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MILLENNIAL-LENGTH RECORDS OF STREAMFLOW FROM THREE MAJOR UPPER COLORADO RIVER TRIBUTARIES[1]

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ABSTRACT: Drought, climate change, and shifting consumptive use are prompting a widespread reassessment of water availability in the Upper Colorado River basin. Here, we present millennial-length records of water year (October-September) streamflow for key Upper Colorado tributaries: the White, Yampa, and Little Snake Rivers. Based on tree rings, these records represent the first paleohydrological reconstructions from these subbasins to overlap with a series of Medieval droughts (~AD 800 to 1300). The reconstructions show marked interannual variability imbedded in nonstationary behavior over decadal to multidecadal time scales. These reconstructions suggest that, even in a millennial context, gaged flows from a handful of years (e.g., 1977 and 2002) were extremely dry. However, droughts of much greater duration and magnitude than any in the instrumental record were regular features prior to 1900. Likewise these reconstructions point to the unusual wetness of the gage period, and the potential for recent observations to paint an overly optimistic picture of regional water supplies. The future of the Upper Colorado River will be determined by a combination of inherent hydroclimatic variability and a broad range of human-induced changes. It is then essential that regional water managers, water users, and policy makers alike consider a broader range of hydroclimatic scenarios than is offered by the gage record alone.

(KEY TERMS: drought; paleoclimate; paleohydrology; tree rings; Upper Colorado River basin; Yampa River; White River; Little Snake River.)

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INTRODUCTION

Over the past decade severe drought conditions in the western United States (U.S.) have driven a growing interest in the range of natural hydrologic variability that has occurred over past centuries to millennia. Concerns related to the detection and prediction of anthropogenic climate-change impacts have also further increased calls for datasets that capture long-term hydroclimatic variability in the region. The Upper Colorado River basin has been the focus of a large number of studies that have used tree rings to reconstruct past flows (e.g., Stockton and Jacoby, 1976; Hidalgo *et al.*, 2000; Woodhouse *et al.*, 2006; Meko *et al.*, 2007). These reconstructed streamflow records

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are increasingly used in water resource management and drought planning (Rice *et al.*, 2009). In this study, we target two major tributaries of the Green River that are often overlooked because of the relative lack of historical development of their water resources: the Yampa River with its tributary, the Little Snake River, and the White River. Together, these rivers account for over 40% of the Green River's contribution to the Colorado River. The Green River in turn accounts for ~36% of the total annual Colorado River flow at Lees Ferry, Arizona, which is the key point for determining compact compliance among the seven western states (Wyoming, Colorado, Utah, New Mexico, Arizona, Nevada, and California) that depend on this water.

The Yampa, Little Snake, and White Rivers are among the only remaining rivers in the Colorado River basin that still largely feature natural flow regimes. With no major mainstem impoundments and relatively low consumptive use, these rivers provide key habitats for native fish – some of which are threatened or endangered – along with a wide range of recreational uses. But this may change soon with the prospect of large diversions for water-intensive development of gas and oil shale resources within the Yampa and White basins, and for urban water demand in Colorado's Front Range. A better understanding of the range of past hydrologic variability, including the nature of pluvials and droughts, is critical to an accurate assessment of how much water the Yampa and White basins might yield for development, and how such development might impact aquatic biota and nonconsumptive uses. While future planning efforts must now consider the regional impacts of anthropogenic climate change, knowledge about the long-term natural variability provides the necessary baseline for that planning.

As in previous studies, we use the extended records of annual streamflow to assess the gage record in the context of a much longer period of time, here the past millennium. The distribution and frequency of extreme single year low flows in the Yampa, Little Snake, and White River reconstructions, and the spatial extent of these extreme years across the Colorado River basin are then evaluated by combining our results with existing reconstructions (Woodhouse *et al.*, 2006). To assess and compare the various flavors of extreme wet and dry multiyear events, we use runs analysis (Salas *et al.*, 1980) paired with stochastic modeling of flows (Biondi *et al.*, 2002, 2005). In particular, we explore key drought characteristics – duration, magnitude, and intensity – for the study watersheds. Because the so-called Medieval Climate Anomaly (~AD 800 to 1350) is notable for sustained drought conditions in the Colorado River basin and the western U.S. as a whole (Cook *et al.*, 2004; Meko *et al.*, 2007), we focus on regional expressions of streamflow during this period. Finally, we discuss the implications these records have for management of these still relatively undeveloped watersheds, in light of increasing demands and future climate change.

