

1 **Medieval Drought in the Upper Colorado River Basin**

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8 New tree-ring records of ring-width from remnant preserved wood are analyzed to extend
9 the record of reconstructed annual flows of the Colorado River at Lee Ferry into the
10 Medieval Climate Anomaly, when epic droughts are hypothesized from other
11 paleoclimatic evidence to have affected various parts of western North America. The
12 most extreme low-frequency feature of the new reconstruction, covering A.D. 762-2005,
13 is a hydrologic drought in the mid-1100s. The drought is characterized by a decrease of
14 more than 15% in mean annual flow averaged over 25 years, and by the absence of high
15 annual flows over a longer period of about six decades. The drought is consistent in
16 timing with dry conditions inferred from tree-ring data in the Great Basin and Colorado
17 Plateau, but regional differences in intensity emphasize the importance of basin-specific
18 paleoclimatic data in quantifying likely effects of drought on water supply.

1 **1. Introduction**

2 Improved understanding of the variability of runoff and streamflow in the Upper
3 Colorado River Basin (UCRB) on decadal and longer timescales is essential to regional
4 water resources planning and management in the western United States. Well-replicated
5 networks of tree-ring sites in the UCRB have yielded annual streamflow reconstructions
6 back to the 1400s (e.g., Woodhouse et al. 2006). Paleoclimatic data from elsewhere in
7 the western United States suggest that these reconstructions fall short of sampling some
8 of the most important hydroclimatic fluctuations of the past thousand years. Hydrologic
9 droughts were unusually widespread and persistent in the Medieval Climate Anomaly
10 (MCA), roughly A.D. 900-1300 (e.g., Stine 1994; Hughes and Graumlich, 1996; Hughes
11 and Funkhouser, 1998; Benson et al. 2002; Cook et al. 2004). For example, Mono Lake
12 low stands reported by Stine (1994) are estimated to have been accompanied by multi-
13 decadal precipitation decreases of greater than 20% in the Sierra Nevada of California
14 (Graham and Hughes, in review). In this paper we attempt to quantify MCA drought
15 magnitude in the UCRB by analysis of a newly developed network of tree-ring sites
16 located within the basin. Annual flow of the Colorado River at Lee Ferry, Arizona, is
17 reconstructed to A.D. 762 with ring-width using tree-ring samples from living trees,
18 augmented by samples from logs and dead standing trees (remnant wood). We identify
19 multi-decadal UCRB droughts of the MCA, quantify the year-by-year sequence of flow
20 anomalies in the most severe drought, and check the consistency of the new
21 reconstruction with other tree-ring evidence of regional-scale moisture and temperature
22 departures.

1 **2. Data and Methods**

2 Cores from living trees and cross-sections from remnant wood were collected between
3 2002 and 2005 at 11 sites in the UCRB (Figure 1 and Supplemental Material). Ring
4 widths were dated and measured by conventional methods (Stokes and Smiley 1968), and
5 dimensionless core indices were computed as the ratio of ring width to an empirically fit
6 growth curve (Cook et al. 1990). For uniformity of treatment and to reduce loss of low-
7 frequency variance, a cubic smoothing spline (Cook and Peters 1981) with frequency
8 response 0.95 at a wavelength twice the series length was used as the growth curve. Core
9 indices were converted to autoregressive residuals to remove the low-order persistence,
10 which varies widely among trees and is likely due at least in part to biological factors
11 (Cook et al. 1990). Indices at each site were then averaged over cores to compute “site
12 chronologies”. Segment-lengths shorter than 250 were excluded from chronology
13 development to reduce possible damping of the low-frequency climatic signal (e.g., Cook
14 et al. 1995, Ni et al. 2002), and site chronologies were truncated to begin when the
15 subsample signal strength first reached a threshold of $SSS \geq 0.85$ (Wigley et al. 1984). As
16 the number of cores averaged varies over time, variance-stabilization, following Osborn
17 et al. (1997), was applied to the retained portion of the site chronology to reduce the
18 likelihood of spurious residual trends in variance.

