MULTI-CENTURY TREE-RING RECONSTRUCTIONS OF COLORADO STREAMFLOW FOR WATER RESOURCE PLANNING*

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Abstract. Water resource management requires knowledge of the natural variability in streamflow over multiple time scales. Reconstructions of streamflow derived from moisture-sensitive trees extend, in both time and magnitude, the variability provided by relatively short gage records. In this study, we present a network of 14 annual streamflow reconstructions, 300–600 years long, for gages in the Upper Colorado and South Platte River basins in Colorado generated from new and existing tree-ring chronologies. Gages for the reconstruction were selected on the basis of their importance to two of the largest Colorado Front Range water providers, who provided the natural flow data for the calibration with tree-ring data. The reconstruction models explain 63–76% of the variance in the gage records and capture low flows particularly well. Analyses of the reconstructions indicate that the 20th century gage record does not fully represent the range of streamflow characteristics seen in the prior two to five centuries. Multi-year drought events more severe than the 1950s drought have occurred, notably in the 19th century, and the distribution of extreme low flow years is markedly uneven over the past three centuries. When the 14 reconstructions are grouped into Upper Colorado, northern South Platte, and southern South Platte regional flow reconstructions, the three time series show a high degree of coherence, but also time-varying divergences that may reflect the differential influence of climatic features operating in the western U.S. These reconstructions are currently being used by water managers to assess the reliability of water supply systems under a broader range of conditions than indicated by the gage records alone.

1. Introduction

Water resource management in the western United States is increasingly challenged by a host of factors that include greater municipal demand, changes in land use, recently recognized instream requirements for recreation and ecosystem health, the uncertainty of natural climate variability, and the impacts of anthropogenic climate change (Getches, 2003). Paleoclimatic studies indicate that the natural variability in the 20th century gage records is likely only a subset of the full range of natural variability possible (e.g., Stockton and Jacoby, 1976; Smith and Stockton, 1981; Meko et al., 2001; Woodhouse, 2001). In addition, future climate projections

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suggest, among other things, greater variability in the form of an increase in regional droughts and heavy precipitation events (IPCC, 2001; Karl and Trenberth, 2003). Judicious management of water resources must look beyond the limited gage records to consider the additional variability seen in both paleoclimatic records and projected under future climate conditions. In this paper, we present evidence of hydroclimatic variability over the past three to five centuries from a set of annual streamflow reconstructions for the Upper Colorado and South Platte River basins in Colorado.

Extended records of hydroclimatic variability, generated from tree-ring data over the past several decades, have had important implications for water resource management. One of the best examples is the tree-ring reconstruction of streamflow of the Colorado River at Lees Ferry by Stockton and Jacoby (1976), which indicated that the early 20th century was the wettest multidecadal period in the past 400 years. Ironically, the 1906–1919 period was used to allocate Colorado River flow in the 1922 Colorado River Compact. In spite of this over-allocation, water supplies in the Upper Colorado River have been adequate to meet demands in the 20th century (Christensen et al., 2004). Until recently, basin water supplies have matched the growing demands of the basin states, and the information contained in the extended paleoclimatic records has not received much attention.

In the state of Colorado, the sustained wet period from 1982 to 1999 coincided with a period of rapid population growth. This period of unusually abundant moisture ended with the onset of drought conditions in late 1999, which reached a peak in 2002. Snowpack was extremely low across the state and water year flows were the lowest on record for most gages, making it the driest year, statewide, on record (Douglas et al., 2003). Severe drought conditions, coupled with a high level of demand, resulted in unprecedented impacts on managed water supplies (Wiley, 2003). Since gage records did not contain such an extreme event, water managers in Colorado began to seriously consider the utility of examining extended records of streamflow from tree rings to assess how rare the 2002 drought year were.

This drought, although devastating to many sectors, presented us with the opportunity to pursue collaborations with water managers interested in exploring the usefulness of tree-ring based reconstructions of hydroclimatic variability. Of immediate interest was the use of centuries-long reconstructed streamflow records to place the 2002 drought event into a long-term context. However, a broader question was whether the 20th century record of flow is an adequate frame of reference for planning. We developed partnerships with water agencies that included Denver Water, Colorado's oldest and largest water provider, serving over one million people in the Front Range metropolitan area, and the Northern Colorado Water Conservancy District (NCWCD), the primary water provider in northeastern Colorado for agricultural, municipal, and industrial uses. Both Denver Water and NCWCD utilize water supplies from east and west of the Continental Divide, with gages in the Upper Colorado and South Platte River basins (Figure 2). Although both water providers were aware of existing tree-ring reconstructions of streamflow, along with the lack of need prior to this drought, the limited availability of reconstructions for relevant gages had limited the decision-support role for tree-ring reconstructions. In this paper we describe the network of annual streamflow reconstructions that was generated for use by these water managers and others, and analyze some of the drought characteristics in these reconstructions.

2. Tree-Ring and Streamflow Data

The tree-ring data that formed the basis for the annual streamflow reconstructions came from both new collections sampled between 1998 and 2003 (Figure 1, Table I) and from existing chronologies in the International Tree-Ring Data Bank (ITRDB, Grissino-Mayer and Fritts, 1997). In the Upper Colorado, Arkansas, and South Platte River basins, tree-ring collections targeted moisture-sensitive species (*Pinus ponderosa, Pseudotsuga menziesii, Pinus edulis*) growing in open stands on well-drained slopes. Samples from 38 sites were prepared, crossdated, and measured using standard dendrochronological methods (Stokes and Smiley, 1968; Fritts, 1976). Five additional tree-ring data sets from the ITRDB were obtained for the South Platte River basin. These were selected on the basis of species and beginning and end dates (at least 1685 to 1987) (Table II).

All ring-width measurement series were standardized using a conservative detrending method (negative exponential, straight line, or a smoothing spline two-thirds the length of the series) to remove the growth trend, and processed into site tree-ring chronologies using the computer program ARSTAN (Cook, 1985; Cook and Kairiukstis, 1990). The tree-ring chronologies exhibited significant low-order autocorrelation, likely related to biological factors (Fritts, 1976), which was removed using auto-regressive (AR) modeling. The resulting residual chronologies were used in the reconstructions. Because each chronology consists of two samples from each of about 20–30 trees of different ages, the number of samples in each typically decreases back in time. Each chronology was evaluated to assess the loss of common variance (signal strength) over time with decreased sample size using the Expressed Population Signal (EPS, Briffa, 1984; Wigley et al., 1984) statistic. No chronologies were abbreviated, but values for the earliest parts of the chronologies were noted if EPS dropped below 0.85, a suggested threshold (Wigley et al., 1984). All chronologies were significantly correlated ($p < 0.05$) with water year precipitation in their respective climate divisions (1896–1987, average $r = 0.46$).

