October 2, 1921, view of the ferry crossing the Colorado River at Lees Ferry, Arizona. Photograph taken by Roger C. Rice (U.S. Geological Survey) from the ferry landing on the right bank. Source of this photograph: 1921–37 Surface Water Records File, Colorado River at Lees Ferry, Arizona, file stored at the Federal Records Center in Laguna Niguel, California, in Accession No. 57-78-0006, Box 2 of 2 , Location No. MB053635.

Computation and Analysis of the Instantaneous-Discharge Record for the Colorado River at Lees Ferry, Arizona—May 8, 1921, through September 30, 2000

By David J. Topping, John C. Schmidt, and L.E. Vierra, Jr.

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CONTENTS

FIGURES

TABLES

CONVERSION FACTORS AND VERTICAL AND HORIZONTAL DATUMS

CONVERSION FACTORS

In this paper, all measurements are reported in the inch-pound system to maintain consistency with historical and current U.S. Geological Survey data. Unpublished raw data and historical memoranda presented in this paper refer to stage in feet and discharge in cubic feet per second, and historical photographs show staff gages marked in feet. For readers who wish to convert stage, discharge, and water volume from the inch-pound system of units to the metric system of units, the conversion factors are listed below:

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
mile	1.609	kilometer (km)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
acre-foot	1,235	cubic meter (m^3)
ton, short (2,000 pounds)	0.9074	metric ton (t)

VERTICAL AND HORIZONTAL DATUMS

Sea Level—In this paper, vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD1929). Thus, the term "sea level" refers to NGVD1929. Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD83).

Computation and Analysis of the Instantaneous-Discharge Record for the Colorado River at Lees Ferry, Arizona—May 8, 1921, through September 30, 2000

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ABSTRACT

A gaging station has been operated by the U.S. Geological Survey at Lees Ferry, Arizona, since May 8, 1921. In March 1963, Glen Canyon Dam was closed 15.5 miles upstream, cutting off the upstream sediment supply and regulating the discharge of the Colorado River at Lees Ferry for the first time in history. To evaluate the pre-dam variability in the hydrology of the Colorado River, and to determine the effect of the operation of Glen Canyon Dam on the downstream hydrology of the river, a continuous record of the instantaneous discharge of the river at Lees Ferry was constructed and analyzed for the entire period of record between May 8, 1921, and September 30, 2000. This effort involved retrieval from the Federal Records Centers and then synthesis of all the raw historical data collected by the U.S. Geological Survey at Lees Ferry. As part of this process, the peak discharges of the two largest historical floods at Lees Ferry, the 1884 and 1921 floods, were reanalyzed and recomputed. This reanalysis indicates that the peak discharge of the 1884 flood was 210,000±30,000 cubic feet per second (ft^3/s), and the peak discharge of the 1921 flood was 170,000±20,000 ft^3/s. These values are indistinguishable from the peak discharges of these floods originally estimated or published by the U.S. Geological Survey, but are substantially less than the currently accepted peak discharges of these floods. The entire continuous record of instantaneous discharge of the Colorado River at Lees Ferry can now be requested from the U.S. Geological Survey Grand Canyon Monitoring and Research Center, Flagstaff, Arizona, and is also available electronically at http://www.gcmrc.gov. This record is perhaps the longest (almost 80 years) high-resolution (mostly 15- to 30-minute precision) times series of river discharge available. Analyses of these data, therefore, provide an unparalleled characterization of both the natural variability in the discharge of a river and the effects of dam operations on a river.

Following the construction and quality-control checks of the continuous record of instantaneous discharge, analyses of flow duration, sub-daily flow variability, and flood frequency were conducted on the pre- and post-dam parts of the record. These analyses indicate that although the discharge of the Colorado River varied substantially prior to the closure of Glen Canyon Dam in 1963, operation of the dam has caused changes in discharge that are more extreme than the pre-dam natural variability. Operation of the dam has eliminated flood flows and base flows, and thereby has effectively "flattened" the annual hydrograph. Prior to closure of the dam, the discharge of the Colorado River at Lees Ferry was lower than 7,980 ft^3/s half of the time. Discharges lower than about 9,000 ft^3/s were important for the seasonal accumulation and storage of sand in the pre-dam river downstream from Lees Ferry. The current operating plan for Glen Canyon Dam no longer allows sustained discharges lower than 8,000 ft^3/s to be released. Thus, closure of the dam has not only cut off the upstream supply of sediment, but operation of

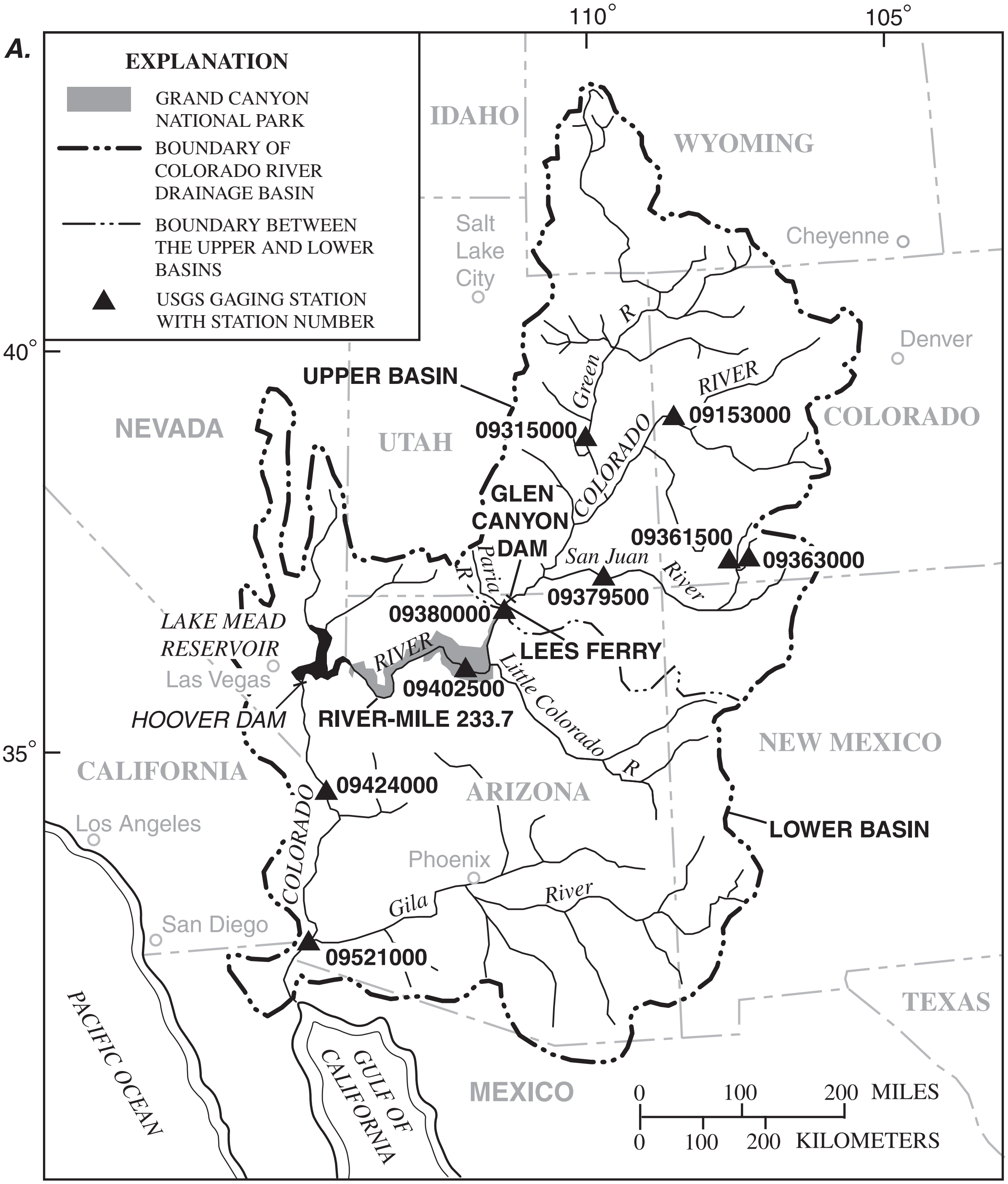
the dam has also largely eliminated discharges during which sand could be demonstrated to accumulate in the river. In addition to radically changing the hydrology of the river, operation of the dam for hydroelectric-power generation has introduced large daily fluctuations in discharge. During the pre-dam era, the median daily range in discharge was only 542 ft^3/s, although daily ranges in discharge exceeding 20,000 ft^3/s were observed during the summer thunderstorm season. Relative to the pre-dam period of record, dam operations have increased the daily range in discharge during all but 0.1 percent of all days. The post-dam median daily range in discharge, 8,580 ft^3/s, exceeds the pre-dam median discharge of 7,980 ft^3/s. Operation of the dam has also radically changed the frequency of floods on the Colorado River at Lees Ferry. The frequency of floods with peak discharges larger than about 29,000 ft^3/s has greatly decreased, while the frequency of smaller floods, with peak discharges between 18,500 and 29,000 ft^3/s, has increased substantially. Operation of the dam has greatly extended the duration of smaller floods; for example, each of the four longest periods of sustained flows in excess of 18,500 ft^3/s occurred after closure of the dam.

INTRODUCTION

Lees Ferry on the Colorado River was initially chosen by the U.S. Geological Survey (USGS) as a measurement site because it was strategically located with respect to the hydrology of the Colorado River drainage basin and was readily accessible (Rusho and Crampton, 1992; Reilly, 1999). Lees Ferry was readily accessible by automobile in the 1920s, and was the first point where the combined runoff could be measured from the upper part of the Colorado River drainage basin, which includes the upper Colorado, Green, and San Juan Rivers (fig. 1*A*). Lees Ferry also was chosen as the location for a gaging station because it was several miles downstream from a proposed dam site in lower Glen Canyon favored by the Southern California Edison Company, the cooperator who maintained this gaging station for the first several years.

Stage of the Colorado River at Lees Ferry, Arizona, has been measured since May 8, 1921, when the first staff gage was installed by E.C. LaRue of the USGS. Subsequently, stage was read at least twice daily on several or more staff gages installed in the Lees Ferry reach. Discharge has been measured at Lees Ferry since August 3, 1921, when the first cableway across the river was completed. Stage of the Colorado River at Lees Ferry has been measured continuously since January 19, 1923, when a permanent recording stage gage, consisting of a strip-chart recorder connected to a float assembly housed in a concrete stilling well, became operational. This recording stage gage is the modern gage and is located in Glen Canyon National Recreation Area, 15.5 miles downstream from Glen Canyon Dam, and 1 mile upstream from the mouth of the Paria River and the northeastern boundary of Grand Canyon National Park (fig. 1*B*). In this paper, the recording stage gage housed in the concrete stilling well is referred to as the Lees Ferry Gage. The historical staff gages in the reach (fig. 1*C*) and the Lees Ferry Gage together are referred to as the Lees Ferry gaging station. The official USGS station names and numbers for the Lees Ferry and other gaging stations used in this study, and the shortened names used in this paper are listed in table 1.

The Lees Ferry gaging station has been continuously maintained since 1921 because the site is also strategically located in a political sense. One year after the establishment of this gaging station, the 1922 Colorado River Compact was negotiated between the seven states in the Colorado River drainage basin. The Compact divided the drainage basin into two parts: the Upper Basin and the Lower Basin (fig. 1*A*). In the Compact, the dividing point between the basins was defined as a "point in the main stream of the Colorado River one mile below the mouth of the Paria River." Thus, the Lees Ferry gaging station and another gaging station installed in November 1923 on the Paria River became the measurement points used to determine compliance with the terms of the Compact. Under the Compact, the United States-Mexico Water Treaty of 1944, and the Colorado River Basin Project Act of 1968, 8.25 million acre-feet of water must pass to the Lower Basin each year, of which 8.23 million acre-feet must pass the Lees Ferry gaging station (June 8, 1970, Criteria for coordinated long-range operation of Colorado River reservoirs pursuant to the Colorado River Basin Project Act of September 30, 1968).



Base modified from Figure 1 in Smith and others (1960).

Figure 1. The Colorado River drainage basin and Lees Ferry. (*A*) The Colorado River Basin showing the location of Lees Ferry, Glen Canyon Dam, and the Lees Ferry and other U.S. Geological Survey gaging stations (with station numbers) used in this study. See table 1 for the official and shortened names of these stations.

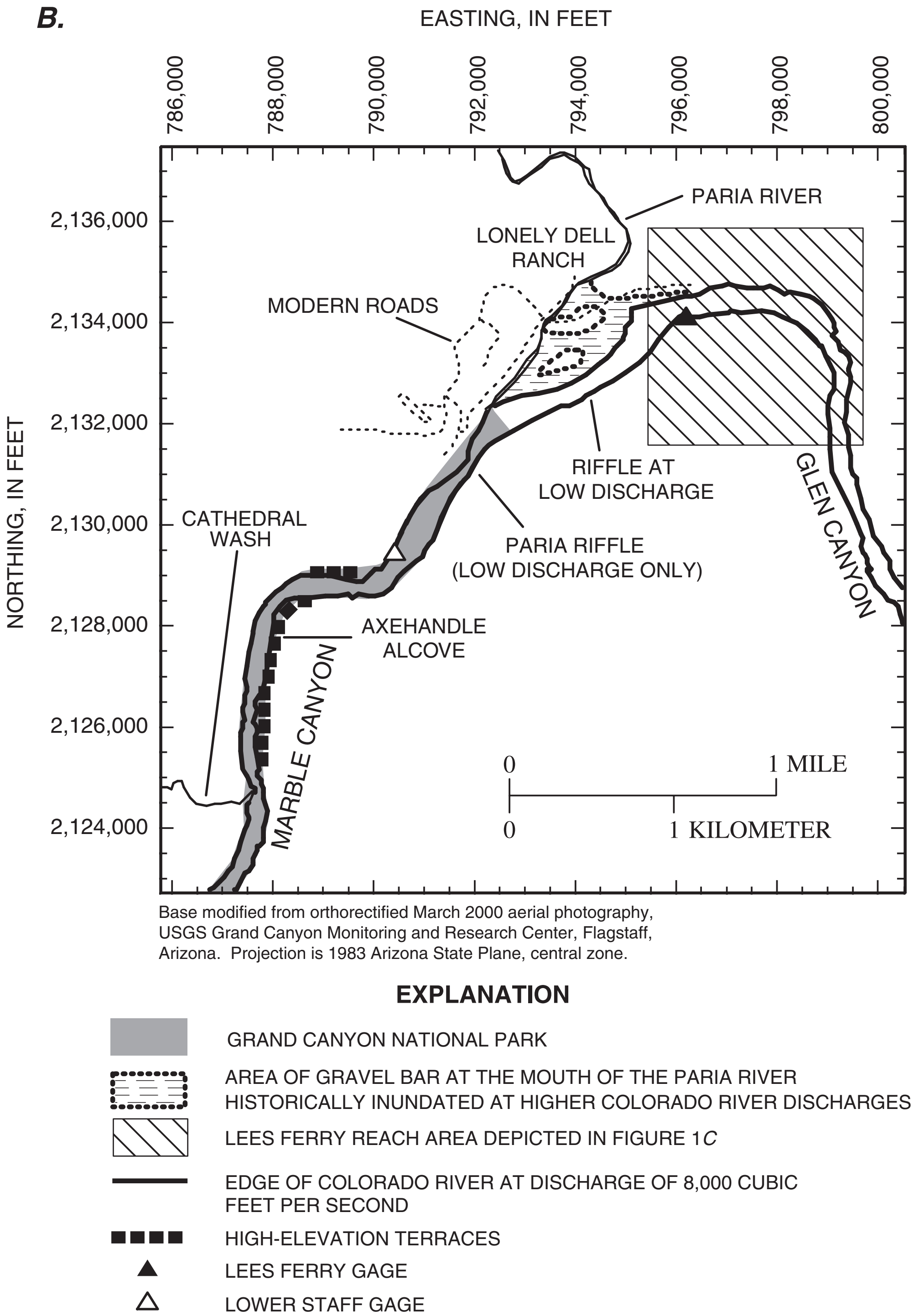


Figure 1—*Continued.* The Colorado River drainage basin and Lees Ferry. (*B*) The Lees Ferry area showing the Lees Ferry Gage, the Lower Staff Gage, the area of the gravel bar at the mouth of the Paria River inundated by the Colorado River at higher discharges, and the high-elevation terraces between the Lower Staff Gage and Cathedral Wash studied by O'Connor and others (1994). See photographs in figs. 5*A*–*C*.

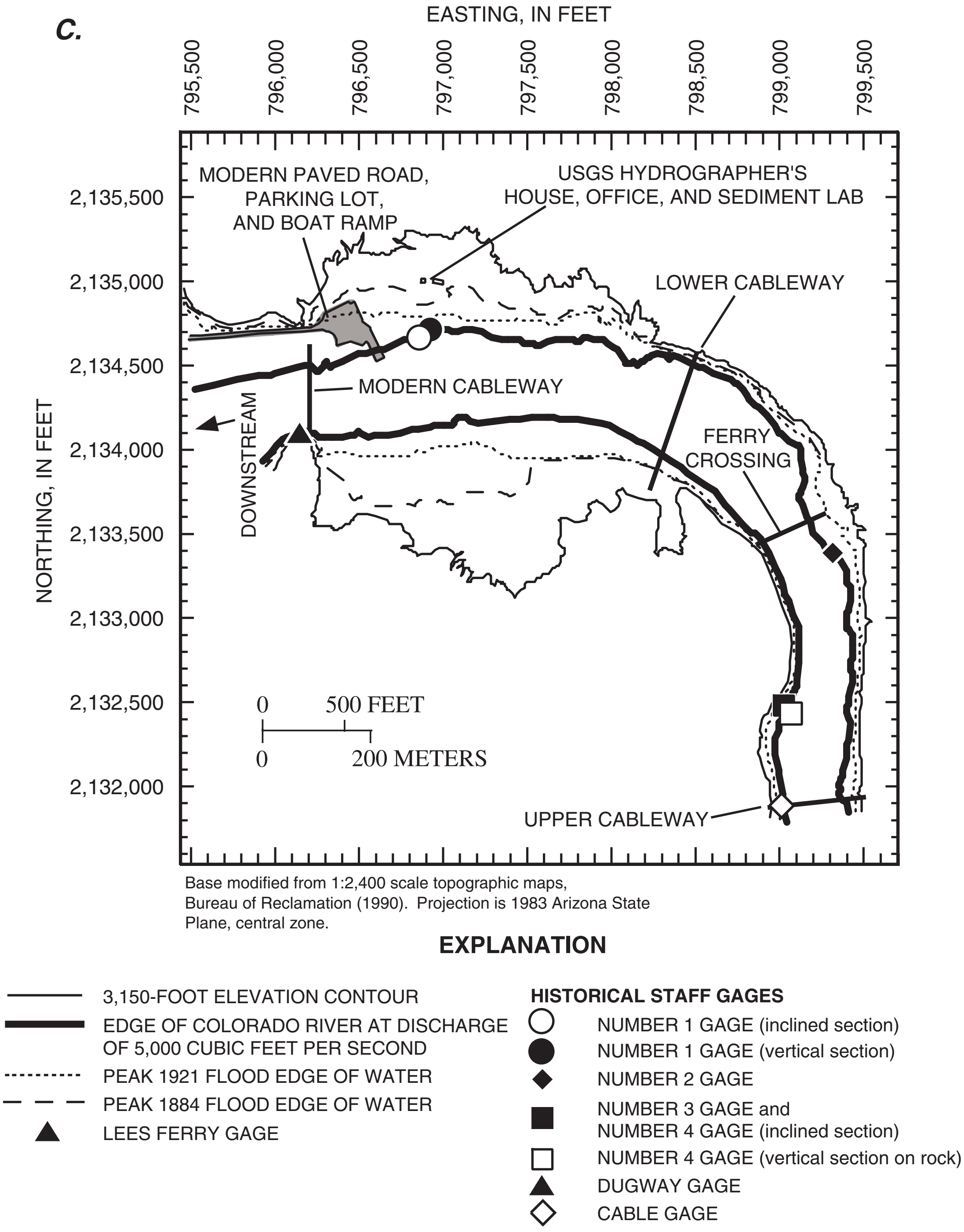


Figure 1—*Continued.* The Colorado River drainage basin and Lees Ferry. (*C*) The Lees Ferry reach showing the Lees Ferry Gage, the six historical staff gages (Number 1 Gage, Number 2 Gage, Number 3 Gage, Number 4 Gage, Dugway Gage, and Cable Gage), and the extent of inundation at 5,000 cubic feet per second and during the 1921 and 1884 floods. Extent of inundation during the peak of the June 1921 flood is based on the peak stage of this flood at the Number 1, Dugway, and Number 4 staff gages and topography surveyed in 1990. Extent of inundation during the peak of the July 1884 flood is based on the assumption that the water surface was essentially flat upstream from the Lees Ferry Gage (as justified based on fig. 4*A*).

Table 1. U.S. Geological Survey gaging stations used in this study

Station number	Official station name	Shortened name used in this paper
09153000	Colorado River near Fruita, Colorado	Colorado River near Fruita
09315000	Green River at Green River, Utah	Green River
09361500	Animas River at Durango, Colorado	Animas River
09363000	Florida River near Durango, Colorado	Florida River
09379500	San Juan River near Bluff, Utah	near Bluff
09380000	Colorado River at Lees Ferry, Arizona	Lees Ferry
09402500	Colorado River near Grand Canyon, Arizona	Grand Canyon
09424000	Colorado River near Topock, Arizona	Topock
09521000	Colorado River at Yuma, Arizona	Yuma

Thus, measurements at Lees Ferry are essential to the management of water in the entire Colorado River drainage basin. These legal documents that govern the discharge of the Colorado River at Lees Ferry constitute part of the "The Law of the River" and are available electronically from the Bureau of Reclamation (Bureau of Reclamation, 2000).

Widespread development of water resources within the Upper Colorado River Basin began with authorization of the Colorado River Storage Project in 1956 (Martin, 1989). Glen Canyon Dam was the largest of the dams constructed under this act. The gates of this dam were closed on March 13, 1963, regulating the discharge of the Colorado River at Lees Ferry and initiating the storage of water in the reservoir known as Lake Powell. This reservoir filled for the first time on June 22, 1980, and its 27 million acre-foot capacity is the second largest in the United States. The largest reservoir in the United States is Lake Mead, at the downstream end of Grand Canyon (fig. 1*A*).

Detailed analysis of the Lees Ferry discharge record is valuable for a variety of purposes, including evaluation of natural hydrologic variability within the Upper Basin and evaluation of the effects of upstream dams and diversions on the discharge of the Colorado River. Although water was exported from the headwaters of the Colorado River Basin as early as 1892 (Fradkin, 1984), discharge at Lees Ferry was only slightly affected by upstream water development prior to the closure of Glen Canyon Dam in March 1963. Pre-1963 depletion of water from the headwaters of the Colorado River resulted in only a 10–15 percent reduction in the "virgin flow" of the Colorado River at Lees Ferry, with very little change in the amount of water depleted from the Upper Basin occurring between 1921 and 1963 (see fig. 4 in Ferrari, 1988). Thus, analysis of the first 42 years of record at the Lees Ferry gaging station (from May 1921 to March 1963) provides information on the quasi-natural hydrology of the Upper Basin. The following 37 years of record at the gaging station (from March 1963 to September 2000) were dominated by the effects of upstream water development and regulation of discharge by operation of Glen Canyon Dam. Analysis of this later part of the period of record, therefore, provides information on the effect of upstream water development on the discharge of the Colorado River in Grand Canyon National Park, because no large tributaries enter the Colorado River between Glen Canyon Dam and the Lees Ferry gaging station.

Interest in the Lees Ferry discharge record increased after 1983 when comprehensive environmental studies were initiated by the Bureau of Reclamation to evaluate the effect of the operation of Glen Canyon Dam on the Colorado River ecosystem downstream from the dam (U.S. Department of the Interior, 1995). Previous analysis of the hydrologic effects of dam operation involved visual comparison of the record of stage and discharge for some years (Turner and Karpiscak, 1980), and visual and statistical comparison of post-dam bi-hourly, hourly, or 30-minute discharge data with pre-dam daily mean discharge data (U.S. Department of the Interior, 1995). These analyses were hindered by the fact that only daily mean discharge data at the Lees Ferry gaging station were available prior to February 2, 1967, and 30-minute discharge data were only available after October 1, 1986. Thus, the value of these analyses was limited because pre-dam and post-dam hydrologic data at the Lees Ferry gaging station were not of comparable precision.

Purpose and Scope

This paper describes the results of a study that had three main goals. The first goal was to reanalyze, and revise if necessary, the record of floods for the period prior to construction of Glen Canyon Dam. The second goal was to rectify the differing precision between the various parts of the Lees Ferry gaging-station record by developing a continuous record of instantaneous discharge for the entire period of gage record (May 8, 1921, through September 30, 2000). This computed record of instantaneous discharge is perhaps the longest (almost 80 years) high-resolution (mostly 15- to 30-minute precision) times series of river discharge available for any river in the world. As used in this paper, the term "instantaneous discharge" is defined as the discharge of the river at any given instance in time. The third goal was to fully describe the hydrologic characteristics of the Colorado River at Lees Ferry during the pre- and post-dam eras, and the implications for sediment transport and storage in the reach downstream from Lees Ferry in Grand Canyon National Park, through analyses of flow duration, sub-daily discharge variability, and flood frequency. These analyses were conducted on the Lees Ferry instantaneous discharge data for May 8, 1921, through September 30, 2000, the available pre-gage historical flood data, and the 4,500-year paleoflood data of O'Connor and others (1994).

It is anticipated that the basic data presented in this paper will be of value for a wide range of subsequent analyses by scientists and engineers. Most of the information presented in this paper is from unpublished USGS reports and gaging-station technical files stored in the Federal Records Centers, and was not previously accessible to the public. A complete list of all USGS files used in this paper and where they are stored is appended (Appendix A). The previously unavailable stage and discharge data presented in this paper can be either requested from the USGS Grand Canyon Monitoring and Research Center, Flagstaff, Arizona, or obtained electronically at http://www.gcmrc.gov.

Acknowledgments

Funding for this study was provided by the Grand Canyon Monitoring and Research Center through a cooperative agreement with Utah State University and the National Research Program of the USGS. Lisa Dierauf did much of the early work on digitizing the first 10 years of the strip-chart record from the Lees Ferry Gage. Thoughtful reviews of earlier versions of this paper were provided by James Bennett, Randolph Parker, Theodore Melis, David Jay, John Gray, and James O'Connor.

