Upper Green River Basin (United States) Streamflow Reconstructions

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Abstract: The Upper Green River represents a vital water supply for southwestern Wyoming and Upper/Lower Colorado River Compact states. Rapid development in the southwestern United States combined with the recent drought has greatly stressed the water supply of the Colorado River system, and concurrently increased the interest in long-term variations in streamflow. The current research developed six new tree-ring chronologies in and adjacent to the Upper Green River Basin (UGRB). Nine proxy reconstructions (three main-stem streams and six headwater streams) of UGRB streamflow were created by combining these new tree-ring chronologies with existing tree-ring chronologies from sites adjacent to the UGRB. All UGRB streamflow reconstructions extended back to the year 1615 or earlier. The variance explained (r^2) by these reconstructions ranged from a low of 0.44 at one headwaters gauge to 0.65 for the lowest main-stem gauge in the drainage. An extended reconstruction of the main-stem Green River gauge near Greendale, Utah extends back to 1439. As a group, the nine reconstructions show that strong regional coherency in interannual flow variability and multiyear to decadal flow regimes are consistent features of the preinstrumental period. Focusing on the Green River at Greendale reconstruction, our analyses point to unusual wetness in the 20th century and a regional hydroclimate characterized by inherent nonstationarity. Overall, these results suggest that instrumental records capture a relatively small subset of potential streamflow variability in the UGRB.

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Introduction

The Upper Green River Basin (UGRB) (Fig. 1) is a vital contributor to the Colorado River system, and the severity of the current multiyear drought has raised concerns about the ability of the Upper Basin states (states within the Colorado River Basin—Wyoming, Utah, and Colorado—that contribute water above Lee's Ferry, Ariz.) to meet obligations set forth in the Colorado River Compact. Approximately 13% percent of the available surface water in the Upper Colorado River Basin (UCRB) originates in the headwaters of the UGRB [Wyoming Water Development Commission (WWDC) 2007]. In turn, multiple stakeholder groups from the central Rocky Mountains to the southwestern United States and northwestern Mexico have a strong interest in understanding the potential range of variability in UGRB flows.

In the semiarid western United States, tree rings offer the primary means for exploring long-term variations in regional hydroclimate, and for characterizing the range of droughts and wet events that have occurred in a given area (Meko and Woodhouse 2009). The UGRB headwaters was a region of interest in the first attempts of Stockton and Jacoby (1976) at using tree rings to reconstruct Upper Colorado River flows. The resulting proxy records have provided tremendous insights into the effects of severe sustained drought and the resulting economic impacts on water users within the Colorado River System (Lord et al. 1995; Young 1995). A small number of subsequent studies aimed at reconstructing the UCRB flows have also included gauges in the UCRB (Woodhouse et al. 2006), but for the most part these efforts have focused on flows at higher volume, main-stem Colorado River gauges (e.g., Meko et al. 2001, 2007). Gauges on smaller tributaries and in areas like the UGRB headwaters have received even less attention, even though these streams can be extremely important to local irrigators and municipal and industrial users. Headwaters reconstructions may also offer important information on patterns of spatial variability within a basin (Woodhouse and Lukas 2006; Woodhouse 2001; Watson et al. 2009).

Given the relatively small numbers of attempts to reconstruct Upper Green River streamflows and the paucity of headwaters reconstructions, the research presented here seeks to develop a network of new and updated proxy streamflow records for the UGRB. In order to create this network two obstacles had to be overcome. First, there are many stream gauging stations in the UGRB but few have the required length and continuity of record required to calibrate a streamflow reconstruction model. Second, prior to the current study there were relatively few tree-ring chronologies available from the UGRB and surrounding areas, and of those that were available, the majority ended in the 1960s–1980s.

Preliminary efforts yielded a total of nine stations with suffi-

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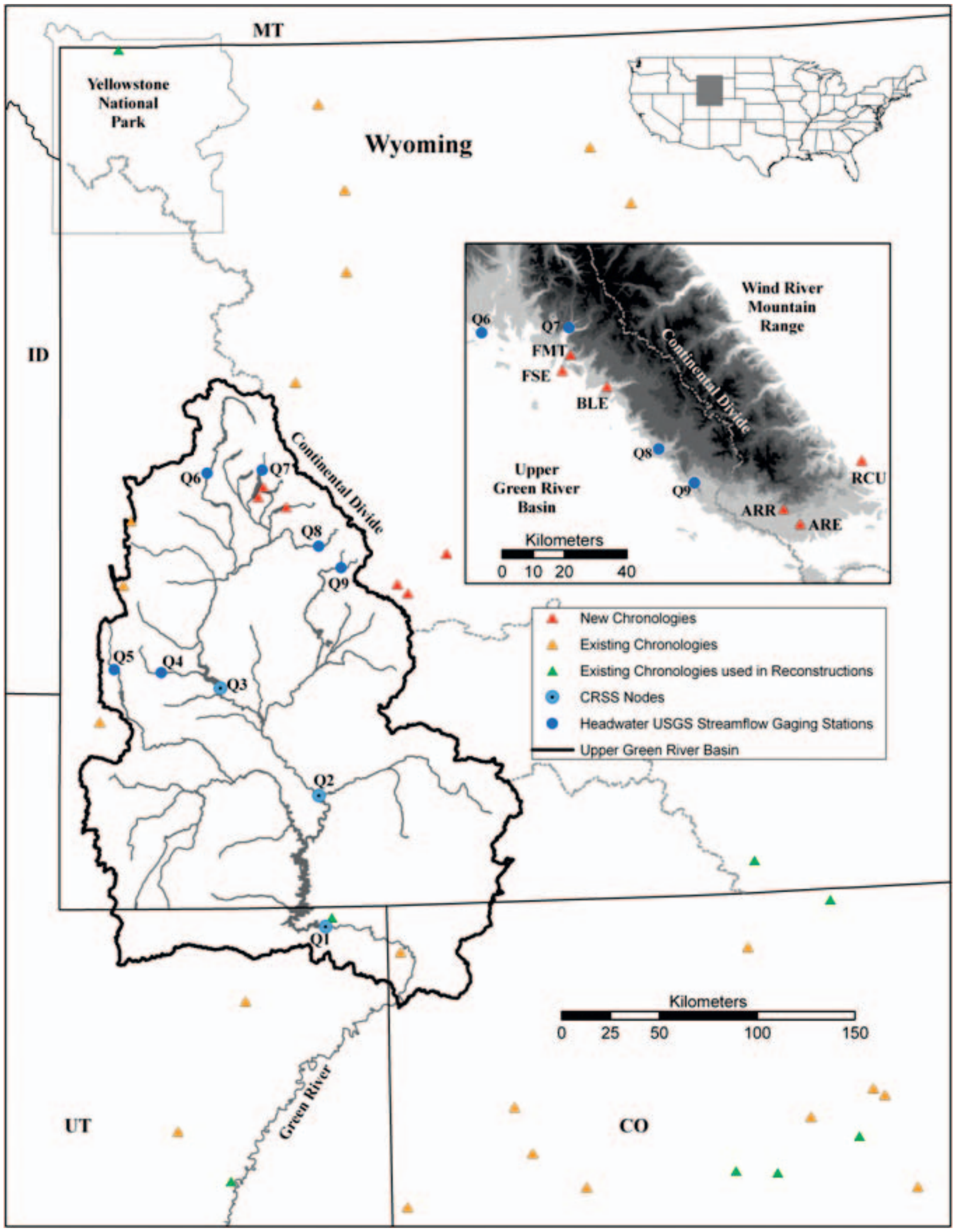

Fig. 1. (Color) Map of the Upper Green River Basin including gauge locations and tree-ring sites

cient length of record to calibrate tree-ring reconstructions (Meko and Woodhouse 2009), and where either naturalized flow records were available (James Prairie, personal correspondence) or the gauges met the criteria for unimpaired flows outlined by Slack et al. (1993). At the same time we created six new tree-ring chronologies from the UGRB region. Two of the current chronologies represent a resampling of sites used in the work of Stockton and Jacoby (1976), while the remaining four chronologies were from previously unknown sites. When combined with existing chronologies from surrounding regions, these tree-ring records formed the basis of this study. The resulting reconstructions were subjected to a series of analyses designed to characterize intrabasin variability in streamflow and to place the instrumental record in a longer-term context. We also performed a detailed examination of individual wet/dry years and decadal flow regimes using the Green River near Greendale, Utah as our test case.

