 1b. Location of gages at Green River at Green River, Utah (A), Colorado River near Cisco, Utah (B), San Juan River near Bluff, Utah (C), and Lees Ferry, Arizona (D) (dots) and tree-ring chronologies (triangles). The upper Colorado River basin is outlined in a solid line, and the Green, Colorado with Yampa and Gunnison, and San Juan sub-basins are outlined by the dotted lines.

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Updated Streamflow Reconstructions

Using an updated and expanded set of tree-ring chronologies which end in 1997 or later, the authors created high-quality streamflow reconstructions for four key gages in the Upper Colorado River basin (hereafter the "WGM" reconstructions) . The reconstructions were generated by calibrating the tree-ring chronologies with the most recent naturalized flows from the USBR, including data that were available as of summer 2004. The WGM reconstructions span the common years 1569 to 1997, with the Lees Ferry reconstructions extending to 1490 (available at: www.ncdc.noaa.gov/paleo/pubs/woodhouse2006/woodhouse2006.html.

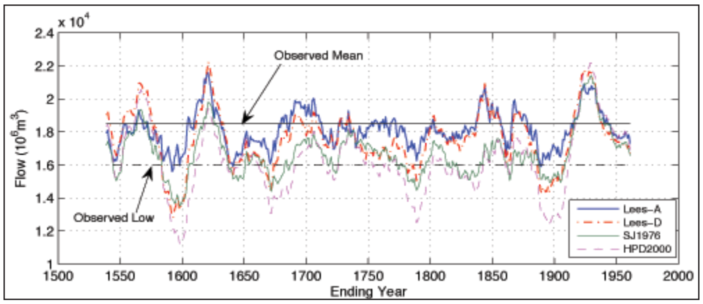

Figure 1c. Twenty-year running means of four alternative reconstructions of the annual flow of the Colorado River at Lees Ferry for common period 1520-1961. Lees-A and D are from WGM (2006), SJ1976 is the mean of two reconstructions from Stockton and Jacoby (1976), and HPD2000 is from Hidalgo et al. (2000). The horizontal lines are the 1906-2004 observed mean (solid) and the lowest observed 20-year running mean of the 1906-2004 period (dash-dot).

Because reconstructions can be sensitive to different modeling methods, two different models were tested for the Green, Colorado near Cisco, and the San Juan gages, and four different models were tested for Lees Ferry flows. The models vary in the pool of chronologies used and the statistical approaches used for handling the data. However, the authors found that different modeling methods had little significant impact on important features of the reconstructions, for example, the long-term annual mean, or the runs of drought years.

However, one factor that does have some impact on the magnitude of reconstructed high and low flows is how the persistence in year-to-year growth is treated in the tree-ring data. In the Lees Ferry reconstructions, the authors tested the effects of either retaining the year-to-year persistence in the tree growth in the chronologies, or removing this persistence The persistence-retained chronology models retain a degree of year-to-year persistence similar to that in the gage record, but overestimate the severity of multi-decadal droughts (20-year means) in the calibration period.

Comparison with Previous Lees Ferry Reconstructions

Hidalgo et al. (2000) generated reconstructions at Lees Ferry as well as Stockton and Jacoby (1976). Both of these reconstructions were calibrated on the years 1914-1961, using similar sets of tree-ring data but slightly different modeling approaches. Interannual variations in streamflow are similar across all of the reconstructions, and a comparison of these Lees Ferry reconstructions and that of WGM shows a relatively close match in variations of streamflow at decadal and longer time scales (Figure 1c). The WGM reconstructions differ from those of Stockton and Jacoby (1976) and Hidalgo et al. (2000) in suggesting a somewhat higher long-term mean for Upper Colorado River flows (Table 1, after Table 9 in WGM, 2006). The most conservative and most extreme Lees Ferry reconstructions generated by this study (called Lees A and Lees D) had long term (1520-1961) means that ranged from 14.3 to 14.7 maf, compared to Stockton and Jacoby's preferred Lees Ferry reconstruction, and the Hidalgo et al. reconstruction with means of 13.5 maf and 13.2 maf, respectively. The set of chronologies and gage records used for the reconstruction calibration may contribute to these differences, but the reconstruction methods used are likely also a factor. The causes of the differences are currently under investigation.