Water managers provided the synthetic natural flow records needed for calibration of the reconstruction models (Figure 2, Table III). Six gage records were provided by Denver Water (three in the Upper Colorado and three in the South Platte River basins), all of which began in 1916. NCWCD provided data for eight gages (four in the Upper Colorado and four in the South Platte) with variable starting dates

TABLE I
New Colorado tree-ring chronologies, and site details

Code	Site name	Species[a]	Period	Lat. N	Long. W	Elev.
ATR	Almont Triangle	PSME	1319–1999	38 44	106 48	2926
BEN	Bennett Creek	PIPO	1394–2002	40 40	105 31	2301
BTU	Big Thompson Update	PSME	1550–2000	40 25	105 17	2012
CAT	Cathedral Creek	PSME	1372–2000	38 05	107 00	2895
COD	Cochetopa Dome	PIPO	1437–2000	38 15	106 40	2835
DIL	Dillon	PSME	1372–2000	39 36	105 54	2880
DMU	Deer Mtn Update	PIPO	1547–2000	40 22	105 35	2652
DOU	Douglas Pass	PSME	1382–2000	39 36	108 48	2591
EAG	Eagle Rock	PIPO	1401–1997	39 23	105 10	2103
EFU	Escalante Forks Update	PIED	1569–1999	38 39	108 20	1737
ELE	Elevenmile	PIPO	1507–1997	38 52	105 26	2743
GMR	Green Mtn. Res.	PSME	1378–2000	39 51	106 14	2514
GOU	Gould Reservoir	PIED	1385–2000	38 36	107 35	2271
HOT	Hot Sulphur Springs	PSME	1571–1999	40 04	106 08	2499
JAM	Jamestown	PIPO	1354–2000	40 08	105 25	2469
JFU	Jefferson County Update	PIPO	1487–2003	39 41	105 12	1981
JOP	Johnny Park	PIPO	1615–2000	40 15	105 26	2377
LAN	Land's End	PSME	1135–2000	39 00	108 09	2987
MCG	McGee Gulch	PSME	1483–1997	38 51	106 01	2743
MEY	Meyer Ranch	PIPO	1553–2002	39 16	105 16	2438
MTR	Montrose	PIED	1440–2000	38 23	108 01	2286
OWU	Owl Canyon Update	PIED	1508–2002	40 47	105 11	1874
PLU	Plug Hat Butte	PIED	1270–2000	40 47	108 58	2133
PRD	Princeton Douglas-fir	PSME	1169–2000	38 48	106 14	2956
PRP	Princeton Pinyon	PIED	1462–1999	38 48	106 13	2774
PUM	Pump House	PIED	1320–2000	39 58	106 31	2194
RCK	Red Creek	PSME	1525–2000	38 32	107 13	2835
RED	Red Canyon	PIED	1336–1999	39 42	106 44	2164
SAP	Sapinero Mesa	PIPO	1511–2000	38 19	107 12	2700
SAR	Sargents	PSME	1275–2000	38 24	106 26	2621
SEE	Seedhouse Rd.	PSME	1539–2000	40 45	106 51	2377
SPP	Soap Creek	PIPO	1541–1999	38 32	107 19	2417
STD	Stultz Trail	PSME	1480–1997	38 20	105 16	2465
TRG	Trail Gulch	PIED	1402–2000	39 43	106 59	2210
UNA	Unaweep Canyon	PIED	1296–2000	38 50	108 34	2225
VAS	Vasquez Mtn.	PSME	1454–1999	40 02	106 04	2865
WIL	Wild Rose	PIED	1232–2000	39 01	108 14	2636
WMC	Wet Mountains	PSME	1336–1997	37 54	105 09	2690

[a] PIED = *Pinus edulis*, PIPO = *Pinus ponderosa*, PSME = *Pseudotsuga menziesii.*

TABLE II
Tree-ring data obtained from International Tree-Ring Data Bank

Site name	Site code	Species	Years
Deer Mountain	DEE	PIPO	1625–1987
El Dorado Canyon	EL1	PSME	1541–1987
Jefferson County	JEF	PIPO	1548–1987
Turkey Creek	TUR	PIPO	1640–1988
Van Bibber Creek	VAN	PIPO	1685–1987

All chronologies collected by D. Graybill, University of Arizona.

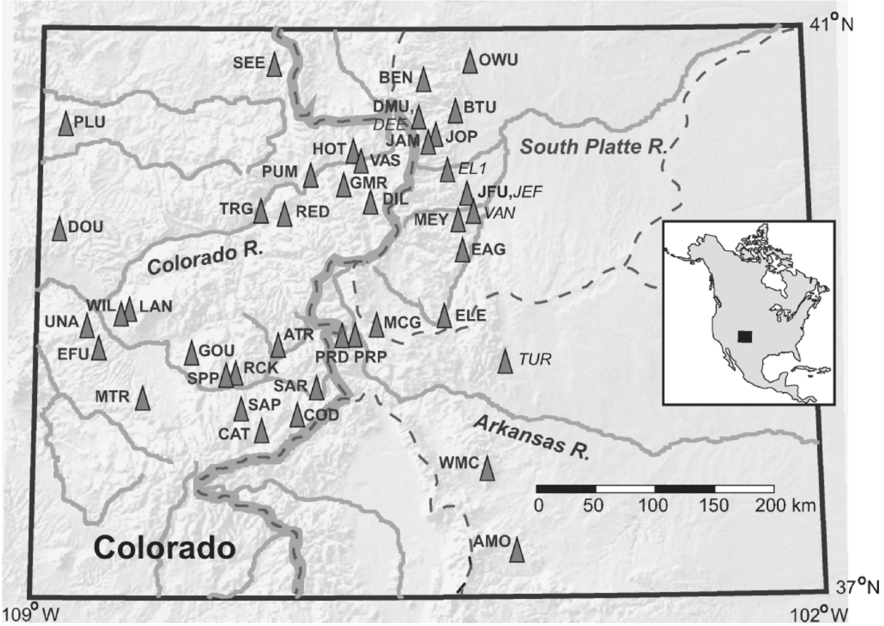

Figure 1. Locations of tree-ring chronologies used in this study (triangles). Three-letter codes correspond to site names listed in Tables I and II. Site codes in italics are chronologies from the ITRDB.

between 1884 and 1953. Two of the Denver Water gages were on the same rivers as the NCWCD gages, though in different locations. For each of the gages, synthetic natural flows had been estimated from the raw gaged flow using records or estimations of diversions, water importations, reservoir evaporation, and return flows. Water management personnel acknowledge that in many cases, estimated natural flow values in the early part of the record are based on scant water use information. Consequently, there are uncertainties in the calibration data that are not well defined or quantified. On the basis of documentation of estimations and the recommendation of water managers, the earliest years for two of the gage records were excluded from the calibrations (Poudre, 1884–1905; Boulder, 1907–1921). Time series of