Study Area and Background

The UGRB has a watershed area of approximately 58,500 km^2 and is located between the Wind River Mountain Range and the Wyoming Mountain Range in southwestern Wyoming. Winter snowpack is responsible for the majority of the water-year streamflow, which peaks during the spring-summer season. Due to the limited spring-summer season for peak streamflow, reservoir storage within the UGRB is designed to capture peak runoff allowing year-round distribution to the Colorado River System. The UGRB reservoir storage capacity is 5,380 million m^3 in the ten largest reservoirs (Wyoming State Water Plan 1970). This storage volume is over twice the average water-year streamflow for the Green River near Greendale, Utah, near the lower extent of the UGRB. The storage capacity in the basin has allowed water

Table 1. USGS Stream Gauges Selected for Reconstruction

ID[a]	USGS stream gauge information: Name	ID number	Gauge record	Basin area (km^2)	r[b]
Q1	Green R. nr. Greendale, UT	09234500	1906–1995[c]	50,116	0.23
Q2	Green R. nr. Green River, Wyo.	09217000	1906–1995[c]	36,260	0.19
Q3	Green R. bel. Fontenelle Res., Wyo.	09211200	1906–1995[c]	11,085	0.15
Q4	Fontenelle C. nr. Fontenelle, Wyo.[d]	09210500	1952–2006	394	0.07
Q5	Hams Fork nr. Frontier, Wyo.[d]	09223000	1953–2006	332	0.14
Q6	Green R. nr. Daniel, Wyo.[d]	09188500	1932–1992	1,212	0.04
Q7	Pine C. ab. Freemont Lake, Wyo.	09196500	1955–1997	197	−0.06
Q8	East Fork R. nr. Big Sandy, Wyo.	09203000	1939–1992	205	0.09
Q9	Big Sandy R. nr. Big Sandy, Wyo.[d]	09212500	1940–1987[e]	243	−0.06

[a]Gauge identification shown on the map in Fig. 1.

[b]Lag-1 autocorrelation.

[c]Record is naturalized flow (USBR).

[d]Full gauge names—Fontenelle C. nr. Herschler Ranch, nr. Fontenelle, Wyo.; Hams Fork below Pole Creek, nr. Frontier, Wyo.; Green River at Warren Bridge, nr. Daniel, Wyo.; Big Sandy R. at Leckie Ranch, nr. Big Sandy, Wyo.

[e]Spring-summer instrumental record only.

managers and planners to mitigate the effects of drought events in the decades since the construction dams of various sizes in the region.

Long-term hydroclimatic variability within individual river basins contributing to the Colorado River System has recently become an issue of greater interest given the current (1999 to the present) drought. The UGRB headwaters were first studied as part of the *Lake Powell Research Project* (Stockton and Jacoby 1976), where headwater gauge records as well as main-stem river gauge records were reconstructed (using tree-ring data) to examine long-term variability in streamflow. In the resulting 1976 report, two headwaters gauge reconstructions were completed for the Green River at Warren Bridge, Wyo. and New Fork River.

Recent research has attempted to update and improve the Stockton and Jacoby (1976) UGRB results. Two projects directed at new and/or improved streamflow reconstructions include Timilsena et al. (2007) and Woodhouse et al. (2006). Timilsena et al. (2007) attempted reconstructions at three gauge locations in the UGRB including the Green River at Green River, Wyo., Green River at Warren Bridge, and East Fork River near Big Sandy, Wyo. For the Green River at Warren Bridge and East Fork River, Timilsena et al. (2007) determined that an insufficient number of predictors (i.e., tree-ring chronologies) were available for the reconstruction regression model. Additionally, the Timilsena et al. (2007) Green River near Green River, Wyo. reconstruction was only able to achieve a variance explained of 0.40, which was partly attributed to a lack of tree-ring data in the headwaters region. Woodhouse et al. (2006) likewise developed a reconstruction for the Green River near Green River, Wyo. streamflow station. This reconstruction did show a slightly higher amount of variance explained ($r^2=0.48$) when compared to Timilsena et al. (2007), but the study also raised concerns regarding the heavy reliance on tree-ring chronologies from northern Colorado and Utah due to few updated chronologies being available in southwest Wyoming.

Data and Methods

Streamflow Data

To create statistically robust streamflow reconstructions that represent actual hydroclimatic streamflow variability, it is necessary to use unimpaired or naturalized streamflow data (Slack et al. 1993). An unimpaired stream gauge station is defined as a station with minimal effects of anthropogenic uses including storage, diversion, and consumptive use. The difference between unimpaired and naturalized streamflow is that naturalized flow is back-calculated from an impaired gauge record to represent a prehistoric flow at that station using information from unimpaired instrumental records higher in the watershed (Prairie and Callejo 2005).

The USGS stream gauge information was obtained for unimpaired UGRB stream gauges via the National Water Information System (NWIS 2007) (http://waterdata.usgs.gov/nwis/sw). Unimpaired stations were identified using the hydroclimatic data network (Slack et al. 1993; Wallis et al. 1991), and then the full available records were downloaded from NWIS. Although there are multiple unimpaired gauges in the UGRB, few have the continuous 40–50 year instrumental record necessary to calibrate a regression model. Of the gauges meeting these criteria, six gauges were selected for their spatial distribution within the UGRB and an additional three naturalized gauges were added at three locations on the Green River. The naturalized data were provided by the U.S. Bureau of Reclamation (James Prairie, personal correspondence) at river nodes used in the Colorado River Simulation System (CRSS). In the case of naturalized flows, most records begin in 1906. However, we used only the portion of these records after 1913, the time when the first actual gauges in the UGRB became operational (James Prairie, personal correspondence) in our calibration exercises. A total of nine gauges were selected for reconstruction (Fig. 1, Table 1).

The monthly streamflow data were converted to water year (October–September) streamflow for all gauge stations except the Big Sandy River near Big Sandy, Wyo. (Q9). In the case of the Big Sandy River, the available data were limited to seasonal (March through September) instrumental flow records. However, previous results from adjacent regions (i.e., Watson et al. 2009) have demonstrated that such seasonal records can be of value because they represent the bulk of total water-year discharge. Moreover, flows over this March through September period are likely to be of practical importance for applications in water-resource management because they coincide with the season for irrigation withdrawals in this region.

