Relation of sediment load and flood-plain formation to climatic variability, Paria River drainage basin, Utah and Arizona

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ABSTRACT

Suspended-sediment load, flow volume, and flood characteristics of the Paria River were analyzed to determine their relation to climate and flood-plain alluviation between 1923 and 1986. Flood-plain alluviation began about 1940 at a time of decreasing magnitude and frequency of floods in winter, summer, and fall. No floods with stages high enough to inundate the flood plain have occurred since 1980, and thus no flood-plain alluviation has occurred since then. The decrease in magnitude and frequency of floods appears to have resulted from a decrease in frequency of large storms, particularly dissipating tropical cyclones, and not from a decrease in annual or seasonal precipitation.

Suspended-sediment load is highest in summer and fall, whereas flow volume is highest in winter. Fall shows the greatest interannual variability in suspended-sediment load, flow volume, and flood size because climatic conditions are most variable in fall. The relation between sediment load and discharge apparently did not change within the period of sediment sampling (1949–1976), even though the channel elevation and width changed significantly. Annual suspended-sediment loads estimated for periods before and after 1949–1976 show that decrease in suspended-sediment load caused by flood-plain alluviation in the Paria River and other tributaries could have been a significant part of the decrease of suspended-sediment load in the Colorado River in the early 1940s.

INTRODUCTION

Long-term change in sediment transport of the Colorado River is an important factor in understanding the potential lifespan of dams (Thomas and others, 1960) and changes in sand bars used for recreational camping in Grand Canyon (Schmidt and Graf, 1990). Suspended-sediment load for a given discharge declined abruptly in the early 1940s in the Colorado River at Grand Canyon (Daines, 1949; Howard, 1960; Thomas and others, 1960; Hereford, 1987a). The decline in suspended-sediment loads has been attributed to improved land use and conservation measures initiated in the 1930s (Hadley, 1977). A change in sediment-sampler type and in methods of analysis have been discounted as causes for the observed decrease (Daines, 1949; Thomas and others, 1960).

Flood plains began to aggrade in tributaries of the Colorado River upstream from Grand Canyon in the early 1940s (Graf, 1987; Hereford, 1987b, 1987c). Investigations of flood-plain stratigraphy in the Paria and Little Colorado Rivers (Hereford, 1984, 1986) show that 1940–1980 was a period of development and aggradation of flood plains in northern Arizona and southern Utah. Channels were wide and unvegetated before about 1940, and subsequent aggradation produced narrow channels that became bounded by vegetated flood plains. Thus decreased sediment load in the Colorado River may have resulted from storage of sediment in tributary flood plains.

This paper builds on Hereford's (1986) work by investigating frequency of large floods and their relation to regional climatic variations and sediment load of the Paria River (Fig. 1). We relate changes in flood-plain aggradation along channels of the Paria River basin to regional climatic fluctuations and to local hydrologic characteristics. We examine whether flood-plain aggradation in this century is related to temporal variability in (a) basinwide precipitation, (b) low-frequency climatic and hydrologic variables, and (c) suspended-sediment load.

FLOOD-PLAIN SEDIMENTS AND STRATIGRAPHY

Modern flood-plain sediments have been deposited in the Paria River basin within arroyos cut into a terrace of late Holocene alluvial fill that rises 1–5 m above the modern channel bed. Flood-plain deposits are present in all major tributaries of the Paria River. The area of flood plains is slightly greater than 20 km^2, and sediment volume is estimated to be about 40 million m^3 (Hereford, 1987c). Typically, flood plains are not present in first-order drainage basins but are present in basins of second and higher order where the stream channel is unconfined and crosses nonresistant bedrock formations. Flood plains are absent in the deeply entrenched bedrock reaches, such as Kaibab Gulch, Buckskin Gulch, and Paria Canyon (Fig. 1), because the greatly reduced channel width and steep longitudinal gradient prevent deposition of sediment.

The stratigraphy of the modern alluvium has been described in detail by Hereford (1986). Flood-plain deposits are underlain by the "older channel alluvium" deposited during a period of frequent large floods between about 1880 and 1939. The older channel alluvium probably was deposited as bars and other transient channel features that were frequently reworked. Flood-plain deposits consist of three units that are present throughout the basin and average about 2 m in total thickness. The basal and intermediate units constitute about 25% of the total thickness. Flood-plain units are stratigraphically correlative throughout the basin, suggesting similar depositional histories for the Paria River and its tributaries.

The basal flood-plain unit is gravel with some sand, pebbles, and cobbles and is present locally. The intermediate unit is characterized by thin, discontinuous stratification and distinctive dark-colored beds of carbonaceous clay, silt, and minor sand. No basis for correlation of individual beds in the basal and intermediate units between outcrops has been found. These beds, therefore, have no clear relation to specific flood events. The upper flood-plain unit is mostly sand that typically has thick beds with continuous and parallel stratification separated by scour surfaces and accumulations of organic matter. Beds

Geological Society of America Bulletin, v. 103, p. 1405–1415, 11 figs., November 1991.

in this unit are clearly distinguished and are traceable in the cutbanks of mainstem and tributary stream channels. Beds are homogeneous and can be correlated wherever deposits are present in the drainage basin. Flood-plain units probably were deposited largely by vertical accretion that took place simultaneously throughout most of the basin. Each upper-unit bed probably represents deposits of a single overbank flood (Hereford, 1986).

Flood-plain deposits were dated at numerous localities (Fig. 1) by tree-ring and repeat photographic methods (Hereford, 1986). Deposition of the basal and intermediate units began after October 1939 and before 1946 and ended by about 1956. The upper unit was deposited between 1956 and February or September 1980.

DATA USED IN THE ANALYSIS

Streamflow and sediment data were collected by the U.S. Geological Survey (USGS) at the gaging station 09382000, "Paria River at Lees Ferry, Arizona" (Fig. 1). The station is near the mouth of the drainage basin, and data collected from this point represent discharge and sediment load from 3,650 km^2. Discharge and stage have been measured continuously at the gaging station from 1923 to the present. Daily suspended-sediment load was computed from daily or more frequent samples from 1949 to 1976. The Paria River is perennial, with a base flow of about 0.1–1 m^3/s, but most sediment is transported during floods of only 1–2 days duration. Daily mean concentrations as large as 780,000 mg/L have been measured during floods.

Published daily sediment load, daily mean discharge, and annual peak discharge (U.S. Geol. Survey, published annually) were used except for September 12 and 13, 1958. Discharge and sediment load were recomputed for those days using a revised peak discharge of 322 m^3/s (Anderson and White, 1979). The revision resulted in about a 40% decrease in suspended-sediment load for the 2-day runoff event. Daily precipitation values for 1923–1986 were obtained from the National Oceanographic and Atmospheric Administration, National Climatic Data Center, for Alton, Bryce Canyon National Park, Escalante, Kanab, and Tropic, Utah; and Lees Ferry, Arizona (Fig. 1).

