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TRENDS IN SELECTED HYDRAULIC VARIABLES FOR THE COLORADO RIVER AT LEES FERRY AND NEAR GRAND CANYON, ARIZONA, 1922-1984

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TRENDS IN SELECTED HYDRAULIC VARIABLES FOR THE COLORADO RIVER AT LEES FERRY AND NEAR GRAND CANYON, ARIZONA--1922-1984

Sediment and Hydrology

of the

Glen Canyon Environmental Studies

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16. Abstract (Limit: 200 words)
Geomorphic and sediment trends are interpreted from historic stream flow records for 62 years from 1922 to 1984 at two gaging stations: Colorado River At Lees Ferry and Colorado River Near Grand Canyon, Arizona. The relationship between riverbed level, discharge, velocity, and riverbed scour and fill are discussed. Trend analyses were preformed in which curves were developed to show temporal change in: riverbed level, discharge-to-velocity relationships, and discharge-to-stage relationships. Five variables were used in the analyses: time, water discharge, stage, velocity, and depth. For each gaging station, about 1,400 sets of data for 1922-84 were available for study. The Colorado River in Grand Canyon, because of the stability of the rapids, does not represent a typical degrading stream. The rapids are eroding only gradually, if any, during the present regulated flow regime. The elevations of rapids, however, are subject to abrupt increases during periods of debris flow in tributaries.

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INTRODUCTION

General Statement

The study described herein is one of several being conducted as part of the Glen Canyon Environmental Study (GCES). An intent of GCES is to find meaningful answers to the many questions concerned with the magnitude and rate of change in the physiographic characteristics of the Colorado River in the Grand Canyon National Park that have or will occur as a result of regulation of water and sediment at Glen Canyon Dam. Researchers for GCES recognize that meaningful answers will be difficult to obtain because the physical laws pertinent to changes in a major river are incompletely known. Furthermore, the processes involved when changes occur are complex and inter-related. The Colorado River in the Grand Canyon has all the normal complexities and more. To find meaningful answers, it is necessary to become thoroughly familiar with the river's many facets.

Finding meaningful answers to questions pertinent to changes in selected alluvial deposits--locally called beaches--that result because of regulation of water and sediment is a main objective of GCES. The physical character--size, location, stability, composition--of the alluvial deposit, a component of the river system, is controlled, or closely related to, many of the factors, processes, and physical laws that control the physical character of other components--main channel, flood plain, rapids, eddies--of the river system. Clearly, an understanding of the dynamics of erosion, transport and deposition of sediment--clay to boulder sizes--for all components of the river system must be developed before questions concerned with the beaches can be completely answered. In seeking this understanding, all sources of information available for each of the different components of the Colorado River in the Grand Canyon National Park should be closely examined.

Purpose, Scope, and General Approach

The general objective of the study described herein is to glean factual information about the dynamics of the Colorado River from historical streamflow data for the two gaging stations "Colorado River at Lees Ferry, Arizona" and "Colorado River near Grand Canyon, Arizona". The study period is 1922-84. Specifically, for each of the two sites, information is sought that concerns: (1) scour and fill at cross sections of the river where discharge measurements are made, (2) scour and fill in the rapids--controls for the gaging stations--immediately downstream from the gage sites, (3) changes in the ability of the Colorado River, for a given stage, to transport water and sediment, and (4) the relation between regulation of flow and changes found in 1, 2 and 3.

The general approach used to seek information required the development of trend curves depicting temporal changes in riverbed levels, the development of discharge-to-velocity relations, a description of the relation that exists between channel-bed scour and streamflow velocity, and the development of discharge-to-stage relations. Also necessary for the study was the development of trend curves that show temporal changes in the discharge-to-velocity and discharge-to-stage relations. The procedure used required that significant changes in trend curves be correlated, as near as possible, to factors that cause the change. The different relations are developed using standard procedures (Burkham and Guay, 1981), which are described in the text when they are first used. The mathematical models and statistical handling of the data used in the development of the two relations also are described when they are first used.

Definitions for a few terms are given in the report. A definition is given when a term in question is first used. The term "control", when used in discussion of streamflow gage sites and open-channel flow, means the establishment of definite flow conditions in the channel or, more specifically, a definite relation between discharge and depth of flow (Chow, 1959; Rantz, 1968; Burkham, 1977). True controls in an open channel are of two types: channel and section. A true channel control exists when the physical characteristics of a reach of a uniform channel downstream from a site of interest determines the relation between discharge and depth at the site. A true section control exists when the physical characteristics of a single cross section of a stream controls the relation between discharge and stage. True controls may exist in a natural channel. Typically, however, for the Colorado River in the Grand Canyon, relatively short lengths of channel (at rapids) having the characteristics of a section control exist for many sites and relatively long lengths of channel having the characteristics of channel control are effective for other sites. The section-control condition may be the result of a single riffle (or rapid) or the result of a restricted width for a single short length of channel. The channel-control condition may be the result of a long reach of a fairly uniform channel; however, it ordinarily results from the composite effects of restricted widths at several relatively short lengths of channel.

CHARACTERISTICS OF THE GAGING STATIONS

General Statement

The streamflow reaching the two stations--Colorado River at Lees Ferry and near Grand Canyon, Arizona--was uncontrolled (or natural) prior to March 13, 1963. After March 13, 1963, the streamflow has been regulated at Glen Canyon Dam.

Pre-dam streamflow in the Colorado River is classified, for this report, as winter flow and summer flow. Winter flow primarily takes place from November through June, and summer flow usually occurs from July through October. Main sources of winter flow are: Precipitation during frontal storms, snowmelt, or a combination of the two. The discharge during winter flow may be fairly constant for several days, and the sediment concentration usually is relatively low compared to its maximum capacity to carry sediment or compared to that for summer flow. The causes of major winter floods are widespread heavy rainfall of long duration, warm weather after a large snow accumulation, and widespread rainfall on snow.

Local thunderstorms provide the main source of summer streamflow. Individual summer thunderstorms characteristically produce high unit rates and unit volumes of flow from small watersheds. The crest of a flood from a thunderstorm typically is very sharp near the site of the thunderstorm, but it may become rounded or flattened downstream because of the dampening effects of infiltration and temporary storage in the conveyance channel. During September and October, thunderstorms and frontal activity occasionally occur together and produce relatively large floods. As previously indicated, sediment concentrations generally are high during summer flows. Also, sediment concentrations can be relatively high during the first few days of winter flow.

Colorado River at Lees Ferry

Flow past the gage on the Colorado River at Lees Ferry, Arizona, as previously indicated, has been completely regulated at Glen Canyon Dam (16 miles (mi) upstream) since March 13, 1963 (U.S. Geological Survey, 1983). No diversions or inflow points exist between Lake Powell and the gage.

The gaging station at Lees Ferry is in Coconino County, on the left bank at the head of Marble Canyon, about 200 feet (ft) upstream from the delta of Paria River. Datum of the gage is 3106.16 ft (National Geodetic Vertical Datum of 1929). Prior to January 1967, all discharge measurements, except for extremely high flow rates, were made at a cableway approximately one mile upstream from the gage site. Measurements of extremely high discharge were made at a cableway approximately 3/8 mi upstream from the site. After January 1967, all discharge measurements were made at a cableway located about 40 ft upstream from the gaging station. The rapid at the mouth of Paria River is the control for the Lees Ferry gage. The drainage area for the basin above the gage is approximately 111,800 square miles (sq mi), including 3,959 sq mi in the non-contributing Great Divide Basin in southern Wyoming.

Records of streamflow for 1895 to present are available for the site at Lees Ferry (U.S. Geological Survey, issued annually). Only calendar year estimates and monthly discharges are available for some years prior to 1922.

The pre-dam average discharge for (1912-62) at the site at Lees Ferry was 17,850 cubic feet per second (cfs). The post-dam average discharge for (1965-82) was 12,170 cfs. The pre-dam maximum discharge for 1895-62 was 220,000 cfs, which occurred on June 18, 1921. The maximum discharge since 1868 was about 300,000 cfs, which occurred on July 7, 1884. The pre-dam minimum was 750 cfs, which occurred in December 1924. The post-dam (1963-84) maximum discharge was about 97,000 cfs, which occurred in June 1983. The post-dam minimum daily discharge was 700 cfs, which occurred January 23 and 24, 1963. The post-dam maximum discharge, 97,000 cfs, was usually equalled or exceeded annually prior to the construction of the Glen Canyon Dam.

Colorado River near Grand Canyon

Flow past the site near Grand Canyon includes that moving past the gage at Lees Ferry plus the flow from tributary streams between the two sites. Streamflow depletion by infiltration and evaporation between the two sites apparently is insignificant in most years. The combined area of the tributary streams is about 29,800 sq mi. Paria River, drainage area of 1,410 sq mi, and Little Colorado River, drainage area of 26,500 sq mi, are the largest of the intervening streams.

The gaging station near Grand Canyon is in Coconino County, in Grand Canyon National Park, on the left bank, about 0.4 mi upstream from the delta at the mouth of Bright Angel Creek, and about 26 mi downstream from Little Colorado River (U.S. Geological Survey, issued annually). Datum of the gage is 2,418.7 ft (National Geodetic Vertical Datum of 1929). The rapid at the mouth of Bright Angel Creek provides a control for the Grand Canyon gage. The drainage area for the basin above the gage is approximately 141,600 sq mi, including the non-contributing Great Divide Basin in southern Wyoming.

Records of streamflow from October 1, 1922 to present are available for the site near Grand Canyon. All discharge measurements are made at a cableway approximately 700 ft below the gage.

The pre-dam average discharge for 1923-62 at the site was 16,930 cfs. The post-dam average discharge for 1965-82 was 12,710 cfs (U.S. Geological Survey, issued annually). The pre-dam maximum discharge for 1923-62 was 127,000 cfs, which occurred on July 2, 1927. The maximum discharge since at least 1868 was about 300,000 cfs, which occurred on July 8, 1884. The pre-dam minimum discharge was 700 cfs which occurred on December 28, 1924. The post-dam (1963-84) maximum discharge was about 95,000 cfs, which occurred in June 1983. The post-dam minimum discharge was 850 cfs, which occurred on January 23, 1963.

ANALYSIS OF DATA FOR THE SITE AT LEES FERRY

Introduction

The variables--time, discharge, stage, velocity and depth--used in the different analyses described in this report were taken directly from streamflow measurement notes. Because the discharge measurements for the Lees Ferry site were made at three different locations--one mi, 3/8 mi, and 40 ft upstream--during 1922-84, brief examinations of the data had to be made to insure that the variables were compatible when used in trend investigations. Of the five variables, only velocity and maximum depth were of concern. The other variables are applicable regardless of which location was used for measurement.

Any possible problem introduced by using data for measurements made at the cableway 3/8 mi upstream was avoided by excluding those data from the set used in the analysis. As previously indicated, only extremely high discharges were measured at the cableway 3/8 mi upstream. Figure 1 shows the relation between mean velocity and discharge for sites one mile and 40 ft upstream from the gaging station. The illustration indicates that velocities measured in 1966-68 at the two sites are compatible for discharges in the range from about 2,500 to 25,000 cfs. The assumption is made that data for velocities representing all discharges in the range from 2,500 to 33,000 cfs at the two sites can be used in a single trend analysis for a relation between velocity and discharge without introducing significant bias in results. A discussion of the analysis made to determine the useability of data representing maximum depth is presented on page 11.

Trends in Channel-bed Scour (or Fill) for 1922-84

Figure 2, with supporting information in Figures 3 and 4, represents a continuous history of the riverbed at the Lees Ferry gage. The low point in the bed, or stage at the thalweg, was obtained by subtracting the maximum depth from the water-surface stage (gage height) of the river. Unless otherwise stated, each set of data (date, time, stage and maximum depth) was treated as if the discharge measurement was made at the gage site. Data for all measurements, except for those made 3/8 mi upstream, were used in the development of Graph A in Figure 2. However, only data for discharges less than 33,000 cfs were used in the development of Graph B in Figure 2. The smoothed effect in Graph B in Figure 2 was obtained by using a 20-point moving (progressive) average. The average is plotted at the midpoint of the 20 values.

The large scatter of data for 1922-62, shown in Graph A in Figure 2, is typical for a measurement section in a pool of a pool-and-

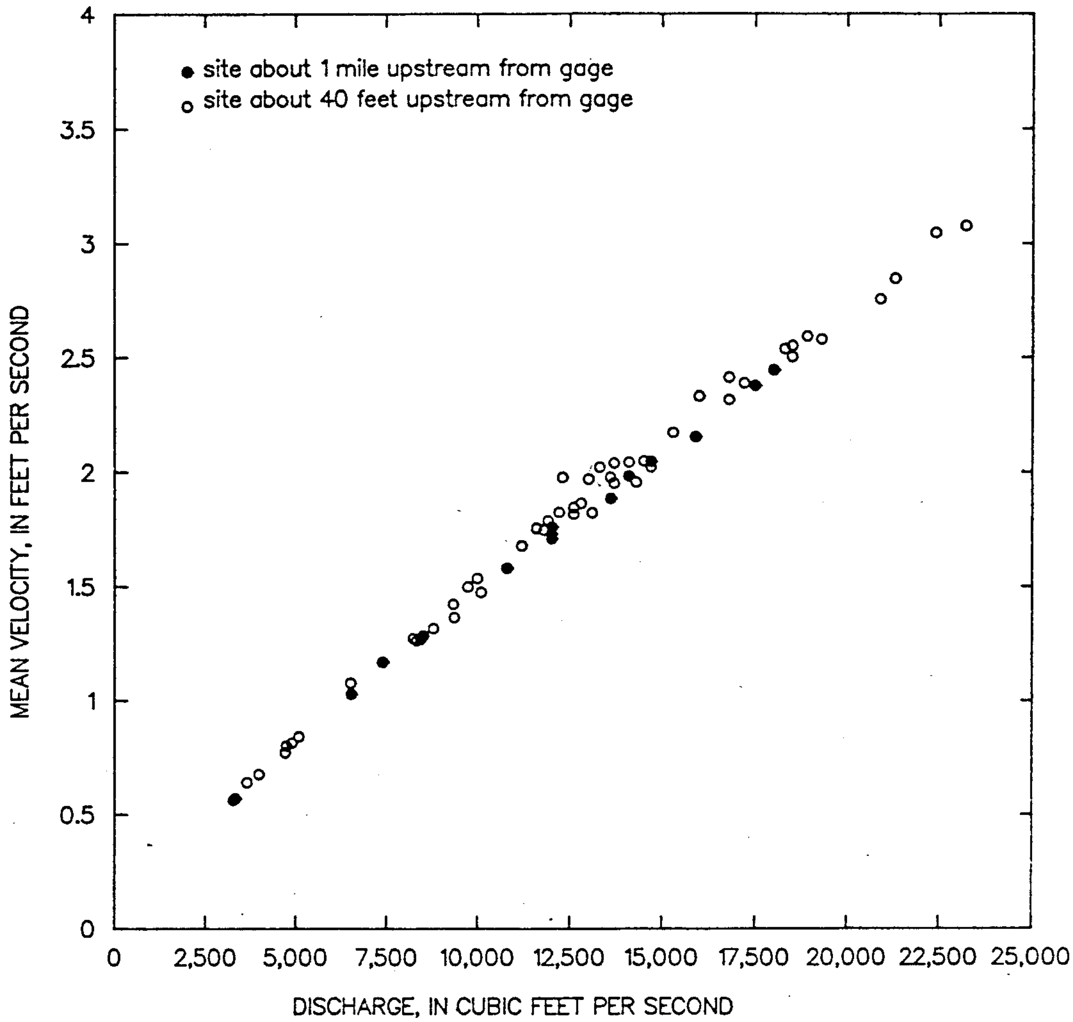


Figure 1.--Relation of mean velocity to discharge at two discharge measurement sites, 1966-1968, Colorado River at Lees Ferry, Arizona.

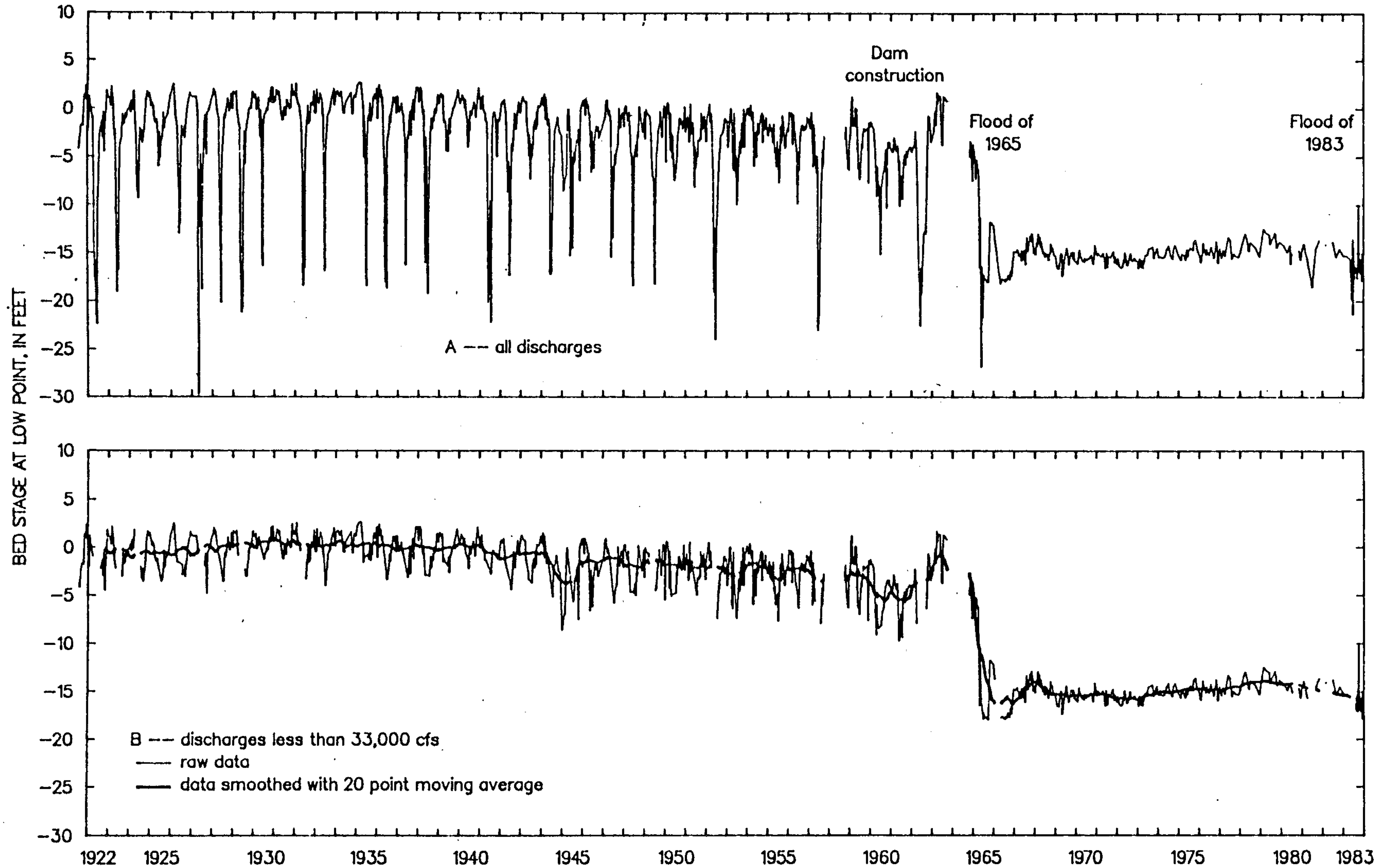


Figure 2.--Bed stage at the low point in the cross section, Colorado River at Lees Ferry, Arizona, 1922-1984. A, entire range of discharges. B, discharges less than 33,000 cubic feet per second.