PHYSICAL CHARACTERISTICS OF THE LEES FERRY GAGING REACH

The Lees Ferry gaging station on the Colorado River is located at the downstream end of Glen Canyon, and just upstream from Marble Canyon. Marble Canyon extends from Lees Ferry to the mouth of the Little Colorado River, and Grand Canyon extends from the mouth of the Little Colorado River to the Grand Wash Cliffs above Lake Mead reservoir (fig.1*A*). On the basis of the convention of Topping and others (2000), that portion of Grand Canyon between the mouth of the Little Colorado River and the Grand Canyon gaging station in fig. 1*A* is referred to as upper Grand Canyon. Today, there are only a few abandoned stone buildings and some recreational boating facilities at Lees Ferry. Between 1872 and 1929, however, this ferry crossing was the only point within hundreds of miles where wagons or vehicles could cross the Colorado River, or where boats could be launched (Rusho and Crampton, 1992; Reilly, 1999). A nearby farm, the Lonely Dell Ranch (fig. 1*B*), was occupied from 1871 until 1974, and buildings at Lees Ferry, including the house and laboratory of the USGS hydrographer (fig. 1*C*), were occupied until 1976 (Reilly, 1999).

The physiography of the Lees Ferry area is determined by the regional structure of the Echo Cliffs monocline, which crosses the Colorado River nearby. The upstream dip of the monocline brings the highly erodible Moenkopi and Chinle Formations to river level here (Hereford and others, 2000), and the Colorado River can be easily reached by following bedding planes within these formations to the river's edge. In addition, Lees Ferry is also made accessible, because the Paria River has eroded an open valley in the Moenkopi Formation 1 mile downstream from the old ferry crossing on the Colorado River.

Stage and Discharge Measurements in the Lees Ferry Reach

The modern Lees Ferry Gage is located on the left (east) bank (figs. 1*B–C*), just upstream from the gravel bar at the mouth of the Paria River. It is housed in a concrete structure adjacent to the old dugway road to the ferry crossing, near the base of a cliff within the Shinarump Conglomerate member of the Chinle Formation (fig. 2). Since December 1966, all discharge measurements have been made from the Modern Cableway located 50 ft upstream from the Lees Ferry Gage (fig.1*C*). Prior to this date, discharge measurements were made from two cableways farther upstream. Most measurements were made from the cableway located 1 mile upstream and informally called the Upper Cableway (figs. 1*C*, 3*A–B*). At discharges exceeding about 60,000 ft^3/s, discharge measurements were typically made from a second cableway located 0.4 miles upstream from the gage house. This second cableway crossed the river at a much wider cross-section and was informally called the Lower Cableway (figs. 1*C* and 3*C–D*).

The recording Lees Ferry Gage became operational on January 19, 1923. Prior to this date, stage was read twice daily on various staff gages in the 1-mile-long reach upstream (fig. 1*C*). These historical staff gages were known as the LaRue Gage, the Number 1 Gage, the Number 2 Gage, the Number 3 Gage, the Number 4 Gage, and the Dugway Gage. Each of these staff gages had a different period of record and datum. The LaRue Gage was installed on May 8, 1921, and was destroyed during the peak of the June 1921 flood; the Number 1 Gage was installed at the site of the LaRue Gage on June 24, 1921, but at a different datum; the Number 4 Gage was installed upstream on the left bank on August 3, 1921; and the Dugway Gage was installed on August 5, 1921, near the future location and at the same datum as the Lees Ferry Gage. The Number 2 and 3 Gages were used only during June–August 1921. Another staff gage, known as the Cable Gage, was installed on the left bank under the Upper Cableway in April 1924. Stage was read on this gage during most of the Upper Cableway discharge measurements until 1964. In March 1941, a final staff gage, herein referred to as the "Lower Staff Gage," was installed on the right bank of the Colorado River 1.5 miles downstream from the Lees Ferry Gage, below the mouth of the Paria River (fig. 1*B*). Stage was read on the Lower Staff Gage periodically until 1959. The important events in the history of the Lees Ferry gaging station are listed in Appendix B.

The Hydraulic Control and its Effect on the Shape of the Stage-Discharge Rating Curve

The location and geometry of the hydraulic control for the Lees Ferry Gage changes as a function of stage. During large floods, these changes cause the water-surface profile in the reach downstream from the gage to flatten with increasing stage (fig. 4*A*). During the largest floods, this flattening of the water-surface profile (that is, the development of backwatered flow conditions) extends from some unknown point downstream in an upstream direction past the Lees Ferry Gage. This phenomenon produces a reversal in the curvature of the stage-discharge rating curve at a stage of about 15 ft (figs. 4*B–C*); above this stage, stage increases at a progressively faster rate than does discharge. This reversal in the curvature of the stage-discharge rating curve has not always been explicitly considered in estimations of the peak discharges of large floods nor in estimations of paleoflood discharges (O'Connor and others, 1994).

The existence of backwatered flow conditions near Lees Ferry at high stage is evident not only in the stage measurements at the staff gages, but also in photographs of the reach at higher discharge (figs. 5 and 6). At stages lower than about 10 ft (that is, discharges less than about 20,000 ft^3/s), the gravel bar at the mouth of the Paria River confines the flow to a channel adjacent to the left bank, and the constriction at the entrance to this channel forms a stable hydraulic control for the Lees Ferry Gage (fig. 5*B*). Under these conditions, a riffle exists in the left-bank channel, and a second riffle, called the Paria Riffle by modern river runners (Stevens, 1983), exists at a debris fan downstream from the mouth of the Paria River (figs. 1*B*, 4*A*, and 5*B*). As the stage increases above 10 ft, these riffles begin to "wash out" as the overall water-surface slope flattens (figs. 6*A–B*). At stages between 13 and 15 ft (that is, discharges between about 40,000 and 60,000 ft^3/s), the flow divides into two or more channels across the gravel bar (fig. 5*A*), and the entire gravel bar forms the hydraulic control for the gage. Due to this change in the location and geometry of the hydraulic control, the water surface flattens considerably in the 0.3-mile-long reach immediately downstream from the gage (figs. 4*A* and 6*B*); and at a stage of about 15 ft, the curvature of the stage-discharge rating curve reverses (fig. 4*C*). In contrast to the behavior of the water-surface slope in this reach, the water-surface slope in the reach upstream from the gage generally increases with increasing stage, and begins to flatten only at stages between 20 and 25 ft (figs. 4*A*, 6*C–E*).

A.

B.

Figure 2. Lees Ferry Gage. (*A*) View from the right bank downstream from the Number 1 Gage. Photograph taken by G.C. Stevens of the U.S. Geological Survey at 9:00 a.m. on September 21, 1923, when the stage was 11.05 feet and the discharge was 27,000 cubic feet per second. Source of this and the photographs in figs. 2*B*–3*D*, and 16*B*: 1921–37 Surface Water Records File, Colorado River at Lees Ferry, Arizona, file stored at the Federal Records Center in Laguna Niguel, California, in Accession No. 57-78-0006, Box 2 of 2 , Location No. MB053635. (*B*) View from the edge of the dugway road downstream. Photograph taken by G.C. Stevens of the U.S. Geological Survey just after sunset on September 22, 1923.

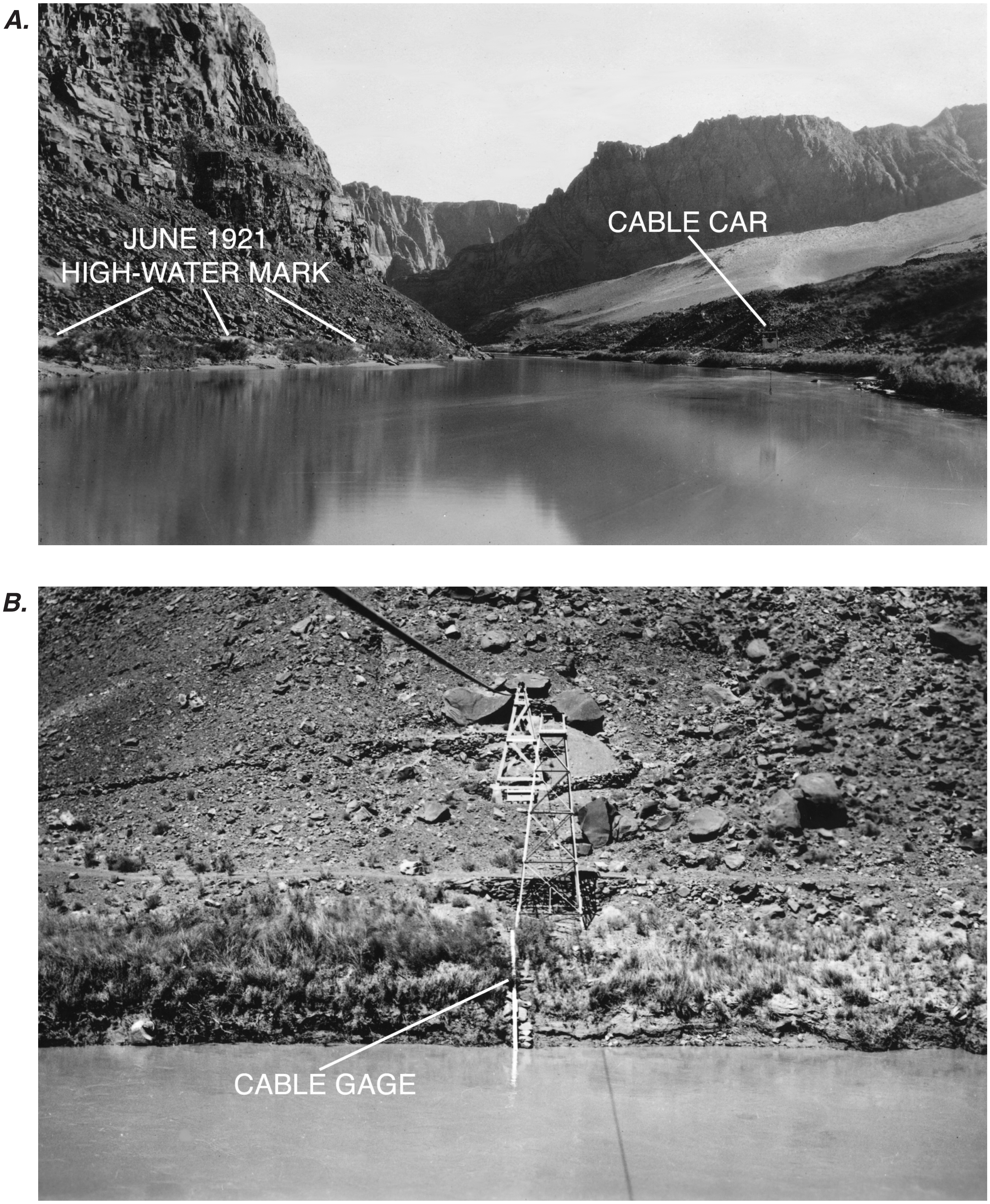
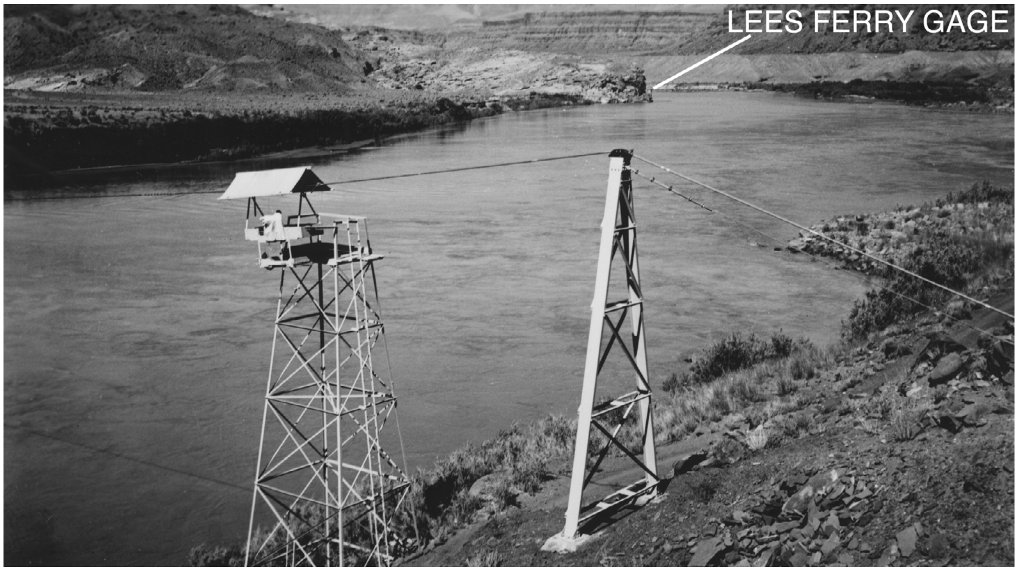


Figure 3. Upper and Lower Cableways. (*A*) Upstream view of Upper Cableway and cable car. High-water marks from the June 1921 flood are visible on the right bank (on the left side of the photograph). Photograph taken by R.C. Rice of the U.S. Geological Survey on October 2, 1921. (*B*) Left bank A-frame and landing tower for the Upper Cableway. U.S. Geological Survey photograph taken from cable car over mid-channel in June 1939. The Cable Gage, installed in April 1924, is visible in the foreground below the left (upstream) support for the landing tower.

C.



D.

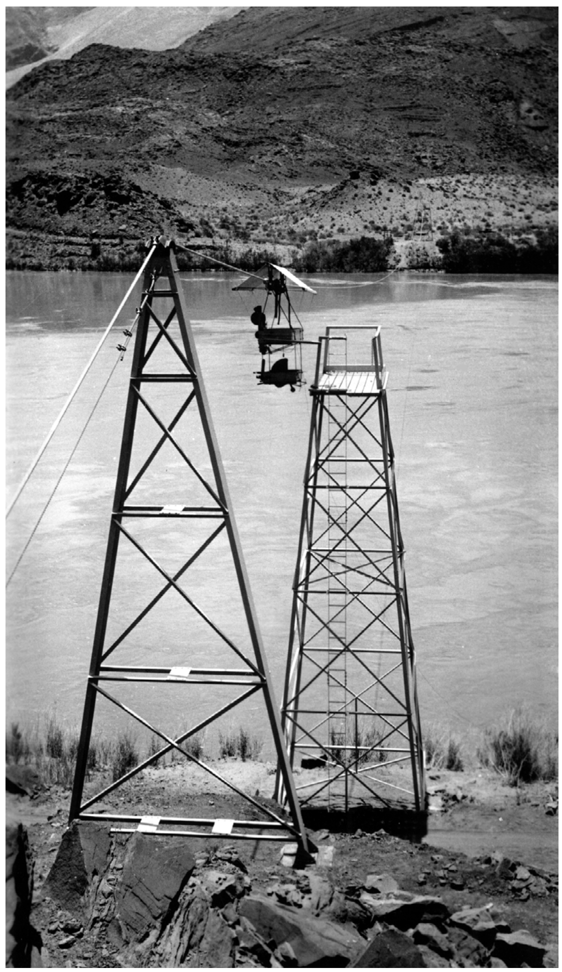


Figure 3—*Continued.* Upper and Lower Cableways.(*C*) Downstream view of right-bank A-frame and landing tower for the Lower Cableway. Lees Ferry Gage is in the distance on the left bank. U.S. Geological Survey photograph taken in June 1939. (*D*) View from right to left bank of Lower Cableway. Photograph taken by J.A. Baumgartner of the U.S. Geological Survey in June 1933.

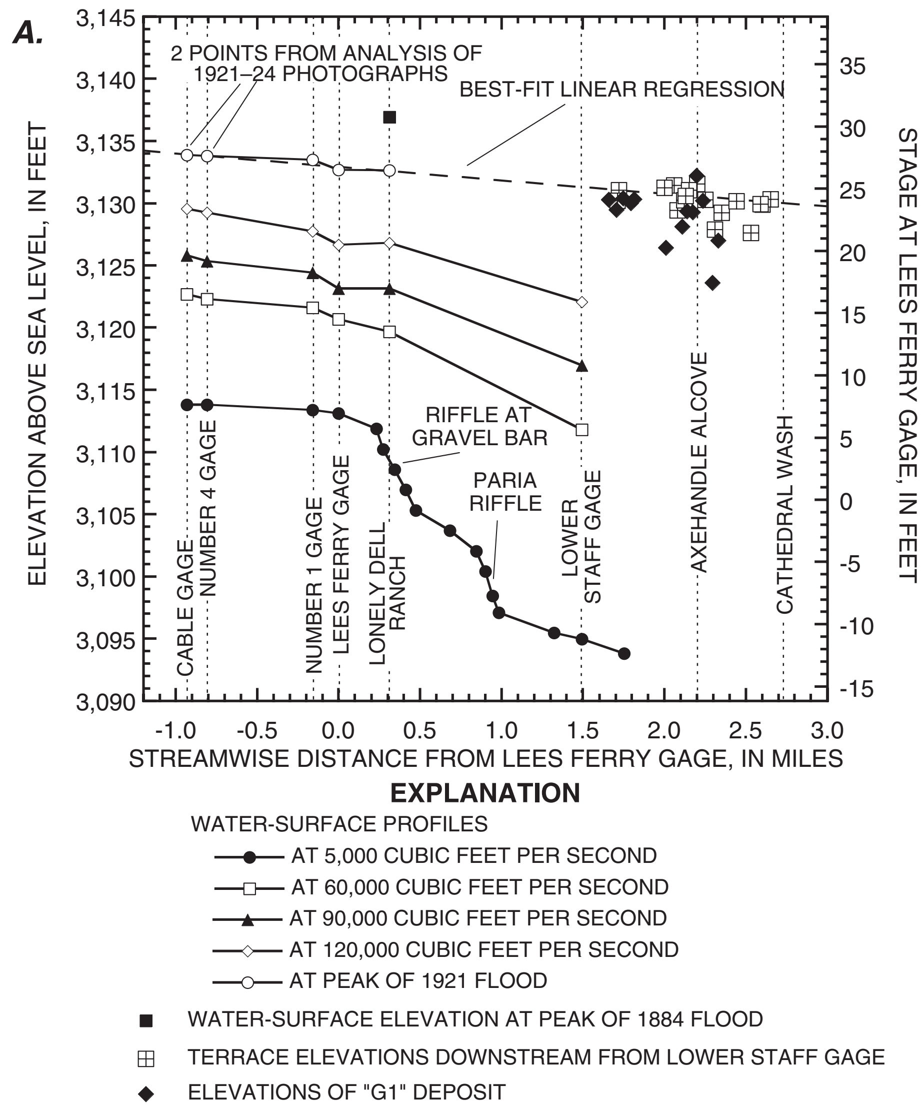


Figure 4. Flattening water-surface profiles with increasing stage and the reversal in curvature of the stage-discharge rating curve. (*A*) Water-surface profiles in the Lees Ferry reach at 5,000 cubic feet per second, 60,000, 90,000, 120,000 cubic feet per second, and during the peak of the 1921 flood. Shown are locations of the gages and the Lonely Dell Ranch where stages were measured. Stages at the Cable and Number 4 Gages during the 1921 flood were determined by analysis of the September–October 1921 and May 1924 photographs in Appendix B. Points between the gages on the 5,000 cubic feet per second profile were obtained from 1:2,400 scale topographic maps (Bureau of Reclamation, 1990). Elevations of terraces capped by the G1 deposit of O'Connor and others (1994) in the reach below the Lower Staff Gage were determined using airborne LIDAR data collected by the Grand Canyon Monitoring and Research Center in March 2000.

The reversal in the curvature of the stage-discharge rating curve was first recognized by the USGS in 1923, but was not accounted for in estimates of peak flows until 1927. Because the USGS did not account for this reversal in curvature, slightly more water was computed passing the Lees Ferry Gage during high-discharge months than was computed passing the Grand Canyon gaging station prior to 1927. This problem motivated J.S. Gatewood and H.S. Hunter in 1938 (in an unpublished USGS report) to recompute the discharges during water years 1921 through 1926 by fitting a mean stage-discharge rating curve to the data from this period. They then used the now standard shifting-control method (Kennedy, 1984, p. 25) to bring their discharges computed on the basis of this mean curve into better agreement with the measured discharges. The shifting-control method had not been

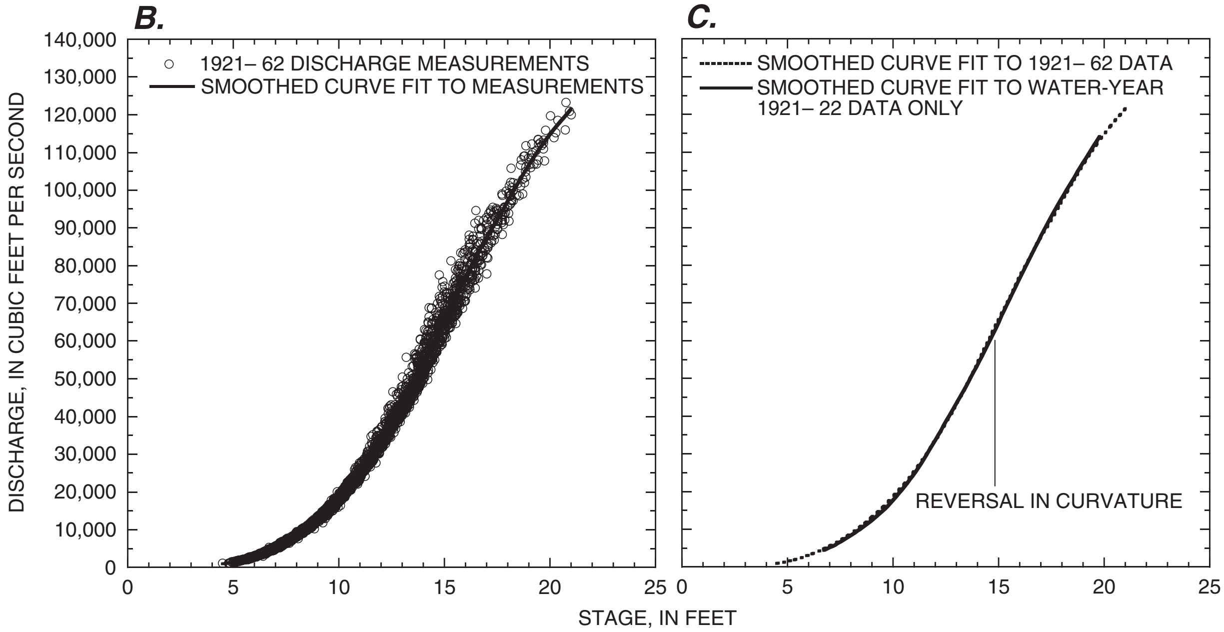


Figure 4—*Continued.* Flattening water-surface profiles with increasing stage and the reversal in curvature of the stage-discharge rating curve. (*B*) Stage-discharge rating curve at the Lees Ferry Gage defined by 4,114 discharge measurements made between August 3, 1921, and December 30, 1962. Excluded from this figure are: (1) the data after 1962 because of the influence of Glen Canyon Dam, (2) the 29 pre-dam discharge measurements affected by ice, and (3) the 1 discharge measurement made on August 2, 1929, while backwatered flow conditions existed at the gage as a result of a large flood on the Paria River. (*C*) Smoothed curve fit to the data in part B (without the data plotted) showing the reversal in curvature that occurs at a stage of about 15 feet. As shown in part A, this reversal in curvature arises as the water-surface profile flattens in the 0.3-mile-long reach immediately downstream from the gage as the hydraulic control shifts downstream. Also plotted is the smoothed curve fit to only the 193 non ice-affected measurements made during the first 14 months of gage operation during water years 1921 and 1922. Although the stage-discharge rating curve varied from year to year, this graph illustrates that the mean 1921–62 and the 1921–22 rating curves were nearly identical.

used to compute daily mean discharges at Lees Ferry prior to May 7, 1926, so the revision greatly improved the accuracy of the 1921–26 daily mean discharge data. Gatewood and Hunter used this approach to recompute the daily mean discharge for the following days: June 26, 1921, through September 10, 1921; April 22, 1922, through July 17, 1922; April 17, 1923, through July 31, 1923; April 8, 1924, through July 16, 1924; April 1, 1925, through July 21, 1925; and, April 16, 1926, through July 20, 1926. On the basis of their computations, only the data with the largest errors, that is, the data from water years 1921 through 1923, were revised and republished by the USGS in Grover and others (1939).

At stages higher than about 19 to 20 ft (that is, discharges higher than about 110,000 to 120,000 ft^3/s), the gravel bar at the mouth of the Paria River is almost overtopped (fig. 5*C*), and the progressive flattening of the water surface propagates upstream past the Lees Ferry Gage (fig. 6). At stages above 20 ft, the water-surface slope in the reach upstream from the gage is approximately equal to the water-surface slope in the reach downstream from the gage (fig. 4). A. Wilson (unpublished USGS analysis, April 20, 1962) compared the stage-discharge rating curves of the Lees Ferry Gage and the Lower Staff Gage and concluded that the hydraulic control for both gages was the same at stages above about 25 ft. Therefore, the decrease in the water-surface slope in the reach above the Lees Ferry Gage at stages between 20 and 25 ft is caused by the progressive development of backwatered flow conditions in the reach downstream from the gage, as the hydraulic control for the gage shifts farther downstream.