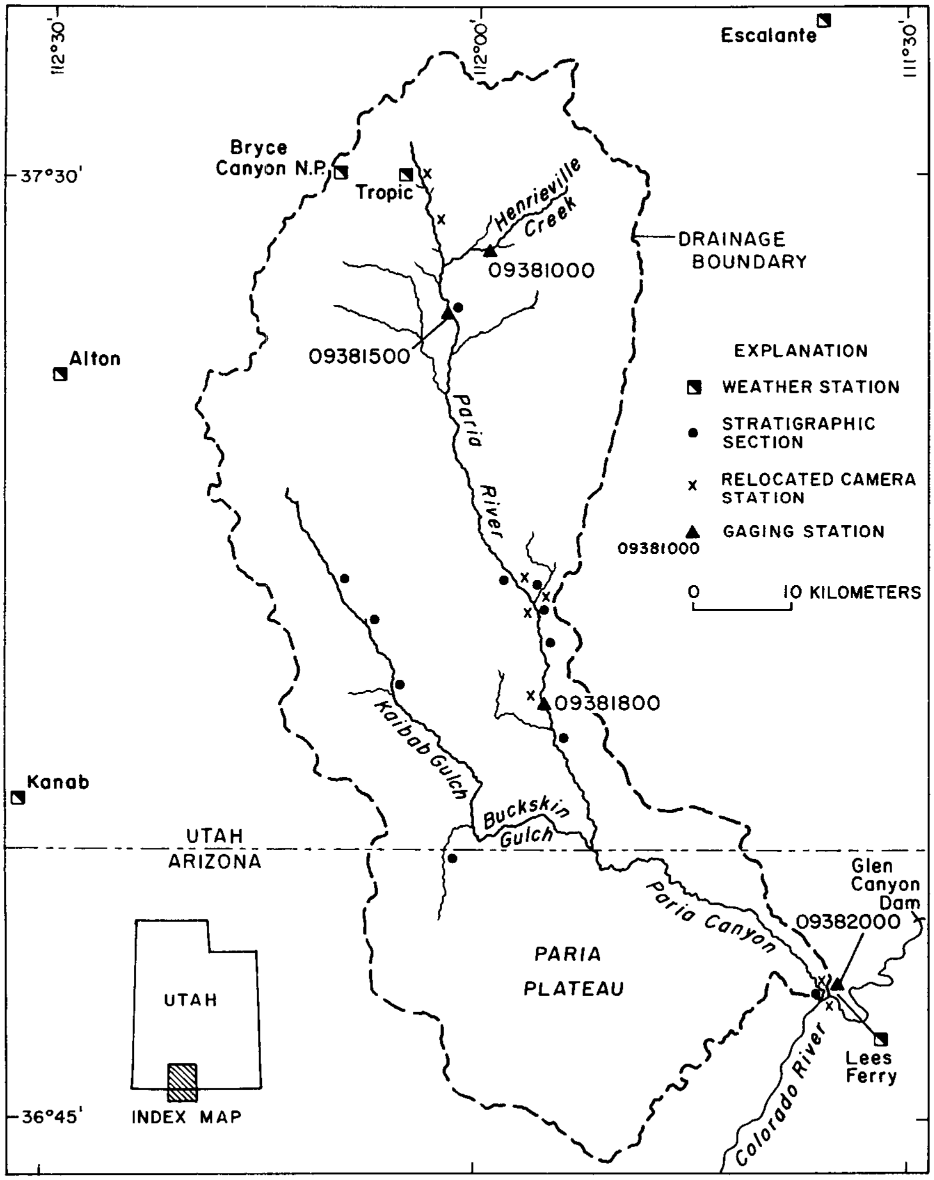

Figure 1. Paria River drainage basin in southern Utah and northern Arizona.

All sediment loads discussed in this report refer to suspended sediment and not total load. Samples of sediment moving along the bed have not been collected at this site, but unmeasured load estimated for four suspended-sediment samples collected in 1983 was 4% to 12% of the total load (Randle and Pemberton, 1987). Similarly, we assume that only a very small proportion of flood-plain sediment was bedload.

Daily sediment load of the Paria River has a large uncertainty, as does that of most streams, because of errors incurred in sampling, discharge measurement, and estimation of discharge from stage records in unstable channels (Burkham, 1985; Burkham and Dawdy, 1970). Sediment samples collected during runoff periods did not always define the shape of the sediment-concentration curve because floods on the Paria River are of short duration, and peak flow typically occurs at night. Data for the Paria River are not sufficient for a detailed numerical analysis of errors such as Burkham (1985) presented. We have assumed that errors, although large, are unbiased and have not changed with time.

CHARACTERISTICS AND VARIABILITY OF CLIMATE AND HYDROLOGY

Southern Utah has a highly variable semiarid climate because of its position between the temperate and tropical latitudes. Winter and spring precipitation results from frontal systems within a general westerly air flow associated with the circumpolar jet stream. Precipitable moisture in winter and spring originates from the North Pacific Ocean (Hansen and Shwarz, 1981). Summer precipitation results from local convective thunderstorms caused by moisture-laden air associated with large subtropical high-pressure cells, a phenomenon referred to as the "summer monsoon" (Reyes and Cadet, 1988). Fall precipitation typically results from cutoff low-pressure systems (Douglas, 1974), dissipating tropical cyclones (Smith, 1986), or frontal systems. Precipitable moisture in summer and fall originates from either the Gulf of Mexico or the tropical eastern North Pacific (Hansen and Shwarz, 1981).

Precipitation, runoff, and sediment transport are not uniformly distributed throughout the year (Fig. 2). We divided the year into four seasons to examine the seasonal characteristics of climate and hydrology. The seasons as defined here are winter, November 10 to April 17; spring, April 18 to July 3; summer, July 4 to September 3; and fall, September 4 to November 9. The water year, normally defined as October 1 to September 30, is redefined for purposes of this study as November 10 to November 9. The breaks between seasons were selected from examination of the annual cycles of rainfall, discharge, and sediment transport (Fig. 2) to define periods that are approximately uniform. Although rainfall, discharge, and sediment were all considered in determination of the seasonal boundaries, for clarity the boundaries are shown only on the center graph of Figure 2.

Basinwide Precipitation Estimates and Runoff

Precipitation data from the six weather stations in Figure 1 were combined to obtain an estimate of basinwide precipitation. Daily precipitation at each station was summed for each season of each year. Annual seasonal precipitation at each station was weighted by the percentage of drainage area in the elevation range represented by the station. Elevation ranges were established at 460-m intervals between the lowest (1,100 m) and highest (3,140 m) points in the basin. This method is better than weighting by area alone, as in the more traditional Thiessen method (Linsley and others, 1982), because of the strong orographic effect on precipitation (Hansen and Shwarz, 1981). The stations with the highest weights were Tropic (1,960 m) and Alton (2,100 m), because 57% of the basin is between 1,830 and 2,290 m. Tropic was given a higher weight than Alton because Tropic is in the drainage basin. The stations with the lowest weights were Bryce Canyon National Park (2,430 m) and Lees Ferry (1,100 m), because only 11% of the basin is either below 1,370 m or above 2,290 m. Seasonal basinwide precipitation (*BWP*) is defined as

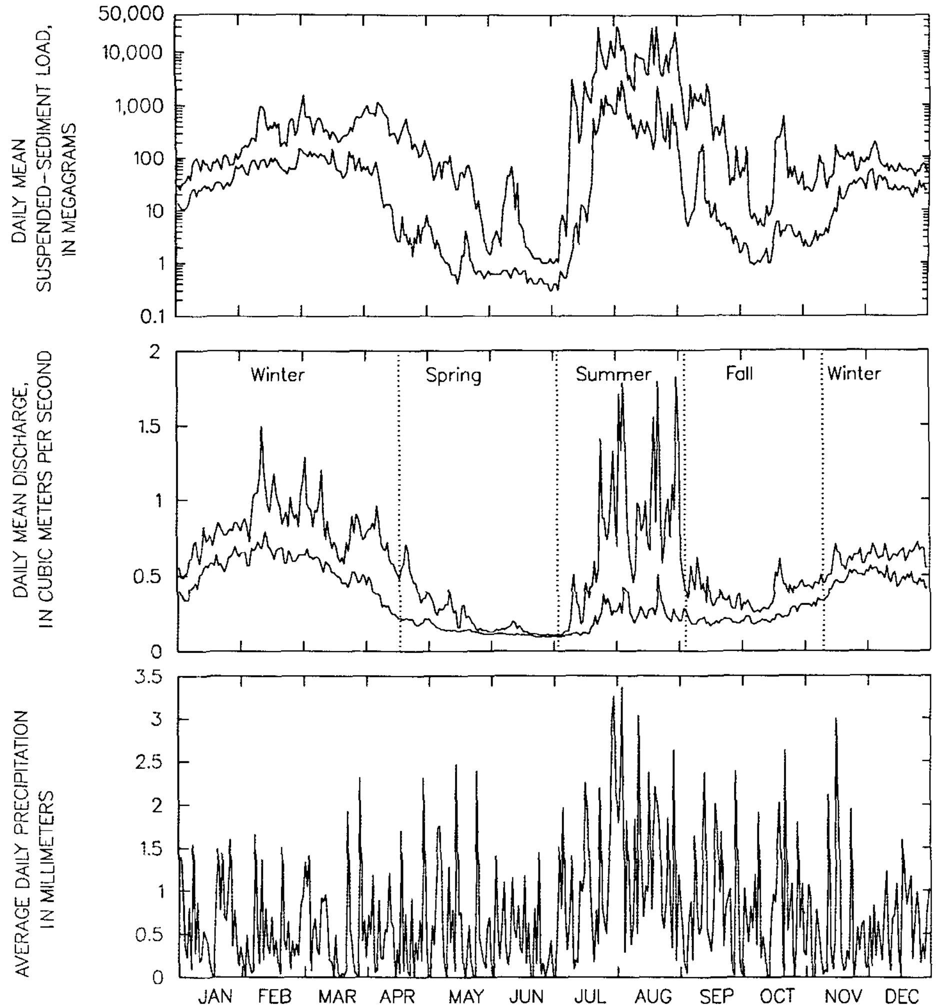

Figure 2. Seasonal variation in precipitation, runoff, and suspended-sediment load, Paria River basin, 1949–1976. Precipitation (bottom) is illustrated using average daily precipitation at Escalante, Utah, filtered to remove variations of less than 5-days duration. Five other stations were also used in the determination of basinwide precipitation. Daily mean discharge (middle graph) and daily suspended-sediment load (upper graph) are from the gage on the Paria River at Lees Ferry. The solid line on the upper two graphs is the median; the dotted line is the 75th percentile. Seasons as defined in this report are indicated on the middle graph.

$$BWP = 0.07\,PB + 0.34\,PT + 0.23\,PA + 0.16\,(PK + PE) + 0.04\,PLF \quad (1)$$

where *PB*, *PT*, *PA*, *PK*, *PE*, and *PLF* are seasonal precipitation at Bryce Canyon National Park, Tropic, Alton, Kanab, Escalante, and Lees Ferry, respectively.