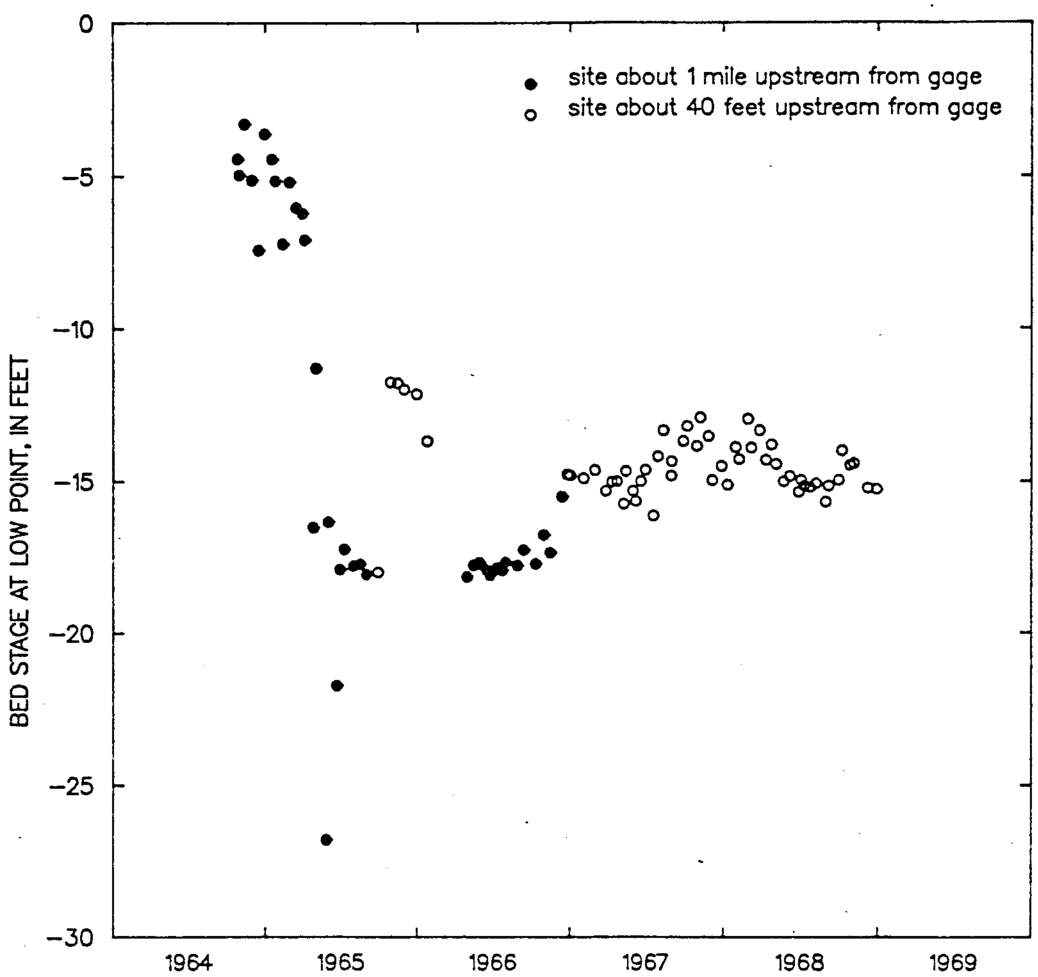


Figure 3.--Bed stage at the low point in the cross section at two discharge measurement sites, Colorado River at Lees Ferry, Arizona, 1964-1969.

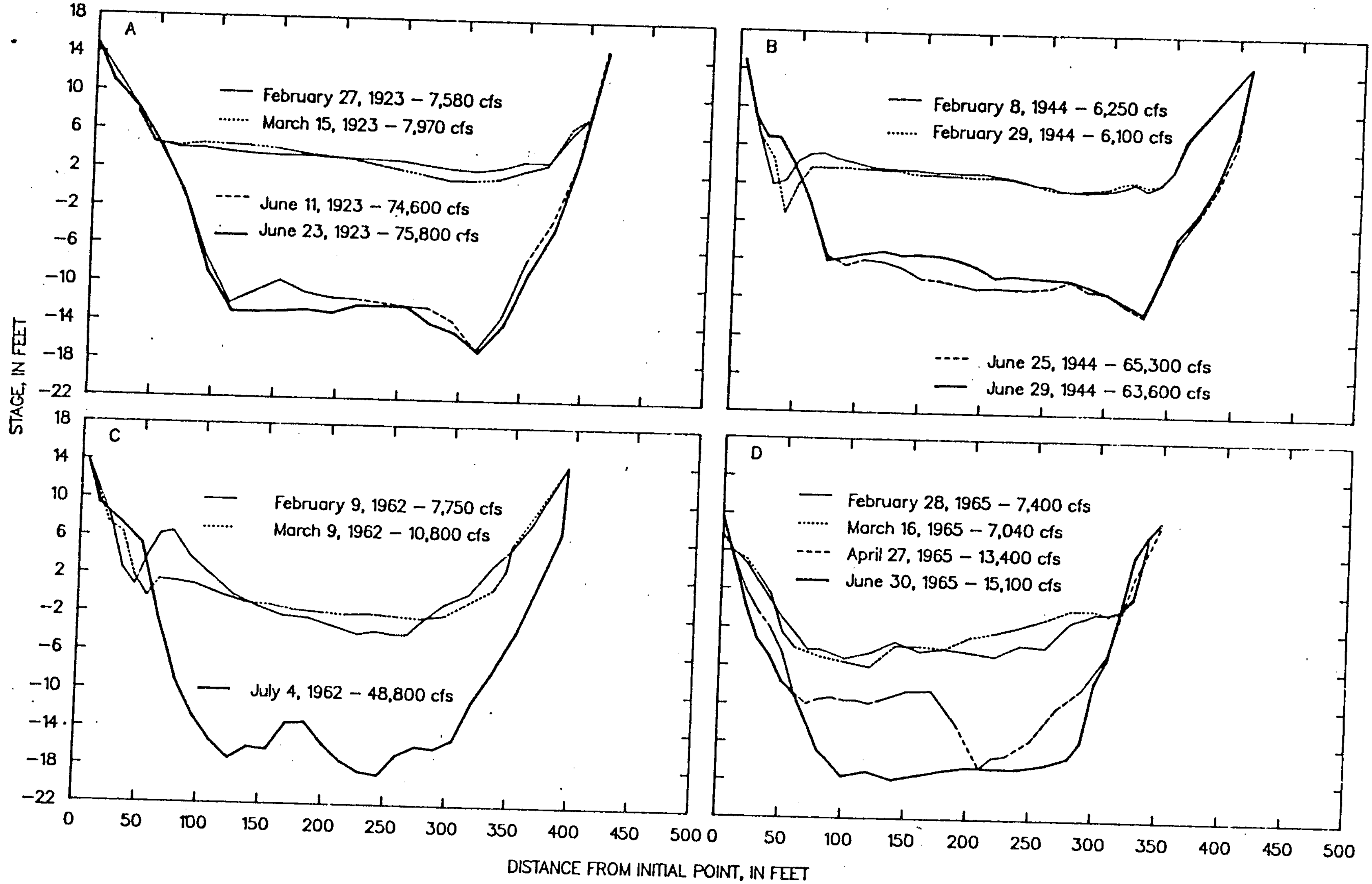


Figure 4.--Bed stage in cross section at discharge measurement sites, Colorado River at Lees Ferry, Arizona, at selected times. A and B, cross sections at the site about 1 mile upstream from the gage. C and D, cross sections at the site about 40 feet upstream from the gage. E, comparsion of cross sections at the two measurement sites.

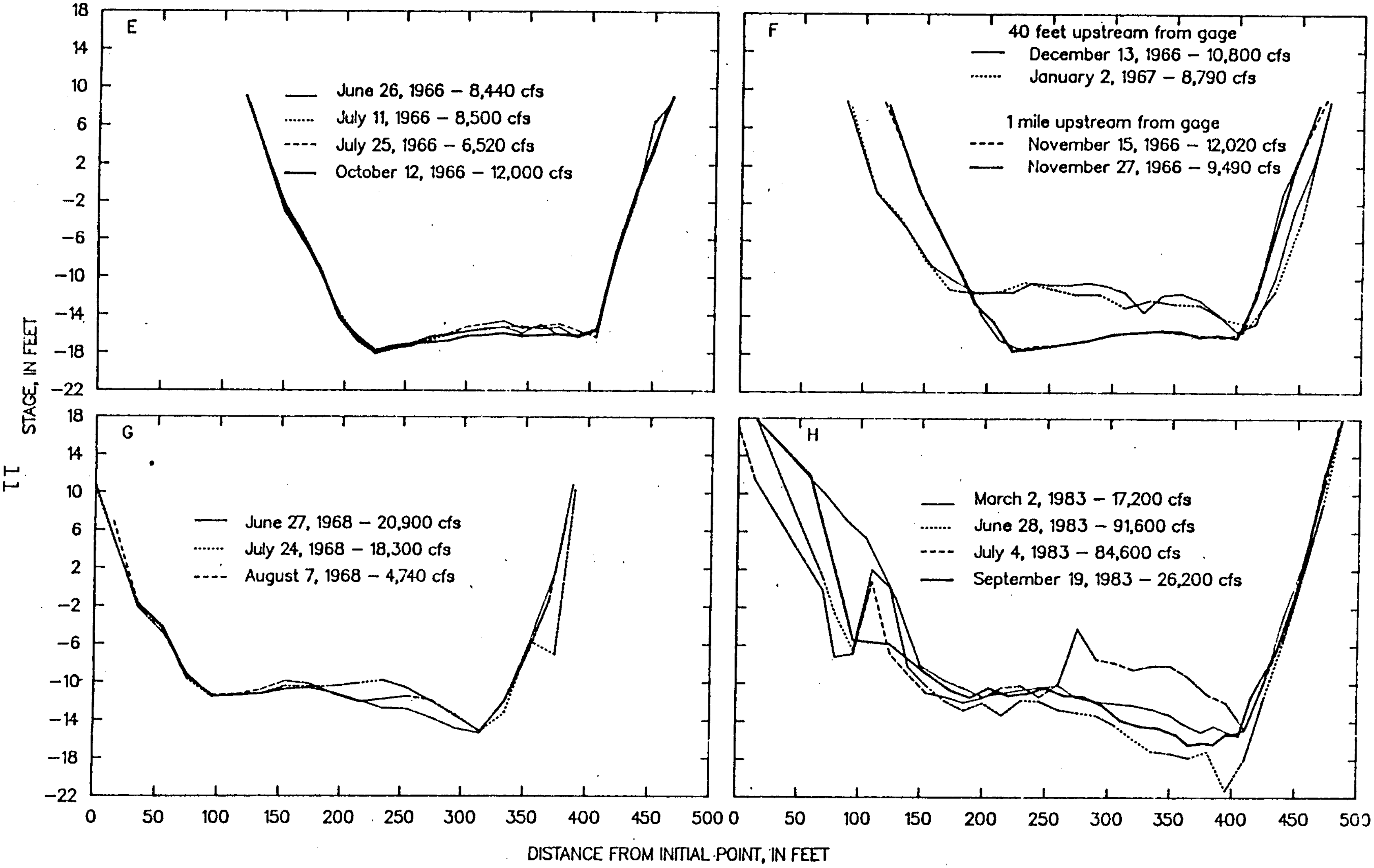


Figure 4.--Continued.

rapid stream that has a highly variable discharge and a large movement of sand-to-gravel size sediments. Typical for such pools, the amount of scour in the alluvial deposit of sand and gravel progressively increases as the discharge increases and fill occurs as the discharge decreases. Because periods of large scour correspond in time to occurrences of high annual discharges (Graph A in Figure 2), a tentative assumption is made that the riverbed in the Lees Ferry pool responds to high discharge in a typical way. When the discharge was less than 33,000 cfs at the site at Lees Ferry, the riverbed at the low point most of the time in 1922-40 ranged from a high elevation of 0 ft (local datum) to a low of -2 ft (Graph B in Figure 2) but the scour in the alluvial deposit usually amounted to more than 20 ft (Graph A) during high winter discharges in 1922-62. Annual high discharges at the site at Lees Ferry usually lasted about 5 months in 1922-62: Thus the cycle of scour and fill, greater than the usual range of 1 to 3 ft, was about 5 months in most years.

Prior to about 1940, the riverbed at the low point annually returned to about its pre-flood elevation soon after the cessation of high discharges. After annual high discharges in 1940-62, however, the low-point elevation did not return to a level as high as that for the preceeding year (Graph B in Figure 2). This may indicate that the yearly supply of sediment reaching the pool was gradually declining in 1940-62.

The amount of scour at the low point in the alluvial deposit at the measurement section was about 27 ft in 1965, which occurred during high discharges of sediment-free (post-dam) water (Graph A in Figure 2). However, the amount of fill in 1965 and 1966, after the high discharges had receded, was only about 12 ft. The daily discharge at Lees Ferry was in the range of 40,000 to 60,000 cfs (U.S. Geological Survey, issued annually) when most of the scour occurred. Instantaneous discharges of 65,000 cfs were measured at Lees Ferry in 1965.

The expanded-scale view of the bed level in Figure 3 indicates that, after the large scour in 1965, the bed filled to about the -12 ft level. However, the bed again scoured to about the -18 ft level in 1966 and filled to about the -15 ft elevation in 1967 where it stayed fairly stable until 1983.

The expanded-scale view in Figure 3 also indicates that, in general, conclusions pertinent to bed-level changes probably would not be greatly affected by assuming that the data for the measurement site 40 ft upstream from the gaging station are compatible with those for the site one mile upstream. A one-time difference in bed level is indicated when the measurement-site change was made. If a large difference in conclusion was indicated, a different type of trend analysis would have been necessary.

The riverbed at the low point scoured 6 to 7 ft in 1983 but filled back to about its pre-flood level during the recession of the high discharges (Figure 2). As previously indicated, discharges of about 97,000 cfs occurred in 1983.

The scour-fill regimes for the low point in the measurement section are indicative of the scour-fill regimes along the total cross section (Figure 4). The cross-sectional profiles for the different periods and discharges in 1923 (Graph A), 1944 (Graph B) and 1962 (Graph C) are representative of typical pre-dam flow and scour-fill regimes. For each of the three years, the sets of profiles include two representing riverbed conditions during low discharges, immediately before the beginning of high discharges, and one or two representing conditions during high discharges.

The profiles in Figure 4 were developed using data recorded on measurement notes. For each profile, the elevation of the river bed was obtained by subtracting the water depth from the water-surface stage (gage height) of the river. Using this procedure, 15 or more independant observations of the river-bed elevation were obtained for each profile. The end points for profiles representing relatively high discharges extend to higher elevations along the banks of the river than those for low discharges. For each group of high- and low-discharge profiles shown in Figure 4, the low-discharge profiles were extended to the end-points of the high-discharge profiles. The justification for this extention of the low-discharge profiles for each group is based on arguments that: (1) the river-bank elevations at the streamflow measurement site did not change significantly during the interval of time from a low-flow measurement to a high-flow measurement and (2) conclusions mainly are based on the main-channel part of the profiles and do not consider end-point elevations.

The cross-sectional profiles for February 28, 1965 and March 16, 1965 (Graph D in Figure 4) represent riverbed conditions immediately before the release of relatively high rates of sediment-free water. The profiles for April 27, 1965 and June 30, 1965 (Graph D) represent riverbed conditions immediately after the release of the high discharges.

The cross-sectional profiles for the different discharges during June 26 to October 12, 1966 (Graph E in Figure 4) represent riverbed conditions approximately one year after the 1965 high release rates. As previously discussed, the riverbed, after the high discharges in 1965, did not return to its pre-dam level.

The cross-sectional profiles for November 15, 1966 to January 2, 1967 (Graph F in Figure 4) illustrate differences in bed level for the upstream site, about one mile upstream from the gage, and those for the site at the gage. For the period, the indicated bed level for the measurement section near the gage is 2-3 ft higher than that for the upstream site. Also, the width of the section near the gage is roughly 30-40 ft greater than that for the upstream gage. As previously indicated, an assumption is made that the differences in bed levels and channel widths will not greatly affect conclusions pertinent to bed-level changes that are developed.

The cross-sectional profiles for 1968 (Figure 4) are given to show that very little change in bed level, if any, occurred as the discharge in 1968 ranges from about 4,800 cfs to 21,000 cfs at the gage site. Also, very little change in bed level, if any, occurred from December 13, 1966 (Graph F) to August 7, 1968 (Graph G).

The cross-sectional profiles for 1983 (Graph H in Figure 4) show changes in the riverbed which occurred as a result of the 1983 flood. The profile for March 2, 1983 is not greatly different than those for 1968. However, the profile for June 28, 1983, representing a discharge of 91,000 cfs, indicates that a significant amount of scour had occurred along the riverbed bank for the distance from 10 to 150 ft, shown to the left in all graphs of Figure 4. The profile for July 4, 1983 representing a discharge of 84,600 cfs also indicates that a large amount of scour had occurred along the right side of the river, however, a significant amount of fill occurred along the opposing (left) side of the cross section during June 28-July 4, 1983. The indicated fill along the left part of the channel may have been a sand wave moving through the pool. A possibility exists that the indicated fill may not be real, but instead represents an error in the data. By September 19, 1983 fill along the right bank for the distance from 10 to 100 ft had already begun and the sand wave, or whatever, was gone from along the left part of the section.

Relation Between Velocity and Discharge

Scour and fill have been associated with discharge in discussions presented thus far. Actually, scour and fill in a pool (in a pool-and-rapid reach) can be better correlated with streamflow velocity than with discharge. For this report, the relation between velocity and discharge is presented first. Subsequently, scour and fill are correlated with changes in velocity.

The procedure used to study the relation between velocity and discharge for the site at Lees Ferry involves steps as follows:

1. Using all data for which the discharge is less than 33,000 cfs, an equation is developed that represents the average relation between velocity and discharge for the period 1922-83.

2. Shifts in the relation of velocity to discharge developed in step 1 are determined.

3. Shifts determined in step 2 are plotted against discharge and against time.

4. A smoothing procedure is used to develop a diagram that represents trends.

A preferred procedure would have been to study the relation between velocity and discharge for the full range of discharge in 1922-84--from 750 cfs to 200,000 cfs. However, after 1963, the measured values of velocity were for regulated flow and, except for a few relatively short periods, the regulated discharge ranged from about 2,500 to 33,000 cfs. Thus trend analyses for discharges greater than 33,000 cfs were not possible for 1963-84. Trend analysis for 1922-84 were limited to discharges less than 33,000 cfs because of (1) lack of data for discharges greater than 33,000 cfs for 1963-84 and (2) the uncertainty of compatability of (velocity) data for discharges greater than about 33,000 cfs (see page 6).