Although its precise location is not known, the likely hydraulic control for the Lees Ferry Gage at stages greatly in excess of 20 ft is either at Badger Rapids, 7.8 miles downstream from the gage, or at the riffle at the mouth of Cathedral Wash, 2.7 miles downstream from the gage (fig. 1*B*). In 1983, the water surface between the Lees Ferry Gage and Badger Rapids was observed to be relatively smooth at a discharge of about 90,000 ft^3/s, with the riffle at Cathedral Wash "washed out" (Kenton Grua, river guide, oral commun., 2002); this observation

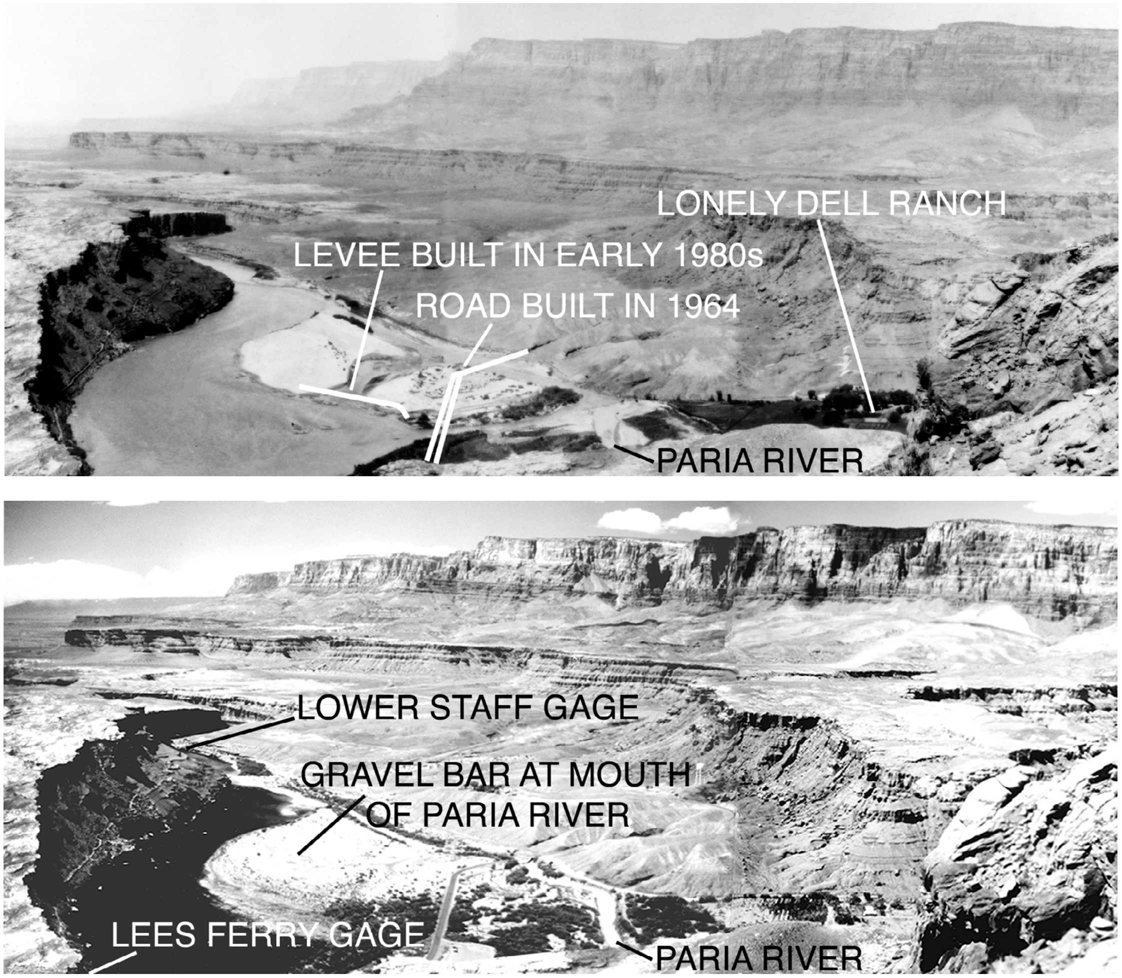


Figure 5. Flow over the gravel bar at the mouth of the Paria River at a range of discharges. (*A*) Downstream view in June 1915. The Colorado River is flowing through the left-bank main channel and through two channels across the bar into the lower portion of the Paria River. Estimated discharge of the Colorado River is 50,000 cubic feet per second, based on records from the Yuma gaging station. The location of the Lonely Dell Ranch is indicated, where elevations of the high-water marks of the 1884 and 1921 floods were measured on June 7, 1922. Also shown are the future locations of the road and levee in part B, built by the National Park Service after regulation of flows by Glen Canyon Dam. Source of photograph: H.E. Gregory photographs 297 and 298, U.S. Geological Survey Photographic Library, Denver, Colorado. (*B*) Same view as in *A* on April 15, 1995. Discharge of the Colorado River is 9,500 cubic feet per second and flow is restricted to only the left-bank main channel. Photograph taken by D.J. Topping of the U.S. Geological Survey.

suggests that the first hydraulic control downstream from Lees Ferry at high stage is Badger Rapids. Evidence for the Cathedral Wash riffle being the high-stage hydraulic control is provided by the presence of high-elevation terraces that extend downstream from the Lower Staff Gage (figs. 1*B* and 4*A*). The first high-elevation terraces occur on the right bank for about 700 feet downstream from the Lower Staff Gage, then continuously on the left bank for more than 0.6 miles, and terminate just above the riffle at Cathedral Wash. Although high-elevation terraces are present locally downstream, they are far less continuous than those above Cathedral Wash. Flood deposits preserved within the high-elevation terraces between the Lower Staff Gage and Cathedral Wash were first studied by O'Connor and others (1994). They determined that the uppermost unit within these terraces, the "G1" deposit, was likely deposited during a historical flood, which they speculated was the 1884 flood. In making this stratigraphic call, however, O'Connor and others (1994) did not have access to the historical data from the Lower Staff Gage. Extrapolation of the measured water-surface profile during the peak of the 1921 flood by means of a best-fit linear regression (fig. 4*A*) indicates that the G1 deposit was more likely formed during the 1921 flood than during the 1884 flood.

C.

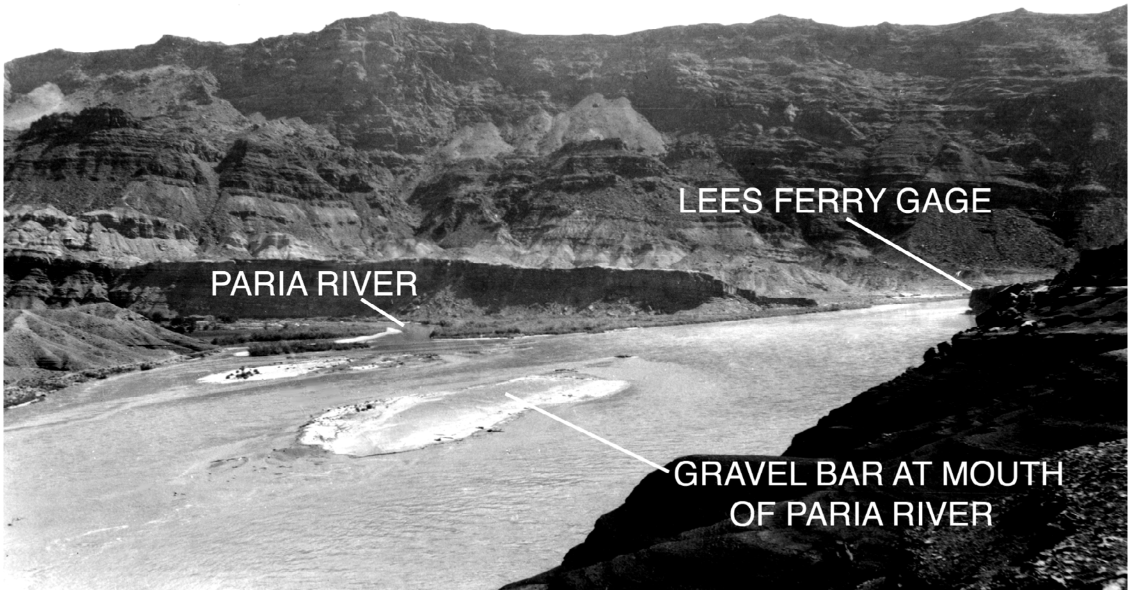


Figure 5—*Continued.* Flow over the gravel bar at the mouth of the Paria River at a range of discharges. (*C*) Upstream view on about June 1, 1928. Discharge of the Colorado River is approximately 110,000 cubic feet per second. Bar is almost completely overtopped by the Colorado River, and backwatered conditions extend far up the Paria River. At lower discharges, a riffle is present in the left-bank channel (in foreground). At 110,000 cubic feet per second, however, the riffle is washed out as the hydraulic control for the Lees Ferry Gage shifts farther downstream. Photograph taken by the U.S. Geological Survey. Source of this photograph: wall display in the Flagstaff, Arizona U.S. Geological Survey office.

Pre-Dam Hysteresis in the Water-Surface Slope in the Reach Upstream from the Lees Ferry Gage

In a one-dimensional sense, the longitudinal water-surface slope in a river at a given sub-critical discharge is governed by the geometry of the downstream hydraulic control, cross-sectional geometry, streamwise changes in cross-sectional geometry, and bed roughness (for example, see Chow, 1959). Thus, the longitudinal water-surface slope can vary as a function of the volume of sediment stored in pools because changes in the volume of stored sediment can affect the mean cross-sectional geometry, streamwise variation in cross-sectional geometry, and bed roughness. Analysis of the water-surface-slope data in the reach upstream from the Lees Ferry Gage indicates that prior to the construction of Glen Canyon Dam, seasonal scour and fill of the pools upstream from the gage (Leopold and Maddock, 1953; Colby, 1964; Howard and Dolan, 1981; Burkham, 1986; Topping and others, 2000; Grams and others, Utah State University, written commun., 2002) caused hysteresis in the water-surface profile, with the water-surface slope being steeper during the rising limb than during the receding limb of the annual snowmelt flood (figs. 6*C*–*E*). Following the extensive scour of these pools during high dam releases in 1965 (Pemberton, 1976; Williams and Wolman, 1984; Burkham, 1986; Grams and others, Utah State University, written commun., 2002), however, this secondary control on water-surface slope near Lees Ferry ceased to be important.

The effect of the seasonal pre-dam scour and fill of the pools upstream from the Lees Ferry Gage on the water-surface slope is evident in figs. 6*C*–*E*. As shown in fig. 6*B* of Topping and others (2000), the bed at the Upper Cableway scoured each spring during the rising limb of the annual snowmelt flood, then filled during the receding limb (with only a slight lag between the time of the flood peak and the time of maximum scour). Colby (1964) and Topping and others (2000) concluded that scour and fill of the bed at the Upper Cableway was largely driven by the interaction between the flow and the geometry of the reach, and not by changes in the upstream sediment supply [as was the case at the Grand Canyon gaging station downstream (Topping and others, 2000)].

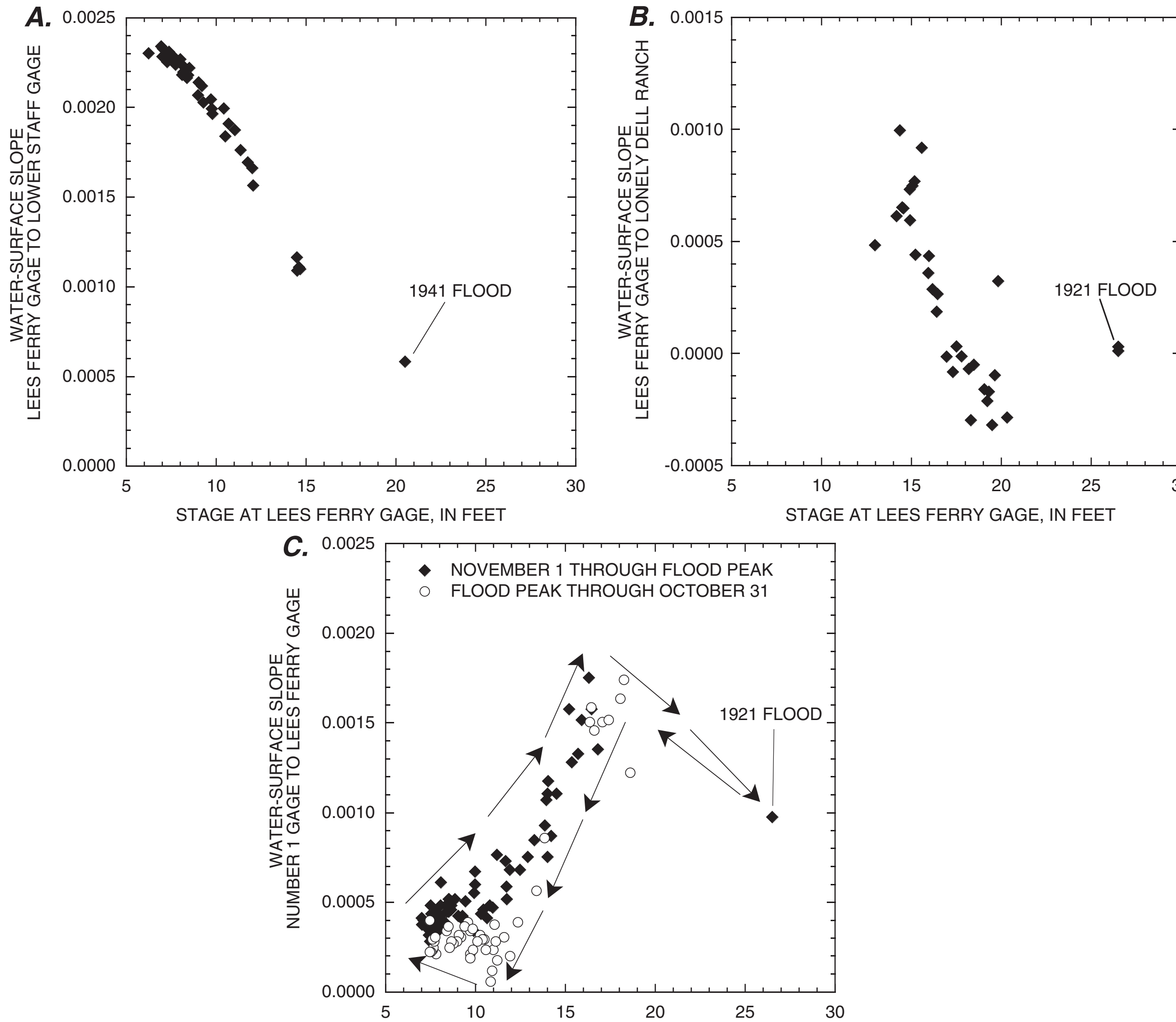


Figure 6. Water-surface slopes as a function of stage: (*A*) In the 1.5-mile-long reach between the Lees Ferry Gage and the Lower Staff Gage, determined from 27 stage measurements made at the 2 gages during 1941 and 1942, and 11 stage measurements made at the 2 gages during 1958 and 1959. (*B*) In the 0.3-mile-long reach between the Lees Ferry Gage and the lower reach of the Paria River at the Lonely Dell Ranch, determined from the June 7, 1922, surveys of the June 1921 high-water marks, and from 30 surveys made during higher-water periods in 1927, 1928, and 1929. Because the Lees Ferry Gage and the Lonely Dell Ranch are on opposite banks of the river above the gravel bar, there is a cross-stream component of the water-surface slope in this figure that would be absent if these sites were on the same side of the river. This leads to the water-surface slope between the gage and the ranch becoming negative at stages above 17 feet (at discharges above 90,000 cubic feet per second). At extremely high stages, as during the 1921 flood, the water-surface slope is of the order of 0.00001, as fully backwatered flow conditions develop in this reach. (*C*) In the 820-foot-long reach between the Number 1 Gage and the Lees Ferry Gage, determined from 136 stage measurements made at the two gages between June 18, 1921, through September 15, 1922. Similar to the case in part *B*, because the Number 1 Gage and the Lees Ferry Gage are located on opposite banks of the river in a meander, there is a cross-stream component of the water-surface slope in this figure. Data in this figure and in parts *D*–*E* are segregated into: (1) slopes measured each year between November 1 and the peak of the subsequent snowmelt flood, and (2) slopes measured each year between the peak of the snowmelt flood and October 31. Because of the seasonal scour and fill of sediment in the pools upstream from the Lees Ferry Gage, hysteresis during the annual snowmelt flood (indicated by arrows) exists in the water-surface slope in this figure and in parts *D*–*E*.

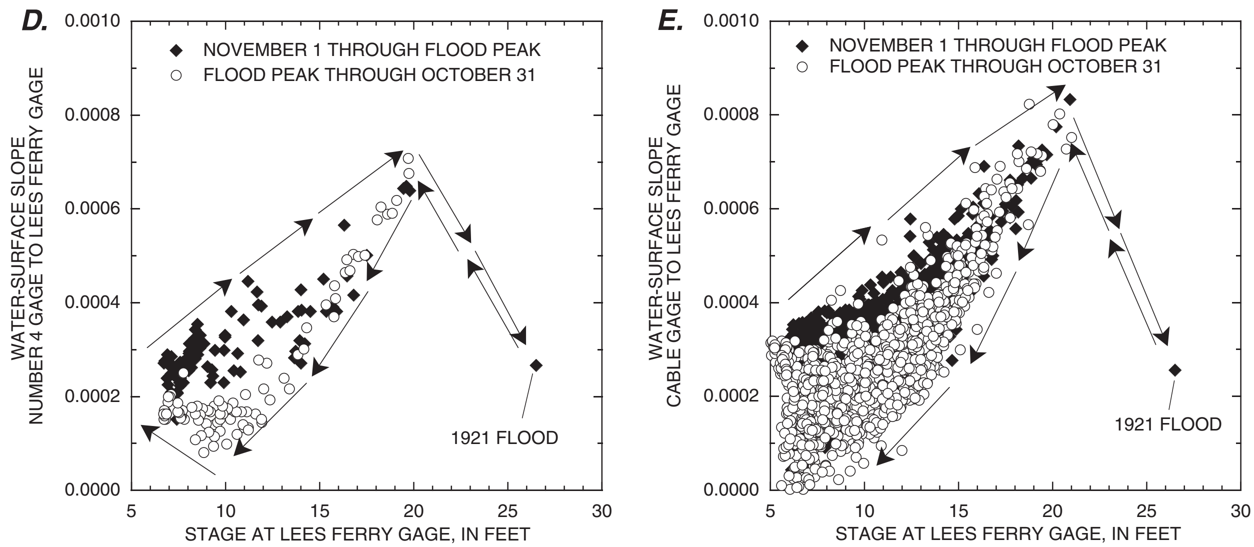


Figure 6—*Continued.* Water-surface slopes as a function of stage: (*D*) In the reach between the Number 4 Gage and the Lees Ferry Gage, determined from 209 stage measurements made at the 2 gages between August 14, 1921, and September 22, 1923. Peak stage during the June 1921 flood at the Number 4 Gage was determined by analysis of the photographs taken by R.C. Rice in September–October 1921 (figs. B1 and B3). (*E*) In the reach between the Cable Gage (490 feet upstream from the Number 4 Gage) and the Lees Ferry Gage, determined from 3,196 stage measurements made at the 2 gages between April 26, 1924, and July 30, 1962. Peak stage during the June 1921 flood at the Cable Gage was determined by analysis of the photographs taken by R.C. Rice in September–October 1921 and W.E. Dickinson in May 1924 (figs. B1 and B5).

The bed generally scoured between April and the third week in June each year, and filled between the third week in June and the end of October (Topping and others, 2000, fig. 6*B*). At stages less than about 15 ft (the stage of the reversal of curvature in the stage-discharge rating curve), the water-surface slope in the reach upstream from the gage was about a factor of two steeper during the months when the bed was scouring than it was during the months when the bed was filling. Above a stage of about 15 ft, the water-surface slopes during the rising and receding limbs of the annual snowmelt flood were approximately the same in the reach upstream from the gage.

COLORADO RIVER FLOODS AT LEES FERRY

It is important to determine accurately the magnitudes of the largest floods in the recent history of the Lees Ferry gaging station because these floods may have had a large role in determining the present morphology of the Colorado River, and because these floods are an essential component of the natural hydrology of the pre-dam Colorado River. Although the magnitudes of floods after August 1921 were measured from existing cableways, the magnitudes of earlier floods can only be estimated from direct or indirect measurements of flood stage and estimates of the discharges at these stages.

There is no way to determine the maximum stage of every annual flood before August 1921, but it is possible to estimate the discharges of the two largest floods during the 37 years prior to installation of the cableway because both floods were observed. A flood whose stage was higher than any in subsequent years occurred in June 1921, 1 month after the first staff gage was installed and 2 months prior to the installation of the cableway. An even higher-discharge flood in 1884 was witnessed by Jerry Johnson, the ferry operator, and his family. The date of the peak of the 1884 flood at Lees Ferry has been reported to have been either June 18 (Reilly, 1999) or July 7 (LaRue, 1925; Patterson and Somers, 1966). Because the peak of this flood was observed at the Yuma gaging station (660 miles downstream from Lees Ferry) on June 28, the correct date for the peak of the 1884 flood at Lees Ferry is probably June 18. Estimation of the peak magnitudes of the 1884 and 1921 floods depends on the accurate determination of maximum flood stages and appropriate extrapolations of the stage-discharge rating curves at the various staff gages in the Lees Ferry reach. Because of the importance of the 1884 and 1921 floods, all available information about the magnitudes of the peak stage and the methods by which discharge was estimated from the stage data for each of these floods was assembled and reviewed.

Estimate of the Peak Discharge of the 1921 Flood at Lees Ferry

Because estimation of the peak discharge of the 1884 flood depends on estimation of the peak discharge of the lower June 1921 flood, estimation of the peak discharge of the 1921 flood is described first. The peak discharge of the 1921 flood at Lees Ferry was unknown and had to be estimated, but the peak stage was precisely measured at the Number 1 Gage, the Dugway Gage, and at two different locations at the Lonely Dell Ranch. Analysis of photographs taken of the Number 4 and Cable Gages in 1921–24 (Appendix B) allow the peak stage of the 1921 flood to be determined at these two additional sites, but with less precision (fig. 4*A*).

The original USGS estimate of the peak discharge of the June 1921 flood was 174,000 ft^3/s; this value was based on extrapolation of the first available stage-discharge rating curve for the Number 1 Gage (unpublished USGS 1921 annual technical file for the Lees Ferry gaging station). This rating curve was based on 120 discharge measurements made between August 5, 1921, and June 15, 1922. The original estimate of 174,000 ft^3/s was not published. The first published estimate of the peak discharge of the 1921 flood at Lees Ferry was "about 190,000 ft^3/s " (Grover and others, 1923); this value was based on comparison of the estimated daily mean discharges during the 1921 flood at Lees Ferry with those measured downstream at the Topock and Yuma gaging stations. This value of "about 190,000 ft^3/s " was the official USGS estimate of the peak discharge of the June 1921 flood until 1939, when the USGS revised the estimate to 220,000 ft^3/s (Grover and others, 1939), on the basis of the 1938 study of J.S. Gatewood and R.S. Hunter. The 1939 revision remains the currently accepted estimate of the peak discharge of this flood.

The Key Assumption of J.S. Gatewood and R.S. Hunter

The 1939 revision of the estimate of the peak discharge of the 1921 flood was based on a key assumption now known to be false. Because the reversal in the curvature of the stage-discharge rating curve at the Lees Ferry Gage made extrapolation of this curve difficult, Gatewood and Hunter decided to estimate the peak discharge of the 1921 flood at the Grand Canyon gaging station. They chose the Grand Canyon gaging station over Lees Ferry as the place to perform this extrapolation because (1) the stage-discharge rating curve was more stable at the Grand Canyon gaging station than at the Lees Ferry Gage, and (2) there was no known reversal in the curvature of the stage-discharge rating curve at the Grand Canyon gaging station. The chief problem with this approach, however, was that unlike at Lees Ferry, where the high-water marks from the 1921 flood were at known stages, there was no certainty of the peak stage of the 1921 flood at the Grand Canyon gaging station because this station was not established until November 1922. Unfortunately, Gatewood and Hunter did not correctly interpret the dates of the various high-water marks at the Grand Canyon gaging station, and mistook the likely 1884 high-water mark for the 1921 high-water mark. This misinterpretation led to an overestimation of the peak discharge of the 1921 flood by about 30 percent.

Gatewood and Hunter assumed that the high-water mark found in 1933 by J.A. Baumgartner of the USGS in a left-bank recess upstream from the measurement cableway at the Grand Canyon gaging station was from the 1921 flood. By extrapolation of the stage-discharge rating curve at the Grand Canyon gaging station to the stage of this high-water mark (37.5 ft), they estimated that the peak discharge of the 1921 flood was about 220,000 ft^3/s at the Grand Canyon gaging station. Because very little tributary inflow or attenuation of the peak discharge occurred between the Lees Ferry and Grand Canyon gaging stations during snowmelt floods, they then assumed that the peak discharge of the 1921 flood at Lees Ferry was also 220,000 ft^3/s.

To make the stage-discharge rating curve at the Lees Ferry Gage pass through a discharge of 220,000 ft^3/s at the measured peak stage of the 1921 flood (26.5 ft), Gatewood and Hunter imposed a second reversal in curvature at a stage of 17 ft (fig. 7). As shown in a preceding section of this paper, the water-surface slope at the Lees Ferry Gage decreases with increasing stage as a result of the progressive development of backwatered flow conditions in the reach. When water-surface profiles progressively flatten with increasing stage, discharge is proportional to stage raised to a power less than one. Beginning in water year 1939, the USGS adopted the 1938 assumption of Gatewood and Hunter that there is a second reversal in the curvature of the Lees Ferry stage-discharge rating curve at a stage of about 17 ft. Thus, they assumed that, at discharges above about 85,000 ft^3/s, discharge returned to being proportional to stage raised to a power greater than one. Dickinson (1944) reiterated this assumption, stating that a "moderate reversal in the station rating curve occurs in the range from 60,000 to 80,000 second-feet [ft^3/s], above and below which rating has normal curvature." Though this assumption was made, it was not supported by the data (fig. 8). Analysis of the data from the six highest flow years at Lees Ferry provide no support for the existence of this second reversal in curvature. No second reversal in curvature is evident in any of the individual years with substantial data above a stage of 17 ft (water years 1921–22, 1928, 1941, 1949, 1952, and 1957, fig. 8).

An earlier USGS memorandum written by G.C. Stevens on May 25, 1925, suggests that the more likely peak stage of the 1921 flood at the Grand Canyon gaging station was 33 ft, not 37.5 ft. As stated in this memorandum, on September 13, 1923, J.W. Johnson, resident USGS hydrographer at the Grand Canyon gaging station, wrote that the highest visible high-water mark on the cliff on the south side of the river at the Grand Canyon gaging station was at a stage of about 32 ft. This high-water mark was at a much higher stage than the peak stage of any flood at this gaging station since its establishment in November 1922. On March 14, 1924, G.G. Sykes of the USGS used a level to determine that the stage of this high-water mark was 33 ft (figs. 9*A*–*C*). Because it was much higher than the peak stage of any flood on the Colorado River after June 1921, the high-water mark at a stage of 33 ft was probably from the June 1921 flood.

These data from the early 1920s suggest that the high-water mark at a stage of 37.5 ft found in 1933 at the Grand Canyon gaging station was probably from the 1884 flood, and not from the 1921 flood. The 1884 flood was the largest historical flood prior to 1921, and the peak stage of this flood was about 4 ft higher than that of the 1921 flood at Lees Ferry. If the high-water mark at a stage of 37.5 ft was from the 1921 flood, then the high-water mark at a stage of 33 ft should have been erased by the 1921 flood, and should not have been prominent in photographs taken at the site in November 1921 (figs. 9*A*–*B*). Power-law extrapolation of the stage-discharge rating curve fit to the pre-dam data from the Grand Canyon gaging station suggests that, at a stage of 33 ft, the peak discharge of the 1921 flood would be about 163,000 ft^3/s, and, at a stage of 37.5 ft, the peak discharge of the 1884 flood would be about 214,000 ft^3/s. Extrapolation along this same curve suggests that the peak discharge of a prehistoric flood associated with the highest high-water marks found near the gage by the National Park Service during construction of the Kaibab Bridge would be in excess of 300,000 ft^3/s, and possibly as high as about 360,000 ft^3/s (fig. 9*D*).