MATERIALS AND METHODS

The Yampa, White, and Little Snake River Basins

The Yampa and White River basins together cover 34,500 km^2 in northwest Colorado and south-central Wyoming (Figure 1). The Little Snake River is the largest tributary of the Yampa River, and joins below

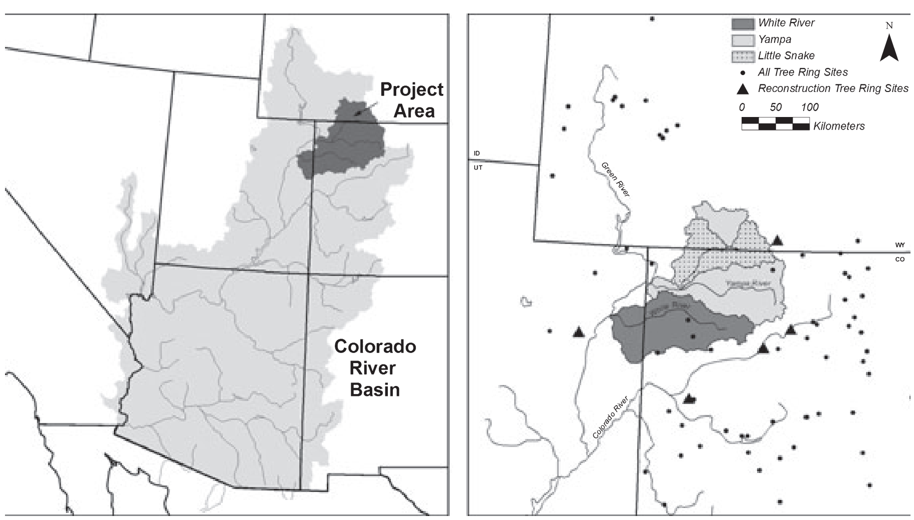

FIGURE 1. Maps Showing the Colorado River Basin (left) With the Project Area Depicted in Dark Gray, and the Project Subbasins (right) Shown Along With Major Colorado River Tributaries and Tree-Ring Sites.

the Maybell gage. Both the Yampa and White Rivers discharge into the Green River, itself the principal tributary of the Colorado River. Elevations in the Yampa and White basins range from 1,500 m at the mouth of the White River up to 3,700 m in the headwaters of the Yampa and White Rivers. The headwaters of the upper Yampa River in the Park Range are ideally positioned to wring moisture from the prevailing westerly and northwesterly flow during the cool season, building prodigious winter snowpacks. The Tower automated snow observing (SNOTEL) site in the upper Yampa basin has the highest mean April 1 snow-water equivalent (116 cm) of all of the >100 SNOTELs in the Upper Colorado River basin. Accordingly, the mainstem Yampa River, as measured at the Maybell gage, contributes over half of the total flow of the Yampa and White basins from about one-quarter of its total area.

The Yampa and White River basins are lightly populated (<1 person/km^2), and the local economy relies primarily on agriculture, tourism, and recreation (CWCB, 2006). The main uses of water are for agriculture (primarily hay pasture and alfalfa), coolant for power generation plants, and municipal use. The city of Cheyenne in southeast Wyoming, through transbasin diversions and water transfers, is the largest municipal user of Yampa basin water (CWCB, 2004). Basin-wide, current consumptive use represents only about 10% of mean annual flow. However, gross water demand for nonagricultural uses is projected to nearly double by 2030 (CWCB, 2009).

Because the Yampa and White Rivers represent much of the water in the Upper Colorado River basin that is still unappropriated and available for consumptive use, these rivers are increasingly attractive to those seeking new water supplies. In 2006, a large water utility serving municipal and agricultural use in northeastern Colorado investigated the feasibility of a project that could divert more than 240 MCM annually from the Yampa River below the Maybell gage (~25% of the river's mean flow) and convey it by pipeline over 400 km to Colorado's Front Range (NCWCD, 2006). More recently, with a revival of oil-shale projects in northwest Colorado, a major energy company applied for a conditional right for 11 m^3/s of flow from the Yampa River, or about 20% of mean flow. The scale of these two potential future diversions dwarfs the current uses in the Yampa River basin, and would dramatically impact the flow regime of the Yampa River. The White River is also facing increased diversion for both oil-shale and natural gas development.

The Yampa River has retained its complete complement of native fish, including regionally important populations of four endangered species: the Colorado pikeminnow, razorback sucker, humpback chub, and bonytail. Water from the Yampa and White Rivers is also important for fish species in the mainstem Green River as these unregulated flows help normalize the highly modified thermal and flow regimes downstream (Benke and Cushing, 2005). Likewise recreational uses such as whitewater rafting that depend on natural flow regimes and higher water levels are growing in economic importance. These habitat needs and recreational uses will be a major consideration, if not a constraint, as water development in the Yampa and White basins moves forward.

Gage Data for Model Calibration

Estimates of natural or unimpaired streamflow covering the year 1906-2002 were obtained from the U.S. Bureau of Reclamation (J. Prairie, personal communication, 2007) for gages on each of the three rivers. These data were used as the basis for tree-ring model calibration. Specific gages (Table 1) were the Yampa River near Maybell, Colorado (U.S. Geological Survey gage #09251000); Little Snake River near Lilly, Colorado (USGS #09260000); and White River near Watson, Utah (USGS #09306500). All three gages are primary analysis nodes in the U.S. Bureau of Reclamation's Colorado River Simulation System (CRSS). The Yampa gage has previously been described as "relatively unimpaired" and records from this site were included in the Hydro-Climatic Reference Network of

TABLE 1. Gage Records Used to Calibrate the Tree-Ring Reconstructions.