The model used to represent the relation between velocity to discharge relationship is $V=a(QM)^b$ in which a is a coefficient, V is mean cross-sectional velocity, QM is measured discharge, and b is an exponent. Iteration routines and least-square regression analyses are used to develop estimates for a and b. The equation representing the average (1922-84) relation between velocity and discharge for the site at Lees Ferry is

$$VHAT=0.21(QM)^{0.30} \qquad (1A)$$

in which VHAT=computed velocity, in feet per second (fps); and QM=measured discharge, in cfs.

Equation 1A is applicable to discharges in the range from 2,500 to 33,000 cfs. The standard error of estimate is 1.42 fps or about 38 percent of the mean of measured velocities for discharges in the range from 2,500 to 33,000 cfs.

The shifts were plotted against discharge in step 3 (not shown) in order to verify that equation 1A adequately represents the average relation between velocity and discharge for the study site. A need to modify the equation would be indicated if the plotted shifts were not approximately isometrically grouped around a shift of zero for the full range of velocities being studied. The sum of all computed shifts is not significantly different from 0.

The Graphs in Figure 5 are used to investigate temporal changes (or shifts) in the relation of velocity to discharge relationship for the site at Lees Ferry. The shifts plotted in Graph A in Figure 5 were determined by subtracting computed velocity from measured velocity where the computed velocity was obtained by using equation 1A. The points plotted in Graph B in Figure 5 represent 20-point moving (progressive) averages of shifts shown in Graph A.

The large scatter of data in Graph A in Figure 5 is assumed to be due mainly to differences in approach velocity, which result from scour and fill in the pool upstream from the control. Even though only discharges less than 33,000 cfs were considered in the velocity-discharge study, the resulting scour from a large discharge often causes relatively low velocities and large negative shifts for measurements made immediately after the occurrence of the large discharge. The large negative shifts in 1922, 1927-29, 1941, 1948, 1952 and 1957 represent examples of this phenomenon.

The mean cross-sectional velocity for a given discharge at the measurement site decreased an average 3.5 fps during 1922-1984 (Figure 5). A significant part of the decrease may have occurred in 1940-62, prior to the completion of Glen Canyon Dam.

The different relation of velocity to discharge shown in Figure 6 offer an opportunity to compare velocities for a wide range of discharges for different periods. Data for all measurements with discharge less than 100,000 cfs were used in the least-squares development of the different relationships. For a discharge of 80,000 cfs, the mean velocity decreased from about 10.2 to 7.0 fps in the period from 1931-33 to 1982-84: However, a part of the difference in velocity may be due to a change in measurement sites. For discharges of 20,000 and 10,000 cfs, the decreases were from 6.8 fps to 2.3 fps and from 5.5 fps to 1.7 fps, respectively, during the same time interval. Percentage decrease for the three discharges are 31.3, 66.2 and 69.1, respectively.

Relation Between Velocity and Scour (or Fill)

The procedure used to develop a better understanding about the relation that exists between streamflow velocity and scour (or fill) is indirect and uses two types of graphs. The two types are: (1) graphs for selected periods which show mean cross-sectional velocity and elevation at the lowest point in the cross section plotted against time, and (2) graphs showing mean velocity plotted directly against elevation at the low point.

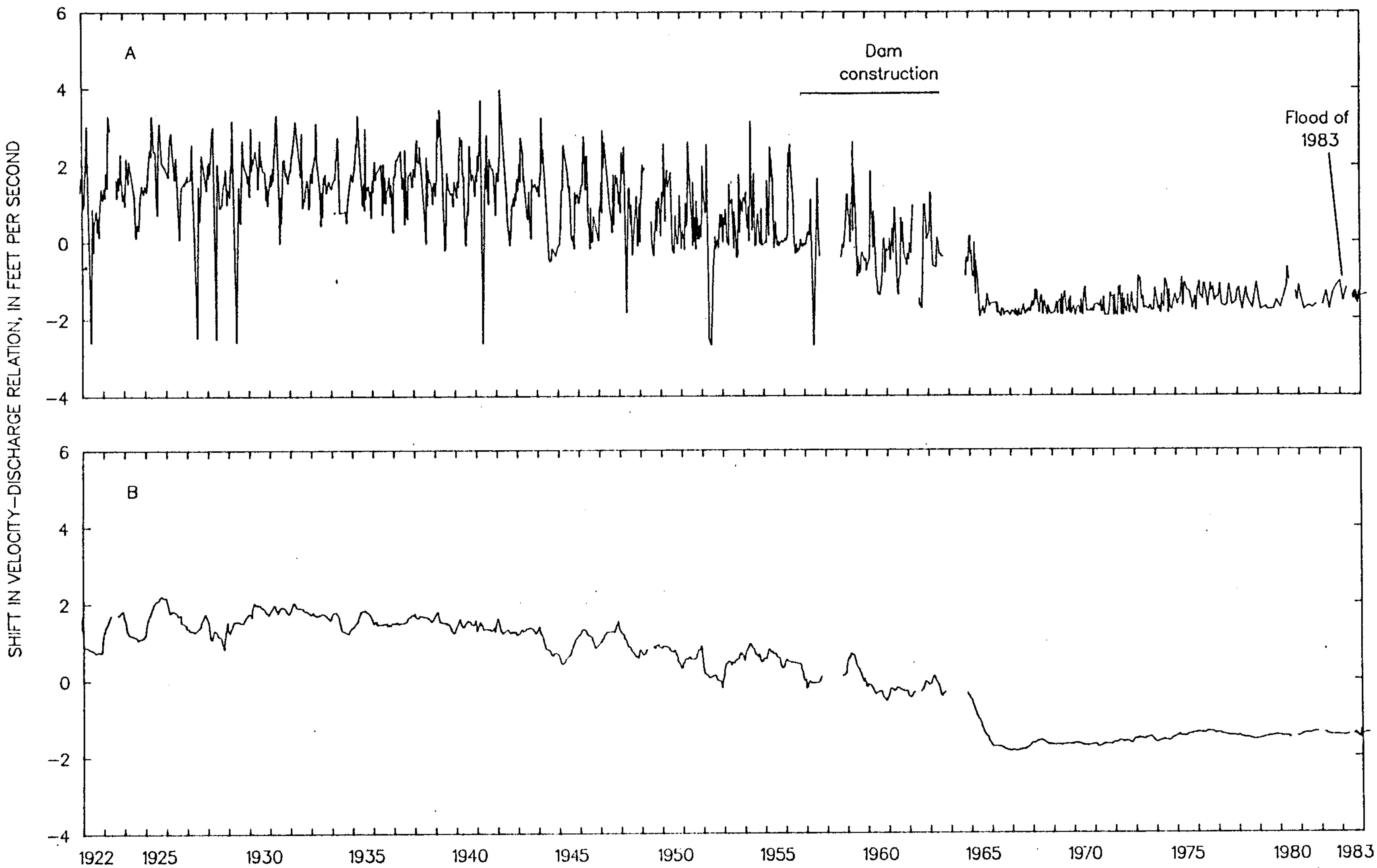
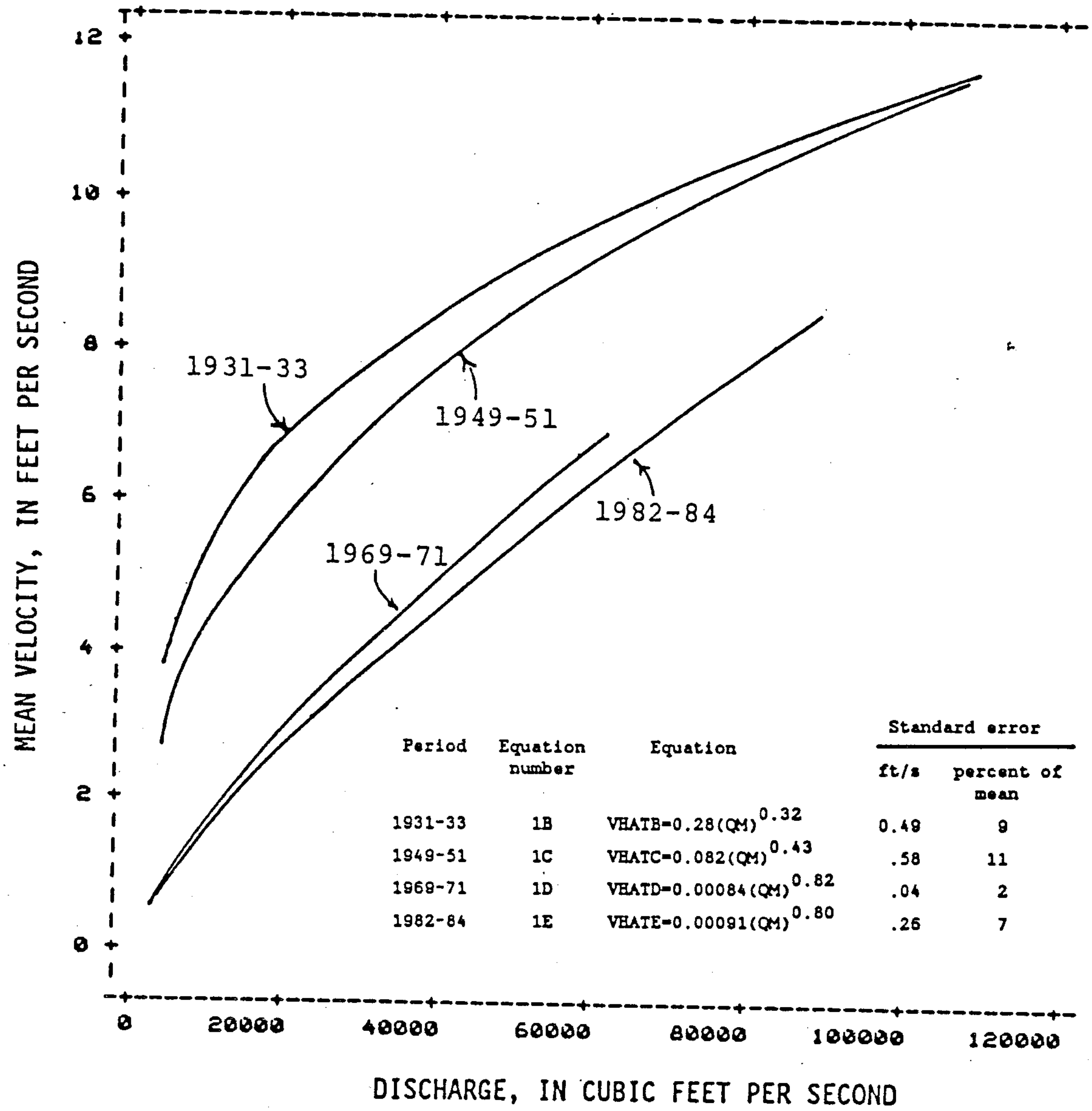


Figure 5.--Shift in relation of velocity to discharge, Colorado River at Lees Ferry, Arizona, 1922-1984. A, discharges less than 33,000 cubic feet per second. B, 20-point moving average of data in A. The average is plotted at the midpoint of the 20 values used to compute the average. Shift was computed as the measured velocity minus velocity computed with equation 1A.



Period	Equation number	Equation	Standard error ft/s	Standard error percent of mean
1931-33	1B	$VHATB=0.28(QM)^{0.32}$	0.49	9
1949-51	1C	$VHATC=0.082(QM)^{0.43}$	.58	11
1969-71	1D	$VHATD=0.00084(QM)^{0.82}$	.04	2
1982-84	1E	$VHATE=0.00091(QM)^{0.80}$	.26	7

Figure 6.--Relation of velocity to discharge for selected periods, Colorado River at Lees Ferry, Arizona.

Sixty-three graphs of the first type, one for each year in 1922-84, were developed for the present study. Examples of these graphs are shown in Figure 7. Graphs for years prior to about 1962 clearly indicate that:

1. The low point of the riverbed was at about +1 to -2 ft elevation most of the time in 1922-40 when the discharge was less than 33,000 cfs.

2. The riverbed begins to unravel (scour) when the mean velocity exceeds about 5 fps.

3. The bed continues to scour as long as the velocity is increasing above 5 fps.

4. The maximum scour during a high-flow season (usually March-August) coincides approximately with the occurrence of the maximum velocity. The low point of the bed often reached a -20 ft level during a high-flow season.

5. Fill occurs during the recession of a flood as the velocity recedes.

6. Soon after high velocity ceases, the bed level returns to about +1 to -2 ft elevation in 1922-40, and to a progressively lower elevation in 1941-62.

Post-dam graphs of the first type indicate that bed elevations and streamflow velocities are significantly lower than those for pre-dam dates (Figure 7). The lower bed elevations and velocities were consequences of the presence of Glen Canyon Dam.

Graphs of the second type are shown in Figure 8. Data for 1922-62 are shown in Graph A in Figure 8; those for 1967-82 are shown in Graph B; and those for 1983-84 are shown in Graph C.

A scatter graph on which all values of mean velocity and bed elevation, except those less than -25 ft, are plotted in Graph A in Figure 8. The solid lines in Graph A in Figure 8 were drawn to encompass all the plotted points except for those that deviate greatly in plotting position from most of the points. Line cf is drawn to represent approximately the mean velocity at which scour begins. If line cf correctly represents the velocity at which scour begins, the inference is that the bed can only be in a stable-state (no scour or fill is occurring) or fill regime when the velocity is less than about 5 fps. The plotted points which represent a stable-state or fill regimes are bounded by the quadrangle abcf. The plotted points which represent scour, stable-state, or fill regimes are bounded by the quadangle cdef.

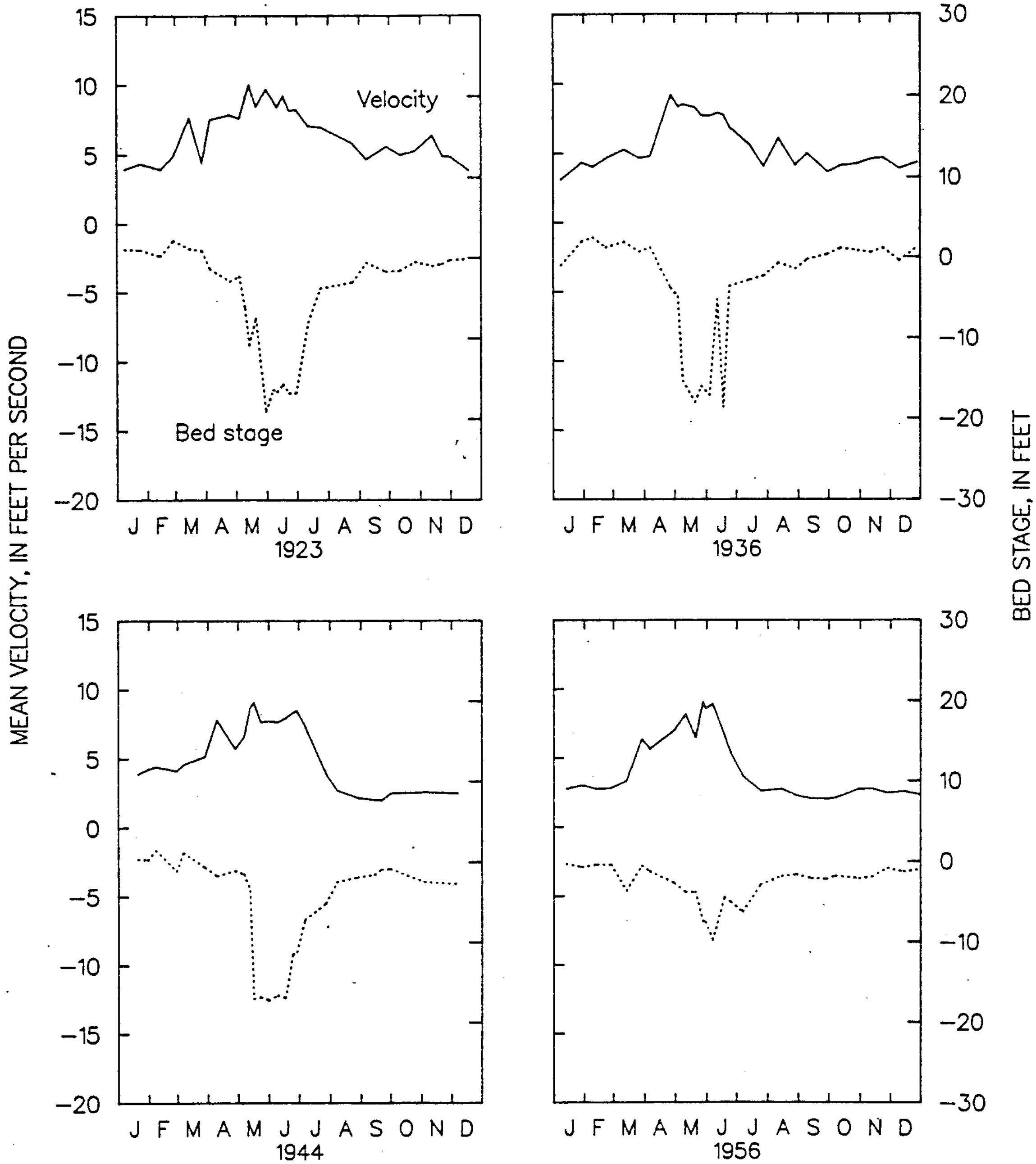


Figure 7.--Bed stage at low point in the cross section and mean velocity, Colorado River at Lees Ferry, Arizona, for selected years.

