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Variation of Warm-Season Rainfall Frequency in the Southern Colorado Plateau and its Effect on Runoff and Alluvial-Channel Morphology: A Preliminary Analysis

by

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Figure 12. Empirical quantile-quantile plots of rainfall frequency from figure 11 comparing the quantiles of four segments with 14 years per segment. Diagonal line extending between corners is the theoretical line of equality between the two distributions. Short diagonal line is a linear least squares regression fitted to the 14-paired observations. A), B), and C) compare the quantiles of the 1929-1942 segment with the quantiles of the 1943-1956, 1957-1970, and 1971-1984 segments. D) and E) compare 1943-1956 quantiles with 1957-1970 and 1971-1984. F) compares the quantiles of 1957-1970 with 1971-1984.

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Abstract

Decreased runoff beginning in the early 1940s was probably the main cause of extensive sediment storage in alluvial-channel tributaries of the Colorado River. Most sediment is transported in these tributaries during summer and early fall, and a long-term change of runoff during the warm season (June 15 to October 15) would alter channel equilibrium. Runoff occurs in direct response to rainfall from subtropical moisture transported from the Gulf of Mexico or tropical Pacific Ocean onto the normally dry plateau through monsoon or tropical cyclone circulation. Analysis of average daily rainfall at 13 weather stations suggests that after the early 1940s the rainy season ended earlier, decreasing the length of the season as much as 40 percent. Moreover, regionally averaged rainfall frequency and amount for the season also decreased in the early 1940s. Total seasonal rainfall is closely related to rainfall frequency ($r = 0.95$), which in turn is correlated with runoff frequency ($r = 0.79$). In the Little Colorado River basin, measured runoff was unusually high from the beginning of the record in 1925 until the early 1940s. The high runoff, however, began before 1910, based on a multiple linear regression with rainfall frequency as the predictor variable. A long-term change of either monsoon strength or tropical-cyclone frequency or a change of both would reduce rainfall and runoff. Evidence for a long-term change in monsoon strength before 1945 is unavailable due to a lack of upper air pressure data. The number of tropical cyclones, however, decreased substantially after the early 1940s, which reduced average daily rainfall in the latter part of the season. In addition, decreased rainfall in late summer and early fall might be related to relatively low frequency of well developed El Nino-Southern Oscillation between about 1940-1985.

Introduction

This report is an exploratory data analysis of the frequency and amount of rain during the warm season June 15 to October 15 in the southern Colorado Plateau (fig. 1). The analysis was undertaken to understand the climatic causes of reduced runoff, sediment yield, and changes of alluvial-channel morphology that occurred in the early 1940s in tributaries of the Colorado River (Hereford, 1984, 1987a). Runoff from warm-season rain produces from 50 to 90 percent of the large floods on the Colorado Plateau (Webb, 1987). Thus, variation of rainfall may cause a corresponding change in the size and frequency of channel-forming floods, and a change in flood regimen will directly affect runoff and sediment yield. Moreover, alluvial-channel morphology will probably adjust to the new regimen through aggradation or degradation.

Several studies have shown that alluvial channels of the southern Colorado Plateau streams have changed substantially since the early 1940s (Hereford, 1984, 1986, 1987a, 1987b; Graf, 1987). The geomorphic changes were mainly from aggradation and include reduced channel width and widespread development of floodplains (Hereford, 1987a). The immediate cause of aggradation was probably a change in the frequency and magnitude of floods in the early 1940s (Hereford, 1987a; Webb and Baker, 1987).

This recent alluviation has practical applications for land management and theoretical implications for fluvial geomorphology of semiarid regions (Hereford, 1987c; Gellis and others, 1988). The new deposits have created a floodplain in formerly unusable, frequently flooded channels. These floodplains are now favorable sites for grazing, agriculture, and construction. Mining and exploration for uranium and thorium were widespread in the Colorado Plateau during the 1950s. Erosion of mine tailings and other disturbed areas probably increased input of these elements into channel systems where they probably accumulated on floodplains. Moreover, widespread sediment storage in tributary channels reduces long-term sediment load of the Colorado River. Therefore, understanding the causes of reduced sediment yield and floodplain development is desireable for improved reservoir design and long-term management of the floodplain resource.

The processes and causes of stream aggradation and degradation are poorly understood from a theoretical point of view. Nonetheless, the frequency and amount of rainfall logically have an important influence on fluvial processes (Leopold, 1951; Leopold and others, 1966; Cooke and Reeves, 1976; Webb, 1985). A significant change in the frequency or amount of rain, therefore, will probably directly affect flood frequency and size, which in turn will affect channel equilibrium and sediment load. Results of this analysis suggest that the frequency and amount of one and two-day rainfall decreased in the early 1940s through the late-1970s in most of the southern Colorado Plateau. This change in storm characteristics was coincident with the beginning of regional floodplain alluviation, with reduced peak-flood discharge of Colorado River tributaries, and reduced sediment load of the Colorado River.

Finally, increasing concentrations of atmospheric CO_2 and other trace gases are expected to produce changes in future climate that will effect the hydrologic cycle (Bradley and others, 1987; Lockwood, 1989). Most general circulation models indicate that surface temperature will increase significantly. Although the effect of increased temperature on precipitation is not firmly established, models suggest that a doubling of CO_2 will increase precipitation by 3 to 11 percent (Bradley and others, 1987). This increase, although of opposite sign, is similar in size to the historic rainfall change discussed in the present study. Thus, a thorough understanding of historical rainfall variability and its effect on the fluvial system is essential to assessing the significance of future climate change.

Data and Methods

Data used in this preliminary analysis are daily rainfall recorded at 13 weather stations in the southern Colorado Plateau (fig. 1), daily discharge of the Little Colorado and Paria Rivers, and daily sediment load of the Paria River and Colorado River in the Grand Canyon. Most of the rainfall data, as well as maximum and minimum daily temperature, were obtained on magnetic tape from the National Center for Atmospheric Research, Boulder, Colorado and National Oceanic and Atmospheric Administration, Asheville, North Carolina. The data consist of 24-hour rainfall measurements collected, for the most part, at cooperative stations staffed by volunteers (NOAA, 1986). These are the only daily weather data available for the region and they have two shortcomings. In several cases, the data furnished on magnetic tape did not include the complete station record, and several stations have numerous data gaps of several years duration, which makes them difficult or impossible to use.

Table 1 lists the complete weather and hydrologic data set processed in this study, as well as the percent of missing values and the reason for not including the station in the rainfall frequency analysis. The 29-station data set contains 1.87 million observation days of precipitation and maximum and minimum daily temperature. Computer programs for manipulation and analysis of this type of data are not readily available. Several programs were written specifically for this study to analyze and plot daily rainfall and temperature. These programs are written in Hewlett-Packard Technical Basic and are available from me on request.

Data from only 13 of the 29 stations in table 1 were used in this study because of the previously discussed shortcomings. The location and elevation of these stations are listed in table 2. Most of the stations are in the southern Colorado Plateau (fig. 1), and they are distributed in three groups as shown in table 2. The stations range in elevation from 842 to 2,239 m and have an average elevation of 1,650 m. The Little Colorado River and northeast group (Table 2) lie southeast of the so-called "summer monsoon air-mass boundary," a region of broadly similar climate that crosses the Colorado Plateau diagonally in northwest Arizona and southeast Utah (Mitchell, 1976). The northwest group (Table 2) lies within this air-mass boundary. The stations are clustered along the southern and western edge of the Colorado Plateau, and they occupy a region of broadly similar physiography and climate.

Time series were developed from the rainfall data (Table 2) to search for changes in the frequency and amount of rain in the warm season of June 15 to October 15. The series were developed in the following manner: Weather stations with data before 1940 with no missing entries in the late 1930s to early 1940s were analyzed (Tables 1 and 2). For each station, the number of days annually with more than 5 mm of rainfall of one and two days-duration was counted, and the rainfall of these events was accumulated. Rainfall up to 15 consecutive days was counted, but rain longer than two days is extremely rare and did not, therefore, change the conclusions. A missing value was assigned to a season if more than 5 percent of the daily entries of a particular station were missing. The rain frequency and total data for each station (Table 1) were obtained by dividing the rain frequency and accumulated rainfall per year by the number of reporting stations. The 13 stations used in the analysis (Table 2) were chosen because they have a fairly complete record from 1928 through 1985.

Despite the shortcomings of the climate data, I developed annual time series of the frequency and amount of rainfall from 1928-1985 for two of the groups and from 1910-1985 for the Little Colorado River basin group. The results of this study, however, are preliminary because of the incompleteness of the data. Work in progress will attempt to fill data breaks, obtain complete station records, and check each record for inhomogeneities. Spatial variation of rainfall frequency and amount and the relation with synoptic circulation patterns will also be undertaken.

Previous Studies of Rainfall Frequency

Several studies of southwestern streams have used rainfall frequency to interpret changes of alluvial-channel morphology (Leopold, 1951; Leopold and others, 1966; Cooke and Reeves, 1976; Webb, 1985). These studies were concerned primarily with climatic explanations of arroyo cutting during the late 1800s and early 1900s. Data from one or two stations was used to develop seasonal time series of various size classes of rainfall frequency. These studies showed that rainfall frequency varied with time, whereas total annual and seasonal rainfall did not change significantly.

A study by Englehart and Douglas (1985) addresses the statistical characteristics and spatial variation of rainfall frequency that is relevant to the present study. Rainfall frequency is a relatively new and unfamiliar measure in the climatologic literature, as most studies of rainfall typically treat monthly and annual totals. In general, monthly or seasonal rainfall frequency has a normal probability distribution. Therefore, rainfall frequency is better suited to linear analysis than total rainfall, which has appreciable positive skewness. Although the statistical characteristics of rainfall frequency varies regionally within the United States, the Colorado Plateau is characterized by normally distributed rainfall frequency (Englehart and Douglas, 1985, fig. 3). For this reason, the rainfall frequency data of the present study are assumed to have an approximately normal probability distribution.

Types of Runoff Producing Warm-Season Rainfall

Definition of Rainy Season

Figure 2 shows the annual precipitation cycle at Fort Valley, and Winslow Arizona, stations having a typically developed rainy season from mid-June to mid-October or early November. The principal difference between these stations is the lack of a winter maxima at Winslow and the amount of precipitation. The rainy period is not strictly limited to summer, rather it typically begins in late spring and lasts until early to mid-fall at most stations. This rainy period is a climatic singularity (Barry and Parry, 1973,

p. 292) because of its tendency to recur at the same time each year. Although the rainy season recurs each year, the beginning and ending date vary by several weeks from station to station. For regional comparison, therefore, the rainy season was defined as June 15 to October 15, a definition that includes most of the rainy season of each station, as will be shown in a following section.