Table 2. Descriptive Statistics for New Tree-Ring Chronologies

Site name	Species	Elevation (m)	Time span (year A.D.)	Year SSS > 0.85	Number of trees	Number of series	Interseries correlation
ARE	PIFL	2,450–2,575	1200–2006	1203	20	28	0.71
ARR	PSME	2,600–2,625	1519–2006	1615	25	53	0.77
BLE	PSME	2,230–2,285	1576–2006	1672	21	41	0.79
FMT	PSME	2,290–2,560	1507–2006	1603	35	70	0.77
FSE	PIFL	2,330–2,440	1654–2006	1692	23	35	0.80
RCU	PIFL	1,980–2,015	1600–2006	1613	24	41	0.69

Tree-Ring Chronologies

Tree-ring data were obtained from multiple sources including the International Tree Ring Data Bank (ITRDB 2007) (20 chronologies) (http://hurricane.ncdc.noaa.gov/pls/paleo/fm_createpages.treering; recent, published records in regions surrounding the UGRB (nine chronologies) (Woodhouse et al. 2006; Gray et al. 2004a,b; Gray et al. 2007); and new tree ring collections (six chronologies). All of the existing chronologies selected had been used in previous hydroclimatic studies, and all of these chronologies have been shown to have statistically significant correlations with precipitation, streamflow, or drought indices in the region. Collection of new tree-ring samples was targeted specifically on gaps in existing chronology coverage within the headwater areas of the UGRB, along the Wind River Mountain Range. A total of 35 tree-ring chronologies were considered in the UGRB streamflow reconstructions (Fig. 1). The tree species used in these chronologies are considered moisture sensitive and include Douglas-fir (*Pseudotsuga menziesii*, PSME), piñon pine (*Pinus edulis*, PIED), limber pine (*Pinus flexilis*), and ponderosa pine (*Pinus ponderosa*, PIPO) (Fritts 1976).

New Tree-Ring Chronologies

Six new tree-ring chronologies were developed from samples taken in the foothills of the Wind River Mountain Range. Three sampling sites were located within the UGRB and additional three sites were located (east of the continental divide) in adjacent river basins (Fig. 1). Open stands of the available moisture sensitive species, Douglas-fir and Limber pine, were sampled at elevations ranging from 1,980 to 2,625 m. The sites were selected in areas having poorly developed and shallow soil, typically on rocky slopes, to minimize effects of moisture storage in the soil (Fritts 1976).

In an attempt to capture a broad spectrum of climatic variability, three Douglas-fir sites and three Limber pine sites were sampled. Douglas-fir were sampled at one site near the southern terminus of the Wind River Mountain Range on Anderson Ridge (ARR), and at two sites on the southwest face of the Wind River Mountain Range near Boulder Lake (BLE) and near Fremont Lake (FMT). Limber pine were sampled at one site on the southwest face of the Wind River Mountain Range southeast of Fremont Lake (FSE) and two sites near the southern terminus of the Wind River Range, on the eastern end of Anderson Ridge (ARE) and near Red Canyon (RCU).

Trees were sampled using increment borers and a minimum of two cores were taken from each tree. After drying, the cores were glued to mounting blocks to preserve the samples. Cores were then progressively sanded and individual ring widths were measured with an accuracy of 0.001 mm. The resulting series were cross-dated using a combination of standard visual and statistical methods (Stokes and Smiley 1968; Swetnam et al. 1985; Cook and Kairiukstis 1990). More specifically, plots of measured ring widths from each core were visually compared to a master series, and each ring assigned a precise date. Accuracy of the cross-dating procedure was verified using the COFECHA statistical program (Holmes 1983). COFECHA compares the ring width measurements of a given series to the measurements for the same year within the site or against a previously dated master series, and provides statistics such as the overall interseries correlation for a given site (Table 2). The number of trees used in the new chronologies ranged from 20–35 trees and the number of core samples used in the new chronologies ranged from 28–70 samples (Table 2).

Chronologies were created using the autoregressive standardization (ARSTAN) program (Cook, 1985; Cook and Kairiukstis 1990). As employed here, ARSTAN removes geometric growth trends in an individual tree-ring series using a negative exponential curve fit or linear fit. The program then creates a chronology using a biweight robust mean approach, and outputs different chronology types; a chronology without detrended series (raw), a detrended chronology that is standardized to an average value of one (standard), and a detrended residual chronology (residual). Low order autocorrelation that may be attributed to biological tree-growth factors has been removed from the residual chronology (Fritts 1976).

Since chronologies consist of two or more samples from 20–35 trees of differing ages, the number of samples typically decreases as the chronology extends back in time. The loss of sample depth can lead to increased variance in the early portions of the chronology. Rather than trying to account for this change in variance through statistical manipulations, we chose to truncate the chronologies based on the subsample signal strength (SSS) criterion (Wigley et al. 1984). A chronology cutoff point was established at $SSS < 0.85$ (85% of the common variance is retained in the chronology of reduced sample depth when compared to the complete chronology), a threshold recommended by Wigley et al. (1984).

Pearson correlation values between the newly developed chronologies were significant at a 99% level ($r=0.32$ to 0.80), with the exception of RCU (Table 3). The new chronologies were also compared to others within the immediate region ($r=0.14$ to 0.53) to determine if regional growth relationships exhibit continuity

Table 3. Correlation Matrix of Newly Developed Tree Ring Chronologies

	ARE	ARR	BLE	FMT	FSE
ARR	0.74				
BLE	0.47	0.60			
FMT	0.54	0.63	0.80		
FSE	0.53	0.52	0.66	0.75	
RCU	0.45	0.45	0.32	0.32	0.32

between individual tree-ring width indices. Evaluation of these intersite relationships also provides an additional check of the cross-dating procedure performed in the creation of the new chronologies.

New Chronology Precipitation and Temperature Growth Linkages

Climate-growth relationships between the six new chronologies and different combinations of precipitation and temperature were evaluated by correlating instrumental climate records against both standard and residual chronologies. This procedure verifies the moisture sensitivity within each chronology (Fritts 1976). Precipitation and temperature data were obtained for the surrounding climate divisions from the Western Regional Climate Center (WRCC 2007) (http://www.wrcc.dri.edu). Climate divisions roughly correspond to major watersheds, and in this case encompassed the Green and Bear River drainages (Wyoming Climate Division 3), Snake River headwaters (Climate Division 2), Wind River basin (Climate Division 9), and Bighorn River basin (Climate Division 4). Records for all climate divisions span the period 1895–2007. Additionally, we obtained records from individual National Weather Service Cooperative Observer (COOP) stations in the UGRB and surrounding areas. However, because most of these COOP records were far shorter than the divisional records and often incomplete, our analyses focused on the climate-division level. Climate-growth relationships for each month of the year and all possible 3-month seasonal combinations (e.g., December through February, January through March, etc.) were evaluated. Tree growth at five of the six new sites proved to be significantly correlated (95% level) with water-year precipitation, as well as precipitation throughout most months of the year, and the spring (March through May or April through June) and winter seasons (3-month combinations December through March). Monthly correlations tended to be the strongest when growth indices were compared against the December and May precipitation. The tree-ring growth indices were negatively correlated with climate-division temperature records in all chronologies, with the strongest negative correlations occurring over the summer season (June through August), as well as for individual summer months. Growth at RCU showed some sensitivity to both precipitation and temperature but was not significantly correlated to either at the 95% level.

Reconstruction Procedure

Using 29 existing tree-ring chronologies and the six newly developed chronologies (35 total), regression models were calibrated to create reconstructions for the nine selected stream gauge stations. All tree ring predictors were subjected to a rigorous prescreening process (as described below) for use with specific instrumental stream gauge records before being considered in the regression model for that station.

Prescreening of Predictors

When comparing low order autocorrelation displayed in the nine instrumental stream gauge records ($r=-0.06-0.23$, Table 1) to autocorrelation in both the standard chronologies ($r=0.46-0.55$) and the residual chronologies ($r=0.00-0.01$) it is evident that streamflow will be more accurately represented by the residual chronologies. Therefore, residual chronologies were considered in the regression model for each of the nine gauge stations and were selected from the original pool of 35 tree-ring chronologies (predictors) using two methods in succession. First, using criteria outlined in Woodhouse et al. (2006) and Watson et al. (2009), only chronologies where tree-growth and instrumental streamflow were correlated at $r \geqslant 0.30$ were considered for use in a gauge reconstruction. The retained chronologies were then subjected to bootstrapped correlation using evolutionary and moving intervals applying DENDROCLIM2002 (Biondi and Waikul 2004), a program designed to test stability in the relationship between the predictor and the hydroclimatic variable. Forward and backward evolutionary windows were evaluated for various base lengths and predictors that maintained stable correlations over time were retained in the pool of predictors for each stream gauge reconstruction model. The numbers of chronologies retained in each potential predictor pool ranged between 7 for the Pine Creek (Q7) headwaters gauge and 21 for the Green River at Greendale (Q1).

