A tree-ring reconstruction of streamflow in the Santa Fe River, New Mexico

Ellis Q. Margolis *, David M. Meko, Ramzi Touchan

Laboratory of Tree-Ring Research, The University of Arizona, 105 W. Stadium, Tucson, AZ 85721, United States

SUMMARY

The upper Santa Fe River provides up to 50% of the water supply for the growing population of Santa Fe, NM. Recent droughts have dramatically lowered reservoir levels and raised concern about the future of the water supply, particularly when combined with projections of a warmer and drier future climate. In this study, new and updated tree-ring chronologies are used to reconstruct annual discharge for the upper Santa Fe River and place the short period of gaged flows, 1914–2007, in a long-term context. Principal components analysis and forward stepwise multiple linear regression were used to produce two reconstructions: (1) a better fit, "short reconstruction" (adjusted R^2 = 0.62, 1592–2007) and (2) a less robust, "long reconstruction" (adj. R^2 = 0.50, 1305–2007). Both reconstructions indicate that recent extreme low flow events (e.g., 2002) are rare (5th percentile) in the long-term records and that the 1950s drought contained the lowest 7-year mean flows over the past 400–700 years. However, longer, multi-decadal dry periods not present in the gaged flows occurred in the past. For example, the 40-year mean for 1544–1583 is estimated at just 86% of the 1914–2007 mean. During extended dry periods in the 16th and 18th centuries the probability that annual flow would *not* meet the current surface water allocation and instream flow target (7.52 million cubic meters, MCM) was up to 10% greater (78.7% non-exceedence probability) than during the instrumental period. The results indicate that the gaged record does not contain the full range of high and low flows or the variability in the probability distributions of flows present in the long-term record. Therefore current and future water management and planning based on the instrumental period may not adequately buffer against the natural variability in the climate and streamflow systems. This valuable paleo-hydrologic information is in the process of being incorporated into water supply planning for the City of Santa Fe (e.g., modeling future water supply scenarios directly from reconstructed periods of streamflow).

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1. Introduction

The Santa Fe River and the system of reservoirs in the upper watershed provide up to 50% of the water supply for the city of Santa Fe (City of Santa Fe, 2009). Recent drought dramatically lowered reservoir levels and raised concern about the future of city's water supply in the face of steady population growth and projections of a more arid future climate (Seager et al., 2007). In addition, the threat of flooding or debris flows following a catastrophic fire has further raised concerns about the reliability and dependence of this water source (Margolis and Balmat, 2009). Efforts are underway to reduce fire risk, but the long-term probabilities and effects of severe, multi-year droughts on the water supply are largely unknown.

Instrumental stream gage records beginning in the 20th century are too short to address these questions because they may not contain the full range of drought durations or magnitudes that have occurred in the past. Retrospective analysis of drought or flood occurrences and magnitudes is a standard hyrdoclimatic approach for assessing recurrence probabilities in water planning and engineering (e.g., Dunne and Leopold, 1978). Tree rings have been used to reconstruct hundreds of years of streamflow for rivers across the arid western United States (Meko and Graybill, 1995; Smith and Stockton, 1981; Stockton and Jacoby, 1976; Woodhouse and Lukas, 2006). The extended record of streamflow variability derived from tree-ring reconstructions has been an important addition to water management plans for federal agencies, states, and municipal areas throughout the western US (e.g., USBR, 2007).

The hydrological and biological basis for using tree rings to reconstruct streamflow in the southwestern US has been well documented. Tree-ring widths of montane conifers on well drained, south-facing slopes in the region have a high positive correlation with cool season (prior year October–current year May) precipitation (Fritts, 1976; Grissino-Mayer, 1996; Touchan et al., 2010). This cool season moisture, minus losses from evapotranspiration, largely determines the vigor and the duration of cell production at the onset of cambial activity in the spring (Fritts, 1976). In this

* Corresponding author. Tel.: +1 520 626 2733; fax: +1 520 621 8229.
E-mail address: ellisqm@ltrr.arizona.edu (E.Q. Margolis).

study we use new and updated tree-ring width chronologies from moisture sensitive sites to develop two reconstructions of mean annual calendar year flow for the upper Santa Fe River, NM and interpret the reconstructions in terms of water management.

2. Study area

The upper Santa Fe River watershed is located on the west slope of the Sangre de Cristo Mountains, northeast of Santa Fe, NM, in the Middle Rio Grande Basin (Fig. 1). The watershed is small, steep and generally south/southwest-facing. The area contributing to the streamflow at the reconstructed gage is 4714 ha. Elevation ranges from 2353 m at the gage to 3847 m on the peaks that define the headwaters of the basin. Dominant vegetation types vary along an elevation gradient from ponderosa pine, to mixed-conifer, to spruce-fir forests, with alpine grasslands at the highest elevations.

At Santa Fe (elev. 2060 m) annual average minimum and maximum temperatures are 2.3 °C and 18.2 °C respectively, average annual precipitation is 38.4 cm, and average annual snowfall is 44.2 cm (1972–2005, Western Regional Climate Center, http://www.wrcc.dri.edu). Precipitation peaks during summer monsoon convective storms, with July through September precipitation contributing 43% of the annual total (1895–2007, http://www.prism.oregonstate.edu/). Persistent winter snowpack is common in the

upper watershed. Although monthly precipitation peaks in the summer, peak monthly runoff typically occurs in May, resulting from spring snowmelt (Fig. 2). A second, smaller peak in flow may occur in August during the monsoon and on rare occasions, after dry winters, can exceed the snowmelt peak.

3. Data

3.1. Santa Fe River streamflow data

The longest record of calendar year (January–December) discharge for the upper Santa Fe River extends back to 1914 (USGS Gage No. 08316000 – *Santa Fe River near Santa Fe*). McClure reservoir was built upstream of the gage in 1926 and the dam was raised in 1935, 1947, and 1995 (Goldman, 2003), therefore this record reflects the effects of reservoir storage and evaporation after 1926. Natural flow, adjusted for reservoir storage, was modeled for this gage from 1944 to 2003 (City of Santa Fe, unpublished data). Above McClure reservoir a short record of continuous mean daily flow extends from 1998 to the present (USGS Gage No. 08315480 – *Santa Fe River Above McClure*). High correlation between modeled calendar year natural flow and the uncorrected *Santa Fe River near Santa Fe* gage record ($r = 0.96$; 1943–2003) indicates that errors related to evaporation and reservoir storage are minimal. Based on this result and a thorough discussion with the local water managers regarding the strengths and weaknesses of each gage record we decided to retain the uncorrected portion of the *Santa Fe near Santa Fe* record (1926–1943) for model calibration.

