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Temporal and Seasonal Trends in Streamflow in the Uinta Mountains, Northeastern Utah, and Relation to Climatic Fluctuations

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Abstract

Over the past half century there has been a trend in numerous regions of the western United States toward a declining portion of the total annual streamflow occurring during the snowmelt season (April through July). Changes in the seasonality of discharge primarily reflect a shift in the seasonal distribution of precipitation. Years with an unusually large fraction of annual streamflow occurring during the spring snowmelt coincide with winters with unusually high precipitation. Years with an unusually small fraction of annual streamflow occurring during the spring snowmelt coincide with unusually low precipitation during the winter and unusually warm temperatures during the spring. The magnitude of the peak annual flood is sensitive to amount of winter precipitation and variations in spring and early summer temperatures. Large peak annual floods occur in years with high precipitation and low temperatures in the late winter and spring, which preserve the maximum snowpack. Small peak annual floods occur in years with low precipitation throughout the winter and high temperatures in the spring. During the period of gage record, peak annual flood magnitudes exhibit temporal variability. Extreme events in the peak annual flood record, particularly years of large snowmelt floods, have increased in frequency since 1960. Large floods during this time period occur in years with atypically cool temperatures in April and May, which would likely preserve the winter snowpack through the spring.

Introduction

Variations in amount of runoff from streams in the western United States, and the timing of that runoff throughout the water year, play a critical role in domestic policy. Water resource demands on runoff from the Uinta Mountains have steadily increased through the 20th century as the result of increasing local irrigation, regional demand along the Wasatch Front, and basinwide demand in the upper Colorado River basin.

The distribution of total annual discharge throughout the water year is a significant indicator of basin response to climatic variation, particularly in streams whose annual distribution of runoff is strongly controlled by spring snowmelt (Aguado et al., 1992; Pupacko, 1993; Jain and Lall, 2000). Even modest changes in the seasonality of precipitation or shifts in temperature can cause recognizable changes in the timing of annual discharge (e.g., Gleick, 1989). Statistical analyses of historic stream gage data are often used to assess flood hazards and develop water-use public policy in the United States (Thomas, 1985; Interagency Advisory Committee on Water Data, 1986; Cayan and Webb, 1992). The analyses typically employ the annual flood series, which is the instrumented record of the largest discharges that occur each water year at a gage station, to predict the magnitude of discharges with various recurrence intervals. Discharges associated with specific recurrence intervals—such as the 100-year recurrence flood—are then frequently used for the management and development of floodplain areas (Federal Emergency Management Agency, 1986).

This paper compares the instrumented stream gage records from the Uinta Mountains of northeastern Utah with records of regional temperature and precipitation to identify the factors that control the distribution of total annual runoff that occurs during the spring snowmelt season and factors that control the magnitude of the peak annual flood. The behavior of floods in this subalpine setting is of particular interest because of the area's geographic setting and resultant hydroclimatology. The study site lies near the southern boundary of North Pacific winter storm tracks and the northern boundary of extratropical cyclones migrating north from Baja California (Mitchell, 1976). The fraction of total annual discharge occurring during the spring snowmelt season and the magnitude of the annual maximum flood, therefore, reflect a combination of the amount of winter snowpack accumulation, the rate of snowmelt in the spring, and precipitation during the early spring. Thus, climatic fluctuations that lead to shifts in the timing of annual precipitation and melt period temperatures can readily impact the long-term means and variances of the local flood records. This information is particularly critical in regions such as the semiarid western United States, where the spring runoff is critical to the maintenance of reservoirs and other water supplies.

Setting

The Uinta Mountains are an east-west–trending mountain range that extends approximately 200 km eastward from near Heber City, Utah, into northwestern Colorado (Fig. 1). The crest of the Uinta Mountains contains the highest peaks in the state of Utah. Hansen (1986) divided the range into the glaciated western physiographic region, and the nonglaciated eastern region. The boundary between these two areas is located approximately 40 km west of the Utah-Colorado border, at about the same longitude as Vernal, Utah.

