JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION

Vol. 45, No. 1 AMERICAN WATER RESOURCES ASSOCIATION February 2009

RECONSTRUCTED STREAMFLOWS FOR THE HEADWATERS OF THE WIND RIVER, WYOMING, UNITED STATES[1]

Thomas A. Watson, F. Anthony Barnett, Stephen T. Gray, and Glenn A. Tootle[2]

ABSTRACT: Tree rings offer a means to extend observational records of streamflow by hundreds of years, but dendrohydrological techniques are not regularly applied to small tributary and headwaters gages. Here we explore the potential for extending three such gage records on small streams in the Wind River drainage of central Wyoming, United States. Using core samples taken from Douglas fir (*Pseudotsuga menziesii*), piñon pine (*Pinus edulis*), and limber pine (*Pinus flexilis*) at 38 sites, we were able to reconstruct streamflows for the headwaters of the Wind River back to 1672 AD or earlier. The streamflow reconstructions for Bull Lake Creek above Bull Lake; the Little Popo Agie River near Lander, Wyoming; and Wind River near Dubois, Wyoming explained between 40% and 64% of the observed variance, and these extended records performed well in a variety of statistical verification tests. The full reconstructions show pronounced inter-annual variability in streamflow, and these proxy records also point to the prevalence of severe, sustained droughts in this region. These reconstructions indicate that the 20th Century was relatively wet compared to previous centuries, and actual gage records may capture only a limited subset of potential natural variability in this area. Further analyses reveal how tree-ring based reconstructions for small tributary and headwaters gages can be strongly influenced by the length and quality of calibration records, but this work also demonstrates how the use of a spatially extensive network of tree-ring sites can improve the quality of these types of reconstructions.

(KEY TERMS: climate variability and climate change; dendrochronology; drought; streamflow; Wyoming, United States; Wind River.)

Watson, Thomas A., F. Anthony Barnett, Stephen T. Gray, and Glenn A. Tootle, 2009. Reconstructed Streamflows for the Headwaters of the Wind River, Wyoming, United States. *Journal of the American Water Resources Association* (JAWRA) 45(1):1-13. DOI: 10.1111/j.1752-1688.2008.00274.x

INTRODUCTION

As highlighted by recent and ongoing drought, the availability and sustainable use of surface water is a major concern in the western United States (U.S.). Sustainable water resource management relies on having detailed information related to natural hydroclimatic variability, and such efforts are often hampered by a lack of long-term streamflow data. Even the longest stream gage records from the western U.S. cover only the last 70-100 years, and these records capture only a limited number of multi-year and decadal-scale wet and dry events. Tree rings offer one means to overcome the relatively short duration of instrumental streamflow records (Meko

[1]Paper No. JAWRA-08-0002-P of the *Journal of the American Water Resources Association* (JAWRA). Received January 7, 2008; accepted July 8, 2008. **Discussions are open until August 1, 2009**.

[2]Respectively, (Graduate Student, Graduate Student, Associate Research Scientist, Assistant Professor) (Watson, Barnett, Gray, Tootle), Department of Civil and Architectural Engineering, University of Wyoming, Laramie, Wyoming [Tootle now at Department of Civil and Environmental Engineering (Assistant Professor), University of Tennessee, Knoxville, Tennessee]; and Director and Wyoming State Climatologist (Gray), Wyoming Water Resources Data System and Wyoming State Climate Office, University of Wyoming, Laramie, Wyoming (E-Mail/Gray: sgray8@uwyo.edu).

and Woodhouse, 2009). Though successful tree-ring reconstructions have been performed on a limited number of gage records from smaller tributary and headwaters streams (e.g., Woodhouse, 2001; Woodhouse and Lukas, 2006), the majority of dendrohydrological studies have focused on main stem gages at sites with very large flow volumes (e.g., Meko *et al.*, 2001; Gedalof *et al.*, 2004; Woodhouse *et al.*, 2006).

Understanding the range of natural variability in smaller tributary or headwaters streams is critical for managing water supplies in many mountainous regions. Defining patterns and sources of longer-term hydroclimatic variability in these streams is also essential for improving run-off forecasts at key downstream lower-elevation locations (Pagano *et al.*, 2004). Moreover, in the semi-arid western U.S., smaller streams provide critical aquatic and riparian habitats, and may serve as the only source of surface water for hundreds of square kilometers (Belsky *et al.*, 1999). In many areas small tributary streams also provide the only records of unregulated flow, and such observations can be critical for a variety of hydroclimatic analyses.

There are often significant obstacles to using tree rings as a proxy for measurements at small tributary and headwaters gages. First and foremost is the frequent lack of reliable gage data for calibrating tree growth against streamflows. Flows at main stem gages are often heavily regulated by upstream reservoirs and diversions. However, these gages also tend to have much longer periods of record than are found on smaller streams. Once the flows are corrected or "naturalized" for depletions and/or additions, main stem records are often more complete than those from tributaries (Slack *et al.*, 1993; Tootle and Piechota, 2006). There is also a common misconception that tree-ring collections must come from within a watershed so as to produce a valid reconstruction. Few such chronologies exist within most small watersheds, especially when compared to the number of tree-ring sites within a major drainage basin like the Upper Colorado (e.g., Woodhouse *et al.*, 2006).

In this paper we explore the prospects for reconstructing a set of headwaters gages in the Wind River drainage of north-west Wyoming (Figure 1). Though total discharge from this basin is relatively small, the Wind River provides a large portion of the agricultural, municipal, and industrial water used in north-central Wyoming (WWDC, 2007). After changing names to become the Bighorn River near Thermopolis, Wyoming, these waters eventually flow into Montana, and the river has become the subject of an interstate compact dispute that is currently before the U.S. Supreme Court. To date there have been no successful attempts at tree-ring based flow reconstructions in this area, although annual precipitation has been reconstructed back to the 10th or 11th Centuries AD in neighboring regions (Gray *et al.*, 2004a, 2007). Coarse scale ($2 \times 3°$ grid) reconstructions of the June-August Palmer Drought Severity Index are also available for the continental U.S. (Cook *et al.*, 1999, 2004), but these estimates may not capture important aspects of snowpack-dominated runoff dynamics in the Wind River drainage.

We developed three new sets of tree-ring based reconstructions of streamflow in the Wind River drainage covering the past 320-484 years. The reconstructions are based on data from six new tree-ring chronologies, complemented by existing chronologies from surrounding regions. Water-year (October through September) streamflow was reconstructed at two gage stations, the Wind River near Dubois and Bull Lake Creek, while spring-summer (April through September) flows were reconstructed on the Little Popo Agie River. The gage records are relatively short, covering between 34 and 54 years. In turn we use these extended records to explore how the quantity of available gage data can affect the results of such reconstruction efforts, and we examine the potential benefits of using data from a wide spatial network of tree-ring sites as a proxy for streamflow in a small watershed. Finally, we use these new reconstructions to examine the longer-term history of droughts and wet events in the Wind River drainage, with a particular emphasis on comparing events recorded in the gage period to those of the past several centuries.