Stepwise Multiple Linear Regression and Validation Statistics

Three regression techniques commonly applied in hydroclimatic studies were assessed for use in these reconstructions. Techniques included stepwise multiple linear regression (Woodhouse et al. 2006), principal component regression (PCR) (Hidalgo et al. 2000), and partial least-squares regression (PLSR) (Tootle et al. 2007). In the end, stepwise multiple linear regression was selected based on its wide acceptance in water resources and the fact that similar skill levels obtained when comparing all of the methods. Moreover, visual comparisons, correlation analyses, and ranked correlation tests (i.e., Spearman's test) showed that the differences between the resulting reconstructions were minimal. A forward and backward stepwise regression process entered and removed predictors with a threshold F significance of 0.05 (Draper and Smith 1998). The statistical strength and fit of the resulting regression models are summarized by the following statistics: r^2, r^2 (adjusted), r^2 (predicted), F statistic, root-mean-square error (RMSE) (Weisberg 1980), cross-validated standard error (CVSE) Garen 1992), variance inflation factor (VIF) (Haan 2002), Mallows' C-p (Weisberg 1980), the predicted error sum of squares (PRESS) (*Handbook of hydrology* 1993), and the Durbin-Watson statistic (Draper and Smith 1998).

The regression models were evaluated using two techniques. A regression model was first calibrated on the first half of the data and validated on the second half of the data. This procedure is then reversed by calibrating on the second half of the data and validated on the first half. A second approach, leave-one-out cross validation, was also applied (Michealson 1987). Leave-one-out cross validation creates a validation series by omitting 1 year, creating a new regression equation, and then predicting the value for the dropped year. The process is repeated for all the years in the series.

Preliminary reconstruction attempts showed that combining the new chronologies from within the UGRB with chronologies from the surrounding region produced the strongest regression models. As shown in previous studies, including regional chronologies in a reconstruction can provide information related to synoptic-scale climate variability, whereas local chronologies help capture finer-scale climate variations that might impact the runoff at the level of individual gauges (Gedalof et al. 2004; Cook et al. 1999; Watson et al. 2009). Regression models using all available regional chronologies were statistically evaluated against models calibrated with only intrabasin chronologies (of which fewer exist). However, the intrabasin only models were noticeably weaker than the all chronology models in a variety of verification tests, and were therefore not considered for further analysis.

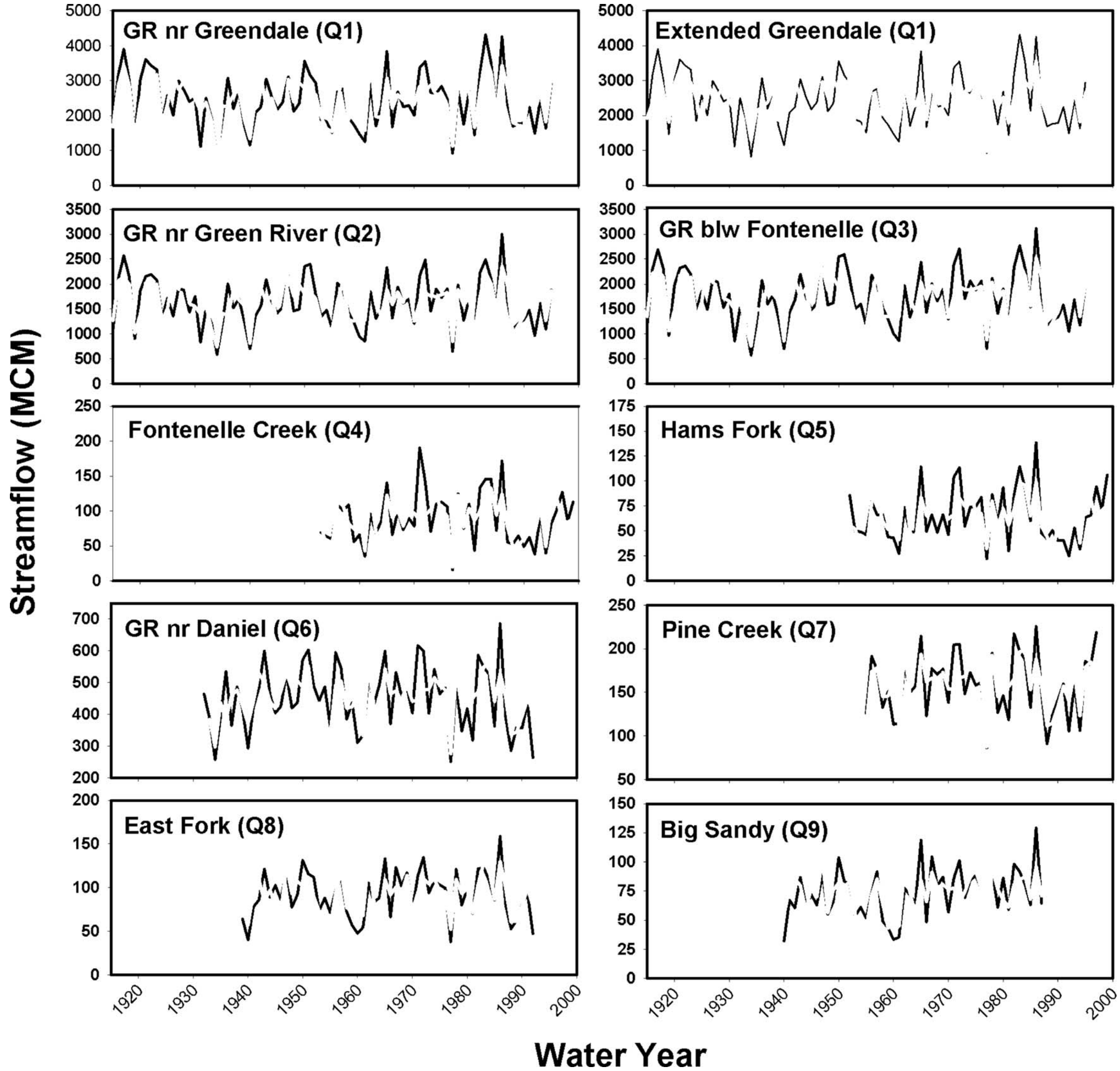

Fig. 2. Comparison of observed (black) and reconstructed (gray) streamflow for the nine study gauges. Both the original and extended versions of the Green River near Greendale, Utah (Q1) reconstructions are shown.

Results and Discussion: Streamflow Reconstruction and Analysis

Streamflow reconstructions were completed for the nine gauges identified as having adequate, continuous gauge records suitable for calibration purposes. Eight of these reconstructions included at least one of the new intrabasin chronologies developed for this study. Of these eight reconstructions, new chronologies were the strongest predictands (i.e., largest coefficients) in the models. Variance explained and other model diagnostics tended to improve in cases where gauges had been reconstructed previously (see below), and we were able to reconstruct gauge records that could not be previously reconstructed by Timilsena et al. (2007).