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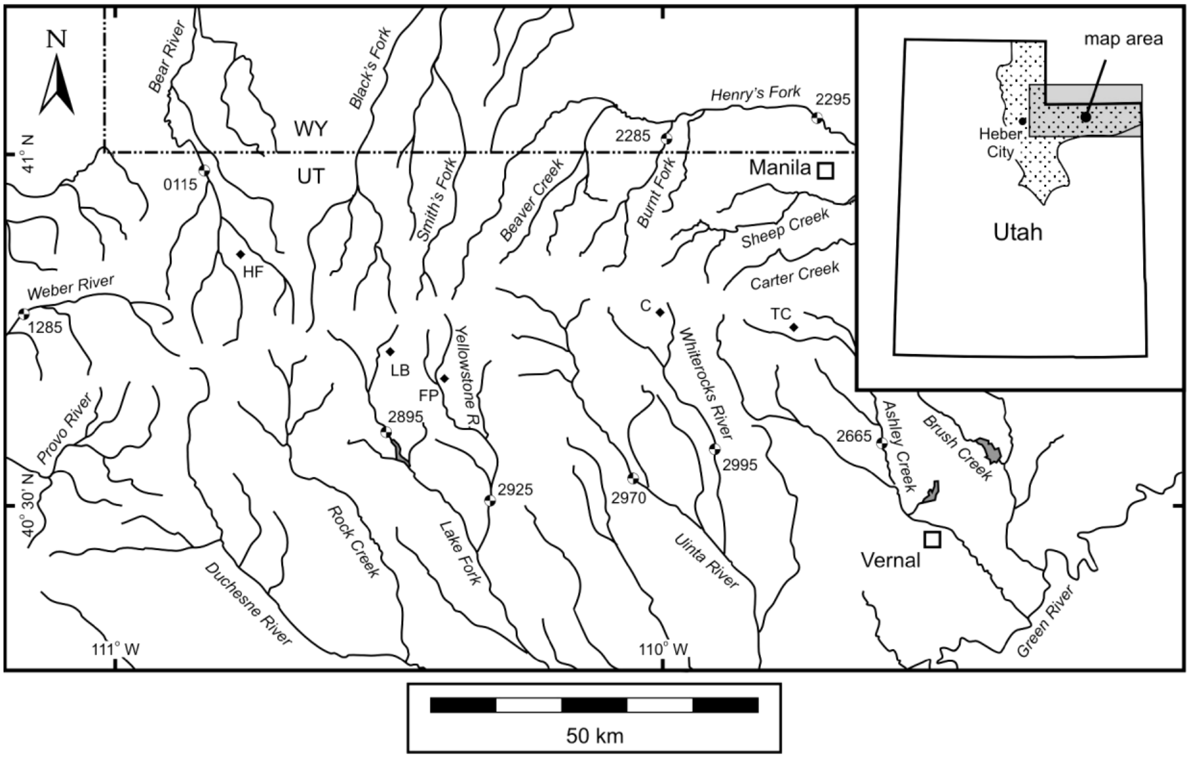


FIGURE 1. Location map of Uinta Mountains in northeastern Utah, showing the long-term U.S. Geological Survey (USGS) stream gage stations used in this study (gage locations denoted by the ⊕ symbol); locations and periods of record for gages are detailed in Table 1. The four-digit numbers next to each gage location are the middle four digits of the USGS gage numbers from Table 1. Black diamonds indicate the locations of SNOTEL (Snowpack Telemetry) stations in the upper drainage basins: C = Chepeta, FP = Five Points Lake, HF = Hayden Fork, LB = Lakefork Basin, and TC = Trout Creek. The stippled region in the area map of Utah delineates National Climatic Data Center climate division 5.

Owing to its history of multiple Pleistocene glaciations, the topography of the Uinta Mountains is dominated by deep, glacially scoured valleys separated by broad, unglaciated interfluves (Atwood, 1909; Bradley, 1936; Hansen, 1969; Munroe, 2001). The westernmost streams in the Uinta Mountains—Bear River, Weber River, and Provo River—drain into the Great Salt Lake basin; all other streams on the north slope flow into the Green River. All streams on the south slope flow either into the Duchesne River, a tributary of the Green River, or directly into the Green River (Fig. 1).

The seasonal distribution of total annual discharge and the magnitude of the peak annual floods in the Uinta Mountains are dominated by the influence of the accumulation and melting of the winter snowpack (Carson, 2003). Precipitation in northern Utah has a strong annual cycle, with a peak in the winter months as frontal storm systems from the North Pacific Ocean provide much of the annual precipitation. In the high elevation basins of the subalpine Uinta Mountains, the annual hydrograph shows a similar seasonality, with the majority of the water year's discharge occurring during the months of April through July as snowmelt runoff (Fig. 2). Thus, there are two variables that are easily recognizable in the annual hydrograph for gages in the Uinta Mountains: the proportion of total annual discharge that occurs during the snowmelt season, and the magnitude of the peak annual flood. Broadly speaking, the fraction of annual discharge occurring during the runoff season is related to the amount of annual precipitation that occurs as snow, whereas the peak annual discharge more strongly reflects the timing of snowmelt (that is, whether or not the snowpack melts as a single pulse of runoff).