Total annual and seasonal annual precipitation for 1923–1986 was estimated using equation 1. Estimated basinwide annual precipitation is 347 mm, with 166 mm (47%) occurring in winter; 40 mm (12%), in spring; 76 mm (22%), in summer; and 65 mm (19%), in fall. In comparison, the percentage of average annual flow volume at the Lees Ferry gaging station is 42% in winter, 7% in spring, 26% in summer, and 25% in fall. For 1949–1976, 8% of the annual flow volume and 2% of the annual sediment load passed the gage in spring. Spring was excluded from further analysis because that season has insignificant precipitation, runoff, and sediment load (Fig. 2). The time series of seasonal basinwide precipitation over the period of gaging record (Fig. 3) illustrates high interannual variability in fall and, to a lesser degree, in summer; winter precipitation is less variable. Nonpara-

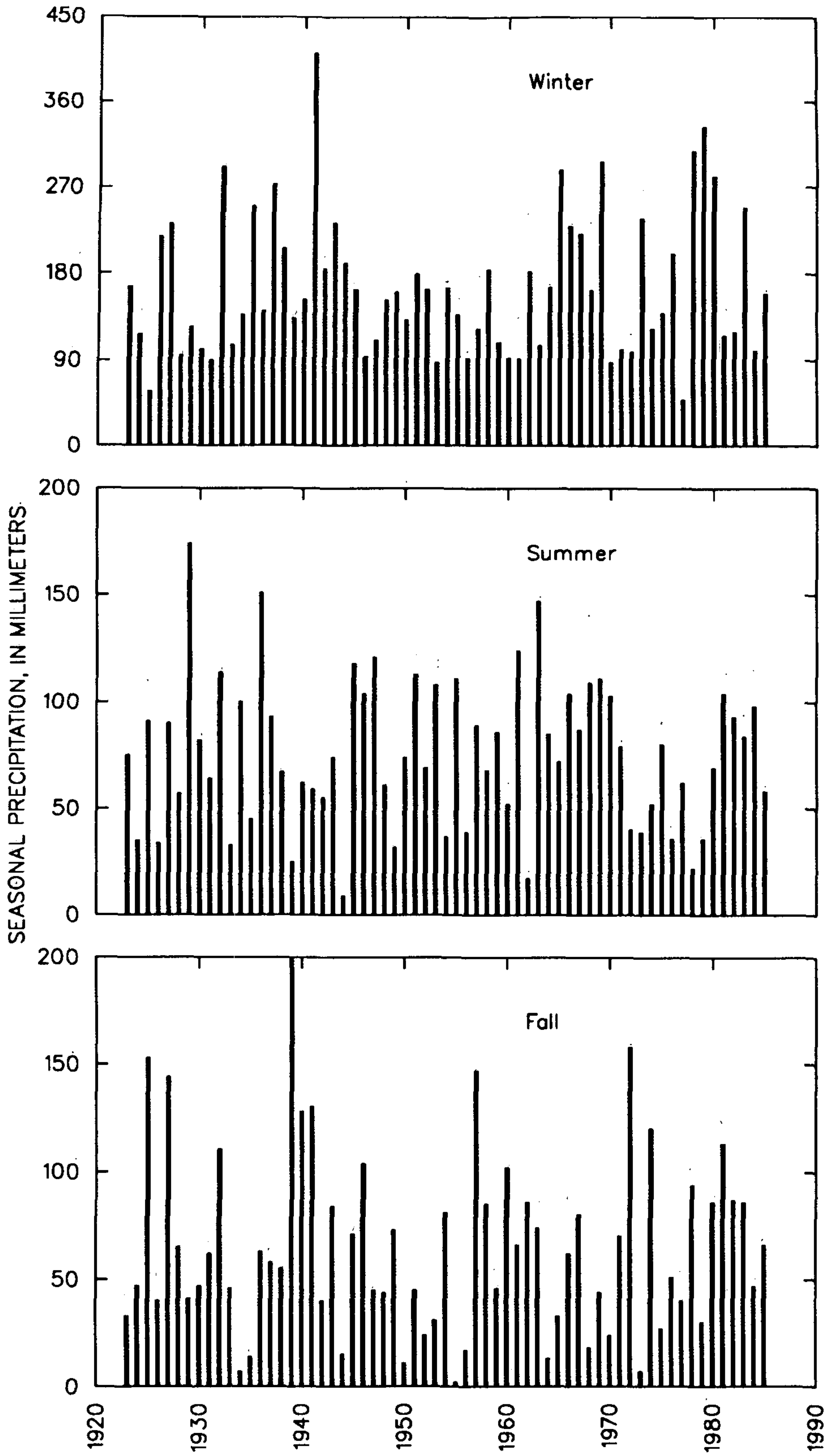

Figure 3. Basinwide precipitation in the Paria River basin, 1923–1986, for summer, fall, and winter seasons, developed from six point rain gages. The locations of the gages are shown in Figure 1.

metric Kendall's tau analysis (Conover, 1980) yields no systematic changes in the seasonal precipitation between 1923 and 1986.

Low-Frequency Climatic and Hydrologic Fluctuations

Twentieth-century fluctuations of storm types may explain temporal variation in precipitation, runoff, flood frequency, sediment load, and flood-plain formation. Fluctuations in intensity of precipitation that have affected Southwestern rivers are reported by Leopold and others (1966) and Cooke and Reeves (1976). Precipitation intensity increased in about 1880 and decreased in the 1920s in northern New Mexico and southern Arizona. Webb (1985) found that the period of greater precipitation intensity lasted until about 1940 in southern Utah and northern Arizona.

Changes in precipitation intensity are related to changes in storm types, which are related to atmospheric circulation and oceanic processes. El Niño–Southern Oscillation (ENSO) conditions occur when abnormally warm water is present in the eastern equatorial Pacific Ocean; ENSO conditions are related to anomalous atmospheric circulation and climate worldwide (Rasmussen, 1984). The low frequency of extratropical cyclones passing over North America during the early 1940s (Reitan, 1980) coincides approximately with the strong ENSO conditions of 1940–1941 (Quinn and others, 1987). Temperatures in the Northern Hemisphere were at a maximum in 1942 (Kalnicky, 1974). The frequency of cyclonic activity decreased between 1950 and 1977 (Zishka and Smith, 1980) and the interannual variability in cyclones decreased in the early 1960s. These changes probably coincide with the ENSO conditions of 1957–1958 and 1963 (Quinn and others, 1987). Dzerdzeevskii (1970) and Kalnicky (1974) found an increase in meridional circulation in the upper atmosphere in the early 1950s and about 1960.

Although transitions in general circulation and precipitation series appear to be gradual (see Dzerdzeevskii, 1970; Kalnicky, 1974; Leopold and others, 1966), we broke the meteorological and hydrological time series for the Paria River basin at 1942, 1958, and 1980 to determine if differences among periods could be identified. The years 1942 and 1958 coincide approximately with climatic changes described above, and flood-plain aggradation ceased about 1980, although no general circulation or meteorological changes have been associated with that year. Major floods occurred on the Paria River in or near the years selected for breaks.

The percentage of time a given daily mean discharge was equaled or exceeded (duration of daily mean discharge) was calculated for 1923–1942, 1943–1957, 1958–1980, and 1981–1986. The duration curves (Fig. 4) illustrate the differences in hydrologic conditions among periods. In summer, discharges that were exceeded 10% or more of the time are about the same among the periods. Discharges exceeded less than 2% of the time (very high discharges), however, differ significantly among the periods (Fig. 4). For example, the discharge exceeded less than 1% of the time in summer decreased from 25 m^3/s in 1923–1942 to 9 m^3/s in 1981–1986. Similarly, the discharge exceeded less than 1% of the time in fall decreased from 42 m^3/s in 1923–1942 to 9 m^3/s in 1981–1986.