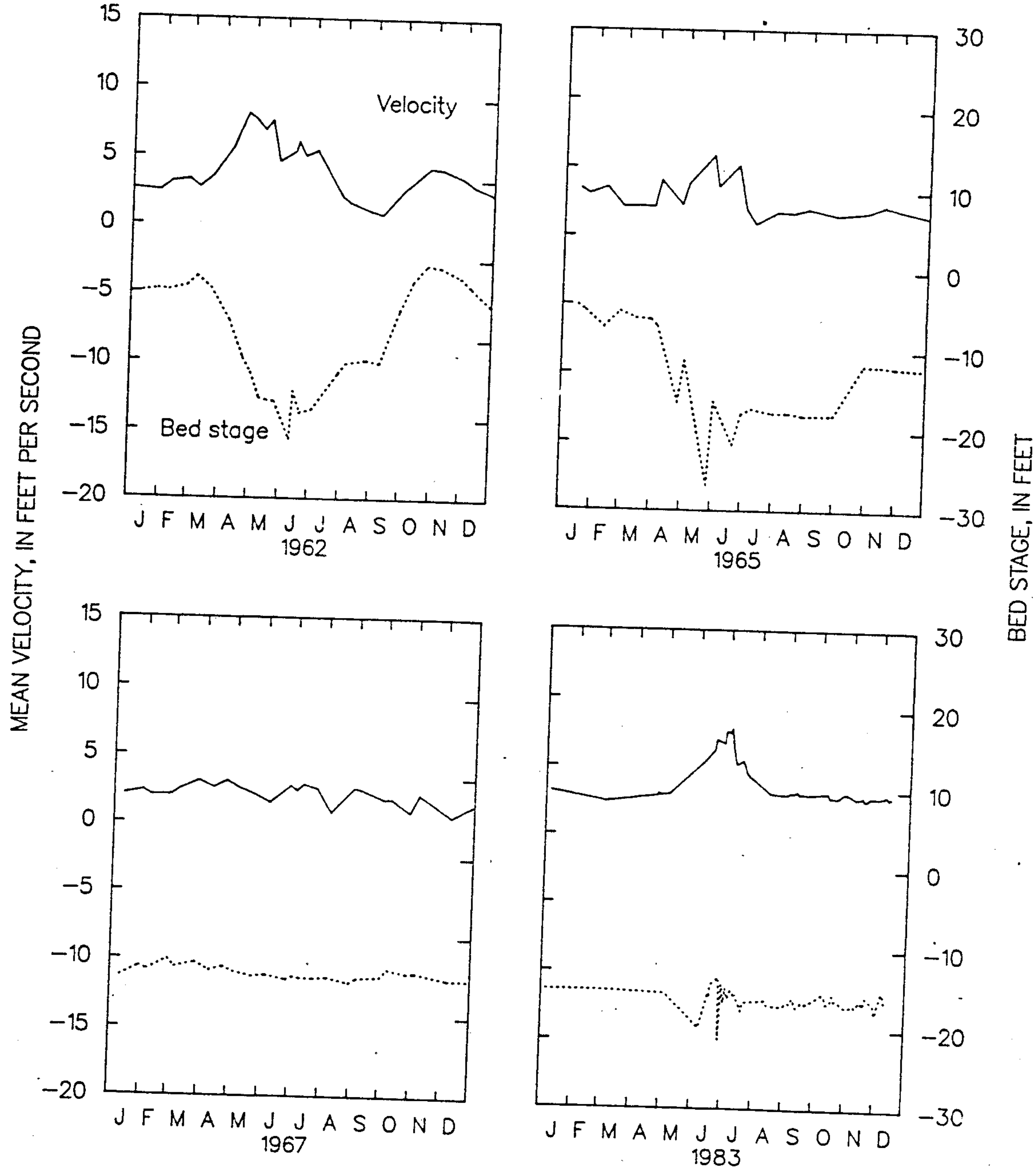


Figure 7.--Continued.

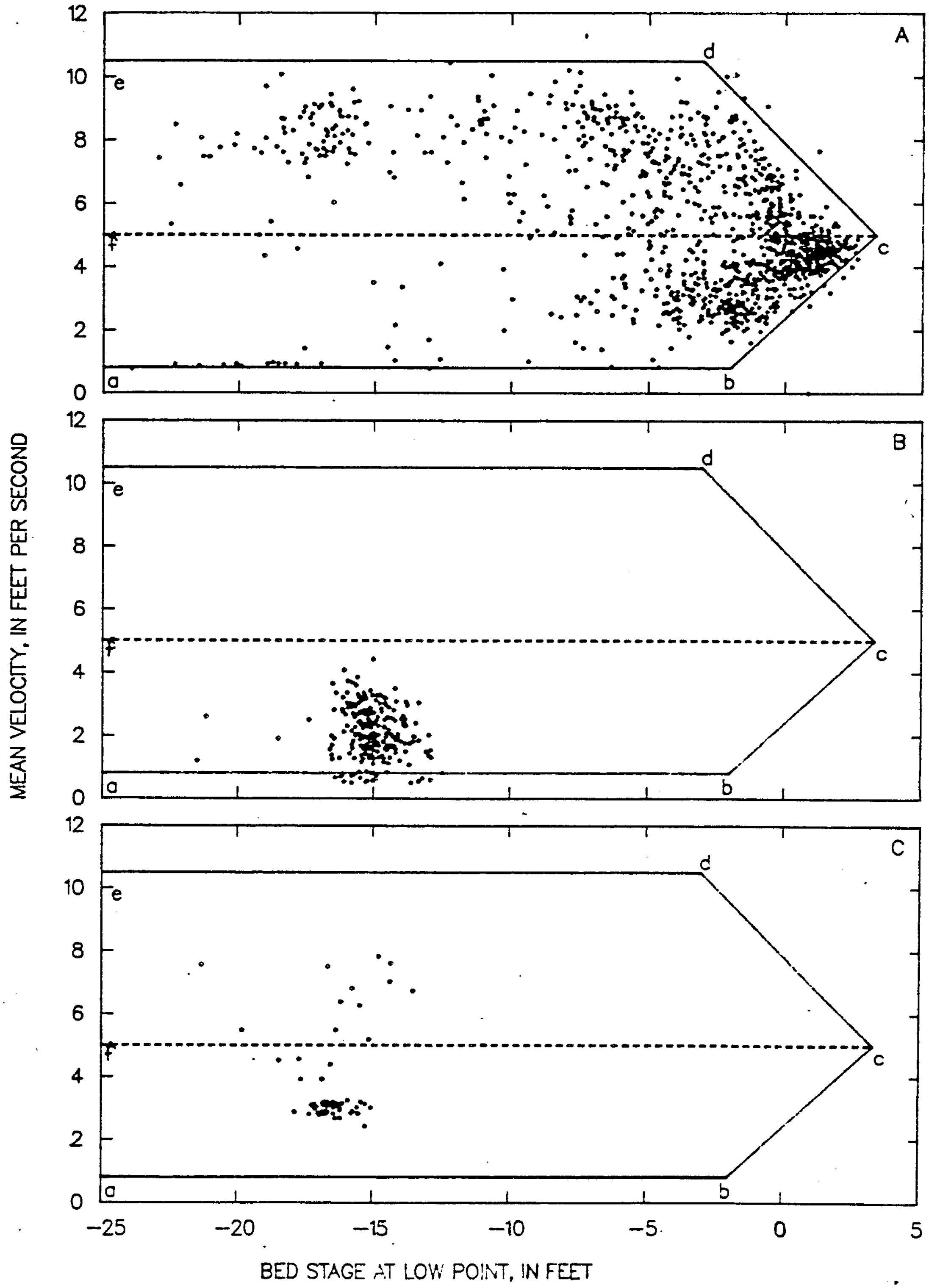


Figure 8.--Relation of mean velocity to bed stage at the low point in the cross section, Colorado River at Lees Ferry, Arizona, for selected periods. A, the pre-dam years of 1922-1962. B, the post-dam, pre-flood years of 1967-1982. C, the post-dam, post-flood years of 1983-1984. Solid lines were drawn to encompass most of the data points from the 1922-1962 period. The dashed line indicates the velocity at which scour begins when the bed is at a high level. Lowercase letters mark line segments discussed in the text.

The bed, as previously indicated, did not reach a stable state in 1922-62. As indicated by a cluster of points in Graph A (Figure 8), a tendency existed for the bed to scour to only about -17 to -18 ft elevation, and no more, during floods in 1922-62. As indicated by the relatively small number of measurements, the bed was in the zone of -8 to -15 ft elevation only a small part of the time, which seems to indicate that the riverbed was very unstable in this zone. As defined by measurement, the mean velocity ranged from about 1 to 10 fps (Graph B in Figure 8). However, the mean velocity was in the range from 3 to 5 ft per second most of the time in 1922-62.

The riverbed at the low point was fairly stable at about -14 to -16 ft elevation during 1967-82 (Graph B in Figure 8). The velocities and riverbed elevations for 1967-82 plotted in the area bounded by abcf, which as previously discussed, infer that scour was not possible.

The mean velocity for discharges measured in 1983-84 ranges from about 2 to 8 fps and as previously stated, scour occurred (Graph C in Figure 8). After the 1983 flood, the bed returned to an elevation about the same as that for 1967-82. As indicated by several measurements made in 1983-84, the bed was at a fairly constant level (about -15 to -16 ft level) during a relatively long period when the streamflow velocity was greater than 5 fps. A combination of constant bed levels and high velocities (greater than 5 fps) indicate that the bed at Lees Ferry had become resistant to further scour. A more detailed discussion of riverbed scour in reference to possible armoring is given in a subsequent section (page 27).

The Graph in Figure 9 clearly supports an argument that the mean velocity at which scour begins is about 5 fps. The Graph in Figure 9 represents a smoothed relation of riverbed level to streamflow velocity for 1922-62. The smoothed effect was obtained by using a 50-point progressive average of riverbed levels. The average was plotted at the midpoint of the 50 values.

Relation Between Stage and Discharge

The scour that occurred after the completion of Glen Canyon Dam caused a change in the relation of stage to discharge for the Lees Ferry gage. The magnitude of the change is described in this section.

The procedure used to study the relation between stage and discharge primarily involved the same steps as described previously for the relation between velocity and discharge. The model used to represent the relation between stage and discharge is:

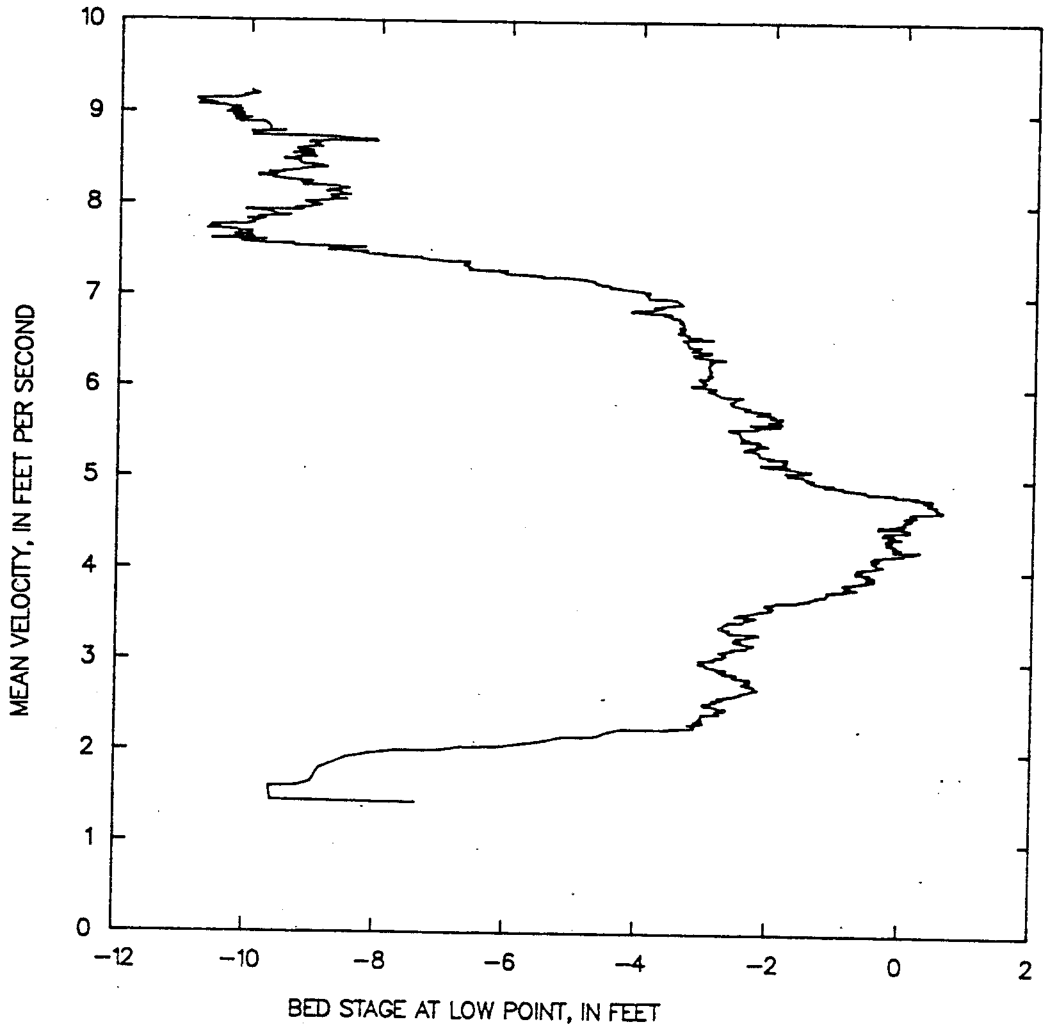


Figure 9.--Relation of mean velocity to bed stage at the low point in the cross section, Colorado River at Lees Ferry, Arizona, 1922-1962. Bed stage values were smoothed with a 50-point moving average.

$$GH=A(QM)^{B}+C$$

in which GH is gage height or stage of water surface, A is a coefficient, QM is measured discharge, B is a exponent and C is a parameter. Iterations routines and least-square regression analyses were used to develop estimates for A, B and C. Equations representing the average (1922-84) relation between stage and discharge for the site at Lees Ferry are:

$$GHHAT=0.48(QM)^{0.30}+0.57 \qquad (2A)$$

$$GHHAT1=0.54(QM)^{0.30}-0.34 \qquad (2B)$$

in which GHHAT, GHHAT1=computed gage height or stage, in ft; and QM=measured discharge, in cfs.

Equations 2A and 2B represent two parts of a single relation between stage and discharge. Equation 2A applies to discharges in the range from 2,500 to 10,000 cfs and equation 2B applies to discharges in the range from 10,000 to 33,000 cfs. The standard error of estimate for the relation is 0.15 ft or 1.7 percent of the mean of apparent depths. The term "apparent depth" is defined as the difference between water-surface stage at a time of interest and the riverbed elevation at which flow past the gage would cease.

The numbers 0.57 and -0.34 taken from equation 2A and 2B, respectively, represent, on an average, the stage below which flow apparently ceases. The discrepancy, or disagreement, in the (apparent) point of zero flow (stage below which flow ceases) occurs often among gage sites in pool-and-rapid streams. The fact that the point of zero flow decreased with an increase in discharge indicates that either (1) scour in the pool affected the relation of stage to discharge as the flow increased or (2) the gage site has one or more channel conditions--another gravel bar, a bend in the river, a restricted section--downstream that acts as a partial control. The number representing the apparent point of zero flow for the higher discharges probably would have been greater than the number for the lower flow rates had the discharge at the gage exceeded the discharge at bankful capacity.

A shift of the relation of stage to discharge amounting to about 0.45 ft apparently occurred in 1922-84 (Figure 10). This is about three times the standard error for the relation. Stated differently, the stage needed to pass a given discharge in 1984, was about 0.45 ft higher on the average than the stage required to pass the same discharge in 1922. It should be noted that the sum of all shifts for 1922-84 is not significantly different from

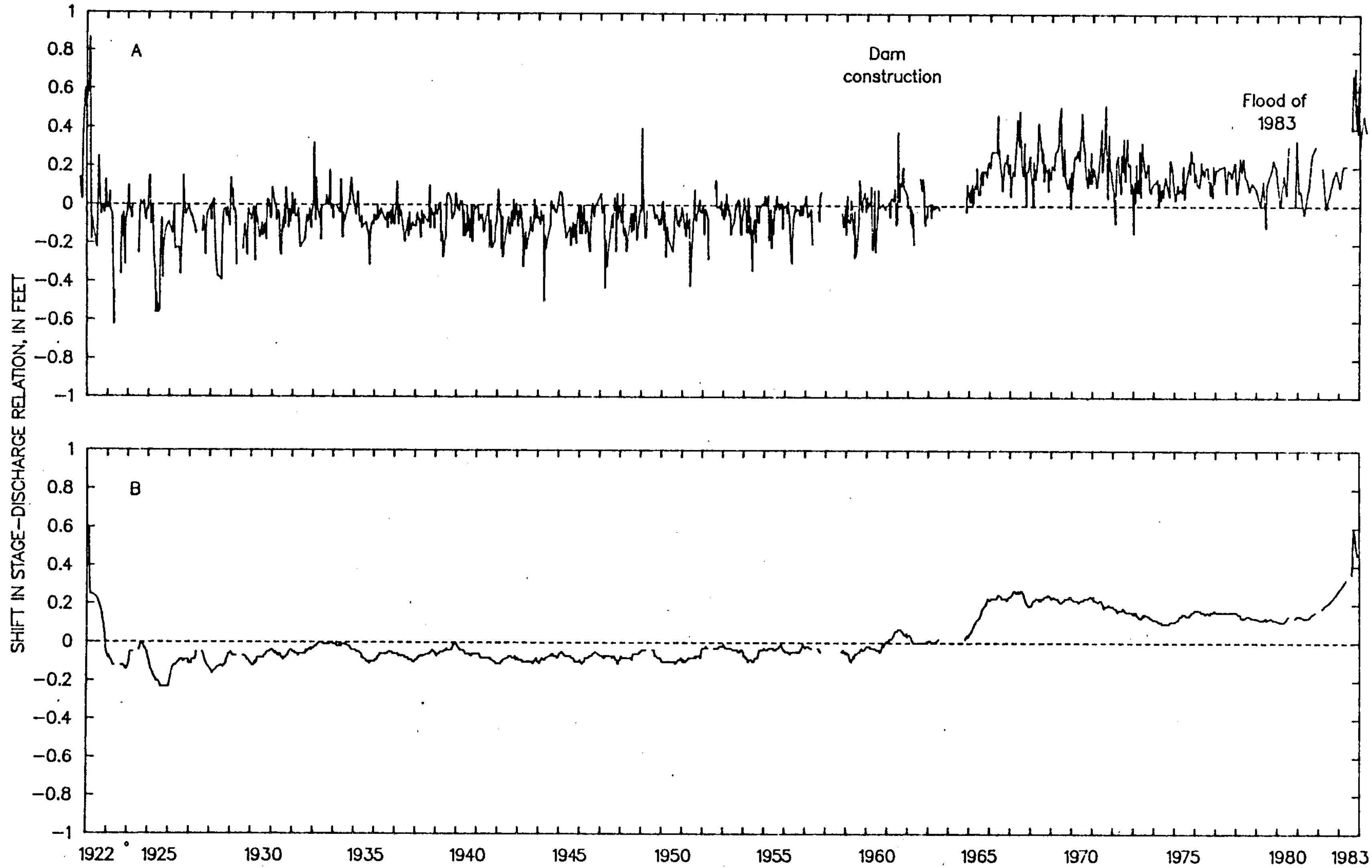


Figure 10.--Shift in relation of stage to discharge, Colorado River at Lees Ferry, Arizona, 1922-1984. A, discharges between 2,500 and 33,000 cubic feet per second. B, 20-point moving average of data in A. Shift was computed as the measured stage minus stage computed with equations 2A and 2B. Equation 2A was used for discharges up to 10,000 cubic feet per second, and equation 2B for discharges between 10,000 and 33,000 cubic feet per second.

0. From about 1940 to 1962, a progressively higher stage was required to pass a given discharge--for the period, a total increase in stage required to pass the given discharge amounted to about 0.10 ft. From about 1965 to 1967, the average increase in stage required to pass a given discharge was about 0.25 ft.