Data and Methods

HYDROLOGIC DATA

Hydrologic data for this study have been compiled from U.S. Geological Survey stream gage stations within the Uinta Mountains. Each of the major streams draining the range has at least one continuous gage record of 30 years or more, and most streams have longer records. From the available data, the monthly mean discharge and peak annual flood series for nine gages have been selected for analysis (Fig. 1, Table 1); eight of these records are in excess of 50 years of continuous data. The catchments selected are largely undisturbed mountain watersheds within the Ashley and Wasatch-Cache National Forests, with rangeland and recreation uses. Over 180,000 ha (450,000 acres) of the subalpine portion of the Uinta Mountains that span the crest of the range—covering the headwater regions of most catchments in the study area—are within the High Uinta Wilderness Area, a federally designated primitive area. In the lower elevation areas of the Uinta Mountains, historic impacts to watersheds have occurred from logging during construction of railroads and diversion of runoff for irrigation and municipal use.

Under contract to the Union Pacific Railroad Company, Standard Timber Company conducted logging operations in Bear River and Black's Fork watersheds in the late 19th and early 20th centuries (Baker and Hauge, 1913) (Fig. 1). Current logging in the Uinta Mountains is focused in the northeastern portion of National Forest lands. The two primary catchments involved, Sheep and Carter Creeks, have been excluded from this study.

The greatest anthropogenic impact on flood magnitudes in the Uinta Mountains is associated with the construction of

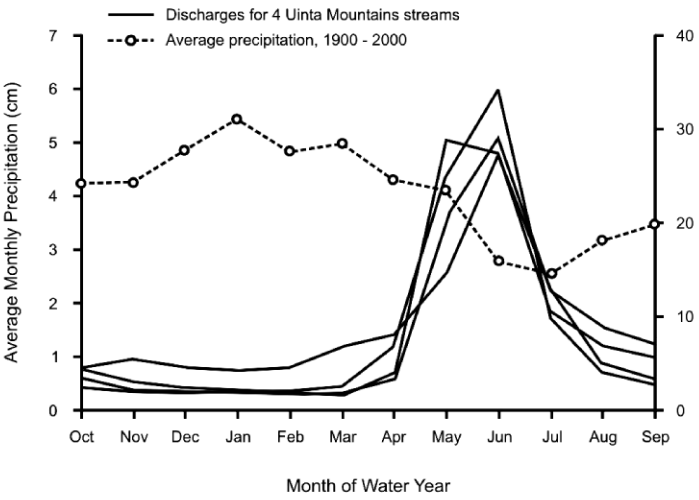


FIGURE 2. Representative monthly distribution of precipitation and stream runoff for the Uinta Mountains. Precipitation data is monthly averages for NCDC Utah climate division 5. Runoff data are monthly averages for Weber River, Henry's Fork, Ashley Creek, and Whiterocks River.

reservoirs for irrigation and municipal use. Significant diversion tunnels draw water from Duchesne River and Rock Creek for use in the Great Basin; control structures have been built for numerous high elevation lakes on Uinta, Lake Fork, and Whiterocks Rivers (Fig. 1); and minor irrigation canals have been built on several streams (Schmidt et al., 2005). The periods of gage records for affected gages have been selected to negate anthropogenic impacts on the magnitude of annual floods. Lake Fork River (gage number 09289500) is located immediately upstream from Moon Lake Reservoir; however, discharge data were not recorded during construction of the dam from 1956 to 1963.

To study the seasonal distribution of discharge of streams in the Uinta Mountains, the discharge that occurred during the spring snowmelt season (April, May, June, July) was examined as a ratio of the water year total discharge; this will be referred to as the 'AMJJ fractional streamflow.' Spring snowmelt season fractional streamflow and water year statistics for the studied gages are shown in Table 2, including the long-term mean, standard deviation, record maximum, and record minimum. These data illustrate the seasonal distribution of discharge, with between 56.5% (on Henrys Fork) and 80.1% (on Bear River) of the total annual discharge occurring as AMJJ fractional streamflow.

To study trends in peak annual discharge, the peak discharge series for the studied gage records were converted from units of cubic feet per second to standard deviation units (Knox, 1999). Normalized peak discharge series were computed by subtracting the long-term mean and dividing by the standard deviation of the annual series. The resultant record for each gage station has a mean of 0.0 and a standard deviation of 1.0, and flood magnitudes are recorded in standard deviation departures from mean.

LOCAL CLIMATE DATA

While local climate information would be preferable for analysis, data particular to the Uinta Mountains are limited in duration. Automated snowpack telemetry (SNOTEL) stations in the Uinta Mountains continuously record a host of climatic parameters, including snow-water equivalent during the winter months, temperature, and precipitation. However, these data are limited to the past 20 to 30 years depending on the station, making them undesirable for comparison to the long-term gage data. These shorter term data sets are useful, however, for illustrating the fundamental importance of snowmelt accumulation and release on annual discharge patterns. Five SNOTEL stations are located in the Uinta Mountains in the headwater regions of drainage basins with long stream gage records: Chepeta, Fiver Points Lake, Hayden Fork, Lakefork Basin, and Trout Creek (Fig. 1). The instrumented records from these sites show that winter snowpack accumulation peaks with a maximum snow-water equivalent typically occurring between April 1 and May 1 of each year (Fig. 3). As such, the snow-water equivalent measured on May 1 provides a significant control on the size of the peak

TABLE 1

Long-term gage station records analyzed for this study.