STUDY AREA

The Wind River (Figure 1) drains approximately 19,950 km^2, much of it within the Wind River Indian Reservation. The basin is bordered on the southwest by the Wind River Mountain Range, the southeast by the Beaver Divide, and on the north by the Absaroka Mountains. The Wind River is primarily fed by Bull Lake Creek, now impounded by Bull Lake Reservoir [180 million cubic meters (mcm)], and the Little Wind and Popo Agie Rivers. The Wind River turns north and flows into Boysen Reservoir (990 mcm), and soon after changes names to become the Bighorn River. When supplemented with ground water, the Wind-Bighorn River and its tributaries provide irrigation for approximately 240,000 ha of cropland and municipal water supplies for over 80,000 people (WWDC, 2007). The Bighorn River eventually flows north into Bighorn Lake (1640 mcm), and then joins the Yellowstone River near Bighorn, Montana.

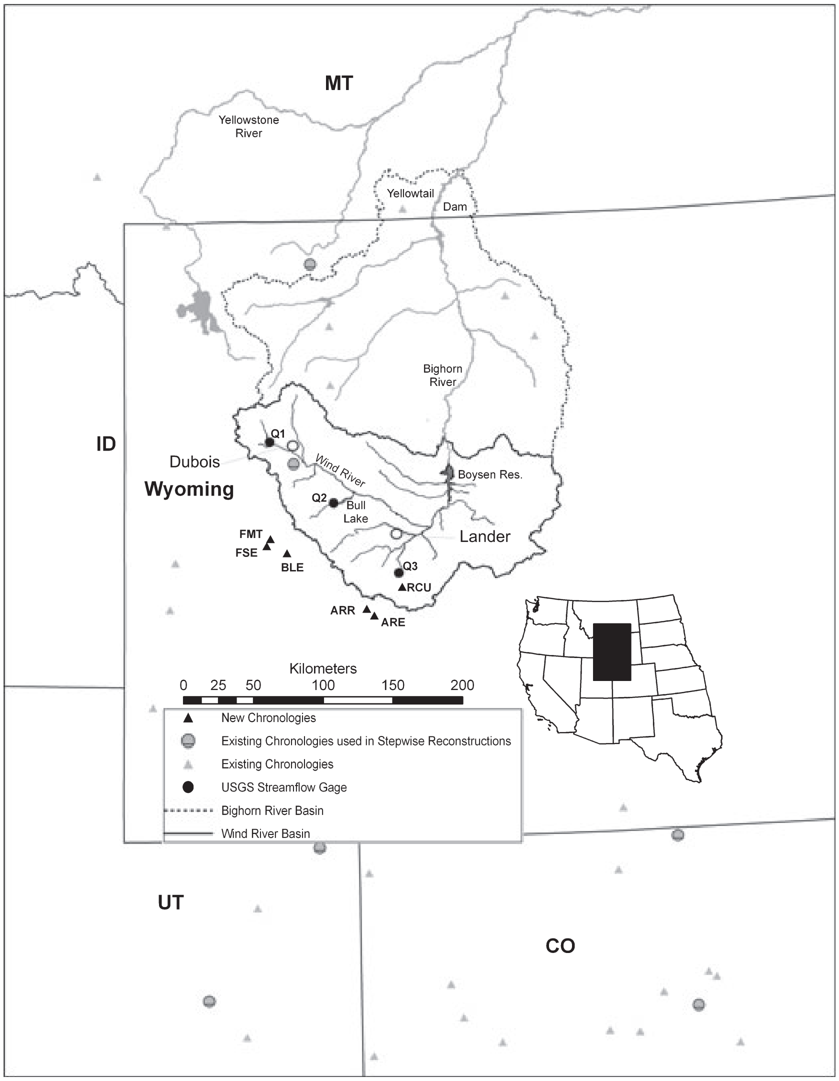

FIGURE 1. Map of Study Area Showing Gage Locations and Study Sites.

DATA AND METHODS

Streamflow Data

Unimpaired streamflow stations in the Wind River Basin were identified from sites included in the Hydro-Climatic Reference Network (Slack *et al.*, 1993), and further screened by Tootle and Piechota (2006). Monthly streamflow data for Bull Lake Creek above Bull Lake (USGS Station #06224000); Little Popo Agie River near Lander, Wyoming (USGS Station #06233000); and the Wind River near Dubois, Wyoming (USGS Station #06218500) were obtained from the United States Geological Survey (USGS) National Water Information System (http://waterdata.usgs.gov/nwis/monthly/). These stations provided the longest continuous, unimpaired records available within the Wind River drainage. The streamflow record for Bull Lake Creek was limited to 1967-2000 (Figure 1, Table 1). The Little Popo Agie River streamflow record encompasses the years 1946-1999, while the record for the Wind River spans 1946-1992. We examined total water-year (October-September) discharge at the Wind River and Bull Lake Creek gages, but due to a lack of data for the winter and fall months, only spring-summer (April-September) flows were examined on the Little Popo Agie River. However, analysis of the full water-year records showed that spring-summer flows represent approximately 83% of total annual discharge, so we considered the Little Popo Agie record to be roughly comparable to other gages in the system. Visual inspection and the Kolmogorov-Smirnov test (Draper and Smith, 1998) show that flows at these

TABLE 1. Descriptions of Wind River Basin Stream Gages Reconstructed in This Study.

ID	Gage Name	USGS Gage #	Years	Mean (mcm)	Standard Deviation	r(1)*
Q1	Wind River near Dubois	6218500	1946-1992	154.4	38.1	−0.03
Q2	Bull Lake Creek above Bull Lake	6224000	1967-2000	262.6	57.9	−0.11
Q3	Little Popo Agie River near Lander	6233000	1946-1999	62.7	24.4	−0.04

Notes: Site IDs match those used in Figure 1.
*Autocorrelation at a lag of one year. None of these values are significant at the p = 0.05 level.

sites are essentially normal. Likewise there was no significant first-order autocorrelation in the streamflow records.

New Tree-Ring Data

We sampled six new tree-ring sites in the foothills of the Wind River Range (1980-2625 m a.s.l.; Figure 1). All sites were characterized by shallow, poorly developed soils on rocky slopes, and trees were generally selected from open-canopy stands. Limber pines (*Pinus flexilis*) were sampled at two sites, Anderson Ridge (ARE) and Red Canyon (RCU), near the southern terminus of the Wind River Range (Table 2). Limber pines were also sampled on the southwest side of the Wind River Range near Fremont Lake (FSE). Additionally we sampled Douglas fir (*Pseudotsuga menziesii*) at one site on Anderson Ridge (ARR), and two sites on the southwest face of the Wind River Range, Boulder Lake (BLE), and Fremont Lake (FMT). At least two cores were taken from each tree sampled, and sites were searched for any dead wood that might extend the length of these chronologies.

After drying, cores were mounted, progressively sanded, and individual rings were measured to the nearest 0.001 mm. The series were cross-dated using standard methods (Stokes and Smiley, 1968; Swetnam *et al.*, 1985; Cook and Kairiukstis, 1990). The accuracy of cross-dating was confirmed using the COFECHA program (Holmes, 1983). We successfully cross-dated 104 samples from 67 trees at the three limber pine sites and 164 samples from 81 trees at the Douglas fir sites (Table 2).