El Niño, Storm Types, and Flood Frequency

Precipitation variability and flood frequency in the Paria River basin are affected to some extent by the periodic occurrence of ENSO conditions in the Pacific Ocean (Rasmussen, 1984). During ENSO conditions, the combination of increased sea-surface temperatures and anomalous circulation patterns can lead to the incursion of severe storms in the western United States. ENSO conditions have occurred in fifteen of the years between 1923 and 1986 (see Quinn and others, 1987). Although average winter precipitation during ENSO conditions is 180 mm, or only 24 mm above the average for normal years, the highest amount of winter precipitation during the period of study (411 mm) occurred during the ENSO conditions of 1940–1941. Other years with ENSO conditions, such as 1930–1931 and 1953, coincided with winter droughts in the Paria River basin. The four highest precipitation totals in fall, however, occurred during the ENSO conditions of 1925–1926, 1939, 1957–1958, and 1972–1973. Average fall precipitation during ENSO conditions is 86 mm, or 42 mm above the average for normal years. Summer precipitation averages 71 mm during ENSO conditions and 78 mm during normal years.

ENSO conditions may affect the intensity and frequency of types of storms that cause floods in the Paria River basin. Winter floods are caused by several types of frontal systems (Hansen and Shwarz, 1981), and frontal systems may be enhanced by ENSO conditions (Rasmussen and Wallace, 1983). Summer floods typically result from convective thunderstorms of limited areal extent, although tropical cyclones can occur in summer months (Smith, 1986). Dissipating tropical cyclones, cutoff lows, or a combination of the two cause most fall floods (Hansen and Shwarz, 1981). The frequency of tropical cyclones that affect the southwestern United States may be increased as a result of warmer sea-surface temperatures in the tropical North Pacific Ocean during ENSO conditions. For example, the highest frequencies of tropical cyclones affecting the southwestern United States in the 20th century occurred during the ENSO conditions of 1925–1926, 1939, 1957–1958, 1976–1977, and 1982–1983 (see Smith, 1986).

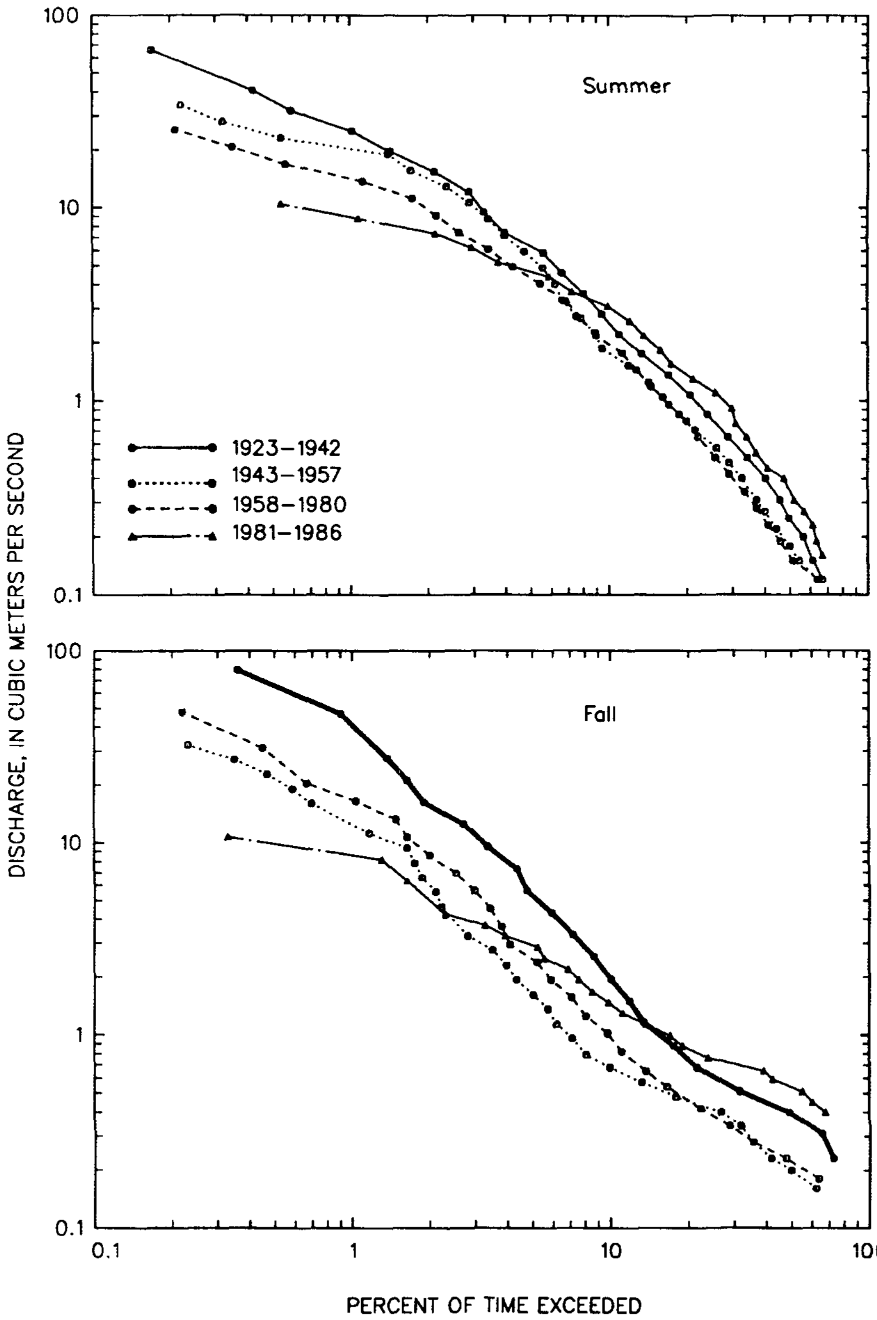

Figure 4. Duration of daily mean discharge, Paria River at Lees Ferry, for four periods.

Flood frequency on the Paria River was examined in three ways. First, the time series of peak discharges in each season within the hydroclimatic water year (November 10 to November 9) was examined and tested for trend. Second, all floods above a certain discharge were classified to determine the largest annual flood caused by three storm types: monsoonal storms, dissipating tropical cyclones, and frontal systems. Cutoff low-pressure systems, which could not be identified routinely before 1950 because of a lack of upper-atmospheric data, were included with frontal systems unless they were associated with tropical cyclones. Finally, two periods—before and after 1942—were examined for changes in flood frequency.

The distribution with time of the annual maximum flood of a season indicates that floods greater than 40 m^3/s can occur in winter, summer, and fall (Fig. 5). Four of the five largest floods occurred in the fall. Annual maximum floods occurred nearly equally in summer and fall. Winter floods were only 12% of the annual maximum floods. Annual maximum floods decreased significantly ($P < 0.000006$) from 1923–1986 (Fig. 5), according to a Kendall's tau trend analysis.

Floods above a base discharge of 40 m^3/s were segregated by season, and the largest in each of three seasons in each year were plotted (Fig. 5, left). The base discharge is defined for each gaging station as part of normal station operation to be that which is exceeded by three or four floods a year, on the average. These floods form a "partial duration series." Spring floods are not shown because only three floods were above base discharge. Summer and fall floods above the base discharge appear to be distributed evenly over the study period and to decrease in magnitude with time. Trend analysis using the Kendall tau test yields significantly negative slopes at $P < 0.016$ and $P < 0.005$ for summer and fall peaks, respectively. Winter floods appear to be clustered into two periods without trend.

Segregation of partial-duration series floods by storm type shows the controlling influence of tropical cyclones on flood frequency (Fig. 5, right). The flood of October 5, 1925 (456 m^3/s), which is the flood of record (rank 1), was caused by the combination of a cutoff low and a dissipating tropical cyclone (Hansen and Shwarz, 1981). Other large floods caused by dissipating tropical cyclones (Fig. 5) include the floods of September 13, 1927 (rank 2); September 12, 1958 (rank 5); August 28, 1932 (rank 6); and September 13, 1939 (rank 7). In contrast, the largest flood caused by a frontal system occurred March 3, 1938, and is ranked 15th. The frequency of tropical cyclone incursions that caused floods on the Paria River decreased significantly from 1923 to 1986. Of the 18 floods caused by dissipating tropical cyclones, 9 occurred in the 19 yr between 1923 and 1942, 6 in the 15 yr between 1943 and 1958, and only 3 in the 28 yr between 1958 and 1986. After 1963, most fall floods were caused by cutoff low-pressure systems without an associated tropical cyclone.