Other Measurements of the Peak Discharge of the 1921 Flood Made Downstream and Upstream from Lees Ferry

Peak discharges measured at gaging stations downstream and upstream from Lees Ferry during the June 1921 flood indicate that the original USGS estimate of the peak discharge of the June 1921 flood at Lees Ferry of 174,000 ft^3/s was probably correct, because these other measurements range between 167,000 and 188,000 ft^3/s. None of the observations made at these other gaging stations indicate that the discharge was as high as the 220,000 ft^3/s value estimated by Gatewood and Hunter in 1938.

Comparison with measurements made at downstream gaging stations is valid because snowmelt floods on the tributaries entering the Colorado River downstream from Lees Ferry would have peaked earlier than late June. Thus, there would have been very little inflow from these tributaries to increase the peak discharge substantially. Furthermore, because the volume of water within the 1921 snowmelt flood was large and the duration of this flood was long, there would have been very little attenuation in the peak discharge of this flood between Lees Ferry and downstream gaging stations.

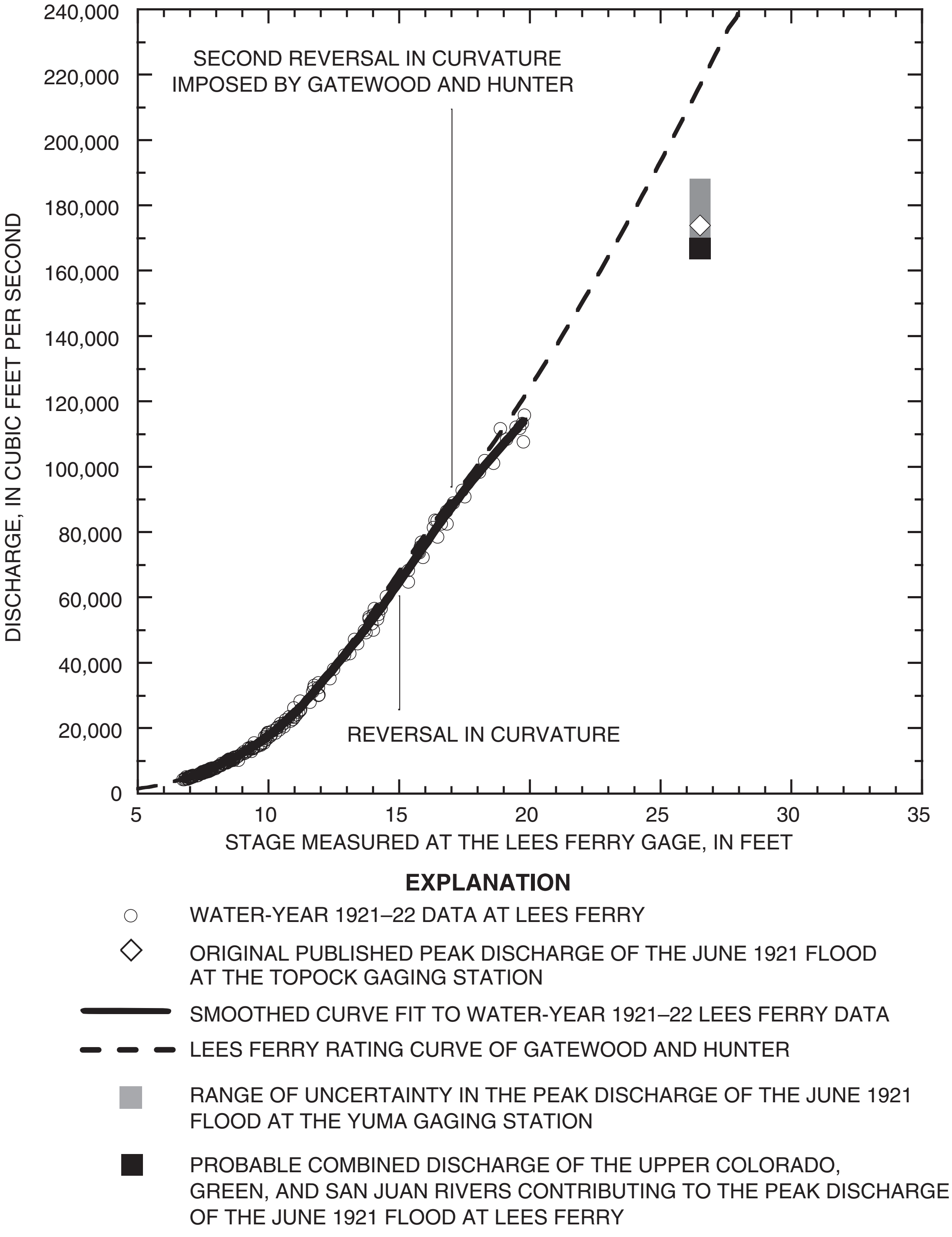


Figure 7. Comparison of the stage-discharge rating curve defined by the discharge measurements made during water-years 1921–22 with the revised stage-discharge rating curve of Gatewood and Hunter (unpublished U.S. Geological Survey report, 1938). Though their revised curve plotted slightly high relative to the measurements at stages of 18 to 20 feet, they corrected for this in their revision of the 1922–26 data by using the shifting-control method. Also shown are: the original published peak June 22, 1921, discharge of the Colorado River at the Topock gaging station; the peak June 27, 1921, discharge (with uncertainty) of the Colorado River at the Yuma gaging station; and the probable combined discharge of the upper Colorado, Green, and San Juan Rivers contributing to the June 18, 1921, peak at Lees Ferry.

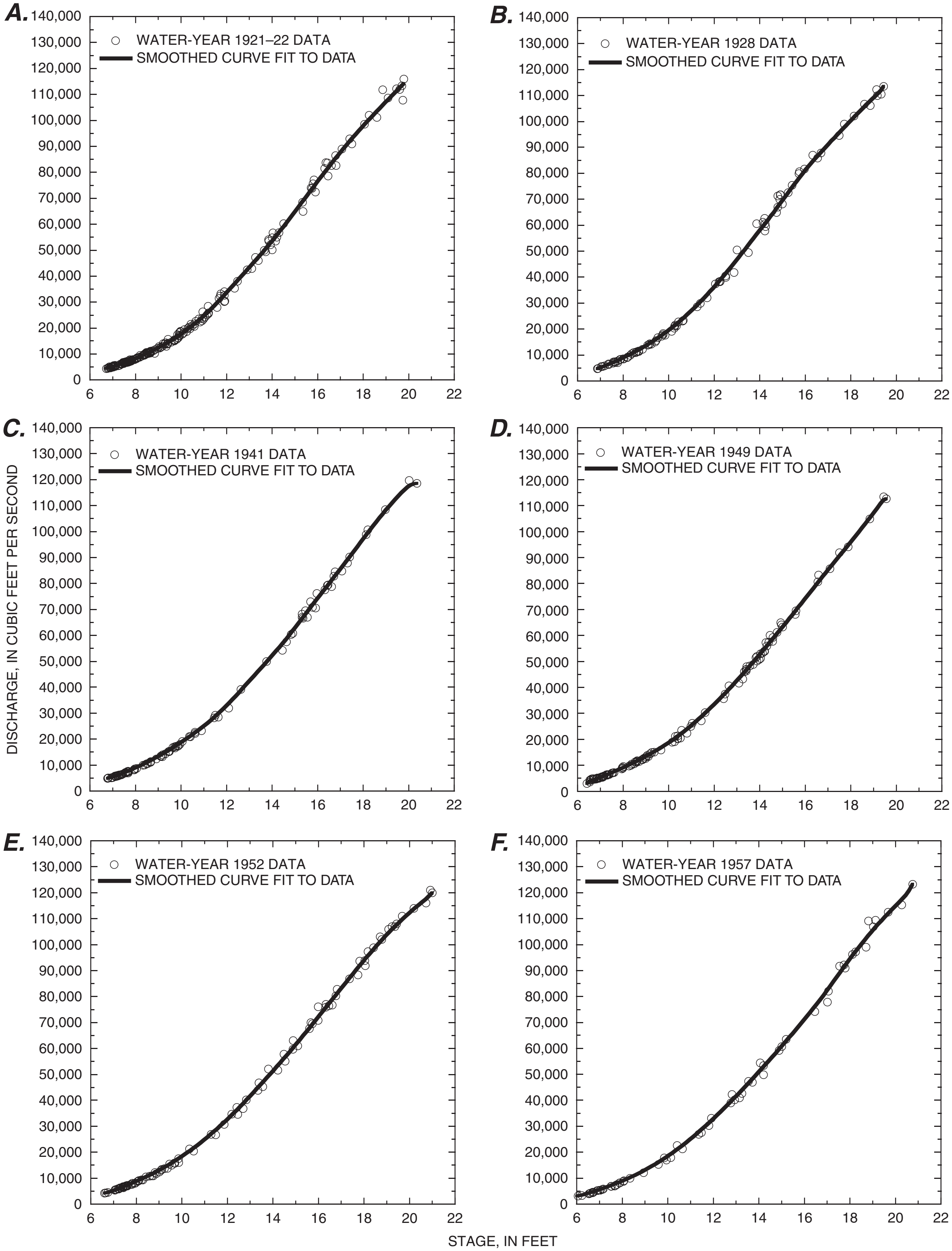
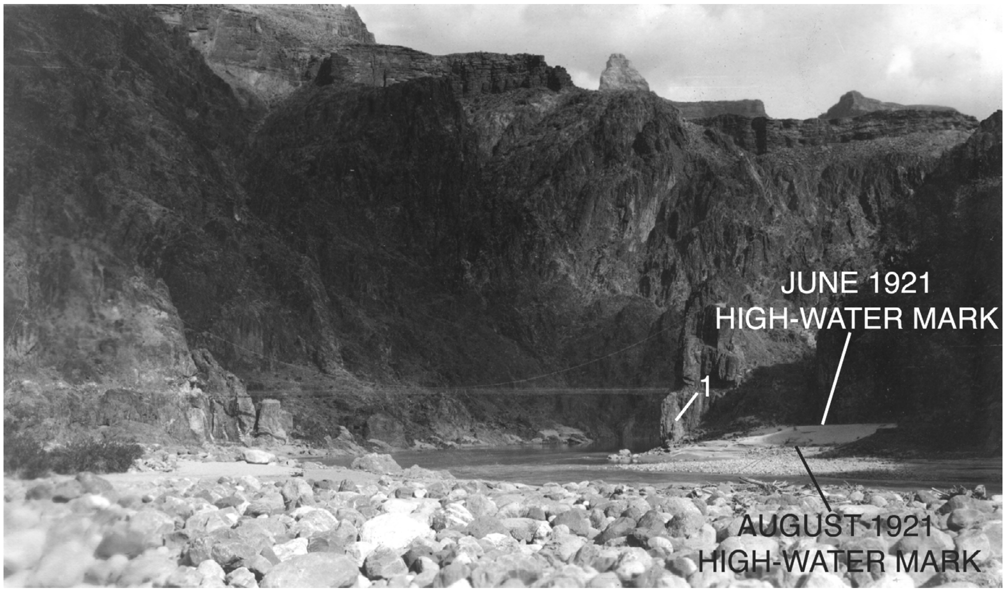


Figure 8. Stage-discharge rating curves at the Lees Ferry Gage defined by discharge measurements during the 6 high-discharge water years with substantial data above a stage of 17 feet. (*A*) 1921–22. (*B*) 1928. (*C*) 1941. (*D*) 1949. (*E*) 1952. (*F*) 1957.

A.



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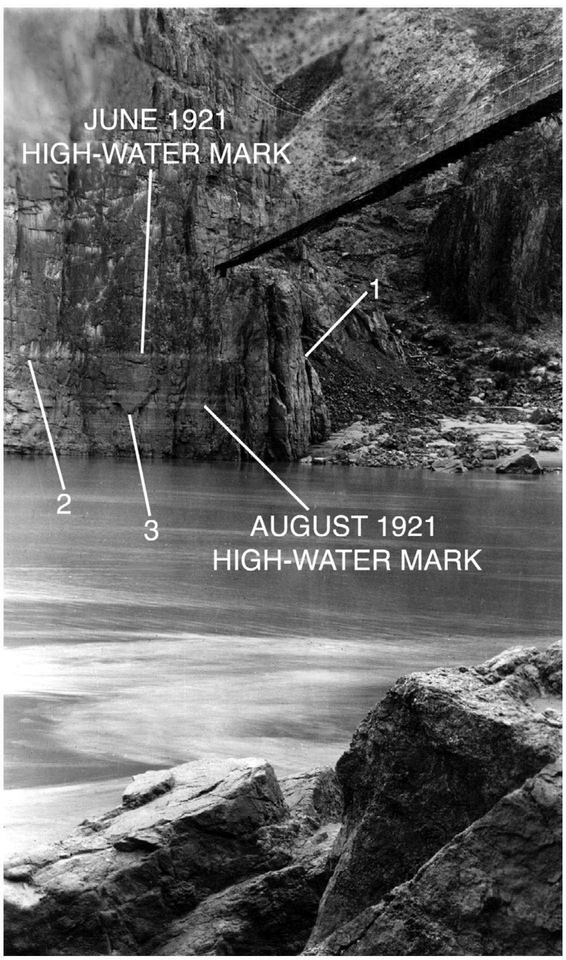
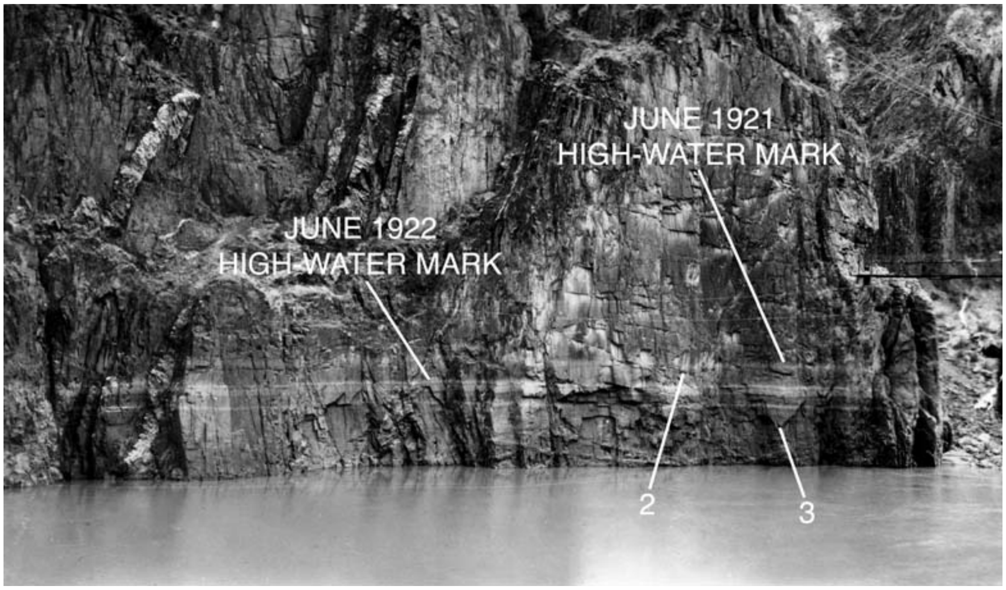


Figure 9. High-water marks from the 1921 flood and estimated peak discharges of the 1921 and 1884 floods at the Grand Canyon gaging station. (*A*) November 16, 1921, upstream view of the future reach of the Grand Canyon gaging station. Visible on the left bank (right side of photograph) is the likely high-water mark from the 1921 flood. This high-water mark is at the same elevation as the highest high-water mark in parts *B* and *C*. "1" indicates the position of a reference point on the cliff common to this view and to the view in part *B*. The lower high-water mark was probably produced during a flood that had a peak discharge of 67,000 cubic feet per second at the Lees Ferry Gage on August 25, 1921. Photograph taken by R.C. Rice of the U.S. Geological Survey. Source of this and the photographs in parts *B* and *C*: Gaging station reconnaissance and construction reports, Colorado River near Grand Canyon, Arizona, file stored at the Federal Records Center in Denver, Colorado, in Accession No. 57-64A-0423, Box 1 of 24 , Location No. 62478. (*B*) November 16, 1921, view of the cliff on the left (south) bank of the Colorado River across from the future site of the lower (right-bank) gage at the Grand Canyon gaging station. "1" indicates the position of the reference point in part *A*. Visible are the likely high-water marks from the June 1921 flood and the lower-magnitude August 1921 flood. "2" and "3" indicate the positions of two reference points common to this view and to the view in part *C*. Measurements made with hand levels in December 2000 (N.J. Hornewer, U.S. Geological Survey, written commun., 2000) and July 2001 confirm that the likely June 1921 high-water mark in this photograph and in part C was the high-water mark at a stage of 33 feet measured by G.G. Sykes in 1924. Photograph taken by R.C. Rice of the U.S. Geological Survey.

C.



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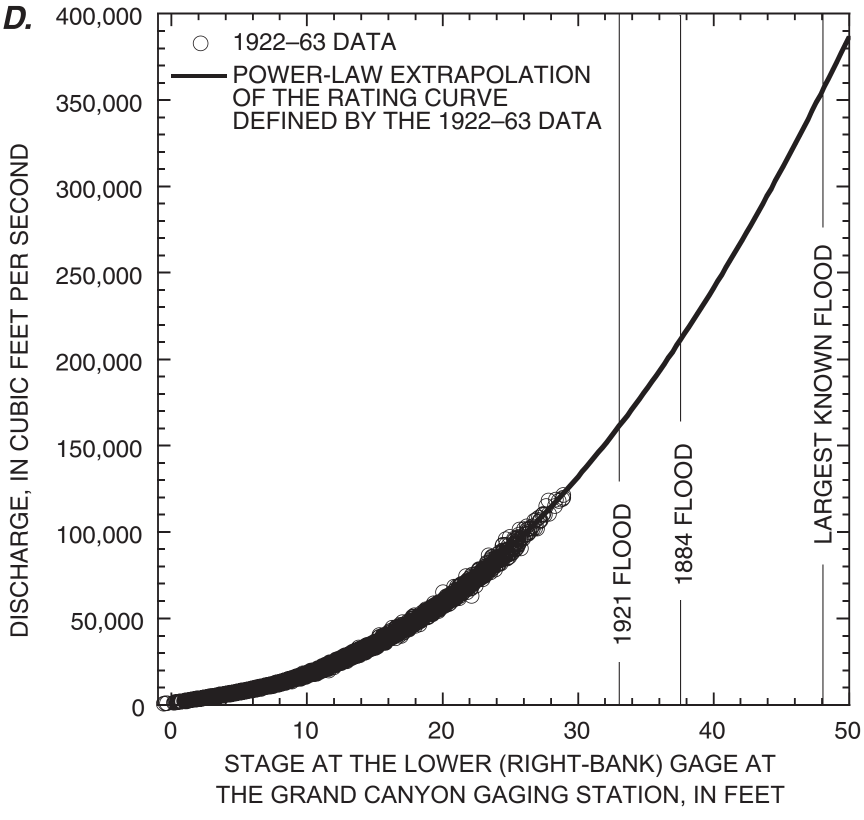

Figure 9—*Continued.* High-water marks from the 1921 flood and estimated peak discharges of the 1921 and 1884 floods at the Grand Canyon gaging station. (*C*) Fall 1922 view of the cliff in part *B*. "2" and "3" indicate the positions of the two reference points in part *B*. The likely high-water mark from the June 1921 flood is still visible 1 year after the photograph in part *B* was taken. Also visible is the likely high-water mark from the June 1922 flood that had a peak discharge of 116,000 cubic feet per second at Lees Ferry. Note that the high-water mark from the 67,000 cubic feet per second August 1921 flood has been erased by the larger, more recent June 1922 flood. Photograph taken by F.C. Ebert of the U.S. Geological Survey during the construction of the Grand Canyon gaging station. (*D*) Stage-discharge rating curve at the lower gage at the Grand Canyon gaging station defined by 3,703 pre-dam discharge measurements made between November 12, 1922, and March 6, 1963. The "largest known flood" refers to the flood associated with the highest high-water mark found by the National Park Service on September 24, 1919, during the construction of the Kaibab (Black) Bridge (bridge shown in parts *A*–*C*). Description of the bridge construction was published in the Engineering News Record of February 10, 1921.

Therefore, the peak discharge of the 1921 flood at the Lees Ferry should have been similar to that at the Topock gaging station, which is approximately 450 miles downstream from Lees Ferry, and the Yuma gaging station, which is approximately 660 miles downstream from Lees Ferry (fig. 1*A*). Support for this is provided by the measured peak discharges during the high-discharge, large-volume, long-duration snowmelt floods of 1922 and 1923, which had virtually identical peak discharges at the Lees Ferry, Topock, and Yuma gaging stations (U.S. Geological Survey, daily mean and peak discharge data, accessed November 22, 2000). During the 1922 snowmelt flood, peak discharges at the Lees Ferry, Topock, and Yuma gaging stations were 116,000 ft^3/s, 125,000 ft^3/s and 117,000 ft^3/s, respectively; during the 1923 snowmelt flood, peak discharges at the Lees Ferry, Topock, and Yuma gaging stations were 98,300 ft^3/s, 103,000 ft^3/s, and 101,000 ft^3/s, respectively. Only during lower volume snowmelt floods, with peaks of much shorter duration than during the 1921, 1922, or 1923 floods, was substantial attenuation of the peak discharge observed between the Lees Ferry and Yuma gaging stations.

The estimated peak discharge of the 1921 flood at the Topock gaging station was 174,000 ft^3/s on June 22, 1921 (Grover and others, 1922). This peak discharge was estimated by extrapolating the stage-discharge rating curve that applied to this site in 1921. This rating curve was defined by 30 discharge measurements covering a discharge range between 8,000 and 80,000 ft^3/s (Grover and others, 1922). Based on an evaluation of the discharge data at the Topock gaging station by Dickinson (1944), the 174,000 ft^3/s estimate of the peak discharge may be, if anything, too high. Dickinson (1944) stated, "In general, records prior to 1924 tend to show the discharge too great above about 20,000 second-feet [ft^3/s] owing to equipment and methods then in use in making discharge measurements." In 1942, the USGS revised its estimate of the 1921 flood at the Topock gaging station to "greater than 200,000 ft^3/s" (Parker and others, 1942), but there was no basis for this revision except to make it consistent with Gatewood and Hunter's 1938 revision of the estimated peak discharge of the 1921 flood at Lees Ferry.

Discharge data collected farther downstream at the Yuma gaging station during the 1921 flood are inconsistent with Gatewood and Hunter's 1938 estimate of the peak discharge at Lees Ferry and Parker and others' 1942 revision of the peak discharge at the Topock gaging station. The peak discharge of the 1921 flood measured at the Yuma gaging station was 188,000 ft^3/s on June 27, 1921 (Grover and others, 1922). This value was never revised by the USGS and is still the accepted peak discharge at Yuma during the 1921 flood. The computed discharges at the Yuma gaging station during 1921 were based on 164 measurements made during the year (Grover and others, 1922). Indeed, a discharge measurement was made on the morning of June 27, 1927, near the peak of the flood (fig. 10).

The published estimate of 188,000 ft^3/s at the Yuma gaging station may be slightly high because (1) the cross-sectional area of the flow at the Yuma gaging station was determined by primitive sounding methods that would have overestimated the cross-sectional area of flow, and (2) the mean velocities in the higher flow discharge measurements during 1921 were estimated by multiplying surface velocities by a coefficient of 0.9 (Dickinson, 1944). In evaluating the discharge data at the Yuma gaging station, Dickinson (1944), stated:

> Prior to 1926, measurements are generally subject to errors of varying amounts due to methods and equipment used, including the use of relatively few measuring points. During 1911–15 and at stages above low-water during 1916–22, most measurements were based on observations of surface velocity using a coefficient of 0.9 to obtain the mean. At stages above low-water, soundings were made separately from velocity observations prior to 1926, and prior to 1923 a cylindrical weight suspended from one end (axis vertical) was used which was apt to be carried downstream by drift and high velocity, resulting in too large soundings. Soundings and velocity observations were further complicated by a stayline 1918–25.

When the roughness elements on the bed are small relative to the flow depth, velocity profiles in steady, uniform flow tend to have a logarithmic shape in only the lower 20 percent of the flow, and an approximately parabolic shape in the upper 80 percent of the flow (Rattray and Mitsuda, 1974; Wiberg and Smith, 1991; Long and others, 1993). The coefficient relating surface to mean velocity in this type of profile is not 0.9, but 0.8 (at one significant figure). The peak discharge of the 1921 flood at the Yuma gaging station, based on a velocity coefficient of 0.8 and the assumption that the sounding methods did not introduce too much error, is 167,000 ft^3/s. The peak discharge of this flood at the Yuma gaging station was therefore between 167,000 and 188,000 ft^3/s; the uncertainty of this estimate is associated with the accuracy of the sounding and the cross-sectionally averaged shape of the velocity profile.