Chronologies were created using the Auto-Regressive Standardization program (ARSTAN; Cook, 1985) with negative exponential or straight line detrending. Correlations between series at each site ranged from r = 0.69 to 0.80 (Table 2). Correlations between the six site chronologies were generally strong (with the exception of RCU) with values ranging from 0.32 to 0.80. The new chronologies were also significantly correlated ($p < 0.05$) with existing chronologies from as far away as northern Colorado and southwestern Montana. First-order autocorrelation at the six tree-ring sites averaged 0.52 compared to −0.06 for the stream gages. Because such high levels of persistence may result from ecological or biological factors (Fritts, 1976), we used residual chronologies (i.e., serial autocorrelation removed) in all subsequent analyses. Finally we assessed chronology fidelity through time using the subsample signal strength (SSS) criterion (Wigley *et al.*, 1984). We limited our analyses to the period when all site chronologies within an individual reconstruction achieved SSS > 0.85 (i.e., 85% of common signal retained).

Testing Climate-Growth Relationships. Tree growth at the six sites was compared with precipitation over various temporal windows (e.g., monthly, seasonal, water-year) in order to verify a hydroclimatic signal within the chronologies. Tree growth at these sites was also compared against temperature records across the same set of temporal windows. For the bulk of our analyses we focused on climate division data obtained from the Western Regional Climate Center (http://www.wrcc.dri.edu), though records from individual climate stations were also

TABLE 2. Descriptive Statistics for New Tree-Ring Chronologies Collected During This Study.

Site	Species	Elevation (m)	Time Span (year AD)	Year SSS >0.85*	Number of Trees	Number of Series	Mean Sensitivity	Inter-series Correlation
ARE	Limber pine	2,450-2,570	1200-2006	1203	20	28	0.30	0.708
ARR	Douglas fir	2,600-2,625	1519-2006	1615	25	53	0.24	0.765
BLE	Douglas fir	2,230-2,290	1576-2006	1672	21	41	0.34	0.786
FMT	Douglas fir	2,285-2,560	1507-2006	1603	35	70	0.30	0.77
FSE	Limber pine	2,330-2,440	1654-2006	1692	23	35	0.46	0.804
RCU	Limber pine	1,980-2,015	1600-2006	1613	24	41	0.28	0.685

*Subsample signal strength (SSS) Wigley *et al.*, (1984) provides a measure of chronology strength through time.

examined. Climate divisions roughly correspond with the major river drainages in a state (see Guttman and Quayle, 1996), and data from individual stations within these areas are combined to produce divisional averages for temperature, precipitation, and other basic climatological variables. Wyoming Climate Division 9, the basis for the bulk of our analyses, closely follows the boundaries of the Wind River Basin, and data for this climate division were available back to 1895 with no missing values (see Peterson and Easterling, 1994). Tree growth at five of the six sites was significantly correlated ($p < 0.05$, $r = 0.20$ to 0.56) with climate division precipitation, with the strongest relationships seen over the water-year (October-September) and July-June periods. Growth at RCU was not significantly correlated with precipitation from any of the climate divisions ($p > 0.05$, $r = 0.11$ to 0.14). Growth at all of the sites except RCU was negatively correlated with climate division temperatures, and in all cases the relationships between temperature and tree-growth were noticeably weaker than those with precipitation. As is common in surrounding regions (e.g., Gray *et al.*, 2004a,b, 2007), correlations between tree-growth and individual station records (temperature and precipitation) were lower than those with climate divisional records. Such differences are largely attributable to the substantial straight-line distances and elevation change between most individual observing stations and our tree-ring sites. The averaging process used to create the divisional records also deemphasizes small-scale variations in climate that may not be shared between the tree-ring sites and individual observing stations. Due to its weak correlations with hydroclimatic variables, RCU was excluded from further analyses.

Tree-Ring Network

Thirty-two existing chronologies from moisture-sensitive trees used in previous hydroclimatic reconstructions (e.g., Graumlich *et al.*, 2003; Gray *et al.*, 2004a,b, 2007; Woodhouse *et al.*, 2006) were also employed as potential predictors of streamflow. Of these 32 additional chronologies 13 are from Douglas fir, 11 from piñon pine (*Pinus edulis*), seven limber pine, and one ponderosa pine (*Pinus ponderosa*). All of these chronologies cover the period from 1650 to 1995 AD, and showed significant ($p < 0.05$) correlations with precipitation, drought, or streamflow in surrounding regions. The majority of these chronologies are available via the International Tree Ring Data Bank (ITRDB, 2007; http://hurricane.ncdc.noaa.gov/pls/paleo/treering.html), and they represent sites throughout Wyoming, southern Montana, northeastern Utah, and northwestern Colorado.

Screening Potential Predictors

Potential predictor chronologies were chosen from the original pool of 37 using a series of correlation analyses. First, we selected chronologies that were significantly correlated with historical flows at the 99% significance level or better. The remaining chronologies were then subjected to bootstrapped correlation analyses with evolutionary and moving intervals (Biondi and Waikul, 2004). In the evolutionary interval analysis used here, bootstrapped correlation values are calculated across a series of temporal windows, with the size or length of the window increasing by one year at each step. The analysis proceeds both forward and backwards until the window encompasses the entire period of overlap between variables. As employed here, moving interval analysis uses the same length of window throughout, but the window advances forward in one-year steps from the oldest common year to the most recent year in the series. Chronologies that maintained stable correlations throughout the evolutionary and moving intervals (i.e., $r > 0.20$ for all windows) were then divided into three sets of potential predictor pools. The first predictor pool (PP1) includes all available screened chronologies, while the second predictor pool (PP2) was created using chronologies located within 100 kilometers of the Wind River drainage. Finally, a third predictor pool (PP3) was created by removing the two shortest site chronologies (BLE and FSE), thereby extending the length of potential reconstructions to at least 1603. Pool sizes ranged between 5 and 23 potential predictors.

Modeling Streamflow

Forward and backward stepwise regression was utilized to develop streamflow reconstructions (Draper and Smith, 1998). Predictors were entered into and retained in the model at an F-level with $p < 0.05$. The strength and fit of the regression model was evaluated using a variety of measures including R^2, adjusted R^2, cross-validation standard error (CVSE) (Weisberg, 1980), prediction sum of squares test (PRESS) (Weisberg, 1980; Maidment, 1993), F level, and Mallows' Cp (Weisberg, 1980). Multicollinearity of the predictors was also investigated using the variance inflation factor (Haan, 2002), and the Durbin-Watson statistic (Draper and Smith, 1998) was used to examine autocorrelation within the residuals. To avoid over-fitting, the stepwise process was stopped when the root mean square error (RMSE) (Weisberg, 1980) increased from one step to the next. Resulting reconstructions were tested for normality using the Kolomogorov-Smirnov test (Maidment, 1993).

Two additional regression approaches, Principal Component Regression (PCR) and Partial Least Squares Regression (PLSR) were also investigated. PCR can take advantage of spatial patterning in the climate system to improve tree-ring based reconstructions, and PCR has been widely used in paleohydrology (e.g., Woodhouse *et al.*, 2006). Likewise PLSR has shown the potential for improving total variance explained in past tree-ring studies (Kalela-Brundin, 1999). However, in the present case PCR-based reconstructions for each gage performed poorly compared to stepwise versions (e.g., r^2 roughly 0.1-0.2 lower), and PLSR-based models showed signs of significant over-fitting (e.g., high Mallows' Cp). Therefore we limited our subsequent analyses to the stepwise reconstructions.