Streamflow Reconstructions

CRSS Node Reconstructions

Three statistically robust reconstructions of the main-stem CRSS node gauge stations were completed (Figs. 2 and 3). The regression models for Green River gauges Q1–Q3 incorporate four to six tree-ring chronologies extending back to 1615 A.D. (or earlier). The models were all calibrated from 82 years of naturalized gauge record (1914–1995). A set of descriptive statistics were developed to describe the final reconstruction models (Table 4), which captured 59 to 65% of the observed variance in the gauge record. Collectively, statistics testing the strength and the fit of the Green River Q1–Q3 reconstructions were favorable. The analyses showed little variance inflation due to multicollinearity of predictors (i.e., VIF not significantly greater than 1), and the Durbin-Watson statistic revealed no significant autocorrelation in the model residuals. The RMSE and CVSE calculated for the calibration periods were smaller than one standard deviation. The Green River Q1–Q3 reconstructions (Figs. 2 and 3) display well-known droughts in the 1930s and 1950s as well as wet periods in the 1920s and 1980s. Additional comparisons (not shown) with reconstructed precipitation from the neighboring Uinta Basin in northeastern Utah (Gray et al. 2004b) show that preinstrumental wet years (e.g., 1680 and 1701) and dry years (e.g., 1685, 1735, 1756, 1773, and 1871) from the two regions coincided well.

Comparing the calibration and verification statistics from the newly developed UGRB streamflow reconstructions with other reconstructions from surrounding regions shows similar levels of model performance [i.e., Front Range and Upper Colorado River

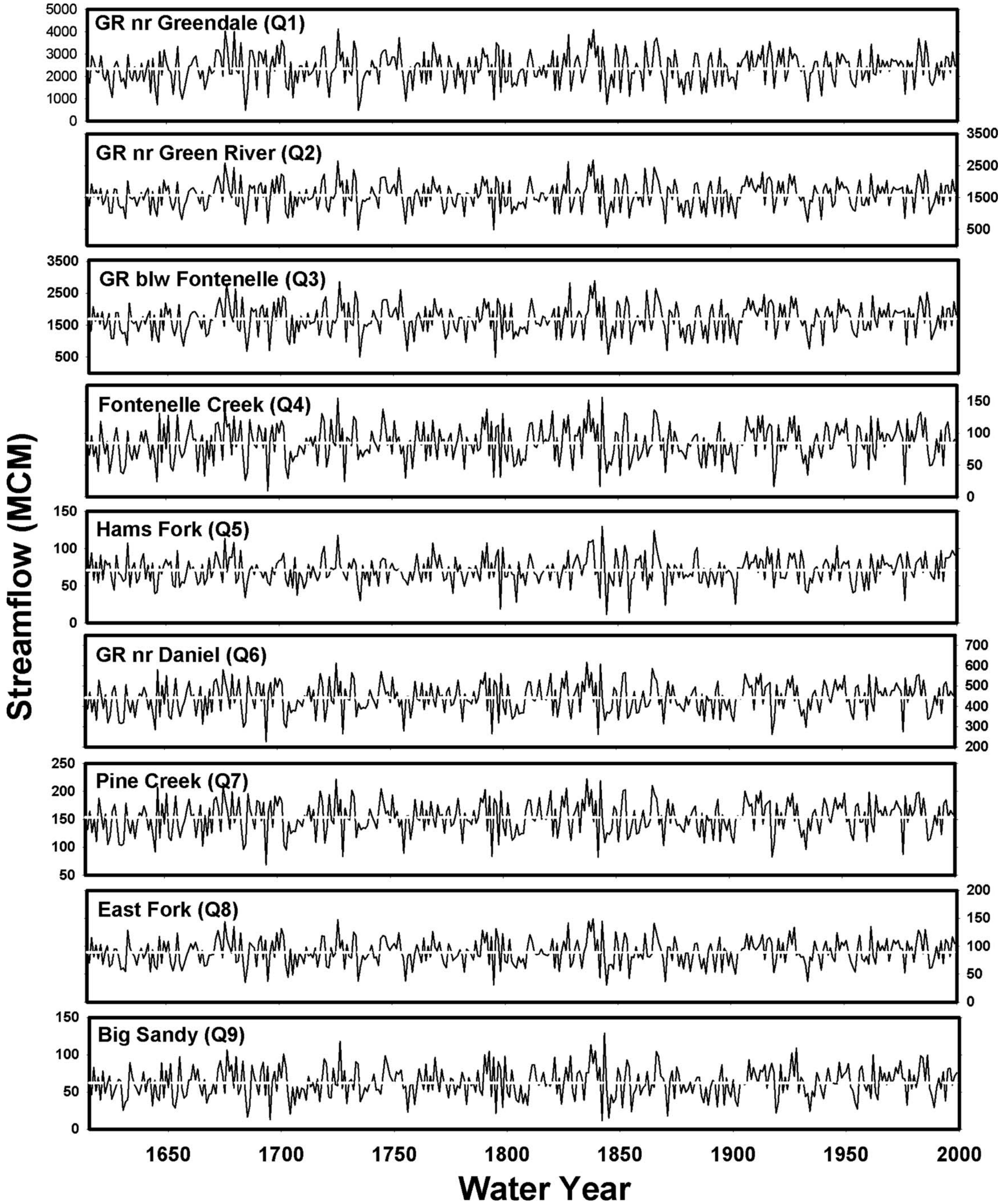

Fig. 3. Reconstructed annual (water year) streamflow for the nine study gauges. Annual values (black) are plotted against the mean of each full reconstruction (gray dashes).

Basin reconstructions (r^2=0.63–0.76) per Woodhouse and Lukas (2006) and Yellowstone River (r^2=0.52) as per Graumlich et al. (2003)]. The reconstruction for the Green River near Green River, Wyo. (Q2) gauge showed a marked improvement in variance explained over previous efforts (e.g., 0.59 versus 0.48 in Woodhouse et al. 2006). However, it must also be noted that the reconstruction for Q3 presented here only extends back to 1615 A.D., whereas the reconstruction in Woodhouse et al. begins in 1525.

Headwaters Reconstructions

Six streamflow reconstructions (Q4 through Q9) were completed for headwaters gauge stations (Figs. 2 and 3). The total variance explained in the headwaters gauge reconstructions ranged from r^2=0.44–0.58 (Table 4). Verification results and comparisons with instrumental records were similar to those for the main-stem CRSS nodes (Table 4). Most notably VIF and Durbin-Watson indicated no obvious multicolinearity of predictors or autocorrelation of residuals. The Green River at Warren Bridge, near Daniel, Wyo. (Q6) was previously reconstructed by Stockton and Jacoby (1976), and the variance explained improved slightly from 0.41 to 0.44.

Extended Greendale Reconstruction. A second, extended reconstruction spanning the period 1439 to 1999 was also completed for the Green River near Greendale, Utah (Q1) gauge

Table 4. Calibration and Verification Statistics for the Reconstruction Models

Gauge name	Calibration period	R^2	F	Mean[a]	RMSE[a]	CVSE[a]
Green River (Q1)	1914–1995	0.65	23.27[b]	2355	456	497
Green River (Q1)[c]		0.50	19.21[b]	2381	539	570
Green River (Q2)	1914–1995	0.60	28.43[b]	1690	344	366
Green River (Q3)	1914–1995	0.59	27.29[b]	1581	321	342
Fontentelle Creek (Q4)	1952–1999	0.48	14.09[b]	63	20	20
Hams Fork (Q5)	1953–1999	0.48	20.48[b]	85	27	27
Green River (Q6)	1932–1992	0.44	22.46[b]	442	76	79
Pine Creek (Q7)	1955–1997	0.53	22.73[b]	153	25	26
East Fork River (Q8)	1939–1987	0.58	22.81[b]	89	17	19
Big Sandy River (Q9)	1940–1987	0.54	12.52[b]	72	16	17

[a]Mean, RMSE, and cross-validated standard error (CVSE) are expressed in $m^3 \times 10^6$.