19
20 Streamflow data consisted of water-year-total natural flow of the Colorado River at Lee
21 Ferry, Arizona, 1906-2004. These data, obtained from the U.S. Bureau of Reclamation
22 (James Prairie, personal communication), represent the best available estimate of what
23 the flow at Lee Ferry would have been without reservoir regulation and other

1 anthropogenic influences. For brevity, the time series of water-year-total natural flows is
2 referred to hereafter as “flow”.

3
4 The reconstruction was generated in a two-stage linear regression procedure previously
5 described in greater detail elsewhere in the context of a precipitation reconstruction
6 (Meko 1997). The first stage is regression of flow in year t separately on each residual
7 site chronology in years $t-2$ to $t+2$ (five predictors). This steps yields a single-site
8 reconstruction of flow (SSR) for each chronology. A principal components analysis
9 (PCA) on the covariance matrix of the SSRs yields an orthogonal set of new variables
10 that are linear combinations of the SSRs. The second stage of the regression procedure is
11 stepwise regression of flow on the scores of the most important PCs, defined arbitrarily
12 as those contributing at least 5% of the variance of the SSRs. This regression equation
13 essentially “weights” the individual SSRs into a single reconstructed time series of flow.
14 The PCA and second stage of regression is repeated several times using different sets of
15 tree-ring chronologies to extend the reconstruction, albeit with diminished accuracy, to
16 the earlier and more poorly replicated part of the tree-ring record. For any given year of
17 the tree-ring record, the most accurate available model – lowest root-mean-square error
18 of validation ($RMSE_v$) -- was used to generate the final reconstructed flow value. Error
19 bars for the final reconstruction were estimated by Monte Carlo simulation following
20 Meko et al. (2001): 1000 different time series of random noise were drawn from a
21 normal distribution with zero mean and standard deviation equal to $RMSE_v$ and were
22 superimposed on the reconstruction to produce 1000 noise-added reconstructions. Each

1 of these is a plausible realization of true natural flow given the reconstruction model and
2 its uncertainty.

3

4 **3. Results and Discussion**

5

6 Single-site regression modeling indicated that each of the 11 tree-ring chronologies has a
7 statistically significant signal for flow, with chronologies individually capable of
8 explaining 25% to 57% of the flow variance (Supplemental Material). Split-sample
9 validation (Snee 1977) of these models using the reduction-of-error statistic (Fritts et al.
10 1990) to measure accuracy indicated that all 11 models have positive skill when fit to one
11 half of the data and validated on the other (Supplemental Material). From an assessment
12 of signal strength and time coverage of the SSRs, four groupings of chronologies were
13 selected for PCA and subset reconstruction modeling. The chronology subsets have
14 starting years (A.D.) 762, 1182, 1365 and 1473. Model subsets of chronologies are
15 cumulative for the earliest three models: three sites were available by A.D. 762, three
16 more by A.D. 1182, and three more by A.D. 1365. The model for the subset starting in
17 A.D. 1473 is based on four sites whose tree-ring data extend to 2005, and was used only
18 to generate reconstructed flows for years 2004 and 2005.

19

20 Results for the second stage of regression are summarized in Table 1. As indicated by
21 column “q”, each of the final reconstruction models includes just the first principal
22 component of the SSRs as a predictor of flow. The variance of flow explained by the
23 reconstruction increases with number of chronologies. In the earliest centuries, the

1 reconstruction relies on three chronologies and explains 60% of the calibration variance.
2 This percentage jumps to 74% by A.D. 1182, and to 77% by A.D. 1365. Cross-
3 correlation analysis, cross-spectral analysis, and time series plots of observed and
4 reconstructed flows indicated that each of the four sub-period reconstructions
5 successfully tracks the observed flows for the instrumental period, and that coherence of
6 observed and reconstructed flows remains significant at wavelengths longer than about
7 10 years (Supplemental Material). The reconstructions by the four sub-period models
8 are consistent with the Woodhouse et al. (2006) Lees-A flow reconstruction over the
9 common period A.D. 1490-1997: $r=0.76$ for the A.D. 762 model and $r=0.91$ for the A.D.
10 1182 model.