RESULTS

Streamflow Reconstructions

For the gage at Bull Lake Creek, stepwise regression on all available predictors (PP1) and only those predictor chronologies within 100 km of the Wind River Basin (PP2) both yielded reconstructions spanning 1672-2000 AD (Table 3). However, the reconstruction based on PP1 explained a higher percentage of the variance in streamflow when compared to the PP2 model ($r^2 = 0.59$ *vs.* 0.49). Removing the two shortest tree-ring records (BLE and FSE) from the pool resulted in a 485 years reconstruction that explained 64% of the variability in observed streamflow, despite the fact that these chronologies were among the closest to Bull Lake Creek.

Total variance explained was similar across all of the Wind River at Dubois gage reconstructions ($r^2 = 0.41$ to 0.42), but the PP3 version begins in 1603 AD as opposed to 1672 for PP1 and PP2. In the case of the Little Popo Agie the stepwise procedure resulted in identical reconstructions from PP1 and PP3 that span 1560 to 2000 AD. Again these models using a wider network of predictors (i.e., PP1 and PP3) accounted for a larger portion of the variability in observed streamflow when compared to the basin-limited PP2 model ($r^2 = 0.58$ *vs.* 0.43). The resulting PP1/PP3 reconstruction was also 112-years longer.

Wet year (e.g., 1986) and dry year (e.g., 1977) flows within the gage records were well represented in all versions of the reconstructions, as were extreme drought years (e.g., 1902, 1934, and 1955) known from regional precipitation records (Figure 2). Longer-term trends and multi-year wet/dry events were also captured by the reconstructions. In particular both the 1950s drought and wetness in the 1980s are evident in the reconstructions, as is the infamous 1930s drought and an early 20th Century pluvial. However, tree-ring estimated discharge volumes in high-flow years tended to be lower than those in the actual observations (Figure 2, Table 4). Flows for the driest years in the Little Popo Agie River and Wind River reconstructions were higher than in the instrumental record, but the minimum flow from the PP1 reconstruction at Bull Lake Creek was less than the minimum flows recorded at that gage. During the period of overlap the reconstructions and gages have similar skews (not shown), and all stream reconstructions were determined to be normally distributed.

Preinstrumental Streamflow Variability

Gauged mean flows and mean flows from the preinstrumental portions of the reconstructions were similar (Table 4). Likewise the highest flows in the preinstrumental tree-ring estimates were similar in magnitude to the highest flows in the instrumental observations. The one exception was Bull Lake Creek, where the estimated flow in 1843 AD exceeded the instrumental period's (1967-2000) highest flow by

TABLE 3. Calibration and Verification Statistics for the Reconstructed Gage Records.

Gage	Predictors (Used/Pool)	Recon Start Year	R^2	R^2 (adjusted)	R^2 (PRESS)	F^*	RMSE (mcm)	CVSE (mcm)
Bull Lake Creek								
PP1	3/15	1672	0.59	0.55	0.50	14.41	38.81	42.13
PP2	2/5	1672	0.49	0.46	0.40	14.85	42.63	45.63
PP3	2/13	1516	0.64	0.61	0.56	18.07	36.19	39.62
Little Popo Agie								
PP1/3	3/23 & 3/21	1560	0.58	0.55	0.50	22.55	16.34	17.49
PP2	2/5	1672	0.43	0.40	0.35	18.95	18.8	19.76
Wind River								
PP1/2	2/11 & 2/5	1672	0.40	0.38	0.33	14.39	30	31.43
PP3	2/10	1603	0.41	0.38	0.34	15.19	29.9	31.33

Note: Results obtained when using each of the three potential predictor pools are shown for all gages.

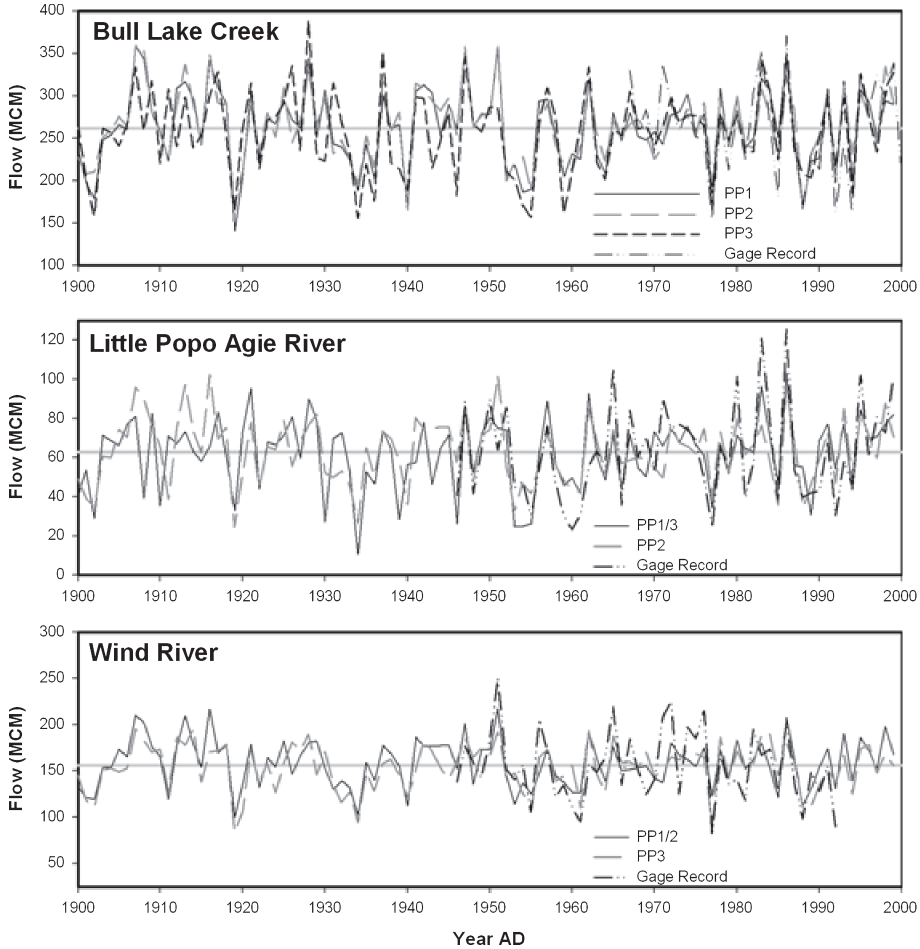

FIGURE 2. Comparisons Between Tree-Ring Reconstructed Flows and Gaged Flows at the Three Study Sites. Values are plotted against gage mean (horizontal gray line).

TABLE 4. Descriptive Statistics for Observed and Reconstructed Flows at Each Gage.

	Instrumental Period				Reconstructed Period			
Gage Name	**Mean**	**Standard Deviation**	**Min (year)**	**Max (year)**	**Mean**	**Standard Deviation**	**Min (year)**	**Max (year)**
Bull Lake Creek								
Observed	262.3	57.8	155.7 (1977)	370.6 (1986)				
PP1	262.3	48.6	127.1 (2000)	345.5 (1986)	258.1	48.3	127.1 (2000)	392.2 (1676)
PP2	262.3	40.4	168.3 (1988)	334.8 (1998)	260.7	45.6	132.6 (1795)	387.3 (1676)
PP3	262.3	46.4	153.6 (2000)	349.5 (1986)	252.8	54.6	115.1 (1607)	461.5 (1843)
Little Popo Agie								
Observed	62.7	24.4	23.2 (1960)	125.6 (1986)				
PP1/3	62.7	18.5	24.8 (1953)	103.5 (1986)	60.8	19.5	2.2 (1855)	110.1 (1768)
PP2	62.7	15.9	33.0 (1953)	102.1 (1951)	62.5	18.5	7.1 (1717)	118.4 (1676)
Wind River								
Observed	155.3	38.0	80.4 (1977)	249.9 (1951)				
PP1/2	155.3	24.2	112.9 (1988)	217.7 (1951)	156.8	28.8	75 (1717)	244.4 (1676)
PP3	155.3	24.3	89.4 (1977)	193.3 (1962)	148.9	28.3	67.5 (1695)	226 (1564)

Note: Units are millions of cubic meters (mcm).

