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TREE-RING BASED RECONSTRUCTIONS OF INTERANNUAL TO DECADAL SCALE PRECIPITATION VARIABILITY FOR NORTHEASTERN UTAH SINCE 1226 A.D.[1]

Stephen T. Gray, Stephen T. Jackson, and Julio L. Betancourt[2]

ABSTRACT: Samples from 107 piñon pines (*Pinus edulis*) at four sites were used to develop a proxy record of annual (June to June) precipitation spanning the 1226 to 2001 AD interval for the Uinta Basin Watershed of northeastern Utah. The reconstruction reveals significant precipitation variability at interannual to decadal scales. Single-year dry events before the instrumental period tended to be more severe than those after 1900. In general, decadal scale dry events were longer and more severe prior to 1900. In particular, dry events in the late 13th, 16th, and 18th Centuries surpass the magnitude and duration of droughts seen in the Uinta Basin after 1900. The last four decades of the 20th Century also represent one of the wettest periods in the reconstruction. The proxy record indicates that the instrumental record (approximately 1900 to the Present) underestimates the potential frequency and severity of severe, sustained droughts in this area, while over representing the prominence of wet episodes. In the longer record, the empirical probability of any decadal scale drought exceeding the duration of the 1954 through 1964 drought is 94 percent, while the probability for any wet event exceeding the duration of the 1965 through 1999 wet spell is only 1 percent. Hence, estimates of future water availability in the Uinta Basin and forecasts for exports to the Colorado River, based on the 1961 to 1990 and 1971 to 2000 "normal" periods, may be overly optimistic.
(KEY TERMS: drought; tree rings; water resources planning; timeseries analysis; paleohydrology; Uinta Basin Watershed, Utah.)

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INTRODUCTION

Recent and ongoing droughts provide stark reminders for the importance of understanding precipitation variability in western North America. Most efforts aimed at examining precipitation variability are, however, hindered by limitations of the instrumental climate record. Numerous studies show that instrumental records (most beginning after 1900 AD) are too short to capture the full range of climate variability any region has experienced in the past (Cook and Evans, 2000). Instrumental records capture, at most, only four to five examples of decadal scale droughts and wet periods (Cayan *et al.,* 1998), which is insufficient for assessing the range of potential natural variability and risk of severe drought in a given region. Decadal scale precipitation variability also modulates high frequency events like floods and fires while exerting strong controls over the biota (Swetnam and Betancourt, 1998). Tree rings offer the primary means for evaluating decadal scale precipitation variability, as well as interannual variability in a long term (> 100 year) context. Tree rings yield continuous, exactly dated proxies of annual climate that are highly replicable and often encompass multiple centuries (Fritts, 1976; Cook and Kairiukstis, 1990).

The Uinta Basin Watershed in northeastern Utah (Figure 1a) is one of the primary headwaters for the Colorado River, contributing approximately 10 percent of the mean annual flow at Lees Ferry, Arizona (UDWR, 1999). The Uinta Basin Watershed also provides significant amounts of water to the Salt

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[2] Respectively, Post-Doctoral Research Associate, Big Sky Institute, Montana State University, Bozeman, Montana 59717 (formerly Graduate Student, University of Wyoming-Laramie); Professor, Department of Botany, University of Wyoming, Laramie, Wyoming 82071-3165; and Physical Scientist, Desert Laboratory, U.S. Geological Survey and University of Arizona, 1675 West Anklam Road, Tucson, Arizona 85745 (E-Mail/Gray: sgray@montana.edu).

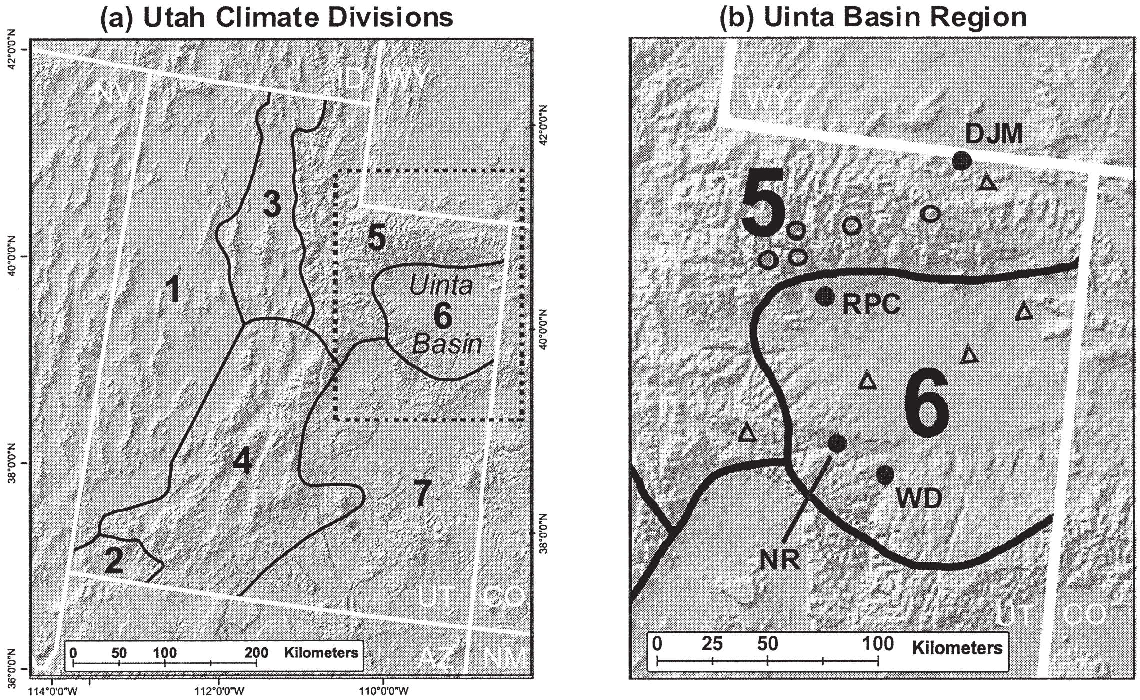

Figure 1. (a) Map of the Utah State Climate Divisions. The Uinta Basin is encompassed by Utah Climate Division 6. (b) Close Up of the Uinta Basin Region, Area in Dotted Outline in (a), With Tree-Ring Sites Shown as Black Dots (DJM = Dutch John Mountain, NR = Nutter's Ridge, RPC = Red Pine Canyon, and WD = Well's Draw). Key meteorological stations (triangles), and snow courses (dots) discussed in the text are also shown.

Lake City metropolitan area via transbasin diversions. Some 25 percent of the Uinta Basin Watershed falls within the Ashley and Uinta National Forests, and another 31 percent is held by the Bureau of Land Management, making it a major area for timber production, grazing, and outdoor recreation.