Gage	USGS ID	Area Above Gage (km^2)	Mean Annual Flow (MCM)	Lag-1 Autocorrelation	Coefficient of Variation (CV)
Yampa near Maybell, Colorado	09251000	8,828	1,515	0.22	0.32
Little Snake near Lilly, Colorado	09260000	9,657	571	0.17	0.36
White near Watson, Utah	09306500	10,407	710	0.34	0.29

Correlation Among Gage Records

	Yampa	Little Snake
Little Snake	0.86	
White	0.91	0.79

Slack *et al.* (1993). However, extensive analysis by the U.S. Bureau of Reclamation and others shows that upstream diversions for irrigation and other uses impact flows at this gage, and we used the natural streamflow estimates accordingly. Flows at the White and Yampa gages showed significant temporal autocorrelation at a lag of one year ($r = 0.34$ and 0.22, respectively). While the Little Snake gage record did show some year-to-year persistence in flows ($r = 0.17$), this was not significant at the 95% level. Based on the Kolomogorov-Smirnov test (Maidment, 1993) distributions for all three gage records were essentially normal.

Tree-Ring Data

Seventy-five chronologies from sites throughout the region were considered as potential predictors of river flow (Figure 1). Each chronology represents average annual ring-widths as measured from at least 15 and as many as 80 trees at a site, and ring-widths from each tree are converted to a common scale before averaging. Sites typically encompass a small drainage or hillslope, with an area of 1-10 hectares. These chronologies were selected for having been used in previous reconstructions of regional hydroclimatic variability for the Upper Colorado River basin and adjacent areas (e.g., Woodhouse *et al.*, 2006; Watson *et al.*, 2009), and for having annual ring-widths that are significantly correlated with precipitation at monthly to annual time scales. Of these chronologies, 27 were collected from Douglas-fir, 21 from piñon pine, 18 from ponderosa pine, and 9 from limber pine. Lag-one autocorrelation generally ranged from $r = 0.2$ to 0.4, with a few records showing $r > 0.5$. Given the significant lag-one autocorrelation found in the White and Yampa gage records, standard (i.e., serial persistence retained) chronologies were used for reconstructing flows at these gages. In the case of the Little Snake, the gage record with no significant autocorrelation, residual versions (i.e., serial persistence removed) chronologies were used. All potential predictor chronologies cover the period AD 1575 to 1997, and most are freely available through the International Tree Ring Data Bank (ITRDB; http://hurricane.ncdc.noaa.gov/pls/paleo/treering.html).

Modeling Streamflow

For each gage, the original pool of 75 predictors was reduced via a series of correlation analyses. First, unimpaired flow records for the period 1906 to 1997 were compared with overlapping tree-ring values. Chronologies with Pearson $r > 0.5$ ($p < 0.001$) were then subjected to correlation tests over half-sample subsets. Only chronologies with $r > 0.5$ over the full and $r > 0.4$ over both the early (1906 to 1951) and late (1952 to 1997) periods were allowed into the final predictor pool. We selected these stringent cut-offs for the full and half-sample subset comparisons in light of the large number of potential predictors.

The reconstruction model for each gage was selected from the final predictor pool using a stepwise regression approach outlined in Woodhouse *et al.* (2006). Briefly, predictors enter or leave the model based on *F*-level, which must show $p < 0.05$. To avoid overfitting the stepwise process was stopped when the root mean square error (Weisberg, 1980) was no longer reduced by the entry of additional predictors. Variance inflation factor (Haan, 2002) and Mallows Cp (Weisberg, 1980) were also used to test for multicollinearity of the predictors.

Initially stepwise regression produced models that allowed for streamflow reconstructions extending back to AD 1571 for the Yampa River ($r^2 = 71.4$), 1524 for the Little Snake River ($r^2 = 65.2$), and 1382 for the White River ($r^2 = 70.0$). However, further inspection of the regression results showed that the predictor pools could be narrowed to chronologies beginning in 1200 or earlier with no significant loss of variance explained. Furthermore, exclusion of the Pump House, Colorado chronology from each of the predictor pools allowed for extensions back to 1000 or earlier. The final reconstructions are a composite generated from these two longer models (Gray *et al.*, 2007; Meko *et al.*, 2007). Based on standard cut-off values related to sample depth through time and the fidelity of the overall chronology signal (Wigley *et al.*, 1984) the Pump House chronology was used in estimates for 1315 and later, but not in earlier portions of the record. Before the two longer models were combined, variance in the pre-1315 portion of the record was rescaled to match the variance in the post-1315 reconstruction.

The strength and fit of the regression models was assessed using r^2, adjusted r^2, and the reduction of error test (RE) (Fritts, 1976). Leave-one-out cross-validation was performed using the PRESS method (Weisberg, 1980; Maidment, 1993). The Durbin-Watson statistic (Draper and Smith, 1998) was used to examine autocorrelation within the residuals. Resulting reconstructions were tested for normality using the Kolomogorov-Smirnov test (Maidment, 1993).

RESULTS

Streamflow Reconstruction Models

The reconstructions for the Yampa and White River gages extend from AD 1000 to 2002, while the

TABLE 2. Calibration and Verification Statistics for the Pre-AD 1315 and Post-AD 1315 Portions of the Reconstructions.