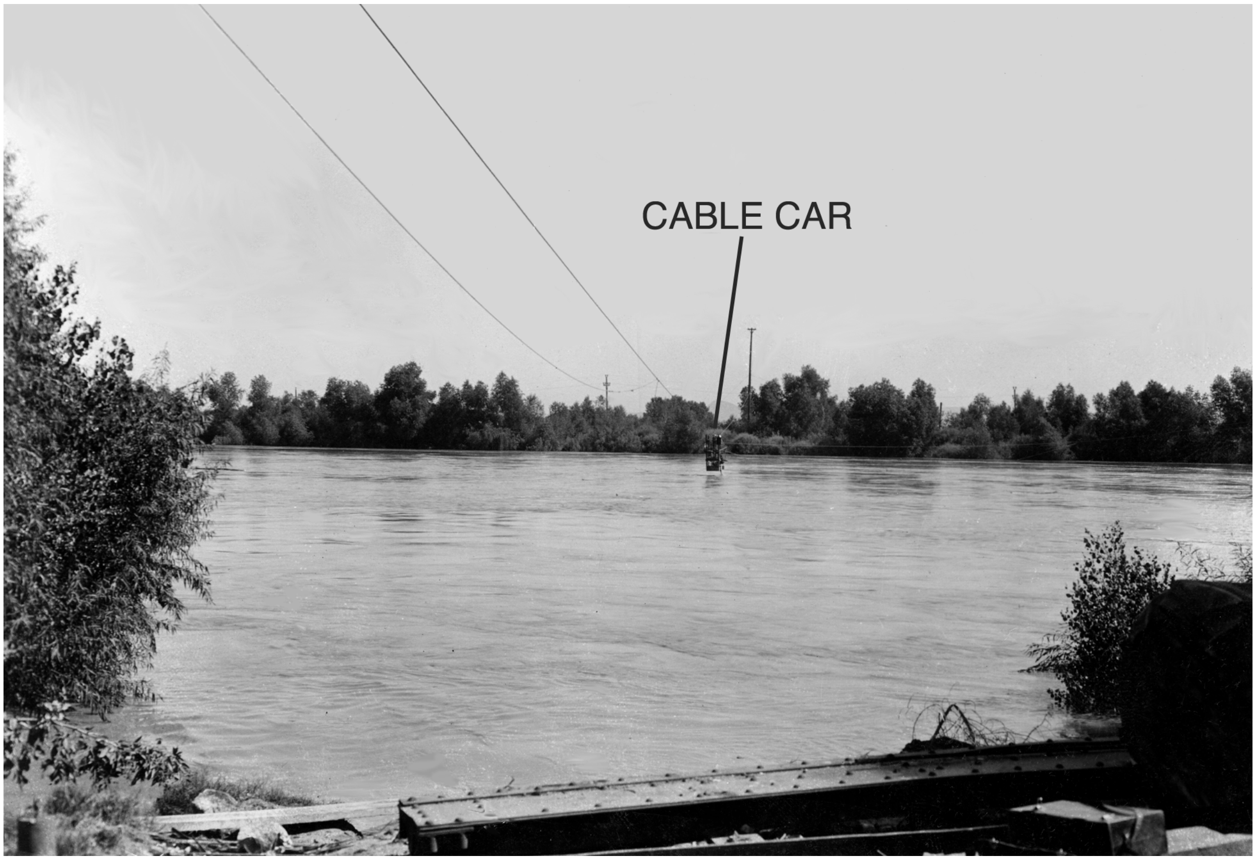

Figure 10. Discharge measurement being made by the U.S. Reclamation Service (the former name of the Bureau of Reclamation) on the morning of June 27, 1921, at the Yuma gaging station, near the peak of the June 1921 flood. At the time of the photograph, measured discharge (based on the measured surface velocity and a coefficient of 0.9) was 182,000 cubic feet per second, and stage was 31 feet. Photo "Yuma 1094" taken by the U.S. Bureau of Reclamation. Source of this photograph: 1891–1937 Surface Water Records File, Colorado River at Yuma, Laguna Niguel Federal Records Center, Accession No. 57-78-0006, Box 2 of 2, Location No. MB053635.

The June 18 peak discharge of the 1921 flood at Lees Ferry can also be estimated on the basis of the records from upstream gaging stations. Based on an extrapolation of the stage-discharge rating curve above 40,000 ft^3/s, the June 16, 1921, peak discharge at the Colorado River near Fruita gaging station (fig. 1*A*) was estimated to be 81,100 ft^3/s (Grover and others, 1922). The June 17, 1921, peak discharge at the Green River at Green River gaging station (fig. 1*A*) was computed to be 65,500 ft^3/s (Grover and others, 1922). The stage-discharge rating curve for the Green River at this site was well defined by discharge measurements up to 70,000 ft^3/s (Grover and others, 1922), so 65,500 ft^3/s was probably an accurate value.

Although no gaging stations were operating on the mainstem of the San Juan River during 1921, gaging stations on two of the major tributaries, the Animas and Florida Rivers, were used to estimate the likely discharge contribution of the San Juan River to the June 18, 1921, peak discharge at Lees Ferry (fig. 1*A*). The first decade of overlap between the Animas and Florida River gaging stations with the near Bluff gaging station, the most downstream gaging station on the San Juan River, was 1928–37. During May through June in this period, the combined daily mean discharge of the Animas and the Florida Rivers accounted for about 40 percent of the next day's discharge of the San Juan River at the near Bluff gaging station (fig. 11); thus, the daily mean discharge of the San Juan River at the near Bluff gaging station during May 1921 was estimated by multiplying the combined previous day's discharge of the Animas and Florida Rivers by a factor of 2.5. On June 16, 1921, the combined daily mean discharge of the Animas and Florida Rivers was about 8,000 ft^3/s. Thus, it is likely that the San Juan River contributed about 20,000 ft^3/s to the June 18, 1921, peak discharge at Lees Ferry.

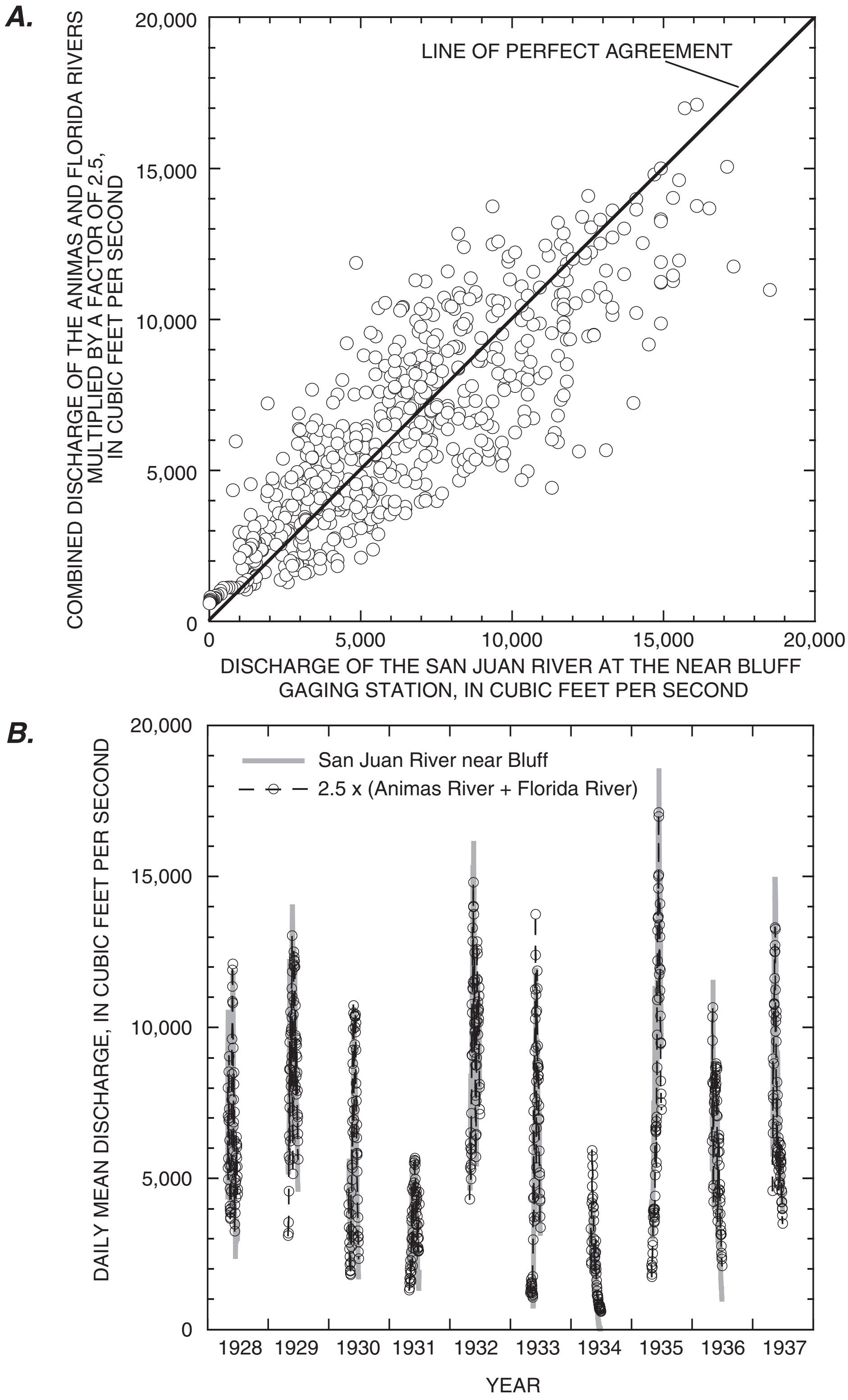

Figure 11. Comparison of the May through June daily mean discharge of the San Juan River with the combined previous day's discharge of the Animas and Florida Rivers during water years 1928–37. Daily mean discharge data obtained electronically from U.S. Geological Survey (accessed November 22, 2000). (*A*) 2.5 times the combined previous day's discharge of the Animas and Florida Rivers in relation to the daily mean discharge of the San Juan River at the near Bluff gaging station. (*B*) Daily mean discharge of the San Juan River at the near Bluff gaging station compared to 2.5 times the previous day's combined discharge of the Animas and Florida Rivers during May through June of each water year.

Therefore, the combined discharge of the upper Colorado, Green, and San Juan Rivers contributing to the peak discharge of the June 1921 flood at Lees Ferry was approximately 167,000 ft^3/s.

Revised Estimate of the Peak Discharge of the 1921 Flood at Lees Ferry

Because the peak discharge of the June 1921 flood had to be the same throughout the Lees Ferry reach, extrapolations of the stage-discharge rating curves at the Lees Ferry Gage and the three staff gages in the 1-mile-long reach upstream were used to establish constraints on the peak discharge of this flood (fig. 12). A strong reversal in curvature is evident in the stage-discharge rating curves defined by the data from the Lees Ferry, Number 4, and Cable Gages, and a mild reversal in curvature is evident in the stage-discharge rating curve defined by the data from the Number 1 Gage. At stages in excess of those at which the reversal in curvature occurs at these four gages, analyses of the goodness of fit of linear and power-law regressions indicate that the high-stage parts of the stage-discharge rating curves at these gages are best approximated by either a linear or a power-law relation, in which discharge is proportional to stage raised to a power of less than one (fig. 12).

The reversals in curvature of the stage-discharge data at the Lees Ferry Gage for the entire pre-dam period of 1921–62 and for only water-years 1921–22 both occur at a stage of 15 ft. Linear regressions fit to the 1921–62 and 1921–22 data above this stage are virtually identical (fig. 12*A*), and have R^2 values of 0.929 and 0.932, respectively. Similarly, power-law regressions fit to the 1921–62 and 1921–22 data above this stage are also virtually identical (fig. 12*A*), and have R^2 values of 0.932 and 0.974, respectively. The similarity of the regressions fit to the 1921–62 and the 1921–22 data indicates that the upper end of the stage-discharge rating curve at the Lees Ferry Gage was fairly stable over time.

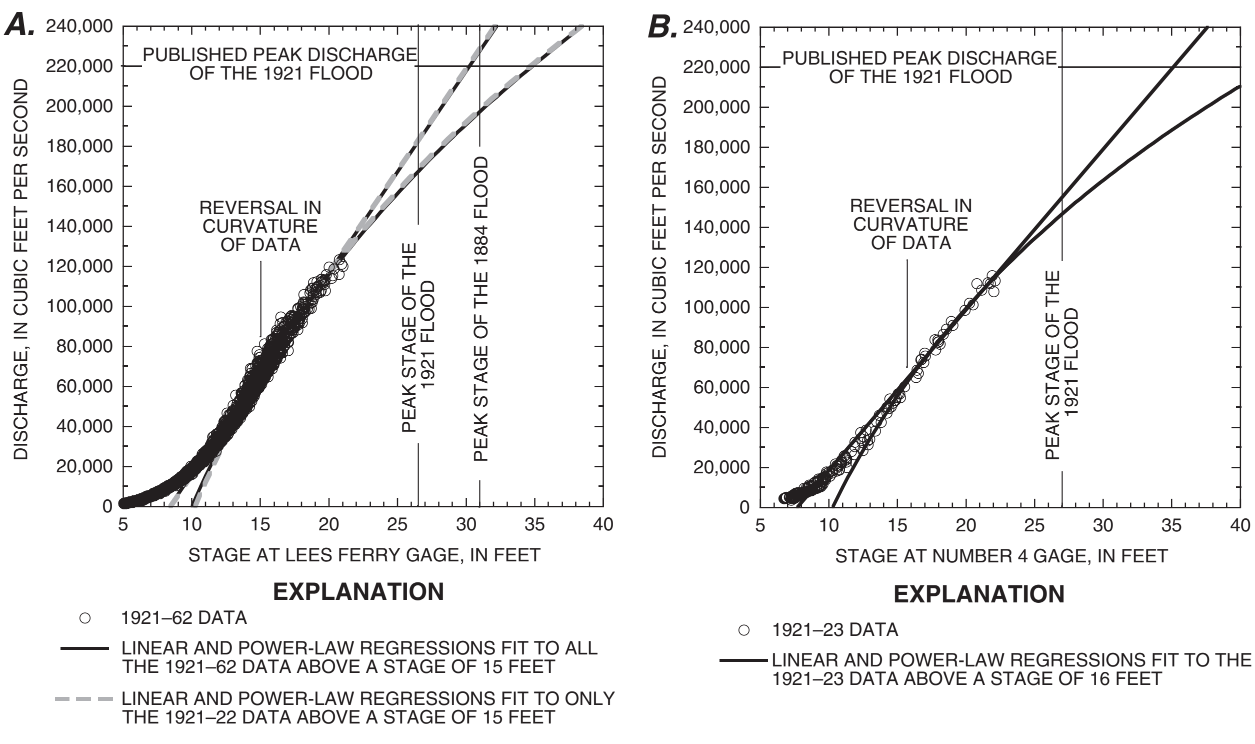

Figure 12. Linear and power-law extrapolations of the stage-discharge rating curves at the Lees Ferry, Number 4, Cable, and Number 1 Gages. (*A*) Rating curve at the Lees Ferry Gage defined by the 4,114 non-ice-affected discharge measurements made during water years 1921–62. Stage is relative to the Dugway Gage and Lees Ferry Gage datum of September 21, 1921 (see Appendix B). Shown for comparison are the peak stages of the 1921 and 1884 floods and the published peak discharge of the 1921 flood. (*B*) Rating curve at the Number 4 Gage defined by the 209 discharge measurements made during water years 1921–23 that included stage observations at the Number 4 Gage. Stage is relative to the Number 4 Gage datum of September 29, 1921 (see Appendix B). Shown for comparison are the peak stage and published peak discharge of the 1921 flood. Stage is relative to the Number 1 Gage datum of September 26, 1921 (see Appendix B). Shown for comparison are the peak stage and published peak discharge of the 1921 flood.

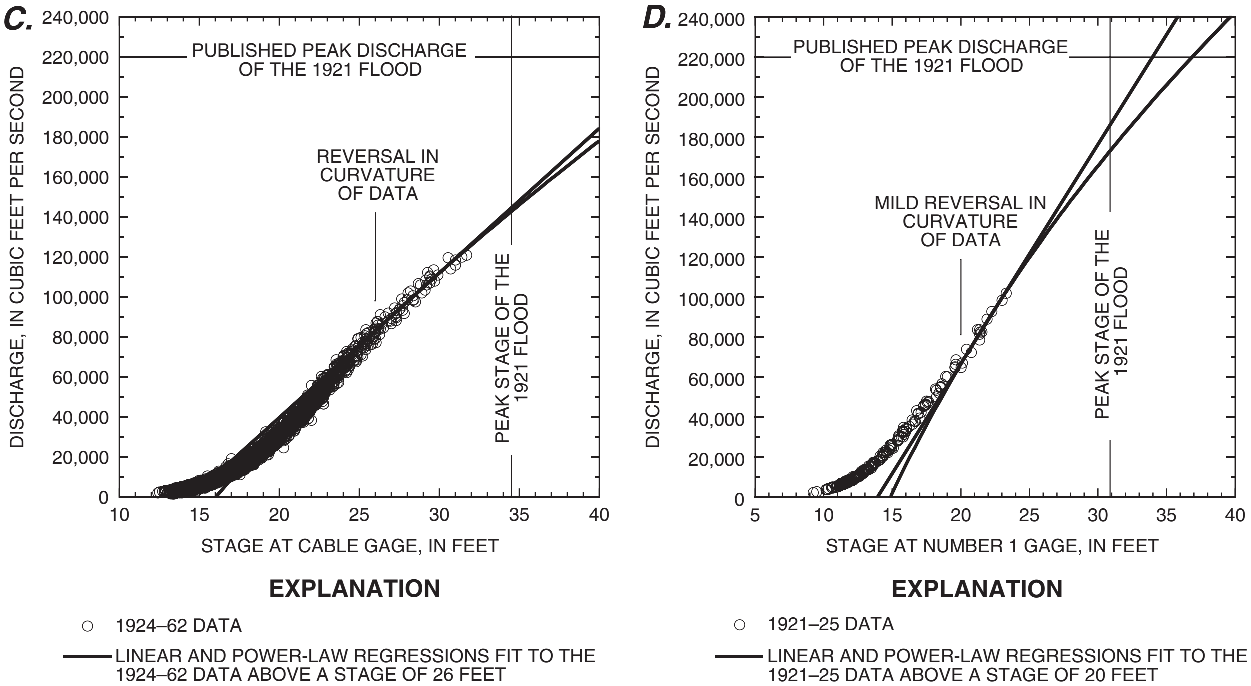

Figure 12—*Continued.* Linear and power-law extrapolations of the stage-discharge rating curves at the Lees Ferry, Number 4, Cable, and Number 1 Gages. (*C*) Rating curve at the Cable Gage defined by the 3,196 discharge measurements made during water years 1924–62 that included stage observations at the Cable Gage. Stage is relative to the revised Cable Gage datum of October 12, 1924 (see Appendix B). Shown for comparison are the peak stage and published peak discharge of the 1921 flood. (*D*) Rating curve at the Number 1 Gage defined by the 136 discharge measurements made during water years 1921–22 that included stage observations at the Number 1 Gage and by the 81 discharge measurements during water years 1924–25 on days with stage observations at the Number 1 Gage. Stage is relative to the Number 1 Gage datum of September 26, 1921 (see Appendix B). Shown for comparison are the peak stage and published peak discharge of the 1921 flood.

This result suggests that extrapolation of either the data from 1921–62 or only the data from 1921–22 should provide a reasonably good estimate of the peak discharge of the 1921 flood. The similar goodness-of-fit values for the linear and power-law regressions suggest that the upper end of the stage-discharge rating-curve at the Lees Ferry Gage can be approximated either as a line or as a power-law function. Linear extrapolations of both the 1921–62 and 1921–22 data suggest that the peak discharge of the 1921 flood was about 182,000 ft^3/s, and power-law extrapolations of both the 1921–62 and 1921–22 data suggest that the peak discharge of the 1921 flood was about 168,000 ft^3/s.

The reversal in curvature of the 1921–23 stage-discharge data at the Number 4 Gage occurs at a stage of 16 ft on this gage. The linear regression fit to the data above this stage has an R^2 value of 0.971; the power-law regression fit to the data above this stage has an R^2 value of 0.975. As at the Lees Ferry Gage, the similar goodness-of-fit values for the linear and power-law regressions suggest that the upper end of the stage-discharge rating-curve at the Number 4 Gage can be approximated either as a line or as a power-law function. Linear extrapolation of the data suggest that the peak discharge of the 1921 flood was about 156,000 ft^3/s, and power-law extrapolation of the data suggest that the peak discharge of the 1921 flood was about 147,000 ft^3/s (fig. 12*B*).

The reversal in curvature of the 1924–62 stage-discharge data at the Cable Gage occurs at a stage of 26 ft on this gage. Linear and power-law regressions fit to the data above this stage both have R^2 values of 0.971. The identical goodness-of-fit values for the linear and power-law regressions suggest that the upper end of the stage-discharge rating-curve at the Cable Gage can be approximated either as a line or as a power-law function. Linear extrapolation of the data suggest that the peak discharge of the 1921 flood was about 145,000 ft^3/s, and power-law extrapolation of the data suggest that the peak discharge of the 1921 flood was about 143,000 ft^3/s (fig. 12*C*).

The mild reversal in curvature of the 1921–25 stage-discharge data at the Number 1 Gage occurs at a stage of 20 ft on this gage. The linear regression fit to the data above this stage has an R^2 value of 0.982; the power-law regression fit to the data above this stage has an R^2 value of 0.983. As at the other gages, the similar goodness-of-fit values for the linear and power-law regressions suggest that the upper end of the stage-discharge rating-curve at the Number 1 Gage can be approximated either as a line or as a power-law function. Linear extrapolation of the data suggest that the peak discharge of the 1921 flood was about 187,000 ft^3/s, and power-law extrapolation of the data suggest that the peak discharge of the 1921 flood was about 174,000 ft^3/s (fig. 12*D*).

Linear and power-law extrapolations of the stage-discharge rating curves at these four gages by means of best-fit regressions lead to an estimated peak discharge of the June 1921 flood that ranges between 143,000 and 187,000 ft^3/s. This discharge range is somewhat wider than the 163,000 to 188,000 ft^3/s range that was based on the data from the Grand Canyon gaging station and other upstream and downstream gaging stations described above, but the upper ends of the ranges are nearly equal. Based on all of the data from the Lees Ferry and other gaging stations, the best estimate of the peak discharge of the June 1921 flood at Lees Ferry is 170,000 ft^3/s, at two significant figures (fig. 13). Given the range in the estimates of the peak discharge at the Lees Ferry and other gaging stations, the uncertainty in this value is approximately 20,000 ft^3/s. Our estimate of 170,000± 20,000 ft^3/s is therefore indistinguishable from both the original USGS unpublished estimate of 174,000 ft^3/s and the original USGS published value of "about 190,000 ft^3/s." This estimate of 170,000±20,000 ft^3/s is incompatible, however, with the 1939 upward revision of 220,000 ft^3/s based on Gatewood and Hunter's 1938 study.

Estimate of the Peak Discharge of the 1884 Flood at Lees Ferry

Estimation of the peak discharge of the 1884 flood depends on accurate determination of maximum flood stage and appropriate extrapolation of stage-discharge rating curves to higher elevations. The original unpublished estimate of the peak discharge of this flood at Lees Ferry was between 210,000 and 250,000 ft^3/s (G.C. Stevens, unpublished U.S. Geological Survey memorandum, May 28, 1925), and this estimate was revised by Gatewood and Hunter in 1938 to 300,000 ft^3/s. They made this revision because they had revised the magnitude of the 1921 flood upward; this revision resulted in a change in the stage-discharge rating curve which, in turn, necessitated revision of the 1884 estimate. Reevaluation of stage-discharge data indicate that the probable range of the peak discharge of this flood was between 199,000 and 228,000 ft^3/s.

The Original U.S. Geological Survey Estimate of the Peak Discharge of the 1884 Flood

The original USGS estimate of the peak discharge of the July 1884 flood was based on extrapolation of the stage-discharge rating curve at the Lees Ferry Gage, and on extrapolation of crude stage-discharge relationships developed for the Colorado River at three sites downstream in Grand Canyon (G.C. Stevens, unpublished U.S. Geological Survey memorandum, May 28, 1925). These values ranged from 210,000 ft^3/s at River-mile 233.7 (fig. 1*A*) to 250,000 ft^3/s at Lees Ferry.

For example, Stevens calculated that the discharge of the July 1884 flood at River-mile 233.7 was approximately 210,000 ft^3/s, based on data collected on October 8, 1923, during the USGS Birdseye Expedition (Westwood, 1992). Stevens wrote:

> During the survey of the Colorado River in 1923, an exceptionally high flood mark consisting of a pile of old drift was noted at Mile 233.7. The following information has been furnished by Mr. Herman Stabler:
>
> High-water mark, date unknown - - - - - - - - 1298.4′
> High-water mark, Sept, 20–23, 1923 - - - - - - 1275.1′
> Water level, October 8, 1923
> (date of survey) - - - - - - - - - - - - - - - - 1244.9′
>
> The flow at the Bright Angel station [the Grand Canyon gaging station] a few days before October 8, 1923, was 13,000–14,000 second-feet [ft^3/s]. The flow during the September flood was 112,000 second-feet. [This flood largely originated in the Little Colorado River.] Using these two points and extending as a straight line to elevation 1298.4′ gives 190,000 second-feet. By a curved extension, from 210,000 to 220,000 may be obtained. Accept 210,000 second-feet for the present. If the crest of the September, 1923, flood at Mile 233.7 was lower in discharge than at Bright Angel [i.e., the Grand Canyon gaging station] the extension would give a lower figure for the high-water mark.

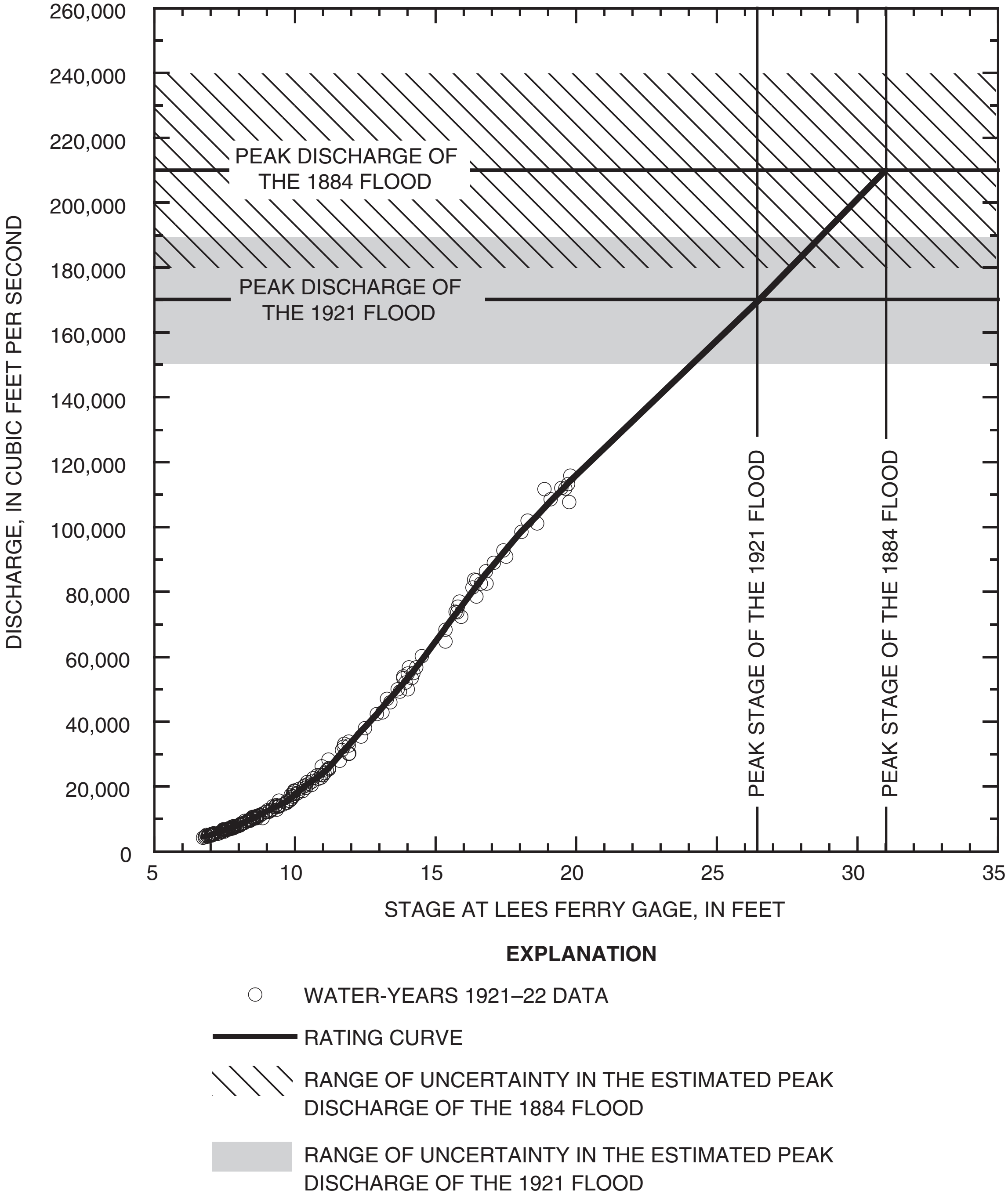

Figure 13. Stage-discharge rating curve used in this study for the period between May 8, 1921, and June 25, 1921. This rating curve consists of a smoothed curve fit to the discharge measurements from water years 1921 and 1922, and a linear extrapolation to the 170,000±20,000 cubic feet per second peak of the 1921 flood at a stage of 26.5 feet, and the 210,000±30,000 cubic feet per second peak of the 1884 flood at a stage of 31 feet.