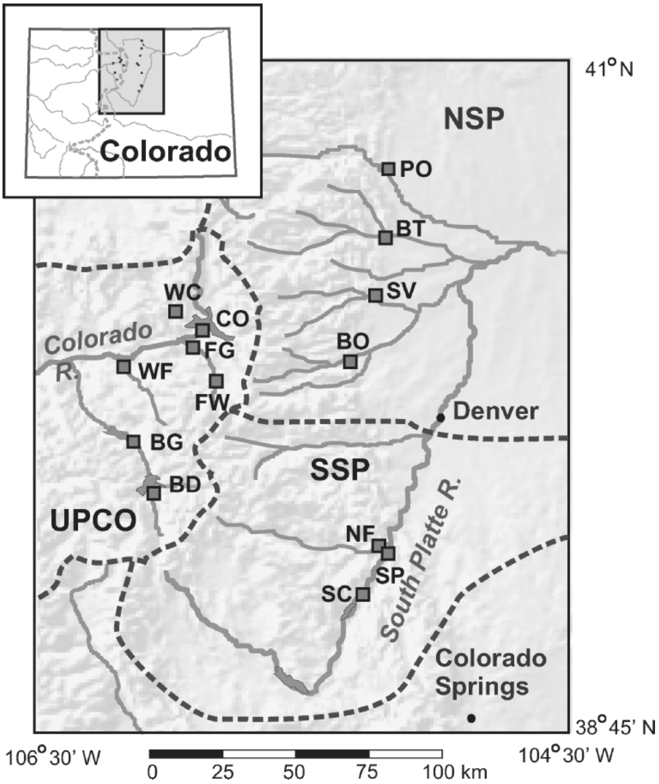

Figure 2. Locations of gages for which streamflow reconstructions were generated (squares). Two-letter gage codes correspond to gages listed in Table III. Dashed lines represent major watershed boundaries. SSP = southern South Platte, NSP = northern South Platte, and UPCO = Upper Colorado River basins.

flows were essentially normally distributed, except for one gage on the South Platte River (South Platte at South Platte). This record was log-transformed to meet the assumptions of the multiple linear regression process used in the reconstruction, and estimates were then back-transformed into the original units. All annual flows are based on the water year (October-September).

3. Reconstruction Methods and Results

3.1. METHODS

Stepwise regression was used to calibrate each of the gage records with a set of tree-ring chronologies, which were used as predictor or explanatory variables (Fritts, 1976; Cook and Kairiukstis, 1990). For the Upper Colorado gages, the pool of potential predictor variables included the set of 25 chronologies located in the

TABLE III
Gage record information

Gage	Mean annual flow[a]	Code[b]	Basin	Calibration period	Record provided by
Cache la Poudre R., mouth of canyon	358	PO	S. Platte	1906–1999	NCWCD
Big Thompson R., mouth of canyon	156	BT	S. Platte	1947–1999	NCWCD
St. Vrain Creek at Lyons	153	SV	S. Platte	1896–1999	NCWCD/City of Longmont
Boulder Creek at Orodell	89	BO	S. Platte	1922–1999	Hydrosphere Res. Consultants
South Platte R. at South Platte	363	SP	S. Platte	1916–1987	Denver Water
North Fork of the S. Platte at South Platte	127	NF	S. Platte	1916–1987	Denver Water
South Platte R. below Cheesman Res.	200	SC	S. Platte	1916–1987	Denver Water
Blue R. above Green Mt. Reservoir	469	BG	Colorado	1947–1999	NCWCD
Blue R. at Dillon	274	BD	Colorado	1916–1999	Denver Water
Fraser R. at Granby	180	FG	Colorado	1947–1999	NCWCD
Fraser R. nr. Winter Park	34	FW	Colorado	1916–1999	Denver Water
Colorado R. above Granby	333	CO	Colorado	1951–1999	NCWCD
Willow Creek	72	WC	Colorado	1953–1999	NCWCD
Williams Fork near Leal	94	WF	Colorado	1916–1999	Denver Water

[a] Cubic meters × 10^6.
[b] Gage codes correspond to Figure 2.

Upper Colorado and Arkansas River basins that ended in 1999 or later. For the South Platte gages, a different set of strategies was used to select the pool of predictor candidates because the portion of the South Platte drainage over which the seven gages are located is more climatically heterogeneous than the Upper Colorado part of the study area (Collins et al., 1991). First, chronologies from the South Platte River basin were included in the predictor pool if they were significantly correlated ($p < 0.05$) with the gage records. Since synoptic weather systems influencing the western part of the state frequently impact conditions east of the Continental Divide as well, the relationships between Upper Colorado/Arkansas River basin chronologies and South Platte gages were also assessed for possible explanatory capability. Chronologies from outside the South Platte Basin that displayed significant ($p < 0.05$) correlations with gage records that also appeared to be stable over the 20th century (assessed with split-sample correlations) were added to the pool of explanatory chronologies. Finally, the selection process also considered the end dates of the chronologies available (e.g., chronologies in the southern South Platte region have not yet been updated from 1987, while updates for the northern South Platte region had just been completed). For the three gages in the southern South Platte region, the set of explanatory variables included chronologies that ended in 1987 or later, with nine from the South Platte, 11 from the Upper Colorado, and four from the Arkansas River basin. Because of the availability of updated and/or new collections in the northern part of the South Platte, the four gages in this region were calibrated on chronologies that ended in 1997 or later. Eight chronologies from the South Platte, one from the Arkansas, and between 15 and 21 (depending on the gage) from the Upper Colorado comprise the pool of explanatory variables for these four northern South Platte gages.

The full set of years common to both tree-ring data and the gage data was used for calibrating tree-ring data with each of the gages. These calibration periods ranged from 49 to 104 years (Table III). The leave-one-out cross validation method was used to generate a set of validation data (Michaelsen, 1987). Using this method, a model is calibrated on all values but one, which is then estimated, and the process is repeated, until each value has been left out of the calibration and estimated. In addition, a linear neural network (LNN), which uses an iterative model-fitting process, was run to assess the robustness of the set of predictor variables selected in the stepwise regression process. The LNN is numerically equivalent to a linear regression when the same set of predictor variables is used to run the LNN, and the resulting explained variance should be the same (Goodman, 1996). Bootstrapping, an iterative resampling approach (Efron and Tibshirani, 1993), was used in the LNN process to further validate the model and generate confidence intervals. The models were then applied to the full length of the tree-ring data to generate reconstructions for each gage.