~74 mcm. At Bull Lake Creek, preinstrumental minimum flows were noticeably lower than the observations, but still within one standard deviation of the gauged minimum. Preinstrumental estimates for minimum flows on the Little Popo Agie and Wind River fall well below those from the gages.

Examination of the full Bull Lake Creek PP3 reconstruction, the reconstruction with the greatest length of record and representing the highest total discharge, shows marked interannual variability in preinstrumental streamflow (Figure 3a). Changes in total discharge from one year to the next regularly exceed 100 mcm in the preinstrumental period, with a maximum change of ~270 mcm from 1842 to 1843 AD. The preinstrumental period also contains several remarkable runs of below-average streamflow years when compared to the gage record, the longest being from 1566 to 1576. After a single wet year this dry run continues through 1582. Likewise during the period from 1703 to 1718 only one year exceeds the gage-period mean. The longest uninterrupted runs of severe dry years (25th percentile or lower) span two four-year periods from 1887 to 1890 and 1952 to 1955. With five years above the 75th percentile, the period from 1601-1605 is the wettest uninterrupted run in the reconstruction. The longest runs above the 75th percentile in the gage record lasted just two years (1982-1983 and 1998-1999).

The full Bull Lake Creek record also contains marked variability over multi-year to decadal time scales (Figure 3b). Of particular significance are two dry periods from roughly 1875 to 1900 and 1570 to 1600 AD when 10-years average flows on Bull Lake Creek dropped to 240 mcm or below. Neither event featured more than one or two extreme drought years (i.e., less than 5th percentile), but a preponderance of

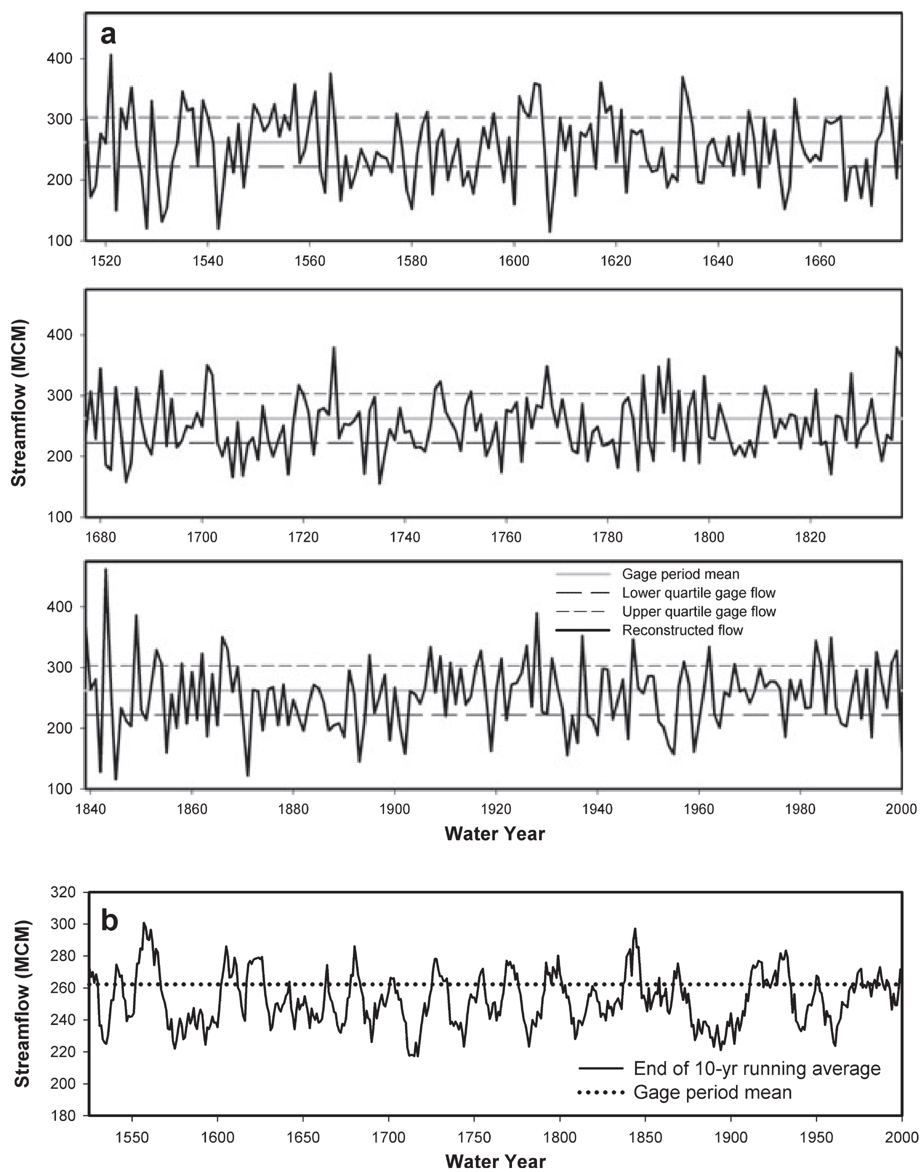

FIGURE 3. Reconstructed Streamflow for Bull Lake Creek. Upper plots (a) show estimated water-year streamflow *vs.* gage period observations. Lower plot (b) shows 10-year averages for estimated flow *vs.* gage period mean.

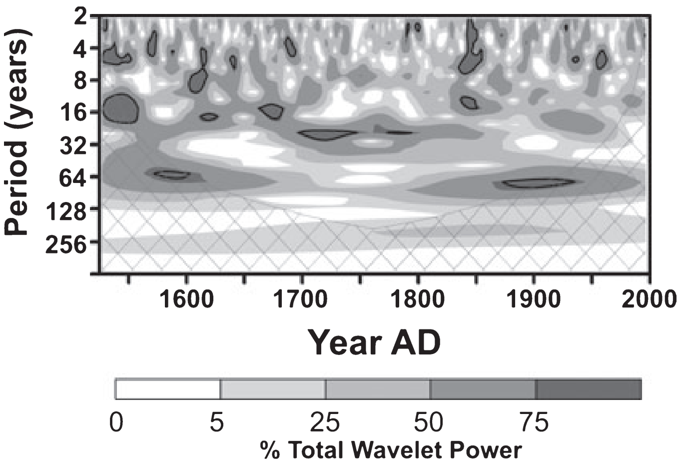

FIGURE 4. Wavelet Power Spectra for Reconstructed Streamflows at the Bull Lake Creek Gage. Black contours represent the 95% confidence level for signals within the spectrum, and the cone-shaped net shows areas where the power spectrum may not be fully resolved (Torrence and Compo, 1998).

moderate dry years and a lack of years above the 75th percentile suppressed cumulative discharge over decadal time scales. The earlier of these two periods coincides with the well-known "megadrought" of the late 16th Century (Stahle *et al.*, 2000). The late-19th Century low-flow event occurred during an intense drought that affected much of the western U.S., with this dryness being particularly severe in the Colorado River Basin (Cook *et al.*, 2004; Woodhouse *et al.*, 2006). In the context of this extended record the "worst case" drought scenarios of the 1930s and 1950s are regularly exceeded in both duration and magnitude. Likewise such extended low-flow periods are intermixed with persistent wet events, the most notable of which occurred in the mid 1500s. Spectral analysis (Torrence and Compo, 1998) reveals that this switching between predominately wet/dry regimes is couched in significant decadal to multi-decadal variability (Figure 4), with peak power centered on periods of ~24 and 64 years. However, spectral analysis also reveals that the dominant frequencies and strength of this lower-frequency variability changes through time, and that the progression of wet/dry regimes is far from cyclic.