Gage No. Stream	Location Lat (N)	Long (W)	Elevation (m a.s.l.)	Area (km^2)	Record (yr)
North Flank Streams					
09229500 Henry's Fork	41°00′45″	109°40′20″	2171	1347	65
09228500 Burnt Fork	40°56′47″	110°03′56″	2530	137	35
10011500 Bear River	40°57′57″	110°51′10″	2428	445	58
10128500 Weber River	40°44′14″	111°14′50″	2024	420	95
South Flank Streams					
09266500 Ashley Creek	40°34′39″	109°37′17″	1899	262	88
09299500 Whiterocks River	40°35′37″	109°55′54″	2195	279	86
09297000 Uinta River	40°32′08″	110°03′46″	2107	422	57
09292500 Yellowstone River	40°30′43″	110°20′27″	2265	342	56
09289500 Lake Fork River	40°36′24″	110°31′35″	2494	202	52

TABLE 2

AMJJ* fractional streamflow statistics for Uintas streams.

Stream	Mean	St. Dev.	Max.	Min.
North Flank Streams				
Henry's Fork	56.5	14.3	79.8	19.5
Burnt Fork	72.3	5.1	78.4	60.8
Bear River	80.1	4.3	87.6	66.8
Weber River	76.7	4.4	84.2	60.8
South Flank Streams				
Ashley Creek	70.9	7.1	84.9	53.9
Whiterocks River	65.3	7.9	78.7	44.7
Uinta River	60.3	7.2	74.5	38.1
Yellowstone River	61.3	5.6	70.3	40.0
Lake Fork River	74.3	4.5	85.0	65.6

* AMJJ = April, May, June, July

annual discharge (Fig. 4). The two pairs of SNOTEL stations and gage records shown in Figure 4 are representative of the relationship observations at the other SNOTEL stations. At all five of the SNOTEL sites, the May 1 snow-water equivalent explains between 43% and 51% of the variance in peak annual discharge.

The Uinta Mountains are part of the National Climatic Data Center's (NCDC's) climate division 5. Climate division 5 encompasses mountainous northeastern Utah, primarily the Uinta and Wasatch Mountains (Fig. 1). Monthly data for average temperature and precipitation for the climate division are available online for 1895–2005 (see http://www.ncdc.noaa.gov). Annual and winter averages of precipitation and temperature have been compiled from these data for the period of overlap with the gage records. While this data set does average climate conditions throughout the Wasatch Range and Uinta Mountains, it provides a record of similar length as the historic gage data.

To evaluate the significance of various regional climate parameters on fractional streamflow during the snowmelt months of April through July (referred to as 'AMJJ fractional streamflow'), monthly anomalies of temperature and precipitation were compared to years in which fractional streamflow in the Uinta Mountains was in the upper and lower terciles. The extreme fractional streamflow years were identified based on each of the nine gage records used. Because of the common meteorology of basins in the range, each gage identified similar years in the upper and lower terciles. Data will be shown based on selecting the upper and lower terciles from the longest continuous gage record in the study, Weber River (10128500), which is largely representative of the other gage records in the range. Identical data were compiled

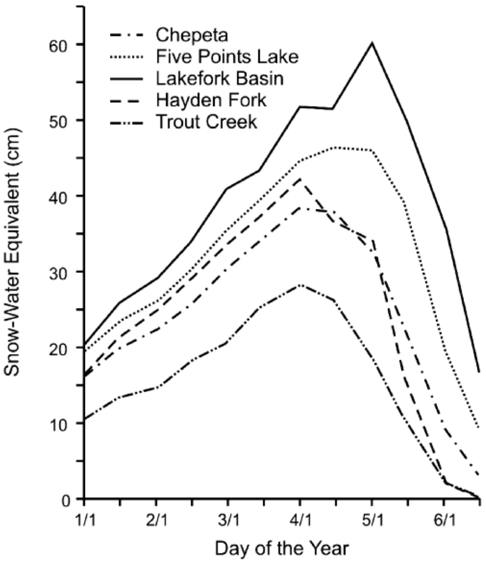


FIGURE 3. Average snow-water equivalent at five Snowpack Telemetry (SNOTEL) sites in headwater of gaged streams in the Uinta Mountains, showing occurrence of peak snow-water equivalent in the month of April.