A suite of statistics was used to describe and validate the final reconstruction models. The statistics used to evaluate the calibration models included the variance in the gage record explained by the regression model (R^2_{cal}), and the standard error of the estimate. For the model validation using the leave-one-out-derived estimates, evaluative statistics included the reduction of error (RE), and the root mean squared error (RMSE). The RE tests the skill of the regression model in estimating the gage values relative to an estimate based on no knowledge (the mean of the calibration period for the gage record was used as “no-knowledge”), with positive values (maximum value of 1.0) reflecting some skill (Lorenz, 1956; Fritts, 1976). The RE can be thought of as a validation equivalent of the regression R^2_{cal}. The RMSE is a measure of the average size of the estimate error for the validation series. It is in the original units of the gage data, and is comparable to the standard error of the estimate.

TABLE IV
Reconstruction model calibration and verification statistics

Gage	R^2_{cal}	RE	R^2 LNN	R^2 LNN bias adj.	Standard Err. Est.[a]	RMSE[a]
Cache la Poudre R.	0.637	0.560	0.635	0.572	78.4	82.0
Big Thompson R.	0.720	0.645	0.720	0.659	29.0	30.3
St. Vrain Ck.	0.652	0.608	0.650	0.613	28.9	29.9
Boulder Ck.	0.641	0.577	0.641	0.588	13.7	14.3
South Platte at South Platte	0.734	0.688	0.728	0.684	90.6	97.7
North Fork of S. Platte R.	0.670	0.610	0.684	0.634	30.3	31.5
South Platte R. below Cheesman	0.630	0.578	0.623	0.577	55.2	56.8
Blue R. above Green Mt. Res.	0.763	0.696	0.756	0.699	65.9	70.2
Blue R. at Dillon	0.626	0.560	0.625	0.566	46.2	48.2
Fraser R. at Granby	0.729	0.686	0.733	0.693	25.2	26.1
Fraser R. near Winter Park	0.647	0.588	0.657	0.610	4.7	4.9
Colorado R.	0.649	0.587	0.655	0.598	52.1	54.1
Willow Ck.	0.728	0.674	0.728	0.685	14.3	15.0
Williams Fork	0.627	0.577	0.626	0.589	14.9	15.4

[a] Cubic meters × 10^6 (estimated for South Platte at South Platte).

For additional validation, the R^2 values resulting from LNN were compared to the R^2_{cal}, and 500 bootstrapped runs of the LNN were used to generate a bias-adjusted R^2, which is a more conservative estimate of the explained variance than the R^2 adjusted for numbers of explanatory variables in a linear regression.

3.2. RECONSTRUCTION MODEL RESULTS

The statistical evaluation of the reconstruction models is shown in Table IV. The explained variance in the models ranges from 0.626 to 0.763, and the validation statistic, RE, ranges from 0.560 to 0.696. The LNN-explained variance values are all close to the regression R^2 values and the bias-adjusted R^2 from the LNN compare quite favorably to the RE values, indicating the stability of the solution generated by the set of predictors selected by the stepwise regression process. In comparing calibration and verification statistics from gage to gage, it is necessary to consider the different lengths of the calibration period. The impact of the calibration period length can be seen in a comparison of the two pairs of gages on the Blue and Fraser Rivers. Although the explained variance is higher for NCWCD's Upper Colorado gages (Blue R. above Green Mountain Reservoir and Fraser at Granby) than for Denver Water's gages on the same rivers, these models are based on shorter

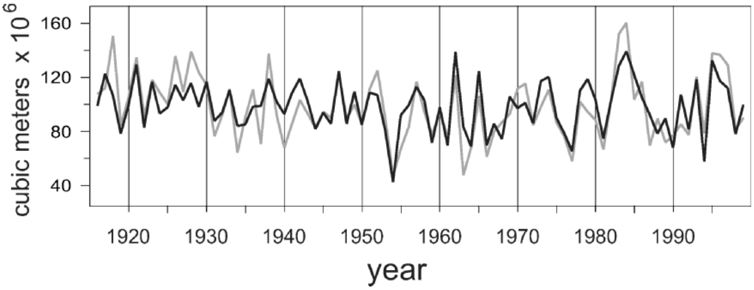

Figure 3. Observed (*gray line*) and reconstructed (*black line*) annual streamflow for Williams Fork, 1916–1999.

calibration periods and are likely less robust than the models based on longer calibration periods. In particular, in the models with the longer calibration periods, the fit in the 1930s is not as good as for other drought periods, reducing the overall explained variance (e.g., Figure 3). This lack of fit is also evident in the South Platte flow reconstructions and the reason for this has not yet been fully investigated. It also should be noted that the variance not explained by the reconstruction models is commonly in the extreme values, a consequence of the use of empirical statistical models, and thus reconstructed values tend to be conservative estimates of flow.

These streamflow reconstruction model results compare quite favorably with others in the western U.S. (e.g., Gila River, $R^2 = 0.66$, Meko and Graybill, 1995; Sacramento River, $R^2 = 0.64$–0.81, Meko et al., 2001; Boulder Creek, $R^2 = 0.70$, Woodhouse, 2001; Yellowstone River, $R^2 = 0.52$, Graumlich et al., 2003). The reconstruction for the one gage, Fraser River near Winter Park, that was also reconstructed by Stockton and Jacoby (1976), has been improved. The updated reconstruction is based on an increased number of calibration years (83 vs. 51) and has a higher correlation with the gage record than the original reconstruction ($r = 0.804$ vs. $r = 0.660$).

The set of explanatory chronologies for each gage reconstruction is shown in Table V. A number of gages share some of the same chronologies. In particular, nearly all Upper Colorado River gages share the PUM chronology (Figure 1). To test whether the relationships between reconstructed gage records are inflated due to shared explanatory chronologies, correlations between sets of gage records (Upper Colorado, northern South Platte, and southern South Platte) and reconstructions were compared for the common time period (Table VI). In all cases, the sets of gage records within a region are highly correlated with each other. The reconstructions for the Upper Colorado gages tend to show slightly higher correlations (17 of 21 pairs) between reconstructions than between the actual gage records, and although the differences are not large, suggesting a moderate enhancement of the similarity between the gage reconstructions. Conversely, the intercorrelations for the southern South Platte sets of gages show a tendency for higher correlations