The significant decrease in magnitude of Paria River floods described above indicates that flood frequency has changed during the study period. Because small sample size yields large standard errors in flood-frequency estimates, the annual flood record was divided into only two periods (1923–1942 and 1943–1986). Log-Pearson Type III distributions were fitted to annual flood data from each period using standard techniques (U.S. Water Resources Council, 1981). The resulting distributions (Fig. 6) show a significant decrease after 1942 in flood frequency at all recurrence intervals greater than 1 yr. For example, the 10-yr flood decreased from 410 to 200 m^3/s after 1942 (Fig. 6). Similar changes in flood frequency were reported for the Escalante River basin, which borders the Paria River basin to the northeast (Webb and Baker, 1987). The changes in flood frequency (Fig. 6) and duration of daily mean discharge (Fig. 4) appear to be related to a decline in storms caused by dissipating tropical cyclones and winter frontal systems.

As noted above, the period of flood-plain aggradation began about 1940, and deposition of the upper unit began about 1956. Flood-plain formation, therefore, began during a period of decreased frequency of tropical cyclones, and the greatest rate of aggradation occurred during the period of lowest frequency of tropical cyclones. Flood-plain aggradation appears to occur when floods are large enough to overtop existing deposits but are too small to significantly erode the deposits. The coincidence of the initiation of the most recent period of flood-plain aggradation with the decrease in frequency of cyclonic activity in 1940–1942 and between 1950 and 1977 adds strong support to the hypothesis that flood-plain aggradation is related to the climate changes.

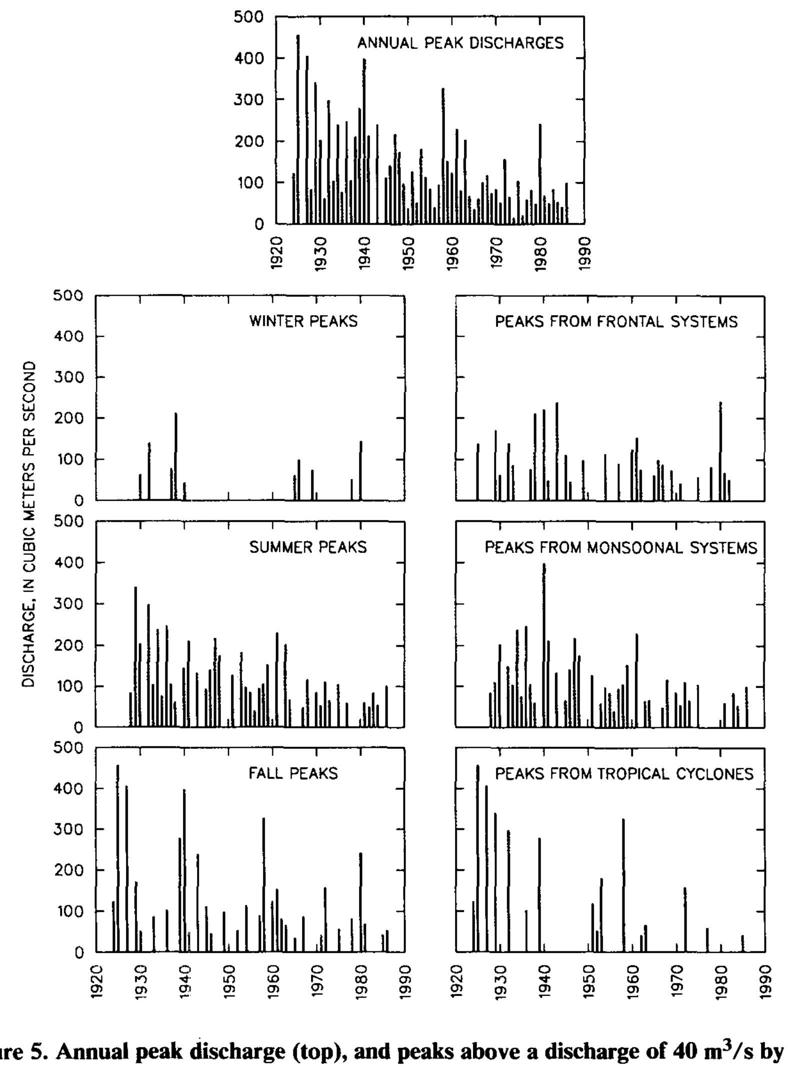

Figure 5. Annual peak discharge (top), and peaks above a discharge of 40 m^3/s by season (left) and by storm type (right), Paria River at Lees Ferry, 1923–1986. The water year is November 10–November 9 for the annual series.

CHARACTERISTICS AND VARIABILITY OF SUSPENDED-SEDIMENT LOAD

Seasonal Variation of Sediment Load

Sediment load of the Paria River varies greatly throughout the year (Fig. 2), and seasonality of flow volume and sediment load are significantly different. The seasonal distribution of flow volume was about the same during the pe-

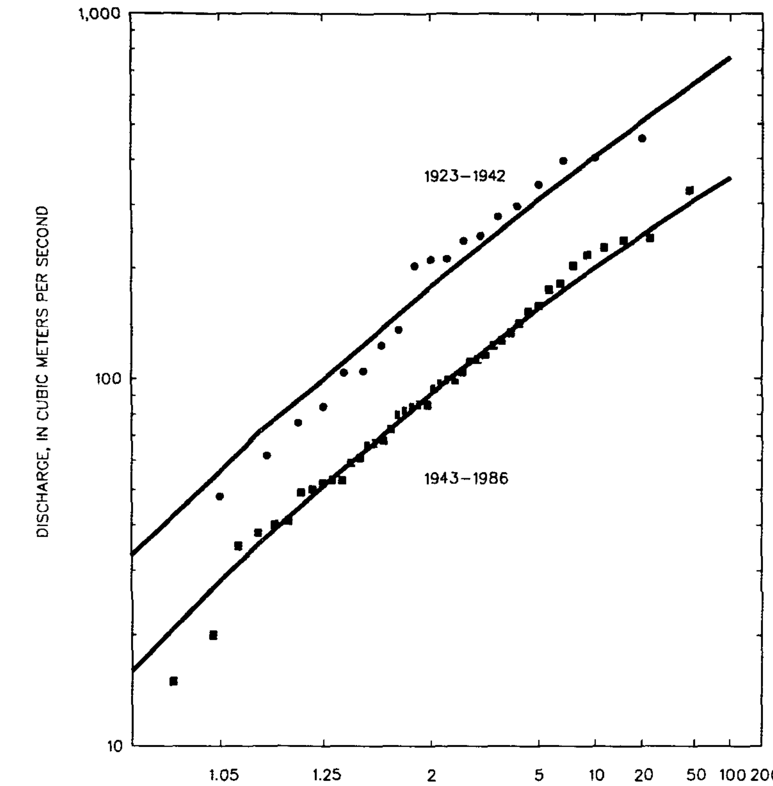

Figure 6. Log-Pearson type III flood-frequency relations, Paria River at Lees Ferry, for 1923–1942 and 1943–1986. The 95-percent confidence limits (not shown) indicate that the two relations are significantly different.

riod of sediment sampling (1949–1976) and the period of flow record (1923–1986), with 26% of the total annual flow in summer; 22%, in fall; and 44%, in winter; however, 57% of the sediment load was in summer; 34%, in fall; and 7%, in winter. Therefore, summer and fall seasons accounted for 48% of the annual flow volume but 91% of the annual sediment load. The seasonal difference in sediment loads also is shown by annual sediment load (Fig. 7), the duration of daily sediment loads (Fig. 8), and the regression relations between daily sediment load and daily mean discharge (Fig. 9) and between annual sediment load and annual flow volume (Fig. 10).

The seasonal distribution of sediment loads appears to be related to seasonal distribution of storm types. The intense thunderstorms typical of summer monsoons produce high sediment loads per unit volume of water (Fig. 7). The cutoff low-pressure systems, dissipating tropical cyclones, and frontal storms in fall produce sediment loads that are high but lower than those of summer storms. The frontal systems that produce widespread but less intense rainfall characterize the winter season and entrain little sediment (Fig. 7). Frozen ground and precipitation occurring as snow also may contribute to lower sediment loads in winter.

