Tree-ring based streamflow reconstruction for Ashley Creek, northeastern Utah: implications for palaeohydrology of the southern Uinta Mountains

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Abstract: Two ring-width chronologies from Douglas fir (*Pseudotsuga menzeisii*) and one from pinyon pine (*Pinus edulis*) were used to reconstruct mean annual discharge of Ashley Creek in the Uinta Mountains, Utah, for the years AD 1637–1970. A backward-elimination multiple linear-regression model identified six statistically significant variables, including annual lags ranging from −1 to +2 years. The final model explains 71% of variability (R^2 adjusted for degrees of freedom lost) when regressed against the annual discharges recorded for 1915–72. Statistical analysis of the model reconstruction using the reduction-of-error statistic, the Durbin–Watson statistic and the hypergeometric distribution all indicate fidelity of the model for reconstructing discharge. The Lilliefors' test indicates that years of extreme discharge (greater than the 90th percentile or less than the 10th percentile) are non-randomly distributed between 1637 and 1970. Persistent years of above-median discharge as well as non-random clustering of years above the 90th percentile occurred from 1692–1704 and 1898–1945. Analysis of the modern gauge data set shows that mean annual discharge on Ashley Creek explains between 81% and 91% of the variations of mean annual discharge on the other main stream in the southern Uinta Mountains, indicating that reconstructed mean annual discharge on Ashley Creek is representative of palaeohydrologic conditions across the south flank of the range. These data suggest that the southern Uinta Mountains experienced persistent below-median discharge for 1741–1897, through the peak of the 'Little Ice Age' as identified in numerous surrounding mountain ranges in the Central Rockies. This interpretation agrees with lichenometric evidence for extremely limited 'Little Ice Age' glacial activity in the Uintas, indicating that the range experienced unusually warm/dry conditions at this time.

Key words: *Pseudotsuga menzeisii*, *Pinus edulis*, dendroclimatology, palaeohydrology, drought, Uinta Mountains, Utah.

Introduction

Dendrohydrology is the study of ancient long-term trends in hydrology using streamflow and precipitation reconstructions based on tree-ring records. The widths of annual tree rings respond to hydrologic 'forcing' – limiting environmental conditions such as near-surface temperature, evapotranspiration or precipitation – to create a record of responses of trees to hydrologic phenomena over timescales often significantly longer than the modern instrumented period. This relationship potentially allows researchers to evaluate changes and long-term trends in these hydrologic phenomena over centuries or even millennia in certain situations. The quantitative analysis of long-term hydrologic records is of considerable significance for current water-resource assessment and management, the understanding of hydrologic response to changes in atmospheric circulation patterns

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and the prediction of hydrologic response to future warming trends (Loaiciga and Marino, 1991; Loaiciga *et al*., 1993).

Researchers have long understood the linkages between tree-ring widths and climatic conditions such as precipitation, runoff, near-surface temperature and evapotranspiration (Douglass, 1920). However, only more recently have techniques been developed to reconstruct past hydrology from the tree-ring record (Fritts *et al*., 1971; Loaiciga *et al*., 1993). Studies conducted in southern Utah and northern Arizona have verified the sensitivity of dendrochronologic records in the southwestern USA to temporal variations in precipitation, as well as the strong relationship between tree-ring widths and local streamflow (Smith and Stockton, 1981; Meko and Graybill, 1995; Hereford *et al*., 1996).

Recent and current research in the Uinta Mountains is evaluating the geomorphological record of Holocene climate variability (e.g. Carson, 2002; Munroe and Laidlaw, 2002; Munroe, 2003). The instrumented gauge record for streams in the Uinta Mountains provides a relatively short sample of hydrologic variability: most streams in the range have continuous gauge records from 40 to 60 years in length. The longest continuous local gauge record, on Ashley Creek, dates to 1915. While the total number and length of gauge records in the Uintas are superior to many surrounding mountain ranges, historic gauge records are by nature inherently limited for evaluating Holocene-scale hydrologic variability and responses to climatic change. Tree rings have proven useful for analysing hydrologic supply and variability during the past several centuries (Loaiciga *et al*., 1993). This trait is particularly well-suited for evaluating water supply during the 'Little Ice Age' in the Uintas. Munroe (2002) analysed *Rhizocarpon geographicum* (L.) lichen diameters at several sites on the north flank of the Uinta Mountains and suggested that moraine and rock glacier surfaces in the Deadhorse Lake area have been stable since 1300–1650 ^{14}C yr BP. This interpretation indicates minimal or no glacier readvances in the Uintas during the 'Little Ice Age', despite abundant evidence for such readvances at this time in surrounding ranges in the Central Rockies. This research project presents an opportunity to quantify surface water flow in the southern Uintas back to and preceding the peak of the 'Little Ice Age', thus allowing independent evaluation of the hypothesis of a scarcity of 'Little Ice Age' glacial activity in the Uintas.

Geographic setting

The main area of study for this project is in the Uinta Mountains, an east–west trending mountain range that extends approximately 200 km eastward from the Wasatch Front at Kamas, Utah, into northwestern Colorado (Figure 1). The crest of the Uinta Mountains contains the highest peaks in Utah, with Kings Peak at 4124 m as the highest. The Uinta Mountains are the surficial expression of a complex doubly plunging anticline that was uplifted during the Laramide Orogeny. The bedrock core of the range is the Precambrian Uinta Mountain Group, a series of orthoquartzites, shales and slightly to moderately metamorphosed metaquartzites (Hansen, 1969; Sears *et al*., 1982). The Uinta Mountains were glaciated during both the penultimate and last glacial maxima in the western USA (Atwood, 1909; Bradley, 1936). Alpine-style glaciers occupied all of the major drainages in the Uinta Mountains, but there is no evidence that these glaciers ever overtopped the crest of the range or coalesced into an ice cap (Hansen, 1969; Munroe, 2001). On the south flank of the Uintas the resultant stream systems are dominated by the history of Pleistocene glaciation.

The location and orientation of the Uinta Mountains make them ideal for studying the sensitivity of sub-alpine streams to changing climatic conditions. The Uinta Mountains lie near the northernmost influence of the summer 'monsoonal' systems and the southernmost influence of the North Pacific frontal storms that occur during the winter (Bryson and Hare, 1974; Mitchell, 1976). Precipitation data for the southern Uinta Mountains are provided by six snowpack-telemetry (SNOTEL) stations located between 2650 and 3300 m a.s.l. Mean annual precipitation at these sites ranges between 675 and 925 mm/yr, although precipitation may be as high a 1200 mm/yr at the highest elevations (Munroe, 2001). Depending on elevation, between 40% and 60% of annual precipitation occurs as snow, and late-season maximum snow-water equivalents can be as high as 525 mm. The hydrology of the Uinta Mountains streams is dominated by winter snowpack accumulation and release of the snowpack during the early summer months. Reorganization of large-scale atmospheric circulation patterns therefore could significantly impact the amount of precipitation received by the range and the resultant streamflow.