To calibrate the reconstruction we combined these records into a continuous time series of calendar year flow (1914–2007). This combined record consisted of (1) *Santa Fe near Santa Fe* (1914–1943), (2) modeled natural flow at *Santa Fe near Santa Fe* (1944–1997), and (3) *Santa Fe River Above McClure* (1998–2007). We reconstructed calendar year flow (January–December) so the results could ultimately be input directly into the City of Santa Fe Water Management And Planning Simulation model (WaterMAPS).

3.2. Tree-ring data

Most existing tree-ring chronologies located near the Santa Fe watershed end in 1972 (International Tree-Ring Data Bank, http://www.ncdc.noaa.gov/paleo/treering.html). In 2007 we updated the two existing chronologies located within 100 km of the watershed that correlated highest with the Santa Fe River gage record (1914–2007), Glorieta Mesa (GLO) Piñon pine (*Pinus edulis*) and Ruidosa Ridge (RUD) Douglas-fir (*Pseudotsuga menziesii*, Fig. 1, Table 1). Updating the chronologies consisted of relocating the original sites and trees, and collecting new tree-ring samples from 10 to 15 living trees at each site. We also developed a new Douglas-fir chronology within the upper Santa Fe watershed (SFW PSME, Fig. 1). Tree-ring samples from living Douglas-fir trees and remnant wood were collected from a dry, south-facing site near the local lower elevation limit of the species in the watershed (2400 m). As part of our effort to reconstruct a streamflow record that extended prior to the 17th century, we developed a second new chronology within the Santa Fe watershed from Southwestern white pine (*Pinus strobiformus*) living trees, remnant snags and logs. Because of the relative scarcity of old material we combined samples from two adjacent sites with a similar climate response, located at similar elevations, 2580 m and 2700 m (SFWPIST, Fig. 1).

The chronologies from the two updated sites (GLO and RUD) and the new Santa Fe watershed sites (SFW PSME and SFW PIST) are hereafter referred to as the "local chronologies" (Table 1). The local chronologies were used as the potential predictors for the "short reconstruction." After we completed the short recon-

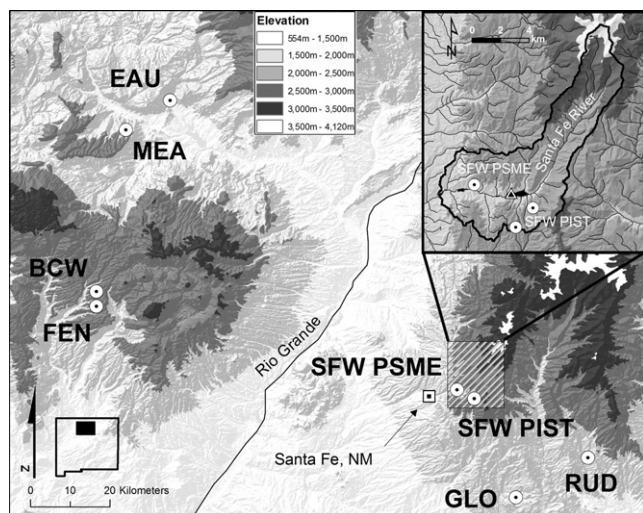**Fig. 1.** Location of tree-ring sites (circles) and upper Santa Fe River watershed (hatched box) in northern New Mexico. (Inset) Tree-ring sites and *Santa Fe River near Santa Fe* gage location (triangle) within the watershed.
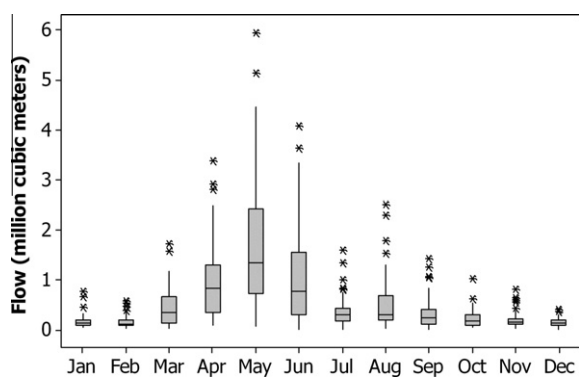

Fig. 2. Boxplots of modeled monthly natural flow for USGS Gage 08316000 *Santa Fe River near Santa Fe* (1943–2007) indicating median, interquartile range and outliers.

Table 1
Site information for tree-ring chronologies.

Site name	Site ID	Species[a]	Elev. (m)	Latitude	Longitude	Period	Trees (#)	Samples (#)	Mean series length (years)	Source[b]
Local chronologies										
Glorieta Mesa	GLO	PIED	2164	35.27	–105. 44	1556–2007	29	73	265	1 and 2
Ruidosa Ridge	RUD	PSME	2238	35.32	–105.34	1690–2007	27	52	198	1 and 2
Santa Fe Watershed	SFW	PSME	2400	35.41	–105.52	1592–2007	19	37	259	1
Santa Fe Watershed	SFW	PIST	2640	35.40	–105.49	1275–2008	29	35	287	1
Jemez Mountains long chronologies										
Bear Canyon West	BCW	PIST, PSME	2561	35.55	–106.41	1298–2007	30	56	222	3
Echo Amphitheater	EAU	PSME	2059	36.21	–106.31	1295–2007	18	19	294	3
Fenton Lake	FEN	PIPO	2529	35.53	–106.41	1304–2007	37	66	262	3
Mesa Alta	MEA	PIST, PSME	2525	36.17	–106.37	644–2007	47	82	243	3

[a] PIED = *Pinus edulis*, PIPO = *Pinus ponderosa*, PIST = *Pinus strobiformus*, PSME = *Pseudotsuga menziesii*.
[b] 1 = Current study; 2 = submitted to ITRDB by Dean, J.S. and Robinson, W.J.; 3 = Touchan et al. (2010).

struction, four newly developed and updated long chronologies (>700 years) from the Jemez Mountains, NM became available (Touchan et al., 2010). In combination with the new long chronology from the Santa Fe watershed (SFW PIST) these chronologies provided the opportunity to produce a "long reconstruction" that included known drought periods not covered by the short reconstruction (e.g., late 1500s).

The four Jemez Mountains long chronologies are from precipitation sensitive sites in northern New Mexico, located approximately 100 km northwest of the upper Santa Fe watershed (Touchan et al., 2010). The climate of the Jemez Mountains is similar to the Santa Fe watershed, particularly in regards to the cool-season precipitation that drives variability in annual streamflow and tree-ring width. This similarity is indicated by a high correlation ($r = 0.87$) between Jemez and Santa Fe watershed cool-season precipitation totals (prior year October–current year May, 1914–2007, PRISM 4 km gridded precipitation data, http://www.prism.oregonstate.edu/). The similar climate of these sites and the precipitation-sensitive climate response of the chronologies from the nearby Jemez Mountains justify their utility to reconstruct a longer record of Santa Fe watershed streamflow.