Regional and Local Storms

Runoff producing warm-season rainfall in the southern Colorado Plateau is classified by storm size and meteorological type. Two broad, subjective classifications of storm size are recognized--local and general storms (Hansen and others, 1981). A local storm is characterized by unusually heavy rainfall that is isolated from surrounding storms. Typically, this size of storm is not associated with an organized meteorological system. Although local storms produce large, dangerous floods, they probably do not produce significant runoff in intermediate-size drainage basins.

In contrast, general storms produce significant rainfall lasting a day or longer over at least 500 km^2. These storms are typically associated with an organized frontal system or moist airflow whose movement over the region causes widespread rainfall. Because of their size and duration, general storms have the potential for producing regional flooding in intermediate-size basins.

Monsoonal and Tropical Cyclone Rainfall

Significant warm-season rainfall in the southern Colorado Plateau originates primarily from moisture derived from the tropical Pacific Ocean or Gulf of Mexico (Hansen and others, 1981; Smith, 1986). This moisture is transported northward into the normally dry region in local or widespread convective thunderstorms or in dissipating tropical cyclones. The monsoon season typically occurs between mid-June and mid-September, although the beginning and end vary locally and with time. During this season, high humidity and high surface temperatures result in frequent thunderstorms over a large area. At times, these storms cause severe local flooding and disrupt transportation (Carleton, 1985).

The Southwest monsoon is a seasonal shift from southwest to southeast winds that effects the Colorado Plateau in mid-June to early July (Tang and Reiter, 1984). This shift to southeasterly winds results from a rapid, large-scale change in the general circulation (Bryson and Lowry, 1955) in late June and early July. Although the monsoon recurs annually, it shows large seasonal and annual variability (Carleton, 1985). Within season variability causes periods of widespread, heavy thundershower activity alternating with dry spells up to several weeks duration. The wet and dry spells are termed "burst" and "break", respectively, after counterparts in the south Asian monsoon (Carleton, 1986). These are large-scale atmospheric anomalies (Carleton, 1986), and over a period of several days a burst will produce rainfall and possibly increase runoff over a large part of the southern Colorado Plateau, whereas a break will result in dry conditions and reduced runoff in an equally large area.

On an annual basis, the strength of the monsoon season varies substantially, and this variability, which is related to major atmospheric circulation controls, effects total summer rainfall (Carleton, 1987). Using 500 mb geopotential height patterns, Carleton (1987) identified 11 large-scale circulation types that correspond with burst and break monsoonal activity. From these Carleton (1987) developed three seasonal circulation indices that are weakly to moderately well correlated with Arizona summer rainfall. The indices are expressed as a ratio of the number of days of specific types of burst and break circulation patterns.

Generally, the main control of seasonal rainfall is the position of the Bermuda subtropical anticyclone (Carleton, 1986, 1987), one of the two major high-pressure centers of the Northern Hemisphere. High rainfall in the Southwest is associated with northerly displacement of the ridge, whereas dry weather is associated with southerly displacement. Thus, long-term changes in warm-season rainfall are related to the average latitude of the Bermuda subtropical ridge. The type of information needed to develop the "Carleton" indices, however, is not available before 1945 (Carleton, 1987); therefore, the major change in warm-season rainfall of the early 1940s discussed in this paper cannot be evaluated in terms of these indices.

Tropical cyclones occur at anytime of the year, but on the average more than 90 percent occur over the Southwest between June-October, and about 60 percent of the annual total occurs between August-October (Smith, 1986, Table 1). Under appropriate conditions, these storms produce significant rainfall and flooding (Smith, 1986; Webb, 1987). Heavy rainfall occurs when the moisture-laden air of the dissipating storm system is lifted orographically, through strong diurnal heating, or in conjunction with an unseasonably cool mid-latitude trough or cut-off low-pressure system (Smith, 1986). Three of the largest floods of the Paria River in 1925, 1926, and 1939 resulted from tropical storms (Webb, 1987).

Temporal Variation of Rainy Season Duration

Analysis of the rainfall data suggests that the average length of the rainy season decreased after the early 1940s. This decrease is suggested by examination of the average daily precipitation of each station. The station record was divided at 1942, and average daily precipitation was calculated for two periods. One of the periods was from the beginning of the station record through 1942, and the other was from 1943 with the number of years equal to the first period. Selection of 1942 as the dividing year was based on previous work which showed that annual flood magnitude, runoff, rainfall, and temperature decreased in the early 1940s in the Colorado River basin and southern Colorado Plateau (Thomas and others, 1963; Graf, 1986; Hereford, 1984, 1986). In addition, the beginning of floodplain aggradation in the early 1940s is physical evidence of hydrologic change possibly caused by climate fluctuation or change.

Figures 3 and 4 show the pre-1943 and post-1942 average annual precipitation cycle of Fort Valley, Arizona, and Kanab, Utah, which are representative high and intermediate elevation stations (Table 2). At both stations, the average rainfall season before 1943 (figs. 3a and 4a) is about 40 days longer than the season after 1943 (figs. 3b and 4b). Table 3 lists the results of a similar analysis applied to the 13 stations. At 11 of the stations, the post-1942 rainy season is between 5 and 40 percent shorter than the pre-1943 season. Of the two remaining stations, one had no change, whereas the other had a 5 percent increase in the length of the post-1942 season. These results, however, are qualitative because selection of the rainy season is subjective and because the variance of the daily rainfall is unknown, which precludes tests of statistical significance.

The data in table 3 were also analyzed to determine whether the average beginning and ending date of the season were different for each period. The 95 percent confidence interval for the average beginning date of the pre-1943 and post-1942 data is June 17 to June 25 and June 23 to July 4, respectively, suggesting that the average beginning date of each period is similar. The same confidence interval for the average end of the season is October 10 to October 26 for pre-1943 data and September 16 to October 5 for post-1942 data, suggesting that the season ended earlier after 1942. Thus, the average rainy season was probably shortened after 1942 by ending early rather than by beginning late.

A decrease in the number of tropical cyclones after the early 1940s might have reduced the length of the average rainy season. These storms typically occur in late summer and early fall, and a reduced frequency during this portion of the warm season would decrease average daily rainfall and shorten the rainy season. In an analysis of the Paria River basin, Graf and others (written commun.) found that the number of floods resulting from tropical cyclones decreased significantly between 1923 and 1986. In this period, 18 floods were caused by dissipating tropical cyclones, of these nine occurred between 1923 and 1942, six occurred between 1943-1958, and only three occurred between 1958-1986.

Hydrologic and Geomorphic Significance of Warm-Season Rainfall

Runoff of a Typical Colorado Plateau Basin

The Paria River basin (4,070 km^2) in south-central Utah (fig. 1) is a typical intermediate-size Colorado Plateau basin. Unlike other basins of this size, however, daily streamflow measurements from the mouth of the river are available beginning October 1923 (Table 1). These data are important for understanding the relations among climate, hydrology, and channel morphology of southern Colorado Plateau streams.

The geology of the basin consists mainly of gently dipping, locally folded Mesozoic sandstone, shale, and siltstone. These strata weather differentially forming the characteristic cliff/slope topography of the Colorado Plateau. Typically, the relatively hard sandstone layers form ledges or cliffs, whereas the softer siltstone and shale layers form slopes. Because of weak cementation and a vigorus freeze-thaw cycle, the strata weather and decompose rapidly (Colbert, 1956; Schumm and Chorley, 1966), providing the abundant sediment load for which streams in the region are noted (Beverage and Culbertson, 1964).

The Paria River is perennial, although base flow is very low with 80 percent of the daily flows < 1 m^3/s in the season June 15-October 15. The principal tributaries of the Paria are ephemeral, which is typical of many southern Colorado Plateau streams. In these streams, a large portion of annual runoff occurs during July through October in direct response to rainfall. Figure 5 shows the annual runoff cycle of the Paria River, which is probably similar to other streams in the region. Biseasonal variation of runoff and sediment load in response to the biseasonal precipitation pattern (figs. 2a and 4) is demonstrated clearly.

Analysis of Paria River sediment load for the period of record (October 1948 through September 1976) shows that the largest sediment loads occur in the warm season. The average daily sediment load carried between June 15 and September 15 is 22 X 10^4 Mg, whereas between September 16 and February 15 (winter) sediment load is 2.4 X 10^3 Mg and between February 16 and June 14 (spring) it is only 8.8 X 10^2 Mg. Thus, on the average, warm-season sediment load is 10 to 100 times larger than winter or spring sediment load. A long-term change in warm-season rainfall patterns, therefore, would probably affect sediment load and channel morphology.

Temporal Variation of Runoff

A variety of evidence suggests that a major hydrologic change occurred in the southern Colorado Plateau portion of the Colorado River basin in the early 1940s. The warm-season runoff of the Paria River, for example, decreased substantially between about 1942 or 1944, as illustrated in figure 6. This decrease in average daily flows was related to or caused by a reduction in the size of peak-flood discharge. Although sediment load was not measured before October 1948, a reconstruction of Paria River sediment load shows that it also decreased substantially in the early 1940s (Graf and others, written commun.).

This hydrologic change was regional as suggested by the sediment load of the Colorado River in Grand Canyon. Figure 7 shows the annual sediment load of the Colorado River for two thirteen-year periods centered at 1942. Sediment load in both seasons was substantially less in the post-1942 period (fig. 7b). In addition, the rainy season runoff period is several weeks shorter in the post-1942 period, which is consistent with the rainfall data (Table 3). This decrease in Colorado River sediment load occurred at about the same time that Paria River runoff and load decreased, and the decrease was also coincident with the beginning of sediment storage in the Paria River and other intermediate to large basins (Hereford, 1987a; Graf and others, written commun.). Discharge of the Colorado River, however, did not change, probably because runoff originates mainly from snowmelt in the headwaters of the basin, whereas sediment is derived from the Colorado Plateau portion of the basin.

Geologic Effects of Reduced Runoff

Several studies have documented recent changes in alluvial channels of the Colorado Plateau (Emmett, 1974; Leopold, 1976; Dunne and Leopold, 1978; Hereford, 1984, 1986, 1987a,b; Graf, 1987). Photographic evidence shows that the changes are substantial, consisting of reduced channel width and sediment storage through development of floodplains. In most basins, the amount of accumulated sediment is not mapped, but in the Paria River basin mapping shows that the deposits cover about 20 km^2 and have a volume of 40 million m^3 (Hereford, 1987c).

Stratigraphic and sedimentologic studies of the recent deposits show that the floodplains developed mainly through vertical accretion, indicating that sediment was stored in the channels (Hereford, 1984; 1986). Moreover, these studies indicate that deposition of floodplain alluvium began in channels of the southern Colorado Plateau during the early 1940s. This widespread, essentially synchronous alluviation suggests that it resulted from a common causal factor (Hereford, 1987a).