Tree ring data

Four long, continuous tree-ring records were collected from the Whiterocks River drainage basin in 1972 by J.B. Harsha, C.W. Stockton and G.C. Jacoby (Stockton and Jacoby, 1976). To remove the localized noise in the tree-ring data resulting from disease or damage to any single tree (Cook, 1987), multiple core indices from separate trees were averaged to produce 'site chronologies', designated Records A, B, C and D by the original investigators (Figure 1 and Table 1). The data were detrended by the collecting investigators to remove the signal of preferentially large tree-ring widths during the early years of an individual tree's life by fitting a negative exponential or straight line to each core's ring-width series and dividing ring widths by corresponding values of the fitted line (Fritts, 1976). This procedure transformed ring-width measurements (recorded in thousandths of millimetres) to a ring-width index with a mean of 1.0 over the length of the records. Multiple samples were averaged for each record to remove any non-climatic effects on ring width (Table 1), such as disease or damage to any single tree (Cook, 1987). The data have not been 'prewhitened' to remove inherent autocorrelation. All four records show significant one-year lag autocorrelation, and Record D additionally shows two-year lag autocorrelation. Record A was collected from *Picea engelmanii* (Engelmann spruce) at the headwaters region of the drainage basin. It was collected near several rock glaciers, which appeared to have disturbed the growth of the trees. The reconstructed tree-ring chronology for this site contained numerous internal inconsistencies, for which it was deemed unsuitable for further analysis by the original investigators (G.C. Jacoby, personal communication, 2000). Records B and C were collected from *Pseudotsuga menzeisii* (Douglas fir) and date to AD 1731 and AD 1636, respectively. Record D was collected from *Pinus edulis* (pinyon pine) and contained a continuous record to AD 1424.

These data were originally collected for a research project funded by the US National Science Foundation. The goal of that project was to reconstruct streamflow at several sites on the mainstem Colorado River based on tree-ring chronologies from sites throughout the Upper Colorado basin (Stockton

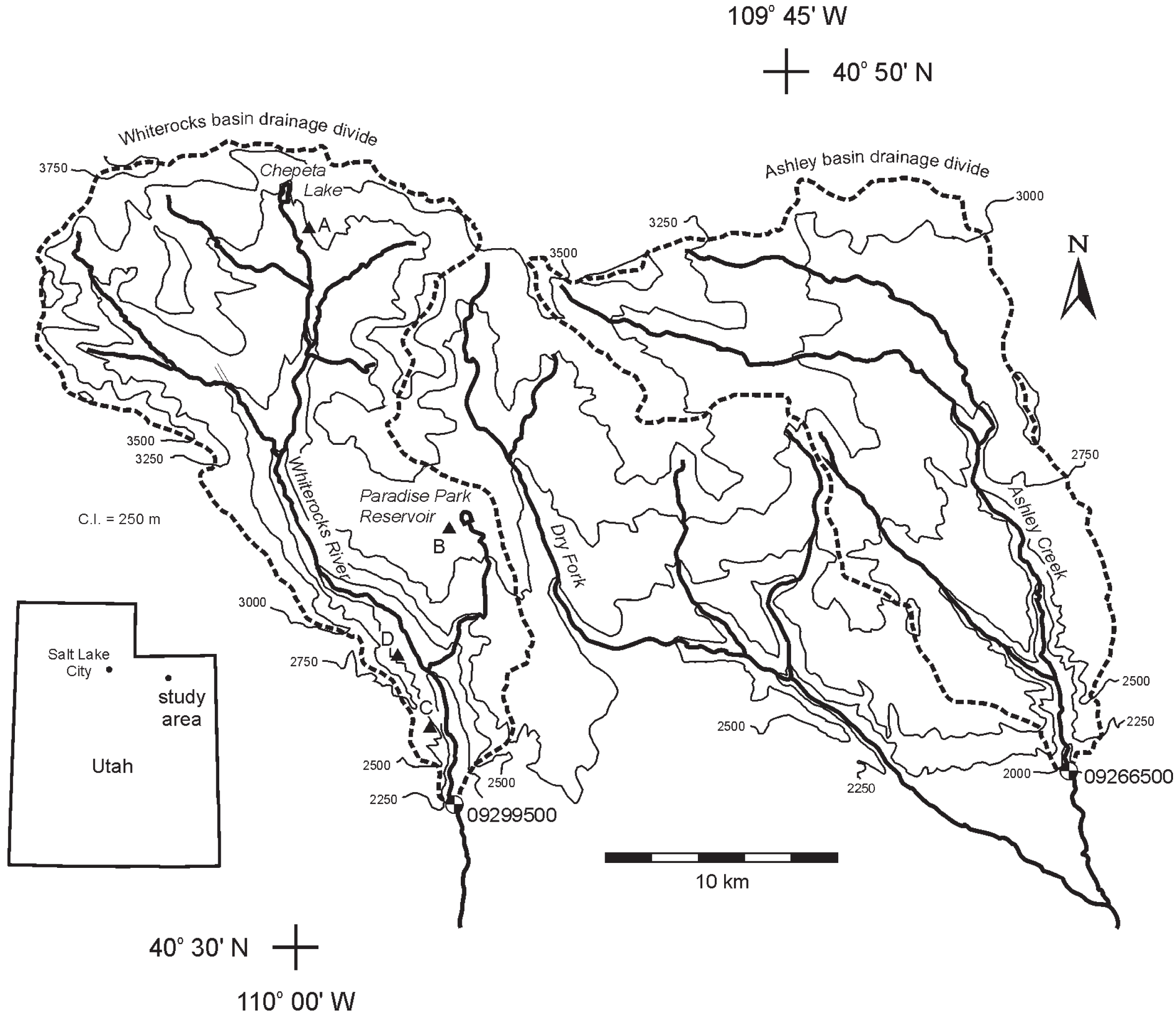

Figure 1 Location of study area in southern Uinta Mountains, showing the drainage basins for Whiterocks River above USGS gauge station 09299500 and Ashley Creek above USGS gauge station 09266500. The four Whiterocks River tree-ring chronologies collected in 1972 are shown by the black triangles

Table 1 Characteristics of the four tree-ring chronologies used for reconstruction of Ashley Creek mean annual discharge

	Sites			
	A	B	C	D
Characteristics:				
Latitude	40°47′N	40°40′N	40°34′N	40°37′N
Longitude	110°00′W	109°54′W	109°57′W	109°57′W
Species	*Picea engelmanii*	*Pseudotsuga menzeisii*	*Pseudotsuga menzeisii*	*Pinus edulis*
Dates	1433–1971	1731–1971	1636–1971	1424–1971
Tree Ring Statistics:[a]				
Mean width	1.00	1.00	1.00	1.00
Standard deviation	0.71	0.47	0.55	0.46
Mean sensitivity[b]	0.11	0.30	0.33	0.31
Replication (no. trees):[c]				
At 1650	13	0	2	6
At 1700	16	0	3	6
At 1750	18	4	6	6
At 1800	19	10	9	8
At 1850	20	10	15	8
At 1900	20	19	18	8
At 1950	20	20	18	8

[a] *Source*: Stockton and Jacoby (1976).
[b] Mean sensitivity, the average of summed absolute values of first differences of the chronology indices. The statistic is a measure of frequency variation (Fritts, 1976).
[c] *Source*: NOAA International Tree-Ring Data Bank, http://www.ngdc.noaa.gov/paleo/ftp-treering.html (last accessed 21 February 2005).

and Jacoby, 1976). The three records employed in the present study were therefore selected specifically for sensitivity to hydrologic variation (G.C. Jacoby, personal communication, 2000). While the data collected in the Uinta Mountains had been used for reconstruction of discharge on the Colorado River, the data were never employed for any palaeoclimate study specific to the Uinta Mountains. The data were formatted and archived in the NOAA International Tree-Ring Data Bank. They are combined with the relatively long-term USGS stream-gauge data to evaluate long-term trends in streamflow for the southeastern Uinta Mountains.