This paper presents a new tree-ring based reconstruction of precipitation spanning the last 776 years (1226 to 2001 AD) from a network of sites in the Uinta Basin Watershed. A combination of standard dendroclimatological techniques and intervention analysis (Box and Tiao, 1975) was used to characterize the variability in reconstructed precipitation at interannual to decadal scales. Previous studies of multiyear precipitation anomalies have generally employed the use of runs analysis (Salas *et al.,* 1980; Sadeghipour and Dracup, 1985). Runs analysis identifies droughts or wet periods as a series of years where precipitation falls above or below an arbitrary threshold. This means, however, that one year of normal to above average precipitation would split a single long drought into two separate droughts. By contrast, intervention analysis (Box and Tiao, 1975) compares values of a climatic variable between time periods to determine if the mean of that variable has changed (an event termed a "regime shift"). This eliminates the problem of single years with high (low) precipitation falsely signaling the end of a drought (wet period). In addition, recent advances in stochastic modeling of multiyear climatic regimes (Biondi *et al.,* 2002) allow objective comparisons between decadal-scale droughts and wet periods on a statistically robust and multiparameter basis. All of these techniques are applied to compare the magnitude and duration of droughts and wet periods in the instrumental (approximately 1895 to the Present) and pre-instrumental periods (1226 to 1894) of the precipitation reconstruction. These results show that the 20th Century precipitation record is by itself insufficient as a basis for water resources planning in the Uinta Basin Watershed because the instrumental record inadequately represents the risk of severe, sustained (> 10 year) droughts, while over representing the frequency and duration of wet periods.

STUDY AREA

The Uinta Basin Watershed (Figure 1a) encompasses more than 28,000 km^2 of mainly desert grasslands, sagebrush steppe, semi-arid woodlands, and irrigated fields in northeastern Utah (UDEQ, 2003). Mixed conifer and aspen dominated forests are also common at higher elevations (> 2,500 m). While vegetation in the area shows a strong affinity with the Colorado Plateau, it also includes elements of the Rocky Mountain and Wyoming Basin flora (Powell, 1994).

Elevations on the floor of the Uinta Basin can be as low as 1,500 m, but the Uinta Mountains, located to the north, crest at over 3,900 m. The Tavaputs Plateau and Book Cliffs, which in some areas reach 3,000 m, form the southern boundary of the Uinta Basin Watershed, while the Wasatch Range (approximately 3,300 m) borders to the west. The Uinta Basin Watershed includes the headwaters for several major tributaries to the Green River such as the Duchesne River, Ashly Creek, and Brush Creek draining from the southern slope of the Uinta Mountains (UDWR, 1999). The Strawberry River also flows through the Uinta Basin but originates in the eastern Wasatch Range.

Climate of the Uinta Basin Watershed

At lower elevations, the climate of the Uinta Basin Watershed is characterized by relatively dry conditions throughout the year. The basin floor (1,500 to 1,800 m) receives only 20.3 cm of precipitation each year on average (WRCC, 2003). However, high elevation climate stations (> 2,700 m) in the Uinta Mountains may receive as much as 100 cm/yr. Both high and low elevation sites in the Uinta Basin Watershed experience peak precipitation in the late spring and early summer months of April to June (Mock, 1996). Convective storms during the summer months (July through September) may deliver significant, though heterogeneously distributed, precipitation (Powell, 1994). Because the crest of the Wasatch Mountains rises to over 3,300 m along the western boundary of the region to form an effective rain shadow, winter storms tracking from the Pacific Ocean usually deliver little precipitation to the basin floor. In fact, at elevations between 1,500 and 1,800 m, winter (December through February) precipitation generally accounts for less than 14 percent of total annual precipitation. Temperatures on the basin floor can be relatively warm during the summer, with average maximum air temperatures in July reaching 32°C (Roosevelt, Utah; 1,557 m), and occasionally exceeding 38°C. Winters sometimes produce temperatures below -25°C, particularly during thermal inversions. However, high temperatures during the coldest month of January usually exceed 2°C in the basin.

DATA AND METHODS

The Uinta Basin Watershed Tree-Ring Chronology Network

Piñon pines (*Pinus edulis*) were sampled at four sites in the foothills surrounding the Uinta Mountains of northeastern Utah (Figure 1b). All sites were characterized by poorly developed soils supporting open canopy woodlands of mixed piñon and juniper (*Juniperus osteosperma*). The Uinta Formation, an Eocene group consisting of soft sandstones and interbedded mudstones, forms the substrate at the Wells Draw and Nutters Ridge sites. Trees sampled at Dutch John Mountain were located on outcrops of Navajo Sandstone. At Red Pine Canyon, suitable trees were found on Quaternary glacial materials. Samples were taken from southern and western aspects on slopes ranging from steep canyon walls to broad ridgetops. At least two increment cores were extracted from living trees, and cores or cross sections were taken from available dead wood.

After mounting and progressively sanding to greater than 400 grit, cores and sections were subjected to standard graphical dating methods (Stokes and Smiley, 1968; Swetnam *et al.,* 1985; Cook and Kairiukstis, 1990). After the rings in each series were measured to the nearest 0.01 mm, the COFECHA program (Holmes, 1983) was used to confirm dating for all series. Series were compared within each site and with chronologies from nearby sites. Cross dating for these series was also confirmed against existing shorter (end in the late 1960s) chronologies obtained from the International Tree Ring Data Bank (NOAA-NGDC, 2003). Correlations were high among series at each site (r = 0.71 to 0.80), and dating could be verified for a total of 146 series (Table 1). The ARSTAN program (Cook, 1985) was then used to create standard chronologies with either negative exponential or linear spline detrending (negative or zero slope) in order to preserve both high and low frequency climate related variation.

As is generally the case in dendroclimatic studies, sample depth declines in the early portions of these chronologies. Therefore, subsample signal strength (SSS) was used to provide an assessment of replication through time at each site (Wigley *et al.,* 1984). The SSS measures the agreement between a chronology of reduced sample size and the entire chronology to determine the number of samples (trees) needed to maintain some percentage of the overall site signal. A routine cutoff SSS of 0.85, or 85 percent of the common site signal retained, was set for the inclusion of data from a site chronology in the final reconstructions.

TABLE 1. Descriptive Statistics for Individual Site Chronologies Used in This Study.