Finally, this widespread sediment storage probably reduced sediment accumulation in Lake Powell (fig. 1), one of the major reservoirs of the Colorado River Storage Project. A study of deposition in Lake Powell showed that the measured annual rate of deposition was only 43 percent of the rate estimated during the planning stages of the reservoir (Ferrari, 1988, p. 28). The estimated sedimentation rate did not allow for sediment storage in tributary streams, which was unknown during planning of the reservoir.

Possible Causes of Reduced Runoff and Sediment Load

Results of several studies (Thomas and others, 1962; Hadley, 1974; Hereford, 1987a; Gellis and others, 1989) suggest that landuse, intrinsic geomorphic controls, and climate have altered runoff and sediment yield to some extent; however, it is not possible to specify quantitatively which of these was the dominant influence. Evidence that climate change or fluctuation in the early 1940s was the cause of reduced runoff and alluviation has been presented by several workers (Emmett, 1974; Leopold, 1976, Dunne and Leopold, 1978; Graf, 1986; Hereford, 1984, 1986, 1987a, b). The reduced runoff favored colonization of channels by riparian vegetation, which in turn caused sediment to accumulate in the channels further reducing flood peaks and sediment yield (Hereford, 1984). Although this is a reasonable explanation for alluviation, evidence for a change of rainfall that could alter flood regimen significantly has been lacking.

Relation of Rainfall Frequency and Amount to Fluvial Processes

Previous workers have suggested that a long-term change in annual rainfall frequency would influence fluvial activity (Leopold, 1951; Leopold and others, 1966; Cooke and Reeves, 1976). Stream erosion is associated with increased frequency of large rains, or with less frequent small rains. The hillslope protective vegetative cover is weakened by infrequent small rains, which increases runoff. Thus, a decrease in small rains, an increase in large rains, or a change of both will lead to lead to increased runoff and erosion.

In this study, however, only a change to relatively higher or lower rainfall frequency is thought to affect fluvial processes since at least the early 1940s, if not the late 1800s. Evidence for a change in hillslope vegetation since the early 1940s and earlier is lacking. This is significant because the hillslope system--particularly the steep, barren, and largely ungrazed hillslopes--is probably the principal source of sediment for southern Colorado Plateau streams (Wells and others, 1983; Hereford, 1987a, 1987d). Rangeland vegetation (exclusive of hillslopes), however, has changed noticeably due to grazing and other factors in much of the Southwest (Branson, 1985). In the southern Colorado Plateau, numerous comparative photographs of hillslopes show that the vegetation cover has not changed noticeably during the past 100 years (Stephens and Shoemaker, 1987; Graf, 1987, figs. 6-9; Hereford, 1986, figs. 4-5, 1987b, fig. 15). Thus, the relation of changed hillslope vegetation and rainfall frequency is probably more complex than previously realized.

The relation between rainfall frequency and runoff was investigated using multiple linear regression. The results of this analysis are shown in figure 8, which is a time series of actual and estimated runoff frequency of the Little Colorado River for the rainy season June 15 to October 15. Runoff frequency is the number of times per year that runoff exceeded a base flow of 1.6 hm^3/day for durations of one to seven days. Rainfall frequency is the average number of one and two-day rainfall events per year of the stations in the Little Colorado River basin (Table 2). The regression equation is

$$Q_{rf} = -2.4 + 0.02F_f + 0.3H_f + 0.2Sp_f + 0.1Sn_f + 0.2W_f \ .$$

Where Q_{rf} is runoff frequency, F_f, H_f, Sp_f, Sn_f, and W_f is rainfall frequency at Fort Valley, Holbrook, Springerville, Snowflake, and Winslow, respectively. Table 4 tabulates the regression analysis. The statistical relation has considerable variation; nevertheless, rainfall frequency explains 62 percent of discharge variation, and the regression is statistically significant (Table 4).

In general, the regression reproduces satisfactorily the long-term runoff pattern; however, in detail, runoff is overestimated in 1929, 1961, 1966-1967, and 1971-1972; and runoff is underestimated in 1927, 1931, 1935-1938, and 1968 (fig. 8). A portion of this unexplained variation is due to random errors, but most of the variation probably has a physical explanation. Temperature and antecedent moisture, for example, are probably important variables that might reduce the lack of fit and unexplained variation.

The rainfall data for these stations, unlike many of the others (Table 1), are nearly complete from 1910 to the present. Thus, figure 8 shows the predicted runoff of the Little Colorado River from 1910-1925. High runoff frequency was typical from 1910-1941, and 1920-1941 was particularly high. These results suggest that runoff and rainfall were at their highest levels from at least 1910 until the early 1940s.

Spatial and Temporal Variation of Rainfall

Average annual rainfall frequency of the three groups (Table 2) is shown in figure 9. Missing entries were estimated for each station by the average of six years centered at the missing year. The time series indicate that rainfall frequency varies across the region. Nonetheless, a long-term pattern of reduced frequency from the early 1940s until the late 1970s is evident, particularly at the Little Colorado River and northeast groups (fig. 9a, 9b). Rain frequency of the northwest group (fig. 9c) is broadly similar to the other groups with the exception of the unusually frequent rain during 1945-1946, 1954-1955, 1961, 1963, and 1972. These differences may stem from the location of the northwest group in the monsoon air-mass boundary, as previously discussed. Despite the differences, the three groups are probably representative of the long-term rainfall patterns of the southern Colorado Plateau.

Rainfall frequency is probably the principal control on the amount of rainfall in any year, as illustrated in figure 10 which shows the relation between frequency and amount where both are expressed as a percentage of their 1951-1980 averages. Rainfall frequency of the 13 stations explains 90 percent of the variation of total rainfall. Moreover, rainfall frequency of the Little Colorado River group explains 78 percent of the variation of total rainfall at these stations. The small unexplained variation of total rainfall is due to random errors and variation in rainfall intensity. Englehart and Douglas (1985) also found high correlation between rainfall frequency and total rainfall, although they found that total rainfall was a power function of frequency.

Figure 11 shows time series of average annual frequency and amount of one and two-day rainfall of the 13 stations expressed as a percentage, as explained above. In this case, not less than 11 of the 13 stations were used to estimate the annual average, a procedure that eliminates the need to estimate missing entries. The time series show that rainfall frequency and amount were highest during 1928-1941 and 1980-1984.

Temporal variation of rainfall frequency was analyzed by dividing the time series (fig. 11) between 1929-1984 into four 14-year segments. These segments were chosen to isolate the early period for comparison with the following three periods. The quantiles of each segment were compared using empirical quantile-quantile plots, an effective method of comparing the distribution of data (Chambers and others, 1983). The plots are illustrated in figure 12; figure 12a shows that rainfall frequency during 1929-1942 was larger than 1943-1956; figure 12b indicates that frequency above the 100th percentile during 1929-1942 was higher than 1957-1970; and figure 12c indicates that 1929-1942 frequency was about equal to 1971 to 1984, although figure 11 shows that frequency during 1980-1984 was the highest of the 1971-1984 period. Figure 12d indicates that rainfall frequency for 1943-1956 was less than 1957-1970.

A t-test of the type suggested by Mitchell and others (1966) was used to test the null hypothesis that the average frequency for 1929-1942 is equal to the average frequency of 1943-1956, 1957-1970, and 1971-1984. In addition, the time series was divided at 1942 and the averages of the two segments 1928-1942 and 1943-1979 were tested for equality. In this fourth comparison, the 1980-1985 data were omitted because rainfall frequency during this six-year period was the highest since 1942 (Figs. 9, 11). Moreover, a significant change to erosion occurred in many southern Colorado Plateau streams in 1980 (Hereford, 1987a), and this change might be related to the unusually high rainfall frequency of the 1980-1985 period.

The results of these tests are listed in table 5. Regarding the first three comparisons (Table 5), the null hypothesis is rejected (0.05 level) in the first case (1943-1956), and accepted in the second (1957-1970) and third case (1971-1984). The significance of the second comparison, however, is questionable because figure 12b indicates that the percentiles of the 1929-1942 period are larger even though the averages might not differ significantly. In the third comparison, the averages are about equal as indicated by figure 12c, however, the 1970-1984 average is inflated by the unusually high frequency of the 1980-84 period. Finally, the fourth comparison (1928-1942 with 1943-1979) suggests that the 1928-1942 average frequency is significantly larger than the following 1943-1979 period.

These results yield two conclusions: 1) The 1943-1956 period was characterized by significantly reduced rainfall frequency compared with the preceding 1929-1942 and following 1957-1984 period, or 2) rainfall frequency during 1943-1979 was the lowest of the preceding 1928-1942 and following 1980-1985 periods. Figures 9 and 11 and 12 as well as the final result of table 5 favor the second conclusion. Thus, the 37-year period 1943-1979 was probably characterized by relatively low rainfall frequency compared with 1928-1942 and 1980-1985. Moreover, the early period of high rainfall frequency probably began before 1910, as suggested by figure 8. Finally, this conclusion is consistent with the hydrologic data, which suggests that runoff was unusually high from at least the mid-1920s until the early 1940s (figs. 6 and 8).

Discussion and Conclusions

The results of this study suggest that the length of the average rainy season (June 15-October 15) decreased after the early 1940s in the southern Colorado Plateau. The season was probably shortened by ending early rather than by beginning late, this reduced average daily rainfall in late summer and early fall. The frequency and amount of rainfall also changed. Statistical analysis does not yield a single interpretation of long-term rainfall variation, although the analysis favors the following interpretation: During the period 1943-1979 the frequency and amount of rainfall were lower than in the preceding period 1928-1942 or following period 1980-1985. Moreover, the early period of increased rainfall probably began before 1910. An alternative explanation is that only the early 1940s to mid-1950s were drier than the preceding or following period.

Rainfall frequency and amount are correlated with stream discharge, and the decrease of runoff and peak-flood discharge observed in tributaries of the Colorado River during the early 1940s are probably related, at least in part, to this change in rainfall characteristics. Through its effect on flood regimen, reduced rainfall frequency probably triggered sediment storage and floodplain development in Colorado River tributary channels. This tributary sediment storage in turn reduced the sediment yield of the Colorado River.

A long-term change in either monsoon strength or in the number of tropical cyclones penetrating northward onto the Colorado Plateau or a change of both could reduce warm-season rainfall and shorten the rainy season. According to Graf and others (written commun.), the number of tropical cyclones decreased after the 1940s. Monsoon climatology in the period of interest, however, is not well known because upper air pressure data is unavailable before 1945. Thus, it is unknown whether the increased rainfall of the pre-1940 period is related to a change in the "Carleton" circulation indices.

Southern Colorado Plateau rain in late summer and early fall is influenced by the El Nino-Southern Oscillation (ENSO), a complex, poorly understood global system of climate fluctuations (Andrade and Sellers, 1988). When ENSO is moderately to intensely developed, rainfall is increased during September to November, although its effect on June to August rainfall is negligible. Increased rainfall during this period is caused by warm water in the eastern Pacific Ocean and Gulf of California, a characteristic ENSO feature.