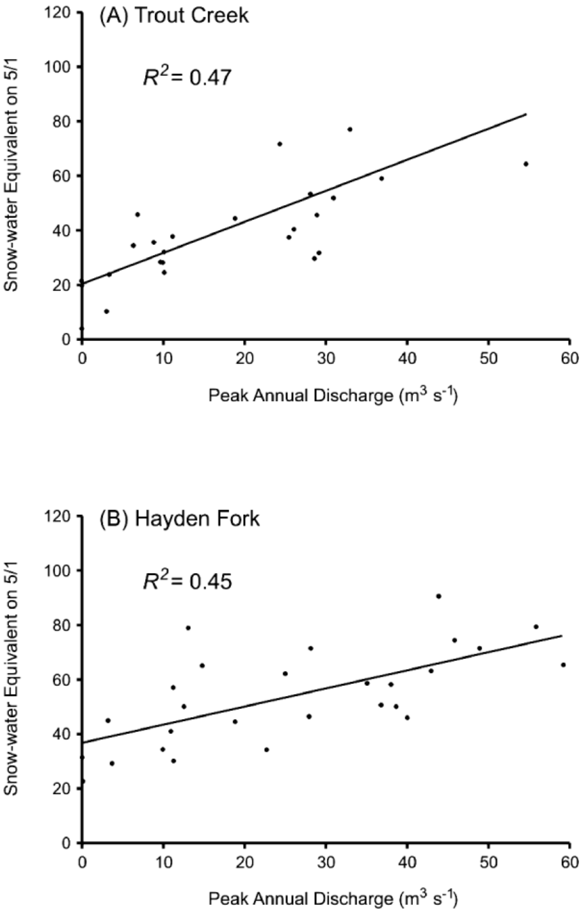


FIGURE 4. Relations between snow-water equivalent on May 1 and peak annual discharge for two representative pairs of SNOTEL stations and stream gages. (A) Trout Creek SNOTEL station and Ashley Creek gage station, and (B) Hayden Fork SNOTEL station and Bear River gage station.

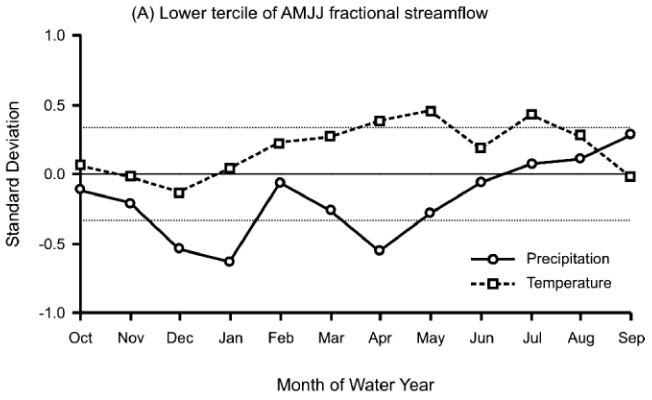
that compared anomalies of temperature and precipitation to peak annual discharge. This provides a means of identifying the climate conditions that favor unusually large and unusually small spring runoff.

Results and Discussion

PRECIPITATION AND TEMPERATURE ANOMALIES ASSOCIATED WITH RUNOFF

Standardized mean month temperature and precipitation anomalies were averaged for years in which the fractional streamflow was ranked in the upper and lower terciles for the period of record for Weber River (gage number 10128500). The period of record for this gage spans 1905–2000, which is the longest of the gages in the study. Because of the common hydrology of the streams in the range, the years identified as ranking in the upper and lower terciles for Weber River represent the upper and lower terciles for the other gage records in over 98% of the gage-years. This indicates that upper and lower tercile fractional streamflow years as identified from the Weber River gage data are representative of the subalpine Uinta Mountains as a whole. The monthly precipitation and temperature anomalies were standardized by subtracting the mean and dividing by the standard deviation for each record. This produces series of precipitation and temperature with means of 0.0 and standard deviations of 1.0. Differences between the standardized precipitation and temperature anomalies are significant at the 95% confidence level if they exceed 0.34, using a two-tailed *t*-test (thus, values greater than +0.34 and less than −0.34 are statistically significant at the 95% confidence level). As shown in Figure 5, low AMJJ fractional streamflow is associated with low precipitation in December and January, low precipitation in April, and to a lesser extent high temperatures in March through May. These conditions tend to reduce the depth of winter snowpack and start the snowmelt runoff process relatively early in the melt season. Thus, the snowpack is anomalously low under these conditions and a portion of it is likely released as early as March, reducing the AMJJ fractional streamflow. High AMJJ fractional streamflow is strongly associated with high precipitation throughout the late winter and spring (particularly January and April), and to a lesser extent low temperature during the late winter and spring. The significantly high precipitation through the late winter and spring favor the accumulation of a deep snowpack and the low temperatures in spring favor the preservation of the winter's snowpack until later in the snowmelt season.