11
12 A 25-year running mean of the reconstructed flows illustrates the overall importance of
13 variations at multi-decadal time scales, and identifies intervals of amplified low-
14 frequency variance (Figure 2). The most recent such interval began in the mid-1800s and
15 has continued to present. The most prominent feature of the smoothed long-term
16 reconstruction is the major period of low flow in the mid-1100s. The lowest
17 reconstructed 25-year running mean occurred in A.D 1130-1154. These results suggest
18 that – at least for this level of smoothing – conditions in the mid-1100s in the UCRB
19 were even drier than during the extremely widespread late-1500s North American
20 megadrought (e.g., Stahle et al. 2000). If “normal” is defined as the observed mean
21 annual flow for 1906-2004, the anomalous flow for A.D. 1130-1154 was less than 84%
22 of normal. By comparison, the lowest 25-year mean of observed flows (1953-1977) was
23 87% of normal. Because regression biases the reconstructed flows toward the

1 calibration-period mean, flows in the mid-1100s were quite possibly lower than indicated
2 by the reconstruction. For example, the 80% confidence band plotted in Figure 3
3 suggests a greater than 10% probability that the true mean for A.D. 1130-1154 was as
4 low as 79% of normal.

5
6 A distinct attribute of tree-ring data is the ability to resolve year-to-year fluctuations in
7 climate. A detailed view of the time series of annual reconstructed flow reveals that the
8 mid-1100s is characterized by a series of multi-year low-flow pulses imbedded in a
9 generally dry 62-year period (1118-1179) (Figure 3a). A signature for this period is the
10 absence of years with flow much above normal. The key drought signature is a stretch of
11 13 consecutive years of below normal flow (1143-1155), with cumulative negative
12 departure from normal of 45 billion cubic meters (Figure 3b). In no other period of the
13 reconstruction was flow below normal for more than 10 consecutive years, and the
14 longest stretch of consecutive dry years in the reconstruction for the modern instrumental
15 period (post 1905) was just 5 years.

16
17 Other tree-ring reconstructions for the western United States allow the mid-1100s
18 drought in the UCRB to be placed in a larger regional context. In a much broader region
19 of the western United States, a 1200-year index of the total area in drought, smoothed to
20 emphasize multi-decadal-to-century variation, reaches its major peak at A.D. 1150 (Cook
21 et al. 2004). Tree-ring data indicate that the correlation of moisture anomalies in the
22 Sierra Nevada and Colorado Rockies is generally weak, but is occasionally enhanced
23 during severe drought (Meko and Woodhouse 2005). The mid-1100s may be an extreme

1 example of such enhancement. A reconstruction of annual flow of the Sacramento River
2 covering more than 1100 years identifies A.D. 1139-1158 as the second-lowest 20-year
3 mean flow (Meko et al. 2001). A 1000-year reconstruction of temperature and
4 precipitation for the southern Sierra Nevada of California identifies A.D. 1150-1169 as
5 the warmest 20-year period, and 1140-1159 as the fourth driest (Graumlich 1993). As
6 the early part of the Sacramento River reconstruction depends greatly on tree-ring
7 chronologies somewhat north of the basin – in south-central Oregon –these two
8 reconstructions are jointly consistent with a northward retreat of the winter storm track
9 over the far western United States during the mid-1100s drought on the Colorado.

10

11 Closer to the UCRB, paleoclimatic records are consistent in identifying the mid-1100s as
12 a regional major or minor low in moisture (dry period) and high in temperature (Figure
13 4). Aligned with the major low in Colorado River flow centered on A.D. 1148 are lows
14 in reconstructed precipitation for the Great Basin (Hughes and Graumlich, 1996; Hughes
15 and Funkhouser, 1998) and the Colorado Plateau (Salzer and Kipfmueller, 2005).