We chose not to include a long tree-ring chronology from the Arroyo Hondo, NM archeological site in our analysis. This chronology extends back to A.D. 985 and has previously been combined with the Glorieta Mesa Piñon pine chronology to reconstruct precipitation at Arroyo Hondo (Rose et al., 1981). The Arroyo Hondo chronology was not included in our analysis because of the uncertainty regarding the climate response of the archeological tree-ring samples.

4. Methods

4.1. Tree-ring analysis

All tree-ring samples were prepared and crossdated according to standard dendrochronological procedures (Stokes and Smiley, 1968). Total ring width was measured to the nearest 0.01 mm. The software COFECHA (Holmes, 1983) was used to check for crossdating and measurement errors. Standard and residual chronologies were produced with ARSTAN software (Cook, 1985). Ring width series were detrended with a rigid (i.e., conservative) cubic smoothing spline (Cook and Peters, 1981) with a 50% frequency response at a wavelength 75% of the series length. Mean series length ranged from 198 years to 294 years among sites (Table 1). Detrended tree-ring indices were produced by dividing the ring-width measurements by the fitted spline (i.e., ratio method; Fritts, 1976). Residual versions of series were computed by fitting the individual detrended index series with an Autoregressive (AR) model that was then applied as a filter to remove autocorrelation

(Box and Jenkins, 1976). The bi-weight robust mean was used to reduce the influence of outliers when combining the individual series into the final standard and residual (pre-whitened) tree-ring index chronologies (Cook, 1985).

4.2. Streamflow reconstruction methods

Standard tree-ring methods were used to reconstruct calendar year annual streamflow for the upper Santa Fe River (Cook and Kairiukstis, 1990; Fritts, 1976). We developed two reconstructions: (1) a more robust, "short reconstruction" derived from the local tree-ring chronologies and (2) a less robust, "long reconstruction" that was based on five long chronologies (>700 years), including the four Jemez Mountain chronologies (Table 1).

All potential predictor tree-ring chronologies and the predict- and streamflow series were run through a series of descriptive analyses before building the regression model. These analyses were used to describe the time series distributions, autocorrelation (persistence) within the time series, and the strength of linear relationships between the time series. The analyses included normal probability plots, autocorrelation function (ACF), lagged scatter plots, Pearson correlation coefficients, scatter plots by tercile, and sliding correlations (results not shown).

The initial descriptive analyses indicated that the gaged flows had strong positive skew and needed to be transformed closer to the distributions of the tree-ring chronologies. We tested (1) a square-root transform and (2) a log 10 transform and re-analyzed the strength of the linear relationship between transformed flow and the tree-ring chronologies to determine the best transform for each reconstruction. In developing the short reconstruction we found the square-root transform sufficient to reduce the strong positive skew of the gaged flows so they were closer to the slight positive skew of the local tree-ring chronologies. This transformation also resulted in better correlations ($r = 0.53$–0.78) and linear-appearing scatterplots of transformed flow on the chronologies. For the long reconstruction we found that a log 10 transformation on the flow series was more appropriate than a square-root transform. Log 10 transformation produced flows with a slight negative skew, consistent with that of the long chronologies used in the long reconstruction, and yielded relatively high correlation between chronologies and transformed flow ($r = 0.54$–0.70). Regression modeling was done on transformed flows, but final reconstructed flows were back-transformed into the original units (MCM) for plotting and analysis.

The short reconstruction was developed by forward stepwise multiple linear regression (FSMLR) of the square root of calendar-year streamflow (predictand) on the local tree-ring chronologies (predictors). We developed and compared four FSMLR models derived from different sets of potential predictors including (1) the four individual local standard tree-ring chronologies, (2) the four

local residual chronologies, (3) the principal components (PC's) of the standard chronologies and (4) the PC's of the residual chronologies. We used principal components analysis to extract variability in common between the local tree-ring chronologies (Fritts, 1976; Kachigan, 1982). A strength of the PC approach is that the predictors in the model are based on a shared (climate) signal that is less likely to be affected by a non-climatic event at one site. The autocorrelation function (ACF) of modeled flow was used to assess whether the standard or residual chronology model had autocorrelation most similar to gaged flows. Residuals analysis of the regression model was used to test model fit and assumptions.

To validate the final model with data not used for model calibration we first used the split-sample procedure (Snee, 1977). The tree-ring model was calibrated on the first half of the instrumental flow record (1914–1960) and validated on the second half (1961–2007), and vice versa. As a second validation method we used the cross-validation (Michaelsen, 1987) or PRESS procedure (Weisberg, 1985), where an omitted value is predicted by calibrating on all other values and the process is repeated until all values are predicted. The following statistics were used to evaluate the quality of the reconstruction: Pearson correlation coefficient (r), explained variance adjusted for loss of degrees of freedom (adjusted R^2), and the reduction of error (RE) statistic for validation, which indicates model skill when RE values are greater than zero (Fritts, 1976). Once the final regression model (transfer function) was successfully validated, it was calibrated on the full instrumental period (1914–2007) and applied to reconstruct calendar-year streamflow for the length of the tree-ring predictor variables.

We used the same procedures described above to develop a second regression model (transfer function) to produce a long reconstruction of the Santa Fe River, based on the four long chronologies from the Jemez Mountains and the long white pine chronology from within the Santa Fe watershed (common period 1305–2007). The predictand was log 10 calendar year flow, and similar to the short reconstruction, we produced four FSMLR models with the following predictor pools: (1) the five individual standard long chronologies, (2) the five residual long chronologies, (3) the PC's of the standard long chronologies, and (4) PC's of the residual long chronologies. The final model was chosen and validated with the same procedure as the short reconstruction described above.

4.3. Analysis of the reconstructions

To better understand the strengths and limitations of the short and long reconstructions we compared the highest and lowest gaged flows during the instrumental period (1914–2007) with the reconstructed values. Specifically, we compared the highest and lowest single-year and 3, 7, 10, 20 and 40-year moving average flows from the gaged record with the reconstructed values for those same periods. Data are presented as percent of instrumental-period mean of the respective series. We also used the Pearson correlation coefficient to compare the two reconstructions during the instrumental period and the full period of overlap (1592–2007).

Because model calibration fits the tree-ring record to the gaged record and this fit is used to reconstruct flows for the pre-instrumental period, all subsequent comparisons between the instrumental period and the pre-instrumental period are made with tree-ring reconstructed flows, and not gaged flows. To place streamflow during the instrumental period in the context of the long-term tree-ring reconstructed record we compared descriptive statistics (mean, median and standard deviation) of the two reconstructions between the instrumental period (1914–2007) and the full reconstructed periods (short reconstruction, 1592–2007 and long reconstruction, 1305–2007). To assess the distribution through time of "extreme" low flows we calculated and plotted the bottom 5th percentile (driest) single-year and 3, 7, and 40-year

moving average flows for both reconstructions. These data were plotted as the departure below the reconstructed instrumental-period (1914–2007) mean annual discharge to put the low flows in the context of the instrumental period. A 40-year moving average was selected as the long-term mean flow; 40 years is commonly used as the long-range water planning period for Santa Fe (Claudia Borchert, personal communication). The "extreme," wettest (95th percentile) flows for the same periods were calculated, but not plotted. Chi-squared analysis was used to test whether the observed frequency of extreme, single-year, low or high flow events in the instrumental period of the reconstruction (1914–2007, $n = 94$ years) was different than the expected frequency. The 5th and 95th percentile flow thresholds were based on the full reconstruction. The expected frequency of events in the instrumental period was calculated based on the assumption of five events per 100 years (i.e., 5th percentile).