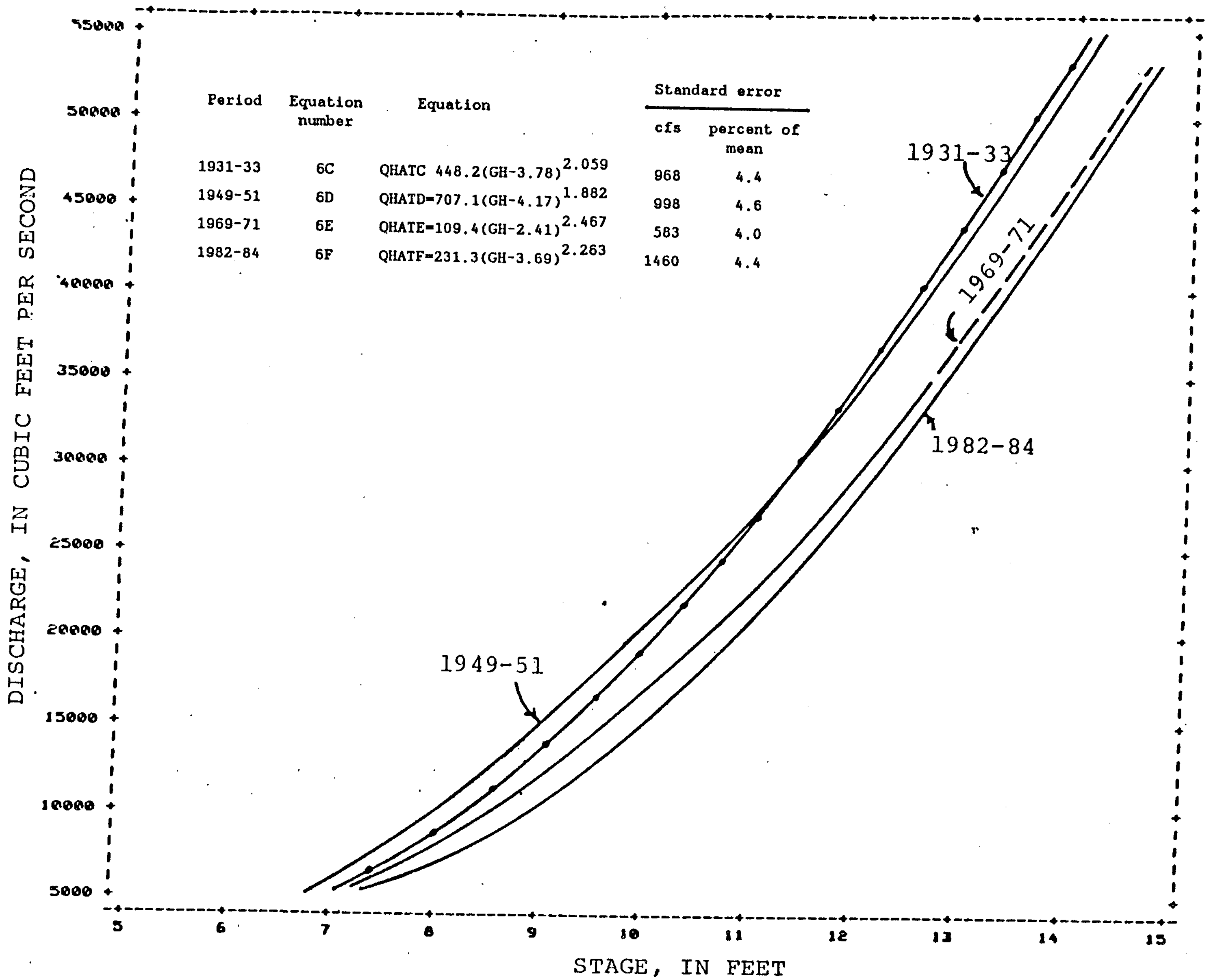
The flood of June 1983 apparently caused another increase in stage needed to pass a given discharge that amounted to about 0.10 ft. Shifts in the relation of stage to discharge from 1931-33 to 1982-84 resulted in a decrease in discharge at a stage of 12 ft that amounted to about 6,500 cfs (Figure 11).

The Graphs shown in Figure 10 are used to investigate temporal changes (or shifts) in the relation of stage to discharge for discharges in the range from 2,500 to 33,000 cfs at the site at Lees Ferry. The shifts plotted in Graph A in Figure 10 were determined by subtracting computed stage from measured stage where the computed stage was obtained using equations 2A and 2B. The points plotted in Graph B in Figure 10 represent 20-point moving (progressive) averages of shifts shown in Graph A.

The reason for the change in the relation between stage and discharge at the Lees Ferry site is not known. However, a relatively large change in velocity for a given discharge in a pool section, such as that at the Lees Ferry site, can significantly affect the relation between stage and discharge at the section. Assuming that a downstream rapid is a control, a decrease in velocity head must be counter-balanced by an increase in stage for the same discharge. Velocity head, Vh, is represented by the formula Vh=a1(V2/2g), in which a1 is a coefficient and g is the gravitational constant. The decreases in velocity, cited on page 16, could possibly cause the stage required to pass discharges of 80,000, 20,000, and 10,000 cfs to increase by about 0.8, 0.6, and 0.4 ft, respectively. It is assumed that the 0.45 ft increase in stage required to pass a discharge in the range from 2,500 to 33,000 cfs at the Lees Ferry site was a direct result of a change in streamflow velocity at the gage. This assumption is based on three considerations: (1) the periods of gradual increase in stage for a given discharge (Figure 10) correspond to periods when there are decreases in velocity for a given discharge (Figure 5); (2) the decreases in velocity for a given discharge are of a magnitude that could cause the changes in stage for the given discharge; (3) other reasons, such as changes in the control section, that could account for the recorded change in the relation between stage and discharge are not apparent.

Discussion of Results

Five hydrologic implications were brought out during the study of historical streamflow data for the Lees Ferry gage. The



Period	Equation number	Equation	Standard error: cfs	Standard error: percent of mean
1931-33	6C	QHATC 448.2(GH-3.78)$^{2.059}$	968	4.4
1949-51	6D	QHATD=707.1(GH-4.17)$^{1.882}$	998	4.6
1969-71	6E	QHATE=109.4(GH-2.41)$^{2.467}$	583	4.0
1982-84	6F	QHATF=231.3(GH-3.69)$^{2.263}$	1460	4.4

Figure 11.--Relation of stage to discharge, Colorado River at Lees Ferry, Arizona, for selected periods. All measurements for discharges less than 100,000 cubic feet per second were used in the least-squares development of the relations.

implications are in relation to armoring of the riverbed, to degradation of the river, to post-dam velocity necessary to cause scour of the bed, to the supply of sediment for transport after the construction of Glen Canyon Dam, and to the decreasing supply of sediment for transport during 1940-62.

The theory often presented to explain the armoring of a riverbed seemly would apply to the Colorado River at Lees Ferry after 1963. The theory involves, among other things, an arguement that the load of bed sediments of streams is finer than the bed sediment from which it is derived, which leads to the conclusion that as a stream degrades its bed will coarsen (Vanoni, 1962). A collateral fact is that the prolonged coarsening of the bed sediment of a stream can lead to armoring, the development of a layer of large size sediments that protects underlying finer sediments from further degradation. The theory is supported by the argument that the riverbed downstream from several large reservoirs are known to have coarsened and become armored as they have degraded (Lane, 1949; Livesey, 1965; Vanoni, 1975).

The theory of armoring, as described in the preceding paragraph, however, does not apply entirely to the situation at Lees Ferry. According to the definition, a degrading stream is a prerequisite to the formation of an armored layer. The riverbed at the measurement section did scour about 15 ft after the construction of Glen Canyon Dam: The measurement section is in the pool of a pool-and-rapid reach of the river. The riverbed scoured to the same level almost annually during 1922-62. The rapid immediately downstream, however, apparently did not erode significantly in 1922-84 and may not erode significantly in the next 50 to 100 years. The Colorado River in the vicinity of Lees Ferry, therefore, does not represent a typical degrading stream.

The fact that the riverbed level at the measurement section became fairly constant after the heavy scour in 1963-65 would seem to support a supposition that the bed had become armored with course-grain sediments. Several other facts and factors indicate that the supposition is partially, but not entirely, correct. Facts and factors pertinent to armoring of the river-bed, to degradation of the river, to post-dam velocity necessary to unravel the riverbed, and to the post-dam supply of sand and gravel-size sediments are as follows:

1. Prior to the construction of Glen Canyon Dam, scour in the riverbed started when the mean cross-sectional velocity exceeded 5 fps and continued as long as the mean velocity was increasing. A velocity of 7 fps (or greater) was required to cause the bed to scour to the -15 to -16 ft level (Graph A in Figure 8). The riverbed, on several high-flow occasions when the mean velocity was greater than about 7 fps, scoured to a level that was several feet below the -16 ft level (Graph A in Figure 8).

2. During a high-flow event in 1922-62, fill began when the velocity started to decrease. Presumably, as the velocity started to decline, the largest sediment particles being carried by the flow were deposited first. Thus, when another flood occurred and scour began, a progressively larger-size sediment was encountered as the depth of scour increased.

3. The riverbed scoured to about the -27 ft level in 1965 when the discharge was 40,000 to 60,000 cfs for several days but immediately filled back to about the -15 ft level.

4. The riverbed did not return to the 0 to -2 ft level in 1967-82 because the amount of sediment input to the pool, if any, was small.

5. From 1967-82, the streamflow velocity did not reach a magnitude that would have caused additional scour even if the sediments on the bed had been of a pre-dam, high-bed size. As previously indicated, a mean cross-sectional velocity exceeding 5 fps was required in 1922-62 before the bed began to unravel. According to the curves in Figure 6, a discharge of about 70,000-80,000 cfs would be required to produce a velocity of about 7 fps, the critical velocity in 1969-71 needed to produce additional scour at the -15 ft level.

6. The bed scoured to about the -21 ft level when the discharge was greater than 90,000 cfs and the mean velocity was about 7.5 fps in June 1983. The bed returned to approximately the -16 ft level while the discharge was still greater than about 60,000 cfs and the velocity was about 6 fps.

7. The sediments on the bed were significantly larger in 1983 than in 1963 (Tables 1a and 1b). In fact, for a relatively large part of the cross section in 1983, the sediment on the bed apparently was too large to be caught in a standard-size sampler. However, for other parts of the cross section, the sediments on the bed were of a sand-to-gravel size.

8. The increase in sediment size with depth is found in other streams embedded in alluvium (Burkham, 1970). For a site at a pool in a pool-and-rapid reach, a progressively higher streamflow velocity is required to continue scour after the initial unraveling of the bed. When scour stops, the notion that a layer of coarse sediments protects an underlying layer of finer sediment may be a theory only and not a fact.

9. The 1983 flood caused a significant amount of sand-size sediment to move past the gage at Lees Ferry (U.S. Geological Survey, issued annually). This sediment was eroded from the river bed and banks in the reach from Glen Canyon Dam to Lees Ferry. A limited supply of alluvial sand- and gravel-size

Table 1a. Bed-sediment sizes for indicated dates and percentages, for the Colorado River at Lees Ferry, Arizona (data from files of U.S. Geological Survey, Tucson, Arizona). The term "Total Section" indicates that the data are for the total cross section. The numbers "305-365" indicated that the data are for the part of the cross section that extends 305 to 365 feet from the point of reference. The term "D35" indicates a grain size, in millimeters, at which 35 percent of the sediment is finer.

COLORADO RIVER AT LEES FERRY, ARIZONA

DATES	SECTION BOUNDS	D35	D50	D65
Oct. 16, 1955	Total Section	0.17	0.20	0.23
Apr. 14, 1956	"	0.26	0.31	0.35
June 3, 1956	"	0.24	0.28	0.32
Apr. 13, 1963	"	0.08	0.09	0.10
Sept. 12, 1963	"	0.11	0.12	0.14
Sept. 19, 1963	"	0.11	0.13	0.15
Sept. 27, 1963	"	0.08	0.10	0.12
Oct. 3, 1963	"	0.12	0.14	0.17
Oct. 10, 1963	"	0.10	0.11	0.12
Oct. 18, 1963	"	0.10	0.11	0.12
Oct. 24, 1963	"	0.15	0.18	0.23
Oct. 21, 1963	"	0.10	0.11	0.13
Nov. 7, 1963	"	0.10	0.11	0.12
Nov. 16, 1963	"	0.10	0.11	0.13
Nov. 20, 1963	"	0.11	0.12	0.14
Nov. 28, 1963	"	0.11	0.12	0.14
Dec. 1, 1963	"	0.10	0.11	0.13
Jan. 7, 1964	"	0.11	0.12	0.13
Jan. 14, 1964	"	0.09	0.10	0.11
Jan. 21, 1964	"	0.10	0.11	0.12
Jan. 28, 1964	"	0.10	0.11	0.12
Feb. 19, 1964	"	0.10	0.11	0.13
Aug. 12, 1965	"	0.30	0.38	0.41
Dec. 13, 1965	"	0.08	10.00	0.13
Sept. 26, 1965	"	0.24	0.28	0.31
Jan. 12, 1968	"	0.38	0.42	0.46
Feb. 29, 1968	"	0.40	0.45	0.48
Oct. 15, 1969	"	0.43	0.49	0.54
Jan. 29 to	305-365	1.69	4.26	9.12
Aug. 31,	365-405	0.76	1.10	1.66
1983	405-525	0.39	0.44	0.49
Sept. 1,	190-245	0.11	0.15	0.20
to	305-365	9.54	14.62	17.16
Dec. 13,	365-405	0.95	1.76	3.40
1983	405-525	0.37	0.42	0.46

Table 1b. Bed-sediment sizes for indicated dates and percentages, for the Colorado River near Grand Canyon, Arizona (data from files of U.S. Geological Survey, Tucson, Arizona). The term "Total Section" indicates that the data are for the total cross section. The numbers "306-365" indicate that the data are for the part of the cross section that extends 305 to 365 feet from the point of reference. The term "D35" indicates a grain size, in millimeters, at which 35 percent of the sediment is finer.

COLORADO RIVER NEAR GRAND CANYON, ARIZONA				
DATES	SECTION BOUNDS	D35	D50	D65
Apr. 12, 1965	Total Section	0.20	0.23	0.27
May 31, 1965	"	0.35	0.40	0.45
Oct. 29, 1965	"	0.21	0.23	0.25
Nov. 22, 1969	"	0.27	0.31	34.00
Feb. 16, 1970	"	0.32	0.36	0.40
June 1, 1970	"	0.31	0.34	0.38
Sept. 14, 1970	"	0.33	0.38	0.44
Dec. 7, 1970	"	0.31	0.35	0.40
Mar. 29, 1971	"	0.32	0.37	0.42
Jun. 21, 1971	"	0.32	0.37	0.42
July 1, to	140-179	0.28	0.32	0.36
Sept. 27, 1983	240-310	0.36	0.41	0.46
Sept. 28, to	90-120	0.14	0.16	0.19
Dec. 14, 1983	140-310	0.30	0.35	0.40

sediments undoubtly still is available in the reach. Of this amount, the part that will erode undoubtly will be relatively low except during periods when the flow rate is greater than about 70,000 to 80,000 cfs.

The concentration of suspended sediment at the Lees Ferry gage may have been gradually decreasing during the pre-dam years of 1940-62. This supposition is supported by 2, and possibly 3, general arguments as follows:

1. After annual high-flow periods the riverbed at measurement section, on an average, was not returning to a level equal to that for the preceding year (Figure 2).

2. For a given discharge, the cross-sectional area was gradually increasing and the mean velocity was gradually decreasing during the period (Figure 5).

3. Further possible support for the supposition can be found by comparing curves for 1950-52 with those for 1960-62 in Figure 12.

The curves in Figure 12 were developed using data for daily discharges and daily suspended-sediment concentrations. As previously stated, suspended-sediment concentration for a given discharge derived from summer precipitation is much greater than that for the same discharge derived from winter precipitation. For this study, the daily discharge and daily suspended-sediment concentrations for individual storm events occurring in July-October were deleted from the data sets used to develop the different curves in Figure 12. In addition, of the 1,095 daily values for each of the three-year periods in 1950-52 and 1960-62, only the tenth value in chronological order was used in the development of the curves. Every fifth value in chronological order was used in the development of the curve for 1965.

The results of the study, in which suspended-sediment concentration is related to discharge, are questionable, however, they do not subtract credence from a supposition that sediment movement per unit of discharge in the Colorado River was gradually decreasing in 1940-62. Results of the study are questionable because the relation between suspended-sediment concentration and discharge shown in Figure 12 are poor--the standard errors are relatively large. In addition, the results are questionable because construction work at the Glen Canyon Dam--including the addition of a coffer dam--may have caused the decrease in suspended-sediment for a given discharge between 1950-52 and 1960-62.

The reason, or reasons, for the decreasing supply of sediment in the Colorado River at Lees Ferry during 1940-62 is not known.

Period	Equation	Standard error mg/l	Standard error percent of mean
1950-52	$CC=80.5\ Q^{0.36}$	1,030	44
1960-62	$CC=288\ Q^{0.19}$	950	69
1965	$CC=0.09\ Q^{0.82}$	294	120

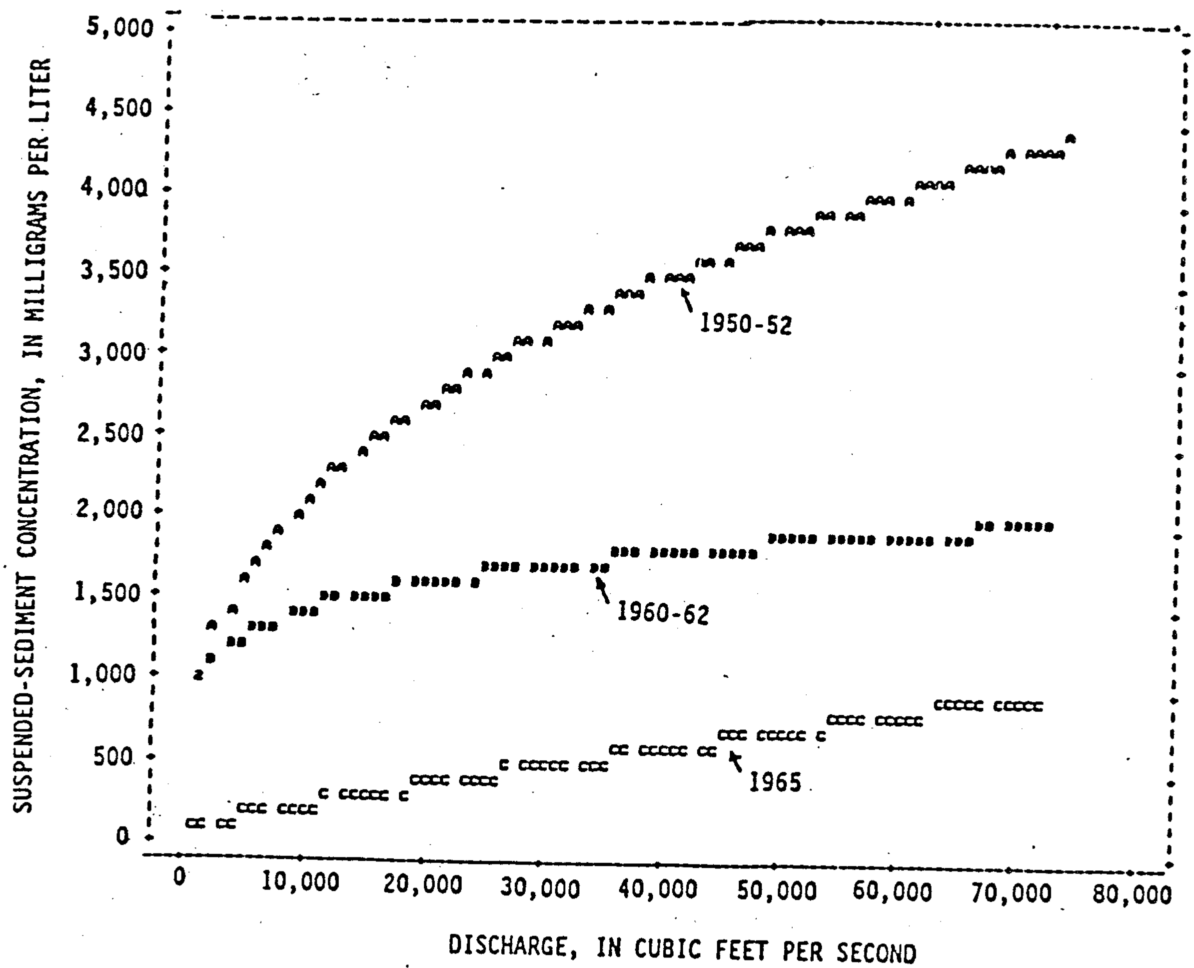


Figure 12.--Average relation between suspended-sediment concentrations and water discharge, Colorado River at Lees Ferry, Arizona, for indicated water years. Equations are valid only for flow events of long duration, because data for storms of short duration, which occur in July-October, were excluded from the data used to develop the relations. In the equations, CC is suspended-sediment concentration in milligrams per liter (mg/l) and Q is discharge in cubic feet per second (cfs).