Discharge data

The Whiterocks River basin, for the purposes of this study, is defined as the catchment above gauge no. 09299500, Whiterocks River near Whiterocks UT. It covers 282 km^2 of subalpine and alpine montane terrain in the south-central Uinta Mountains (Figure 1). The gauge is located at 2195 m a.s.l, and peak elevations in the headwaters of the watershed exceed 3800 m a.s.l. Ashley Creek, the adjacent watershed to the east of Whiterocks River, is gauged at station no. 09266500, Ashley Creek near Vernal UT. This watershed covers 262 km^2 of terrain similar to the Whiterocks River drainage. This gauge is located at 1900 m a.s.l, with peak elevations in the headwaters in excess of 3650 m a.s.l.

The period of record for discharge data in the Uinta Mountains region is surprisingly extensive. The Whiterocks River gauge (09299500) collected data intermittently from 1910 to 1930 and continuously from 1930 to present; the Ashley Creek gauge (09266500) has collected continuous daily discharge data since 1915. Monthly and annual discharge data for Whiterocks River and Ashley Creek were obtained from the US Geological Survey (http://water.usgs.gov; last accessed 21 February 2005). The accuracy of the discharge data for Whiterocks River is rated as 'good' during summer months and 'fair' during winter months; the former indicating that 95% of the daily discharge measurements are within 10% of the true discharge and the latter indicating 95% of the daily discharge measurements are within 15% of the true discharge. The accuracy of the discharge data for Ashley Creek is rated as 'fair' (US Geological Survey, 1973).

The gauge record for Ashley Creek has been minimally impacted by irrigation and municipal diversions. Beginning 1 July, 1940, the Oaks Park canal has diverted an annual average of 0.17 m^3/s (5.9 c.f.s.) from Big Brush Creek into Ashley Creek. Additionally, the city of Vernal UT, has diverted an annual average of 0.14 m^3/s (5.0 c.f.s.) from Ashley Creek during the period 1942 to 1960, and 0.31 m^3/s (11 c.f.s.) from Ashley Creek during the period 1961 to present. Once adjusted for these diversions, the mean annual discharge of Ashley Creek closely corresponds to the mean annual discharge of Whiterocks River (Figure 2). The strong correlation between discharges on the two streams reflects the proximity of the two watersheds to one another, the similar topography and basin orientation (aspect), and the fact that the same meteorological systems produce precipitation and therefore runoff in the two basins.

The gauge records for Whiterocks River and Ashley Creek contain 42 and 57 years, respectively, of overlap with the three tree-ring chronologies. Considering the proximity, physiographic similarity of the two watersheds and the correlation between the Whiterocks River discharge and the adjusted Ashley Creek discharge, the record of Ashley Creek was used for reconstructing mean annual discharge. This allowed the longer period of overlap between discharge data and the tree-ring chronologies to be split into two sections for detailed calibration and verification (Cleaveland, 2000).

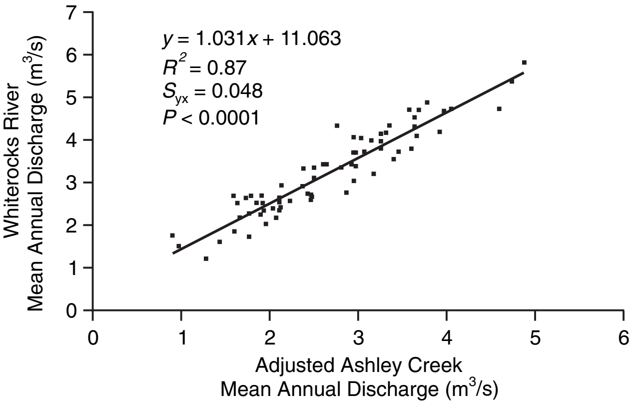

Figure 2 Comparison of mean annual discharges (c.f.s.) between Whiterocks River and Ashley Creek for the period 1930–1999 water years. Mean annual discharge of Ashley Creek has been adjusted to account for water withdrawn from the stream above the gauge station for use by the city of Vernal UT, and to account for water added to the stream from the Oaks Park canal

Statistical procedures

Derivation of model

Two primary hydrologic variables available from the instrumented record are the magnitude of the peak annual discharge and the magnitude of the total annual discharge. The flood hydrology of the Uinta Mountains is closely associated with the accumulation and release of each winter's snowpack. As much as 60% of the annual precipitation received in the headwater areas of Whiterocks River and Ashley Creek is snow derived from North Pacific winter frontal systems. As a result the spring snowmelt flood has produced the peak annual discharge for over 95% of the gauge years in the southern Uinta Mountains. However, the exact magnitude of the spring snowmelt flood is the result of the interaction of winter precipitation (snowpack accumulation), spring precipitation in the early part of the melt season and the temperature regime through the melt season. In contrast, the total annual precipitation (mean annual discharge) incorporates the entire volume of the snowpack released as stream discharge, regardless of timing in the melt season, as well as summer precipitation derived from monsoonal systems migrating from Baja California. Only small isolated snowfields persist through the summer in the Uinta Mountains (Munroe, 2001). Thus each winter's entire snowpack is incorporated into that water year's mean annual discharge. Because tree-ring growth is more closely related to the available water throughout the growing season than are magnitudes of peak annual flood (Fritts, 1976; Stockton and Jacoby, 1976), the former is reconstructed from the available dendrochronologic data.