Gage	r^2	r^2adj	RE	PRESS r^2
Post-AD 1315				
Yampa River	66.2	64.6	0.62	62.3
Little Snake River	61.1	61.1	0.57	56.7
White River	67.2	65.7	0.64	63.7
Pre-AD 1315				
Yampa River	59.8	58.5	0.56	56.2
Little Snake River	58.3	56.9	0.55	54.6
White River	61.3	60.0	0.58	57.5

reconstruction for the Little Snake starts in 996 and ends in 2001. The reconstruction models' explained variance (r^2), ranging from 58 to 67% (Table 2), compares favorably to other Colorado River basin reconstructions (Woodhouse *et al.*, 2006; Meko *et al.*, 2007). The model validation statistics, RE and PRESS r^2, suggesting that the models are skillful in estimating values not contained in the calibration dataset. Comparisons with naturalized flow values (Figure 2) show that the reconstructions capture both interannual variability and longer term trends well. Of particular note is the ability of these reconstructions to estimate flows in extreme dry years such as 1934, 1954, and 1977, although the reconstructions portray 2002 as being drier than the observations. In some of the most extreme wet years, flows are underestimated. Such systematic underestimation of extreme high-flow years is common in tree-ring studies (see Meko and Woodhouse, 2011), and the resulting reconstructions generally provide a conservative estimate of wet events. Testing revealed no problems with autocorrelation of the residuals, and the reconstructions were essentially normal. Reconstruction equations and additional information on the chronologies used to generate these estimates are contained in Table 3, and the site locations for these selected chronologies are shown in Figure 1. All of the reconstructions share predictors in common, but this is to be expected given the strong correlations between observed streamflows on these tributaries (Table 1). Furthermore, the final predictor chronologies have all been shown to have strong hydroclimatic signals in other hydroclimatic reconstructions from the Colorado River basin (e.g., Woodhouse *et al.*, 2006).

Long-Term Streamflow Variability

All three reconstructions show marked interannual variability (Figure 3). Flow estimates for the Yampa, the gage with the highest average water-year discharge, regularly fluctuate >500 MCM (34% of mean water-year flow) between years. Year to year variations on the order of 1,000 MCM (69% of mean flow) are recorded some 46 times in the Yampa reconstruction. In terms of their relative magnitude, even greater interannual swings are seen in the White and Little Snake records.

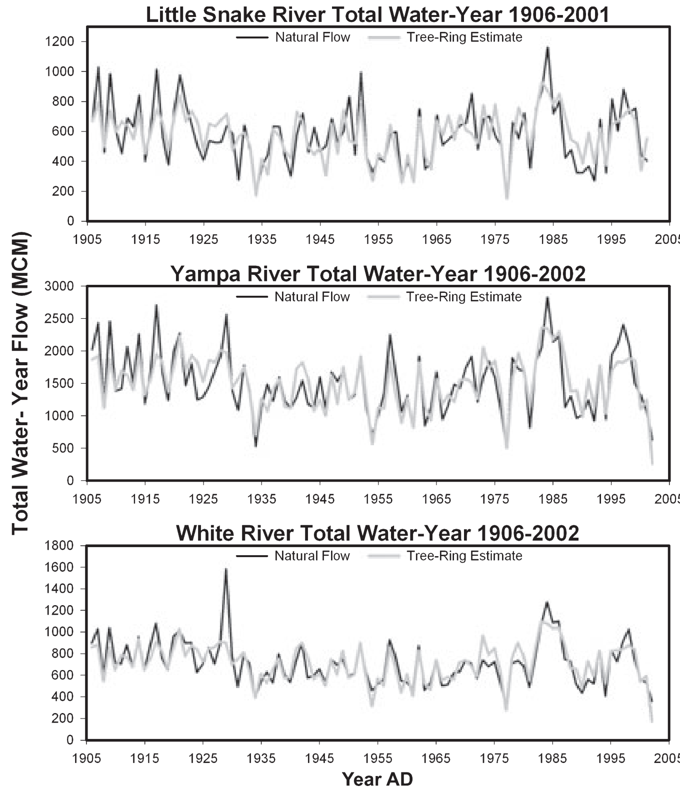

FIGURE 2. Comparison of Estimated Natural Flows on the Little Snake, Yampa, and White Rivers *vs.* Flows Estimated From Tree Rings.

Rankings of extreme (2.5th percentile) low flows for all three gages show that AD 1902 was among the driest years in the last 1,000 years (Table 4). The Little Snake reconstruction ends in 2001, but 2002 appears as an extreme low-flow year in both the White and Yampa records. On the Little Snake the year 1977 also ranks in the extreme category. Prior to 1900 the reconstructions feature numerous extreme dry years that impact all three study basins simultaneously. Severe low-flow years (10th percentile or lower) follow similar patterns of concurrent drought. In the context of these study gages, the tree-ring record suggests that the 20th Century brought relatively few single-year droughts (Table 5). For example, all three reconstructions include 6 severe low-flow years in the 20th Century, compared to an average of 10.4 per century prior to 1900. The 16th Century includes 14-16 such years in each basin.

We also compared severe (10th percentile) drought years in these records with reconstructed flows from key Upper Colorado gages: the Green River at Green

TABLE 3. Reconstruction Equations and Descriptive Information for Chronologies Used in the Final Reconstructions.