TABLE V
Reconstruction model predictor chronologies and reconstruction periods

Reconstructed gage record	Predictor chronologies[a]	Period of reconstruction
Cache la Poudre R.	PUM, OWU, GMR, EFU, RED, BEN, JOP, BTU	1615–1999
Big Thompson R.	OWU, EFU, DIL, BTU, COD, SAR	1569–1999
St. Vrain Ck.	PUM, DMU, BTU, HOT	1571–1999
Boulder Ck.	PUM, RUS, BTU, HOT, LAN	1571–1999
South Platte at South Platte	VAN, TUR, DIL, CAT, UNA	1685–1987
North Fork of S. Platte R.	VAN, TUR, DIL, CAT, UNA	1685–1987
South Platte R. below Cheesman	VAN, TUR, DIL, CAT	1685–1987
Blue R. above Green Mt. Res.	LAN, PUM, DIL, TRG, SEE	1539–1999
Blue R. at Dillon	DIL, PUM, COD, GOU, MTR	1440–1999
Fraser R. at Granby	ATR, DIL, GOU	1383–1999
Fraser R. near Winter Park	DIL, PUM, COD, SAR, RCK	1524–1999
Colorado R.	PUM, CAT, GMR	1383–1999
Willow Ck.	PUM, GMR, GOU	1383–1999
Williams Fork	DIL, GOU, PUM, PRD	1383–1999

[a] Codes correspond to Figure 1 and Tables I and II.

between actual gage records, but again the differences are not large. The correlations between the four northern South Platte gages and reconstructions are mixed. The biggest difference is between the Poudre and Boulder gages, in which the gage record correlation is markedly lower ($r = 0.802$) than the correlation between the reconstructions ($r = 0.923$).

3.3. STREAMFLOW RECONSTRUCTIONS

The full streamflow reconstructions were generated from the models described above. Starting dates ranged from 1383 to 1685 (Table V). The longest reconstructions are located in the Upper Colorado River basin, reflecting the greater availability of long-lived trees in this region. In the course of updating tree-ring chronologies for the north and central South Platte basin, we also were able to extend chronologies back in time, so that three of the four northern South Platte gage reconstructions extend back into the 16th century. The shorter reconstructions for the three southern South Platte gages reflect the importance of one relatively short but critical chronology (VAN) (this chronology has since been updated and extended, but not in time to include in these analyses). Changes in the number of samples within the chronologies contributing to the reconstructions were examined, and signal strength at the point of lowest sample depth corresponded to an EPS of at least 0.85 (Briffa, 1984; Wigley et al., 1984), so none of the

TABLE VI

Correlations between gages and reconstructions

	Blue(DW)	Fraser(DW)	Williams	Colorado	Fraser(NC)	Willow	Blue(NC)
Upper Colorado							
Blue(DW)	1.000						
Fraser(DW)	0.867/**0.962**	1.000					
Williams	0.928/**0.969**	0.908/**0.933**	1.000				
Colorado	0.886/**0.940**	0.887/**0.877**	0.924/**0.954**	1.000			
Fraser(NC)	0.903/**0.957**	0.862/**0.904**	0.934/**0.965**	0.905/**0.960**	1.000		
Willow	0.815/**0.888**	0.837/**0.852**	0.860/**0.931**	0.942/**0.948**	0.851/**0.869**	1.000	
Blue(NC)	0.974/**0.956**	0.898/**0.932**	0.932/**0.932**	0.902/**0.884**	0.903/**0.921**	0.858/**0.838**	1.000
	Big Thompson	Poudre	St.Vrain				
Northern South Platte							
Big Thompson	1.000						
Poudre	0.892/**0.889**	1.000					
St.Vrain	0.942/**0.879**	0.814/**0.902**	1.000				
Boulder	0.863/**0.854**	0.802/**0.923**	0.935/**0.962**				
	S.Platte/SP	N.Fork/SP	S.Platte/Ch				
Southern South Platte							
S.Platte/SP	1.000						
N.Fork/SP	0.977/**0.969**	1.000					
S.Platte/Ch	0.983/**0.963**	0.964/**0.989**	1.000				

DW = Denver Water gage, NC = Northern Colorado Water Conservancy District gage (see Table II). Bold values are correlations between reconstructions. The correlation period is 1953–1999 for the Upper Colorado and northern South Platte regions (top and middle), and 1953–1987 for the southern South Platte region (bottom).

reconstructions were truncated. The reconstructions with estimated confidence intervals, gage data, and reconstruction statistics are available online on the TreeFlow web pages (http://www.paleo.noaa.gov/paleo/streamflow).

4. Analysis of the Streamflow Reconstructions

One of the issues most relevant to water resource management is the characterization of droughts in terms of intensity, duration and spatial extent. Reconstructions of streamflow provide a longer context from which to evaluate 20th and 21st century drought events. The 1950s drought was the most severe multiple-year drought, and 2002 the most severe single year drought, on record for many gages in Colorado. Two questions for water managers in planning for future drought are: How often do 1950s- or 2002-magnitude droughts occur? Have even more severe droughts occurred prior to the 20th century?

To analyze characteristics of droughts, the streamflow reconstructions were grouped into three watershed regions, the Upper Colorado (Blue at Dillon, Fraser at Granby, Williams Fork, Colorado at Granby, and Willow Creek gages), northern South Platte (Poudre, Big Thompson, St. Vrain, and Boulder Creek gages), and southern South Platte (South Platte at South Platte and North Fork of the South Platte gages), and the reconstructed flows in each were summed to represent annual streamflow across the three watersheds. In the case of the Fraser and Blue Rivers, for each of which there were two reconstructions, only the longer one was used. The regions were based on watershed geography and water management considerations. The summed flow reconstructions were evaluated to determine whether relationships between regional gage records were preserved in the reconstructions. Correlations between the summed gages, for the common period of record available for gages and reconstructions (1953–1987) were compared to the correlations between the summed reconstructions (Table VII). The correlations between reconstructions for the three watershed regions were slightly higher than the correlations between the gage records, but the same relative differences between correlations were preserved.

A comparison of the time series of the three regional flow reconstructions allows an evaluation of the 20th century portion of the record relative to the past 300–400 years (Figure 4). The terms used here to describe drought events include duration (years below the long-term average) intensity (a value's departure from the mean), and severity or magnitude (a reflection of both duration and intensity). In the 20th century, all three records show that the most intense low flows occurred in the 1950s. The 1930s Dust Bowl drought is also evident in the two South Platte reconstructions. In agreement with the gage records, the Dust Bowl is more persistent than the 1950s, but less intense. Another notable feature of the 20th century is the period of relatively sustained above average flow in the first two to three decades of the century. As in the Stockton and Jacoby (1976) Lees Ferry reconstruction, this feature does not