ENSO was moderately to intensely developed 13 times between 1928-1985. With only three exceptions, rainfall frequency was above average during these years, as shown in table 6. Thus, rainfall frequency, as defined here, is probably increased in the latter part of the rainy season during years of moderate to intense ENSO, although comparison of figure 11 with table 6 shows clearly that not all wet years are ENSO related.

An increase in the frequency of moderate to intense ENSO should increase rainfall in late summer and early fall. Andrade and Sellers (1988, table 2) data indicate that from 1899-1942 the average recurrence interval of moderate to intense ENSO was 3 years. Whereas, from 1943-1985 the recurrence interval was 5 years. Therefore, a higher frequency of strongly developed ENSO in the early part of the century might have been a contributing factor in the extended rainfall season (figs. 3a and 4a), increased rainfall (figs. 9 and 11), and high runoff (figs. 6-8).

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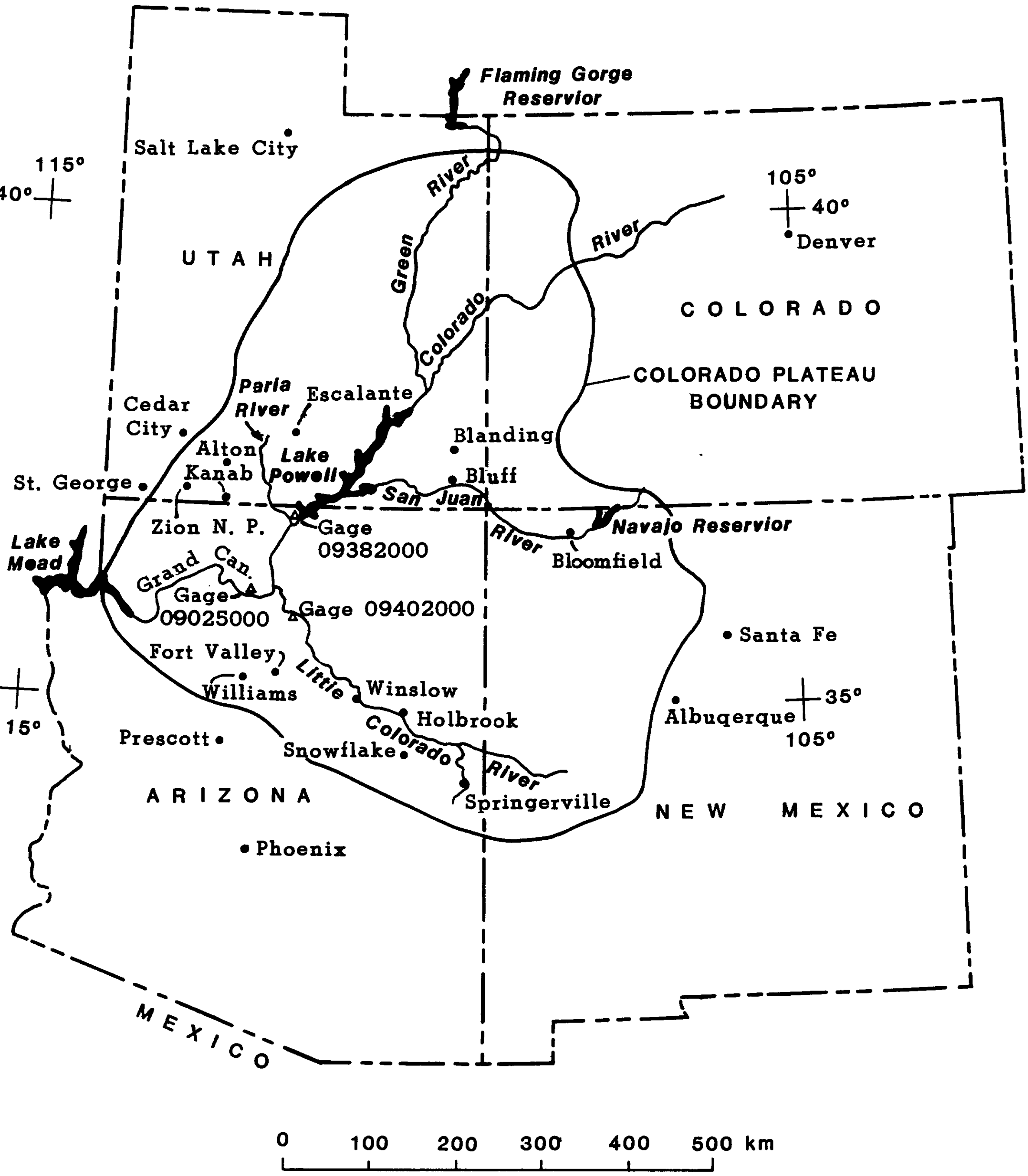


Flaming Gorge Reservior
Salt Lake City
115°
40°
UTAH
Green River
Colorado
River
105°
40°
Denver
COLORADO
COLORADO PLATEAU BOUNDARY
Cedar City
Paria River
Escalante
Blanding
Alton
Kanab
Lake Powell
Bluff
St. George
San Juan
River
Zion N. P.
Gage 09382000
Navajo Reservior
Bloomfield
Lake Mead
Grand Can.
Gage 09025000
Gage 09402000
Santa Fe
Fort Valley
Little Colorado River
Winslow
35°
115°
Williams
Holbrook
Albuqerque
35°
105°
Prescott
Snowflake
Springerville
ARIZONA
NEW MEXICO
Phoenix
MEXICO
0
100
200
300
400
500 km

Figure 1

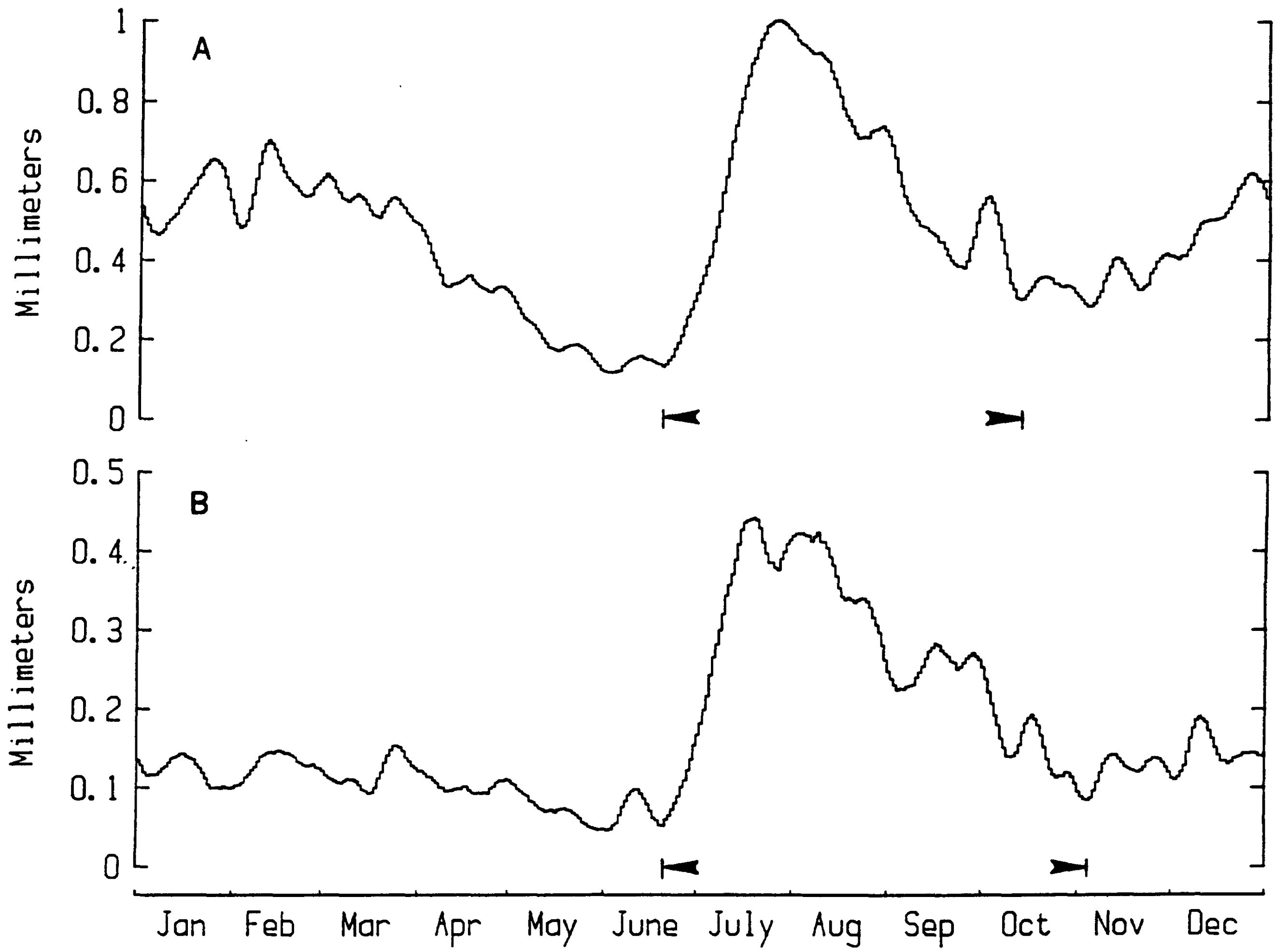
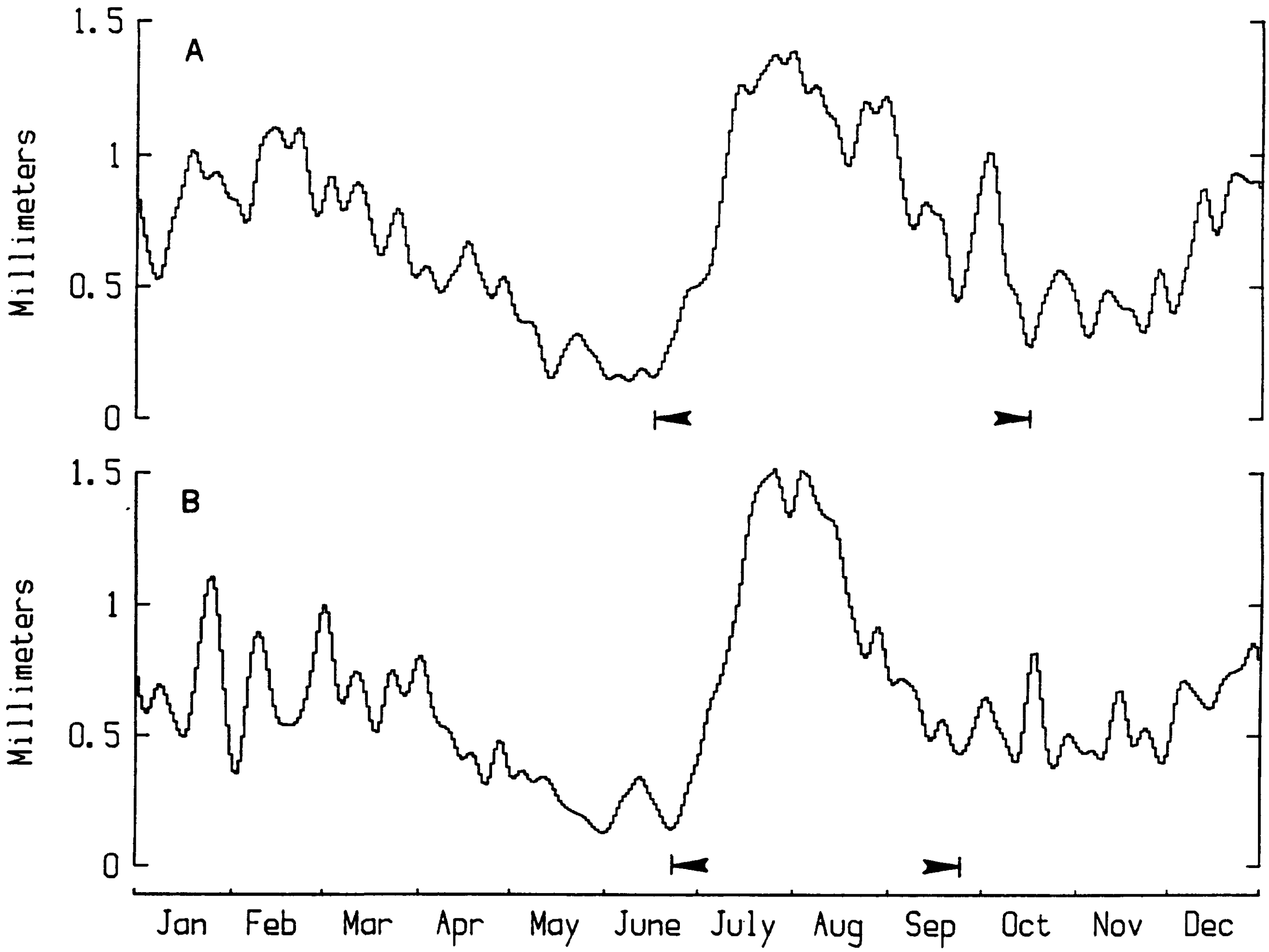