DISCUSSION

Applications for Small-Tributary and Headwaters Reconstructions

The analyses presented here further demonstrate that tree rings can be used to estimate small tributary and headwaters' flows with significant skill, and the resulting reconstructions can extend for hundreds of years into the past. In turn such reconstructions offer a unique means for placing observed flows in a longer-term and more data-rich context (Woodhouse *et al.*, 2006). In the case of the Bull Lake Creek reconstruction, we see that apparent extremes in recent records such as the 1930s and 1950s droughts have been "business as usual" in the past, and actual observations cover only a small range of the potential hydroclimatic variability in this drainage basin. Moreover, these reconstructions present novel scenarios for runs of wet or dry years, rapid switching between wet and dry regimes, and inter-annual variability that are well outside the bounds of the gage record. Such tree-ring derived scenarios can be used to better assess the potential for severe sustained drought (Tarboton, 1995; Young, 1995) and test the ability of water systems to meet future demand (Harding *et al.*, 1995; Jain *et al.*, 2002; Woodhouse and Lukas, 2006).

A growing number of studies address how tree-ring based estimates of past streamflow or climate can be viewed in a probabalistic framework (see Enfield and Cid-Serrano, 2006; Meko and Woodhouse, 2009). These approaches show great promise for facilitating the application of paleoclimatic reconstructions to real-world problems in natural resource management, while at the same time recognizing the uncertainty inherent in these proxy records. Probabalisitic analyses may be especially relevant in small tributary or headwaters gages if short calibration records or other factors introduce a relatively large amount of uncertainty into the resulting reconstructions.

In all of the cases mentioned above, similar analyses could be performed on data generated via statistical or process-based models. However, tree-ring reconstructions offer insights into the range of natural streamflow variability that are grounded in a well-established physical linkage between climate and tree growth. In addition tree-ring reconstructions offer a means to examine longer-term (i.e., decadal to multi-decadal) variability and trends that may not be well-represented in shorter records or simulation data (Gray *et al.*, 2003).

Limitations on Small-Tributary and Headwaters Reconstructions

While these results show the potential for reconstructing small tributary and headwaters gages, they also demonstrate the need for an added measure of caution when working with such records. Lack of high-quality calibration data can be especially acute for small tributary and headwaters gages. To illustrate the potential influence of a short calibration period on reconstructions we divided observations from the Little Popo Agie gage, the longest available observational record from our study area (54 years), into a series of overlapping 30-year segments. The Little Popo Agie reconstruction was then recalibrated on each of these shortened segments. In terms of interannual variability the original reconstruction and versions calibrated on the shortened records were quite similar (Figure 5a). However, the original reconstruction and versions calibrated on the shorter records did show important differences for running means calculated over windows of ~10 years or longer (Figure 5b). Differences in running means were greatest when comparing reconstructions calibrated on the earliest segments of the gage record against those calibrated on the most recent segments, suggesting some temporal bias in the observations. This may result from the presence of the 1950s drought in the early calibration subset, whereas the later subset contains several relatively wet years. In any case, the resulting reconstructions may be tuned to different aspects of regional hydroclimatic variability [e.g., some versions reconstructions are better at capturing wet (dry) years than at capturing dry (wet)]. However, different predictors were also used in the early and late-period reconstructions, so it is likely that changes in both calibration data and tree-ring data led to these disparities. Similar effects of calibration datasets and predictor pools have been observed for reconstructions of high-volume gages (e.g., Woodhouse *et al.*, 2006), but the overall impact is especially pronounced here.

Another perceived issue with small tributary and headwaters reconstructions is an apparent lack of suitable tree-ring data for drainages of interest. In our experience we have seen that water managers often harbor the misconception that the trees used in dendrohydrologic reconstructions must come from within the boundaries of the watershed being studied. This, in turn, would necessitate the development of new tree-ring chronologies before reconstructing streamflow, which can be time-consuming and cost-prohibitive. Moreover, trees suitable for use in dendrohydrology are not evenly distributed throughout a region, and sampling of tree-ring sites is more often governed by the availability of trees and access than it is by the boundaries of a watershed (Fritts, 1976).

As in past studies (e.g., Woodhouse and Lukas, 2006; Woodhouse *et al.*, 2006) the results presented here demonstrate that tree-ring collections from within a watershed of interest are not a requirement

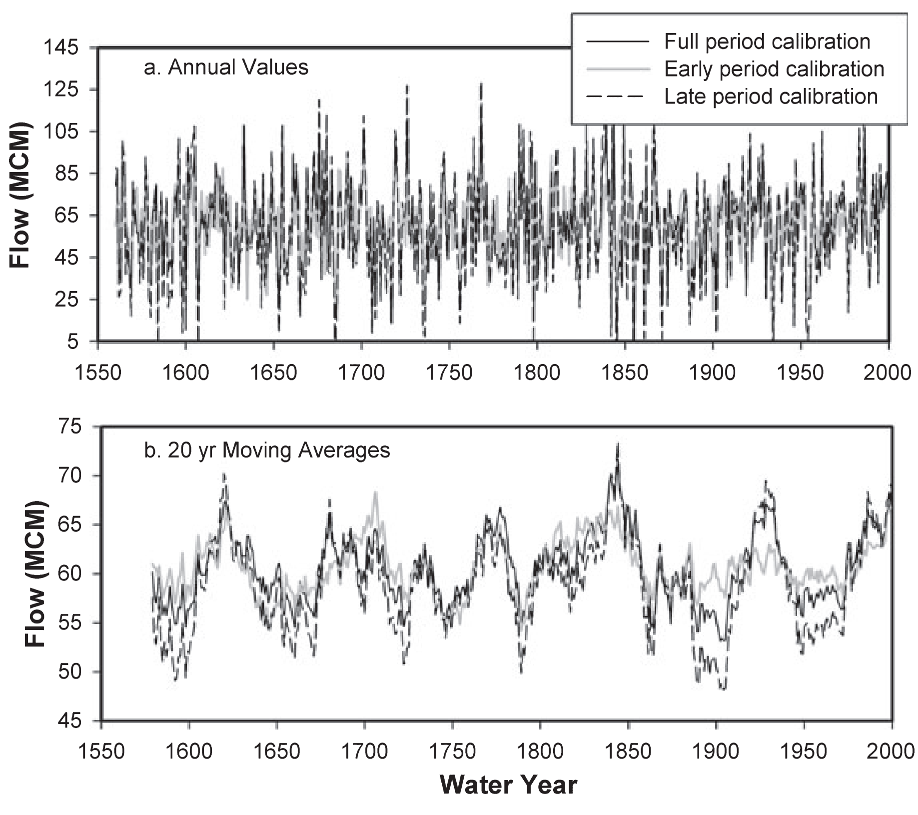

FIGURE 5. Comparisons of Reconstructed Flows at the Little Popo Agie Gage Calibrated Against the Full Gage Record (1946-1999), Earliest 30 Years of Gage Record, and Most Recent 30 Years of Gaged Flows. Plots for both annual values (a) and 20-years moving averages (b) are shown.