The City of Santa Fe determined that 7.52 MCM is the annual discharge that will satisfy the full surface water allocations and instream flow targets for the Santa Fe River below the municipal reservoirs (Lewis and Borchert, 2009). To assess whether the probability of meeting this minimum flow differed between the instrumental period and prior periods we used the cumulative distribution function (CDF) of reconstructed mean annual discharge. Using the lognormal CDF we compared the specific probabilities of not meeting the 7.52 MCM minimum flow level (non-exceedence probability) between the reconstructed instrumental period (1914–2007) and (1) the full reconstructed period and (2) the driest reconstructed period equal in length to the gaged record ($n = 94$ years). This analysis was performed on both reconstructions.

5. Results

We produced two reconstructions of calendar year annual discharge of the upper Santa Fe River: (1) a better fit, short reconstruction based on PC1 and PC3 of three longest local standard chronologies (GLO, SFW PSME and SFW PIST; 1592–2007) and (2) a less robust, long reconstruction based on PC1 and PC2 of the five long residual chronologies (1305–2007, Table 1). For both reconstructions the PC-based regression models had similar skill as those derived from individual chronologies, thus the more robust PC-based models were chosen to develop the final reconstructions. The standard-chronology PC model was selected for the short reconstruction, primarily because it had the best calibration–validation statistics and the autocorrelation of modeled flow was most similar to gaged flows (ACF not shown). For the long reconstruction the residual-chronology PC model was selected based on the same criteria.

5.1. Short reconstruction

The short standard-chronology PC model explained 62% of the variance in the square-root transformed gaged flow record used for model calibration (1914–2007, Table 2). The reconstruction equation is:

Table 2
Regression statistics for the short and long reconstructions.

	Adj. R^2	F	$RMSE_c$	$RMSE_v$
Short reconstruction	0.62	76.35[*]	0.4934	0.5042
Long reconstruction	0.50	47.8[*]	0.2023	0.2060

RMSE values derived from transformed flow (i.e., unitless).
F = overall F for the equation and significance indicates a significant equation.
$RMSE_c$ = calibration root mean square error (regression standard error of estimate).
$RMSE_v$ = validation root mean square error.
[*] $p < 0.01$.

$$\text{Square root of flow} = 2.5359 + 0.3244 \text{ standard PC1}$$
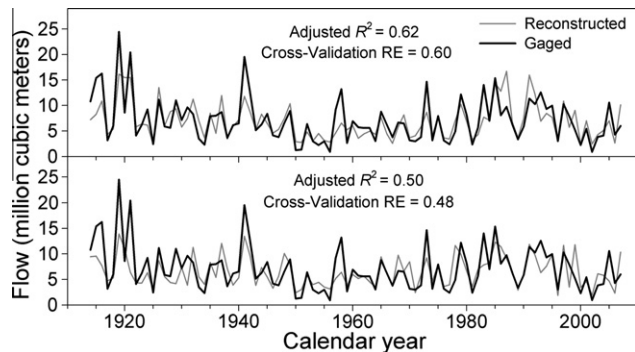$$+ 0.3214 \text{ standard PC3}$$

Fig. 3. Gaged and reconstructed calendar year flow during the calibration period (1914–2007). (Top) Short reconstruction. (Bottom) Long reconstruction.

Table 3
Split sample calibration and verification statistics.

Reconstruction	Calibration period	Adj. R^2	Verification period	r	RE
Short	1914–1960	0.64	1961–2007	0.78	0.54
	1961–2007	0.60	1914–1960	0.81	0.61
Long	1914–1960	0.54	1961–2007	0.71	0.28
	1961–2007	0.50	1914–1960	0.74	0.48

The model residuals were distributed approximately normal, were not correlated with predictor variables, and had no autocorrelation or trend (results not shown). The model validated well, with positive RE values close to the calibration R^2, indicating predictive skill (Fig. 3). The split-sample validation indicates that the model was stable between the first and second half of the instrumental period (Table 3). Modeled mean flow was 0.24 MCM less than the gaged flow during the instrumental period (1914–2007, Table 4). This difference is a product of back transforming the reconstructed square root of flow. Reconstructed median flow was similar to the gaged flow (1914–2007) and the reconstructed standard deviation was lower (i.e., the model underestimated the severity of extreme low flow and high flow years, Fig. 3, Table 4). The model re-produces the dominant droughts (1950s and 2000s) and wet periods (ca. 1920 and 1980) of the gaged record. The largest difference between the reconstruction and the gaged record occurred from 1985 to 1995. Overall, the tree-ring model tracks the interannual and decadal variability of the gaged flow record quite well for a small watershed.

The timeseries plot of the entire, short reconstruction suggests the 1950s was the most severe multi-year low-flow period since 1592 (Fig. 4). Recent single-year extreme low flows (e.g., 2002) are very rare events (lowest 5th percentile) when viewed in the context of the last four centuries, but were equaled or surpassed by other low flow years in the pre-instrumental period. Two multi-year 20th century wet periods (1910s and 1980s) were anomalous in magnitude and duration over the last 400 years. Large decadal wet to decadal dry swings are a notable feature of the recent century (1910s wet to 1950s dry and 1980s wet to 2000s dry) that may be particularly important for future water management. The long-term reconstructed mean (6.70 MCM, 1592–2007) was
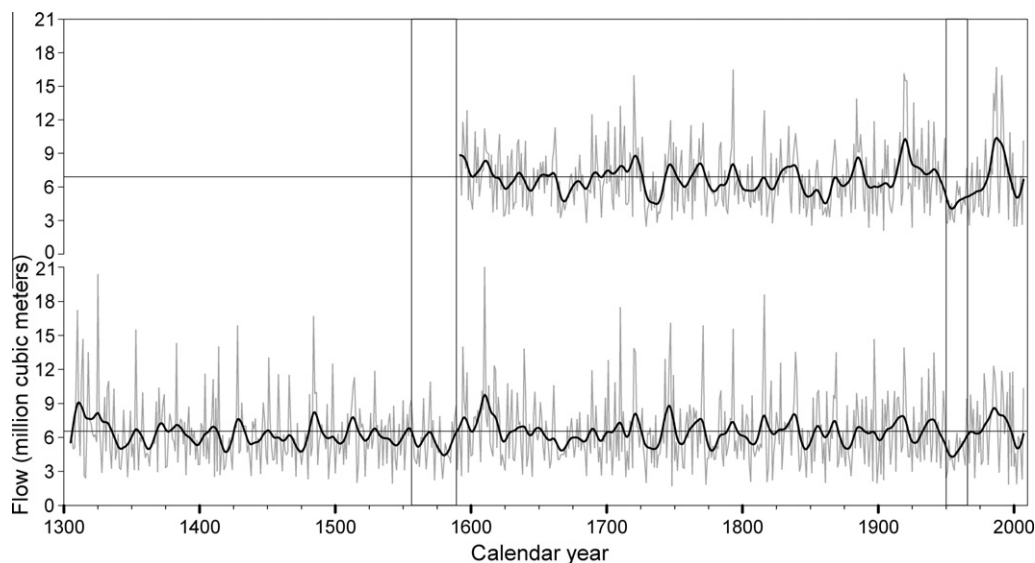
Table 4
Descriptive statistics of gaged and reconstructed flows.