While tree-ring width is primarily a function of available water (discharge) in the year of the ring's growth, the widths of rings also show correlation to preceding and following years' water availability (Stockton and Jacoby, 1976; Meko and Graybill, 1995). Climatic inputs of precipitation, temperature and insolation in any year t are directly reflected in the ring-width for year t. Furthermore, the inputs of year t also affect ring width in year $t+1$ through bud development and sugar and hormone storage and carryover; in year $t+2$ through leaf, root and fruit growth processes; and in year $t-1$ through food storage and soil-moisture carryover that is represented as autocorrelation in the ring-width series (Fritts, 1976). These offsets in response between discharge and tree-ring growth were incorporated into the regression model by including various lagged chronologies. Multiple lagged variables were used for the regression in order to address the autocorrelation of various lags that is evident in the records. Lags greater than -1 years and $+2$ years showed no significant relation to the discharge record and were thus excluded from further analysis. The total data set of predictors therefore contained 12 variables – each of the three chronologies lagged -1, 0, $+1$, and $+2$ years from the year of stream discharge. The final regression equation takes the form

$$\hat{y}_t = b_0 + \sum_{i=1}^{p} b_i x_{t,i} \quad (1)$$

where $\hat{y}_t$ is the estimated mean annual discharge in m^3/s in year t, p is the total number of predictors included in the model, b_0 is the regression constant, $b_1,\ldots,b_p$ are the regression coefficients, and x_{ti} is the ith predictor, a residual chronology in year t, $t-1$, $t+1$, or $t+2$.

A backward-elimination multiple linear regression model removed predictors sequentially to maximize the adjusted R^2 value (Draper and Smith, 1998). Predictors were removed from the model stepwise in with the criterion for probability of F-to-remove ≥ 0.100. Adjusted R^2 value reached a maximum when six significant predictors were employed to predict mean annual discharge of Ashley Creek (Table 2). The model explains 71% of the variance of mean annual discharge on Ashley Creek, with R^2 adjusted downward for loss of degrees of freedom (Draper and Smith, 1998).

Verification of the regression model

A variety of statistical measures were employed to evaluate the ability of the regression model to reproduce the actual gauge data. Additionally, the full calibration period (1915–71) was divided into two portions, and two additional calibrations and verifications were made (Figure 3). The verification statistics suggest that the selected model is capable of reproducing both the mean and variation of the actual gauged data, indicating the model is appropriate for reconstructing mean annual discharge for the entire period of dendrochronologic data.

The Durbin–Watson statistic (d) evaluates the residuals for serial correlation (Draper and Smith, 1998); it has a distribution of $0 \leq d \leq 4$, with values very close to 2 indicating no serial correlation. For both the 1915–71 and 1915–44 calibrations, the Durbin–Watson statistic shows no serial correlation present (Table 3). The calculated Durbin–Watson d statistic for the full-term model (1915–71) is 1.935. This exceeds the associated d_U value of ~ 1.77 for $n = 57$ (number of observations) and $k = 6$ (number of independent variables), and thus falls into the non-rejection region for the Durbin–Watson d test. In this case, failure to reject the null hypothesis (NS) indicates that the residuals are randomly occurring, which suggests that no autocorrelation remains in the regression model. This validates the use of multiple lagged variables from the non-prewhitened tree-ring records.

Table 2 Calibration for reconstruction of Ashley Creek mean annual discharge with 57-year calibration

Site	Lag	b[a]	SE (b)[b]	t-Statistic
C	0	1.334	0.417	3.199***
C	-1	-0.493	0.225	-2.193*
C	$+1$	-1.001	0.405	-2.470**
D	0	1.357	0.425	3.192***
D	$+1$	1.435	0.425	3.376***
D	$+2$	-0.730	0.222	-3.281***
Constant (b)		0.840	0.362	2.316**

*$p < 0.05$; **$p < 0.025$; ***$p < 0.01$.
[a]Estimated regression coefficients.
[b]Standard error of b.

The reduction-of-error statistic (RE) compares each of the estimated discharges with the actual discharge for the period of overlap (Fritts, 1976). Values for this statistic range from $+1.0$ to $-\infty$, with values > 0 indicating statistical significance for contributing unique palaeoclimatic information (Gordon and LeDuc, 1981; Cleaveland and Stahle, 1989); the values obtained here (Table 3) compare favourably with published results from similar studies (e.g., Cleaveland and Duvick, 1992; Meko and Graybill, 1995; Cleaveland, 2000).

Since the reconstructed palaeostreamflow was used to evaluate extreme hydrologic conditions (i.e., floods and droughts), the ability of the regression equation to predict extreme values was examined. For the purposes of this exercise, wet years and dry years were defined for both the actual and estimated records as years when the mean annual discharge lies outside the 0.10 and 0.90 quantiles, shown as horizontal lines on Figure 3. The significance of the relationship between estimated and actual wet and dry years was tested using a hypergeometric distribution (Haan, 1977; Burt and Barber, 1996), which gives the probability P_h that at least m successes are obtained in n trials from a finite population size N containing k successes (Dracup and Kahya, 1994). In the application to wet years, $N = 57$ is the number of years in the actual series, $k = 8$ is the number of wet years in the actual series, $n = 7$ is the number of wet years in the predicted series and $m = 5$ is the number of cases in the actual and estimated series that wet years coincide. The corresponding probability of obtaining $m \geq 5$ by chance according to the hypergeometric distribution is $P_h = 0.0007$. The same test applied to the dry years yields a probability of $P_h = 0.0008$ that the observed relationship between actual and estimated discharges has occurred by chance. While the probabilistic analysis of wet and dry runs is limited (e.g., Loaiciga and Leipnik, 1996), these results do reflect the general ability of the reconstruction to classify unusually wet and dry years.

Results and discussion

As previously discussed, environmental factors precluded use of Record A for model derivation. Furthermore, the backward-elimination regression process removed all the predictors associated with Record B from the final regression model, leaving three terms each from Records C and D. Records C and D began in AD 1636 and AD 1424, respectively. Therefore application of eq. (1) to the appropriate portion of the data set yields the estimated mean annual discharge for Ashley Creek for AD 1637 to AD 1970 (Figure 4).

Analysis of palaeodischarge

Several previous studies have found persistent non-random clustering of extreme discharge events in reconstructed series (e.g., Cleaveland, 2000; Cleaveland and Stahle, 1989). The mean annual discharge for Ashley Creek has been tested for non-randomness of intervals between extremes with the Lilliefors' test (Conover, 1999). The distribution of flows less than the 25th percentile and greater than the 75th percentile proved to be significantly non-random ($p < 0.05$) for both the actual and reconstructed discharges for 1915–70, as well as for

Table 3 Verification statistics for tree-ring reconstruction of mean annual discharge for Ashley Creek, Uinta Mountains, Utah

Period	Adjusted[a] R^2	Pearson correlation	R.E.[b] statistic	Durbin–Watson[c] statistic
1915–1971	0.713	0.82**	–	1.935 NS
1915–1944	0.701	0.85**	+0.65	1.870 NS
1945–1971	0.635	0.80**	+0.63	2.684*

NS, not significant; *$p < 0.05$; **$p < 0.01$.
[a]Adjusted for loss of degrees of freedom (Draper and Smith, 1998).
[b]Any positive result indicates contribution of unique information (Fritts *et al.*, 1990).
[c]Failure to reject the null hypothesis (NS) indicates that the residuals are randomly occurring, indicating a valid regression model with no remaining autocorrelation.

the full reconstructed record of 1637–1970. For the full reconstructed record the occurrences of flows less than the 10th percentile and greater than the 90th percentile were also tested to evaluate clustering of truly extreme discharges (persistent drought or flood conditions) and were also found to be significantly non-random ($p < 0.01$).