Reconstruction Equations Post-AD 1315

Yampa = −85305 + 504649 PUM + 229598 TRG + 188846 WIL + 366095 ENC

Little Snake = −76788 + 96163 TRG + 152228 WED + 126031 ENC + 139678 PUM

White = 18164 + 79008 TRG + 134108 WIL + 128327 ENC + 208476 PUM

Reconstruction Equations Pre-AD 1315

Yampa = 116043 + 508609 TRG + 200288 WIL + 375933 ENC

Little Snake = −24441 + 188390 TRG + 179476 ENC + 112749 WED

White = 101342 + 194270 TRG + 138836 WIL + 132391 ENC

Chronology Information

Site Code	Species	Latitude/Longitude	Elevation (m)	Date Range*
ENC	Douglas-fir	41.15/106.78	2,500	715-2005
PUM	Piñon pine	39.97/106.52	2,194	1175-2002
TRG	Piñon pine	39.72/106.98	2,210	996-2002
WED	Piñon pine	39.83/110.67	2,145	887-2001
WIL	Piñon pine	39.02/108.23	2,635	1000-2002

*Refers to the full period covered by these chronologies. See "Materials and Methods" section for a discussion of chronology fidelity through time.

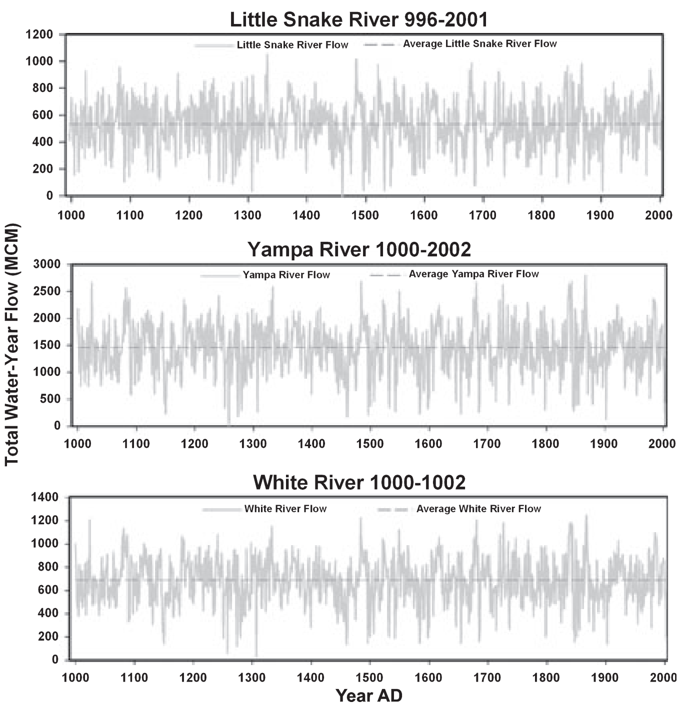

FIGURE 3. Full Reconstructions of Water-Year Flows for Each of the Three Study Gages. Annual flows (gray) are plotted against the mean for each full reconstruction period.

TABLE 4. Ranking of Extreme (2.5th percentile) Low-Flow Years in the Three Stream Gage Reconstructions, AD 998-2002.

Rank	White	Yampa	Little Snake
1	1307	1258	1460
2	1258	**1902**	1307
3	1274	1460	**1902**
4	1460	1274	1532
5	**1902**	1496	1496
6	1150	1150	1542
7	1496	1584	1685
8	1654	1654	1686
9	1584	1685	1274
10	1847	**2002**	1506
11	1685	1307	1845
12	**2002**	1542	1090
13	1251	1847	1258
14	1280	1280	1251
15	1542	1798	1871
16	1598	1598	1150
17	1798	1251	1234
18	1851	1532	1148
19	1500	1845	1824
20	1532	1500	1736
21	1686	1851	1098
22	1506	1686	1279
23	1148	1855	1584
24	1461	1736	1654
25	1879	1879	**1977**

Notes: Extreme dry years since AD 1900 are shown in bold. Note that the Little Snake reconstruction does not extend beyond 2001.

River, Wyoming; the San Juan at Bluff, Utah; the Colorado River at Cisco, Colorado; and the Colorado at Lees Ferry (from Woodhouse *et al.*, 2006). Using the Yampa River reconstruction to represent our study area, we see a strong tendency toward phasing of droughts with those in the Green River and Colorado at Cisco records (Figure 4). Of the 20 instances where severe drought years occurred simultaneously across the Yampa, Green, and Colorado headwaters gages, all were concurrent with severe low-flow years at Lees Ferry, which is consistent with these tributaries accounting for over 80% of total Upper Colorado River discharge. On 12 different occasions reconstructed flows for the San Juan, the south-

TABLE 5. Occurrence of Severe (10th percentile or less) Low-Flow Years in the Three Stream Gage Reconstructions.

Century	White	Yampa	Little Snake
1000-1099	6	10	12
1100-1199	9	10	10
1200-1299	14	14	10
1300-1399	6	4	5
1400-1499	11	11	9
1500-1599	15	14	16
1600-1699	13	11	10
1700-1799	8	7	11
1800-1899	12	13	11
1900-1999	6	6	6

ernmost record in this analysis, also showed severe drought when all four of the other Upper Colorado gages were experiencing the same condition. However, the San Juan regularly breaks from this pattern of basin-wide severe drought, and its reconstructed record includes 16 years where this gage alone showed severe low-flow conditions.