The magnitude of the peak annual flood for each year is controlled by similar processes as the fractional streamflow, although the relative importance of temperature anomalies is more important for flood generation than fractional streamflow distribution. As with fractional streamflow, standardized mean month temperature and precipitation anomalies were averaged for years in which the peak annual flood was ranked in the upper and lower terciles for the period of record for Weber River (gage number 10128500). As with fractional streamflow, the upper and lower tercile peak annual flood years as identified from the Weber River gage data are taken as representative of the entire subalpine Uinta Mountains. Differences between the standardized precipitation and temperature anomalies are significant at the 95% confidence level if they exceed 0.34, using a two-tailed *t*-test. The climate conditions that lead to a low AMJJ fractional streamflow also lead to small peak annual floods. Figure 6 shows that small peak annual floods are associated with low precipitation in December and January, which tends to reduce the depth of winter snowpack for producing the peak runoff flood. This is simply a reflection that amount of winter precipitation (and, thus, depth of snowpack) provides a primary control on the magnitude of the peak annual flood. Large peak annual floods are associated with high precipitation throughout the winter (November through January) and again during April and May. Anomalously low temperatures in April and May are also associated with large peak annual floods. Low temperatures in April and May preserve the snowpack relatively late in the snowmelt season, when it is more likely to be released in a single large pulse. Carson (2005) documented that large peak annual floods in the Uinta Mountains tend to occur late in the melt season, as is suggested by these data.



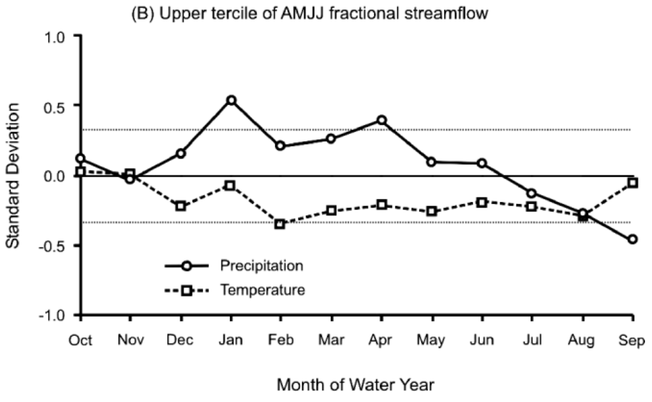


FIGURE 5. Composite precipitation and temperature standard deviation departures from mean in the Uinta Mountains for (A) years of low AMJJ fractional streamflow and (B) years of high AMJJ fractional streamflow. Climate data represents National Climatic Data Center's Utah climate division 5 (mountainous northeastern Utah) for the period 1918–2000.

TRENDS IN THE SEASONAL DISTRIBUTION OF PRECIPITATION

The magnitude of fractional streamflow shows sensitivity to the seasonal distribution of precipitation. To assess temporal trends in the timing of precipitation as a determinant of trends in fractional streamflow, the 20th century record of monthly precipitation for NCDC Utah climate division 5 has been roughly divided into thirds (divisions at 1930 and 1960). While the overall 20th century seasonal distribution of precipitation (Fig. 2) shows that the majority of annual precipitation arrives during the winter months, the data depicted in Figure 7 indicates that precipitation is increasingly arriving during the spring months. Particularly, the April and May precipitation during the period 1961–2000 increased by over 25% as compared to the previous two periods.

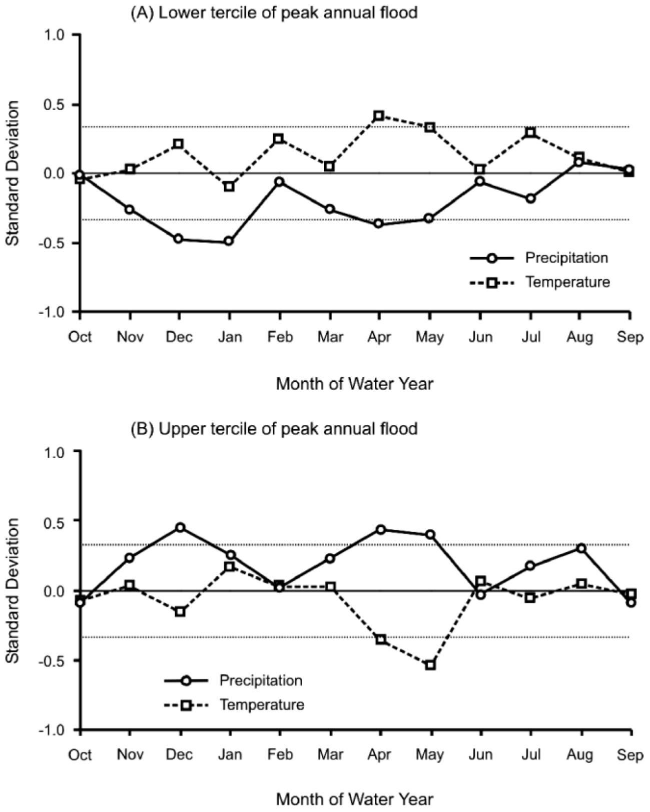


FIGURE 6. Composite precipitation and temperature standard deviation departures from mean in the Uinta Mountains for (A) low flood years and (B) high flood years. Climate data represents NCDC's Utah climate division 5 (mountainous northeastern Utah) for the period 1918–2000.