Period	Gaged	Short reconstruction		Long reconstruction		
	1914–2007	1914–2007	1592–2007	1914–2007	1592–2007	1305–2007
Mean flow (10^6 m^3)	7.15	6.91	6.70	6.54	6.50	6.40
Median (10^6 m^3)	6.26	6.25	6.23	5.93	5.89	5.81
Std. dev. (10^6 m^3)	4.44	3.48	2.76	2.95	3.03	2.94

Fig. 4. Short (top) and long (bottom) tree-ring reconstructions of annual calendar year flow (grey) for the upper Santa Fe River. Horizontal lines are the respective reconstructed instrumental-period means (1914–2007). The black curves are 15 year cubic smoothing splines that highlight low frequency trends. Boxes highlight the 1950s and late-1500s droughts. Correlation between the reconstructions is 0.75 (1592–2007).
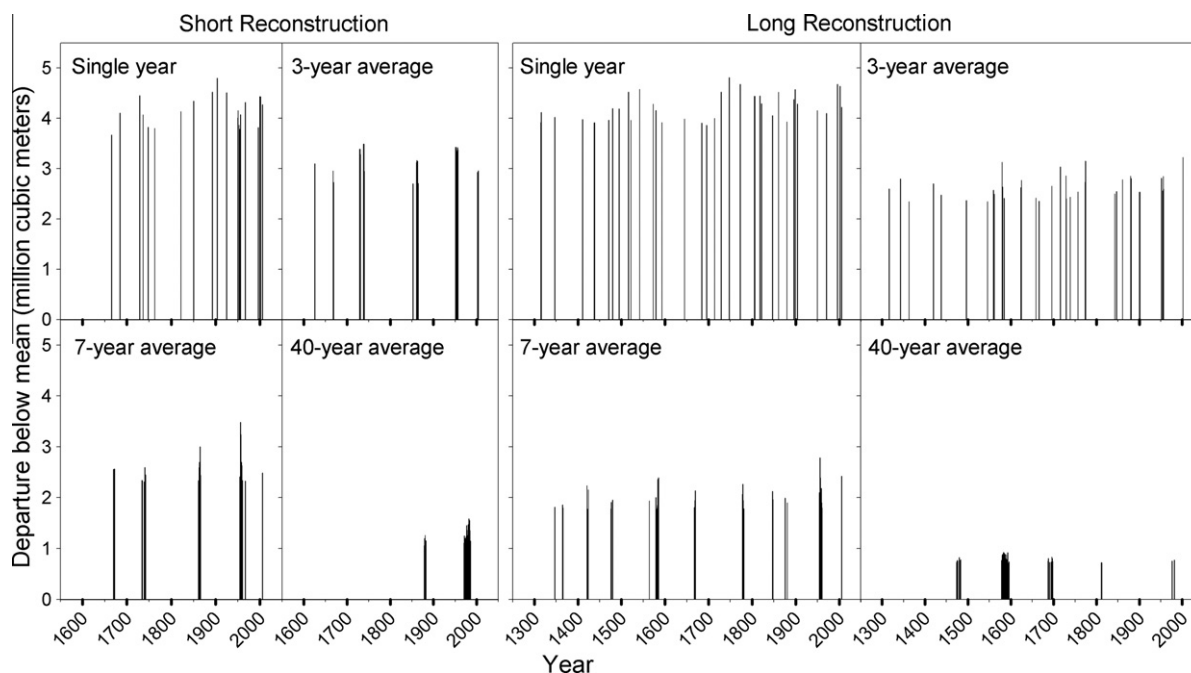
Fig. 5. Time plots of reconstructed extreme (5th percentile) dry events: lowest single-year flows and running means of indicated length. (Left) Short reconstruction, 1592–2007. (Right) Long reconstruction, 1305–2007. Flows plotted as departure below respective reconstructed instrumental-period (1914–2007) mean annual discharge (short reconstruction, 6.91 MCM; long reconstruction, 6.54 MCM). Running averages plotted on last year.

Table 5
Frequency of occurrence of wet and dry extreme events.[a] Expected refers to number events expected in a period as long as the 1914–2007 instrumental period. Observed is a count of reconstructed events in 1914–2007 above (wet) or below (dry) threshold.

Moving average window	Extreme wet				Extreme dry			
	Expected (years)	Observed (years)	Chi squared	p value	Expected (years)	Observed (years)	Chi squared	p value
Short reconstruction (1592–2007)								
1-year	5	11	8.68301	<0.01	5	11	8.68301	<0.01
3-years	5	9	–	–	5	8	–	–
7-years	5	17	–	–	5	8	–	–
40-years	5	17	–	–	5	16	–	–
Long reconstruction (1305–2007)								
1-year	5	4	0.103964	0.747	5	5	0.0230352	0.879
3-years	5	4	–	–	5	5	–	–
7-years	5	7	–	–	5	8	–	–
40-years	5	0	–	–	5	2	–	–

[a] Thesholds for extreme events computed as 5th (dry) and 95th (wet) percentiles of flows based on 1592–2007 or 1305–2007 reconstructions.

97% of the reconstructed instrumental-period mean (6.91 MCM, 1914–2007), the medians were almost equal, and the reconstructed full period standard deviation was 0.72 MCM lower than during the instrumental period (Table 4).