Table 1

Model	Calibration period	Long-term mean & 95% confidence interval
WGM- Lees Ferry-A	1906-1995	14.7 ± 0.2 MAF
WGM- Lees Ferry-B	1906-1995	14.3 ± 0.2 MAF
Stockton & Jacoby (1976)	1914-1961	13.5 *
Hidalgo et al. (2000)	1914-1961	13.2 ± 0.02 MAF

**no confidence interval calculated, not meaningful for the average of two reconstructions*

Highlights of the Reconstructed Streamflows

The recent 2000-2004 drought, as measured by 5-year running means of water-year total flow at Lees Ferry, is clearly a severe event when assessed in the context of the 500-year tree-ring reconstruction. It is highly unlikely (i.e., the probability is less than 10%) that any 5-year flows since 1850 has been as low (Figure 1d). But in considering the uncertainty in the reconstruction and evaluating the reconstruction probabilistically, flows for the period 1844-1848 were lower that 2000-2004, and there are eight periods between 1536 and 1850 that had at least a 10% probability of being as dry as 2000-2004. In addition, droughts longer than any in the gage record have occurred in the past. The Lees

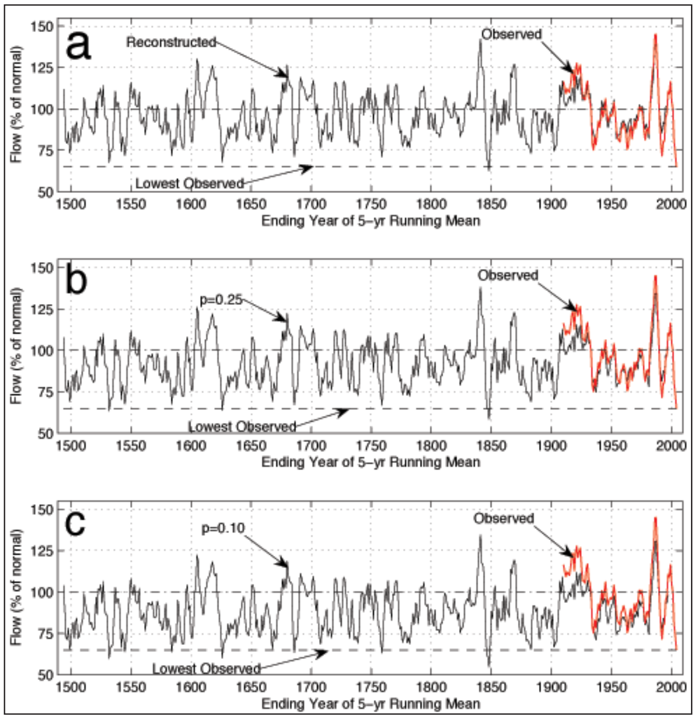

Figure 1d. Current drought in long-term context from Lees- A reconstruction five-year running means of natural flow at Lees Ferry, AZ. Observed flow and reconstructed flow with 0.10 non-exceedance probability. Flow plotted as percentage of 1906-95 mean of observed mean annual flow,15.232 MAF.

Ferry reconstruction includes up to eleven consecutive years with flows below the 1906-1995 average.

Severe multi-year, decadal, and multidecadal periods of droughts in the Upper Colorado River basin have a tendency to be widespread, affecting the Green, San Juan, and Colorado mainstem basins. The most severe multi-year and multidecadal droughts at Lees Ferry are always reflected in the sub-basins, although there are some differences in the magnitude of droughts among the sub-basins. Most periods of low flow in one sub-basin coincide with low flows in the other sub-basins. Very occasionally, periods of low flow (10-year averages) in the Green River have coincided with higher flows in the San Juan basin that resulted in low flows at Lees Ferry flows (e.g. the 1930s). This suggests that drought in the Green River can have a dominant influence on Lees Ferry flows, even when high flows prevail on the San Juan.

The widespread nature of many single and multi-year droughts across the reconstructions suggests a common source of regional low-frequency hydroclimatic variability. Statistical associations have been demonstrated between North American drought and North Atlantic, North Pacific, and Indian Ocean variability (see WGM, 2006 for references), but more research is needed to understand how sea surface temperature variability is related to Upper Colorado River flows. The relationships between atmospheric and oceanic circulation and hydroclimatic variability in the Upper Colorado River basin likely involve complex processes.

Implications for Management

Reconstructions of streamflow for the Upper Colorado River basin confirm that severe, sustained droughts have been a major feature of the Upper Colorado River basin over the past five centuries. These reconstructions also indicate that streamflow varies over decadal and longer timescales, suggesting that short-term records are inadequate for long-term planning. These results suggest eventual conflicts between water demand and supply in the upper Colorado River basin as demands on the Colorado River now exceed average water availability. Predicted climatic changes, in particular, a shift in the ratio of snowfall to rainfall and earlier snowmelt and runoff (Cayan et al. 2001, Stewart et al. 2004), will likely increase the stress on Colorado River water resources. Reconstructions of past streamflow can aid in planning by providing insights into the range of long-term natural variability and extreme hydrologic events that are not observed in gage records. In concert with information on projected climate changes, reconstructions of long-term variability should guide planning for drought management and economic development in the basin in the future.

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On the Web

- For Lees Ferry reconstructions extending to 1490 visit: www.ncdc.noaa.gov/paleo/pubs/woodhouse2006/woodhouse2006.html.
- Tree-ring reconstructions of streamflow for Colorado: http://lwf.ncdc.noaa.gov/paleo/streamflow/