Site Name	Elevation (m)	Time Span (years A.D.)	Year SSS > 0.85	Number of Trees	Number of Series (radii)	Average Series Length (years)	Interseries Correlation (percent)
Wells Draw	2,100 to 2,190	887 to 2001	1061	19	31	488.8	0.80
Nutter's Ridge	2,190 to 2,280	1040 to 2001	1226	17	21	450.7	0.75
Dutch John Mountain	2,100 to 2,280	1365 to 2001	1374	52	73	359.4	0.79
Red Pine Canyon	2,280 to 2,370	1405 to 2001	1411	19	21	333.1	0.71

Testing the Climate Growth Relationship

To determine the suitability of these chronologies for use in precipitation reconstructions, climate growth relationships at the individual tree-ring sites were first investigated using standard correlation analyses that compared ring-width index values from the standardized chronologies to instrumental climate records for the same period (Fritts, 1976). Instrumental climate records were obtained from the National Climatic Data Center (NCDC, 2003) and the U.S. Historical Climatology Network (USHCN, 1999). Comparisons included ring-width index values versus monthly and seasonalized precipitation and temperature records from nearby meteorological stations and Wyoming and Utah state climate divisions (Figure 1b). The NCDC divisional variables also included monthly and seasonal Palmer Drought Severity Index (PDSI) values (Palmer, 1965; Alley, 1984). In addition, tree growth was compared against percentage of average April 1 snowpack from snow courses (NRCS, 2003) within the Uinta Mountains. All variables were also examined at lags of up to approximately three years.

Identifying Decadal Scale Climatic Regimes in the Proxy Record

To identify and characterize different modes of decadal scale precipitation variability within and prior to the instrumental record, the statistical technique known as intervention analysis (Box and Tiao, 1975) was applied to the reconstruction. In this approach transitions from high value (low value) regimes to low value (high value) regimes in a time series are known as interventions. The analysis proceeds by first identifying candidate interventions within the time series and then fitting and evaluating potential regime models within a statistically rigorous framework (Hare and Francis, 1994). To identify potential wet/dry regimes in the reconstruction an intervention detection algorithm developed by Gedalof and Smith (2001) was applied to the time series. This method uses a moving window where reconstructed precipitation values during one period are compared to values within the successive period. Potential regime shifts were identified when a two-sample t-test showed a significant difference ($p < 0.1$) in the mean between the two periods. The window width for this analysis was set at 30 years based on results from previous studies showing significant modes of climate variability at frequencies of 10 to 20 years in both the Uinta Basin Watershed and western North America at large (Biondi *et al.,* 2001; Gedalof and Smith, 2001; Gray *et al.,* 2003). Because of the lack of independence among successive observations in the time series, the t-test approach cannot be used to examine the statistical significance of potential regimes. Candidate interventions were instead evaluated by first fitting the reconstruction with a univariate autoregressive moving average (ARIMA) model. Each potential wet/dry regime was then incorporated into a new ARIMA model as a step change (rapid, persistent change in mean) variable (Box and Tiao, 1975). Step change and univariate models were then compared, and potential regimes whose model coefficient had a p of less than 0.1 were considered significant. The FreeFore software package (Version 0.1.14, Automatic Forecasting Systems, Hatboro, Pennsylvania) was used for all ARIMA analyses.

After identifying the significant decadal scale precipitation regimes in the proxy record, the duration, magnitude, and intensity of individual decadal scale wet/dry regimes was assessed using methods proposed by Biondi *et al.* (2002). Duration was defined as the total number of years between regime shifts. Magnitude was calculated by subtracting the long term mean from each reconstructed annual precipitation value within a regime and summing these values over the entire regime. Intensity was defined as the ratio between magnitude and duration and so is equivalent to average magnitude for an event. Events were then ranked in terms of their duration, absolute magnitude, and absolute intensity. Finally, an event score was calculated as the sum of the rankings for the duration, absolute magnitude, and absolute intensity so that the lower the event score, the "stronger" the event. Once the significant decadal scale drought and wet periods were classified, the empirical probabilities associated with event durations and magnitudes observed in the proxy record were calculated.

RESULTS

Reconstructing Precipitation in the Uinta Basin Watershed

Correlation analysis showed strong relationships between measures of local and regional moisture status and tree growth at all sites. Significant relationships between precipitation and tree growth were seen for all months of the year, with the strongest correlations at all sites occurring between May or June precipitation and standardized ring widths ($r = 0.33$ to 0.40; $p < 0.001$ to 0.007). January precipitation and ring width showed a moderate relationship at all sites ($r = 0.26$ to 0.39; $p < 0.001$ to 0.026). Significant correlations were also observed between total annual (January to December) precipitation and ring growth at the four sites ($r = 0.23$ to 0.51; $p < 0.001$ to 0.006). However, the strongest relationships ($r = 0.46$ to 0.74; $p < 0.001$) between precipitation and tree growth at all sites were seen for previous June through present June total precipitation. Ring widths at all sites were also well correlated ($r = 0.51$ to 0.62; $p < 0.001$) with April 1 snowpack at sites in the Uinta Mountains (Figure 1b). Ring widths for all sites and PDSI values were significantly correlated ($p < 0.05$) over every month of the year, with the strongest relationship ($r = 0.53$ to 0.72; $p < 0.001$) observed for June. All sites displayed significant ($p < 0.05$) negative correlations with monthly mean temperatures for May through September ($r = -0.18$ to -0.40), but these relationships were always weaker than those seen with precipitation over these same months. In general, correlations between tree growth and meteorological variables were higher for divisional precipitation and temperature data than for individual meteorogical stations.

Based on the correlation analyses, previous year's June through current year's June (J to J) total precipitation from Utah Climate Division 6 was selected as the best metric of regional moisture variability for reconstruction. To develop the reconstruction model, the four individual standard site chronologies were used as possible predictors in a "best subsets" multiple regression analysis. The period common to both the tree-ring chronologies and divisional climate records (1896 to 2001) was divided into even and odd numbered years. Data from the even numbered years were used to calibrate the model, and the resulting equation was verified against the odd year data. The resulting model for reconstructing precipitation (PCP) incorporated all four individual site chronologies (WD = Wells Draw, NR = Nutters Ridge, DJM = Dutch John Mountain, and RPC = Red Pine Canyon) as predictor variables

$$PCP_{recon} = 6.46 + 10.2\ WD + 1.85\ NR + 2.95\ DJM - 0.43\ RPC\ (F = 20.13,\ p < 0.001) \qquad (1)$$

Validation statistics indicated that the model performed well in estimating precipitation amounts not included in the calibration dataset (Table 2). The model explained 58 percent of the variance in the verification dataset and estimated the mean of J to J precipitation well. Examination of observed and predicted J to J precipitation also indicated that the model successfully captures both high and low frequency moisture variability (Figure 2). Model predictions of precipitation standard deviation were only slightly lower than observed values. Verification tests using additional subsetting procedures including early year versus late year (1896 to 1948 and 1949 to 2001, respectively) comparisons showed similarly favorable results. These techniques were also used to test various regression models with transformed ring-width chronologies as additional predictors (Graumlich, 1991; Cleaveland, 2000; Woodhouse, 2001). However, these additional variables did not improve the reconstruction model.