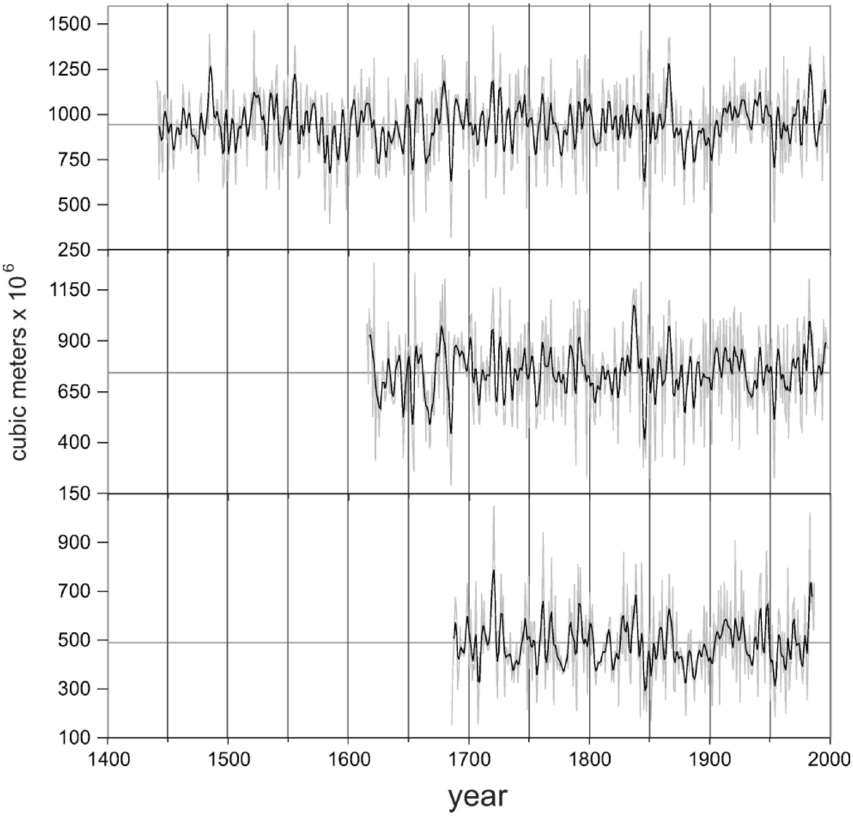

Figure 4. Summed regional water year flow reconstructions for the Upper Colorado, 1440–1999 (*top*), the northern South Platte, 1615–1999 (*middle*), and the southern South Platte, 1685–1987 (*bottom*) basins. Annual values (*gray line*) have been smoothed with a 5-weight binomial filter (*black line*; for display purposes only). Also shown is the long-term mean for each record.

have an equivalent counterpart in the prior four centuries. This period of unusual wetness has also been identified in other reconstructions, such as the gridded Palmer Drought Severity Index (PDSI) reconstructions of Cook et al. (1999) (Woodhouse et al., 2005), and has been shown to extend throughout the western United States (Fye et al., 2003). Another period of marked wetness is evident in the 1980s. The record low flows of the 20th century in the 1950s are exceeded in severity in the late 1840s in all three regional flow reconstructions. This period of drought is noted in historical accounts of travelers across the western Great Plains, but it is difficult to estimate the severity from these accounts since they likely reflect the environmental impacts due to changes in land use from human activities as well as to drought (West, 1995; Woodhouse et al., 2002). Unfortunately, this drought predates any permanent settlements, so there are no historical records of climate in this region. In the southern South Platte reconstruction, this drought is both more intense and more persistent than the 1950s drought. In the northern South

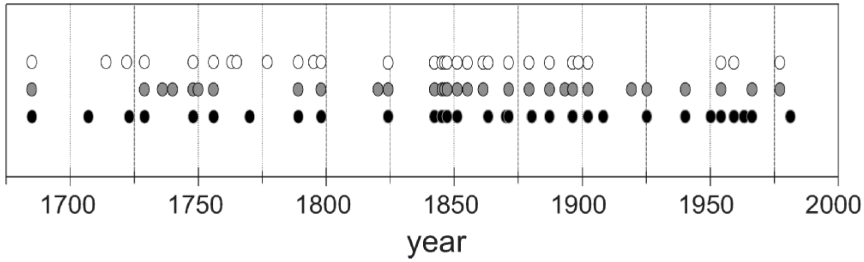

Figure 5. Distribution of extreme low flow years (10th percentile or less), 1685–1987, for the three regional flow reconstructions. *White circles* = Upper Colorado River basins, *gray circles* = northern South Platte, and *black circles* = southern South Platte.

Platte reconstruction, 1950s-magnitude or greater events also occurred three times in the second half of the 17th century, while in the Upper Colorado reconstruction, droughts in the 1880s, 1680s, 1650s, and 1580s matched or exceeded the severity of the 1950s drought.

Severe single-year events in the gage records include 2002, 1977, and 1954. How often do years such as these occur, and how evenly are they distributed over time? To examine this, the years with reconstructed flows in the lowest 10th percentile for the common period of time (1685–1987) were identified for each of the three regional flow reconstructions series and plotted over time (Figure 5). In the Upper Colorado and northern South Platte series, there were fewer extreme low flow years in the 20th century than in prior centuries, particularly in the Upper Colorado, where there are only four extreme events in the 20th century. The common period of analysis ends in 1987, but these two reconstructions extend to 1999, so they were also ranked for the period 1685–1999. One additional year in the Upper Colorado reconstruction ranked in the lowest 10th percentile, bringing the total up to five, still far short of the 14 events in the 19th century and 11 events in the 18th century. In all three series, the greatest frequency of extreme low flow events occurred in the 19th century. Of particular note is the clustering of extreme event years in the 1840s and 1850s in all regions, with three consecutive

TABLE VII

Correlations between regional gage records and regional reconstructions (bold), for common time period, 1953–1997 (left), and for comparison, correlations between region reconstructions for the period 1685–1987 (right)

	UPCO	NSP	SSP	UPCO	NSP	SSP
UPCO	1.000			1.000		
NSP	0.839/**0.897**	1.000		0.811	1.000	
SSP	0.724/**0.779**	0.787/**0.818**	1.000	0.747	0.757	1.000

Upper Colorado regional flow is UPCO, northern South Platte is NSP, and southern South Platte is SSP.