A
B
Millimeters
Millimeters
1
0.8
0.6
0.4
0.2
0
0.5
0.4
0.3
0.2
0.1
0
Jan Feb Mar Apr May June July Aug Sep Oct Nov Dec

Figure 2



A
B
1.5
1
0.5
0
Millimeters
Jan
Feb
Mar
Apr
May
June
July
Aug
Sep
Oct
Nov
Dec

Figure 3

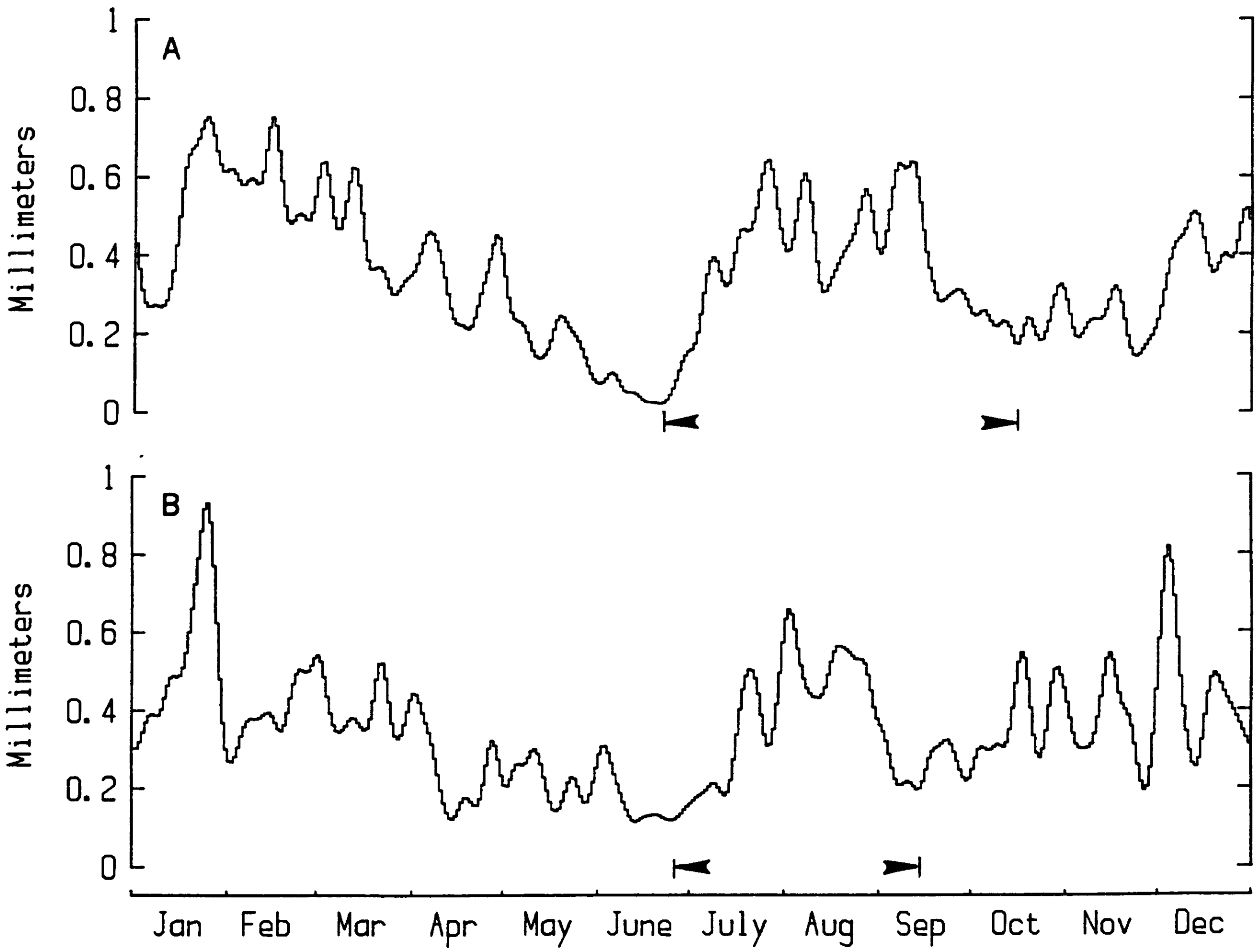
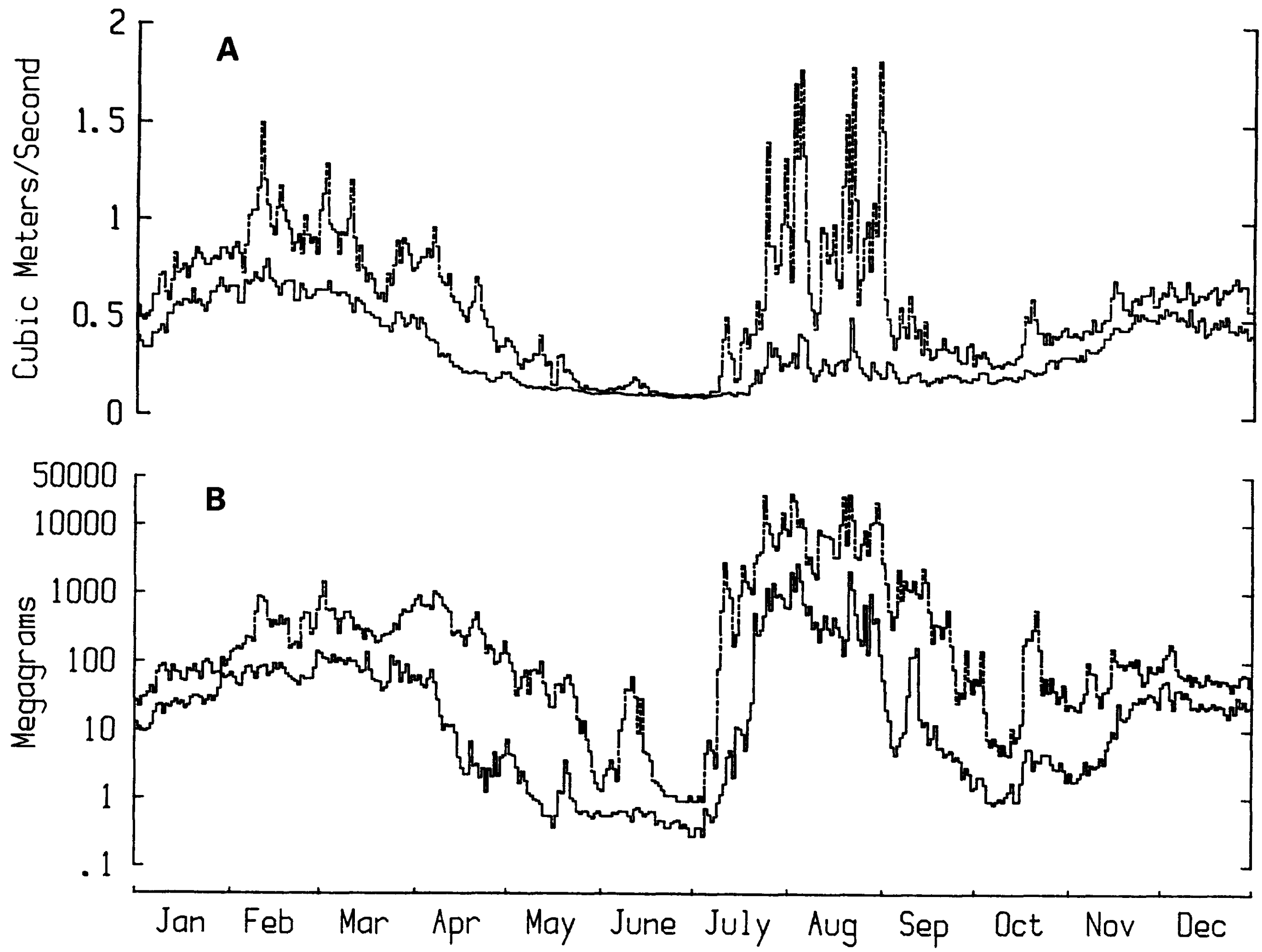

A
B
Millimeters
Millimeters
1
0.8
0.6
0.4
0.2
0
Jan
Feb
Mar
Apr
May
June
July
Aug
Sep
Oct
Nov
Dec