Once this model was developed and verified, standardized ring-width values from all four sites were used to estimate precipitation back to 1411 AD, the year in which the number of samples at Red Pine Canyon falls below the 0.85 cutoff for SSS. Because SSS for Dutch John Mountain drops below the cutoff near this time (1374), a second J to J precipitation reconstruction was created for the years prior to 1411 using only the Wells Draw and Nutters Ridge chronologies as predictors

$$PCP_{recon} = 6.46 + 10.2\ WD + 1.85\ NR\ (F = 38.63,\ p < 0.001) \qquad (2)$$

Despite the loss of two site chronologies from the model, the resulting reconstruction was only slightly less skillful as a proxy for regional precipitation than the four-site model (Table 2). Again, examination of the observed and predicted J to J precipitation demonstrated that the two-site model effectively captured both the high and low frequency trends in

TABLE 2. Model Calibration and Verification Statistics Using the Four Variable and Two Variable (italicized in parentheses) Models to Reconstruct Previous June Through Current June Total Precipitation in the Uinta Basin Region.

	Calibration Dataset (even years)		**Verification Dataset (odd years)**	
r	0.80 (*0.79*)		0.76 (*0.75*)	
r^2 adj.	0.64 (*0.62*)		0.58 (*0.57*)	
	Observed	**Reconstructed**	**Observed**	**Reconstructed**
Mean (cm)	21.71	21.76 (*21.70*)	22.02	22.81 (*22.72*)
Standard Deviation (cm)	5.36	4.31 (*4.22*)	5.48	4.70 (*4.74*)

moisture variability (Figure 2). Mean precipitation was also well predicted.

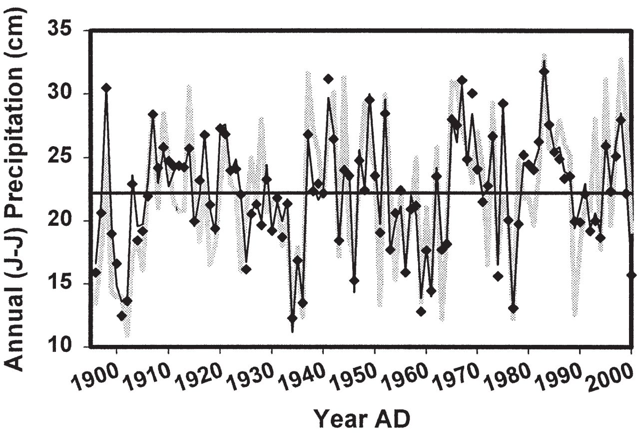

Figure 2. Comparison Between Observed (thick line) and Predicted Values for Previous June and Current June Total Precipitation From the Four Site (fine line) and Two Site (black diamonds) Reconstruction Models.

Output from the the two-site and four-site models was combined into a single composite reconstruction, with the 1411 to 2001 portion derived from the four-site model and the 1226 to 1410 portion developed from the two-site model. Because two of the same four chronologies are used throughout the reconstruction, the early and late portions of the proxy record should be comparable. This assumption was supported by paired t-tests that showed no significant differences between either the mean or variance among the two- and four-site models for their overlapping period (1411 to 2001).

Reconstructed Annual Precipitation Since 1226 AD

The reconstruction of J to J precipitation (Figure 3a) shows that the magnitude of the worst single-year drought events in the 20th Century portion of the proxy record (1934 and 1977) was likely equaled or exceeded as many as 16 times during the preceding seven centuries (Table 3). The 20th Century portion of the record also contains only 2 of the 39 most severe drought years (lowest 0.05 percent quantile of precipitation values) in the time series (Tables 3 and 4). In contrast, the 16th and 18th Centuries each include 8 of the 39 0.05-quantile events. At the 0.10 quantile level, six of the seven previous centuries contained more dry events than the 20th Century. In addition, the 13th, 16th, and 18th Centuries each include twice as many 0.25 quantile dry events as the 20th Century.

The 20th Century contains 9 of the 39 single wettest years (0.95 quantile events) in the proxy record (more than any other 100-year period), while the 18th Century includes only two such years and the 13th Century none (Tables 3 and 4). The 16th and 17th Centuries hold seven and eight extreme wet years, respectively. The distribution of 0.75 and 0.90 quantile years is similar to that for 0.95 quantile events, with the 20th Century having the most and the 13th Century the least number of wet years.

Decadal-Scale Precipitation Regimes in the Uinta Basin Watershed

The 20th Century was marked by three significant decadal scale wet/dry regimes (Figure 3). The 20th Century dry regime at 1953 to 1964 encompasses the worst multiyear drought period to affect this area during the instrumental period. Compared to decadal scale droughts experienced in the Uinta Region over the previous seven centuries, however, the 1953 to

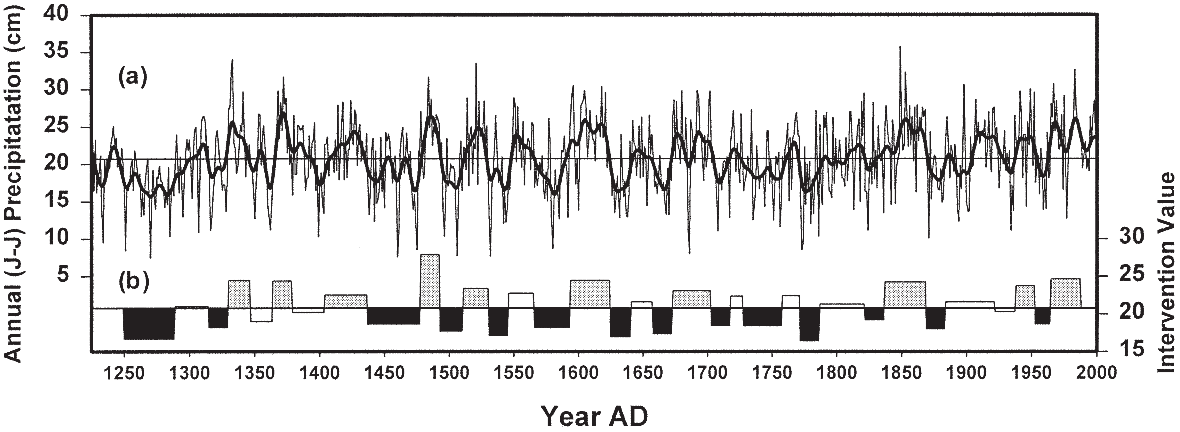

Figure 3. (a) Reconstructed Total Annual (June to June) Precipitation for the Uinta Basin Watershed Over the AD 1226 to 2001 Period. Annual values are shown as thin lines. The thick line represents a 30-year cubic spline fit to the reconstruction. (b) Mean Intervention Values (cm) and Durations of Significant Wet (gray) and Dry (black) Regimes Identified in the Proxy Record Via Intervention Analysis.