[b]$p < 0.001$.

[c]Green River nr. Greendale, UT extended reconstruction.

station in order to examine longer-term changes in streamflow (Fig. 4). Given that all but one of the intrabasin chronologies developed for this study were truncated after 1600 A.D. (see Table 2 and "New Tree-Ring Chronologies" section), the resulting extended reconstruction relied entirely on regional (i.e., outside the UGRB) chronologies. The extended reconstruction achieves a 50% variance explained versus the 65% value obtained for the "original" Q1 reconstruction described in the "CRSS Node Reconstruction" section. This loss of variance explained may in part result from the lack of intrabasin chronologies. However, we deemed the trade-off in the variance explained for added length acceptable in that the extended reconstruction allows us to key events such as the 16th century "megadrought" period (Stahle et al. 2000).

Patterns of Variability in Reconstructed Streamflows

Characteristics of Basinwide Streamflow Variability

Patterns of observed interannual flow variability at the three main-stem CRSS nodes (Q1, Q2, and Q3) were highly consistent, as demonstrated by the strength of correlations between each of these gauge records (Table 5). This interannual coherency in main-stem flows appears to be conserved in the reconstructions, though the fact that each of these proxy records shares at least one tree-ring chronology requires that such comparisons be interpreted cautiously. Smoothing the Q1–Q3 reconstructions with a 10-year moving average (Fig. 5) further demonstrates that variability over multiyear to decadal timescales is similar across the main-stem gauges. Interannual correlations between gauges decline slightly with increasing distance, and correlations among tributary gauges were generally lower than when comparing main-stem gauges (Table 6). However, multiyear to decadal-scale patterns were again generally consistent across the tributary gauges, and over the full course of these records (Fig. 5). Previous work using instrumental observations have identified the El Nino Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) as being significant large-scale drivers of snowpack in the mountains of the UGRB region (e.g., Hunter et al. 2006). The multiscale coherency seen in these reconstructions further supports the role of large-scale forcing—presumably related to ENSO- and PDO-like variability—in driving regional runoff over the past four to five centuries.

Despite the obvious similarities, these reconstructions display a noticeable decrease in interannual variability among headwaters streams that receive significant glacial contributions. Glacially populated watersheds have been shown to provide a more stable water source than nonglaciated basins (Ferguson 1973; Fountain and Tangborn 1985; Braithwaite and Olsen 1988). The two headwates basins with glacial contribution (Q6 and Q7) show less annual variability in the reconstruction than the other headwaters

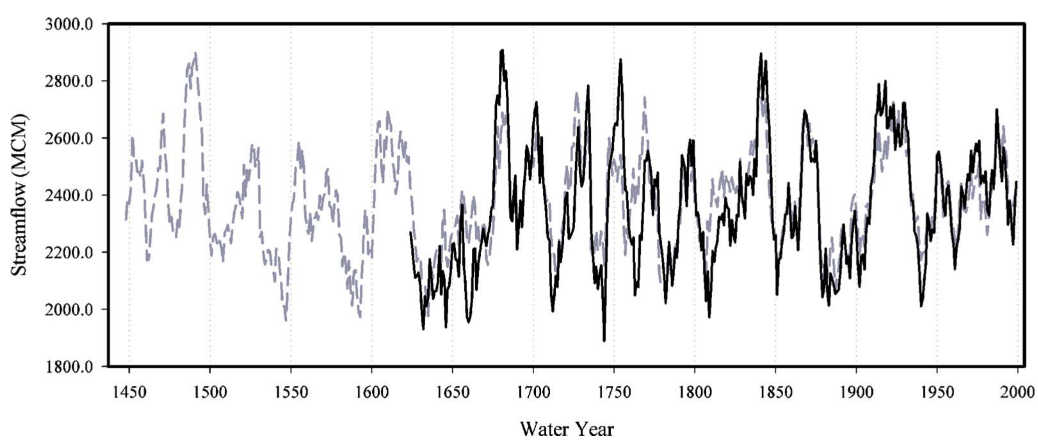

Fig. 4. Comparison of reconstructed streamflow at Greendale, Utah (Q1) as portrayed by the original (black line, 1615–1999) and extended (dashed gray line, 1439–1999) models. Values are displayed as a 10-year moving average.

Table 5. Correlation Matrices for Instrumental (Top) and Reconstructed (Lower Two) UGRB Gauge Records; Matrices for Both Reconstructed Values in Years Coinciding with Available Instrumental Observations (Middle) and for the Full Reconstructions (Bottom) Are Shown

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
Instrumental observations								
Q2	0.97							
Q3	0.97	0.99						
Q4	0.92	0.94	0.94					
Q5	0.90	0.91	0.90	0.94				
Q6	0.88	0.92	0.93	0.84	0.86			
Q7	0.90	0.93	0.94	0.84	0.85	0.97		
Q8	0.91	0.94	0.94	0.87	0.84	0.90	0.93	
Q9	0.88	0.90	0.91	0.84	0.79	0.85	0.89	0.97
Reconstructed values truncated to instrumental period								
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
Q2	0.93							
Q3	0.92	0.99						
Q4	0.88	0.87	0.87					
Q5	0.87	0.83	0.83	0.94				
Q6	0.83	0.85	0.85	0.94	0.98			
Q7	0.88	0.88	0.87	0.94	0.98	0.99		
Q8	0.94	0.96	0.96	0.94	0.88	0.89	0.91	
Q9	0.77	0.78	0.77	0.81	0.86	0.81	0.86	0.80
Reconstructed values 1615–1999								
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
Q2	0.96							
Q3	0.96	0.99						
Q4	0.84	0.88	0.88					
Q5	0.78	0.83	0.82	0.94				
Q6	0.81	0.86	0.85	0.93	0.98			
Q7	0.81	0.86	0.85	0.93	0.99	0.99		
Q8	0.93	0.97	0.97	0.95	0.86	0.89	0.89	
Q9	0.73	0.75	0.75	0.77	0.70	0.68	0.68	0.79

basins (Q4, Q5, Q8, and Q9) when considering the ratio of the standard deviation of the reconstruction to the reconstructed mean (Fig. 6). The Green River at Warren Bridge station (Q6—the most heavily glaciated watershed) has a ratio of approximately 16% and Pine Creek (Q7) has a ratio of approximately 19% while the headwaters basins with little or no glacial coverage have ratios of over 25%.

In the case of the Green at Warren Bridge (Q6), some portion of this diminished interannual variability is likely to result from the relatively large size of this watershed when compared to the tributaries (see Table 1), or its relatively high annual flow volume (446×10^6 m^3 compared to an average of $<100 \times 10^6$ m^3 for unglaciated tributaries). Pine Creek (Q7) also features a relatively large average annual flow volume of 156×10^6 m^3, but with a basin area roughly equivalent to the other tributaries. In addition this comparison does not account for differences in groundwater contributions or the effects of soils and geology in these basins. However, a growing number of studies now show significant decline or loss of alpine glaciers throughout North America (e.g., Moore et al. 2009), including the headwaters of the UGRB. If these UGRB glaciers were to disappear, the consequences for interannual streamflow variability and, in turn, local and regional water management and fisheries could be substantial. Given the importance of flows at both Q6 and Q7 for their contributions to local agriculture and municipal water supplies, as well as their contribution to the Green River system as a whole, differences in interannaul variability among glaciated and unglaciated watersheds should be considered as a part of long-term monitoring and planning efforts.