Figure 4



A
B
Cubic Meters/Second
2
1.5
1
0.5
0
Megagrams
50000
10000
1000
100
10
1
.1
Jan
Feb
Mar
Apr
May
June
July
Aug
Sep
Oct
Nov
Dec

Figure 5

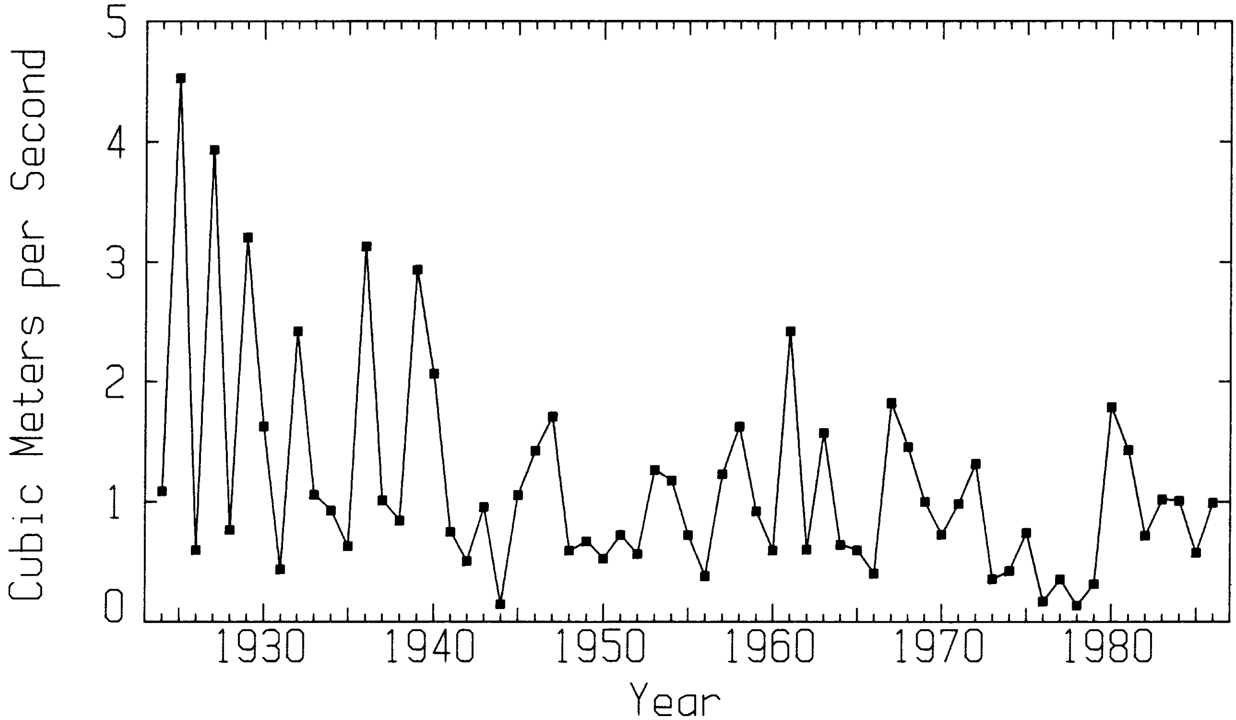

5
4
3
2
1
0
Cubic Meters per Second
1930
1940
1950
1960
1970
1980
Year

Figure 6

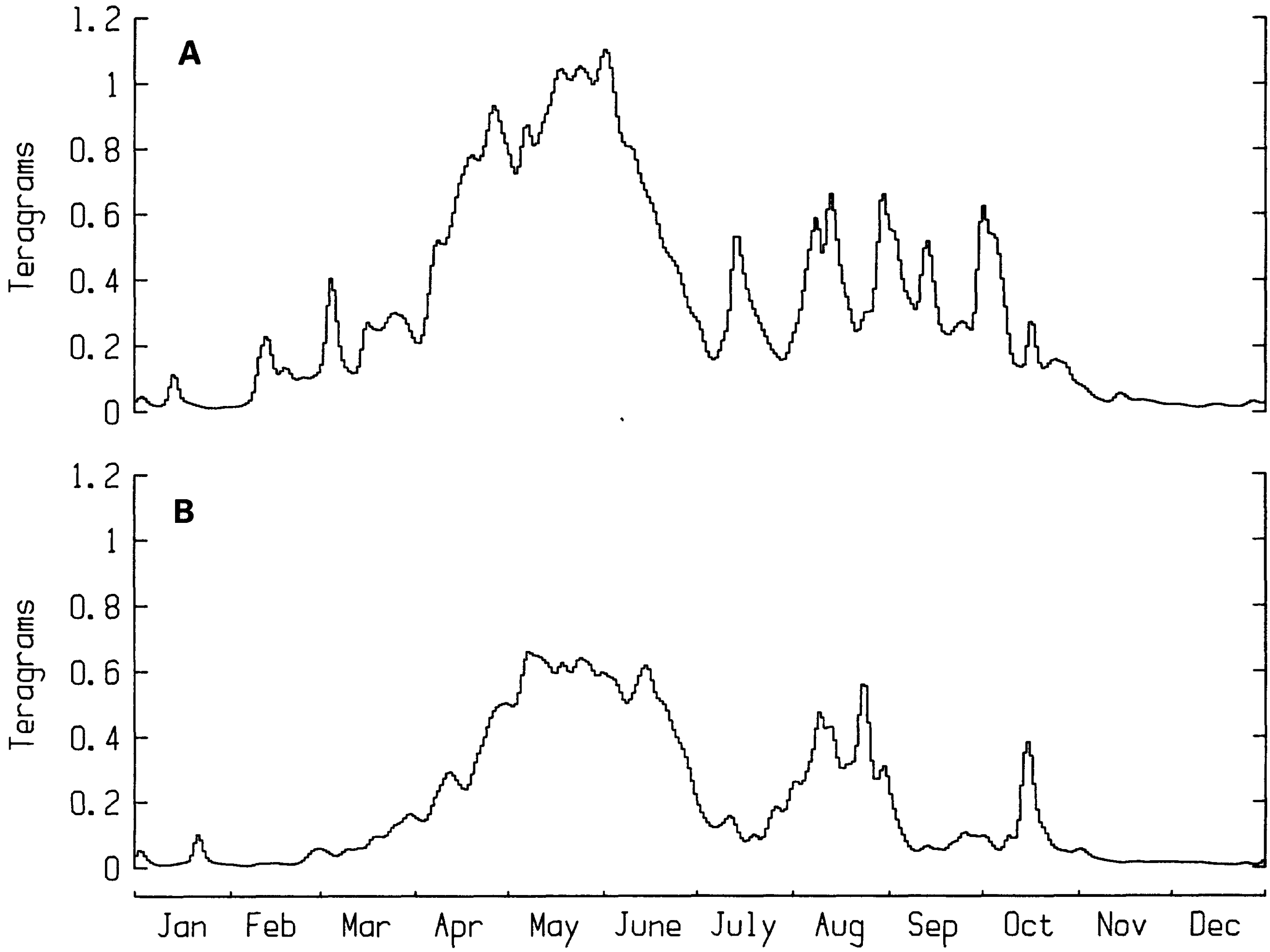
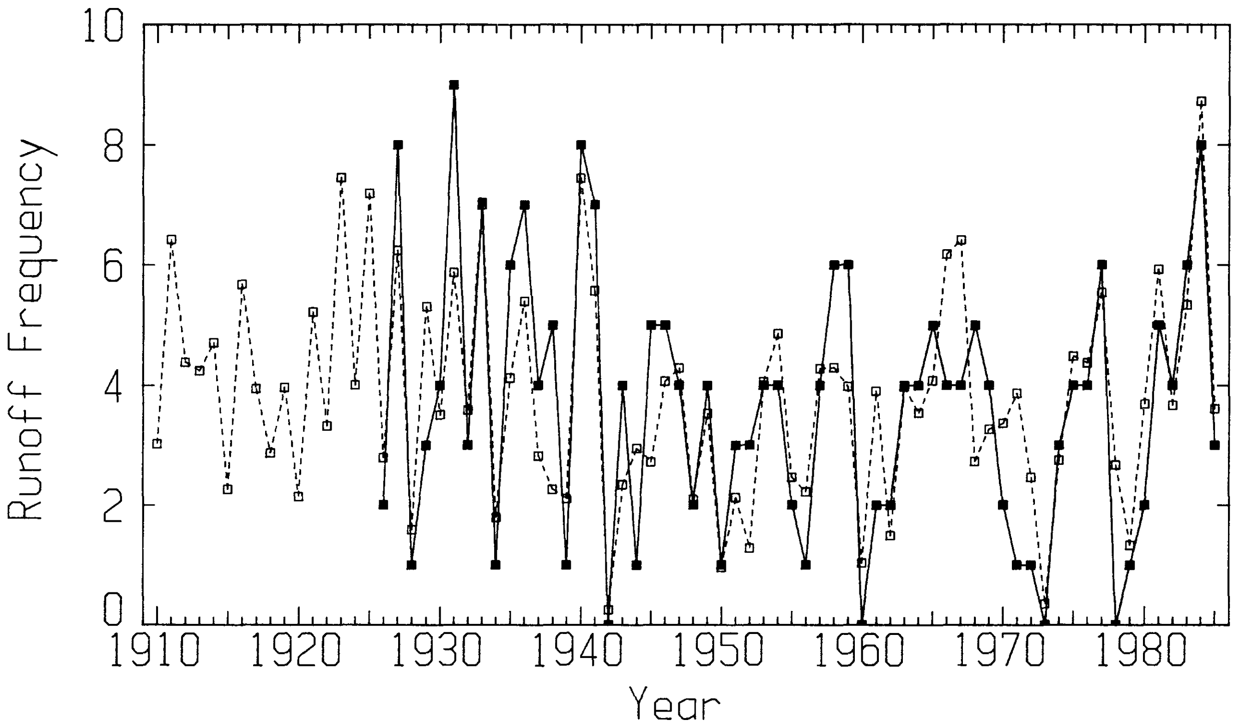

A
B
Teragrams
Teragrams
1.2
1
0.8
0.6
0.4
0.2
0
Jan
Feb
Mar
Apr
May
June
July
Aug
Sep
Oct
Nov
Dec