1964 drought was unremarkable in both duration and magnitude. In particular, this event was brief compared to other decadal scale droughts identified by the intervention analysis. In fact, the probability of any single decadal scale dry regime exceeding the duration of the 1950s drought is 94.2 percent. Even though it encompassed several severely dry years, the 1930s drought was not identified as a decadal scale dry event because of its relatively short duration.

In contrast, the 20th Century contained two of the strongest wet intervals (Figure 3), with 1938 through 1952 and 1965 through 1987 ranking as the seventh and second most intense wet regimes in the proxy record (Table 5). Furthermore, while the moving window used to detect regime shifts runs off the time series at 1987, this last wet regime appears to have persisted until the year 1999, when a series of drought years over western North America began. The empirical probability of any regime event exceeding the magnitude of the 1965 through 1987 event is small (0.34 percent). If this wet period is defined as continuing until 1999, the probability of any one regime exceeding its duration is less than 1 percent.

Several regime scale events predating the instrumental record stand out as remarkable. A wet period in the mid-19th Century (1837 to 1868) is conspicuous in terms of both duration (32 years) and magnitude (112 cm precipitation surplus for the period), while the most intense dry regime in the proxy record occurred during the late 18th Century from 1772 through 1786 (Figure 3; Table 5). Though not especially long, this late-18th Century drought encompasses four of the driest years (1773, 1774, 1780, and 1786) in the entire reconstruction (Table 3).

The late 16th and early 17th Centuries were notable for a series of decadal scale events. In terms of magnitude, the 1566 through 1593 interval was the fourth worst drought in the proxy record (Table 5). However, this severe drought was followed by a 31-year wet regime from 1594 through 1624, with the greatest magnitude and lowest (strongest) wet event score in the reconstruction. This extraordinary wet episode was followed by a period (1625 to 1640) with the third lowest average annual precipitation (16.9 cm) for any interval in the proxy record. Although a strong drought from 1437 to 1477 was also followed by a strong wet period from 1478 to 1492, the progression between strong dry, then strong wet, and finally strong dry regimes in the late 16th and early 17th Centuries was a unique occurrence within the proxy record.

The most significant event of longer than 10 years occurred within the first century of the reconstruction. The 1250 through 1288 drought was the second longest dry period and the second longest decadal scale precipitation regime, wet or dry, within the proxy record (Figure 3; Table 5). At only 16.7 cm/yr, this interval also displays the second lowest average annual precipitation in the reconstruction. This drought had by far the greatest magnitude for any regime in the record. In fact, at a deficit of nearly 125 cm of precipitation, the empirical probability of any regime in the region exceeding the magnitude of this late-13th Century drought is only 0.09 percent.

TABLE 3. Driest and Wettest (0.05 and 0.95 quantile, respectively) Years for the 1226 to 2001 AD Period Based on the Uinta Composite Reconstruction.*

Rank	Dry Year	Precipitation (cm)	Rank	Wet Year	Precipitation (cm)
1	1270	7.5	1	1849	35.7
2	1460	7.6	2	1333	34.1
	1532	7.6	3	1521	33.5
3	1506	7.8	4	1332	32.7
4	1686	8.0		**1983**	32.7
5	1251	8.4	5	1853	32.3
6	1773	8.5	6	1484	31.6
	1475	8.5		1372	31.6
7	1580	8.7	7	**1967**	30.7
8	1774	9.5	8	1898	30.6
	1234	9.5	9	1596	30.5
9	1871	10.1	10	1618	30.3
10	1399	10.3	11	**1949**	30.0
	1786	10.3	12	1605	29.8
11	1285	10.4		1692	29.8
	1496	10.4		1368	29.8
12	1307	10.8		1680	29.8
13	1685	10.9	13	1941	29.7
14	1708	11.0		1702	29.7
15	1824	11.1	14	1341	29.6
	1316	11.1		1621	29.6
16	**1934**	11.2		**1952**	29.6
	1461	11.2	15	1821	29.4
	1362	11.2	16	**1975**	29.1
17	1531	11.3		1595	29.1
18	1756	11.6	17	1550	28.9
19	1780	11.9	18	1514	28.8
20	1542	12.1		1693	28.8
	1474	12.1		1374	28.8
21	1544	12.2	19	1604	28.7
22	1442	12.3	20	1486	28.6
	1894	12.3		**1907**	28.6
24	1751	12.5	21	1674	28.5
	1735	12.5		**1998**	28.5
25	1350	12.7		1424	28.5
	1585	12.7	22	**1969**	28.4
	1977	12.7		1527	28.4
26	1632	12.8		1523	28.4
	1579	12.8		1701	28.4

*Extreme event years from the 20th Century are shown in bold.

DISCUSSION

Evaluating 20th Century Precipitation Variability

Validation statistics show that tree growth at these sites is tightly linked to moisture availability at low to moderate elevations (1,500 to 2,000 m) in the Uinta Basin. Furthermore, the correlation of these chronologies with snowpack in the Uinta Mountains suggests that these reconstructions provide a proxy for total annual (J to J) precipitation within the entire Uinta Basin Watershed. Large sample sizes (Table 1) and conservative cutoff dates for use of individual chronologies in the composite reconstruction also bolster the analyses.

This reconstruction, in turn, provides a long term perspective from which to evaluate 20th Century precipitation variability in the Uinta Basin Watershed. While single drought years such as 1934, 1936, 1959, 1961, and 1977 were undoubtedly severe in terms of their impact on the Uinta Basin Watershed, examination of the proxy record shows that numerous drought years in the 1226 to 1899 period were apparently drier than these most extreme single-year 20th Century events (Figure 3, Table 3). The 20th Century was, in fact, remarkable for its number and magnitude of extreme wet years. The 20th Century contains more 0.95 quantile wet years (nine) than any other 100-year period.

The last full decadal scale event of the 20th Century was noteworthy for its high average annual precipitation compared with previous centuries in the reconstruction (Figure 3; Table 5). Although some tree-ring records may be less suited for assessing the magnitude of wet events than they are for droughts (Fritts, 1976), comparisons between reconstructed and instrumental precipitation (Figure 2) show that the chronologies in this study record wet events reliably. The late 20th Century wet period received the second strongest wet score in the reconstruction. Instrumental data (Figure 4) also indicate a trend toward increasing wetness at the end of the 20th Century caused, in large part, by an increase in late spring and early summer precipitation. Instrumental records and tree-ring reconstructions of streamflow show the last two to three decades of the 20th Century to be unusually wet in the Colorado Front Range as well (McKee *et al.*, 1999; Woodhouse, 2001).