This high driftwood deposit is located at River-mile 233.7 on the right bank at the lower end of 234-mile rapid (fig. 14*A*), and was revisited on November 9, 2002. An old rusty metal can was found placed adjacent to the top of the deposit (fig. 14*B*). This can was likely left by the Birdseye Expedition rodman; the presence of this can suggests strongly that this deposit was the one surveyed in 1923 by the Birdseye Expedition. As indicated in the 1925 Stevens memorandum, the great height of this deposit above the 112,000 ft^3/s water-surface elevation surveyed in 1923 suggests that this deposit was formed during a flood with a peak discharge much greater than that of the 170,000 ft^3/s 1921 flood. The presence of milled lumber (fig. 14*C*) indicates that this deposit was formed during a flood that occurred after white settlement of the Colorado River Basin upstream from Grand Canyon. Thus, it is likely that this driftwood deposit was formed during the 1884 flood.

Revised Estimate of the Peak Discharge of the 1884 Flood at Lees Ferry

Linear and power-law extrapolation of the stage-discharge rating curve at the Lees Ferry Gage suggests that the peak discharge of the July 1884 flood was between 199,000 and 228,000 ft^3/s (fig. 12*A*). This discharge range brackets the estimated 214,000 ft^3/s peak discharge for this flood at the Grand Canyon gaging station (fig. 9*D*), and overlaps with the range of 210,000 to 250,000 ft^3/s originally estimated by the USGS for the peak discharge of this flood at various sites between Lees Ferry and River-mile 233.7. Based on the estimates at Lees Ferry, the revised estimate at the Grand Canyon gaging station, and the previous estimate made at River-mile 233.7, the peak discharge of the July 1884 flood, at two significant figures, was approximately 210,000±30,000 ft^3/s at Lees Ferry and through Grand Canyon (fig. 13).

Implications for Previous Estimates of Paleoflood Discharges

O'Connor and others (1994) determined that during the last 4,500 years, 15 floods at Lees Ferry had peak discharges larger than 190,000 ft^3/s. Ten of these floods had peak discharges larger than 240,000 ft^3/s during the last 2,100–2,300 years, and one flood that occurred 1,200–1,600 years ago had a peak discharge exceeding 490,000 ft^3/s. On the basis of the data presented in this study, the discharges of these paleofloods are overestimated.

O'Connor and others (1994) conducted their paleoflood study in the reach between the Lower Staff Gage and Cathedral Wash, and the principal stratigraphic evidence was at "Axehandle Alcove," 2.2 miles downstream from the Lees Ferry Gage (figs. 1*B* and 4*A*). They speculated that a flood deposit at the top of their section, "G1," was deposited during the July 1884 flood. They estimated their paleoflood discharges by using a step-backwater model with the published 300,000 ft^3/s peak discharge of the July 1884 flood as a guide. In their calculations, they did not take into account the fact that the water-surface slopes in this reach decrease with increasing stage as backwatered flow conditions develop in the reach. In fact, water-surface slopes computed by O'Connor and others (1994) steepen with increasing stage. As shown in fig. 4*A*, it is more likely that "G1" was deposited near the 170,000 ft^3/s peak discharge of the June 1921 flood.

Because the Axehandle Alcove site is just downstream from the Lower Staff Gage, discharges can be directly assigned to these flood deposits on the basis of the data presented in this paper. On May 17, 1941, the discharge of the Colorado River was approximately 120,000 ft^3/s. The stage associated with this flood was observed to be 28.1 ft on the Lower Staff Gage, which corresponds to an elevation of 3,122.0 above sea level. Extrapolation of the 120,000 ft^3/s water-surface profile downstream indicates that the elevation of the May 17, 1941, water surface was approximately 3,120.1 ft above sea level at the Axehandle Alcove site. This elevation is roughly equivalent to the elevation of the base of O'Connor and others (1994) stratigraphic section. If the channel geometry in this reach in 1941 were similar to its geometry 3,000–4,500 years ago, the lowermost flood deposit preserved in Axehandle Alcove was deposited by a flood with a peak discharge just above 120,000 ft^3/s.

On the basis of fig. 4*A*, the elevation of the water surface during the peak of the 1921 flood at Axehandle Alcove was probably about 3,130.6 ft above sea level. This elevation is about 1.3 ft higher than the elevation of the deposit "G1" in fig. 3 in O'Connor and others (1994), and is similar to the highest elevation reported in the reach for "G1." Thus, it is likely that "G1" was not deposited during the 1884 flood, but rather during the 1921 flood.

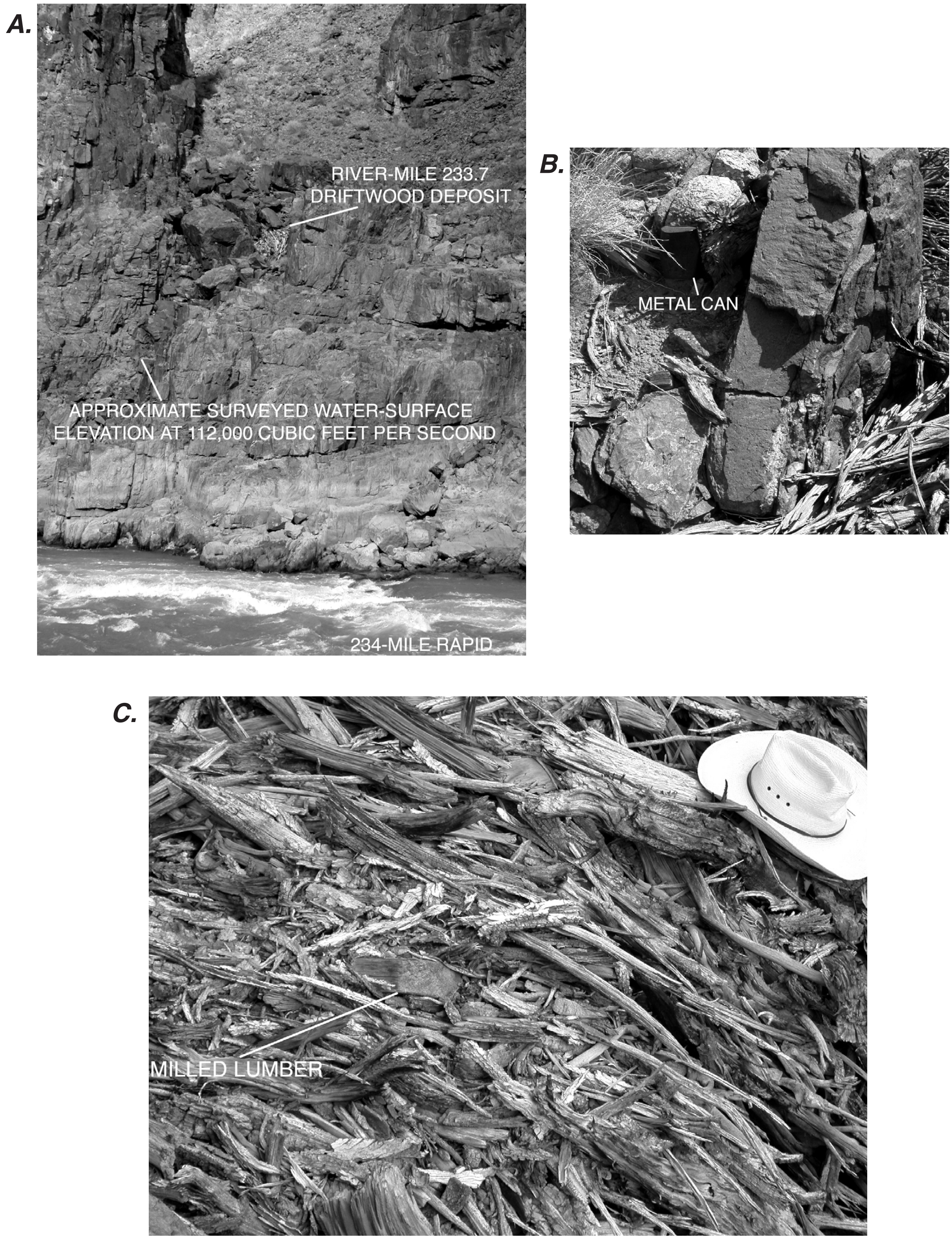

Figure 14. River-mile 233.7 driftwood deposit. Photographs taken on November 9, 2002, by D.J. Topping of the U.S. Geological Survey. (*A*) View from left to right bank of the high driftwood deposit at River-mile 233.7 surveyed by the Birdseye Expedition on October 8, 1923. (*B*) Old rusty metal can placed adjacent to the top of the deposit, likely by the Birdseye Expedition rodman. (*C*) Milled lumber within the driftwood deposit.

On the basis of fig. 4*A*, the water-surface elevation during the peak of the 1884 flood at Axehandle Alcove was probably about 3,136.5 ft above sea level, 6.6 ft higher than deposit "G1."

The highest deposit in Axehandle Alcove, the 1,200–1,600 year-old crevice deposit, is about 16.4 ft higher than deposit "G1," and about 9.8 ft higher than the likely peak stage of the 1884 flood. Given that the water surface was probably almost flat between the site of the Lees Ferry Gage and Axehandle Alcove (fig. 4*A*), the peak stage of this 1,200–1,600 year-old flood at the site of the Lees Ferry Gage would have been about 41 ft. Extrapolation of the stage-discharge rating curve in fig. 13, therefore, suggests that the peak discharge of the paleoflood that deposited the crevice deposit was about 300,000 ft^3/s. Therefore, based on these revised paleoflood discharges and the stratigraphy of O'Connor and others (1994), the deposits of 15 paleofloods during the last 4,500 years with peak discharges larger than 120,000 ft^3/s are preserved at Axehandle Alcove. Of these paleoflood deposits, 10 are preserved from floods during the last 2,100–2,300 years with peak discharges in excess of about 140,000–150,000 ft^3/s, and one deposit is preserved from a flood 1,200–1,600 years ago with a peak discharge in excess of about 300,000 ft^3/s.

COMPUTATION OF THE CONTINUOUS RECORD OF INSTANTANEOUS DISCHARGE AT LEES FERRY FOR WATER YEARS 1921–2000

All of the raw data collected by the USGS at Lees Ferry were retrieved from storage in the Federal Records Centers (Appendix A). After this retrieval, computation of the continuous record of instantaneous discharge was a multi-step process that took almost 4 years to complete.

Methods Used by the U.S. Geological Survey to Compute the Previously Published Daily Mean Discharge Record for Water Years 1921–86

The first step in this process was to review the methods used by the USGS to compute the previously published daily mean discharge record. During water years 1921–86, the USGS computed discharge at the Lees Ferry gaging station by the standard method of using a stage-discharge rating curve to convert measured stage to discharge (Rantz and others, 1982). Prior to January 19, 1923, stage was observed twice daily at the various staff gages in the reach between the Upper Cableway and the Lees Ferry Gage. After this date, stage was measured continuously by the float in the stilling well and was recorded on an analog strip-chart recorder. The chart recorder was replaced as the primary record of stage on February 2, 1967, when a digital recorder was installed in the gage. After this date, the analog chart record was used only as a back-up in case the digital recorder failed. From February 2, 1967, through February 28, 1974, stage was recorded digitally every 2 hours. Subsequently, stage was recorded digitally every 30 minutes to increase the accuracy of the published daily mean discharges. During each water year, between 5 and 200 discharge measurements were made (fig. 15), and used to construct the stage-discharge rating curves and to compute shift curves. Thirty-six different rating curves were used to compute the published record at Lees Ferry from June 13, 1921, through September 30, 1986 (table 2).

During most days in the pre-dam era, daily mean discharge was computed by applying a stage-discharge rating curve to a daily mean stage. During days when the discharge was variable, the day would be first subdivided into portions of comparable stage. Then, the mean stage for each of these portions would be converted into a mean

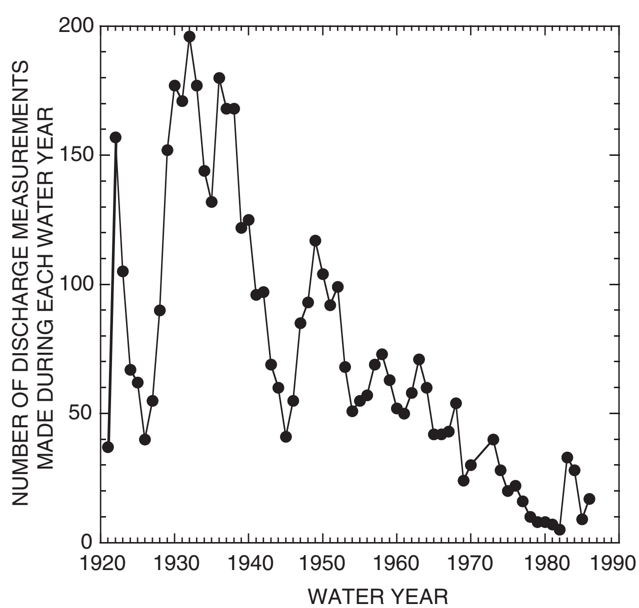

Figure 15. Number of discharge measurements made at Lees Ferry during each water year between 1921 and 1986.

Table 2. Stage-discharge rating curves used to construct the published record of daily mean discharge at the Lees Ferry gaging station during water years 1921 through 1986

Rating curve name	Dates used	Rating curve name	Dates used
[1]5-03-38	6-13-1921 through 7-10-1921,8-23-1921,	10-15-29	10-01-1928 through 5-29-1929
	5-21-1922 through 6-2-1922,	10-18-29	5-30-1929 through 9-30-1929
	5-01-1923 through 5-31-1923	10-15-32	3-20-1932 through 6-12-1933,
11-12-23	7-11-1921 through 8-22-1921,		6-21-1933 through 9-30-1934
	8-24-1921 through 9-30-1921	11-9-33	6-13-1933 through 6-20-1933
11-16-23	10-01-1921 through 5-20-1922,	3-6-36	10-01-1934 through 9-30-1936
	6-03-1922 through 7-10-1922	1-6-38	10-01-1936 through 2-28-1938
11-20-23	7-11-1922 through 1-18-1923	1-14-39	3-01-1938 through 3-20-1939
1-08-24	1-19-1923 through 4-30-1923,	9-5-39	3-21-1939 through 10-31-1939
	6-01-1923 through 9-30-1923	9-10-40	11-01-1939 through 1-20-1943
10-30-24	10-01-1923 through 9-30-1924	8-27-43	1-21-1943 through 4-24-1948,
2-04-26	10-01-1924 through 9-19-1925		1-01-1949 through 4-23-1949
2-15-26	9-20-1925 through 9-30-1925	7-23-48	4-25-1948 through 12-31-1948
12-06-26	10-01-1925 through 5-06-1926,	7-25-49	4-24-1949 through 4-30-1952,
	noon on 2-17-1927 through 4-20-1927		1-01-1953 through 12-31-1955
12-09-26	5-07-1926 through 5-30-1926	8-5-52	5-01-1952 through 12-31-1952
12-08-26	5-31-1926 through 12-16-1926	RT 1	1-01-1956 through 5-31-1963
2-24-26	12-17-1926 through noon on 2-17-1927	RT 2	6-01-1963 through 9-30-1968
12-14-27	4-21-1927 through 7-01-1927	RT 3	10-01-1968 through 9-30-1972
12-15-27	7-02-1927 through 9-30-1927,	RT 4	10-01-1972 through 4-30-1983
	5-15-1928 through 9-30-1928	RT 5	5-01-1983 through 10-18-1984
12-10-28	10-01-1927 through 2-29-1928	RT 6	10-19-1984 through 9-30-1986
12-11-28	3-01-1928 through 5-14-1928		

[1]1938 revision by Gatewood and Hunter.

discharge, which would then be used to compute a daily mean discharge. After the closure of Glen Canyon Dam, when the discharge each day became highly variable due to hydroelectric-power generation, the discharge record for all days would be computed by this subdivision method.

Since May 7, 1926, shifts have been applied to the measured stage prior to computing the discharge with a rating curve (table 3). This standard USGS method is known as the "shifting-control" method (described on page 25 in Kennedy, 1984). Shift curves for each year were based on the smoothed disagreement between the measured discharge and the discharge predicted by the stage-discharge rating curve. For example, if, over a given period, the observed stages during discharge measurements were consistently 0.1 foot higher than the stages associated with those discharges on the rating curve, 0.1 foot would be subtracted from the measured stages for that period prior to computing discharge with the stage-discharge rating curve. Thus, use of the shifting-control method at Lees Ferry allowed the published discharges to agree more closely with the measured discharges.

Glen Canyon Dam has greatly reduced the annual range of water temperature in the river at Lees Ferry. Prior to closure of the dam, ice routinely made the computation of discharge difficult at Lees Ferry during the winter (figs. 16*A*–*B*). During extremely cold periods, the river would completely freeze over, the float would freeze in the well, and no stage record would be obtained. More typically, the river would freeze at night, and the stage would increase slowly. The ice would then begin to melt the next morning, and the stage would decrease quickly around noon (fig. 16*C*). Other types of ice effect at the

Table 3. Dates when the shifting-control method was used to construct the published record of daily mean discharge at the Lees Ferry gaging station during water years 1921 through 1986

Date
5-07-1926 through 5-8-1926
5-31-1926 through 6-16-1926
40-8-1928 through 4-22-1928
5-07-1928 through 5-10-1928
5-15-1928 through 6-12-1933
6-21-1933 through 10-12-1936
10-28-1936 through 11-14-1936
12-24-1936 through 7-18-1937
8-03-1937 through 9-30-1940
5-17-1941 through 5-19-1941
5-30-1941 through 9-30-1968
12-14-1968 through 9-30-1973
6-04-1983 through 6-27-1983
8-03-1983 through 10-18-1984
5-09-1986 through 9-30-1986

Lees Ferry Gage included: (1) the formation of large ice jams on the riffle at the Paria River gravel bar that would back up large quantities of water and cause rises in stage by a foot or more, until the ice jams failed, and (2) the complete freezing of the surface of the river, during which the float would be frozen in the stilling well. During periods when the Lees Ferry Gage was affected by ice, daily mean discharge was typically computed by subtracting the sum of the measured and estimated inflows of water between the Lees Ferry and the Grand Canyon gaging stations from the daily mean discharge computed at the Grand Canyon gaging station.

Between 1931 and 1945, the record at the Grand Canyon gaging station was routinely used to modify the discharge computed at Lees Ferry during periods of higher flow in the spring and summer (Dickinson, 1944). During higher flows, slightly more water was sometimes computed passing Lees Ferry than was computed passing the Grand Canyon gaging station. This artifact was largely due to instability in the Lees Ferry stage-discharge rating curve above the reversal in curvature at a stage of 15 ft. Beginning in water year 1931, the discharge record at the Grand Canyon gaging station (because of its more stable stage-discharge rating curve) was used to reduce the computed discharges at Lees Ferry in order to bring them into agreement with those computed at the Grand Canyon gaging station (fig. 17). Although this was done almost every year from 1931 through 1945, these reductions were the most extensive during water years 1934 and 1936. During water year 1934, the daily mean discharges computed at Lees Ferry were reduced by 1 percent from May 9 through May 28. During water year 1936, the daily mean discharges computed at the gage were reduced by 1 percent from May 20 through June 15, 2 percent from June 16 through June 20, 3 percent from June 21 through June 30, 2 percent from July 1 through July 4, and 1 percent from July 5 through July 25.

Prior to 1931, it was not the policy of the USGS to use the record at the Grand Canyon gaging station to modify the discharge record at Lees Ferry for periods longer than a few days, except during periods of ice at Lees Ferry. The one extended period prior to 1931 when the record at the Grand Canyon gaging station should have been used to modify the discharges at the Lees Ferry gaging station was water year 1929. Between March 6 and September 30, 1929, 2.7 percent more water was computed passing Lees Ferry than was computed passing the Grand Canyon gaging station (after corrections had been made for the tributary inflow of water between the two sites). In an unpublished USGS memorandum dated December 30, 1929, W.E. Dickinson computed that the discharges at the Lees Ferry gaging station were 2.6 percent too high from March 6 through March 21, 3.3 percent too high from April 2 through April 15, 3.4 percent too high from April 15 though May 2, 2.7 percent too high from May 2 through July 16, 3.5 percent too high from July 16 through August 26, 4.9 percent too high from August 26 through September 19, and 2.3 percent too high from September 19 through September 30 (Appendix C). Although the cause of the discharge errors at the Lees Ferry gaging station between March and September 1929 were never officially determined, there are three possible explanations. The Upper Cableway was replaced in March 1929, and this could have affected the discharge measurements. The current meters used at Lees Ferry were changed on February 15, and this change in current meters could also have affected the discharge measurements. Finally, in March 1929, the abandoned dugway road on the left side of the gage was filled with rocks (Appendix B, fig. B6). This fill prevented water from flowing around both sides of the gage house during high discharges and could have affected the stage measurements at the gage.

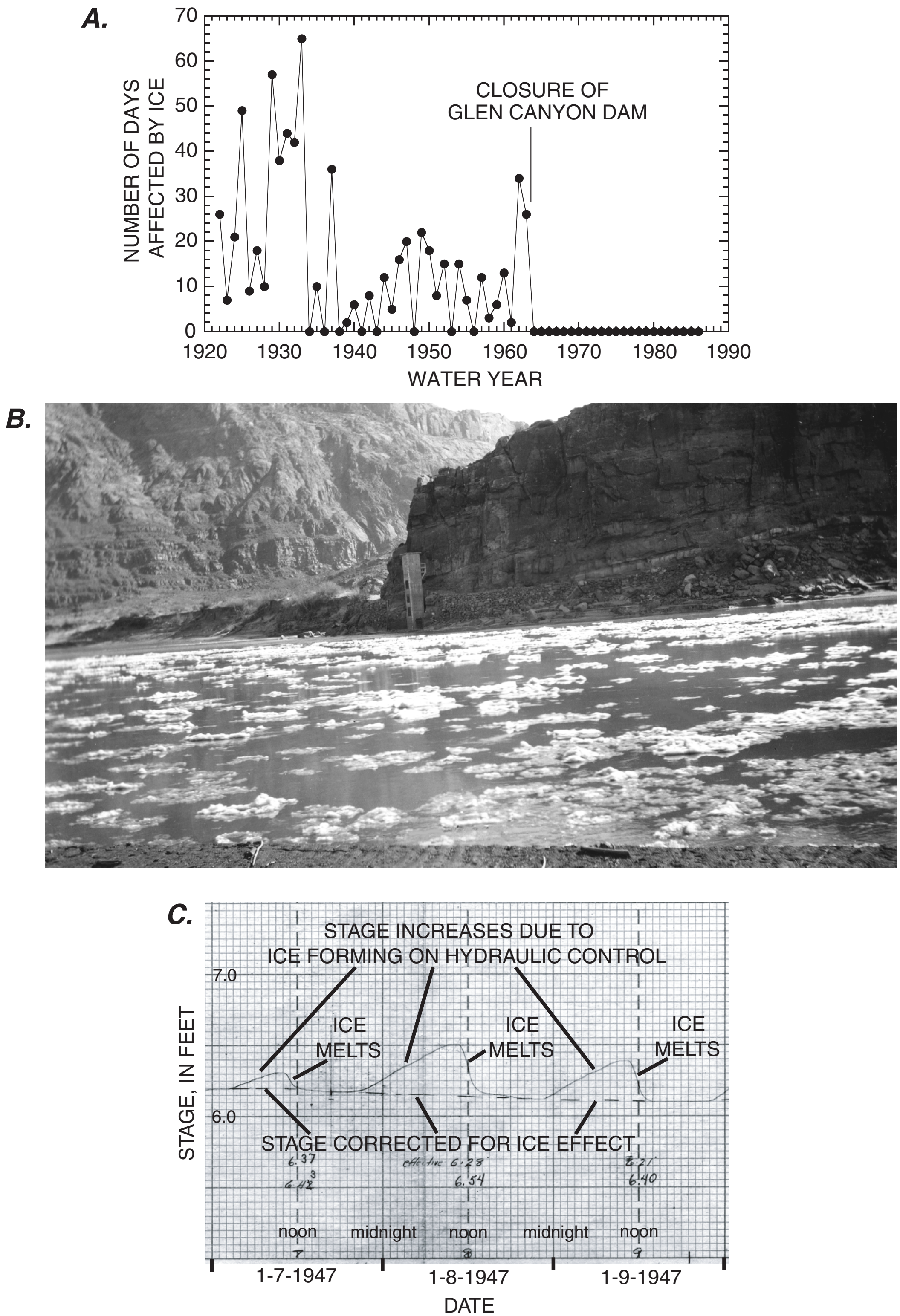

Figure 16. The pre-dam effects of ice at the Lees Ferry gaging station. (*A*) Number of days during each water year between 1922 and 1986 when the stage measured at the Lees Ferry Gage was affected by ice. (*B*) View of the ice breaking up in front of the Lees Ferry Gage from the right bank. Photograph taken by the U.S. Geological Survey, probably between December 17 and 23, 1927. (*C*) The most typical type of ice effect, as shown by the January 7–9, 1947, stage-recorder graph from the Lees Ferry Gage. Dashed line is the stage corrected for the effect of the ice (this is the stage that was digitized in this study).