for the generation of statistically robust reconstructions. In fact, having a wide spatial network of sites that incorporates data from surrounding regions is often the more desirable scenario. Limited access to tribal lands, recent fires, and a scarcity of suitable trees meant that only two potential predictor chronologies were available from sites within our study drainage. One of these chronologies (RCU) did not enter into any of the models, and tree growth at this site showed relatively weak correlations with streamflow in the Wind River Basin. Instead tree growth on the opposite (i.e., west) side of the Wind River Mountains was moderately to strongly correlated ($r > 0.4$) with streamflow at our study gages, as was tree growth at sites >200 km away (Figure 6a). As illustrated by mapping correlations between streamflow in the Wind River Basin and April 1st snowpack in surrounding regions (Figure 6b), a wide network of tree-ring sites allows the reconstruction to capture important synoptic features of the region's climate. More specifically, in the Wind River Basin streamflow is largely a product of winter snowpack in the surrounding mountains, and the majority of this snow results from large winter storm systems that enter the region from the west (Mock, 1996; Gray *et al.*, 2004a). Allowing sites as far away as northeastern Utah or southwestern Montana into the predictor pools resulted in reconstruction models that combine information on these winter storm tracks with information on localized moisture variability. Moreover, some tree species are known to possess relatively-high sensitivity to the climatic factors that drive streamflow in our study area (Fritts, 1976; Woodhouse *et al.*, 2006). In the cases presented here a wide network of sites allowed us to capitalize on the strong relationship between ring-widths in piñon pine from northeastern Utah and southern Colorado (Figure 6a) and regional snow water equivalent during the late spring and early summer months. Many of the tree-ring chronologies available in or adjacent to the Upper Wind River were developed from limber pine, and many of these records were not significantly correlated with streamflow at our study area gages (Figure 6a).

Choices made in the processing of tree-ring data, selection of statistical reconstruction methodology, availability of predictor chronologies, and the length or quality of calibration records all introduce various levels of uncertainty into any dendrohydrological reconstruction (Woodhouse *et al.*, 2006; Meko and Woodhouse, 2009). The impact of these factors – especially the availability of high-quality calibration data – may be especially pronounced when dealing with small tributary and headwaters streams. Detailed sensitivity analyses and ensemble approaches can aid in identifying or overcoming many of these potential issues. Researchers should consider producing a suite of reconstructed flow scenarios, and researchers should work with end-users to select the appropriate reconstructed dataset for a given application. Overall, dendrohydrology offers a unique window into long-term hydroclimatic variability in the Wind River drainage, and a means to better examine the range of natural streamflow variability in this region. Results showing pronounced interannual variability and periods of significant decadal to multidecadal variability in preinstrumental streamflows, and the prevalence of severe, sustained droughts should be of particular interest to water resource managers.

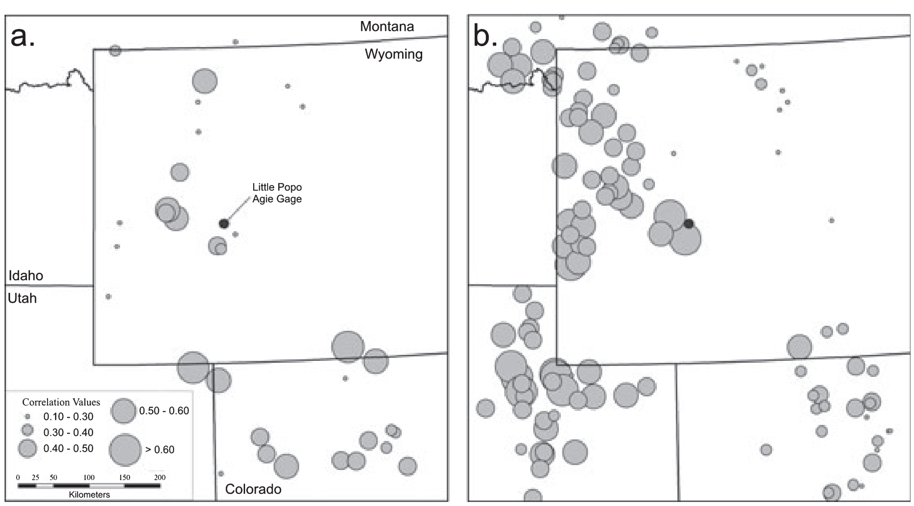

FIGURE 6. Correlations Between Gaged Flows on the Little Popo Agie River and Both Tree-Ring Widths (a) and April 1 Snow Water Equivalent (b) at Sites in the Surrounding Region. Snow data courtesy Tom Pagano, NRCS.

CONCLUSIONS

In spite of the challenges they present, this work again shows that small tributary and headwaters gages can be successfully reconstructed from tree rings. When used in conjunction with instrumental records and model simulations, these tree-ring based estimates should provide an improved basis for decision support systems and a foundation for understanding future water availability. This role in decision support is particularly important in western North America given the combined pressures of climate change, growing human populations, and changing water uses that the region faces. While tree rings cannot speak directly to many of these human issues, they do provide a unique record of natural variations, and it is upon these natural variations that future water supply and demand will be superimposed (Meko and Woodhouse, 2009).

ACKNOWLEDGMENTS

This research was sponsored by the Wyoming Water Development Commission, the USGS/State of Wyoming Water Research Program and the University of Wyoming Office of Water Programs. The authors wish to thank Connie Woodhouse and Jeff Lukas for providing training in field efforts and processing of tree-ring collections. Additionally, the authors wish to thank Tom Pagano for providing snowpack data. Finally, the authors wish to thank the three anonymous reviewers for their helpful comments.

LITERATURE CITED

Belsky, A.J., A. Matzke, and S. Uselman, 1999. Survey of Livestock Influences on Stream and Riparian Ecosystems in the Western United States. Journal of Soil and Water Conservation 54:419-431.

Biondi, F. and K. Waikul, 2004. DENDROCLIM2002: A C++ Program for Statistical Calibration of Climate Signals in Tree-Ring Chronologies. Computers & Geosciences 30:303-311.

Cook, E.R., 1985. A Time Series Approach to Tree-Ring Standardization, Ph.D. dissertation. University of Arizona, Tucson, Arizona.

Cook, E.R. and L.A. Kairiukstis, 1990. Methods of Dendrochronology: Applications in the Environmental Sciences. Kluwer Academic Publishers and International Institute for Applied System Analysis, Dordrecht, The Netherlands.

Cook, E.R., D.M. Meko, D.W. Stahle, and M.K. Cleaveland, 1999. Drought Reconstructions for the Continental United States. Journal of Climate 12:1145-1162.

Cook, E.R., C.A. Woodhouse, C.M. Eakin, D.M. Meko, and D.W. Stahle, 2004. Long-Term Aridity Changes in the Western United States. Science 306:1015-1018.