Multiyear streamflow variability was investigated using runs analysis (Salas *et al.*, 1980) combined with stochastic modeling of flow regimes (Biondi *et al.*, 2002, 2005). Again using the Yampa River as our test case we calculated annual departures from the gage-period mean, and then grouped positive (negative) runs of years above (below) this threshold. Runs were then evaluated based on their duration, magnitude (cumulative departure), and intensity (magnitude divided by duration). Using a modification of Biondi *et al.* (2002) we assigned an event "score" to each run. More specifically, the event score was calculated by summing the overall ranking for magnitude and intensity of events with wet and dry regimes scored separately. Based on event scores, the two most severe low-flow events of the 20th Century occurred from AD 1898 to 1904 and 1953 to 1957 (Table 6). Relative to the other 111 dry runs of two or more years in the reconstruction, the early 1900s and 1950s events rank as only the 25th and 26th most severe low-flow regimes, respectively. While it undoubtedly brought severe impacts to the region, stochastic modeling suggests that any one low-flow event has a 15% probability of lasting as long or longer than the 1950s run, and a 17% chance of having a greater drought magnitude. Prior to the 20th Century, the reconstruction reveals several dry-year runs lasting over 10 years, as well as a wide variety of drought types when the combination of drought duration and magnitude is considered. The two runs with the highest dry scores, for example, are each characterized by markedly different circumstances. The dry run ending in 1461 lasted 10 years, whereas the mid-19th Century event lasted only 4. On the other hand, with an accumulated deficit of almost 3,800 MCM the

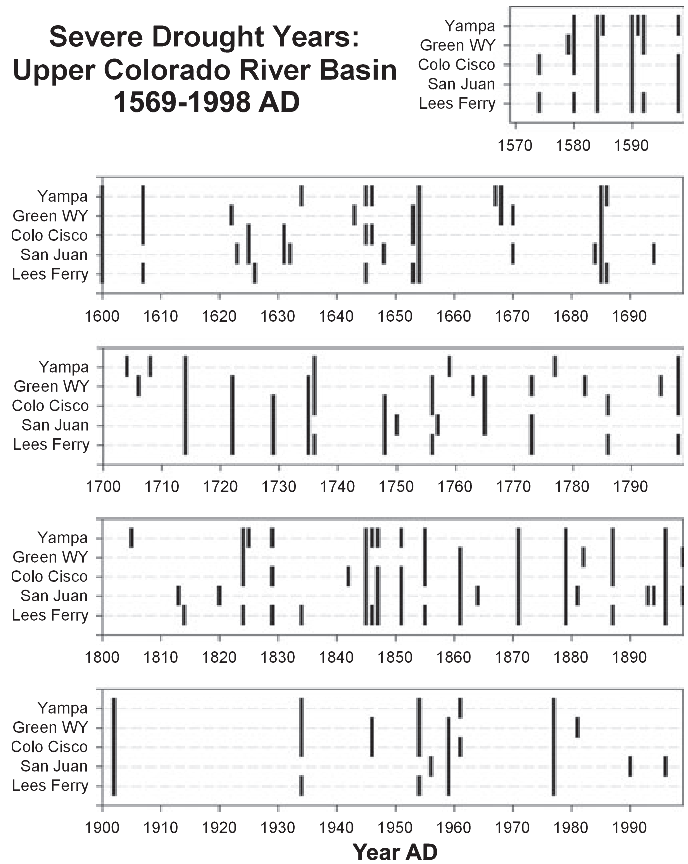

FIGURE 4. Occurrence of Severe (10th percentile or less) Drought Years at Key Locations Throughout the Upper Colorado River Basin. Individual severe low-flow years from each gage are shown as black vertical lines. The new Yampa River reconstruction developed here is compared against existing flow reconstructions for the Green River at Green River, Wyoming and San Juan River at Bluff, Utah (both from Woodhouse *et al.*, 2006) and the Colorado River at Lees Ferry, Arizona (from Meko *et al.*, 2007).

drought from 1845 to 1848 was remarkably intense. Our estimates suggest that runs of dry years on the Yampa have less than a 1% chance of lasting longer than 11 years or of having a magnitude >6,500 MCM.

Runs analysis of wet years on the Yampa River reveals a somewhat different pattern (Table 6). In this case high flows in the mid-1980s scored third highest among all 102 wet runs of two or more years. Likewise estimates from stochastic modeling suggest that wet runs have a <1% chance of reaching the magnitude of events from 1920 to 1930 and 1982 to 1987. Further comparisons between high-scoring wet and dry-year runs show notable examples of strong high-flow regimes being followed by severe drought (e.g., 1676-1683 *vs.* 1684-1687). It is interesting to note that the most recent drought (roughly 2000 to present) was preceded by a run of five wet years.

One major limitation of runs analysis is that it cannot account for single dry (wet) years interrupting what are, in practical terms, extended drought (wet)

TABLE 6. Runs of Years With Reconstructed Yampa River Total Water-Year Flow Above (top) or Below (bottom) the 1906-2002 Mean.