The reconstructed discharges for 1637–1970 were ranked to identify the occurrences of the 10th, 50th and 90th percentiles of discharge (Table 3). From the smoothed series (Figure 4), the two most extreme periods of discharge in the reconstruction are the periods of persistent above-median discharge at 1692 to 1740 and 1898 to 1945. The smoothed series is above median for the entire period of each of these excursions, and extreme discharges for individual years are also evident. The period 1692 to 1740 included more years above the 90th percentile discharge (12) than below the median discharge (10). For the period 1898 to 1945, only four individual years were below median discharge, as compared with ten years above the 90th percentile discharge. This period includes the only two times during the entire reconstructed period (1908–10 and 1929–31) with three consecutive years above the 90th percentile discharge.

The 1637–1970 reconstruction for Ashley Creek (Figure 3) shows non-randomness in the distribution of periods of above- and below-mean discharge. The series is an average of 10.3% below the long-term mean from its inception in 1636 until 1691. This is immediately followed by nearly 50 years of above-median discharge from 1692 to 1740, averaging 14.7% above the long-term mean. From 1741 until 1897, fewer persistent departures from the median occur, although this period averaged 4.6% below mean and did include one interval from 1795 until 1837 of nearly continuous below-median discharge. Finally, above-median conditions prevailed from 1898 until 1945, with mean annual discharges averaging 14.9% above mean.

For each century of reconstructed discharge, the mean and variance has been compared with the preceding century with the *t*-test (Table 4). There is no significant difference between the variances, but significant differences between each of the centuries. The seventeenth century had a significantly lower mean than the eighteenth century ($p < 0.05$); the eighteenth century had a significantly higher mean than the nineteenth century ($p < 0.10$); and the nineteenth century had a significantly lower mean than the twentieth century ($p < 0.025$). Comparatively, the means and standard deviations for the identified periods of predominantly above- and below-median discharge have been computed and compared against each other with the *t*-test (Table 4). As with the values delineated by century, the periods of persistent departure from mean show no significant difference between the variances. For each period, however, the mean is strongly significantly different from the following period ($p \ll 0.01$).

Implications for palaeohydrology of the southern Uinta Mountains

To consider the implications of the dendrohydrologic record for Ashley Creek for the rest of the Uinta Mountains, the

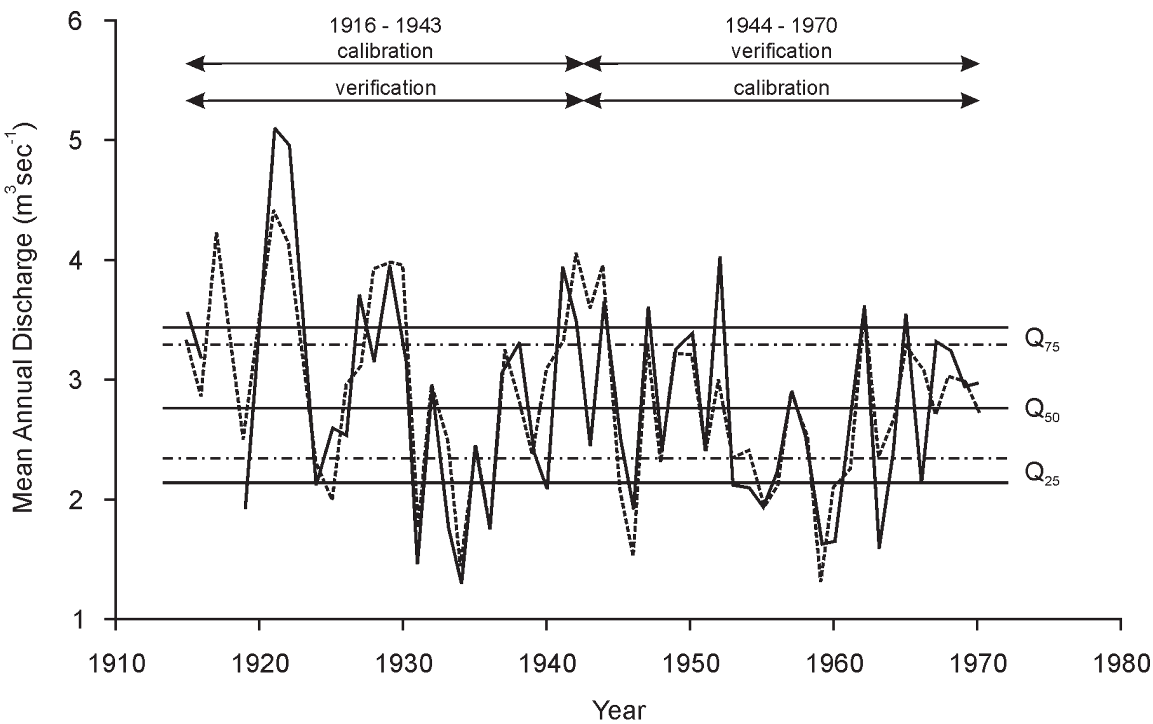

Figure 3 Comparison of gauged (solid line) and reconstructed (dashed line) mean annual discharge on Ashley Creek for period of overlap, 1916–70. The multiple periods of calibration and verification from Table 3 are shown at top of graph. The horizontal lines represent the 75th, 50th and 25th percentiles of discharge for the gauged (solid horizontal line) and reconstructed (dashed horizontal line) mean annual discharge series. The 50th percentile discharge for both the gauged and the reconstructed discharges are the same