Trends in Sediment Load

The durations of daily sediment load for summer and fall have changed during the sediment-sampling period, and the changes mirror changes in the duration of daily mean discharge. To determine if daily sediment load and discharge changed in duration, we looked at data for two periods (1949–1956 and 1957–1976) that coincide with the latter part of the period of deposition of the lower flood-plain unit and the deposition of the upper unit, respectively. The period of most rapid deposition of the flood plain (1957–1976) was one of a higher frequency of high sediment loads than the preceding period, particularly in the fall (Fig. 8). The fact that daily mean discharge had a duration distribution similar to that of daily sediment load (Fig. 8) lends support to the assumption that changes in duration of daily sediment load with time are caused by changes in flow duration and not by changes in the sediment-discharge relation.

The relation between sediment load and discharge has not changed significantly within the period of sampling. No trend with time is shown by residuals from regressions of daily sediment load on daily mean discharge (Fig. 9). Annual sediment load, flow volume, and peak discharges for summer and fall (Fig. 7) do not have trends within the period of sediment sampling that are significant, using the Kendall tau test. As shown in the previous section, annual peaks over the longer period of surface-water analysis (1923–1986) have a significant decreasing trend. Annual flow volume, however, does not have a significant trend even for the longer period 1923–1984 (Webb, 1985).

Estimation of Sediment Loads, 1923–1948 and 1977–1986

We estimated suspended-sediment loads of the Paria River for 1923–1948 and 1977–1986 to test whether decreased loads in the Colorado River after the early 1940s might be related to sediment storage in tributary flood plains. The period 1949–1976, when sediment samples were collected, did not include the time of change from an erosional regime to a depositional one in the flood plain (about 1940). Channel width and rate of flood-plain deposition, however, did change significantly during 1949–1976. The upper flood-plain unit was deposited after 1956, and the major change in rate of decrease of channel width coincided with the beginning of deposition of that unit. That these changes have apparently not caused a change in the relation between suspended-sediment loads and discharge suggests that at least order-of-magnitude estimates of suspended-sediment loads outside the sampling period can be obtained using relations developed from data within the sampling period.

Equations relating annual sediment load to annual flow volume were computed from 1949–1976 data for each season. In summer and fall, sediment load for a given flow volume is high, and load approaches zero as the annual flow volume approaches zero (Fig. 10). Winter data cover a much smaller range in sediment load and a larger range in flow volume (Fig. 10), and winter sediment loads tend to approach zero at flow volumes well above zero.

Least-squares linear regression of annual seasonal suspended-sediment load and flow volume was used to compute equations for summer, fall, and winter seasons (Fig. 10). Annual rather than daily values were used because we believe the uncertainties in the daily values do not warrant extension of the sediment-load record and because annual values are well correlated with flow volume. Application of the summer and winter regression equations beyond the range of data used in their development results in negative loads for years of very low flow volume. The simple expedient of setting to zero any negative loads was used in these calculations. The median value of spring load (0.02 Tg) was used to estimate spring load outside the period of sediment sampling. These equations were used to

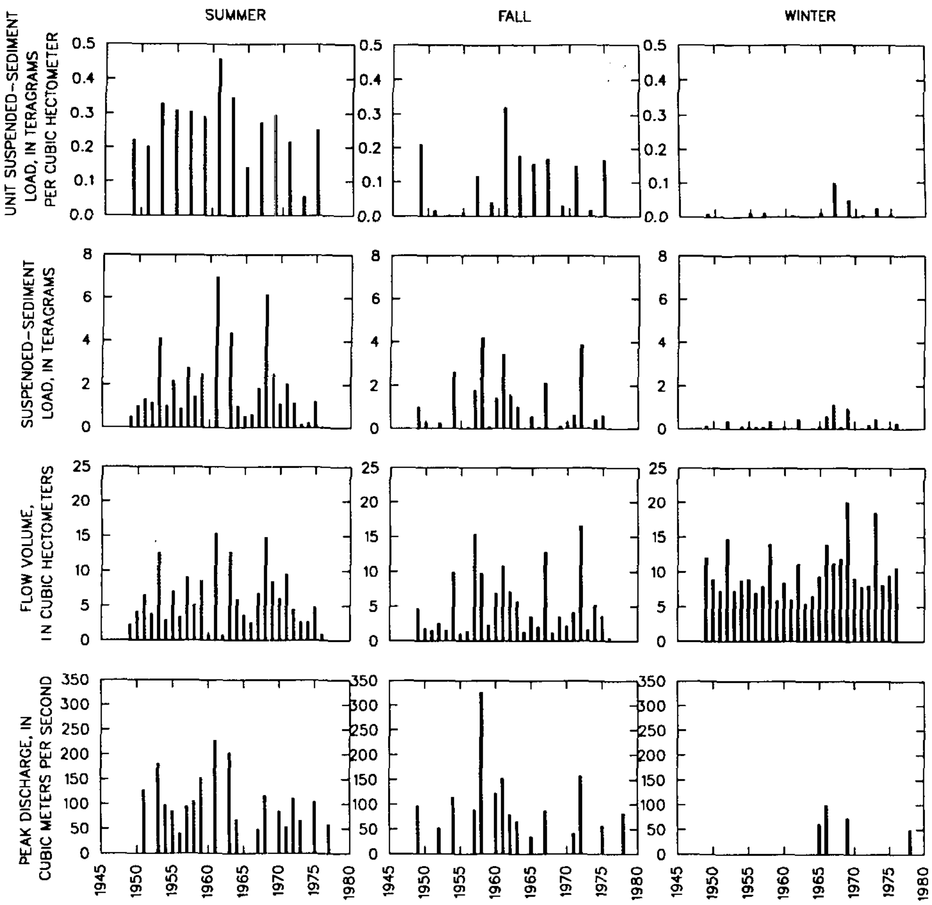

Figure 7. Annual unit suspended-sediment load, total suspended-sediment load, annual flow volume, and annual peak discharge for summer, fall, and winter seasons, 1949–1976, Paria River at Lees Ferry.

estimate sediment load for 1923–1948 and 1977–1986.

We estimated the total load of the Paria River to determine the fraction of total load that was stored on flood plains between 1940 and 1980. The assumption is made that during periods of no flood-plain deposition all sediment delivered is transported through the Paria River drainage to Lees Ferry, where loads can be estimated. We assume that flood-plain deposits are derived only from the suspended load. The grain-size distribution of suspended sediment is highly variable but is similar to flood-plain sediment at flood flows. An average of 107 samples of flood-plain sediment contained 80% sand, 12% silt, and 8% clay. Distributions from four floods (Beverage and Culbertson, 1964, fig. 2) range from about 2.5% to 25% clay, 7.5% to 10% silt, and 50% to 90% sand.

The total volume of sediment stored in the flood plain is estimated from field mapping to be about 40 million m^3 upstream from Lees Ferry (Fig. 1, this report; Hereford, 1987c). Using a density of 1.68 Mg/m^3, we estimate the weight of sediment stored to be 67 Tg and the total measured suspended-sediment load for 1949–1976 to be 86 Tg. Sediment load for 1940–1980 is estimated to be 102 Tg, using the constant value for spring and the regression equations for summer, fall, and winter. Sediment load during flood-plain formation (the sum of the measured and the computed annual loads) is 169 Tg (67 + 102). The fraction of the total that was stored in the flood plain is 67/169 = 0.40. Therefore, the loads estimated using the regression equations are only 60% of the "true" total loads.

Annual suspended-sediment load for 1923–1939 and 1980–1986 was computed from seasonal annual flow volume using the relations given in Figure 10. Annual sediment load was estimated by summing the computed loads for the four seasons and dividing the estimated load by 0.60. The results show that decreased annual flow volume and the advent of sediment storage about 1940 probably reduced annual sediment load from about 6 Tg for 1930–1939 to about 2 Tg for 1940–1949 for the Paria River. In the same periods, annual sediment load in the Colorado River near Grand Canyon decreased from 134 Tg to 107 Tg. The decrease in estimated load from the Paria River may account for about 14% of the total decrease in suspended-sediment load in the Colorado River downstream from the Paria River.

POTENTIAL EFFECTS OF LAND USE ON FLOOD-PLAIN FORMATION

Hereford (1986, 1987b) discussed possible causes of the change from stable or erosional channels to flood-plain aggradation. He concluded that factors such as land use and riparian vegetation changes may have contributed to flood-plain aggradation but that regional factors, such as climate, were the primary cause because flood-plain changes were regional. The regional nature of flood-plain aggradation is shown by the presence of the three stratigraphic units recognized in the Paria River basin in several southern Colorado Plateau streams (Hereford, 1987b). In addition, geomorphic studies show that flood plains, or other features indicative of alluviation, are present throughout the Colorado Plateau (Emmett, 1974; Leopold, 1976; Hereford, 1984; Graf, 1987).