Figure 7



Runoff Frequency
Year
0
2
4
6
8
10
1910
1920
1930
1940
1950
1960
1970
1980

Figure 8

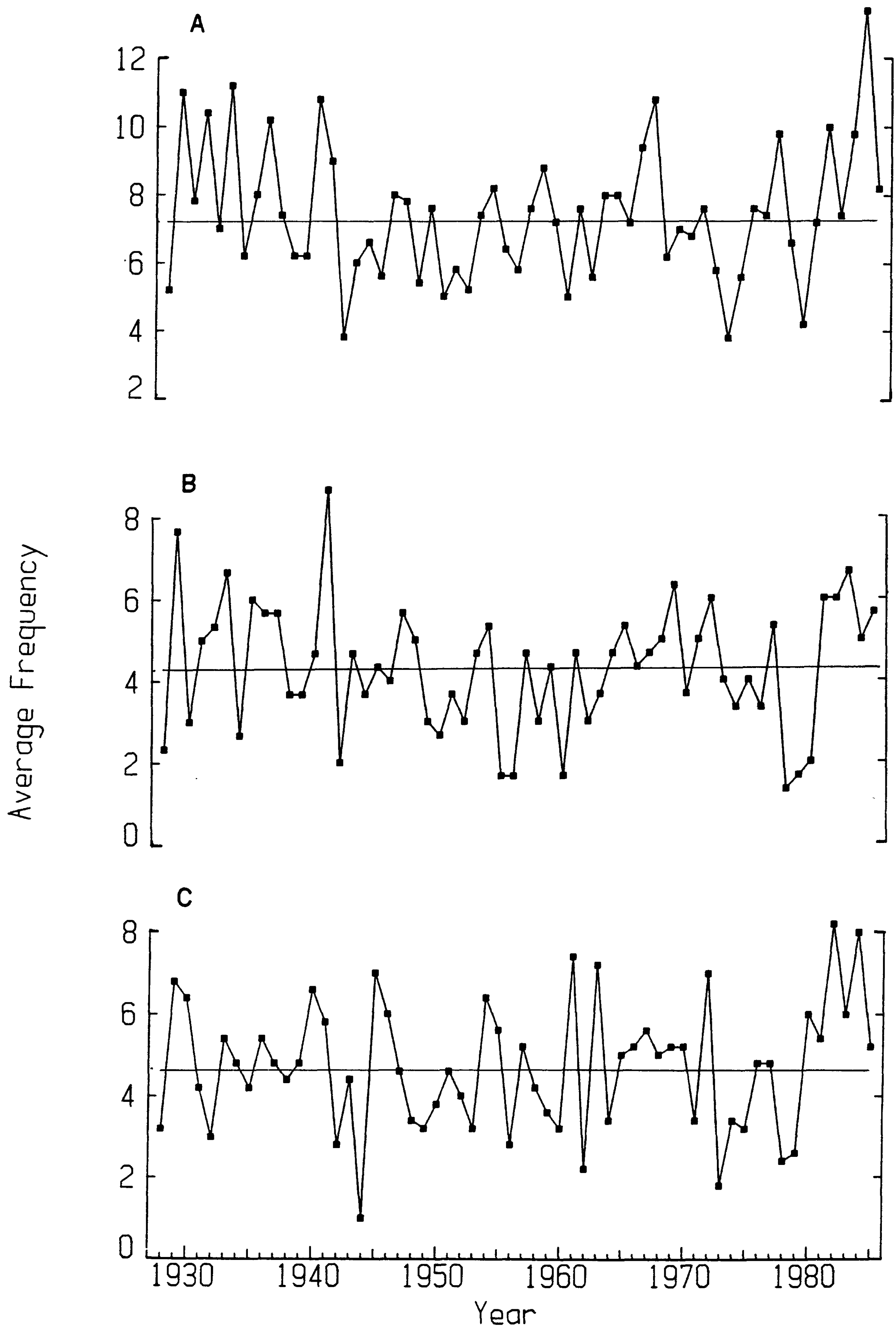

A
12
10
8
6
4
2
B
8
6
4
2
0
C
8
6
4
2
0
Average Frequency
1930
1940
1950
1960
1970
1980
Year

Figure 9

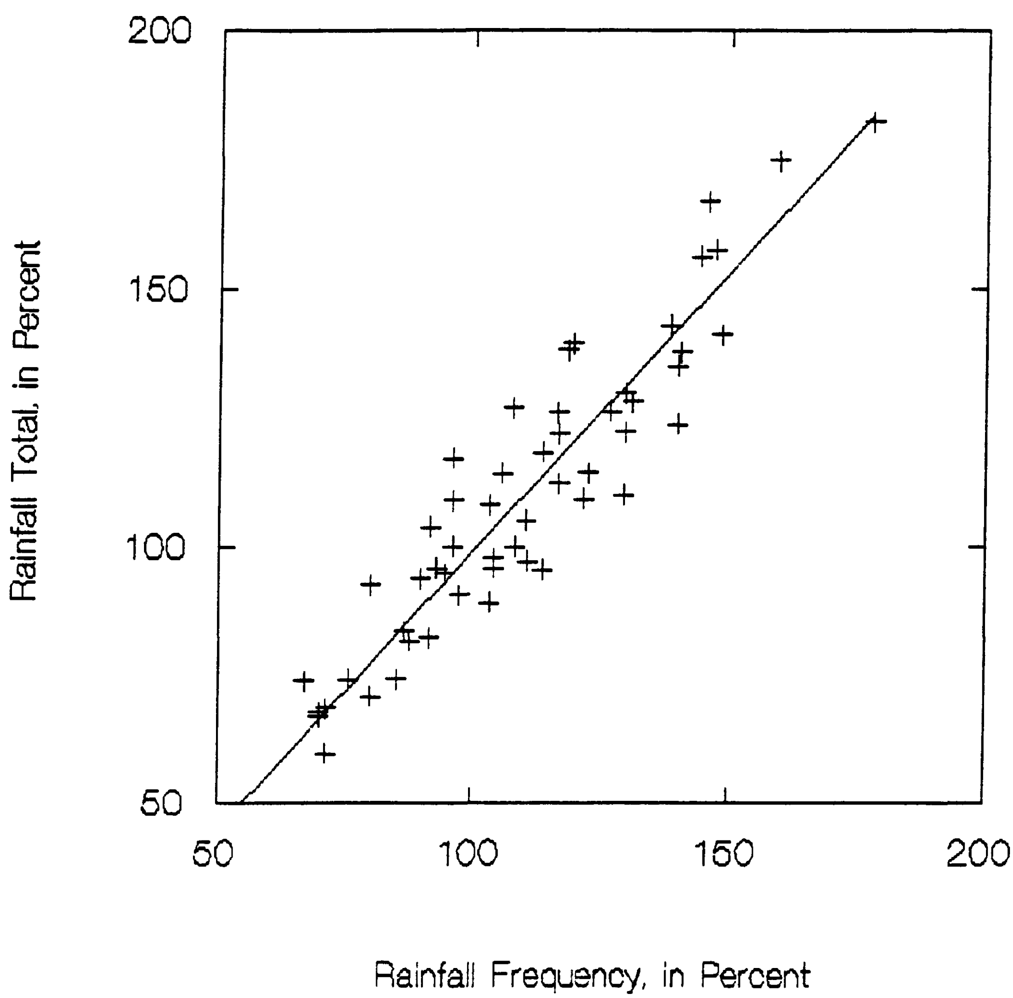
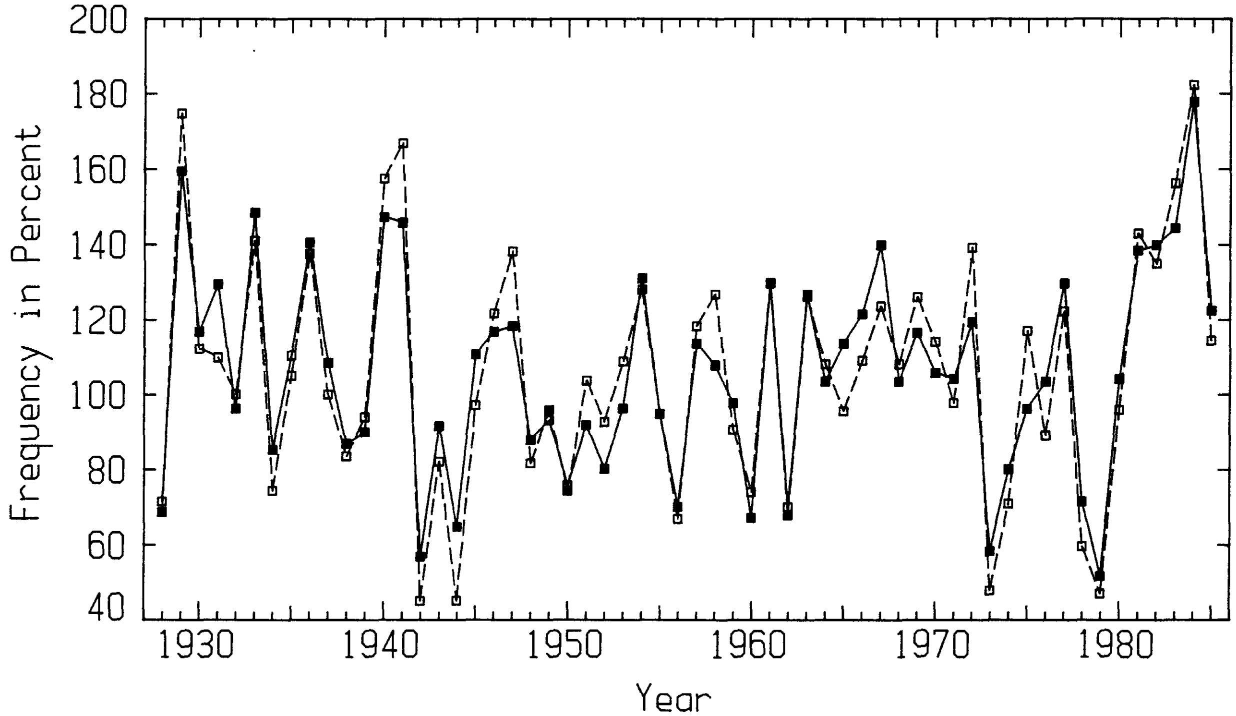
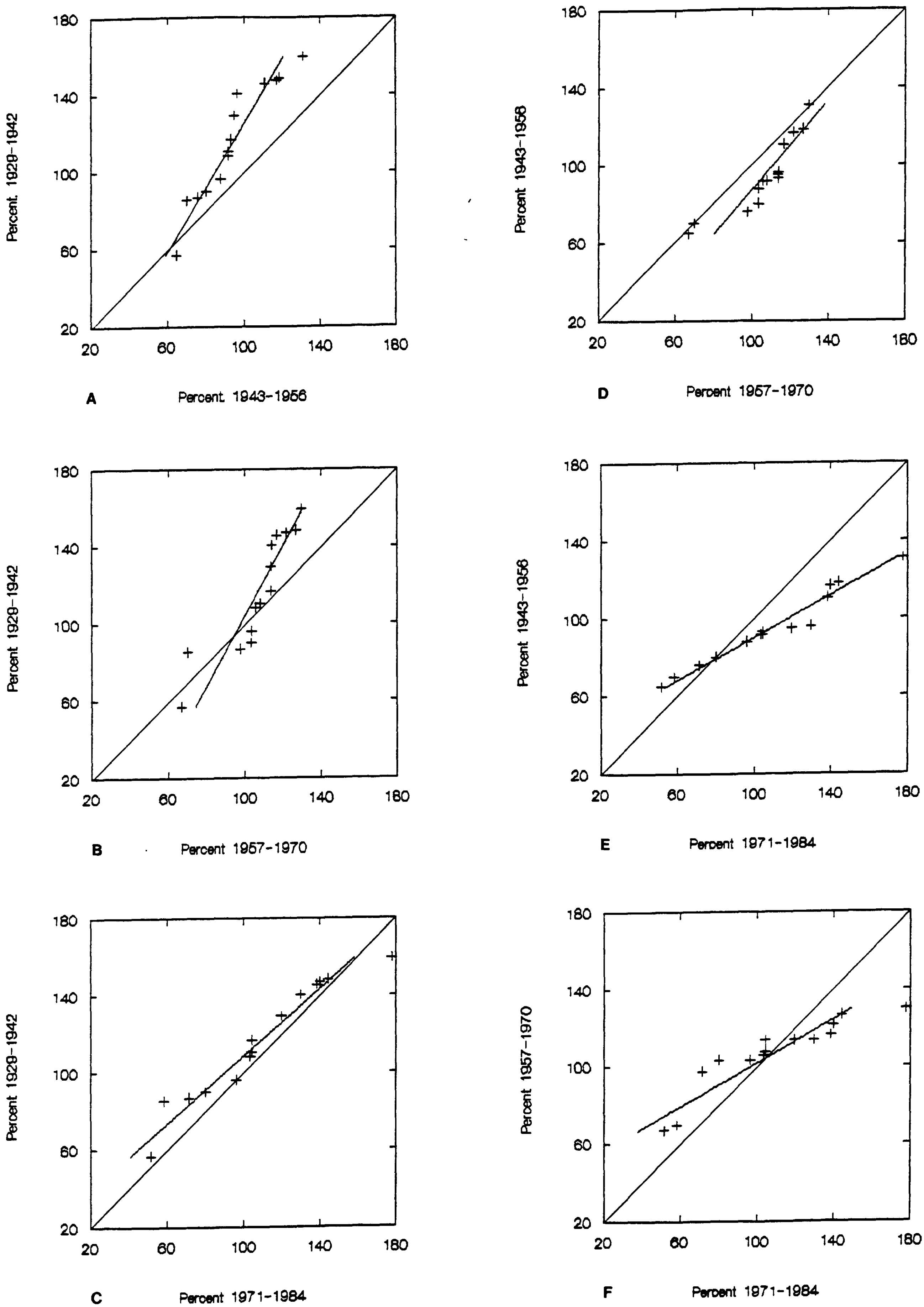