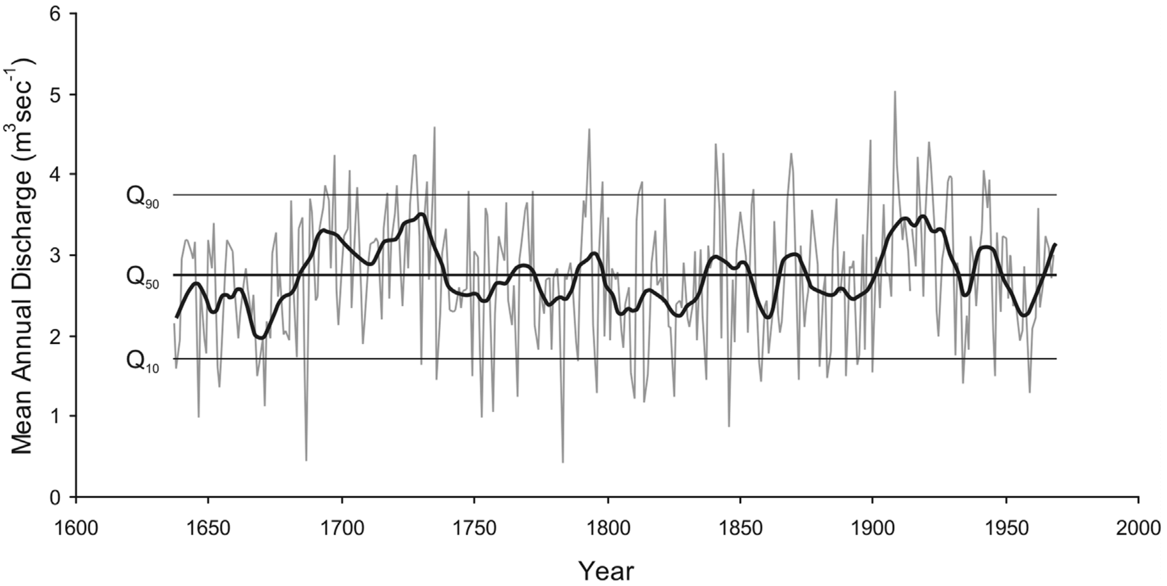

Figure 4 Reconstructed mean annual discharge for Ashley Creek near Vernal UT, for AD 1637–1970 (m^3/s). The horizontal lines represent the 10th, 50th and 90th percentiles for discharge during the entire period of reconstruction. The heavy black line overlain on the reconstruction is a Lowess filter set to include 5% of the data points

instrumented record of mean annual discharge for Ashley Creek has been compared with the mean annual discharges for the other nine gauged streams that drain the Uinta Mountains. As was seen with the initial comparison of Ashley Creek and Whiterocks River (Figure 2), the mean annual discharge for Ashley Creek explains the majority of the variance seen in the records for the streams on the south slope, with R^2 values ranging from 0.81 to 0.91. The correlation between Ashley Creek discharge and the discharges of the north-flank streams varies inversely with proximity to Ashley Creek, with R^2 highest at 0.69 for Henrys Fork and decreasing to 0.48 for Bear River. The relatively high correlation between discharges on Ashley Creek and the rest of the south-slope drainages reflects the fact that the entire southern flank of the Uinta Mountains receives precipitation from a unified source – 'monsoonal' storms from the south during the summer and frontal storms from the Pacific Northwest during the winter. This indicates that the reconstructed streamflow record for Ashley Creek is a significant indicator of streamflow conditions across the south slope of the Uinta Mountains.

Regional perspective of discharge reconstruction

The 'Little Ice Age' (LIA) represents a global readvance of alpine glaciers during the sixteenth through mid-nineteenth centuries (Jones and Bradley, 1992). Historical information from Europe records increased glacial extents, decreased crop production and relocation of populations to warming locales commencing by the mid-fourteenth century and continuing through the late-eighteenth and early nineteenth centuries (Grove, 1988). Throughout the glaciated mountain ranges of the western USA, moraines deposited during the 'Little Ice Age' are the most commonly found, and often the most extensive, Holocene glacial deposits (Davis, 1988). Availability of precise dating of LIA deposits in the western USA varies greatly between ranges. The best dates, provided by multiple dating methods, are from the Cascade Range of Washington, although dates are also available from the Colorado Front Range and Teton Range.

In the Cascade Range, the LIA glacial chronology has been dated using numerous geochronologic tools. On Mt Rainier, Sigafoos and Hendricks (1972) used dendrochronology records

Table 4 Descriptive statistics and occurrences of extreme discharge years for Ashley Creek reconstruction

	Mean (m^3/s)	Standard deviation (m^3/s)	*t*-Statistic[a]	No. of extremes	
				> 90th %ile	< 10th %ile
Century					
17th (1636–99)	2.553	0.775	2.04**	3[b]	13[b]
18th (1700–99)	2.812	0.803	1.67*	12	8
19th (1800–99)	2.623	0.790	2.48***	8	14
20th (1900–70)	2.923	0.769	–	17[b]	6[b]
Period					
1637–1691	2.448	0.732	4.78****		
1692–1740	3.132	0.704	4.46****		
1741–1897	2.603	0.784	4.04****		
1989–1945	3.137	0.806	–		

*$p < 0.10$; **$p < 0.05$; ***$p < 0.025$; ****$p < 0.01$.
[a]Compares mean of given century with following century.
[b]Normed to extremes per 100 years.

to identify the cessation of at least eight glacial advances between AD 1525 and 1910; Burbank's (1981) lichenometry study identified seven periods of glacial recession between AD 1768 and 1924. In the Dome Peak area, Miller (1969) used dendrochronologic data to identify two moraines dating to about AD 1600 and 1850. Fuller *et al.* (1983) also used dendrochronology to identify numerous LIA advances on Mt Baker from the sixteenth through twentieth centuries, and Heikkinen (1984) dated five moraines at Coleman Glacier on Mt Baker to between AD 1740 and 1908. In the Colorado Front Range, Benedict (1973) lichenometrically dated a series of moraines in Arapaho cirque to between 350 and 150 years ago. Davis *et al.* (1979) corroborated these dates based on organic content from sediment cores at Arapahoe cirque, although this interpretation remains tentative because they are based on interpolation of only two radiocarbon dates. In the Teton Range, Fryxell (1935) and Reed (1964) used photographic data to recognize minimal retreat of Teton Glacier between the 1890s and 1935, followed by accelerated retreat following 1935.

While availability of precise dating is more limited in other ranges in the western USA, the evidence for LIA glacial activity is incontrovertible. Relative weathering characteristics have been used to define the 'Gannett Peak' advance as correlative to the Little Ice Age for moraines in the Wind River Range (Currey, 1974; Miller and Birkeland, 1974), which have been correlated with similar deposits in the Yellowstone National Park region (Richmond, 1986). Analyses of ice cores from Fremont Glacier in the Wind River Range suggest an abrupt termination of cool, wet conditions at about AD 1845 (Naftz *et al.*, 1994; Schuster *et al.*, 2000). Using relative age dating techniques in the Stough Creek basin in the Wind River Range, Dahms and Birkeland (2000) identified moraines correlative to the 'Gannett Peak'. In the Sierra Nevadas, the Little Ice Age is represented by moraines of the 'Matthes' advance, which were deposited sometime after $\sim$650 years BP based on tephrochronology (Wood, 1977; Clark and Gillespie, 1997). Analyses of temporal variations in vegetation patterns have indicated LIA glacial activity in Rocky Mountain National Park (Hessl and Baker, 1997). Finally, non-alpine settings in the western USA similarly indicate cool periods from the 1750s to 1770s and 1830s to 1840s (Fritts and Shao, 1992).

The reconstructed discharge for Ashley Creek shows an extended period of below-median mean annual discharge occurring from 1741 until 1897, including the longest period of continuous below mean annual discharge occurring from 1802 to 1839. This period of persistent low discharge coincides with the peak of the LIA identified at *c.* AD 1725 to 1850 in the mountain ranges closest to the Uinta Mountains (Naftz *et al.*, 1994; Hessl and Baker, 1997; Schuster *et al.*, 2000). Numerous years of below-median discharge – drought conditions – therefore would seem contradictory to the regional record of glacial readvances during this time period. However, the western USA is justifiably renowned for spatial and temporal heterogeneities in precipitation and discharge (Bartlein, 1982; Lins, 1985a,b; Piechota *et al.*, 1997; Rajagopalan and Lall, 1998), and the data presented here indicate that the Uinta Mountains experienced climate conditions different from those of surrounding mountain ranges during the 'Little Ice Age'.