The 20th Century also stands out for a lack of strong decadal scale dry events (Figure 3; Table 5). On the whole, the 1930s drought had little effect on decadal scale moisture trends in the Uinta Basin Watershed. Two of these years, 1934 and 1936, were markedly dry. However, these years were quickly followed by a series of relatively wet years from 1937

TABLE 4. Percentage of Dry (wet) Years in Each Time Period at or Below (above) the 0.05, 0.10, and 0.25 (0.75, 0.90, and 0.95) Quantile Levels.

Century*	Percentage of *Q 0.05* Dry Years	Percentage of *Q 0.95* Wet Years	Percentage of *Q 0.10* Dry Years	Percentage of *Q 0.90* Wet Years	Percentage of *Q 0.25* Dry Years	Percentage of *Q 0.75* Wet Years
13th	5	0	13	0	41	3
14th	5	6	9	11	20	33
15th	6	3	12	7	23	24
16th	8	7	11	9	29	19
17th	3	8	10	13	21	30
18th	8	2	12	8	34	17
19th	3	4	6	15	21	29
20th	2	9	8	15	15	39

*Record begins at 1226 AD.

through at least 1941. The 1950s drought did lead to a substantial precipitation deficit (25.0 cm) over a 12-year interval (1953 to 1964). But an absence of 0.05-quantile years (Table 3) and near normal to wet precipitation years at 1955, 1957, 1958, 1960, and 1962 (Figure 3a) eased the overall moisture deficit during this event.

Precipitation Variability Prior to the Instrumental Record

Because they occurred before greenhouse gas buildup could have impacted the climate significantly, wet/dry events prior to the instrumental period furnish insight on the range of natural climate variability in the Uinta Basin. In turn, these reconstructions serve as a benchmark for evaluating the potential for future droughts and wet events within the watershed. In particular, the proxy record provides several examples of greater decadal scale precipitation variability than is captured in the instrumental record. The drought of 1772 through 1786, for example, had duration similar to the 1950s event, but included four of the driest single years (1773, 1774, 1780, 1786) in the proxy (Table 3). Like the 1950s event, this late 18th Century drought included several near normal to wet years that eased the overall impact of the dry spell (Figure 3a). However, the years 1773, 1774, 1780, and 1786 were so dry (all < 11 cm/yr) that they led to a total precipitation deficit of approximately 65 cm, making 1772 through 1786 the most intense drought in the proxy record (Table 5). The 1772 through 1786 drought, while also reported in the southern Great Plains (Stahle and Cleaveland, 1988), appears to have centered over the southwestern United States. Meko *et al.* (1993) identified 1773 through 1782 as the decade with the lowest mean precipitation for Arizona over the 1705 to 1979 period. The Upper Gila River Basin experienced the second lowest discharge between 1663 and 1983 in 1773 (Meko and Graybill, 1995). Like the 1950s event, the 1772 through 1786 drought also affected parts of Wyoming, southern Montana, and the Yellowstone Region (Graumlich *et al.,* 2003) but at decadal scales did not extend into the eastern and southeastern United States (Cook *et al.,* 1999).

A drought in the late 16th Century provides another useful comparison with 20th Century events. This 16th Century drought had a mean annual precipitation of 18.2 cm, close to that during the 1953 to 1964 drought interval (18.6 cm). This event, however, lasts from 1566 through 1593, a full 28 years. This drought was also notable for its widespread nature. In a summary analysis of tree-ring chronologies spanning the late 16th Century, Stahle *et al.* (2000) found strong evidence for this same drought extending from the southwestern United States and northern Mexico through the Rocky Mountains. Using an exceptionally long and well replicated tree-ring chronology from western New Mexico, Grissino-Mayer (1996) suggested that this event was the most severe drought experienced in that area during the last 2,000 years. Based on tree-ring reconstructions of Colorado River flow at Lees Ferry, Arizona, Stockton and Jacoby (1976) estimated 1579 through 1598 to be the driest two decades between 1520 and 1961 in the Upper Colorado River Basin. Furthermore, both tree ring and documentary evidence show that this drought extended into the Carolinas and lower Mississippi Valley (Stahle *et al.,* 2000). All told, this late 16th Century event was just as severe and as widespread as the 1950s drought but lasted twice as long.

TABLE 5. Potential Decadal-Scale Wet and Dry Regimes Identified Using the Intervention Detection Algorithm (Gedalof and Smith, 2001).

Period	Regime p-Value	Average PCP	Duration	Rank	Magnitude	Rank	Intensity	Rank	Score
1250 to 1288	< 0.001	16.7	39	d2(2)	-158.4	d1(1)	-4.1	d2(3)	6
1289 to 1314	0.561	21.0	*	*	*	*	*	*	*
1315 to 1329	0.056	18.2	15	d7(13)	-38.5	d11(21)	-2.6	d8(16)	50
1330 to 1346	0.013	24.4	17	w7(11)	63.1	w5(10)	3.7	w4(7)	28
1347 to 1363	0.252	19.0	*	*	*	*	*	*	*
1364 to 1378	0.053	24.3	15	w8(13)	54.4	w8(16)	3.6	w5(9)	38
1379 to 1403	0.386	20.2	*	*	*	*	*	*	*
1404 to 1436	0.067	22.5	33	w1(3)	59.2	w7(13)	1.8	w10(23)	39
1437 to 1477	0.041	18.6	41	d1(1)	-86.3	d2(5)	-2.1	d12(21)	27
1478 to 1492	0.026	24.9	15	w8(13)	62.2	w6(11)	4.1	w1(2)	26
1493 to 1510	0.063	17.7	18	d5(10)	-54.7	d7(14)	-3.0	d6(12)	36
1511 to 1530	0.039	23.4	20	w6(9)	53.1	w9(17)	2.7	w8(15)	41
1531 to 1545	0.018	17.1	15	d7(13)	-54.6	d8(15)	-3.6	d4(8)	36
1546 to 1565	0.113	22.7	*	*	*	*	*	*	*
1566 to 1593	0.027	18.2	28	d4(7)	-71.8	d3(6)	-2.6	d9(17)	30
1594 to 1624	0.004	24.4	31	w3(5)	115.3	w1(2)	3.7	w3(6)	13
1625 to 1640	0.073	16.9	16	d6(12)	-60.5	d6(12)	-3.8	d3(5)	29
1641 to 1657	0.602	21.6	*	*	*	*	*	*	*
1658 to 1672	0.032	17.4	15	d7(13)	-50.4	d9(18)	-3.4	d5(11)	42
1673 to 1702	0.025	23.1	30	w4(6)	70.3	w4(7)	2.3	w9(18)	31
1703 to 1717	0.049	18.4	15	d7(13)	-34.2	d12(22)	-2.3	d11(20)	55
1718 to 1727	0.134	22.3	*	*	*	*	*	*	*
1728 to 1757	0.043	18.4	30	d3(6)	-69.9	d4(8)	-2.3	d10(19)	33
1758 to 1771	0.111	22.4	*	*	*	*	*	*	*
1772 to 1786	0.003	16.4	15	d7(13)	-65.4	d5(9)	-4.4	d1(1)	23
1787 to 1821	0.196	21.3	*	*	*	*	*	*	*
1822 to 1836	0.056	19.2	15	d7(13)	-23.0	d14(24)	-1.5	d14(24)	61
1837 to 1868	0.002	24.2	32	w2(4)	112.0	w2(3)	3.5	w6(10)	17
1869 to 1883	0.062	18.0	15	d7(13)	-41.1	d10(20)	-2.7	d7(14)	47
1884 to 1921	0.335	21.6	*	*	*	*	*	*	*
1922 to 1937	0.751	20.3	*	*	*	*	*	*	*
1938 to 1952	0.083	23.7	15	w8(13)	44.8	w10(19)	3.0	w7(13)	45
1953 to 1964	0.007	18.6	12	d8(14)	-25.0	d13(23)	-2.1	d13(22)	59
1965 to 1987	0.006	24.7	23	w5(8)	90.5	w3(4)	3.9	w2(4)	16