The reason, however, probably is largely associated with the natural response of upstream drainages to fluctuation in climate (Burkham, 1981). The natural response of drainages to fluctuations in climate has been described for at least two streams draining towards the Colorado River (Burkham, 1972; Hereford, R., written comm., 1982).

ANALYSIS OF DATA FOR THE SITE NEAR GRAND CANYON

Introduction

Each of the different variables for the Grand Canyon site are assumed to be compatible in time and can be used in trend investigations. The variables are time, stage, depth, velocity and discharge. Discharge measurements for the Grand Canyon site, as previously noted, were made at a cableway approximately 700 ft downstream from the gage.

Trends in Channel-bed Scour (or Fill) for 1922-84

The points plotted in Figure 13 represent riverbed levels at the low point in the cross section during the measurement of discharge. The low point in the bed was obtained by subtracting the maximum depth from the water-surface stage of the river. Data for all measurements furnished by the USGS were used in the development of the Graphs in Figure 13. However, measurement notes for several periods were not found among USGS records (written comm. U.S. Geological Survey, 1985). The plotted points in Graph A in Figure 13 represent the full range in scour and fill at the site. Those in Graph B in Figure 13 represent a weighted or smoothed scour-and-fill regime.

The range in scour and fill of the riverbed at the Grand Canyon site for 1922-62 is not nearly as great as that for the same period at the Lees Ferry site (Figures 13 and 2). The range is about 8.0 ft for the Grand Canyon site and more than 20 ft for the Lees Ferry site. Also, unlike the measurement section at Lees Ferry, the riverbed at the Grand Canyon site apparently was at the low-bed level--at about -11.5 ft level and lower--a greater percentage of time than at the high-bed level-- -9.0 ft and higher. As discussed on page 46, the amount of sediment available for deposit in the pool during several years was not sufficient to return the bed to a high level.

Two factors--the regulation of flow at Glen Canyon Dam in 1963, and a flood on Bright Angel Creek in December 1966--apparently caused a change in the scour-and-fill regime at the Grand Canyon site. Starting in about 1967 and ending in 1983, the riverbed at the measurement section stayed at or near the high-bed level. The 1966 flood (Cooley, Aldridge, and Euler, 1977) brought large amounts of debris--large boulders, cobbles, gravel--to the mouth of Bright Angel Creek. Much of this debris became lodged on the control (rapid) downstream from the Grand Canyon gage. The elevation of the riverbed at the rapid increased which caused the riverbed at the Grand Canyon gage to rise by about 4 ft. Most of the debris on the rapid stayed in place during 1967-82 simply because the regulated discharge of the Colorado River did not create enough energy to remove it. However, in 1971-73, the

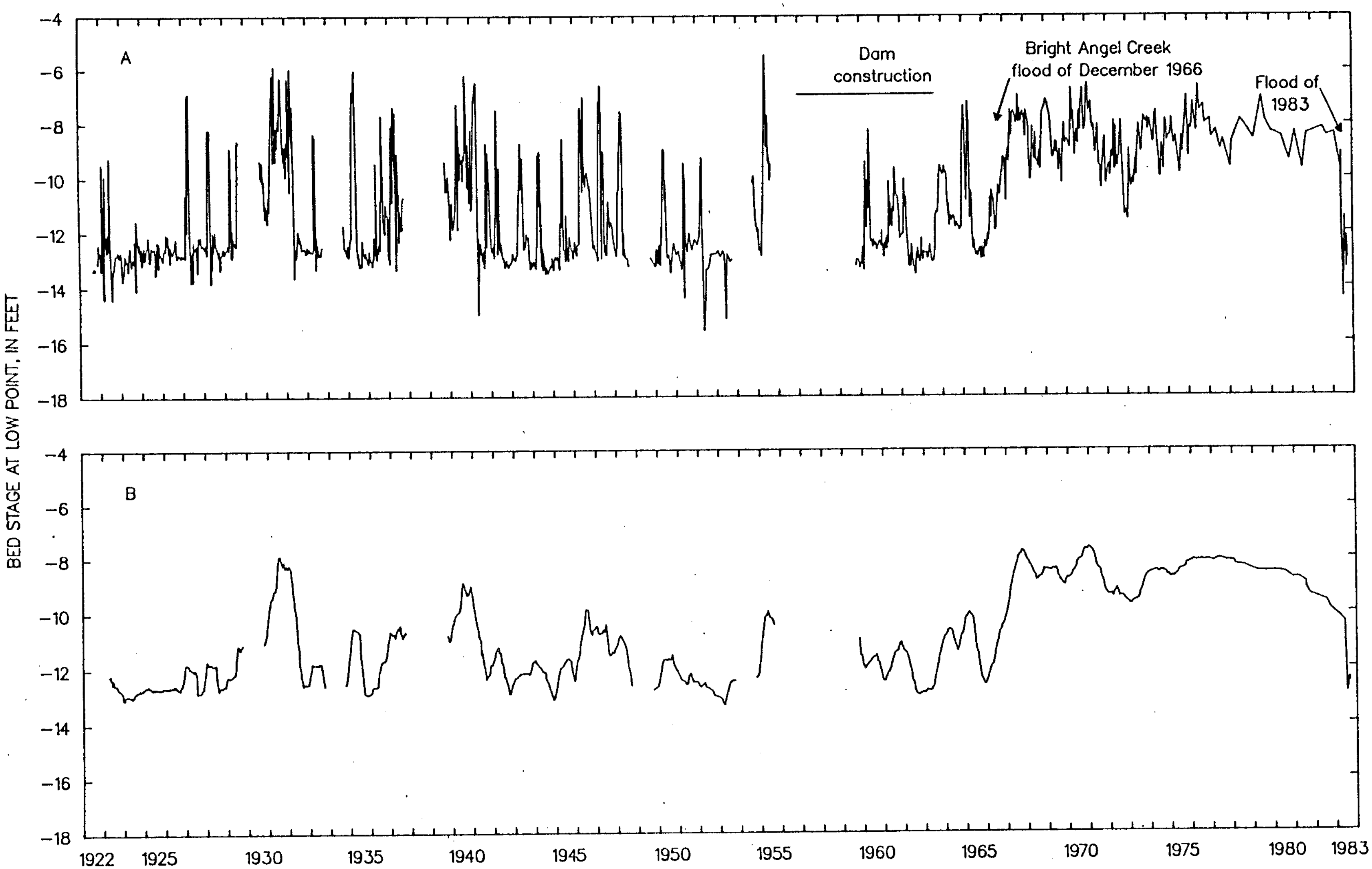


Figure 13.--Bed stage at the low point in the cross section, Colorado River near Grand Canyon, Arizona, 1922-1984. A, entire range of measured discharge. B, 20-point moving average of data in A.

riverbed at the measurement site apparently scoured a significant amount. Also, the bed level at the measurement section was gradually being lowered in 1977-82 which seems to indicate that the debris on the rapid was gradually being weathered away. The 1983 flood on the Colorado River removed the debris from the rapid at Bright Angel Creek and the riverbed at the measurement section returned to a low-bed level.

The cross-sectional profiles in Figure 14 show bed levels for different times and discharges in 1922-84. The profiles for 1931 and 1932 are representative for the different pre-dam discharges and scour-fill regimes. The profiles for October 25, 1931 and September 9, 1931 are representative of relatively low discharges and high-bed regimes. The profile for June 25, 1932 is representative for a high discharge in a period when the bed had not yet reached a low-bed level. The profile for July 26, 1932 is representative of a relatively low discharge in a period soon after the occurrence of a high discharge and large scour. The cross-sectional profiles for relatively low discharges during July 13, 1965 and August 11, 1965 (Figure 14) are representative of low-bed conditions after the high release rates in 1965. The cross-sectional profiles for January 1, 1968 and February 24, 1968 (Figure 14) illustrate high-bed conditions after the occurrence of the 1966 flood on Bright Angel Creek. Except for the distance along the left side of the section (shown at right in illustration) from about 320 to 350 ft, the profiles for January 1, 1968 and February 24, 1968 are not significantly different from those for September 27, 1931 and October 25, 1931. The riverbed along the left side of the section apparently was gradually being lowered in 1968-82. By October 3, 1982, the bed level for the distance along the measurement section from 300- to 350-ft was lower by an average 3 ft than the level that existed in February 24,1968.

The profiles for June 8, 1983 and June 25, 1983 (Figure 14) show the bed level that existed after the 1983 flood. As previously stated, the riverbed at the measurement section and at the Bright Angel rapid in 1983 returned approximately to the level that existed prior to the 1966 flood on Bright Angel Creek.

Relation Between Velocity and Discharge

The procedure used to develop a better understanding of the relation that exists between velocity and discharge is the same as that used for the Lees Ferry site, except all discharge measurements are used. The equation representing the average (1922-84) relation between velocity and discharge for the site near Grand Canyon is:

$$VHAT=0.015(QM)^{0.57} \qquad (3)$$

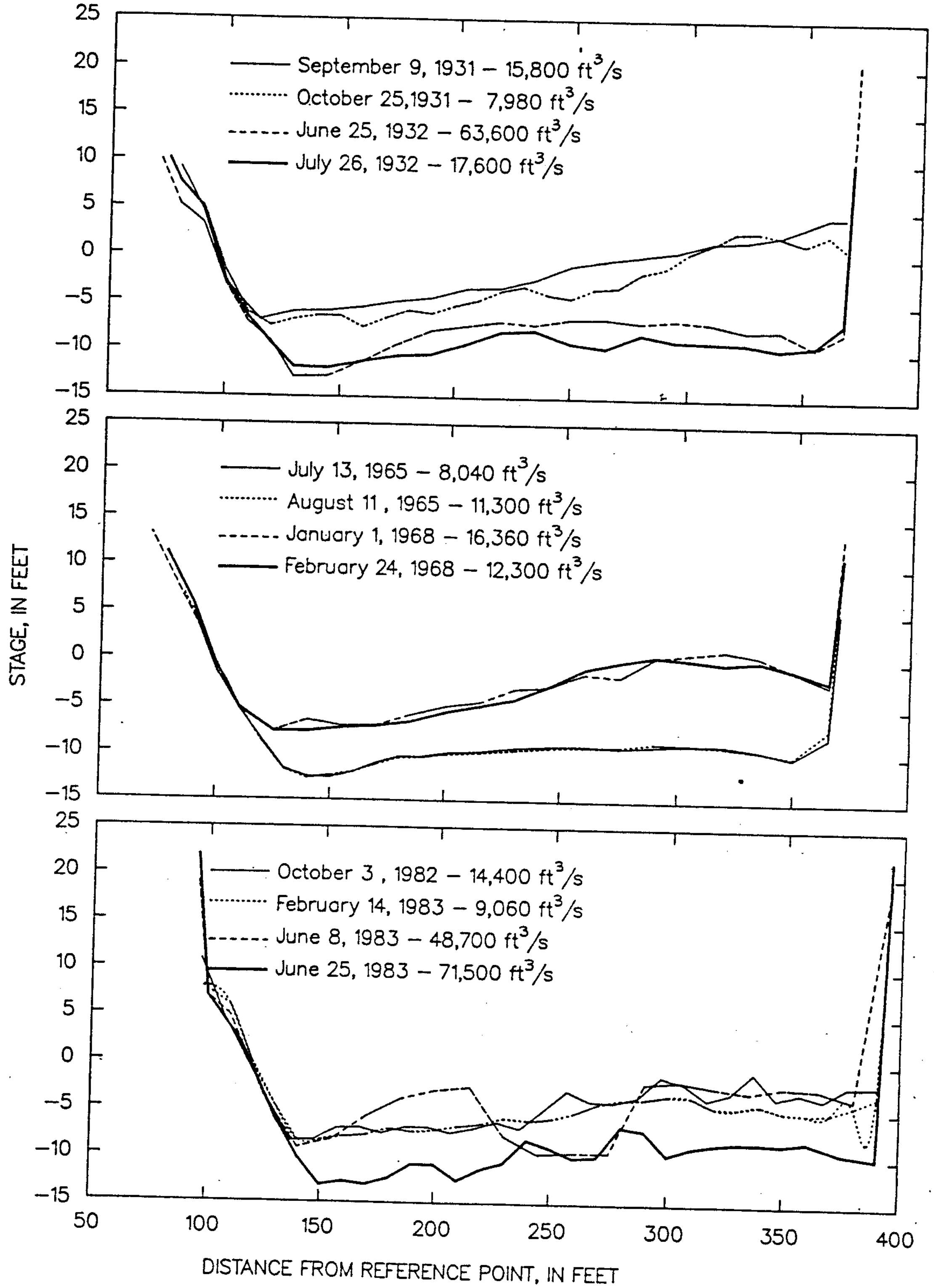


Figure 14.--Bed stage in cross section, Colorado River near Grand Canyon, Arizona, for selected times.

in which VHAT=computed velocity, in fps; and QM=measured discharge, in cfs.

Equation 3 is applicable to discharges in the range from 2,500 to 100,000 cfs. The standard error is 0.56 fps or 14.4 percent of the mean velocity.

The graphs in Figure 15 are used to investigate temporal changes (or shifts) in the relation between mean velocity and discharge for the site near Grand Canyon. The shifts plotted in Graph A in Figure 15 were determined by subtracting computed velocity, obtained from equation 3, from measured velocity. The points plotted in Graph B in Figure 15 represent 20-point moving (progressive) averages of shifts shown in Graph A.

The large scatter of data in Graph A (Figure 15) for 1922-1965 is assumed to be due mainly to scour and fill in the pool upstream from the control. On the one hand, when the riverbed in the pool is at a low level, the cross-sectional area is relatively large for a given discharge and the mean velocity is relatively low. On the other hand, when the pool had filled approximately to its maximum high-bed level, the cross-sectional area for a given discharge is relatively small and the mean velocity is relatively high. As can be seen by comparing Graph B in Figures 13 and Graph B in 15, periods of relative large positive shifts of the relaltion of velocity to discharge in 1926, 1931-32, 1935, 37, 1940-41, 1947, 1954, 1964, and 1965 correspond in time to periods when the riverbed was at (or near) its maximum high-bed level. In contrast, periods of large negative shifts correspond in time to periods when the riverbed was at (or near) its lowest level.

The scatter of plotted data in Graph A (Figure 15) for 1967-82 is not nearly as great as those for 1922-65. Presumably, the regulation of flow after 1963 and the debris lodged on the Bright Angel rapid (in 1966) were two important factors in causing the reduction in magnitude of shift. Some of the debris on the Bright Angel rapid, as previously indicated, apparently eroded in 1971-73. During 1971-73 an increase in velocity is indicated for a period in which the thalweg at the measurement section is being lowered (Figures 13 and 15). In 1974-1982, the mean velocity for a given discharge was gradually decreasing (Graph B in Figure 15): This corresponds in time to the lowering of the bed which was previously described. After the 1983 flood, the velocity for a given discharge was relatively low.

The graphs in Figure 16 give a different view of the relation which exists between mean velocity and discharge. The discharges and velocities for all measurements made in 1922-65 are plotted in Graph A in Figure 16. The low-bed relation shown in Figure 16 was developed using data for discharges for which the low-point in the riverbed in 1922-65 was less than -11.5 ft. The equation

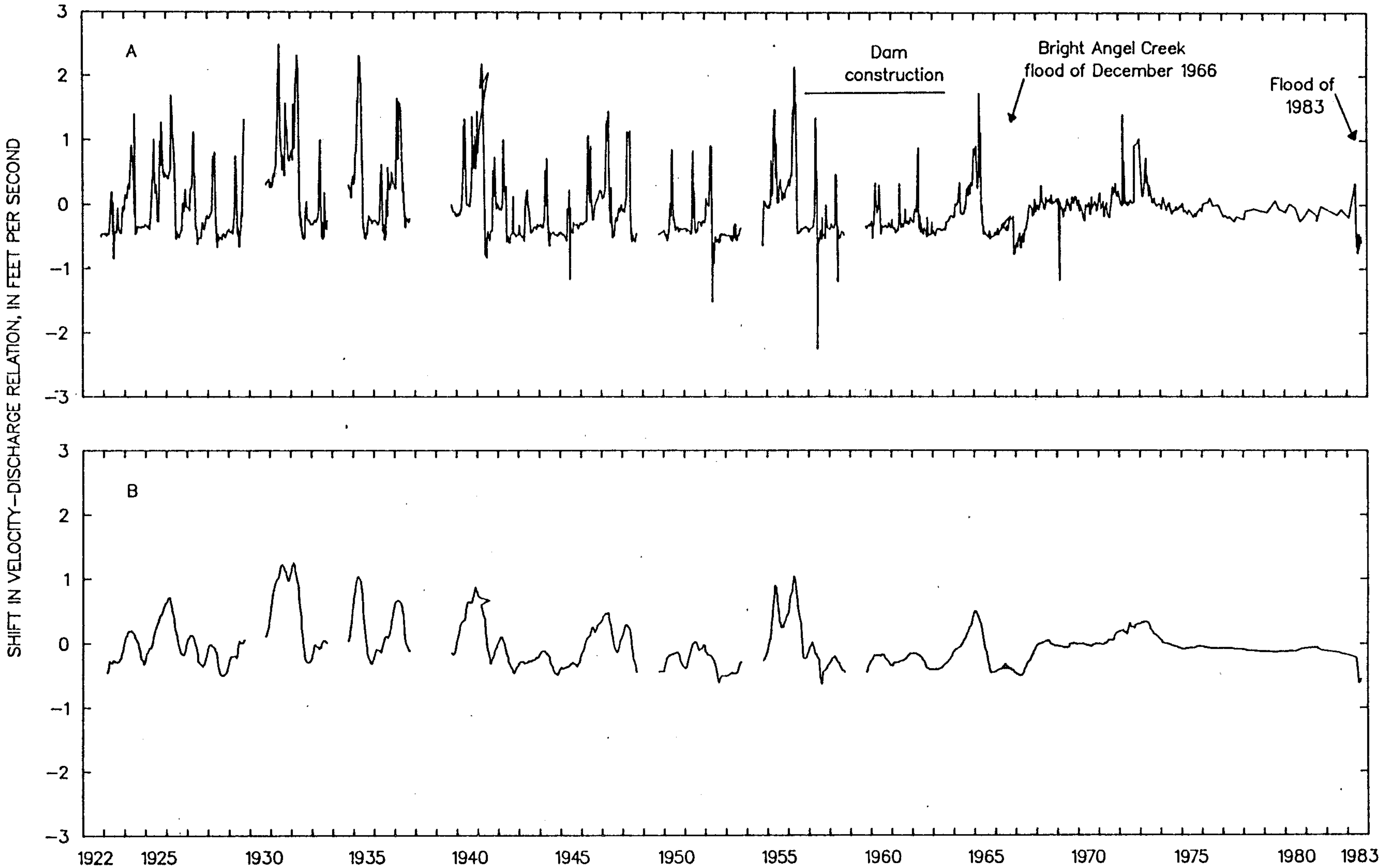


Figure 15.--Shift in relation of mean velocity to discharge, Colorado River near Grand Canyon, Arizona, 1922-1984. A, entire range of measured discharges. B, 20-point moving average of data in A. Shifts were computed as the measured velocity minus the velocity computed with equation 3.