This interpretation is corroborated by an independent study of 'Little Ice Age' climate conditions in the Uinta Mountains. Munroe (2002) analysed *Rhizocarpon geographicum* (L.) lichen diameters at eight sites near Deadhorse Lake on the north flank of the Uinta Mountains and suggested that moraine and rock glacier surfaces in the Deadhorse Lake area have been stable since 1300–1650 ^{14}C yr BP. These data have been interpreted as indicative that the last period of cirque re-occupation in the Uintas predated the LIA, when rock glaciers and other periglacial features were active. The reconstructed streamflow for Ashley Creek, and by extension the southern Uinta Mountains, therefore agrees with Munroe's interpretation that climatic conditions in the Uinta Mountains were sufficiently warm and/or dry to prevent glacier growth.

Conclusions

Mean annual discharge for Ashley Creek in the southern Uinta Mountains was reconstructed using a backward-elimination multiple regression formula. The tree-ring data used in the reconstruction accounted for 71% of the variance observed in the gauged data for the period 1915–71. The period of overlap between the tree-ring record and the gauged data was divided into two segments for calibration and verification of the regression equation. The fidelity of the regression in reproducing both the mean of the overlapping series and the occurrences of extreme events was verified with the sign test, the reduction-of-error statistic, the Durbin–Watson statistic and the hypergeometric distribution. Comparison of the modern gauge data from Ashley Creek with the gauge data for the other streams draining the south flank of the Uinta Mountains suggests that conclusions drawn from the Ashley Creek streamflow reconstruction are germane to the entire southern Uintas. Occurrences of flows less than the 10th percentile and greater than the 90th percentile were clustered in the series. The periods 1637–91 and 1741–1897 experienced reduced numbers of extremely large flows and increased numbers of extremely small flows. In contrast, the periods 1692–1740 and 1898–1945 contained overabundances of extremely large flows and relatively few extremely small flows. The reconstruction of streamflow for the period 1637–1970 shows evidence for significant, persistent departures from the long-term mean of the series that correspond to the non-random occurrences of extremely large and small discharges. From 1637 until 1691, mean annual discharge was approximately 10% lower than the long-term mean. From 1692 until 1740, and again from 1898 until 1945, mean annual discharge was approximately 15% greater than the long-term mean. From 1741 until 1897, a period that coincides with the 'Little Ice Age' glacial readvance in many mountain ranges in the western USA, mean annual discharge for Ashley Creek was approximately 4.5% below the long-term mean, including increased occurrences of discharges below the 10th percentile and decreased occurrences of discharges above the 90th percentile. These data suggest persistent drought or near-drought conditions and corroborate independent evidence for little or no glacial activity in the Uinta Mountains during the 'Little Ice Age'.

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References

Atwood, W.W. 1909: *Glaciation of the Uinta and Wasatch mountains.* U.S. Geological Survey Professional Paper 61. Reston VA: US Geological Survey.

Bartlein, P.J. 1982: Streamflow anomaly patterns in the U.S.A. and southern Canada, 1951–1970. *Journal of Hydrology* 57, 49–63.

Benedict, J.B. 1973: Chronology of cirque glaciation, Colorado Front Range. *Quaternary Research* 3, 584–99.

Bradley, W.H. 1936: *Geomorphology of the north flank of the Uinta Mountains.* U.S. Geological Survey Professional Paper 185-I. Reston VA: US Geological survey, 163–99.

Bryson, R.A. and **Hare, F.K.** 1974: *World survey of climatology: climates of North America*. Amsterdam: Elsevier Scientific Publishing Company.

Burbank, D.W. 1981: A chronology of late Holocene glacier fluctuations on Mt. Rainier, Washington. *Arctic and Alpine Research* 13, 369–86.

Burt, J.E. and **Barber, G.M.** 1996: *Elementary statistics for geographers.* New York: The Guilford Press.

Carson, E.C. 2002: Response of bankfull flood magnitudes to Holocene climatic variation, Uinta Mountains, northeastern Utah. *Geological Society of America, Abstracts with Programs* 34, 203.

Clark, D.H. and **Gillespie, A.R.** 1997: Timing and significance of late-glacial and Holocene cirque glaciation in the Sierra Nevada, California. *Quaternary International* 38/39, 21–38.

Cleaveland, M.K. 2000: A 963-year reconstruction of summer (JJA) streamflow in the White River, Arkansas, USA, from tree-rings. *The Holocene* 10, 33–41.

Cleaveland, M.K. and **Duvick, D.N.** 1992: Iowa climate reconstructions from tree rings, 1640–1982. *Water Resources Research* 28, 2607–15.

Cleaveland, M.K. and **Stahle, D.W.** 1989: Tree ring analysis of surplus and defecit runoff in the White River, Arkansas. *Water Resources Research* 25, 1391–401.

Conover, W.J. 1999: *Practical nonparametric statistics.* New York: John Wiley & Sons.

Cook, E.R. 1987: The decomposition of tree-ring series for environmental studies. *Tree Ring Bulletin* 47, 37–59.

Currey, D.R. 1974: Probable pre-Neoglacial age of the type Temple Lake moraine, Wyoming. *Arctic and Alpine Research* 6, 293–300.

Dahms, D.E. and **Birkeland, P.W.** 2000: Glacial stratigraphy of Stough Creek Basin and a latest Quaternary glacial and periglacial stratigraphy for the Wind River Range, Wyoming. *Geological Society of America, Abstracts with Programs* 32, 60.

Davis, P.T. 1988: Holocene glacier fluctuations in the American Cordillera. *Quaternary Science Reviews* 7, 129–57.

Davis, P.T., Upson, S. and **Waterman, S.E.** 1979: Lacustrine sediment variation as an indicator of late Holocene climatic fluctuation, Arapahoe cirque, Colorado Front Range. *Geological Society of America, Abstract with Programs* 11, 410.

Douglass, A.E. 1920: Evidence of climatic effects in the annual rings of tree. *Ecology* 1, 24–32.

Dracup, J.A. and **Kahya, E.** 1994: The relationships between U.S. streamflow and La Niña events. *Water Resources Research* 30, 2133–41.

Draper, N.R. and **Smith, H.** 1998: *Applied regression analysis.* New York: John Wiley & Sons.

Fritts, H.C. 1976: *Tree rings and climate.* London: Academic Press.

Fritts, H.C. and **Shao, X.M.** 1992: Mapping climate using tree-rings from western North America. In Bradley, R.S. and Jones, P.D., editors, *Climate since A.D. 1500*. New York: Routledge, 269–95.

Fritts, H.C., Blasing, T.J., Hayden, B.P. and **Kutzbach, J.E.** 1971: Multivariate techniques for specifying tree-growth and climate relationships and for constructing anomalies in paleoclimate. *Journal of Applied Meteorology* 10, 845–64.