Notes: Significance for each regime (regime p-value) was determined through intervention analysis (Box and Tiao, 1975). Average PCP = average J to J precipitation over entire regime (compare to mean for entire reconstruction of 20.7 cm). Duration = number of years between regime shifts. Magnitude = sum of the long term mean minus reconstructed annual precipitation values within a regime. Intensity = magnitude/duration. Event duration, magnitude, intensity, and score are ranked for wet and dry events only and among all events (in parentheses). Score = sum of rankings for duration, absolute magnitude, and absolute intensity (lower scores indicate "stronger" events).

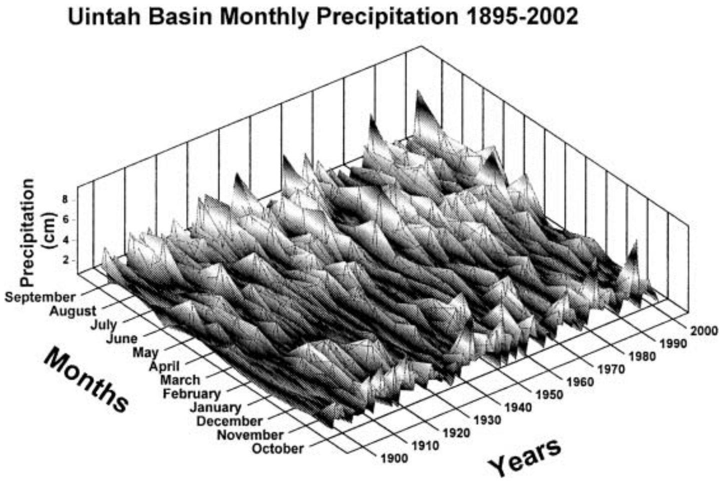

Figure 4. Three-Dimensional Diagram Showing Instrumental Values for Monthly Precipitation in Utah Climate Division 6 (see Figure 1) Over the 1896 to 2002 AD Interval.

This 16th Century "megadrought" was followed by a strong wet event in the Uinta Basin Watershed. The 1594 through 1624 period ranks as the most intense and strongest scoring wet event in the proxy record (Table 5). Like the drought before it, this wet period was also recorded through at least the Central and Southern Rocky Mountain Regions (D'Arrigo and Jacoby, 1991; Grissino-Mayer, 1996; Gray *et al.,* 2003).

The late 13th Century drought provides a truly extraordinary example of a decadal scale climatic event. Not only did this drought last 39 years (1250 to 1288) in northeastern Utah, it was also the decadal scale event of the greatest magnitude (wet or dry) and the second most intense drought in the proxy record (Table 5). Average annual precipitation reached only 16.7 cm for this entire period (compared to the average of 20.7 cm over the entire proxy record), accounting for an astounding 158 cm precipitation deficit during this event. By comparison, the total deficit for the 1930s and 1950s droughts in the Uinta Basin Watershed was 31.7 cm. In addition, this event includes the driest year in the proxy record, 1270, when the reconstruction model estimates that only approximately 7.5 cm of precipitation fell on the study area (Table 3). Although this event occurred early in the reconstruction, sample depth for this interval is reasonably high, with 16 trees from two sites recording this event.

Many paleoclimate reconstructions across the western United States and Great Plains record a severe, multidecadal drought in the late 13th Century (Woodhouse and Overpeck, 1998). Drought sensitive tree-ring chronologies from Nebraska (Woodhouse and Overpeck, 1998), New Mexico (Grissino-Mayer, 1996), the southern Great Basin (Hughes and Graumlich, 1996), northern Great Basin (Woodhouse and Overpeck, 1998), and greater Yellowstone region (Gray *et al.,* 2003) show marked decreases in tree growth at or near this time. Other proxies including Nebraska Sand Hills eolian activation records (Muhs *et al.,* 1997) document this drought. All in all, proxy evidence suggests that this drought covered at least the Rocky Mountain states and Great Plains, was even drier than the 1930s and 1950s droughts, and lasted for nearly 40 years.

Dry conditions at the end of the 13th Century have long been associated with Anasazi abandonment of the Four Corners area and displacement to the Hopi mesas of northeastern Arizona, the Zuni area of western New Mexico, and the northern Rio Grande of north-central New Mexico (Dean, 1988). The exact role of the so called "Great Drought" is still hotly contested by some archeologists who suggest that it was not severe enough to cause evacuation (Lipe, 1995). Agent based modeling of human environment interactions suggest that some areas could have supported a reduced population, hence additional factors must have contributed to total abandonment (Axtell *et al.,* 2002). The proxy record, however, suggests that the socioeconomic impact of the Great Drought remains an open question.

In contrast to more localized dry events, the Anasazi could not have relied on crop surpluses from adjoining regions during the Great Drought. Starvation and disease associated with nutrient deficiencies must have claimed large portions of the Anasazi population. As an example, a drought in the 1660s decimated the Pueblo of Tabira in the Estancia Valley of central New Mexico. By 1669 no crops had been harvested for three years, and more than 450 of Tabira's inhabitants (half of the pueblo) starved to death, "lying dead along the roads, in the ravines, and in their huts" (Hackett 1937, p. 271-272). Three years later, the survivors fled south to pueblos and missions around Socorro and El Paso. Thus, it would have been more surprising for the Anasazi to stay than to have abandoned the Four Corners during the Great Drought. It is precisely this kind of subcontinental scale drought that could now expose vulnerabilities within water resource systems.