This shift in the timing of precipitation from predominantly during the winter to an increasing amount during the spring has direct implications on the magnitude of winter snowpack, because a greater amount of annual precipitation is likely to fall as rain and run off immediately rather than being stored through the winter as snowpack.

TRENDS IN UINTA MOUNTAINS PEAK ANNUAL FLOOD RECORD

The individual peak annual flood records have been combined to form a composite annual maximum flood series for the Uinta Mountains (Fig. 8). For the nine studied gage records, the magnitude of each gage's peak annual flood, expressed in standard deviation departures from mean, has been arithmetically averaged to produce a rangewide composite flood series for the period 1918 to 2000. The composite series has been restandardized to return the mean of the series to 0.0 and the standard deviation to 1.0. Despite increasing temperatures that have been measured across much of the western United States over the past several decades, seven of the eight largest floods recorded in the Uinta Mountains composite series have occurred since 1960.

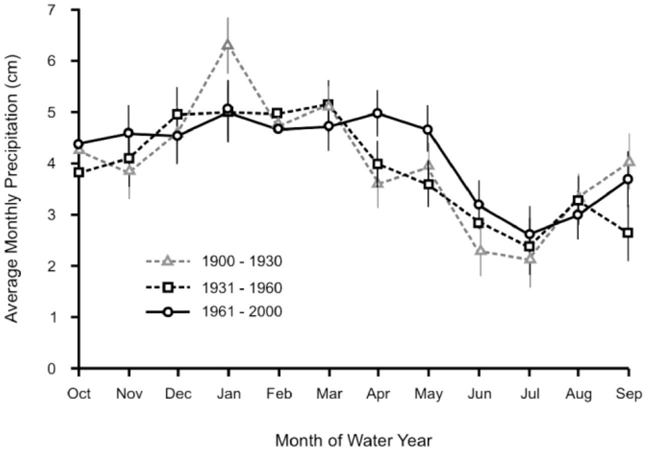


FIGURE 7. Average monthly precipitation for three different periods during the 20th century for NCDC Utah climate division 5.

To elucidate the role and significance of spring climate anomalies on flood generation, standardized temperature anomalies have been calculated for the 10 largest peak annual floods from the composite record since 1960. For this set of 10 floods, differences between the standardized precipitation and temperature anomalies are significant at the 95% confidence level if they exceed 0.40, using a two-tailed *t*-test. The recent episodes of large peak annual flood years have occurred when late winter (January through March) temperatures have been even warmer than the 1961–2000 trend, but the spring months (particularly April and May) have been colder than any other computed time frame in the historic record (Fig. 9). This reflects the combined significance of temperature regimes and seasonal precipitation distribution on peak annual flood magnitude. The importance of spring temperature regimes on peak annual flood magnitude also explains the seemingly apparent contradiction of AMJJ fractional streamflow decreasing at the same time that the largest historic peak annual flood years have occurred.

Winter precipitation is dominated by frontal storms with typical life cycles of 1–4 days that migrate into the central Rocky Mountains from the North Pacific region. Snowpack accumulation generally peaks in late March to early April, at which time advective heat fluxes into the region and begins the annual melt cycle. Since the magnitudes of the peak annual floods are almost exclusively associated with snowmelt (as opposed to summer storms), correlation between peak floods and winter precipitation is expected. The warm temperatures that prevail during January through March of years with large peak annual floods apparently do not inhibit the snowpack accumulation. The departure of temperatures from the mean represents a change of less than 1°C and does not drive mean temperatures above freezing. In fact, the slight increase in temperature during the winter months likely allows more moisture to be carried by the migrating weather systems.