Fritts, H.C., Guiot, J. and **Gordon, G.A.** 1990: Verification. In Cook, E.R. and Kairiukstis, L.A., editors, *Methods of dendrochronology.* Dordrecht: Kluwer, 178–85.

Fryxell, F. 1935: Glaciers of the Teton National Park of Wyoming. *Journal of Geology* 43, 381–97.

Fuller, S.R., Easterbrook, D.J. and **Burke, R.M.** 1983: Holocene glacial activity in five valleys on the flanks of Mt. Baker. *Geological Society of America, Abstracts with Programs* 15, 430–31.

Gordon, G.A. and **LeDuc, S.K.** 1981: Verification statistics for regression models. *Preprints of the seventh conference on probability and statistics in atmospheric sciences.* Monterey CA: American Meteorological Society, 129–33.

Grove, J.M. 1988: *The Little Ice Age.* New York, London: Methuen.

Haan, C.T. 1977: *Statistical methods in hydrology.* Ames IA: Iowa State University Press.

Hansen, W.R. 1969: *The geologic story of the Uinta Mountains.* U.S. Geological Survey Bulletin 1291. Reston VA: U.S. Geological Survey.

Heikkinen, O. 1984: Dendrochronological evidence of variations of Coleman Glacier, Mt. Baker, Washington, U.S.A. *Arctic and Alpine Research* 16, 53–64.

Hereford, R., Jacoby, G.C. and **McCord, V.A.S.** 1996: *Late Holocene alluvial geomorphology of the Virgin River in the Zion National Park area, Southwest Utah*. Geological Society of America Special Paper 310. Boulder CO: Geological Society of America.

Hessl, A.E. and **Baker, W.L.** 1997: Spruce and fir regeneration and climate in the forest-tundra ecotone of Rocky Mountain National Park, Colorado, USA. *Arctic and Alpine Research* 30, 272–84.

Jones, P.D. and **Bradley, R.S.** 1992: Climatic variations over the last 500 years. In Bradley, R.S. and Jones, P.D., editors, *Climate since AD 1500*. New York: Routledge.

Lins, H.F. 1985a: Interannual streamflow variability in the United States based on principal component (eige-vector) analysis to geophysical data. *Water Resources Research* 21, 691–701.

—— 1985b: Streamflow variability in the United States: 1931–1978. *Journal of Climatology and Applied Meteorology* 24, 463–71.

Loaiciga, H.A. and **Leipnik, R.B.** 1996: Stochastic renewal model of low-flow streamflow sequences. *Stochastic Hydrology and Hydraulics* 10, 65–85.

Loaiciga, H.A. and **Marino, M.A.** 1991: Recurrence interval of geophysical event. *Journal of Water Resources Planning and Management* 117, 367–82.

Loaiciga, H.A., Haston, L. and **Michaelsen, J.** 1993: Dendrohydrology and long-term hydrologic phenomena. *Reviews of Geophysics* 31, 151–71.

Meko, D. and **Graybill, D.A.** 1995: Tree-ring reconstruction of upper Gila River discharge. *Water Resources Bulletin* 31, 605–16.

Miller, C.D. 1969: Chronology of Neoglacial moraines in the Dome Peak area, North Cascade Range, Washington. *Arctic and Alpine Research* 1, 49–66.

Miller, C.D. and **Birkeland, P.W.** 1974: Probable pre-Neoglacial age of the type Temple Lake moraine, Wyoming: discussion and additional relative-age data. *Arctic and Alpine Research* 6, 301–306.

Mitchell, V.R. 1976: The regionalization of climate in the western United States. *Journal of Applied Meteorology* 15, 920–27.

Munroe, J.S. 2001: Late Quaternary history of the Uinta Mountains, northeastern Utah. Unpublished PhD dissertation, University of Wisconsin-Madison.

—— 2002: Timing of post-glacial cirque reoccupation in the northern Uinta Mountains, northeastern Utah, U.S.A. *Arctic, Antarctic, and Alpine Research* 34, 38–48.

—— 2003: Holocene timberline and paleoclimate of the northern Uinta Mountains, northeastern Utah, U.S.A. *The Holocene* 13, 175–85.

Munroe, J.S. and **Laidlaw, J.** 2002: A 5000-year record of fire and sedimentary response for the Uinta Mountains, northeastern Utah. *Geological Society of America, Abstracts with Programs* 34, 469.

Naftz, D.L., Schuster, P.F. and **Reddy, M.M.** 1994: Assessment of spatial variability of major-ion concentrations and d18O values in surface snow, Upper Fremont Glacier, Wyoming, USA. *Nordic Hydrology* 25, 371–88.

Piechota, T.C., Dracup, J.A. and **Fovell, R.G.** 1997: Western US streamflow and atmospheric circulation patterns during El Niño-Southern Oscillation. *Journal of Hydrology* 201, 249–71.

Rajagopalan, B. and **Lall, U.** 1998: Interannual veriability in western US streamflow. *Journal of Hydrology* 210, 51–67.

Reed, J.C. 1964: *Recent retreat of Teton Glacier, Grand Teton National Park, Wyoming*. U.S. Geological Survey Professional Paper 501C. Reston VA: U.S. Geological Survey.

Richmond, G.M. 1986: Stratigraphy and chronology of glaciations in Yellowstone National Park. *Quaternary Science Reviews* 5, 83–98.

Schuster, P.F., White, D.E., Naftz, D.L. and **DeWayne, L.C.** 2000: Chronological refinement of an ice core record at Upper Fremont Glacier in south central North America. *Journal of Geophysical Research D: Atmospheres* 105, 4657–66.

Sears, J.W., Graff, P.J. and **Holden, G.S.** 1982: Tectonic evolution of lower Proterozoic rocks, Uinta Mountains, Utah and Colorado. *Geological Society of America Bulletin* 93, 990–97.

Sigafoos, R.S. and **Hendricks, E.L.** 1972: *Recent activity of glaciers on Mt. Rainier, Washington.* U.S. Geological Survey Professional Paper 387B. Reston VA: U.S Geological Survey.

Smith, L.P. and **Stockton, C.W.** 1981: Reconstructed streamflow for the Salt and Verde Rivers from tree-ring data. *Water Resources Bulletin* 17, 939–47.

Stockton, C.W. and **Jacoby, G.C.** 1976: *Long-term surface-water supply and streamflow trends in the Upper Colorado River Basin*. Lake Powell Research Project Bulletin 18. Los Angeles CA: University of California Institute of Geophysics and Planetary Physics.

United States Geological Survey 1973: *Surface water supply of the United States, part 9, Colorado River Basin.* Water Supply Paper 2125. Washington DC: Government Printing Office.

Wood, S.H. 1977: Distribution, correlation, and radiocarbon dating of late Holocene tephra, Mono and Inyo Craters, eastern California. *Geological Society of America Bulletin* 88, 89–95.