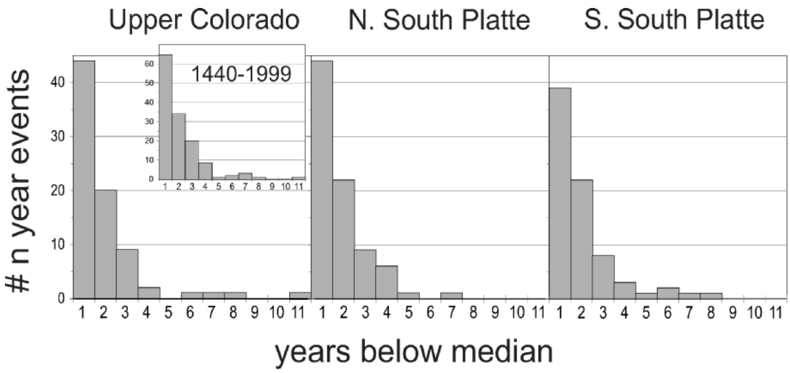

Figure 6. Histograms showing frequency of n-year drought events (one to 11 consecutive years below the median), for the three regional flow reconstructions, 1685–1987. The inset shows the distribution for the full Upper Colorado reconstruction, 1440–1999.

years of extreme drought, 1845–1847 in the northern South Platte and Upper Colorado reconstructions. Extremes are less frequent and more evenly distributed in the 18th century. Several intervals with few extreme years are also evident in the first half of the 20th century (as mentioned above) and from 1800 to about 1845.

Single extreme drought years have significant impacts on water supplies, but sustained periods of drought, even when flow is only somewhat below average, are more likely to challenge water systems with several years of storage. The frequency of single- and multiple-year droughts was assessed for each regional reconstruction. Here, a drought was defined somewhat arbitrarily as a year or set of consecutive years below the long-term median (1685–1987). The median was used because it is a better measure of central tendency when values are not normally distributed, as is the case with the South Platte flow. The number of n-year droughts was tabulated in each of the three series (Figure 6). Results are displayed in a set of histograms that show an expected even decline from a peak in numbers of single year droughts to fewer, increasingly longer droughts. There are some differences from watershed to watershed, but for the most part, the distributions are quite similar. The southern South Platte record has fewer one- to three-year events than the other two records, with a slightly greater proportion of years in periods of drought longer than three years (41% of drought years compared to 36% for the Upper Colorado and 31% for the northern South Platte). For comparison, the histogram for the full Upper Colorado flow reconstruction (1440–1999) was also generated (Figure 6, inset). It shows a distribution very similar to that of the shorter period, but with a somewhat larger proportion of years in two-, three-, and four-year events, relative to single-year drought.

The temporal distribution of multiple-year (two years and greater) low flow events plotted for each of the three watersheds indicates that many drought events are widespread across the three watersheds (Figure 7). The Upper Colorado and northern South Platte reconstructions are the most similar, as would be expected from the

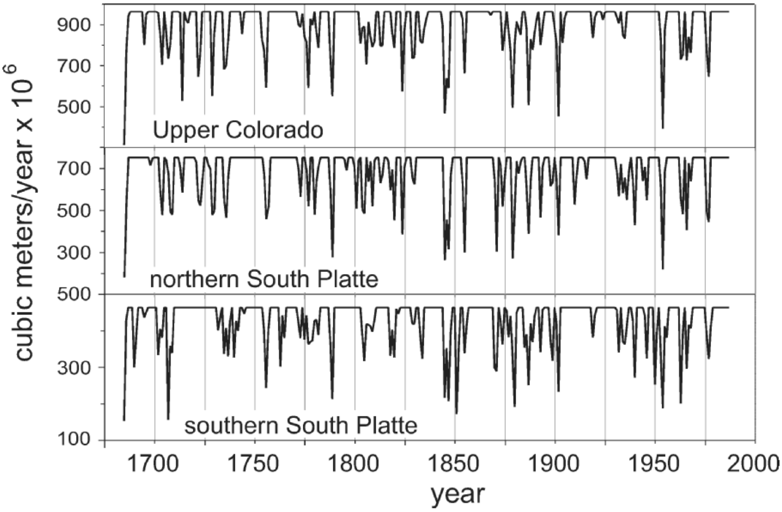

Figure 7. Persistent drought (two or more years) in regional flow reconstructions, 1685–1987. Values are shown only for years with two or more values consecutively below the median.

correlation results (Table VII, $r = 0.811$). While some periods of drought match year to year (e.g., 1788–89, 1953–55), other periods show overlapping drought years that include some mismatched years. In the first decade of the 1800s, sustained drought (eight years below median) in the Upper Colorado corresponds with some drought years in the northern South Platte, but the driest year in this interval in the Upper Colorado (1806) is actually above the median in the northern South Platte region. In the northern South Platte, this eight-year period is broken by several non-drought years, but is preceded by three dry years, which are above the median in the Upper Colorado record. Other differences between the Upper Colorado and northern South Platte, similar to this period, are evident (e.g., 1770s, late 1800s). A few droughts appear in Upper Colorado and not in the northern South Platte, such as 1830s in the Upper Colorado, but these are relatively uncommon. There is less similarity between the southern South Platte series and the other two series. From 1710 to 1731, there are no multiple-year droughts in the southern South Platte, while there are several two- to four-year droughts in the other two watersheds. This period is followed by 14 years of drought broken by only two above median years, while this same period contains only eight drought years in the other two records.

The patterns depicted in the three time series are to some degree a function of the threshold selected. However, the differences between watershed reconstructions do indicate some variations in drought years from watershed to watershed. These subtle differences (e.g., a string of six years below median in one record, and interrupted in another record by one above median year) can be critical to water managers, when a single year break in a period of drought may offer a partial recovery.

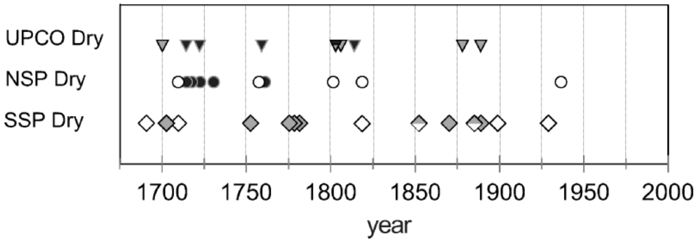

Figure 8. Years (1685–1987) when reconstructed flow is very low (<25th percentile) in one basin ("Dry"), while above the median (>50th percentile) on another basin. The color of the symbol indicates which basin was not dry: white = UPCO; gray = NSP; black = SSP. If the symbol is split, both of the indicated basins were not dry that year.

5. Discussion

5.1. ANALYSES OF RECONSTRUCTED STREAMFLOW

Analyses of reconstructed regional streamflow time series, the distribution of extreme low flow years, and drought frequency and timing indicate that the 20th and 21st century gage records may not be an adequate representation of the range of flow characteristics over previous centuries. Some drought events, including those occurring less than 200 years ago (i.e., the 1840s drought), appear to have been more severe than any in the 20th century. The distribution of extreme low flow years is markedly uneven over the past three centuries, with the 19th century containing a high concentration of extreme years in all three regions. In contrast, in the 20th century, the Upper Colorado regional flow reconstruction indicates only five extreme low flow years, compared to 13 extreme years in the 55-year period from 1845–1899.