16 Suggestions from the Sierra Nevada that the mid-1100s was a relatively warm epoch
17 (Graumlich 1993) are reinforced by the local peak in reconstructed Colorado Plateau
18 annual temperature (bottom plot in Figure 4). If the spline-smoothed flow and
19 precipitation series in Figure 4 are re-expressed as a percentage of the recent (period
20 starting in 1906) mean, the mid-1100s lows range from 83.4% for Colorado River Flow
21 to 89.9% for Colorado Plateau precipitation.

22

1 It is clear from Figure 4 that the mid-1100s UCRB drought does not coincide with either
2 of two century-long Sierra Nevada droughts inferred by Stine (1994) from radiocarbon-
3 dated tree stumps and other material from Mono Lake and nearby lakes and rivers.
4 Radiocarbon-dating uncertainty may contribute to this asynchrony (see Graham and
5 Hughes, in review), but more important probably is the spatial heterogeneity of drought
6 patterns at large regional spatial scales. This heterogeneity underscores the need for more
7 comprehensive and dense spatial coverage by paleoclimatic indicators for resolving
8 regional patterns of drought variability important to water supply in the western United
9 States.

10

11 The results presented here for the UCRB rely on a relatively sparse network of tree-ring
12 chronologies, and assessments of magnitude of flow anomalies will likely change as
13 future remnant-wood collections yield better spatial coverage and sample depth in the
14 MCA. It is also important to consider the possibility that gradual trend in flow is
15 undetected or perhaps underestimated in the reconstructions – especially trends
16 represented by wavelengths longer than 250 years. Additionally, it is also possible that
17 some other climate variables not included in the in the calibration may have had some
18 systematic long-term influence on tree growth. These variables might include direct
19 response of growth to changes in temperature through length of growing season and
20 snowpack storage of available moisture.

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1 **Table 1. Summary statistics of sub-period reconstruction models.**

2 -----

	Calibration ³				Validation ⁴		
	-----				-----		
5 N ¹ Start ²	Years	n-p-q	R ² _{adj}	m	RE	RMSE	
6 -----							
7 1 762	1906-2003	3-3-1	0.60	9	0.58	3.46	
8 2 1182	1906-2002	6-5-1	0.74	9	0.73	2.78	
9 3 1365	1906-2002	9-4-1	0.77	9	0.76	2.64	
10 4 1473	1906-2004	4-4-1	0.57	9	0.54	2.63	
11 -----							

12 ¹sequence number of sub-period model (1 is earliest)

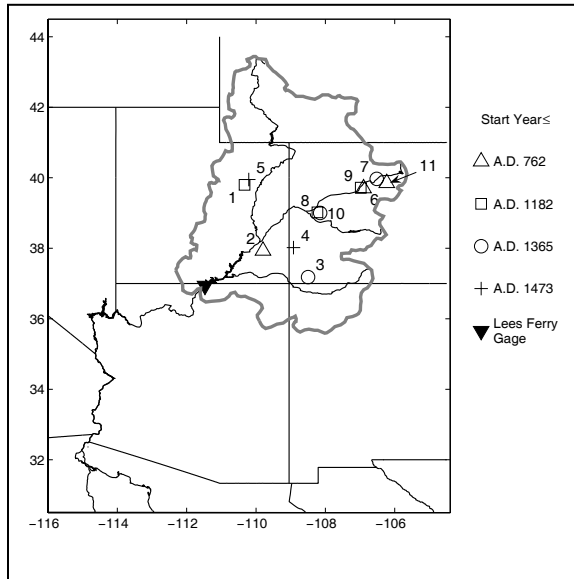
13 ²start year of reconstruction sub-period

14 ³calibration statistics: "Years" is the calibration period;
 15 n is the number of chronologies available; p is the number
 16 of potential predictors in the predictor pool; q is the
 17 number of predictors in the final model; and R²_{adj} is the
 18 adjusted coefficient of determination