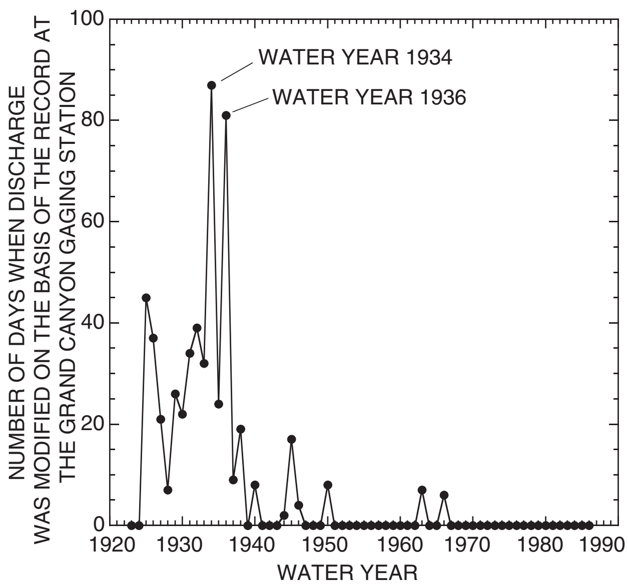

Figure 17. Number of days when the daily mean discharge record at Lees Ferry was modified on the basis of the discharge record at the Grand Canyon gaging station. This figure includes days when discharge was modified because of ice conditions and other reasons, such as during 1934 and 1936 when the computed discharge on many days in the spring and summer was reduced at Lees Ferry.

Methods Used in this Study to Compute the Continuous Record of Instantaneous Discharge for Water Years 1921–86

Following review of the methods used by the USGS to compute the daily mean discharge record, the first step in computing the continuous record of instantaneous discharge was to construct a continuous record of instantaneous stage from May 8, 1921, through September 30, 1986, relative to the datum of the Dugway and Lees Ferry Gages established on September 21, 1921. For the period prior to installation of the continuous stage recorder on January 19, 1923, this step involved first entering the stages measured at the three principal staff gages in the reach (i.e., the LaRue Gage, Number 1 Gage, and Dugway Gage) into computer files from the original USGS field notebooks (see Appendix B for additional background information on these staff gages). Each staff gage had a different period of record and datum; the LaRue Gage was installed on May 8, 1921, and was destroyed during the June 1921 flood; the Number 1 Gage was installed at the site of the LaRue Gage on June 24, 1921, but at a different datum; the Dugway Gage was installed on August 5, 1921, near the future location and at the same datum as the Lees Ferry Gage. Thus, for the period prior to the beginning of record at the Dugway Gage on August 14, 1921, the stages measured on the LaRue and Number 1 Gages were converted into equivalent stages on the Dugway Gage. This was accomplished by first converting the stages measured on the LaRue Gage into stages on the Number 1 Gage by a process described in Appendix D. Then, the stages measured on either the LaRue or Number 1 Gages prior to August 14, 1921, were converted into equivalent stages on the Dugway Gage on the basis of the relationship between the Number 1 and Dugway Gages developed by the USGS on January 25, 1922.

For the period after installation of the Lees Ferry Gage on January 19, 1923, with its continuous strip-chart stage recorder, construction of the continuous record of instantaneous stage involved digitizing all of the stage-recorder graphs between January 19, 1923, and September 30, 1986, such that all major breaks in slope of the continuous stage record were captured. These digitized stage records were then corrected for time and pen errors. During periods of ice effect, the stage-recorder graphs were digitized so that most, if not all, of the ice effect was removed from the stage record. For example, the period in fig. 16*C* was digitized by following the dashed pencil line that was originally drawn on the record by the USGS to correct for the ice-driven rises in stage. During the two periods when large floods on the Paria River caused backwatered flow conditions in the Colorado River at the Lees Ferry Gage (on October 5, 1925, and on August 2, 1929; Appendix B), the resulting increased stages were removed from the digitized stage record by the same method. To augment and check the stage records digitized from the stage-recorder graphs, the digital stage-recorder records from February 2, 1967, through September 30, 1986, were also entered into computer files.

The second step in this process was to convert the continuous record of instantaneous stage into a continuous record of instantaneous discharge by using the stage-discharge rating curves and shift curves originally used by the USGS to compute the published daily mean discharges. To accomplish this, all of the rating curves and shift curves were entered into computer files and then were used to compute instantaneous discharge for the period from May 8, 1921, through September 30, 1986. Finally, the discharges at Lees Ferry were reduced to match the discharges measured at the Grand Canyon gaging station (corrected for tributary inflow) during those non-ice-affected periods when this was originally done by the USGS (see previous section).

The methods used in this study deviated from those used by the USGS during the original computation of the daily mean discharge record in four respects. First, in this study, discharges at the Grand Canyon gaging station were not used to correct any discharges at Lees Ferry on days affected by ice. All ice corrections were made during the digitizing of the stage-recorder graphs. Second, the 1938 revised stage-discharge rating curve and shift curves of Gatewood and Hunter were used during the computation of discharge on the following days: June 26, 1921–September 10, 1921, April 22, 1922–July 17, 1922, April 17, 1923–July 31, 1923, April 8, 1924–July 16, 1924, April 1, 1925–July 21, 1925, and April 16, 1926–July 20, 1926. Unlike their method of estimating the peak discharges of the 1884 and 1921 floods, which was shown to be in error, Gatewood and Hunter's method of computing discharge during these six periods results in computed discharges that agree closely with those measured at the Upper Cableway. In fact, the discharges computed by Gatewood and Hunter's approach during these periods agree much more closely with the measured discharges than do the discharges computed by means of the original USGS rating curves without shifts. Third, in order to compute discharge from May 8, 1921, through June 25, 1921, a smoothed stage-discharge rating curve was fit to the discharge-measurement data from water years 1921 and 1922. This rating curve was extended linearly from 120,000 ft^3/s through the 170,000 ft^3/s discharge determined in this study as the best value for the peak discharge of the June 1921 flood (fig. 13). Because of the uncertainty associated with the datum of the LaRue Gage, the USGS never published daily mean discharges for the period prior to June 13, 1921. The discharges computed in this study from May 8 through June 12, 1921, however, are probably reasonable because they compare favorably with both (1) the combined discharges of the upper Colorado, Green, and San Juan Rivers, and (2) the discharge of the Colorado River at the Yuma gaging station (fig. 18). In fig. 18, the combined daily mean discharge of the upper Colorado, Green, and San Juan Rivers was computed by shifting the measured daily mean discharge record at the Colorado River near Fruita gaging station +2 days, shifting the measured daily mean discharge record at the Green River gaging station +1 day, and estimating the daily mean discharge of the San Juan River at the near Bluff gaging station (by the same approach as in fig. 11). The daily mean discharge record at the Yuma gaging station has been shifted -9 days to account for the approximate travel time of the flood peak between Lees Ferry and Yuma. Fourth, in order to maintain consistency in this data set, the discharges at Lees Ferry during March through September, 1929, were also reduced by the amounts stated in W.E. Dickinson's December 30, 1929, memorandum (Appendix C).

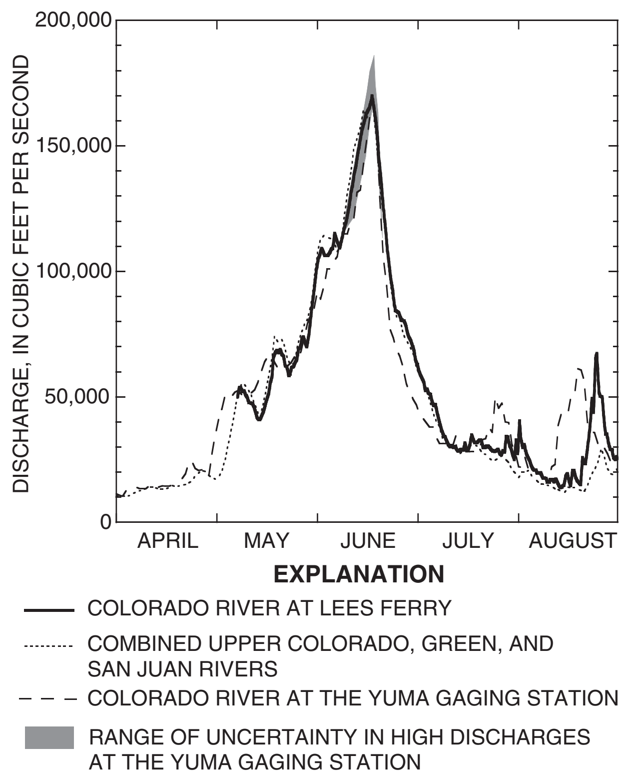

Figure 18. Comparison of the computed instantaneous discharge for April–August 1921 at Lees Ferry with (1) the combined daily mean discharge of the upper Colorado, Green, and San Juan Rivers, and (2) the daily mean discharge of the Colorado River at the Yuma gaging station. The gray shaded region covers the range of uncertainty in discharges in excess of about 110,000 cubic feet per second at the Yuma gaging station (described above in the text).

The final step in the construction of the 1921–86 continuous record of instantaneous discharge was quality control; daily mean discharges were computed from this continuous time series of instantaneous discharge and compared with the daily mean discharges previously published by the USGS. All periods during which the computed daily mean discharges deviated from the published daily mean discharges by 1 percent or more for more than several days were examined for errors. During this process, the major digitizing errors were found and corrected. In addition, errors in the published daily mean discharge data were also identified. The most common type of error found was a transcription or copying error, where either stage or discharge was incorrectly written or copied either on the graph or in the final records (fig. 19). The record for days with substantial ice effects could not always be corrected because the published daily mean discharges on these days were actually based on the record from the Grand Canyon gaging station. Therefore, some disagreement still exists between the instantaneous discharges in the continuous record and the published daily mean discharges on days of extreme ice effect. Appendix E contains a complete listing of the causes of all disagreements greater than or equal to 5 percent between the daily mean discharges computed from the continuous record of instantaneous discharge and the published daily mean discharges.

Average disagreement between the daily mean discharges computed from the continuous record of instantaneous discharge and the published daily mean discharges was found to be only +0.055 percent for the entire period from water year 1921 through water year 1986 (fig. 20). In fig. 20, percent disagreement is defined as

$$100\frac{(Q_{comp} - Q_{pub})}{Q_{pub}} \qquad (1)$$

where Q_{comp} = the daily mean discharge computed from the continuous record of instantaneous discharge and Q_{pub} = the daily mean discharge previously published by the USGS. All days with disagreements greater than 5 percent or less than -5 percent are either (1) days affected by ice, or (2) days in error in the published record. Disagreement increases slightly after the closure of Glen Canyon Dam because the increased variability in discharge within each day made it more difficult for the USGS to compute daily mean discharges prior to the availability of more advanced computers.

The Continuous Record of Instantaneous Discharge for Water Years 1921–2000

Following the computation and quality control of the continuous record of instantaneous discharge for water years 1921–86, these data were combined with 30- and 15-minute stage and discharge data collected after October 1, 1986, to form a continuous record of the instantaneous discharge of the Colorado River at Lees Ferry from May 8, 1921, through September 30, 2000 (fig. 21*A*). Also included in fig. 21*A* is the peak discharge of the 1884 flood, the largest flood between 1884 and 1921 at Lees Ferry. Stage and discharge of the Colorado River at Lees Ferry were recorded at discrete 30-minute intervals between October 1, 1986, and May 31, 1998, and have been recorded at discrete 15-minute intervals since June 1, 1998. These post-October 1, 1986, data were previously and are currently available from the Arizona District of the USGS. The resolution of the May 8, 1921, through January 18, 1923, part of the continuous record (the period before installation of the Lees Ferry Gage with its continuous stage recorder) is twice daily; the resolution of the January 19, 1923, through September 30, 1986, part of the continuous record is approximately 15–30 minutes. The resolution of the October 1, 1986, through May 31, 1998, part of the continuous record is 30 minutes; the resolution of the June 1, 1998, through September 30, 2000, part of the continuous record is 15 minutes. The entire record can be either requested from the USGS Grand Canyon Monitoring and Research Center, Flagstaff, Arizona, or obtained electronically at http://www.gcmrc.gov.

The daily range in the discharge of the Colorado River at Lees Ferry between May 8, 1921, and September 30, 2000, (fig. 21*B*) was computed from the data in fig. 21*A*. The largest daily range in discharge of 68,100 ft^3/s occurred on September 13, 1927, during the rising limb of the September 13, 1927, 125,000 ft^3/s flood. Most of the water in this flood originated within the San Juan River Basin.

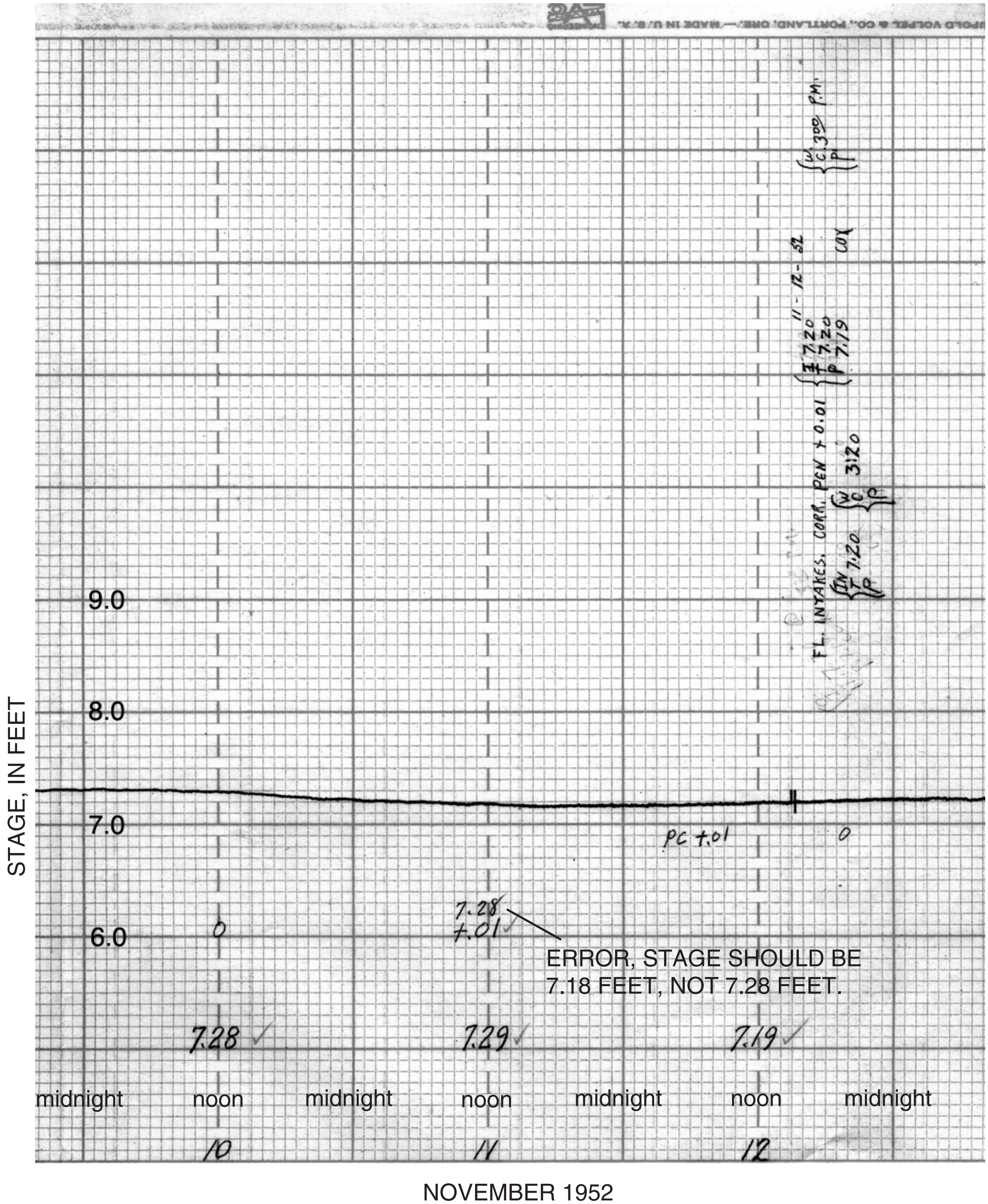

Figure 19. Example of the cause of an error in the published daily mean discharge record shown by the stage-recorder graph from November 10–12, 1952. The daily mean stage for November 11 was 7.19 feet, but was incorrectly written on the graph as 7.29 feet. This mistake resulted in an error of -6.0 percent in the published daily mean discharge for November 11, 1952.

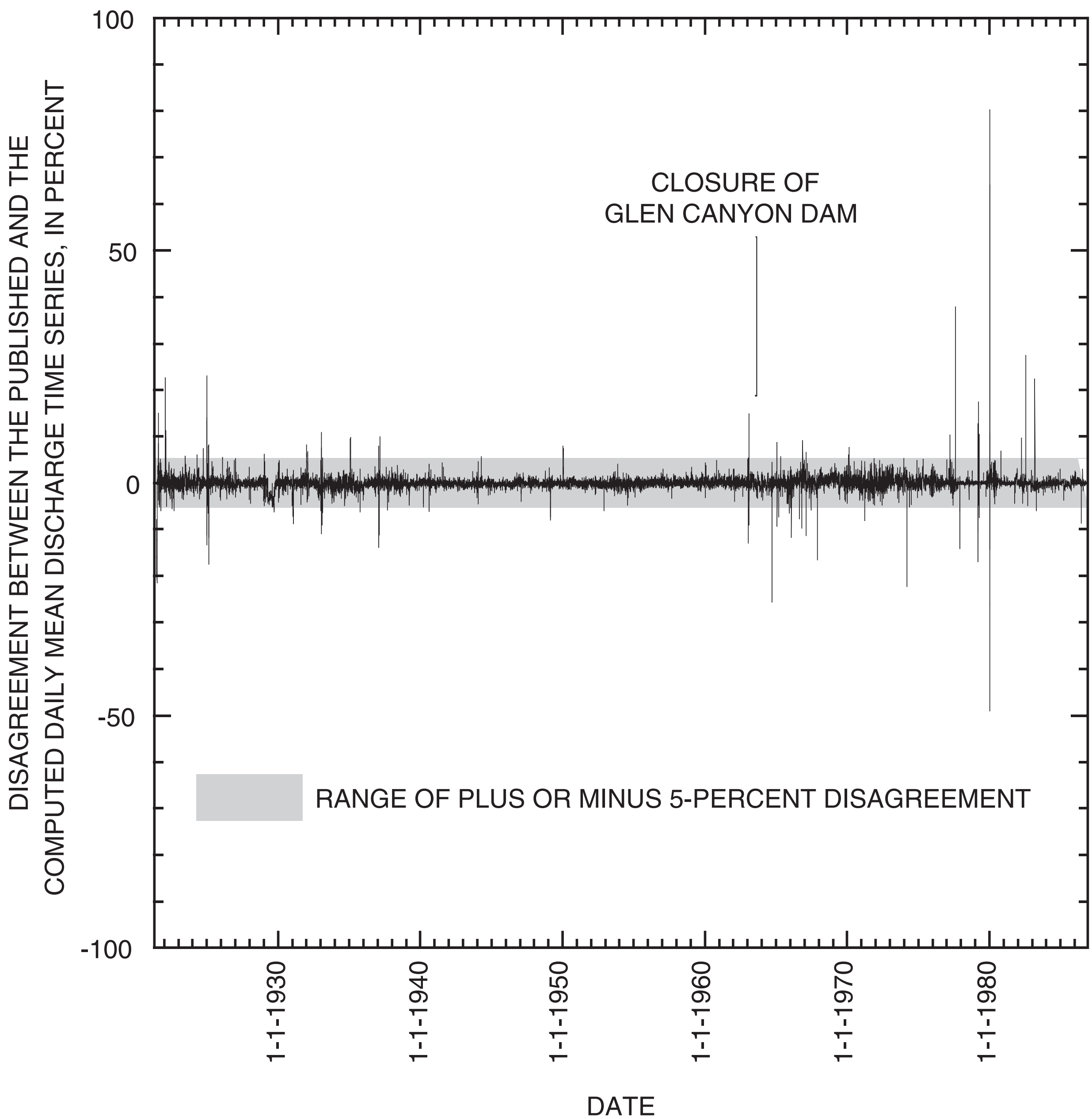

Figure 20. Percent disagreement between the daily mean discharges computed from the continuous record of instantaneous discharge from this study and the published daily mean discharges.

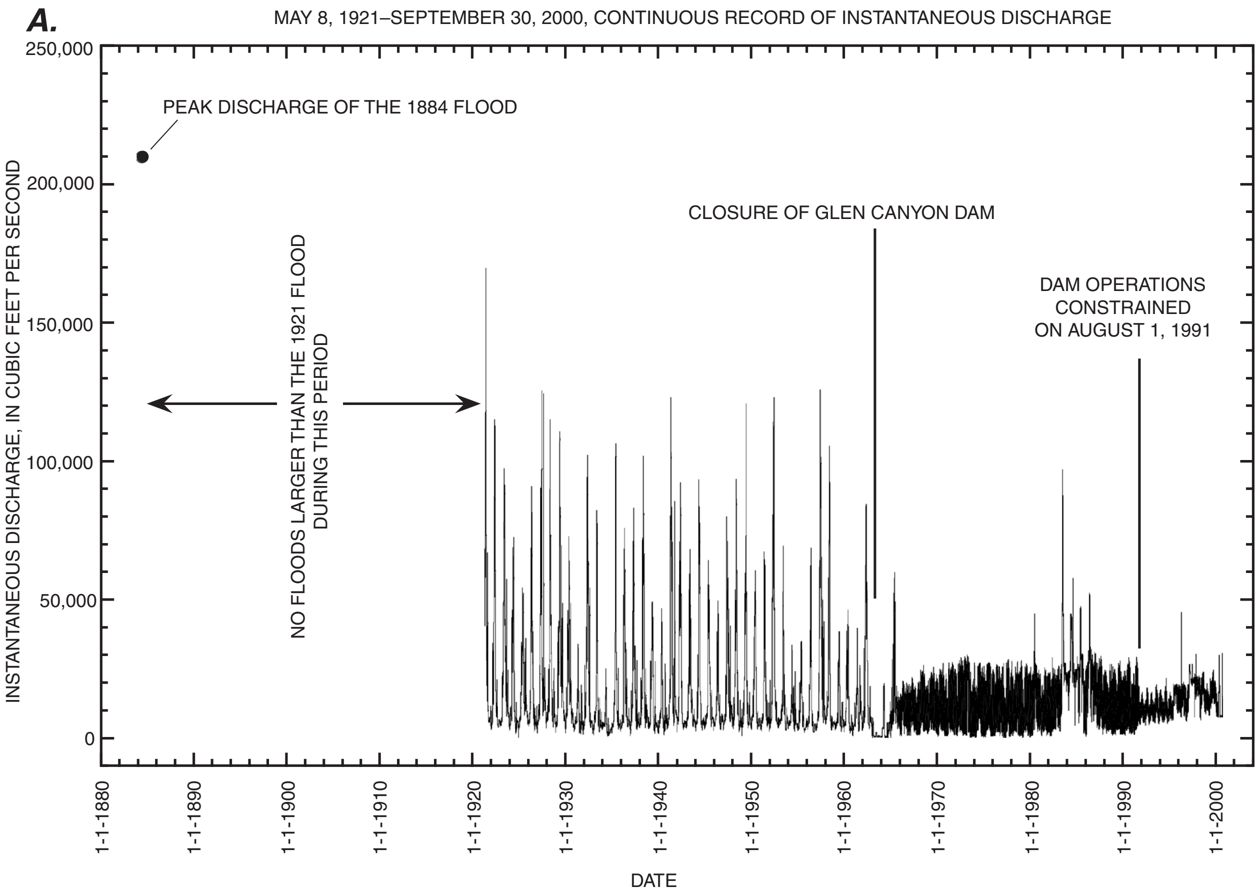

Figure 21. (*A*) The continuous record of instantaneous discharge of the Colorado River at Lees Ferry, Arizona, May 8, 1921–September 30, 2000.

ANALYSIS OF THE CONTINUOUS RECORD OF INSTANTANEOUS DISCHARGE

The final objectives of this study were to determine: (1) the pre-dam natural variability in the hydrology of the Upper Basin, (2) the effects of the operation of Glen Canyon Dam on the discharge of the Colorado River at Lees Ferry, and (3) the implications of the natural variability in hydrology and the effects of dam operations for sediment transport and storage in the reach downstream from Lees Ferry in Grand Canyon National Park. To accomplish these objectives, analyses of flow duration, sub-daily discharge variability, and flood frequency were conducted on the Lees Ferry instantaneous discharge data for May 8, 1921, through September 30, 2000, the available pre-gage historical flood data, and the 4,500-year paleoflood data of O’Connor and others (1994).

Flow Duration, Sub-Daily Discharge Variability, and Sediment Transport during the Pre-Dam Period

To evaluate the natural variability in the discharge of the Colorado River at Lees Ferry over both long and short time scales and the implications of this natural discharge variability for sediment transport downstream from Lees Ferry, flow-duration analyses and analyses of the sub-daily variability in discharge were conducted on the pre-dam part of the continuous record of instantaneous discharge. These analyses indicate that, prior to the closure of Glen Canyon Dam, the duration of flows varied substantially over multi-year and decadal time scales. These analyses also indicate that the discharge of the pre-dam river was fairly steady over sub-daily time scales, and that the daily range in discharge was the most extreme during the summer thunderstorm season.