200
150
100
50
Rainfall Total, in Percent
50
100
150
200
Rainfall Frequency, in Percent

Figure 10



200
180
160
140
120
100
80
60
40
Frequency in Percent
1930
1940
1950
1960
1970
1980
Year

Figure 11



A
Percent 1929-1942
Percent 1943-1956
B
Percent 1929-1942
Percent 1957-1970
C
Percent 1929-1942
Percent 1971-1984
D
Percent 1943-1956
Percent 1957-1970
E
Percent 1943-1956
Percent 1971-1984
F
Percent 1957-1970
Percent 1971-1984
20
60
100
140
180

Figure 12

Table 1. Climatic and hydrologic records processed for this study

Climate Data

Station	Beginning Date	Ending Date	Percent Missing Days
Alton, Utah	06/01/15	12/31/85	.3[a]
Blanding, Utah	12/01/04	12/31/85	2.9[a]
Bloomfield, N. Mex.	03/01/25	12/31/85	9.8[a]
Bluff, Utah	01/01/28	12/31/85	1.2[a]
Bryce Canyon, Utah	07/01/48	05/31/59	.02[b]
Cedar City, Utah	01/01/14	12/31/86	.007[a]
Chaco, N. Mex.	01/01/48	12/31/85	1.6[b]
Chinle, Ariz.	12/01/08	11/30/70	14.9[c]
Dulce, N. Mex.	06/01/06	12/31/85	8.8[c]
Escalante, Utah	05/01/01	12/31/85	11.3[c]
Flagstaff, Ariz.	01/01/50	12/31/85	.3[b]
Fort Valley, Ariz.	01/01/09	12/31/85	.9[a]
Gallup, N. Mex.	04/01/48	12/31/79	6.4[b]
Hatch, Utah	07/01/48	12/31/86	3.0[b]
Holbrook, Ariz.	01/01/00	12/31/85	6.7[a]
Hite, Utah	01/01/49	11/30/62	7.2[b]
Kanab, Utah	01/01/14	12/31/85	.03[a]
Kayenta, Ariz.	06/01/15	03/31/78	14.1[c]
Lees Ferry, Ariz.	04/01/16	12/31/85	11.5[c]
Panquitch, Utah	07/01/48	12/31/86	4.2[b]
Santa Fe, N. Mex.	01/01/00	03/31/72	1.4[b]
Shiprock, N. Mex.	01/01/48	11/30/85	8.2[b]

Table 1 continued

Snowflake, Ariz.	01/01/00	12/31/85	9.0[a]
Springerville, Ariz.	04/01/11	12/31/85	.7[a]
St. George, Utah	01/01/28	12/31/86	1.0[a]
Tropic, Utah	02/01/14	12/31/86	5.4[b]
Tuba City, Ariz.	01/01/00	12/31/75	8.3[b]
Winslow, Ariz.	01/01/00	12/31/85	12.1[a]
Zion NP, Utah	01/01/28	12/31/86	.1[a]
Hydrologic Data			
Little Colorado River	10/01/1925	12/31/87	0.0
Paria River	10/01/1923	12/31/87	0.0
Paria River Sediment	10/01/1948	09/30/76	0.0
Colorado River Sediment	09/30/30	01/01/1964	10.0

[a] Station used in rainfall frequency analysis
[b] Station exlcuded because of short record
[c] Station excluded because of numerous missing days in the studied season, or from 1935-1945, or both

Table 2. Location and elevation of southern Colorado Plateau weather stations used in this study

Station	Latitude	Longitude	Elevation (m)
	<u>Little Colorado River Basin Group</u>		
Fort Valley, Ariz.	35°16'00"	111°44'00"	2,239
Holbrook, Ariz.	34°32'24"	110°06'36"	1,549
Snowflake, Ariz.	34°19'12"	110°03'00"	1,707
Springerville, Ariz.	34°05'24"	109°10'48"	2,124
Winslow, Ariz.	35°00'36"	110°25'48"	1,480
	<u>Northeast Group</u>		
Blanding, Utah	37°22'12"	109°17'24"	1,861
Bloomfield, N. Mex.	36°25'48"	107°35'24"	1,658
Bluff, Utah	37°10'48"	109°19'48"	1,317
	<u>Northwest Group</u>		
Alton, Utah	37°16'12"	112°17'24"	2,145
Cedar City, Utah	37°24'00"	113°02'24"	1,778
Kanab, Utah	37°01'48"	112°19'12"	1,496
St. George, Utah	37°03'36"	113°21'00"	842
Zion NP, Utah	37°12'00"	112°34'12"	1,219

Table 3. Variation in length of summer rainfall season before 1943 and after 1942 at 13 weather stations

Station	Before 1943 Season[a] and Period[b]	After 1942 Season[b] and Period[c]	Difference in Percent[d]
Little Colorado River Basin Group			
Fort Valley, Ariz.	06/14-10/16 1909-1942	06/21-09/15 1943-1976	-30
Holbrook, Ariz.	06/17-10/08 1900-1942	06/28-10/23 1943-1985	5
Snowflake, Ariz.	06/15-11/02 1901-1942	06/27-10/07 1943-1984	-25
Springerville, Ariz.	06/17-10/15 1912-1942	06/26-10/24 1943-1973	0
Winslow, Ariz.	06/22-11/02 1909-1942	06/29-10/07 1943-1976	-25
Northeast Group			
Blanding, Utah	06/15-11/03 1905-1942	06/04-09/02 1943-1980	-35
Bloomfield, N. Mex.	06/17-10/10 1926-1942	06/27-09/03 1943-1959	-40
Bluff, Utah	06/15-11/04 1928-1942	07/13-10/05 1943-1957	-40
Northwest Group			
Alton, Utah	07/03-11/04 1916-1942	06/30-09/30 1943-1969	-25
Cedar City, Utah	06/25-09/25 1914-1942	07/13-09/15 1943-1971	-30
Kanab, Utah	06/21-10/14 1914-1942	06/28-09/13 1943-1971	-35
St. George, Utah	07/03-10/03 1928-1942	07/11-09/16 1943-1957	-25
Zion NP, Utah	07/02-10/03 1928-1942	06/22-09/17 1943-1957	-5

[a] Season beginning and end by month and day
[b] Period is beginning of station record through 1942
[c] Period length equals the number of years in the pre-1943 period
[d] Post-1942 season length as a percent of pre-1943 length rounded to nearest five percent

Table 4. Results of t-test for the difference between two means (Mitchell and others, 1966) applied to the rainfall frequency time series. Comparison is first column with adjoining columns

	1929-1942	1943-1956	1957-1970	1971-1984
Average	115.8	94.5	106.5	108.5
sd[a]	30.4	19.2	18.5	35.8
df[b]		26	26	26
t[c]	2.22	0.981	0.554	
p[d]	0.02*	0.18	0.3	

	1928-1942	1943-1979
Average	112.9	98.8
sd[a]	31.5	22.5
df[b]		50
t[c]		1.82
p[d]		0.04*

[a] Standard deviation
[b] Degrees of freedom
[c] t-statistic
[d] Probability that the two averages are equal

Table 5. Regression analysis of runoff and rainfall frequency.

Analysis of Variance

Source	Sum of Squares	DF[a]	Mean Square	F-Ratio	P[b]
Regesssion	118.8	5	37.0	17.7	0.000
Residual	112.9	54	2.1		
Percent Variance (R^2)		62.1[c]			
Standard Error of Estimate		1.5			

[a] Degrees of freedoom

[b] Probability that no relation exists between runoff and rainfall frequency

[c] Runoff variation explained by regression

Table 6. Year of moderate to intense ENSO (El Nino-Southern Oscillation; from Andrade and Sellers, 1988) and relation to rainfall frequency, 1928-1985

Year	ENSO Intensity	Rainfall Frequency
1929	Moderate	Very High
1930	Moderate	Above Average
1939	Moderate	Average
1941	Intense	Very High
1953	Moderate	Above Average
1957	Intense	Above Average
1958	Intense	Above Average
1965	Moderate	Average
1972	Intense	Above Average
1973	Intense	Very Low
1976	Moderate	Below Average
1982	Intense	Above Average
1983	Intense	Above Average