Years	Duration	Magnitude	Intensity	Score
Dry events				
1452-1461	10	−6791.84	−679.184	215
1845-1848	4	−3789.61	−947.402	213
1146-1161	16	−7787.33	−486.708	201
1684-1687	4	−2758.8	−689.701	199
1276-1282	7	−3612.49	−516.07	196
1542-1545	4	−2637.89	−659.473	195
1250-1258	9	−4243.16	−471.462	194
1579-1589	11	−4690.97	−426.452	191
1704-1717	14	−5792.28	−413.734	191
1877-1883	7	−3266.94	−466.705	188
1898-1904	7	−2827.18	−403.882	171
1953-1957	5	−2022.67	−404.534	151
1976-1977	2	−1144.21	−572.106	149
1958-1962	5	−1718.26	−343.653	131
1933-1938	6	−1763.86	−293.977	117
Wet events				
1836-1842	7	4958.464	708.352	199
1076-1089	14	7289.051	520.6465	195
1676-1683	8	4241.771	530.2214	192
1865-1871	7	3726.454	532.3505	191
1180-1184	5	2848.681	569.7362	186
1481-1494	14	5770.833	412.2024	183
1610-1621	12	4818.184	401.5153	180
1843-1844	2	1570.206	785.1029	179
1546-1550	5	2287.392	457.4784	176
1768-1771	4	1842.634	460.6585	175
1982-1987	6	3838.264	639.7106	195
1920-1930	11	3575.985	325.0895	156
1995-1999	5	1542.614	308.5229	135
1973-1975	3	1099.145	366.3818	133
1916-1918	3	820.0628	273.35	96

Notes: Magnitude is the cumulative departure for each event in MCM and intensity is calculated as magnitude divided by duration (Biondi *et al.*, 2002). The event score is calculated by summing the overall ranking for magnitude and intensity of events with wet and dry regimes scored separately. The ten highest scoring dry/wet events prior to 1900 are shown *vs.* the top five dry/wet events of the 20th Century.

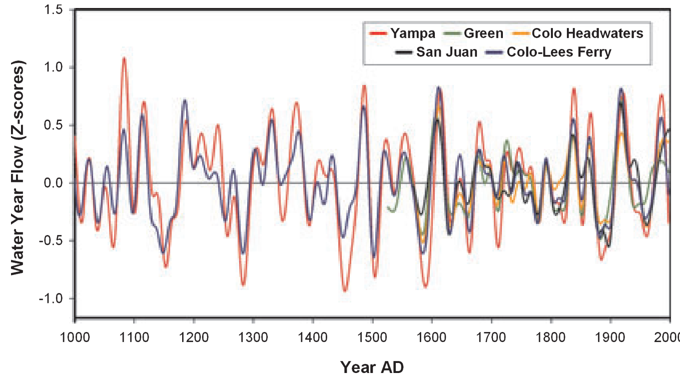

FIGURE 5. Upper Colorado River Region Streamflow Reconstructions Smoothed With a Savitzky-Golay Numerical Filter (Savitzky and Golay, 1964). In all cases the filter window was set to a width of 25 years and the smoothing algorithm used here employs a fourth order polynomial fit. The resulting series highlight variability in a broad band from roughly 10 to 50 years. The new Yampa River reconstruction is compared with previous reconstructions (see Figure 4) from Woodhouse *et al.* (2006) and Meko *et al.* (2007).

events (Salas *et al.*, 1980; Biondi *et al.*, 2002). Moreover, interannual changes in the Upper Colorado River basin's hydroclimate are often embedded within significant decadal to multidecadal nonstationarity (Gray *et al.*, 2003; Hidalgo, 2004; Woodhouse *et al.*, 2006). To address both of these issues we smoothed the Yampa River reconstruction to highlight variability over 10-50 years time scales (Figure 5). When compared with previous reconstructions, the smoothed Yampa River record reveals patterns of extended wet and dry events common to the entire Upper Colorado River basin and surrounding areas (e.g., Gray *et al.*, 2003, 2004, 2007; Woodhouse *et al.*, 2006; Meko *et al.*, 2007). In particular the Yampa reconstruction shows prolonged periods with very low average flows at roughly AD 1130-1180, 1270-1300, 1450-1480, and 1575-1605. The 12th Century event was recently documented in a millennial-length tree-ring reconstruction of Colorado River flow at Lees Ferry (Meko *et al.*, 2007), and the 13th Century and 16th Century dry events coincide with well-known "megadroughts" in the western U.S. (e.g., Stahle *et al.*, 2000; Cook *et al.*, 2004). Note that Meko *et al.*'s (2007) extended Lees Ferry reconstruction suggests that, when runoff is averaged over the entire Upper Colorado River basin, the 1100s drought was likely the most severe decadal-scale event of the past 1,000 years. However, our reconstructions indicate that 15th Century and 16th Century droughts may have been more severe in the White-Yampa-Little Snake subbasins. An additional late-19th to early-20th dry event seen in our reconstructions is also well documented in other Upper Colorado tributaries (Woodhouse *et al.*, 2006). Likewise the early 20th Century is seen as one of the wettest times in the last 1,000 years, and the most recent 2-3 decades appear relatively wet in context of the full reconstructions.