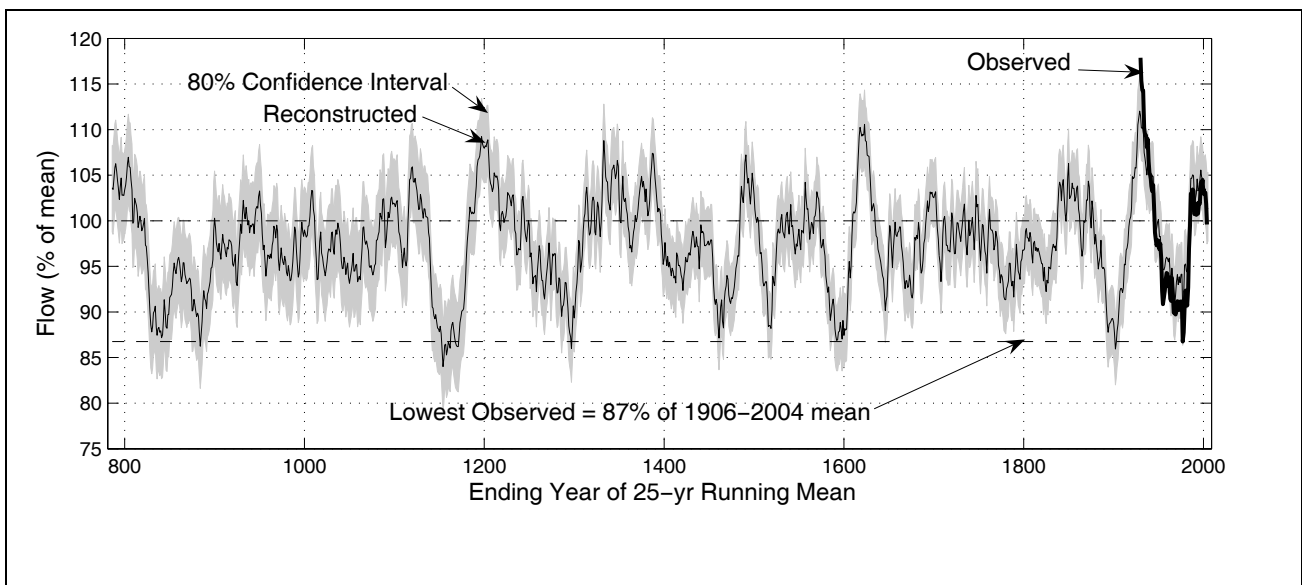
19 ⁴validation statistics (cross-validation): m is the number
 20 of observations left out in "leave-m-out" validation; RE
 21 is the reduction of error statistic; and RMSE is the root-
 22 mean-square error of cross-validation, in billion cubic
 23 meters (BCM)

1

2 **Figure 1.** Tree-ring network for Colorado River reconstruction. Sites coded by start year
3 of earliest sub-period reconstruction model using the chronology (see Table 1).