Changes in land-use practices do not appear to coincide with flood-plain formation, channel-width changes, or changes in suspended-sediment load. The Paria River basin is largely undeveloped, steep, and rugged terrain. Grazing is the primary agricultural activity in the basin, but only about half the area in the Paria and adjacent drainage basins is considered suitable for grazing (U.S. Bureau of Land Management, 1980). Of that half, about 90% is in poor to fair condition because of past grazing or poor soil development (U.S. Bureau of Land Management, 1980). Grazing has declined since the early part of the century (Martha Hahn, U.S. Bureau of Land Management, Kanab, Utah, 1988, written commun.), but we have not been able to find evidence of an abrupt decline in the late 1930s. In the adjacent Escalante River basin, grazing peaked between 1900 and 1915, declined from 1915 to about 1930, and continued to decline more slowly from 1930 to 1950 (Webb and Baker, 1987). The most significant changes in land use appear to have taken place in the 1960s because grazing allotments were reduced after a range survey in 1963–1964 (U.S. Bureau of Land Management, 1980).

Although some small impoundments have been constructed (Hereford, 1987d), no large impoundments exist in the basin (Hereford, 1986). A barrier dam was built on Sheep Creek, a tributary to the Paria River, in about 1960, and 81 km^2 in the Sheep Creek basin were seeded in the late 1960s to improve rangeland (Bruce Greenwood, U.S. Bureau of Land Management, Kanab, Utah, 1988, oral commun.). Repeated surveys of the channel bed upstream from the Sheep Creek barrier dam and measurements of inflow and outflow from the impoundment made from 1960–1967 show that the reservoir was filled almost to the spillway by November 1961. The small number of impoundments and the rapid rate at which the Sheep Creek impoundment filled make it seem unlikely that impoundments could have a significant, long-term effect on sediment loads of the Paria River at Lees Ferry.

The channel near the Paria River gage (Fig. 1) aggraded about 0.4 m and decreased about 5 m in width from the 1940s until the mid-1960s (Fig. 11). Channel changes caused the stage-discharge relation to shift almost 2 m in that time. The channel has since degraded to about the 1950 elevation, but the width has continued to decrease slowly (Fig. 11). Post-1980 floods have failed to exceed the level of the aggraded flood plain near the gage. The present flood-plain elevation near the gage is equal to a stage of about 5.0 m, and the highest stage recorded at the gaging station between 1980 and 1986 was 3.6 m.

In a study of the Gila River in southeastern Arizona, Burkham (1972) concluded that seasonal frequency of floods has been a controlling factor in aggradation and erosion of the Gila River flood plain. The flood plain was eroded between 1905 and 1917 during a period of frequent large winter floods that carried small amounts of sediment and was rebuilt between 1918 and 1970 during years of low winter flood peaks and large sediment load. The coincidence of the onset of channel degradation with the onset of winter floods above the base discharge (Figs. 5 and 11) suggests that seasonal distribution of floods controls the channel aggradation-degradation process in the Paria River as it apparently does in the Gila River (Burkham, 1972). Winter floods, although smaller and less frequent than summer and fall floods, carry very little sediment and have a greater ability to erode the channel than do summer and fall floods.

DISCUSSION AND CONCLUSIONS

The period of flood-plain alluviation in the Paria River basin (1940–1980) was characterized by distinctive climatic processes. Specifically, the magnitude and frequency of summer and fall floods and incursions of dissipating tropical cyclones were low, and winter floods generally were smaller than before 1940. In the Paria River basin, flood-plain alluviation ended at least temporarily in 1980, when summer and fall flood peak discharges had decreased and the flood plain had aggraded to an elevation at which it was no longer inundated by the floods.

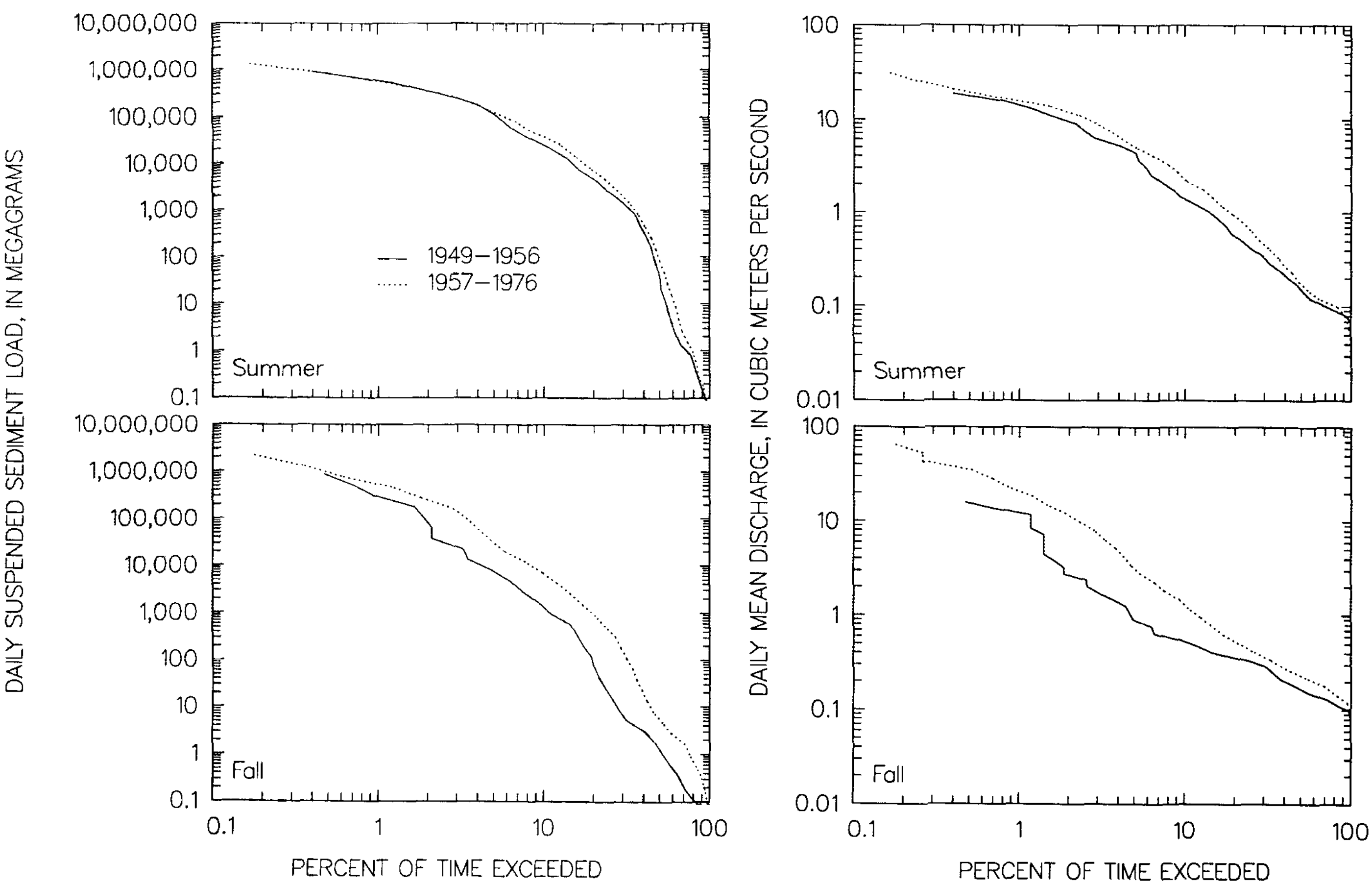

Figure 8. Duration of daily suspended-sediment load and daily mean discharge for summer and fall seasons for 1949–1956 and 1957–1976, Paria River at Lees Ferry.