In addition, a comparison of streamflow values from the pre- and postinstrumental periods for the nine selected UGRB gauges shows a wider range of variability prior to the 20th century (Fig. 3). Of particular note is how the most extreme low-flow years in the reconstruction far exceed anything in the instrumental record (Table 6). These comparisons suggest that instrumental streamflow records alone do not provide a complete picture of regional water-supply variability.

Long-Term Variability at Greendale, Utah

A comprehensive analysis of wet and dry events was completed for the Green River near Greendale, Utah (Q1) reconstruction. We focused this set of analyses on the Greendale gauge for three reasons. First, as the final downstream gauge in our network (Fig. 1), the Greendale record captures the highest volume of basin discharge, and provides the best integrator of regional hydroclimatic variability. Next, the Greendale Q1 reconstruction

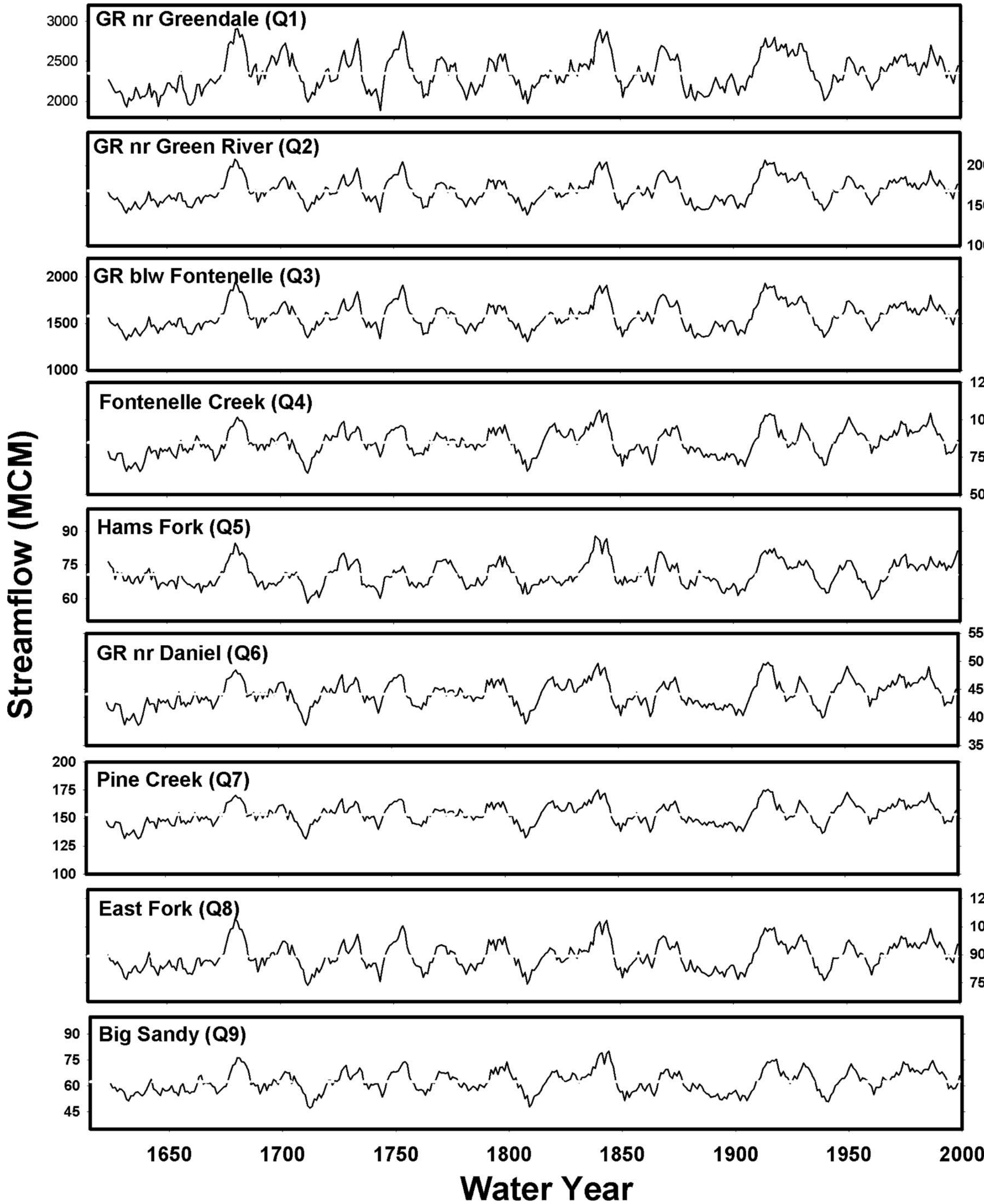

Fig. 5. Comparison reconstructed streamflows for all nine study gauges when smoothed with a 10-year moving average. End-year values (black) are plotted against the mean of each full reconstruction (gray dashes).

performed well in terms of calibration and verification statistics when compared to most tributary models (Table 4). While the Greendale Q1 model's calibration and verification statistics were only slightly more favorable than those for Q2 and Q3, the Greendale record also captures the majority of variability ($r > 0.95$) at these two upstream gauges (see "CRSS Node Reconstructions" section). Last, the extended Q1 record allows a subset of these analyzes to extend back past the early 1600s, the cut-off point for all other reconstructions. More specifically this extended record was used in our examination of multiyear to decadal-scale shifts in streamflow. Because of its lower r^2 when compared to the regular Q1, the extended Greendale record was not used in the analyses of interannual variability.

An examination of the extremes of annual streamflow events in the Q1 record, namely, those exceeding the 95th percentile or failing to reach the fifth percentile, shows that extreme low-flow years were relatively uncommon in the 20th century; only two of the 21 individual water-year streamflow values failing to exceed the 5th percentile occur within this time period (Fig. 7). On the other hand, seven of the 22 individual water-year streamflow val-

Table 6. Comparison of Instrumental and Reconstructed Flow Characteristics at the Nine Study Gauges; All Values Are Millions of Cubic Meters

	Instrumental record				Reconstructed record			
Variable	Mean	Standard deviation	Minimum	Maximum	Mean	Standard deviation	Minimum	Maximum
Q1	2,457	792	813	4,311	2,355	681	484	4,124
Q2	1,753	561	543	3,169	1,690	444	495	2,893
Q3	1,639	516	560	3,026	1,581	406	490	2,680
Q4	63	26	22	138	63	20	11	128
Q5	85	38	16	191	85	27	10	157
Q6	449	100	250	686	442	72	227	617
Q7	158	36	86	226	153	28	69	222
Q8	91	27	38	159	89	22	31	149
Q9	73	22	31	130	72	17	11	130

ues exceeding the 95th percentile fall within the 20th century. Of particular note is a string of three, extreme wet years in the early 1980s, which are also well documented in regional observations. One of these years, 1983, ranks as the third wettest in the entire proxy record. The two water years in the 20th century failing to exceed the 5th percentile (i.e., 1934 and 1977) are known as extreme dry years within the instrumental record.

Prior to the advent of instrumental observations, we see one, roughly 50-year period beginning in the late 18th century with an absence of extreme low-flow years similar to the 20th century (Fig. 7). Generally speaking, extreme low-flow years were far more common before 1900. One interesting preinstrumental event occurred in the mid-1700s. Flows in 1735 rank second driest in the entire reconstruction, but this year is immediately followed by another extreme low-flow year ranking 8th driest in the proxy record. The lowest water-year flows in the regular Q1 reconstruction occurred in 1685. Precipitation reconstructions from northeastern Utah (Gray et al. 2004a) also show 1685 as an extreme dry year. According to Gray et al. (2004a), 1685 ranks as the 13th driest year in northeastern Utah over the past ~775 years.