Analysis of extreme wet and dry single-year and 3, 7, and 40-year moving average flows for the short reconstruction indicates that both extreme high and low flows occurred with anomalous frequency during the instrumental period (1914–2007) when viewed in the context of the past 416 years (1592–2007; Fig. 5, Table 5). Extreme high flows of all lengths occurred with greater frequency during the instrumental period. For example, 81% of the wettest reconstructed 40-year and 7-year high flow periods occurred during the instrumental period (1914–2007), even though it constitutes only 25% of the total record. Fifty-two percent of the wettest single-year flows occurred in the instrumental period, over twice the percent expected if the events were evenly distributed through time. Similarly, all categories of extreme low flow events occurred with increased frequency during the instrumental period, and the single-year low flow frequency was statistically different

than expected (Fig. 5, Table 5). For example, 76% of the driest 40-year flow periods and 52% of the driest single-year flows occurred during the instrumental period.

All of the reconstructed extreme dry single-year flows were less than 50% of the reconstructed instrumental-period mean. The lowest reconstructed flow occurred in 1904 and was 31% of the reconstructed instrumental-period mean, a negative departure of 4.80 MCM (Fig. 5). The driest 3-year (1737–1739) and 7-year (1950–1956) mean reconstructed low flows were both 50% of the reconstructed instrumental-period mean. The maximum long-term average departure below the reconstructed instrumental-period mean (1.58 MCM) occurred during the 40-year period ending in 1982. During this period average flow was 77% of the reconstructed instrumental-period mean.

The CDF analysis suggests that the instrumental period overestimates the long-term probability of meeting the minimum flow requirements to satisfy all surface water demands (Fig. 6). We compared the CDF of mean annual flow during the instrumental period (1914–2007), the full reconstruction (1592–2007), and the
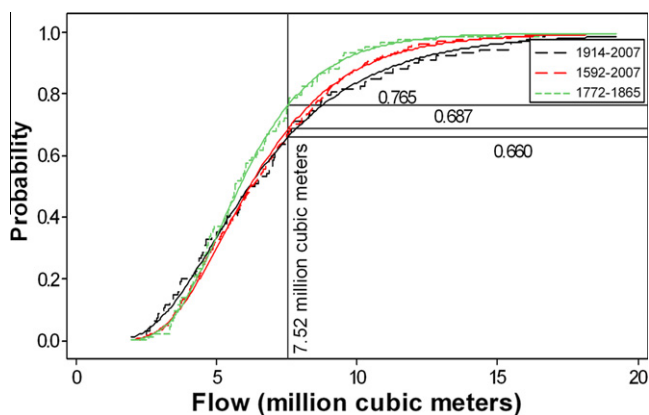
Fig. 6. Cumulative distribution functions (CDFs) of reconstructed annual flows from short-reconstruction model. CDFs plotted for different sub-periods: instrumental (1914–2007), full-length (1592–2007), and driest period of same length as instrumental (1772–1865). Smooth lines are lognormal fits to CDFs. Annotated are empirical probabilities of not exceeding the specified 7.52 MCM allocation plus instream flow target.

driest reconstructed pre-instrumental period equal in length to the instrumental period (1777–1865). The probability that annual yield would *not* satisfy the full surface water allocation and instream flow for the upper Santa Fe River (7.52 MCM) was 10% greater during the driest reconstructed pre-instrumental period (0.765) compared to the instrumental period (0.660).

5.2. Long reconstruction

The long residual-chronology PC model explained 50% of the variance in the log 10 transformed gaged flow record (1914–2007, Table 2). The reconstruction model is:

$$\text{Log 10 flow} = 0.7635 + 0.1009 \text{ residual PC1}$$
$$+ 0.0755 \text{ residual PC2}$$

The variance explained by the long-reconstruction model is less than that of the short-reconstruction model, but the benefit is that the long reconstruction extends back to the early 1300s (1305–2007). The model residuals were distributed approximately normal, not correlated with predictor variables, and had no autocorrelation or trend (results not shown). All validation RE statistics were positive, indicating predictive skill (Fig. 3, Table 3). The split-sample validation indicated that the model was stable between the first and second half of the instrumental period, but validated stronger on the first half of the record (Table 3).

Modeled mean flow was 0.61 MCM less than gaged mean flow during the instrumental period (1914–2007), median flow was 0.33 MCM lower, and the standard deviation was 1.49 MCM less (i.e., the model underestimated extreme high flow events and overestimated extreme low flow events, Fig. 3, Table 4). As with the short reconstruction, the difference between the gaged and reconstructed mean flow during the instrumental period is a product of back transforming the reconstructed log 10 flow. The long-reconstruction model does not track the interannual variability as well as the short-reconstruction model, but it still re-produced the 1950s drought, the 1980s wet period, and recent severe drought years (e.g., 2000, 2002, and 2006). The correlation between the short and long reconstruction is 0.77 during the instrumental period (1914–2007) and 0.75 during the full period of overlap (1592–2007), indicating high similarity between the two reconstructions.

The timeseries plot of the entire, long reconstruction suggests that the 1950s low-flow period is extreme, but not unique in the

context of the last 700 years (Fig. 4). A late-1500s drought appears similar in magnitude to that of the 1950s. Consistent with the short reconstruction, the recent single-year extreme low flow years (e.g., 2002) are relatively rare events (lowest 5th percentile) when viewed in the context of the last seven centuries, but were equaled or surpassed by low flow years in the pre-instrumental period. The two notable multi-year wet periods (1910s and 1980s) identified in the short reconstruction appear to be less rare when viewed in terms of the last 700 years. The long-term mean and median of the long reconstruction (1305–2007) were 98% of the reconstructed instrumental-period mean (1914–2007) and the standard deviations were nearly equal (Table 4).

Analysis of the extreme wet and dry single-year and 3, and 7-year moving average flows for the long reconstruction suggests that the frequency of occurrence of short term ($\leqslant$7-year) high and low flows during the instrumental period (1914–2007) was not anomalous when viewed in the context of the last 700 years (Table 5, Fig. 5). For example, 11% ($n = 4$) of the wettest single-year high flows occurred during the instrumental period (1914–2007, $n = 94$ years), which was not significantly different than expected (13%, $n = 5$) if the events were evenly distributed over the full period (1305–2007, $n = 703$ total years). The frequency of the driest single-year low flow events occurring in the instrumental period (1914–2007, $n = 5$, 14%) was not different from expected. Long-term (40-year) high and low-flow periods did occur less frequently in the instrumental period (Table 5, Fig. 5).

Although the frequency of occurrence of reconstructed extreme dry and wet events during the instrumental period was at or below that expected with an even distribution through time, the severity of recent low flow events from the long reconstruction ranked among the most severe in the entire seven century record. For example, two of the top four reconstructed single-year low flow events occurred within the last 15 years (1996 and 2002, Fig. 5). The driest 3-year low-flow period occurred from 2000 to 2002 and the top two driest 7-year periods ended in 1956 and 2006.