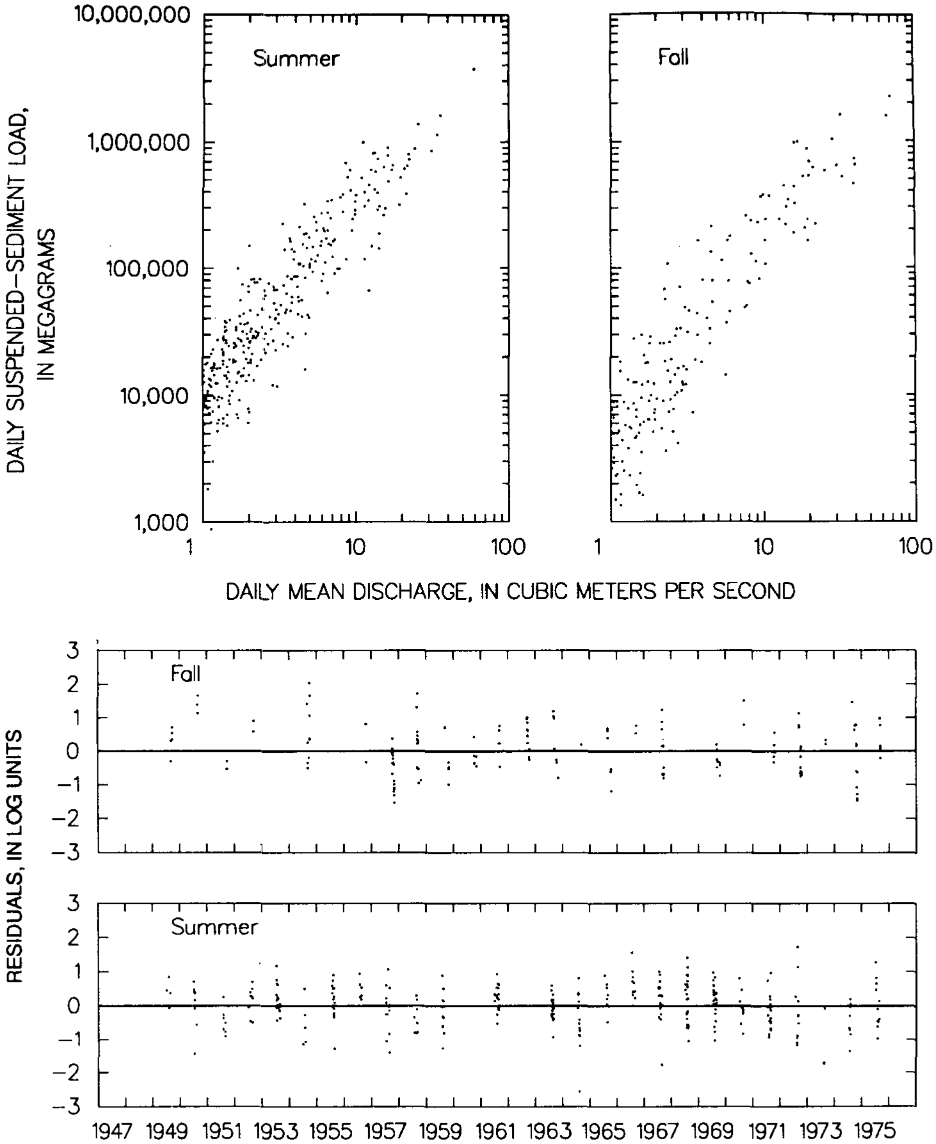

Figure 9. Relation of daily suspended-sediment load to daily mean discharge for summer and fall seasons, 1949–1976, Paria River at Lees Ferry, and residuals from the regressions. For clarity, only every tenth value for samples with discharge greater than 1 m^3/s and suspended-sediment load greater than 1,000 Mg are shown.

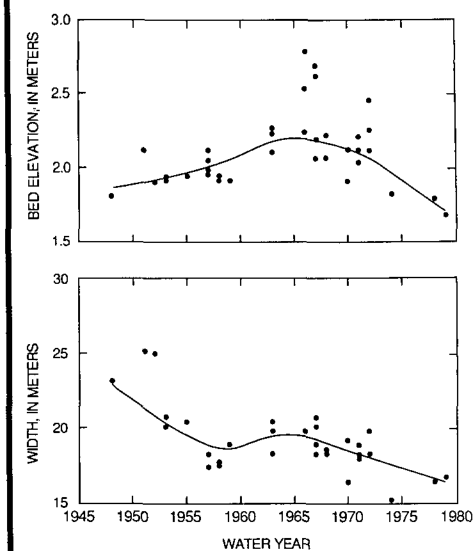

Figure 11. Channel changes, 1927–1986, Paria River at Lees Ferry, Arizona. Values were obtained from measurements of discharge greater than about 14 m^3/s. Measurements above 14 m^3/s were made at a cableway near the gage, whereas measurements at lower discharges were made by wading, and the section measured was not the same from measurement to measurement. Width is defined as the width of the channel at the water surface. Bed elevation is water-surface elevation minus the area divided by the width.

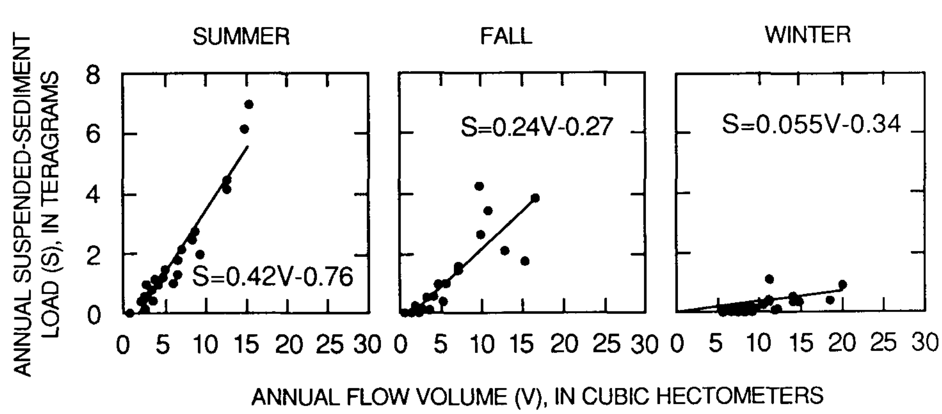

Figure 10. Relation of annual suspended-sediment load to annual flow volume for summer, fall, and winter, 1949–1976, Paria River at Lees Ferry. Suspended-sediment loads in spring are insignificant. Correlation coefficients and standard errors of estimate for the three equations are summer, 0.96 and 0.52; fall, 0.87 and 0.63; and winter, 0.80 and 0.095, respectively.

Flood-plain aggradation appears to be caused by large summer or fall floods, and flood-plain preservation seems to be aided by decreased flood frequency, particularly in winter.

Decreases in flood frequency, duration of high daily mean discharge, and changes in flood-plain alluviation are explained by low-frequency climatic fluctuations. Flood frequency decreased after 1942 in response to a decrease in the frequency of dissipating tropical cyclones and frontal systems. Intensity of precipitation decreased after about 1942, although seasonal amounts of precipitation show no temporal trend. The close relation between changes in frequency of floods, storms, and flood-plain alluviation strongly suggests that climatic fluctuations have a large effect on aggradation and degradation of the flood plain and channel and on sediment load in the Paria River.

Suspended-sediment load and flow volume of the Paria River have a distinct seasonality that is related to regional climatic conditions. Storm type, size, and frequency all affect sediment load and flow volume. About 90% of the annual sediment load is transported in summer and fall seasons (July 4–September 3 and September 4–November 9, respectively) when monsoonal thunderstorms, cutoff lows, or tropical cyclones are the dominant storm types. Only about 7% of the annual load is carried in the winter (November 10–April 17), when most precipitation is produced by frontal systems. Although little sediment is transported in winter, winter flow accounts for almost 50% of the annual flow volume. An insignificant amount of sediment is transported in spring (April 18–July 3).

Variations from year to year in both sediment load and flow volume have been greatest in the fall, when changes in regional climatic conditions also have been greatest. El Niño–Southern Oscillation (ENSO) conditions, which tend to produce large storms from dissipating tropical cyclones, have contributed to the greater variability in the fall.

Sediment storage in tributary flood plains such as the Paria and Little Colorado Rivers could have accounted for much of the decrease in sediment load in the Colorado River in the early 1940s. Flood-plain storage in the Paria River basin probably is controlled largely by variations in regional climatic conditions.

ACKNOWLEDGMENTS

The authors are grateful to David L. Wegner, U.S. Department of Interior, Bureau of Reclamation, for providing support for this study as a part of the Bureau's Glen Canyon Environmental Studies. E. D. Andrews furnished a part of the climatic data. We appreciate the thorough and thoughtful manuscript review of G. P. Williams, E. D. Andrews, and T. A. Cohn, U.S. Geological Survey; D. E. Burkham, Sacramento, California; T. W. Gardner, Pennsylvania State University; and E. Wohl, Colorado State University.

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Manuscript Received by the Society May 14, 1990
Revised Manuscript Received March 20, 1991
Manuscript Accepted March 25, 1991