The streamflow reconstructions for the three regions are highly correlated over the past three centuries, although some proportion of the shared variance is due to shared explanatory chronologies in the reconstructions (Table VII). The differences between the reconstructions are often degrees of relative wetness or dryness across the three watersheds. A very dry year in one region is typically below average in the other two regions. The occurrence of years in which one basin is very dry (<25th percentile) and one or both of the other two basins are above median flow (>50th percentile) is relatively rare (only 27 of 303 years), but these years are indicative of strong spatial variation across the watersheds (Figure 8). An examination of these years shows 14 years when the southern South Platte is dry and the Upper Colorado and/or the northern South Platte is not, ten years when the northern South Platte is dry and one or both of the other two are not, and nine years when the Upper Colorado is the only dry basin.

The dry years in the southern South Platte are slightly more frequent and distributed much more evenly across time than the dry years in the other two basins

(Figure 8). Conversely, the period when the southern South Platte has above median flow, while one or both of the other two basins are very dry, is restricted to the years 1714 to 1814. The other feature of this distribution of years worth noting is the absence of years with spatial differences after 1936, suggesting that the conditions in the three watersheds are more uniform over this period. Streamflow in the three watersheds is just slightly higher than the long-term average during the period from 1937–1987, but a higher percent of years in which flow is greater than the median in all three basins (43% of years vs. 34% of years over the full record) might be contributing to the lack of years with extreme low flow in one watershed and above median flow in one or both of the others. An examination of the gage data for 1916–1987 shows three years since 1936 with spatial difference, which is still far fewer than in the 18th and 19th centuries.

The differences and similarities between the three flow reconstructions may be attributed to the climatic features that influence hydroclimatic variability across the region. In the western U.S., one of the main circulation features influencing winter snowpack is a Pacific-North American (PNA)-like pattern, although the influence of this pattern is weakest in the region including Colorado and New Mexico (Cayan, 1996). The positive phase of the PNA, with a strong Aleutian Low and high pressure over much of the western U.S. leads to low April 1 snow water equivalent (SWE) in the western U.S. by inhibiting the passage of frontal storms. In Colorado, these frontal storms which bear Pacific moisture are the most important seasonal, large-scale atmospheric circulation feature impacting snowpack and water resources (Collins et al., 1991). Snowfall is enhanced at high elevations by the orographic effect of the mountains, with precipitation decreasing with elevation east of the Continental Divide. East of the Divide, winter snowpack, particularly at lower elevations, may be augmented by upslope storms in the late winter and spring, in which Gulf of Mexico moisture is drawn up against the eastern Front Range by frontal systems that strengthen on the east side of the Rocky Mountains (Collins et al., 1991).

In many regions of the western U.S., snowpack and annual streamflow are influenced by El Niño/Southern Oscillation (ENSO) events, and most strongly by cool phase ENSO (La Niña events), which results in dry conditions in the southwest, including the lower Colorado River basin and parts of southern Colorado (San Juan Mountains, southern Rocky Mountains) (Cayan, 1996; Clark et al., 2001). However, an analysis of the relationship between April 1 SWE in years with positive and negative Southern Oscillation Index (SOI) across the western U.S. indicates no significant relationships between snowpack in the watersheds in this study and SOI, and suggests that the region is in a transitional zone with respect to ENSO impacts (Cayan, 1996). An examination of the correlations between streamflow (December-August) measured at gages across the western U.S. and SOI shows streamflow in the study area to be uncorrelated with variations in the SOI as well (Cayan and Webb, 1992). Clark et al. (2001) found only a very modest improvement in streamflow forecast skill using information on ENSO conditions in the Colorado headwaters region.

The lower correlations between southern South Platte streamflow and both northern South Platte and Upper Colorado streamflow records, along with temporal pattern of very low streamflow years at times not corresponding to similarly dry years on the northern South Platte and the Upper Colorado River basins suggests this region may occasionally be influenced by different climate mechanisms. Although the three watersheds are outside the main influence of ENSO, the southern South Platte region is more proximal to regions to the south which have a stronger response to ENSO. A low-frequency component of ENSO could be responsible for the multidecadal behavior of the southern South Platte River basin in the clustering of years when it is markedly wetter or drier in contrast to the other two watersheds. Clearly, more research is needed to determine the combination of mechanisms and modes of climate that influence water supply in the three watersheds.

6. Conclusion

Recent severe drought conditions have motivated water resource managers in Colorado to use tree-ring reconstructions of streamflow in water resource planning. The reconstructions of streamflow described in this paper are now being used as input into water system models to assess the reliability of water supply systems under a broader range of conditions than afforded by the gage record alone. Additional collaborative work with water managers to make streamflow reconstructions compatible with current planning and management tools is ongoing. Several issues that are currently being investigated are (1) the fidelity of the tree-ring data in reflecting the severe drought conditions in 2002, (2) the uncertainty in the reconstructions, and (3) the feasibility of reconstructing other hydroclimatic metrics besides annual flow that are also critical to water management. Results from analyses of streamflow reconstructions now appear to be a consideration, along with information on snowpack, runoff, and estimated diversions, in setting allocations and enacting conservation measures. Future work will investigate more fully how water planning decisions are made, how reconstructions are incorporated into the decision-making process, and what can be done to make reconstructions more applicable to planning.

Although the reconstructions do not allow a direct comparison of the extreme lows flows measured in 2002, it is likely that this event is within the bounds of natural variability of the last three to five centuries, particularly in the Upper Colorado, where the gage values for 1954 and 2002 were very similar. In addition, multi-year events similar to the 1950s drought have occurred in the past, as well as droughts that have no analogue in the 20th century. Besides acknowledging that the streamflow variability described by the tree-ring record is greater than that seen in the gaged records, water management will also need to take into account multidecadal climate changes and trends impacting hydrologic regimes which will be superimposed on natural flow characteristics. The most significant impact will likely be a reduction in mountain snowpack, due to increased temperatures that will influence the amount of rain compared to snow, as well as the timing and amount of runoff (Barnett et al., 2004; Stewart et al., 2004). These changes have already been observed across mountain regions of the western U.S. (Aguado et al., 1992; Dettinger and Cayan, 1995; Cayan et al., 2001).

The climate of the future will not be precisely analogous to the climate of the past because of the unprecedented effect of human activities on climate, but the full range of natural climate variability is likely to underlie future climate. Extended records of past climate variability from paleoclimatic data contain a broader range of extremes than the 20th century, and considering projections of greater extreme events, are thus likely a better representation of the extremes that can be expected in the future. In view of the record of past natural variability and the probable impacts of climate change in the future, a prudent water resource management strategy should consider paleohydrologic analyses such as those presented here, in tandem with climate modeling of future conditions, in developing scenarios for future hydrologic variability.

Acknowledgments

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