Similar to the short reconstruction, all of the extreme single-year low flows were less than 50% of the reconstructed instrumental-period mean. The maximum single-year departure below the instrumental-period mean (4.81 MCM) occurred in 1748 (Figs. 4 and 5), when reconstructed flow was 26% of the mean. The driest 3-year period (2000–2002) averaged 3.23 MCM below (51% of) the reconstructed instrumental-period mean, and the driest 7-year period (1950–1956) was 2.79 MCM below (57% of) the reconstructed instrumental-period mean. The top nine, non-independent long-term low-flow periods occurred in the late 16th century, with the greatest 40-year average departure below the reconstructed instrumental-period mean of 0.93 MCM from 1544 to 1583 (86% of mean flow).

The time periods used for the CDF analysis to determine the probability of meeting both annual and surface water allocations and instream flow targets (7.52 MCM) for the long reconstruction were (1) the instrumental period (1914–2007), (2) the full reconstruction (1305–2007), and (3) the driest reconstructed period equal in length to the gaged record (1500–1593). The results were very similar to those derived from the short reconstruction (figure not shown). The probability that annual yield would *not* satisfy the full surface water allocation and instream flow for the upper Santa Fe River (7.52 MCM) was almost 10% higher during the driest reconstructed period (0.787) compared to the instrumental period (0.698).

5.3. Short vs. long reconstruction: accuracy of extreme events

The short reconstruction provides more accurate, 416-year estimate of pre-instrumental streamflow when compared to the long, 703-year reconstruction. As regression leads to compression of
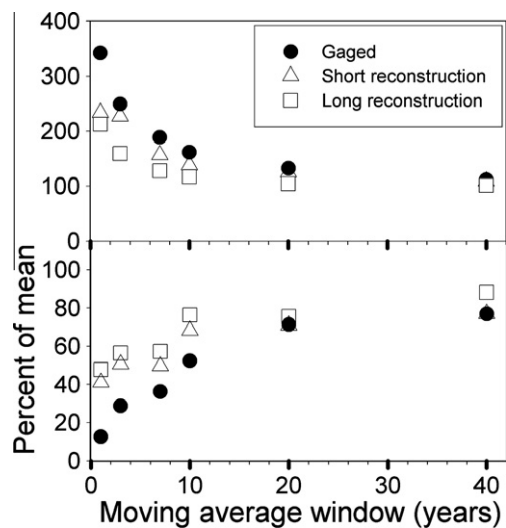
Fig. 7. Highest and lowest *n*-year running means of gaged flow and two reconstructions during the instrumental period (1914–2007). (Top) Wet periods. (Bottom) Dry periods. Percentage computed using instrumental-period mean of the respective series.

variance, both reconstructions tend to underestimate the severity of extreme low flow and high flow events in the instrumental period (Fig. 7). Reconstructed estimates of extreme events are thereby conservative (i.e., reconstructed high flows were likely higher and low flows were likely lower). The error for both reconstructions is most pronounced with shorter events (<10-year running mean). The short reconstruction is consistently more accurate than the long reconstruction, particularly at the extreme 20 and 40-year moving averages where the short reconstruction values are very close to the gaged flows. The long reconstruction estimates of the extreme events generally exhibit the same pattern as the gaged flows and the short reconstruction, but with larger underestimates of the severity of extreme low and high flow events of all lengths (Fig. 7).

6. Discussion

6.1. Evaluation of the reconstructions

We present the first published tree-ring reconstructions of streamflow in New Mexico, specifically developed to inform water management of the upper Santa Fe River. Our multiple-reconstruction approach provides a shorter, but more robust reconstruction (416 years, 1592–2007) and a less robust, but almost 300-year longer reconstruction (703 years, 1305–2007) that encompasses prior periods of known drought not covered by the short reconstruction (e.g., late 1500s). The two reconstructions correlate well with each other during both the instrumental period (r = 0.77, 1914–2007) and the full period of overlap (r = 0.75, 1592–2007), and thus both provide valuable information about past streamflow variability.

The variance explained by our reconstruction models (adj. R^2 = 0.62, short reconstruction; adj. R^2 = 0.50, long reconstruction) is somewhat lower than for other published streamflow reconstruction in the western United States. For example, R^2 = 0.70 for Middle Boulder Creek, Colorado (Woodhouse, 2001); R^2 = 0.66 for the Gila River, Arizona-New Mexico (Meko and Graybill, 1995); R^2 = 0.63–0.73 for rivers in north-central Colorado (Woodhouse and Lukas, 2006); and R^2 = 0.72–0.81 for the Colorado River at Lees Ferry (Woodhouse et al., 2006). Potential reasons for the lower variance explained by our models include (1) a relatively small wa-

tershed, (2) errors in the gage record from uncorrected reservoir effects (1926–1943), (3) errors in the gage record from streamflow rating curve extrapolations, particularly during extreme events, and (4) summer streamflow variability not captured by the tree-rings. We believe the primary source of error in our short reconstruction is the relatively small size of the upper Santa Fe River basin (4700 ha). Localized rain and runoff events that are not adequately captured by the tree rings are more likely to be smoothed out in a larger basin and amplified in a smaller basin. This is particularly the case for high intensity rain events that exceed the soil saturation rate and produce flows that are not proportionally reflected in the soil moisture, and consequently do not influence tree-ring width.

The lower variance explained by the long reconstruction (12% less than the short reconstruction) highlights a tradeoff of length and accuracy. The time extension provided by the chronologies located 100 km from the basin enable us to sample climatologically interesting time periods before the start of chronologies closer to the basin, but at the expense of loss of signal for flow events that might happen to be localized. The sacrifice of signal is reflected in suppressed amplitude of reconstructed extremes on both the wet and dry side (Fig. 7). The obvious benefit of the less robust long reconstruction was that it enabled us to compare recent droughts with the documented late-1500s drought that was not included in the 416-year short reconstruction.

6.2. Instrumental period in the long-term perspective

The combined information from the reconstructions indicates that although the instrumental period used for current water supply planning contains some of the most extreme short-duration (7 years or less) low flows over the last 400–700 years, it likely does not include the full range of natural variability inherent in the system. Recent, severe, individual low flow years (e.g., 2002) are relatively rare events even in the 700-year context, although they have been equaled or exceeded in prior centuries. The 1950s drought likely included the lowest 7-year-mean flow of the last 700 years, but longer (e.g., 40-year) mean flows in prior centuries were likely drier than any in the gaged record (Figs. 4 and 5, Table 5).

Development of the long reconstruction (1305–2007) enabled us to put the instrumental period in the perspective of the past seven centuries, which contained more severe pre-instrumental droughts than the last four centuries. The long and short reconstructions give strikingly differing views of how "anomalous" 1914–2007 is for frequency of occurrence of dry events and wet events (Table 5). For example, the short reconstruction suggests over-representation of single-year wet events in 1914–2007 while the long reconstruction suggests the frequency of such events is close to that expected by chance. Such apparent discrepancies can be explained partly by use of different base periods for computing the 5th and 95th percentiles defining events. The base-period effect is clearly important for 40-year dry events because the severe sustained drought of the late 1500s is sampled by the long reconstruction only. Other factors contributing to the differences in Table 5 for long and short reconstructions are the different sets of chronologies used for the reconstructions, the different modeling choices (e.g., for flow transformation), and geographical differences in climate variations at the tree-ring sites. The geographical effect is likely more important for wet years than dry years because wet anomalies are typically smaller in spatial extent than droughts.