Cold temperatures during April and May retard the melting of the snowmelt, and are coincident with high springtime precipitation which further adds to the snowpack. The combined importance of these two factors in generating large peak annual floods is significant because of recent trends toward warmer temperatures, rather than cooler, during the spring months. The importance of later and heavier spring precipitation for large floods is further elucidated by reviewing the absolute values for climate division 5. Whereas the long-term average shows monthly precipitation dropping through the spring from a high in January, large floods have preferentially occurred after 1960—during a time period of higher precipitation in March through May as compared to previous time periods. The combined effect suggests that large floods are produced in years with large winter snowpacks and, most importantly, increased spring precipitation (either occurring as late season snow or as rain-on-snow events). In years that anomalously cold spring temperatures occur, the preservations of the winter snowpack to later in the melt season has allowed several

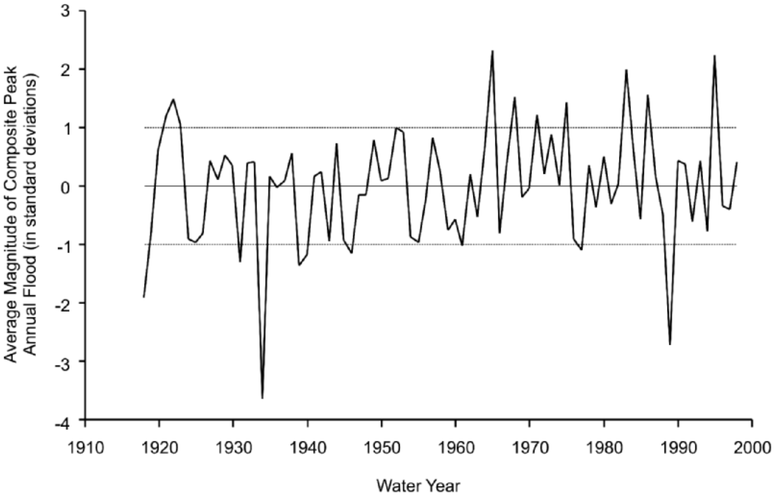


FIGURE 8. Composite flood series for the Uinta Mountains, 1918–2000, expressed in standard deviation departures from mean. Flood magnitudes were calculated by averaging the standardized logarithmically transformed values for nine long-term gage records in the Uinta Mountains. The resultant record (above) has been restandardized to produce a long-term mean of 0.0 and standard deviation of 1.0.

of the largest peak annual floods in the historic gage record to occur despite the general trend toward warming temperatures.

Conclusions

The long-term AMJJ fractional streamflow and peak annual flood series for nine streams in the Uinta Mountains has been assessed for evidence of seasonal and temporal variations, and association with regional records of precipitation and temperature. The Uinta gage records show strong response to local temperature and precipitation data. AMJJ fractional streamflow, which represents the spring snowmelt runoff that dominates the annual hydrologic cycle, is smallest in years when precipitation is significantly below average in December, January, and April, and temperatures are significantly above average in April and May. Conversely, AMJJ fractional streamflow is highest in years when winter precipitation is above average, most significantly so in January and April. In both instances, precipitation anomalies are more significant to runoff than temperature anomalies. Historic trends of precipitation in the region indicate that the seasonal distribution of precipitation is shifting such that an increasing percentage of annual precipitation is occurring during the spring months rather than winter.

Years when small peak annual floods occur rangewide are characterized by below average precipitation during the winter and spring (most significantly in December and January), which likely produces a smaller than average snowpack. Years of large peak annual floods are characterized by above average precipitation during the winter months, especially December, April, and May. This is further accentuated by below average temperature during April and May, which tends to preserve the snowpack later into the melt season and produce a large, late peak annual discharge. Thus, numerous recent years with anomalously cold spring temperatures have caused the largest peak floods in the Uinta Mountains regardless of AMJJ fractional streamflow. The time series record of peak annual flood magnitudes shows that extreme flood events (both above average and below average) have become more frequent since about 1960. Seven of the nine largest flood years have occurred since this time. Historic climate data indicates that large floods since 1960 correlate to years with significantly cold temperatures in December and May.

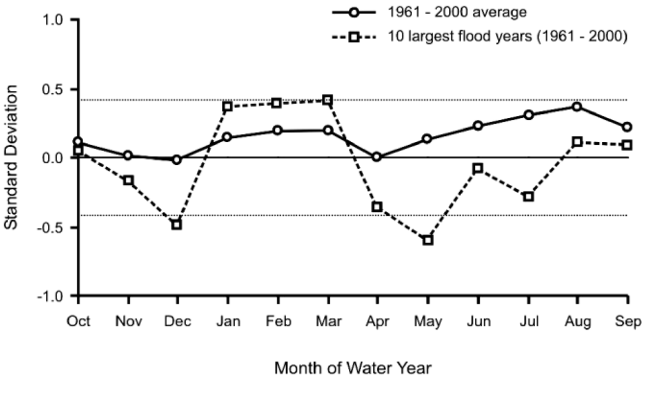


FIGURE 9. Monthly temperature anomalies in NCDC Utah climate division 5 for 1961–2000 and for the 10 largest flood years in 1961–2000, expressed in standard deviation departures from mean. Note that with the standardized series, the long-term (1900–2000) average for temperature is 0.0.

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