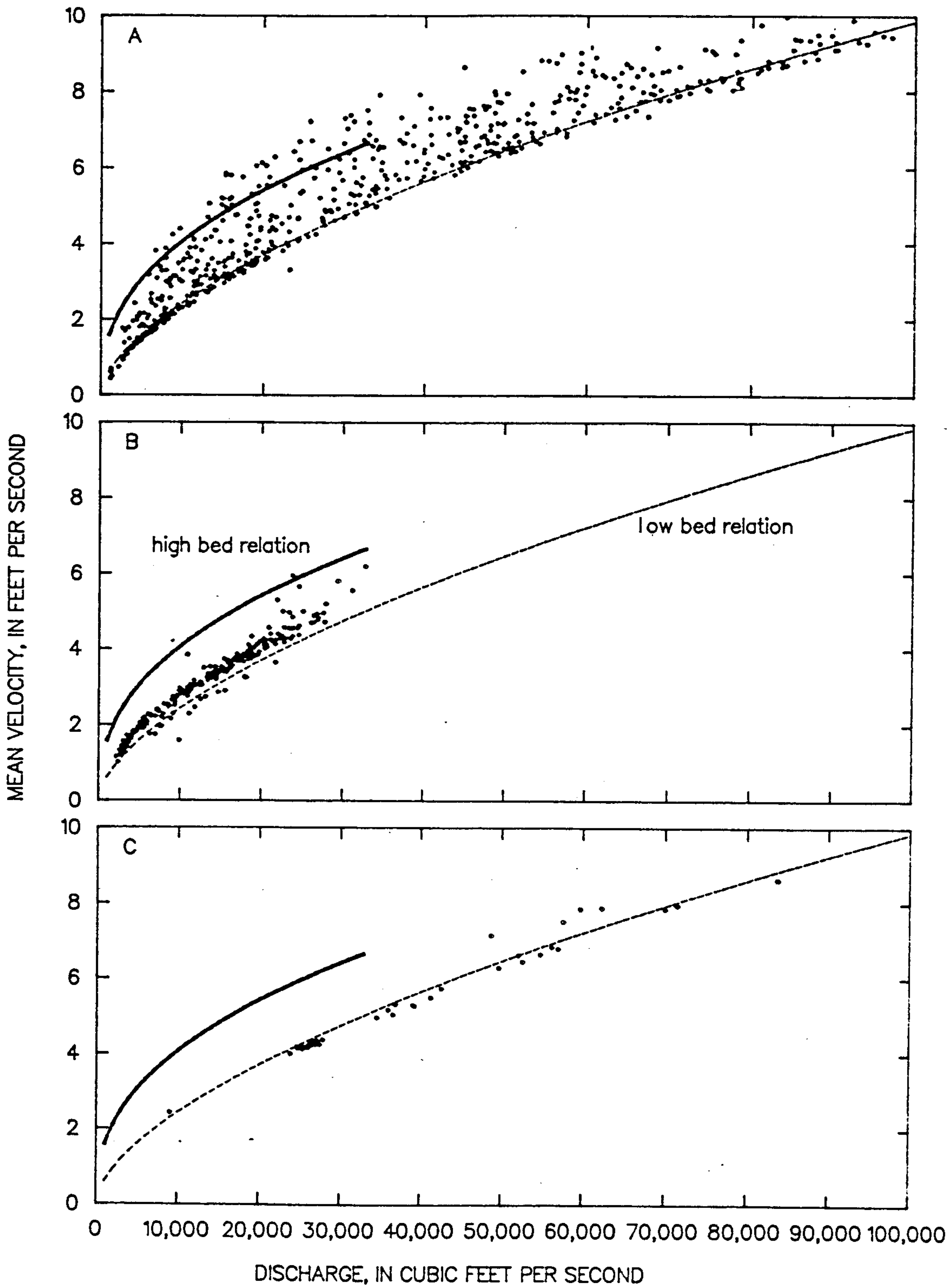


Figure 16.--Relation of mean velocity to discharge, Colorado River near Grand Canyon, Arizona, for selected periods. A, 1922-1965. B, 1967-1982. C, 1983-1984. The low-bed relation is equation 4, and the high bed relation is equation 5.

for the low-bed relation is:

$$VHAT=0.009(QM)^{0.61} \qquad (4)$$

in which, VHAT=mean velocity in fps, and QM=measured discharge, in cfs.

The standard error of estimate for equation 4 is 0.54 fps or 9.2 percent of the mean velocity. Five hundred and three data sets were used to define the equation. The low-bed relation is applicable for discharges in the range from 1,500 to 100,000 cfs when the bed is at -11.5 ft and lower.

The high-bed relation in Figure 16 was developed using data for discharges for which the low point in the riverbed in 1922-65 was greater than -9.0 ft. The equation for the high-bed relation is:

$$VHAT=0.089(QM)^{0.42} \qquad (5)$$

The standard error of estimate for equation 5 is 0.49 fps or 9.0 percent of the mean velocity: Seventy six data sets were used to define the equation. The high-bed relation is valid only for discharges less than about 35,000 cfs. Actually, the high-bed relation should be used with caution for any discharge where the indicated velocity is greater than about 5.5 fps. As discussed in the section "Relation Between Scour (or Fill) and Velocity", the high-bed riverbed apparently begins to erode significantly when the mean velocity exceeds about 5.5 fps. After scour of the bed starts and the discharge and velocity continue to increase, the relation of velocity to discharge moves towards the low-bed relationship.

The data points for 1967-82 lie a little to the left of the low-bed relation (Graph B in Figure 16). It should be noted that only 5 of the data sets for 1967-82 had velocities greater than 5.5 fps. All of the data points for 1982-84 (Graph C) lie along the low-bed relation--the relation that was defined using data set for low-bed conditions in 1922-65.

Relation Between Velocity and Scour (or Fill)

Graphs in Figure 17 show mean velocities plotted against elevations of the riverbed at the lowest point in the measurement section. Data for discharge measurements made in 1922-65 are shown in Graph A; those for 1967-82 are shown in Graph B; and those for 1983-84 are shown in Graph C.

The solid lines in Figure 17 were drawn to encompass all points in Graph A except those that deviate greatly in plotting position

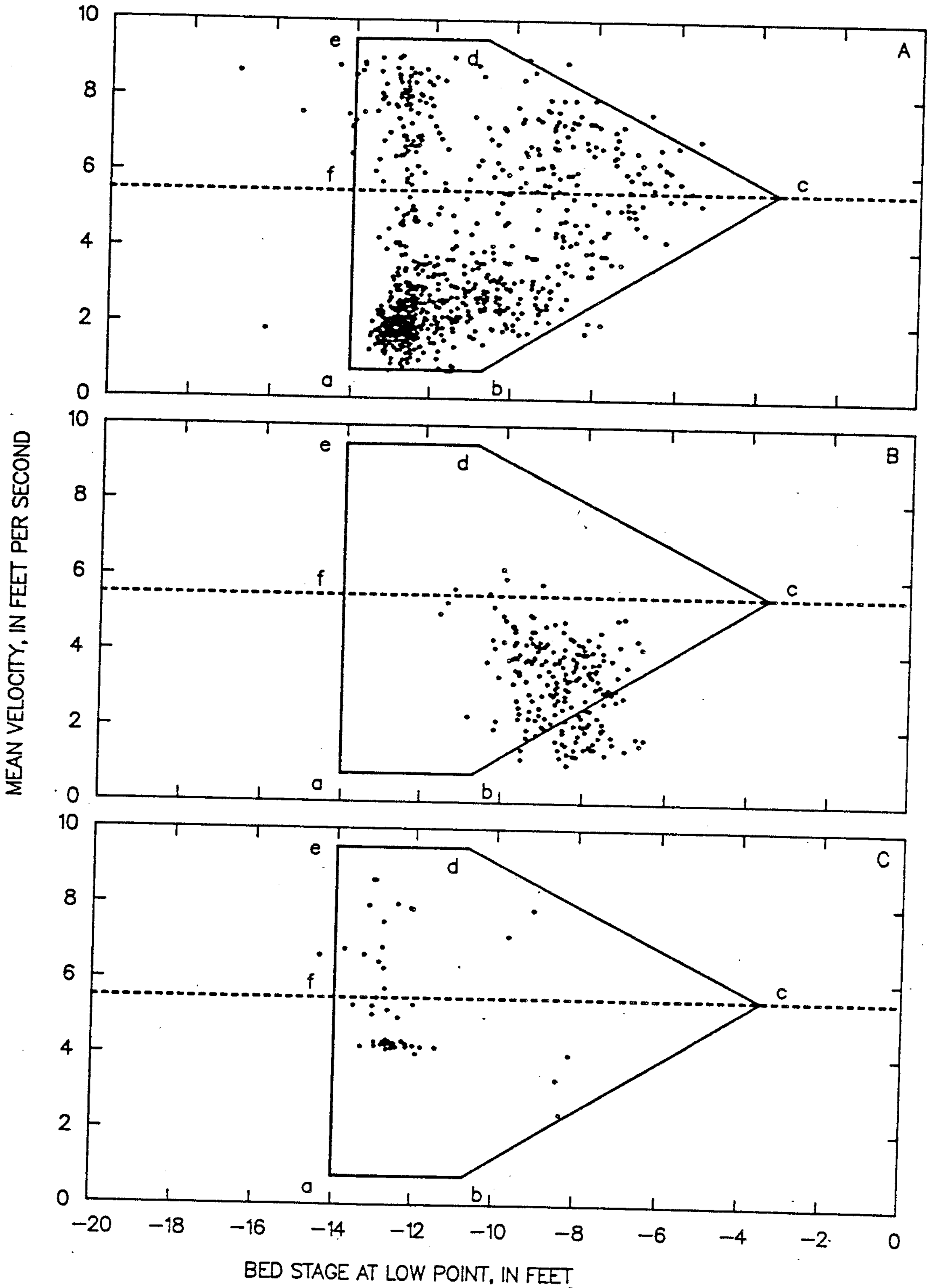


Figure 17.--Relation of mean velocity to bed stage at the low point in the cross section, Colorado River near Grand Canyon, Arizona, for selected periods. A, 1922-1965. B, 1967-1982. C, 1983-1984. Solid lines were drawn to encompass most of the data points from the 1922-1965 period. The dashed line indicates the velocity at which scour begins when the bed is at a high level. Lowercase letters mark line segments discussed in the text.

from most of the points. Line cf in Graph A (Figure 17) is drawn to represent the velocity at which scour begins when the bed is at the high-bed level. If cf adequately represents the velocity at which scour begins, quadrangle abcf encompasses points which represent stable-state or fill regimes, and quadrangle cdef encompasses points which represent scour, stable-state, or fill regimes. Actually, the bed did not reach a stable state in 1922-65. However, the riverbed at the low point in the cross section was at or below -11.5 ft--the low-bed level--a relatively large part of the time. The riverbed at the low point was at an elevation greater than -9.0 ft--the high-bed level--only a relatively small part of the time. As defined by measurements, the mean velocity ranged from 1 to 10 fps in 1922-65.

Graph B in Figure 17 indicates that the bed level in 1967-82 was relatively stable at a high elevation, compared to that for 1922-65. This stability of bed at the high-bed level is a direct result of regulation of flow and the 1966 debris on the control. As previously stated, mean velocities in 1967-82 were less than 5.5 fps except for only five occasions. Several of the points in Graph B (Figure 17) are outside the bounding lines of abcf: This represents another direct result of the debris on the Bright Angel rapid.

The bed, as previously stated, returned to about its pre-1966 low-bed level during the 1983 flood on the Colorado River (Graph C in Figure 17). Even though the flow in 1983-84 had mean velocities greater than 7.0 fps for a relatively long period of time, the bed only scoured to about the -13 ft level.

The graph in Figure 18 supports an argument that, when the riverbed was at a high level in 1922-66, the mean velocity at which scour begins is about 5.5 fps. The graph represents a smoothed relation of mean velocity to riverbed level for 1922-65. The smoothed effect was obtained by using 50-point progressive averages of riverbed levels that are shown in Graph A in Figure 17. The average was plotted at the midpoint of the 50 values. As previously stated, the riverbed is in a stable or filling mode when the mean velocity is less than about 5.5 cfs and in a stable, scour or filling mode when the velocity is greater than about 5.5 cfs. It is important to note that, when the bed was at the high-bed level in 1922-66, a discharge of only about 20,000 cfs was required to produce a velocity of 5.5 fps. Also, discharges greater than about 100,000 cfs in 1922-65, with mean velocities about 10 fps, did not cause the bed to scour to levels much less than -13.0 ft.

Relation Between Stage and Discharge

The regulation of flow at Glen Canyon Dam, the 1966 flood in Bright Angel Creek and the 1983 flood in the Colorado river are

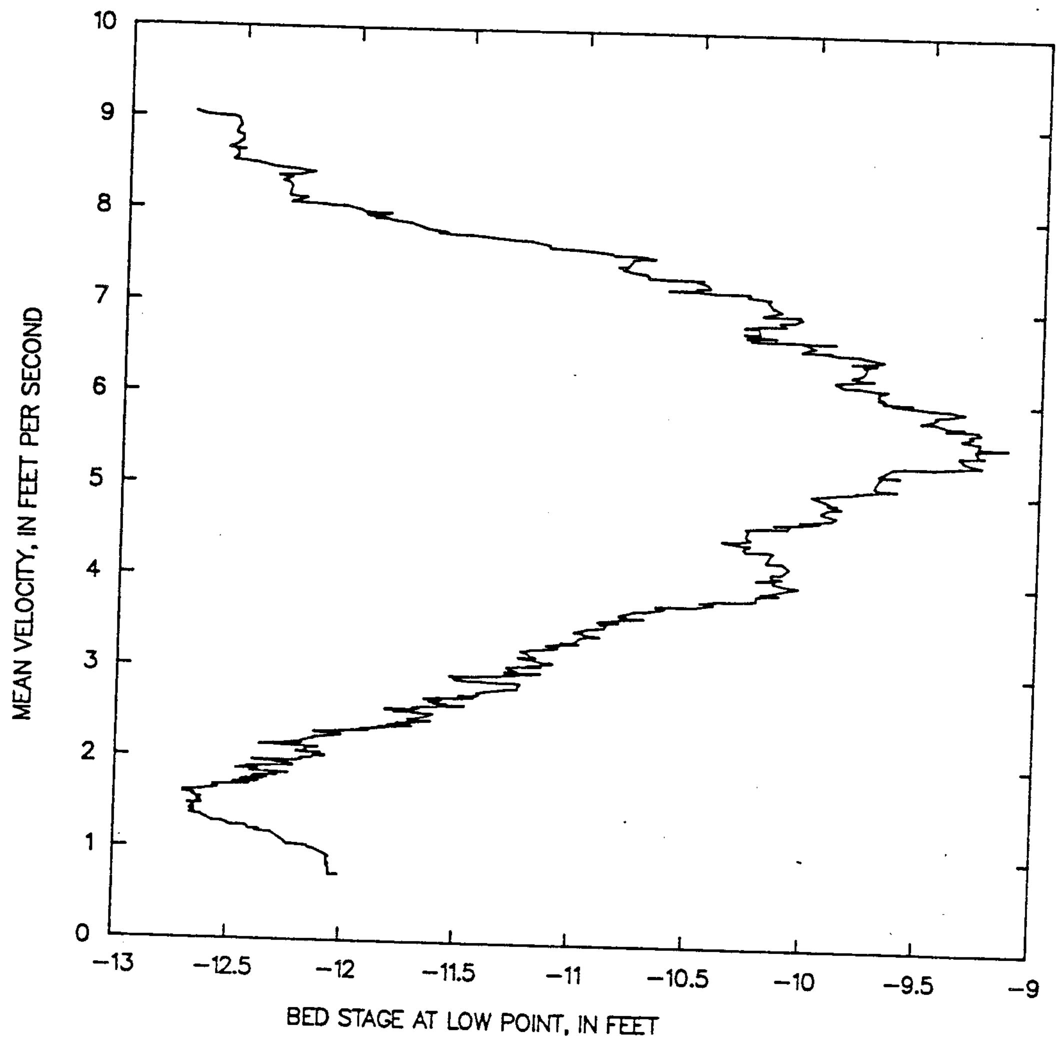


Figure 18.--Relation of mean velocity to bed stage at the low point in the cross section, Colorado River near Grand Canyon, Arizona, 1922-1966. Bed stage values were smoothed with a 50-point moving average.

pertinent factors in causing change in the relation of stage to discharge for the Grand Canyon gage in 1922-84. The magnitudes of change are described in this section.

The procedure used to study the relation between stage and discharge is the same as described previously for the Lees Ferry gage. The model used to represent the relation between stage and discharge also is the same. Equations representing the average (1922-84) relation of stage to discharge for the site near Grand Canyon are:

$$GHHATA=0.23(Q)^{0.44}-5.76 \qquad (6A)$$

$$GHHATB=0.28(Q)^{0.41}-5.08 \qquad (6B)$$

in which GHHATA, GHHATB=computed gage height or stage, in ft; and QM=measured discharge, in cfs.

Equations 6A and 6B represent two parts of a single relation between stage and discharge. Equation 6A is applicable to discharges less than 33,000 cfs and equation 6B is applicable for discharges greater than 33,000 cfs.