Previous research in the Green River Basin and surrounding areas (Gray et al. 2004a) shows significant decadal to multidecadal variability in regional hydroclimate. Smoothing the extended Greendale Q1 reconstruction with a 25-year moving average serves to highlight similar decadal variability [Fig. 8(a)], and reveals how periods of relatively low (high) drought occurrence (absence) are often imbedded in persistent wet (dry) regimes. For

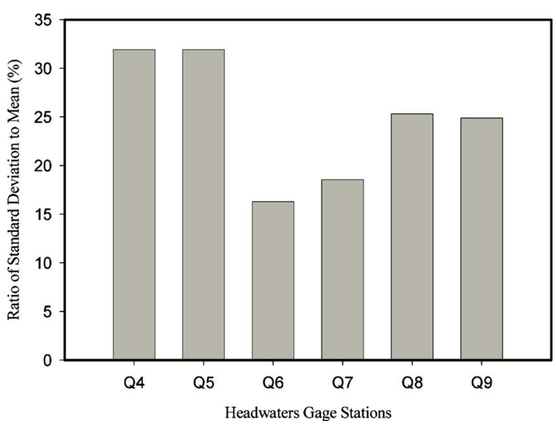

Fig. 6. Ratio of the standard deviation of reconstructed flows to the mean (percent) of reconstructed flows for UGRB headwaters gauges

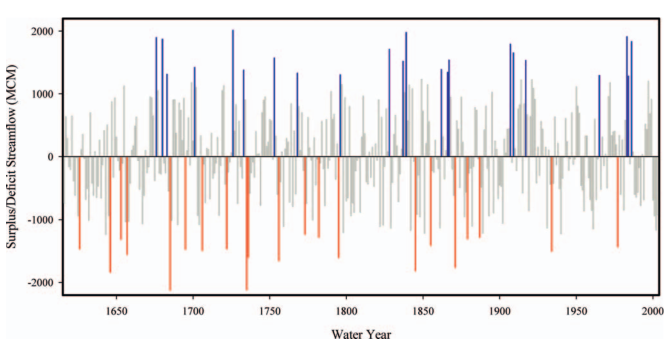

Fig. 7. (Color) Plot of water-year streamflow for the Green River near Greendale, Utah (Q1) with blue bars showing years that exceed the 95th percentile and red bars showing years that fail to exceed the 5th percentile

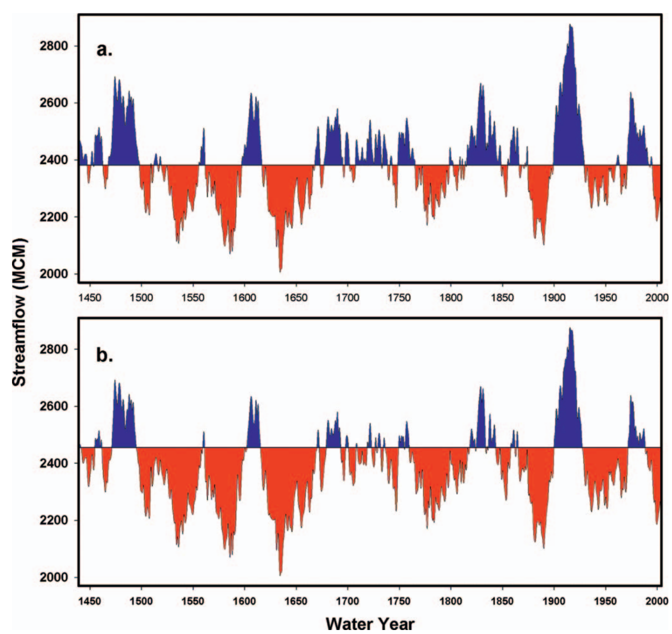

Fig. 8. (Color) (a) 25-year moving average of reconstructed streamflow (extended version) for the Green River near Greendale, Utah. Values are plotted against the long-term (full reconstruction) mean, with periods of below-average streamflow shown in red and above-average streamflow in blue. (b) Same as Fig. 8(a), but with values plotted against the mean of observed values.

example, smoothing the extended Q1 record with the 25-year moving average [Fig. 8(a)] highlights the early 20th century as being one of the wettest periods in the past five centuries. Comparing the smoothed record to the plot of annual departures in Fig. 7 then shows how this early 20th century pluvial featured both several extreme high-flow years and an absence of extreme drought.

The smoothed Greendale reconstruction [Fig. 8(a)] also provides several interesting comparisons between droughts captured by the observational record and those that occurred before gauging operations in the UGRB. In terms of their effects on streamflow over decadal timescales, the 1930s and 1950s droughts appear benign versus events in the late 19th century, mid-17th century and late 16th century. One of these extended preinstrumental dry periods from approximately 1575 to 1590 coincides with the megadrought documented by Stahle et al. (2000) and others. While by all measures this megadrought would have brought severe impacts to the UGRB system, in terms of 25-year moving averages the mid-17th century dry event was even greater in magnitude and duration. In all of these cases we have periods of three or more decades where average streamflows fall well below the reconstruction average, combined with multiple instances where the 25-year moving average is at least 50% less than in the 1930s and 1950s.

Overall, one of the most prominent features of the extended Greendale Q1 reconstruction is the wetness of the 20th century. As discussed previously, this 20th century wetness is manifest variety of ways including an abundance of extreme wet years, lack of extreme dry years, and an extended pluvial. Other studies have documented how this early 20th century pluvial led to overestimates of available water in the Colorado River basin as a whole (e.g., Woodhouse et al. 2006). In addition, the extended Greendale Q1 reconstruction suggests that average flows for the entire instrumental period where higher than the long-term norm. When the 25-year smoothed reconstruction is replotted against the mean of instrumental observations (essentially the same as reconstructed values for the same years), there are relatively few extended periods where flows reach this benchmark level [Fig. 8(b)].

Recently, the concept of stationarity and its application in water resources engineering and management has garnered tremendous attention. Declaring that "stationarity is dead," Milly et al. (2008) argue that climate change and other factors have rendered our ability to rely on the instrumental record as a guide to the future invalid. In effect, the results presented here demonstrate that stationarity has never been a valid assumption for water-resource applications in the UGRB. As an alternative, engineers, water managers, and policy makers operating in the UGRB should look to a wider range of sources, including paleoproxies and Atmosphere-Ocean General Circulation Model (AOGCM) output, to help define the potential range of variability in the region. While none of these sources is likely to provide a perfect window into future water availability, broadening the range of hydroclimatic scenarios considered in engineering and management applications can help us better assess system vulnerabilities and allow us to adapt more easily to the uncertain future that climate change will bring.

Summary and Conclusions

Using a combination of new and existing tree-ring chronologies enabled the creation of nine new or updated streamflow proxy records for the UGRB. Three of the reconstructed gauge records represent important forecasting and analysis points in the Upper Colorado River Basin (i.e., CRSS nodes and National Weather Service and Natural Resources Conservation Service forecast points). Collectively these gauges provide a major portion of flows from the Upper Colorado River basin. While the six upstream and tributary gauges feature much smaller flow volumes, each of these streams plays an important role in UGRB agriculture and municipal water supplies [Wyoming Water Development Commission (WWDC) 2007].

All of the streamflow reconstructions presented here show the 20th century to be markedly wet. While periods of drought observed in the 1930s and 1950s severely impacted water users in the UGRB, it is likely that these droughts have been exceeded by several events occurring prior to instrumental stream gauge records. The historic approximation of streamflow derived from tree rings thus provides vital information for managers and engineers charged with planning for the future of the UGRB. Moreover these reconstructions point to the inherent nonstationarity of regional hydroclimates, and the need to include a wide range of data sources and scenarios in assessments of potential impacts from drought, shifting patterns of water use, and climate change.

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