DISCUSSION

As in previous studies focused on the Upper Colorado River system as a whole (e.g., Meko *et al.*, 2007) our subbasin reconstructions show severe drought years and extended dry periods well outside the range of observed flows. Likewise the current study highlights the range of wet years and sustained high-flow regimes in these drainages, and how these wet events often alternate with severe drought. These large wet-dry swings are, in turn, imbedded in significant decadal to multidecadal variations of a quasi-periodic nature.

This nonstationarity over multiple time scales has several important consequences for current and future water users. In agreement with many previous reconstruction efforts (e.g., Woodhouse *et al.*, 2006; Meko *et al.*, 2007), our study points to the potential for droughts of a greater magnitude and duration than any event captured by the gage record. Compared to the 1950s "drought of record" and other benchmarks previously used in regional water resource management, pre-instrumental dry events often lasted a decade or longer with some extended low-flow regimes persisting for 30 years or more (Figure 5). Moreover, stochastic modeling results and other analyses presented here point to a much wider variety of drought types – essentially combinations of drought duration and severity – than are represented by instrumental observations. As such, these results emphasize the importance of incorporating long-term perspectives on regional hydroclimate into natural resource planning. This may be of particular importance in the White and Yampa drainages as policy makers consider the impacts that climatic variability, climate change, and a growing call for additional withdrawals will have on critical fish populations. Regional water managers are in fact beginning to use the tree-ring record in their planning efforts related to human water supplies (Phillips *et al.*, 2009; Rice *et al.*, 2009), but only a small number of these efforts have expanded to include environmental and recreational uses. A major question for both researchers and resource managers alike then becomes how extended dry events and droughts of varying magnitudes and intensities would impact these river systems when coupled with both the 3-5°C temperature increases forecast for coming decades (IPCC, 2007) and changing patterns of water use.

Our research also shows anomalous wetness in the 20th Century, a finding that has been well documented in the Colorado River basin and surrounding areas (Gray *et al.*, 2004, 2007; Woodhouse *et al.*, 2006; Watson *et al.*, 2009). This wetness has in turn contributed to an overallocation of the Colorado River system as a whole, with attendant consequences for water supplies over a large portion of the western U.S. The current situation in the White, Yampa, and Little Snake River basins is somewhat different. Within these river basins, some reaches have unallocated flows that, in a legal sense, are available for new uses (CWCB, 2006; WWDC, 2007). However, depending on the interpretation of interstate compacts and consumptive use estimates, little or no unallocated water remains once Wyoming and Colorado meet their cumulative obligations to downstream users. In this way the 20th Century pluvials may have also contributed to water supply vulnerabilities in our study basins. Though population growth in the White, Yampa, and Little Snake basins has been relatively slow when compared to neighboring areas (e.g., the Colorado Front Range), municipal and industrial water uses have been on the rise since the 1970s. Likewise, late 20th Century wet runs may have allowed regional water demand to overshoot levels of consistently available supply, particularly as increased evaporation associated with regional warming begins to exacerbate any shortages (McCabe and Wolock, 2007).

In addition to this multiyear to decadal-scale variability, the reconstructions show that large interannual variations are a defining feature of river flows in these subbasins. With its massive reservoirs holding up to four times the average annual flow, the main stem Colorado River is largely buffered from such year-to-year changes (NRC, 2007). Our study basins, on the other hand, feature very little storage and many users are limited to withdrawing water from direct flows. Likewise, critical fish populations and recreation in our study basins depend on these unregulated flows, suggesting that planning and management efforts should consider the full range of interannual variability captured by the tree-ring record rather than applying the instrumental record alone. Climate change assessments indicate that this interannual variability will be intensified over the course of the 21st Century (IPCC, 2007), making it essential to understand how both natural and human-induced climate changes will interact with changing consumptive and nonconsumptive uses to affect these river systems as a whole.

CONCLUSIONS

In this paper, we present the first long-duration tree-ring based reconstructions of streamflow for three major tributaries to the Colorado River, namely the White, Yampa, and Little Snake Rivers. All of these proxy records cover the period from AD 1000-2001, making this study one of only a handful to reconstruct streamflows during the Medieval Climate Anomaly. The reconstructions all show marked variability over a wide range of time scales.

In terms of dry years, our reconstructions indicate that the worst single-year events since 1900 (e.g., 1902 and 2002) were among the most severe in the last ~1,000 years. However, these records also suggest that multiyear droughts and decadal-scale dry events prior to the 20th Century were often much longer and/or more intense than anything in the gage record. On the whole, these reconstructions point to the potential for severe, sustained drought in our study area, and such events will likely be magnified by the effects of climate change. Multiple analyses presented here also point to the general wetness of the 20th Century.

Overall, this study reinforces the value of incorporating information from tree rings and other long-term data sources into water-resources and natural-resources planning. Though ongoing climate change represents a fundamental shift in the processes that govern river flows in our study basins and the Colorado River system at large, tree rings still offer a primary means for exploring the potential range of severe droughts within the region. Tree rings and other paleohydrological archives also provide one of the best means for developing scenarios for wet and dry events that can then be used to identify water supply vulnerabilities and potential environmental impacts in the face of any type of climatic change – natural or otherwise.

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