Draper, N.R. and H. Smith, 1998. Applied Regression Analysis (Third Edition). Wiley, New York, pp. 69 & 330-346.

Enfield, D. and L. Cid-Serrano, 2006. Projecting the Risk of Future Climate Shifts. International Journal of Climatology 26:885-895.

Fritts, H.C., 1976. Tree Rings and Climate. Academic Press, London, United Kingdom.

Gedalof, Z., D.L. Peterson, and N.J. Mantua, 2004. Columbia River Flow and Drought Since 1750. Journal of the American Water Resources Association 40(6):1579-1592.

Graumlich, L.J., M.F.J. Pisaric, L.A. Waggoner, J.S. Littell, and J.C. King, 2003. Upper Yellowstone River Flow and Teleconnections With Pacific Basin Climate Variability During the Past Three Centuries. Climatic Change 59(1-2):245-262.

Gray, S.T., J.L. Betancourt, C.L. Fastie, and S.T. Jackson, 2003. Patterns and Sources of Multidecadal Oscillations in Drought-Sensitive Tree-Ring Records From the Central and Southern Rocky Mountains. Geophysical Research Letters 30:491-494, doi:10.1029/2002GL016154.

Gray, S.T., C. Fastie, S.T. Jackson, and J.L. Betancourt, 2004a. Tree-Ring Based Reconstructions of Precipitation in the Bighorn Basin, Wyoming Since AD 1260. Journal of Climate 17:3855-3865.

Gray, S.T., L.J. Graumlich, and J.L. Betancourt, 2007. Annual Precipitation in the Yellowstone National Park Region Since AD 1173. Quaternary Research doi:10.1016/j.yqres.2007.02.002, 68: 18-27.

Gray, S.T., S.T. Jackson, and J.L. Betancourt, 2004b. Tree-Ring Based Reconstructions of Interannual to Decadal-Scale Precipitation Variability for Northeastern Utah. Journal of the American Water Resources Association 40:947-960.

Guttman, N.B., and R.G. Quayle, 1996. A Historical Perspective of U.S. Climate Divisions. Bulletin of the American Meteorological Society 77:293–303.

Haan, C.T., 2002. Statistical Methods in Hydrology (Second Edition). Iowa State University Press, Ames, Iowa. 378 pp.

Harding, B.L., T.B. Sangoyomi, and E.A. Payton, 1995. Impacts of a Severe Sustained Drought on Colorado River Water Resources. Water Resources Bulletin 31(5):815-824.

Holmes, R.L., 1983. Computer-Assisted Quality Control in Tree-Ring Dating and Measurement. Tree-Ring Bulletin 43:69-95.

ITRDB (International Tree Ring Data Bank), 2007. Tree-Ring Data Search. http://hurricane.ncdc.noaa.gov/pls/paleo/fm_createpages.treering, *accessed* November, 2007.

Jain, S., C.A. Woodhouse, and M.P. Hoerling, 2002. Multidecadal Streamflow Regimes in the Interior Western United States: Implications for the Vulnerability of Water Resources. Geophysical Research Letters 29(21):2036, doi:10.1029/2001GL014278.

Kalela-Brundin, M., 1999. Climatic Information From Tree-Rings of Pinus Sylvestris L. and a Reconstruction of Summer Temperatures Back to A.D. 1500 in Femundsmarka, Eastern Norway, Using Partial Least Squares Regression (PLSR) Analysis. The Holocene 9:59-77.

Maidment, D.R. (Editor) 1993. Handbook of Hydrology. McGraw-Hill, Inc., New York, 1424 pp.

Meko, D.M., M.D. Therrell, C.H. Baisan, and M.K. Hughes, 2001. Sacramento River Flow Reconstructed to A.D. 869 From Tree Rings. Journal of American Water Resources Association 37:1029-1039.

Meko, D.M. and C.A. Woodhouse, 2009. Dendroclimatology, Dendrohydrology, and Water Resources Management. *In:* Dendroclimatology, Progress and Prospects, M.K. Hughes, T.W. Swetnam, and H.F. Diaz. (Editors). Springer, New York. In press.

Mock, C.J., 1996. Climatic Controls and Spatial Variations of Precipitation in the Western United States. Journal of Climate 9:1111-1125.

Pagano, T., D. Garen, and S. Sorooshian, 2004. Evaluation of Official Western U.S. Seasonal Water Supply Outlooks, 1922-2002. Journal of Hydrometeorology 5:896–909.

Peterson, T.C. and D.R. Easterling, 1994. Creation of Homogeneous Composite Climatological Reference Series. International Journal of Climatology 14:671-680.

Slack, J.R., A. Lumb, and J.M. Landwehr, 1993. Hydro-Climatic Data Network (HCDN) Streamflow Data Set, 1874-1998. CD-ROM. U.S. Geological Survey, Reston, Virginia, U.S.A. Available from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. http://www.daac.ornl.gov, *accessed* June, 2007.

Stahle, D.W., E.R. Cook, M.K. Cleaveland, M.D. Therrell, D.M. Meko, H.D. Grissino-Mayer, E. Watson, and B.H. Luckman, 2000. Tree-Ring Data Document 16th Century Megadrought Over North America. EOS: Transactions of the American Geophysical Union 81(12):121.

Stokes, M.A. and T.L. Smiley, 1968. An Introduction to Tree-Ring Dating, University of Arizona Press, Tucson, Arizona.

Swetnam, T.W., M.A. Thompson, and E.K. Sutherland, 1985. Using Dendrochronology to Measure Radial Growth of Defoliated Trees. USDA Forest Service, Agriculture Handbook 639. 39 pp.

Tarboton, D.G., 1995. Hydrologic Scenarios for Severe Sustained Drought in the Southwestern United States. Water Resources Bulletin 31(5):803-814.

Tootle, G.A. and T.C. Piechota, 2006. Relationships Between Pacific and Atlantic Ocean Sea Surface Temperatures and U.S. Streamflow Variability. Water Resources Research 42:W07411.

Torrence, C. and G.P. Compo, 1998. A Practical Guide to Wavelet Analysis. Bulletin of the American Meteorological Society 79:61-78.

Weisberg, S., 1980. Applied Linear Regression. John Wiley & Sons, New York, New York.

Wigley, T., K. Briffa, and P.D. Jones, 1984. On the Average Value of Correlated Time Series, With Applications in Dendroclimatology and Hydrometeorology. Journal of Applied Meteorology 23:201-213.

Woodhouse, C.A., 2001. A Tree-Ring Reconstruction of Streamflow for the Colorado Front Range. Journal of American Water Resources Association 37:561-569.

Woodhouse, C.A., S.T. Gray, and D.M. Meko, 2006. Updated Streamflow Reconstructions for the Upper Colorado River Basin. Water Resources Resesearch 42:W05415, doi:10.1029/2005WR004455.

Woodhouse, C.A. and J.J. Lukas, 2006. Drought, Tree Rings, and Water Resource Management. Canadian Water Resources Journal 31:297-310.

Wyoming Water Development Commission (WWDC), 2007. Wyoming Framework Water Plan: Vol I. http://waterplan.wrds.uwyo.edu/fwp, *accessed* December 2007.

Young, R.A., 1995. Coping With a Severe Sustained Drought on the Colorado River: Introduction and Overview. Water Resources Bulletin 31(6):779-788.