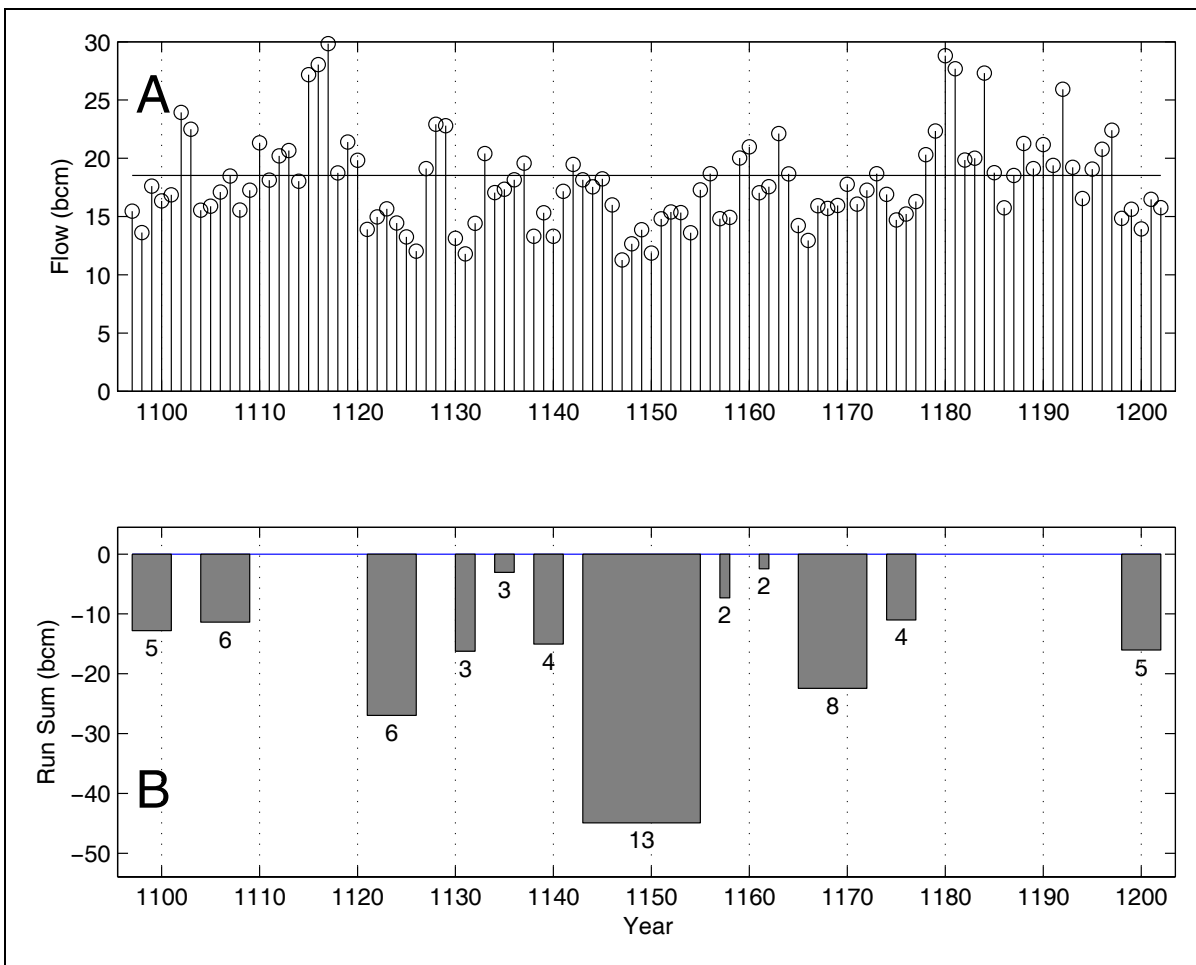


1 **Figure 2.** Time series plot of 25-year running mean of reconstructed flows. Flows are
2 plotted as percentage of the 1906-2004 mean of observed natural flows (18.53 billion
3 cubic meters, or 15.03 million acre-ft). Confidence interval derived from 0.10 and 0.90
4 probability points of ensemble of 1000 noise-added reconstructions. Horizontal dashed
5 line is lowest 25-year running mean of observed flows (1953-1977).
6



1

2 **Figure 3.** Runs properties of 1100s drought. (A) Time series of reconstructed flow in
3 units of billion cubic meters (BCM) for segment A.D. 1098-1202. Horizontal line at
4 18.53 BCM is observed mean for 1906-2004. (B) Time series of runs below the
5 observed mean flow. Bars mark runs of two-or-more years. Run-length annotated below
6 bar. Run-sum (cumulative departure from mean) given by length of bar.



1 **Figure 4.** Figure 4. Medieval drought on Colorado River in regional context of other
2 paleoclimatic reconstructions. Core and broad window for Colorado River drought
3 shaded. Other plotted series are: Great Basin annual precipitation (Hughes and
4 Funkhouser 1998—six-chronology reconstruction), Colorado Plateau October-July
5 precipitation, and Colorado Plateau annual average maximum temperature (Salzer and
6 Kipfmueller 2006). All plotted series generated by converting annual reconstructions to
7 standardized departures (using means and standard deviations for period beginning with
8 1906), followed by smoothing with 41-year spline to emphasize multidecadal departures.
9 Horizontal bars at inferred Mono Lake low stands follow Stine (1994).
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