The agreement between computed stages, obtained using equation 6A and 6B, and measured stages is only fair: the standard error of estimate is 1.25 ft or about 8.2 percent of the mean of apparent depths. The agreement, however, is assumed to be adequate for the purpose of the present study. The graphs in Figure 19 are used to help in describing the magnitude and reasons for large shifts in the relation of stage to discharge for the Grand Canyon site. The shifts plotted in Graph A in Figure 19 were developed by subtracting computed stage, obtained by using equations 6A and 6B, from measured stage. The values plotted in Graph B in Figure 19 represent 20-point moving (progressive) averages of the shifts shown in Figure 19A.

The accumulation of debris on the Bright Angel rapid during the 1966 flood and the erosion of the debris in 1967-83 caused relatively large shifts in the relation of stage to discharge at the Grand Canyon site. The accumulation of debris during the December 1966 flood on Bright Angel Creek caused a shift in the relation of stage to discharge of 3-4 ft (Figure 19). As indicated by progressively smaller positive shifts (Figure 19) and lower bed levels (Figure 13), the debris apparently was gradually being eroded away during 1967-82. The effects of the 1966 debris were almost completely removed during the 1983 flood.

Several shifts during 1922-65 were larger than should be expected by changes in velocity alone. Particularly high positive shifts occurred in 1952 and 1953 (Figure 18), possibly the result of

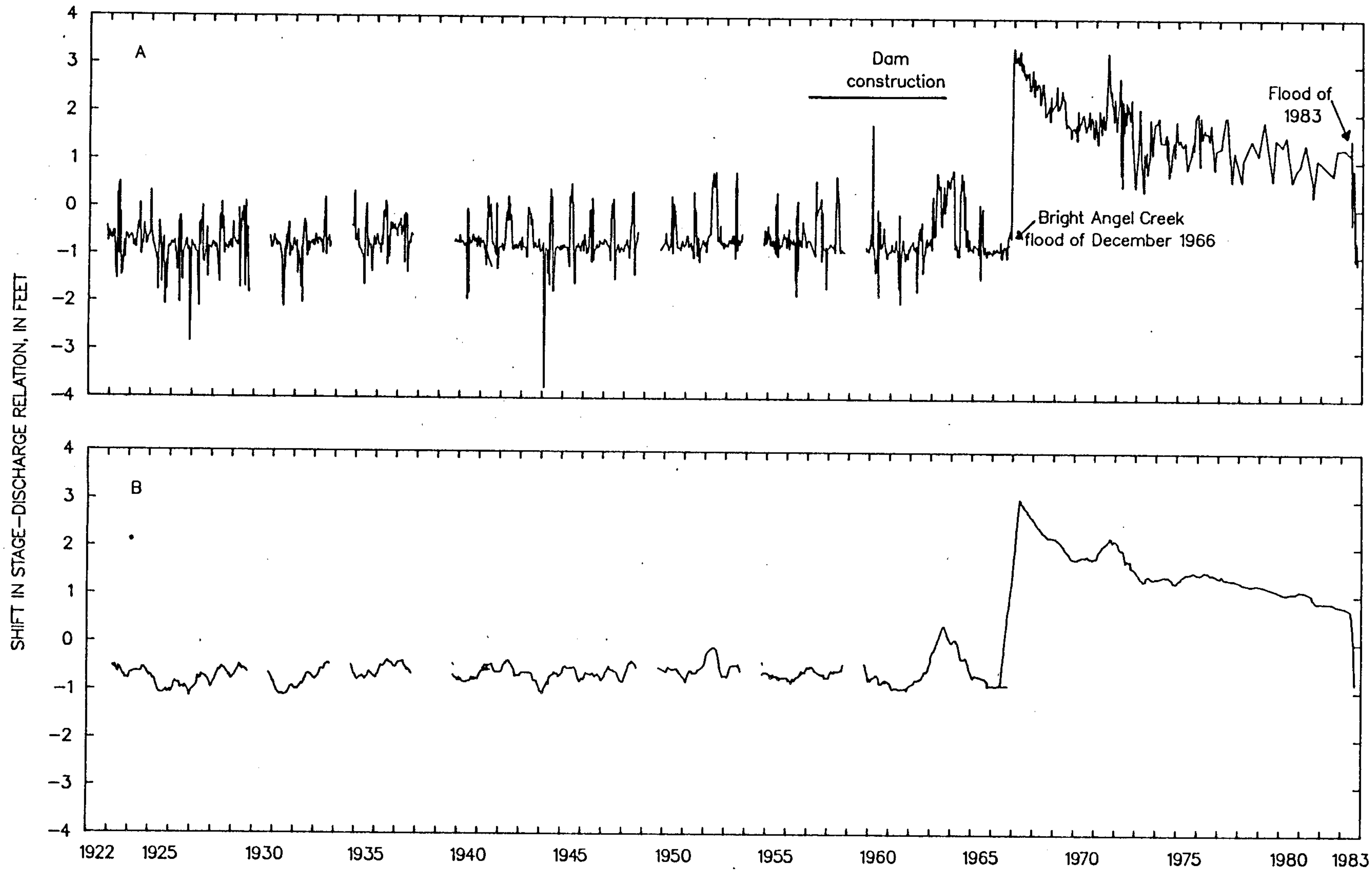


Figure 19.--Shift in relation of stage to discharge, Colorado River near Grand Canyon, Arizona. A, entire range of discharges. B, 20-point moving average of data in A. Shifts were computed as the measured stage minus the stage computed with equations 6A and 6B. Equation 6A was used for discahrges less than 33,000 cubic feet per second, and equation 6B for discharges greater than 33,000 cubic feet per second.

deposition of sediment on the control. The mean of all shifts in the relation of stage to discharge in 1922-65 was -0.62 ft. The standard deviation of shifts about the mean was 0.012 ft.

Discussion of Results

Five hydrologic implications were brought out during the study of historical streamflow data for the Grand Canyon site. The five implications are in relation to (1) armoring of the riverbed, (2) degradation of the stream channel, (3) changes in the Bright Angel rapid, (4) pre-and post-dam discharges and velocities required to start erosion of the riverbed at the measurement section, and (5) the supply of sediment before and after the construction of Glen Canyon Dam. Three of the implications are the same as those listed for the Lees Ferry site. For the three implications, however, the degree of involvement of the different causative factors are not the same for the two gage sites.

The theory of armoring does not apply entirely to the riverbed at the Grand Canyon site. Typically, a degrading stream is a prerequisite for the formation of an armoring layer--a layer of large size sediments that protects the underlying finer sediments from further degradation. The Bright Angel rapid, the control for the Grand Canyon site, did not erode significantly below its pre-dam level and, therefore, the Colorado River in the vicinity of the Grand Canyon site does not represent a degrading stream. In fact, during a flood in 1966 in Bright Angel Creek, the level of the Bright Angel Rapid increased by about 4 ft as a result of deposition of debris. However, the 1966 debris on the Bright Angel Rapid apparently was gradually being removed during 1967-82. The level of the rapid returned approximately to its 1965 level during the 1983 flood in the Colorado River.

The deposition of debris during floods in Bright Angel Creek probably caused significant changes in the Bright Angel rapid in several periods other than that for 1966. According to historical notes in the U.S. Geological Survey files in Tucson, Arizona "The rapid at the mouth of Bright Angel Creek is the control for the Grand Canyon gage.......The control is subject to major shifting with each flooding of Bright Angel Creek." Bright Angel Creek is known to have had relatively high discharges during several periods in 1924-84, but none equal in magnitude to that of the 1966 flood.

The velocity required to start scour of the riverbed at the measurement section at the Grand Canyon site was about 5.5 fps when the riverbed was at a high level-- -9.0 ft level (local datum) and higher. Typically, the pre-dam riverbed scoured to levels less than -11.5 ft as the velocity increased during high discharges, which may start in February-March and continue into June-July. Regardless of how high the discharge became, however, the river- bed did not scour significantly below the -13.0-ft level. Two factors were involved to keep the bed from scouring below the -13.0 ft level (1) the size of sediment in the bed increased with scour depth; and (2) the mean velocity for a given discharge decreased with scour depth.

The riverbed during most years, unlike the riverbed at the Lees Ferry site, did not return immediately to a high-bed level after the cessation of high discharge. On some occasions the riverbed stayed at the low-bed level for more than a year. This indicates that only a very limited part, if any, of the sediment being transported was available for deposition during the recession of some high winter flows. This also suggests that large amounts of sand- and gravel-size sediments, the sizes usually found in the gage-site pool, were not being transported during these recession periods.

Relatively high-bed levels in the pool at the Grand Canyon site in 1967-84 were primarily the result of large inflows of sediment from Paria and Little Colorado Rivers. A statement that appears on several historical notes in USGS files in Tucson, Arizona is as follows: "Occasionally high flows on the Little Colorado and Peoria (Paria) Rivers deposit sand and silt in the gage pool. This deposition decreases the measuring cross section area and increases measuring velocity......"

A detailed investigation to determine if high-bed levels in 1922-62 also were primarily the result of large inflows of sediment from Paria and Little Colorado Rivers could not be made because streamflow data for the Little Colorado near Cameron, Arizona are only available after June 1947 and because of the limited scope of the present study. However, a brief investigation showed that periods of relatively high bed levels and high velocities in 1947, 1954, 1964 and 1965 at the Grand Canyon site correspond in time to periods of high discharge in the Little Colorado River near Cameron, Arizona. Rates and amounts of flow in the Little Colorado River near Cameron, Arizona for the indicated years are as follows:

The Little Colorado River contributed more than 100,000 acre ft (af) of water to the Colorado River during August, 1947. The daily discharge at the gage on the Little Colorado River near Cameron, Arizona was 3,830; 5,380; 4,920; and 2,300 cfs, respectively during a 4-day period in July 24-27, 1954. The total monthly discharge at the gage on the Little Colorado in August, 1955 was 139,000 af: The discharge in August 1964 was 102,000 af. During 9 days in July-September 1965, the discharge at the Little Colorado gage ranged from 1,140 to 3,100 cfs. As previously indicated, large loads of sediment are brought to the Colorado River during high discharges from the Little Colorado River. Some of this sediment is sand and gravel which is deposited in pools along the Colorado River downstream from the mouth of the Little Colorado River where it stays until high flows flush it downstream.

Basically, it appears that even before the construction of Glen Canyon Dam, the input of sand- and gravel-size sediment to the pool at the Grand Canyon gage was not adequate to return the riverbed in the pool to a high level after several high-flow periods in 1922-62. Apparently the riverbed in the pool in 1922-62 was at a high level after relatively high discharges in the Paria and Little Colorado Rivers and when the flow in the Colorado River was relatively low. In 1963-82, after high sediment inflows from Paria and Little Colorado Rivers, the riverbed stayed at a high level for relatively long periods because the mean velocity in the Colorado River, due to flow regulation, was not adequate to remove the sediment from the pool once it was in place.

SUMMARY AND CONCLUSIONS

Summary and/or conclusive statements are listed separately for the two streamflow gaging stations--Colorado River at Lees Ferry and near Grand Canyon. Many of the conclusive statements developed as a result of the study of historical data for the two sites are applicable to similar pool-and-rapid reaches along the Colorado River upstream from the Grand Canyon site. They also may be applicable to similar reaches downstream from the Grand Canyon site. Statements for the **Lees Ferry** site are:

1. In 1922-62, the riverbed at the low point in the measurement section was at 1 to -2 ft elevation (local datum) most of the time. However, the sand and gravel in the pool typically scoured as discharge progressively increased and filled as the discharge decreased. The alluvial deposit at the low point was scoured more than 20 ft during high winter discharges.

2. Each year, prior to about 1940, the riverbed at the low point in the measurement section returned to about its pre-flood elevation--about 1 to -2 ft--soon after the cessation of high discharges. After high discharges in the years from about 1940 to 1962, the riverbed at the low point returned to a level slightly lower than that for the preceeding year. The result was a fluctuating decline in the level of the riverbed.

3. The alluvial deposit at the low point in the measurement section scoured about 27 ft in 1965 when the discharge of sediment-free water was in the range from 40,000 to 60,000 cfs for more than 40 days. The amount of fill in 1965 and 1966, after the cessation of high discharges, was only about 12 ft.

4. The elevation at the low point in the riverbed stayed relatively constant at about -15 to -16 ft during 1967-84. However, during high flows released in 1983, the bed scoured an additional 6 to 7 ft, but filled back to about its former level after recession of the high discharges.

5. For the same discharge in the range from 5,000 to 33,000 cfs, the mean cross-sectional velocity at the measurement site decreased about an average 3.5 fps during 1922-84. For a discharge of 20,000 cfs the decrease in mean velocity in 1922-84 was from 6.8 to 2.3 cfs. About one half of the decrease in velocity for discharges in the range from 2,500 to 33,000 cfs occurred in 1935-62 and about one half occurred in 1965.

6. After high discharges from about 1940 to 1962, the cross-sectional area was slightly greater and the velocity was slightly lower than those for the preceding years. The fluctuating changes in area and velocity for a given discharge in 1935-62 probably occurred because of a decline in upstream inflow of

sediment which resulted in a reduction in the amount of sediment deposited in the pool. The sudden increase in cross-sectional area and abrupt reduction in velocity in 1965 is a direct result of the elimination of sediment due to Glen Canyon Dam.

7. When the riverbed was at a high level, about 1 to -2 ft in 1922-1940 and progressively lower in 1941-62, the riverbed began to scour when the mean velocity was about 5.0 fps. The discharge needed to produce a 5.0 fps velocity in 1922-62, when the bed was at a high level, was about 18,000 cfs.

8. A progressively larger-size sediment apparently was encountered as the depth of scour increased during high discharges in 1922-62. The size of sediment on the bed at the -14 to -16 ft level in 1967-84 was larger than that on the bed at the 1 to -2 ft level in 1922-62.

9. From 1967 to 1982, the streamflow velocity did not reach a magnitude that would have caused scour even if the bed would have been at a 1 to -2 ft level and the sediment on the bed had been of a pre-dam size. At the -15 to -16 ft level in 1967-82, a velocity of about 7 fps would have been required to start scour of the bed. In 1967-82, a discharge of about 70,000-75,000 cfs would have been required to produce a velocity of 7 fps.

10. The riverbed scoured to about the -21 ft level in 1983 when the discharge was about 97,000 cfs, and the mean velocity was about 7.5 fps. However, the bed returned to about the -16 ft level while the discharge was still greater than about 60,000 cfs and the mean velocity was about 6 fps.

11. The 1983 flood caused a significant amount of sand-size sediment to move past the gage at Lees Ferry. This sediment was eroded from the riverbed and banks in the reach from Glen Canyon Dam to Lees Ferry. A limited supply of alluvial sand- and gravel-size sediment undoubtedly still is available in the reach from Glen Canyon Dam to Lees Ferry. Of this supply the part that will erode probably will be relatively low except during periods when the discharge is greater than 70,000 to 80,000 cfs.

12. During the period from about 1940 to 1962, a progressively higher (net) stage was required to pass a given discharge in the range from 2,500 to 33,000 cfs--the shift in the relation of stage to discharge amounted to about an average +0.10 ft. For the total study period, 1922 to 1984, the shift in the relation of stage to discharge for discharges in the range from 2,500 to 33,000 cfs, on an average, was about +0.45 ft. The two net shifts in the relation of stage to discharge are the direct result of scour of the bed in the pool upstream from the Paria rapid and decreased velocities.

13. From 1931 to 1984, the decrease in discharge for a stage of 12.0 ft amounted to about 6,500 cfs.

14. The level of the control section, the Paria Rapid, did not change significantly in 1922-84. However, the Paria Rapid is subject to change at any time during high discharges in the Paria River.

Summary and/or conclusive statements for the site **near Grand Canyon** are:

15. In 1922-62, the riverbed was at a low-bed level-- (-11.5 to -13 ft local datum)--most of the time. The alluvial deposit scoured to about -14 ft on a few occasions. During the remaining time the bed was primarily at a high-bed level-- -9.0 ft and higher elevations. The range in bed level was about 8.0 ft, compared to more than 20 ft for the Lees Ferry site.

16. The bed level at the Grand Canyon site did not return immediately to its pre-flood level soon after the cessation of high discharges during several years in 1922-62: a fact that indicates only a very limited supply of sand- and gravel-size sediments was available for deposition in the pool during the recession of some high flows.

17. Apparently the riverbed in 1922-62 reached a high-bed level mainly in response to high sediment inflows from local tributaries--primarily Paria and Little Colorado Rivers.

18. The riverbed scoured to about the -13 ft level during 1965 when the release rate of sediment-free water was in the range from 40,000 to 60,000 cfs.

19. Starting in 1967 and ending in 1983, the riverbed stayed at the high-bed level. Two factors were involved in keeping the bed at the high level: a flood on Bright Angel Creek in 1966 and the regulation of flow at Glen Canyon Dam, which started in 1963.

20. The 1966 flood brought large amounts of debris-large boulders, cobbles, gravel--to the mouth of Bright Angel Creek. Much of this debris became lodged on the control (rapid) downstream from the Grand Canyon gage. The elevation of the riverbed at the rapid increased, which caused the riverbed at the Grand Canyon gage to rise by about 4 ft.

21. The debris on the rapid stayed in place in 1967-82 because the regulated flow did not create enough energy to remove it. The riverbed at the rapid scoured some in 1971-73.

22. In 1967-82, the bed level at the gage was gradually being lowered, which indicates that the debris on the rapid was

gradually being weathered.

23. The 1983 flood in the Colorado River removed the debris from the rapid at the mouth Bright Angel Creek and the riverbed at the gage returned to a low-bed level.

24. In 1922-62, when the bed was at a high-bed level,a velocity of about 5.5 fps was required before scour began. A discharge of about 20,000 cfs was required to produce a velocity of 5.5 fps when the riverbed was at a high-bed level. However, a discharge of more than 100,000 cfs and velocities of about 10 fps would not cause the bed to scour more than about -14 ft.

25. As defined by discharge measurements, the mean velocity was less than 5.5 fps for all discharges measured in 1967-82, except for five.

26. The accumulation of debris on the Bright Angel Rapid during the Bright Angel flood of 1966 caused a shift in the relation of stage to discharge of about 3-4 ft. The relation of stage to discharge at the Bright Angel rapid is subject to change during any period of significant flow in Bright Angel Creek.

27. Two factors were involved to keep the bed from scouring below the -13.0 ft level-- the size of sediment in the bed increased and the mean velocity for a given discharge decreased with scour depth.

28. In 1984, tributary streams, mainly Paria and Little Colorado Rivers, are the primary source of sediments that are/or will be available to rebuild beaches along the Colorado River from Lees Ferry to the Grand Canyon site, and, even farther downstream: Sediments presently (1984) in pools probably are of secondary, if any, importance.

29. Given that at some time in the future the riverbed in pools in the reach from Lees Ferry to the Grand Canyon site will be at a high-bed level, further imputs of sand-and-gravel-size sediments from tributary streams primarily would be wasted downstream. The regulated streamflow presumably will have the capacity to move the sand-and-gravel-size sediment when the riverbed in the pools are at a high level.

30. The Glen Canyon Environmental Studies span a period when the river bed in pools in the reach from Lees Ferry to the Grand Canyon site probably were at a low level.

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