Implications for Water Resource Management

Comparisons between 20th Century droughts and those reconstructed for the preceding 600-plus years point to fundamental differences between dry events during the instrumental period and those in past centuries. Decadal scale dry events in the past tended to persist longer than those experienced in the 20th

Century; the only statistically significant 20th Century dry regime lasted for 12 years (1953 to 1964), while significant dry regimes before 1900 averaged 21 years in length (Table 5, Figure 3b). Moreover, four of the 13 significant dry regimes before 1900 lasted for at least 28 years. Before 1900 the intensity of many decadal scale droughts in the Uinta Basin Watershed appears greater than for those in the instrumental period.

If a climatic regime characterized by prolonged, severe droughts were to return to the Uinta Basin Watershed, current strategies for drought mitigation and response would be wholly inadequate. The Utah Division of Water Resources (UDWR, 1999) proposes that the effects of future droughts in the Uinta Basin Watershed will be minimized through reservoir storage developed since the 1930s and 1950s, but low precipitation during the years 1999 to 2003 nevertheless led to moderate to severe water shortages. Therefore, it seems unlikely that reservoir storage could overcome a drought longer than 20 years of even the same intensity of any 20th Century drought. Federal and state agencies, municipalities, and irrigation districts should develop contingency plans that include restrictions on water use and development that could be enacted if a prolonged, severe drought like those so commonly seen in the tree-ring record were to occur in the 21st Century.

The overall wetness of the interval 1964 to 1987 indicates that any predictions for the Uinta Basin Watershed based on the 1961 to 1990 normal period may be overly optimistic. The Uinta Basin Water Plan (UDWR, 1999) emphasizes the availability of excess or unallocated water in the Uinta Basin Watershed capable of supporting a doubling of the region's population in coming decades. However, most of the streamflow records used to develop these estimates began after 1947 and are biased by the wetness of the late 20th Century.

The potential for such a bias in estimates of future water availability becomes remarkably high when only the small sample of years captured by the instrumental record is examined. This situation is not unique to the Uinta Basin area. In particular, the Colorado River Compact of 1922 was based on a period of unusually high flow (Meko *et al.,* 1995), so that in the context of the previous 400 years, water that would not be available during more "normal" flow regimes was included in the master allocation scheme. The reference periods for use in water resources planning must be carefully selected to avoid significant overestimates or underestimates of past and future availability.

CONCLUSIONS

Severe, persistent (> 10 yr) droughts have been a common feature of Uinta Basin climate since at least the 13th Century. The instrumental period, however, is unusual because the strongest dry events during this interval were relatively brief. Although undoubtedly severe in terms of their impact on agriculture and water resources, the "worst case scenarios" of the 1930s and 1950s droughts had little effect on long term moisture trends in this area (Figure 5). Many

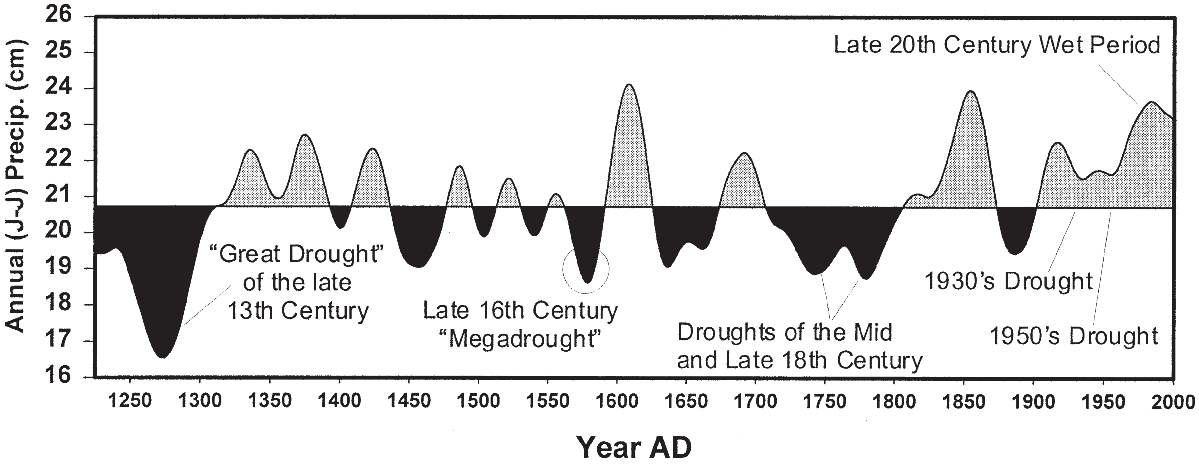

Figure 5. Effect of Instrumental and Preinstrumental Droughts on Multidecadal Precipitation Trends.
Graph shows a 50-year cubic spline fit to the Uinta Basin Watershed precipitation reconstruction.
Values are plotted versus the long term mean for annual precipitation (20.7 cm).
Persistent dry periods are shaded in black and wet periods are shaded in gray.

persistent droughts prior to the instrumental period, however, resulted in major precipitation deficits over 25 to 50 yr periods. Instead the 20th Century was dominated by relatively wet conditions, especially during the last half of the century. The authors caution that this statement may not apply to other areas of the western United States such as the middle Rio Grande Basin where the 1950s drought may indeed be a worst-case situation (Milne *et al.,* 2003).

The tree-ring reconstruction described herein suggests that land and water resource managers in the Uinta Basin Watershed and surrounding areas should place less emphasis on scenarios presented by the instrumental period. Mitigation and planning efforts should, instead, consider a wider range of climatic scenarios, including droughts of different lengths, magnitudes, and intensities. Managers should also consider numerous combinations of wet/dry events in their decision making. Such scenarios may be derived from long term proxies of climate variability such as those provided by tree rings but might also be obtained from model simulations of past and future climates. Furthermore, planning efforts should focus more on the potential for long duration dry events rather than average values for water availability. While the long term mean of Uinta Basin precipitation might be capable of supporting expanded populations or increased agricultural activity, the high empirical probability of frequent decadal scale droughts that exceed the limits of reservoir storage and existing conservation measures should play a major role in policy decisions.

Overall, greater awareness of decadal scale precipitation variability in the Interior West should affect the management of timber production, wildland and prescribed fires, carbon sequestration, both nonnative and native plant populations, wildlife, and water resources. Moreover, understanding the geographic coherency of such decadal scale climatic events and their impacts on water and ecosystem resources is of the utmost importance in the face of predicted global change.

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