This broader window provided by the long reconstruction reveals that some 20th century events that were extreme (5th and 95th percentile) in the context of the last 400 years are not extreme when viewed in the 700-year context (Fig. 5, Table 5). Analysis of this long reconstruction suggests that the lowest long-term

(40-year mean) flows in the last seven centuries occurred during the late 1500s (Figs. 4 and 5). Tree-ring and documentary records from multiple independent sources confirm that a severe, late 16th century "megadrought" was widespread throughout North America and dramatically affected human societies from Virginia to southern Mexico (Fye et al., 2003; Grissino-Mayer, 1996; Meko et al., 1995; Stahle et al., 2000; Woodhouse and Overpeck, 1998). A study specifically focused on probabilities of joint drought between multiple water sources for California concluded that the late 16th century drought was one of the few periods when synchronous low-flow periods occurred in the Upper Colorado River Basin and the Sacramento River, located over 1200 km apart (Meko and Woodhouse, 2005). Re-occurrence of a similar, long-term, widespread drought would likely result in not only a severe reduction of the local surface water supply source, but would also effect the other water supply sources for the City of Santa Fe (see Section 6.4).

6.3. Ecological indicators of climate variability

Is it a coincidence that the short reconstruction does not extend before the late 1500s megadrought? The inner rings from the remnant and living trees sampled at the Douglas-fir site within the upper Santa Fe watershed date to just after this drought. The inner rings from these samples were pith rings, or near pith, and were sampled from near the base of the tree and are therefore good estimates of tree establishment dates. This may provide independent confirmation as to the local severity of the drought. This site is at the lower elevation limit of Douglas-fir in the watershed, surrounded by more xeric tree species (e.g., Piñon pine). It may have been too dry to support Douglas-fir establishment and survival during the late 1500s, but the wet period of the early 1600s likely provided sufficient moisture to establish the Douglas-fir stand we sampled. It is also interesting to note that the common period for the long chronologies (i.e., the long reconstruction) begins in the early 1300s (Fig. 4), also a widespread wet period preceded by the "Great Drought" of the late 1200s (Douglass, 1929; Grissino-Mayer, 1996; Knight et al., 2010). Swetnam and Betancourt (1998) describe a similar regional drop-off of tree recruitment before 1600 and before 1300 in the Southwest, which they attribute to the late 1200s and late-1500s droughts. Ecological processes that are known to be influenced by climate (e.g., timing of stand establishment and mortality) can be used as important independent evidence to corroborate patterns of climate variability reconstructed from tree-ring widths.

6.4. Water management implications

Possible implications of a long-term reduction in mean flow comparable to the 16th century megadrought highlight potential limitations of the three water supply sources for Santa Fe. The water sources include: (1) surface water from the Santa Fe River, (2) a network of ground water wells and (3) San Juan/Chama Project allocation that will be diverted from the San Juan River basin by infrastructure expected to be completed in 2011. In principle, multiple water sources spread risk so that if one is low the others can supplement the supply. The possible re-occurrence of a widespread, long-term severe drought raises potential limitations of this multiple-source approach.

One potential limitation depends on the probability of joint drought in both the San Juan and Santa Fe River basins. The headwaters of the San Juan River are less than 250 km from the Santa Fe watershed and often experience similar cool-season precipitation variability from the same widespread Pacific storms that determine snowpack and vital spring runoff. Joint drought in southern Colorado and northern New Mexico was evident in multiple tree-

ring reconstructed droughts of recent centuries, including the late 16th century (Fye et al., 2003). Although the San Juan/Chama Project allocation is less than the estimated reliable diversion yield (i.e., a built-in drought protection), these values were determined from the gaged record. Future detailed analysis of the frequency and severity of gaged and tree-ring reconstructed joint drought and low streamflows in both the Upper San Juan basin (Woodhouse et al., 2006) and the Santa Fe River (this study) could be used to quantify the probability of one source serving as a buffer for low supply in the other (e.g., Meko and Woodhouse, 2005).

Although planning is often based on extreme high or low flows, the probability distributions of reconstructed flows during pre-instrumental periods provide informative comparisons with the reconstructed instrumental-period "normal" conditions for meeting annual surface water allocations and instream flow targets. The probability of *not* meeting the 7.52 MCM flow target calculated from the CDF of the short reconstruction during the instrumental period (0.66) was remarkably similar that derived from the gage record (0.64, Lewis and Borchert, 2009). In prior centuries there was up to a 10% higher chance that annual flow would not meet this target (Fig. 6). Based on the range of flows reconstructed from 1500 to 1593, there would be a 78.7% chance that annual flow would *not* meet or exceed 7.52 MCM. Thus, in almost eight out of every 10 years the surface water supply would not be sufficient to meet Santa Fe River water right allocations and river flow targets if future climate variability returned to this pre-instrumental period level.

Plans are underway to run the City of Santa Fe Water Management And Planning Simulation model with the reconstructed annual flows to empirically analyze changes in water supply based on the reconstructed long-term variability. At present, a 59-year portion of the gaged record is chopped up, shuffled and splice back together to create different wet/dry scenarios and then run through the model. The use of reconstructed flow data representing the actual climate system would greatly improve upon this method and would more accurately reflect the inherent variability in the climate and streamflow systems.

7. Conclusions

The 703 year reconstructed record of annual Santa Fe River flow indicates that the instrumental period is not representative of sustained low-flow periods of the past few centuries. For example, the 40-year mean for 1544–1583 is estimated at 86% of the 1914–2007 mean. Such sustained events not sampled by the instrumental period may be important to water planning. If this pre-instrumental long-term flow variability re-occurred in the future, the probability of *not* meeting the surface water allocation target on any given year was estimated to be 10% greater than 20th century-based estimates. However, some of the most extreme single-year, 3-year and 7-year average low flow events of the past seven centuries occurred within the last 60 years (e.g., 1950s and 2000s drought) and adequate planning based on these extreme events would likely be sufficient for short term drought contingency strategies. This study is one example of many potential applications of paleo-hydrology records for water supply analysis and planning. Reconstructions such as those generated in this study can complement information from general circulation models in assessing likely impacts of anthropogenic climate change on water supplies (e.g., Barnett and Pierce, 2008). This interdisciplinary, science-based management approach is part of a broader movement in the hydrologic community to help develop and apply these natural archives of hydrologic variability to better manage our limited water supply in the arid West under increasing demand (Woodhouse and Lukas, 2006).

Acknowledgements

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