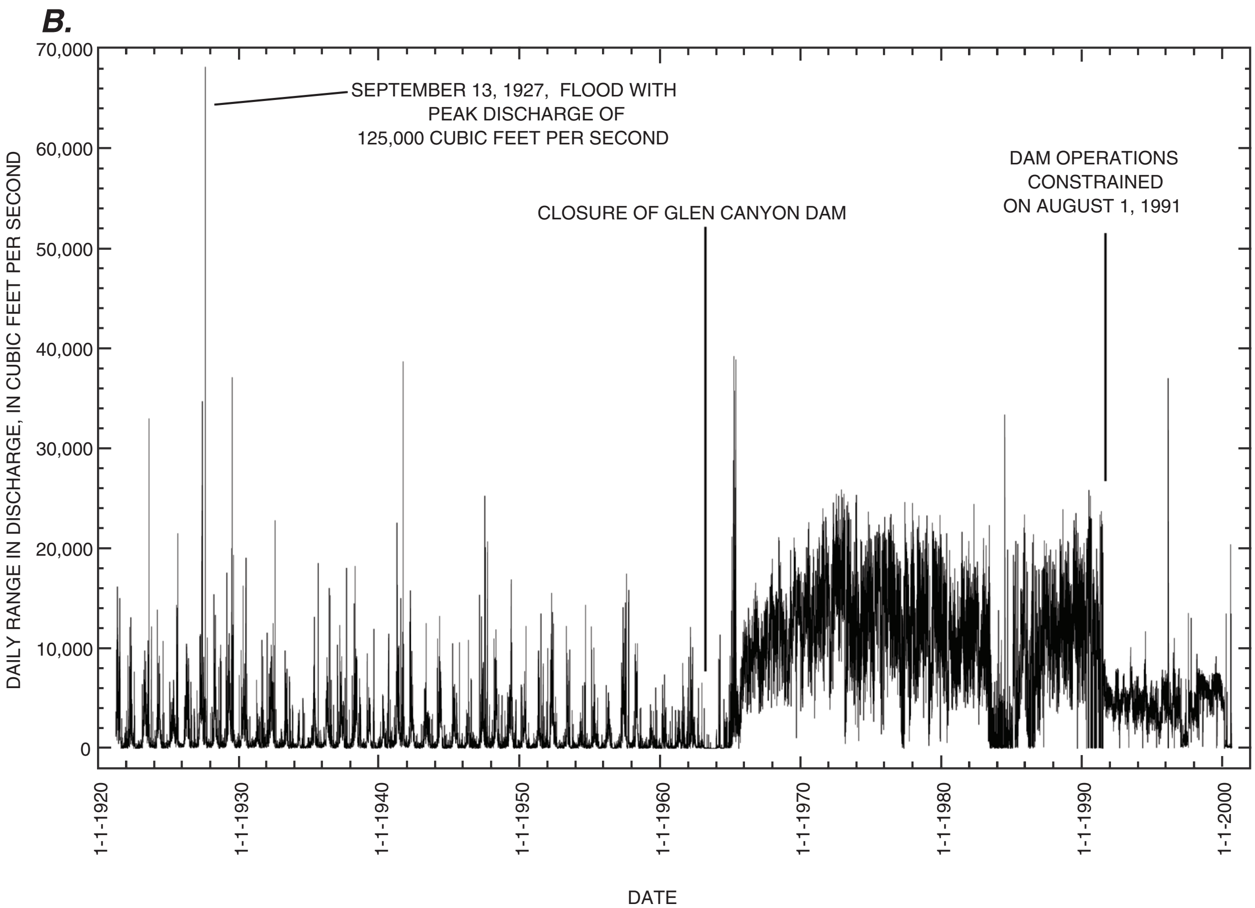

Figure 21—*Continued.* (*B*) The daily range in the discharge of the Colorado River at Lees Ferry between May 8, 1921, and September 30, 2000.

The median discharge of the Colorado River at Lees Ferry during the entire pre-dam period was 7,980 ft^3/s (fig. 22*A*) and discharge varied considerably during each of the four pre-dam decades (fig. 22*B*). The decades with the highest discharges were the 1920s and 1940s, with median discharges of 10,700 ft^3/s and 8,460 ft^3/s, respectively. The periods with the lowest discharges were the decade of the 1930s and the 12-year period between January 1, 1951, and March 12, 1963, with median discharges of 6,720 ft^3/s and 7,210 ft^3/s, respectively. The pre-dam month with the highest discharge was June, with a median discharge of 51,200 ft^3/s; the pre-dam month with the lowest discharge was January, with a median discharge of 5,140 ft^3/s (fig. 23 and Appendix F). Operation of Glen Canyon Dam during 1963–2000 increased the median discharge of the Colorado River at Lees Ferry to 12,600 ft^3/s (fig. 22*A*), a discharge 58 percent higher than the pre-dam median discharge and 18 percent higher than the median discharge during the wettest of the four pre-dam decades, the 1920s (fig. 22*B*).

The decadal variation in the discharge of the Colorado River at Lees Ferry has major implications for the accumulation and storage of sediment in the reach in Grand Canyon National Park between the Lees Ferry and Grand Canyon gaging stations (that is, the reach in Marble and upper Grand Canyons). Topping and others (2000) showed that, as a likely result of the difference in hydraulic geometry between Glen Canyon and Marble Canyon, sand-transport rates at the Lees Ferry gaging station exceeded those at the Grand Canyon gaging station when the discharge was lower than about 9,000 ft^3/s (Topping and others, 2000, fig. 4*B*). At discharges lower than about 7,000 ft^3/s, more than an order of magnitude more sand was transported past the Lees Ferry gaging station than past the Grand Canyon gaging station, and at

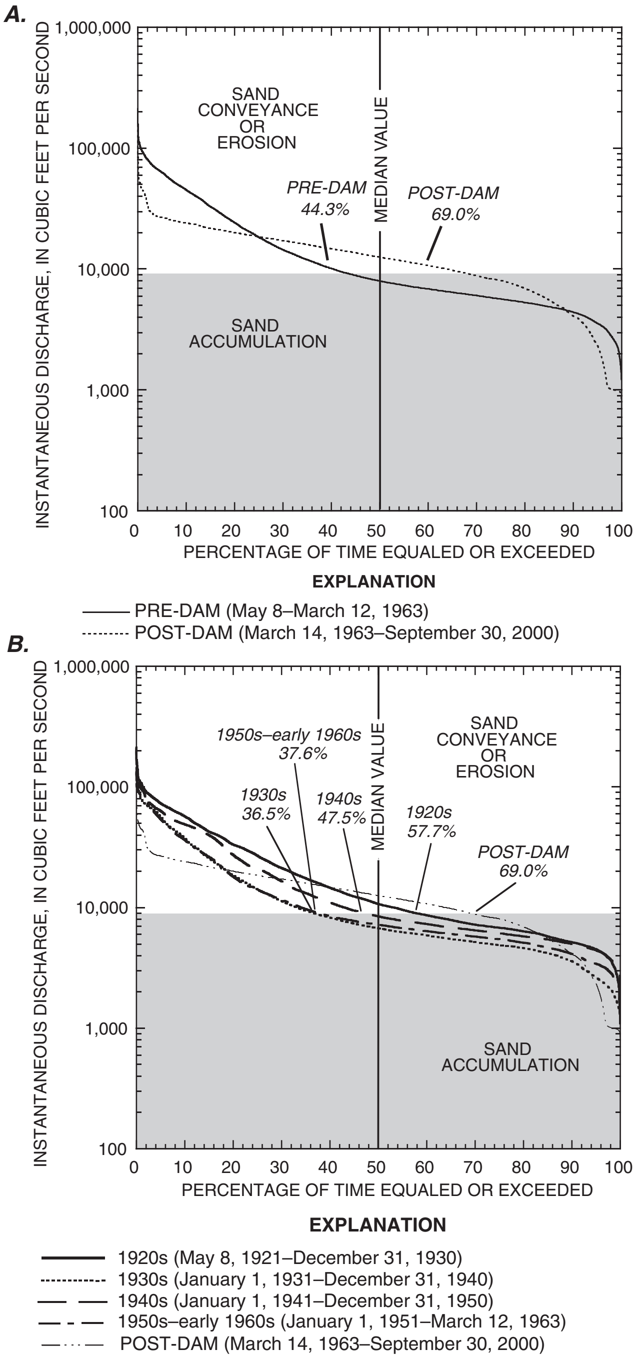

Figure 22. Flow-duration curves for the Colorado River at Lees Ferry. The gray shaded region shows the pre-dam discharge range under which sand accumulated in the reach between the Lees Ferry and Grand Canyon gaging stations, in Marble and upper Grand Canyons (Topping and others, 2000). The percentages of time when these discharges were exceeded during each period are indicated in italics. (*A*) Flow-duration curves for the pre- and post-dam periods. (*B*) Flow-duration curves for the four pre-dam decades and the entire post-dam period.

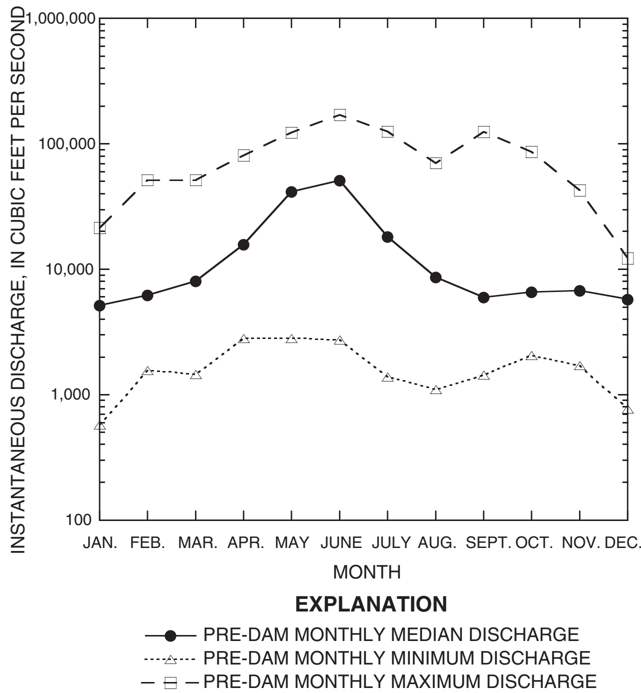

Figure 23. Pre-dam monthly median, minimum, and maximum discharges of the Colorado River at Lees Ferry.

discharges lower than about 5,000 ft^3/s, two orders of magnitude more sand was transported past the Lees Ferry gaging station than past the Grand Canyon gaging station. Therefore, when the discharge of the Colorado River was lower than about 9,000 ft^3/s, sand accumulated in the reach in Marble and upper Grand Canyons. At discharges higher than about 9,000 ft^3/s, however, sand-transport rates at the Grand Canyon gaging station generally equaled those at the Lees Ferry gaging station, and at discharges higher than about 16,000 ft^3/s, sand-transport rates at the Grand Canyon gaging station generally either equaled or exceeded those at the Lees Ferry gaging station. Thus, at discharges greater than about 9,000 ft^3/s, sand was either conveyed through or eroded from the reach in Marble and upper Grand Canyons.

Of the four pre-dam decades, the 1920s were dominated by discharges that likely conveyed or eroded sand, the 1930s and 1950s were dominated by discharges that likely led to the accumulation of sand, and the 1940s were virtually neutral with respect to either accumulation or erosion of sand in Marble and upper Grand Canyons (fig. 22*B*). Discharges under which sand likely accumulated downstream from Lees Ferry were exceeded

57.7 percent of the time during the 1920s, 36.5 percent of the time during the 1930s, 47.5 percent of the time during the 1940s, and 36.6 percent of the time during the 12-year period of the 1950s–early 1960s. During the entire pre-dam period, these discharges were exceeded only 44.3 percent of the time. Likewise, based on discharge alone, the pre-dam months of January through March and August through December would be characterized by the accumulation of sand, and April through July would be characterized by the erosion of sand (fig. 23 and Appendix F). Because of the greater tributary supply of sand during July (Topping and others, 2000, fig. 10*A*), however, sand also accumulated in Marble and upper Grand Canyons during this month (Topping and others, 2000, fig. 10*C*).

Discharge of the pre-dam river at Lees Ferry was fairly steady. Therefore, the difference between flow-duration curves computed from either the continuous record of instantaneous discharge from this study or the published record of daily mean discharge is minimal (fig. 24). The pre-dam median daily range in discharge was only 542 ft^3/s (fig. 25*A*). Over decadal time scales, the daily range in discharge of the pre-dam river was somewhat correlated with discharge (fig. 25*B*). The two wettest decades, the 1920s and 1940s, had the largest median daily ranges in discharge, 808 and 566 ft^3/s, respectively. The 1930s were the driest decade with the lowest discharges, but had the second smallest median daily range in discharge, 516 ft^3/s. The 12-year period from January 1, 1951, through March 12, 1963, was slightly wetter than the 1930s, but had the smallest median daily range in discharge, 416 ft^3/s. The month with the greatest median daily range in discharge was June during the snowmelt flood (fig. 26 and Appendix G), although the daily ranges in discharge were most extreme during the summer thunderstorm season of July through October (fig. 26). The pre-dam daily range in discharge was largest on September 13, 1927, when discharge increased by 68,100 ft^3/s at Lees Ferry to a peak discharge of 125,000 ft^3/s as the result of a flood that mostly originated within the San Juan River drainage basin (fig. 21*B*). Although such extreme examples exist, large daily ranges in discharge were rare during the pre-dam era, with only 1 percent of all days having a daily discharge range in excess of 10,000 ft^3/s (fig. 27). Thus, the median daily ranges in discharge during the months of July through October were actually lower than those during the snowmelt flood months of April through June (fig. 26).

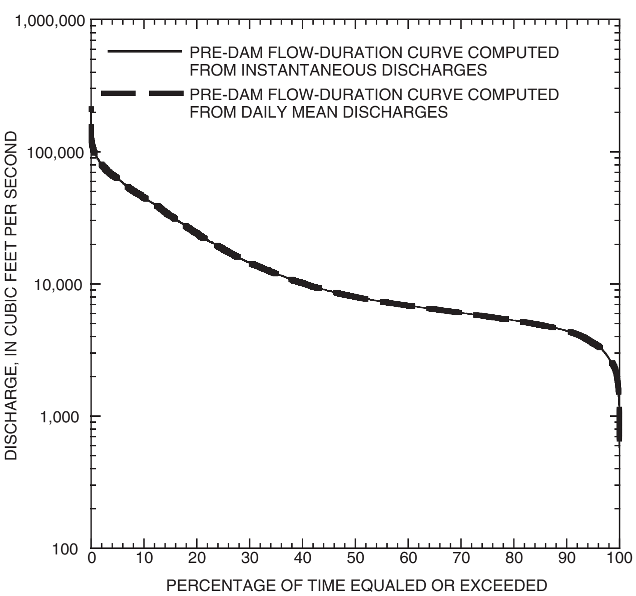

Figure 24. Comparison of the pre-dam flow-duration curve computed from instantaneous discharges with the pre-dam flow-duration curve computed from daily mean discharges.

Effects of the Operation of Glen Canyon Dam on Flow Duration, Sub-Daily Discharge Variability, and Sediment Transport

To determine the effects of the operation of Glen Canyon Dam on the hydrology of the Colorado River at Lees Ferry and on sediment transport in the Colorado River downstream from Lees Ferry, analyses of flow duration and sub-daily variability in discharge were also conducted on the post-dam part of the continuous record of instantaneous discharge. As shown by these analyses, not only has operation of the dam reduced the duration of flood flows, it has greatly reduced the duration of low flows shown by Topping and others (2000) to be important for the accumulation and storage of sand in the Colorado River between the Lees Ferry and Grand Canyon gaging stations (fig. 22*A*). Prior to the closure of Glen Canyon Dam in 1963, the natural discharge of the Colorado River at Lees Ferry was lower than 7,980 ft^3/s half of the time. By the 1990s, operation of the dam had increased the base flows in the river such that the discharge at Lees Ferry was lower than 8,000 ft^3/s only 7 percent of the time. In addition to radically changing the hydrology, operation of the dam for power generation has introduced daily fluctuations in discharge that are much larger and more common than those that generally occurred prior to closure of the dam (figs. 21*B* and 25*A*).

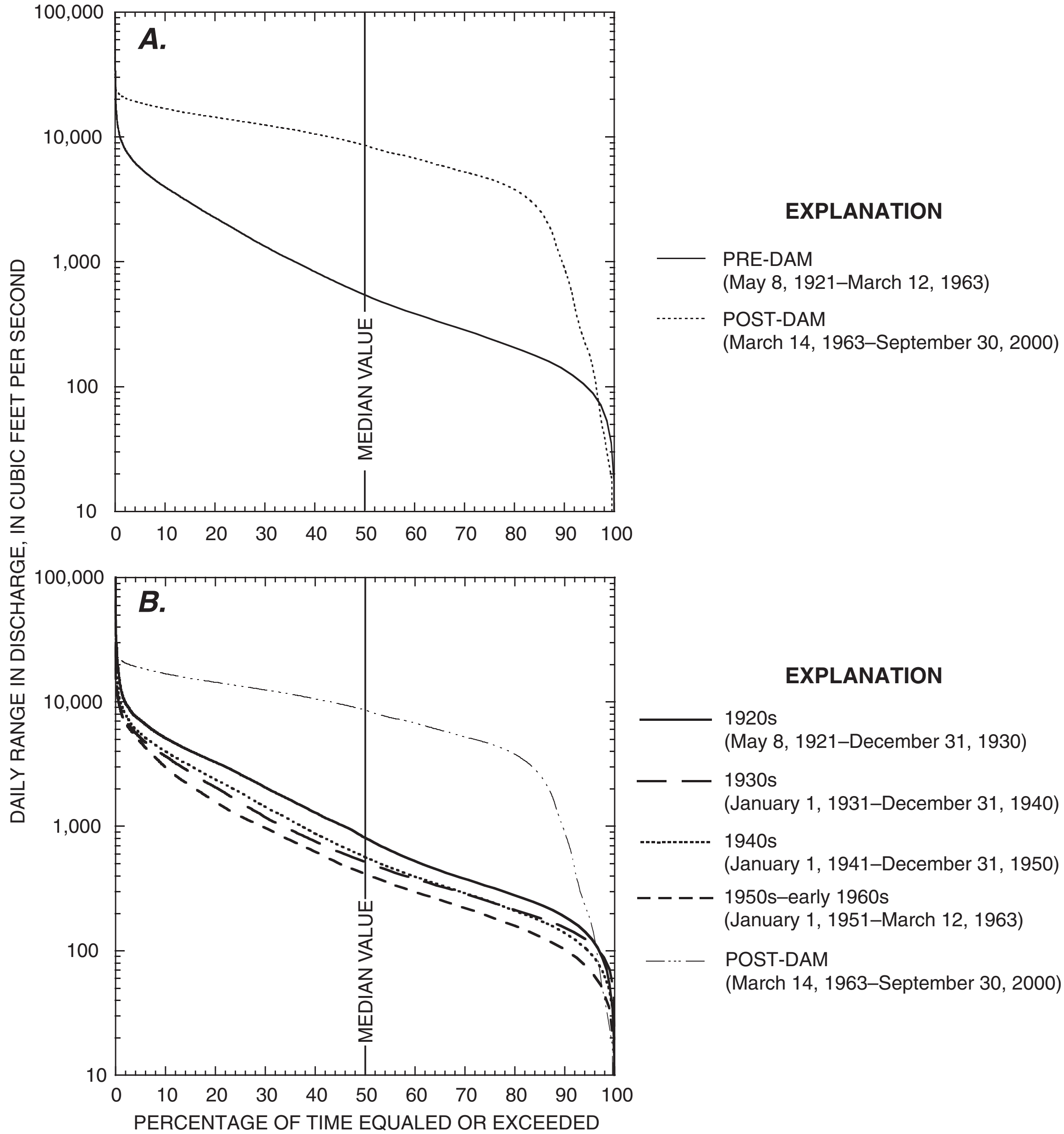

Figure 25. Exceedance curves of the daily range in the discharge of the Colorado River at Lees Ferry: (*A*) For the pre- and post-dam periods. (*B*) For the four pre-dam decades and the entire post-dam period.

Operation of Glen Canyon Dam has evolved over the four decades since closure of the dam on March 13, 1963 (fig. 21*A*). From March 1963 through the latter part of 1964, releases from Glen Canyon Dam were kept low (with discharges kept close to 1,000 ft^3/s for most of this period) to increase the storage of water in Lake Powell reservoir quickly. Then, from April through June 1965, a series of artificial floods was released from the dam, with six of these floods having peak discharges greater than 50,000 ft^3/s. Between these flood peaks, discharges were reduced to as little as 10,000 ft^3/s. These 1965 floods were designed to raise the elevation of Lake Mead reservoir and to scour the reach immediately below Glen Canyon Dam in order to increase the efficiency of the power plant at the

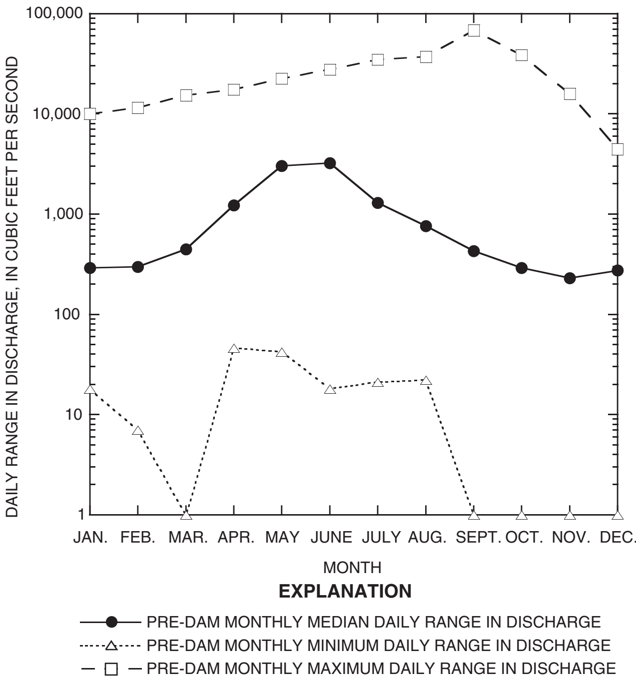

Figure 26. Pre-dam monthly median, minimum, and maximum daily ranges in the discharge of the Colorado River at Lees Ferry. Daily ranges in discharge plotted equal to 1 indicate that the minimum daily range in discharge during these months was less than the level of detection.

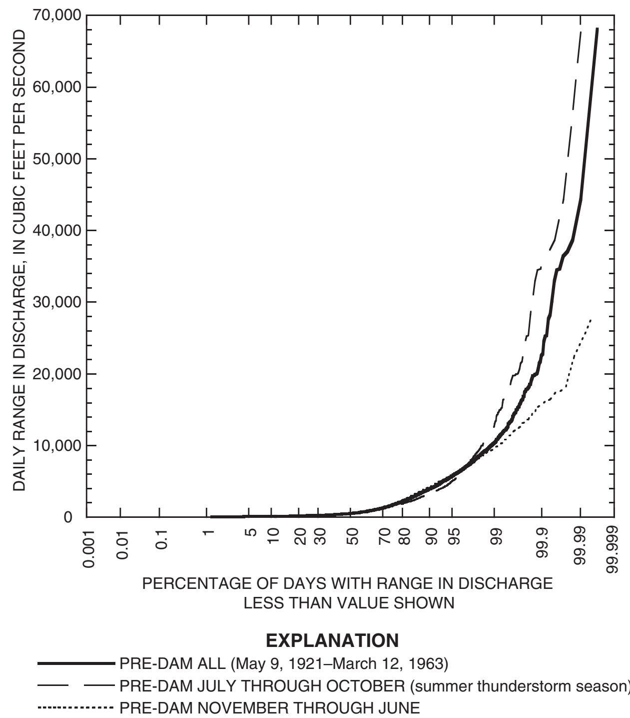

Figure 27. Probability graph of the pre-dam daily range in the discharge of the Colorado River at Lees Ferry. Daily ranges in discharge prior to the closure of Glen Canyon Dam were the most extreme during the summer thunderstorm season (July through October).

dam, and were referred to informally by Bureau of Reclamation engineers as "channel cleaning flows" (Grams and others, Utah State University, written commun., 2002). During these 3 months of high discharge, approximately 5.0 million tons of fine sediment (that is, sand and finer material) were scoured from Glen Canyon between the dam and Lees Ferry (computed on the basis of the USGS daily suspended-sediment data from the Lees Ferry gaging station; U.S. Geological Survey, accessed November 15, 2000), and approximately 17.6 million tons of fine sediment were scoured from the reach between the Lees Ferry and Grand Canyon gaging stations (Rubin and Topping, 2001). From July 1965 to June 6, 1980, the dam was operated in such a way as to fill Lake Powell reservoir gradually, to fulfill downstream water-delivery obligations, and to maximize the generation of hydroelectric power. As shown in this study, this "reservoir-filling period" was the period of the greatest daily fluctuations in discharge for power generation (fig. 28). From the initial filling of the reservoir on June 6, 1980, until August 1, 1991, the dam was operated as it was prior to 1980, with the additional safety constraint of drawing down the reservoir early in the year to provide enough volume for the snowmelt flood. This period included the largest post-dam flood, the 97,000 ft^3/s June 1983 flood (Martin, 1989). After this flood, dam operations were revised to release more water earlier in the spring to reduce the frequency of spills of this magnitude (National Research Council, 1996). Since August 1, 1991, dam releases have been constrained in an attempt to minimize the downstream effects of the dam on the Colorado River ecosystem in Glen Canyon National Recreation Area and Grand Canyon National Park (National Research Council, 1996). Under these constraints, (1) discharges no lower than 5,000 ft^3/s could be released, (2) discharges no lower than 8,000 ft^3/s could be released during the day, (3) discharges no greater than 20,000 ft^3/s could be released (this upper limit was increased to 25,000 ft^3/s under the 1996 Record of Decision signed by the Secretary of the Interior), and (4) additional limits were placed on the daily range in discharge and the rates at which discharge could change (ramping rates).

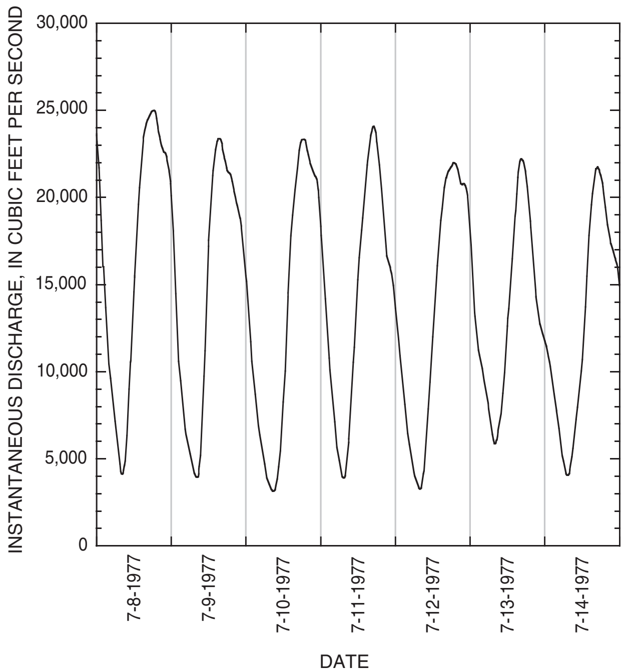

Figure 28. An example of large dam-induced daily fluctuations in the discharge of the Colorado River at Lees Ferry.

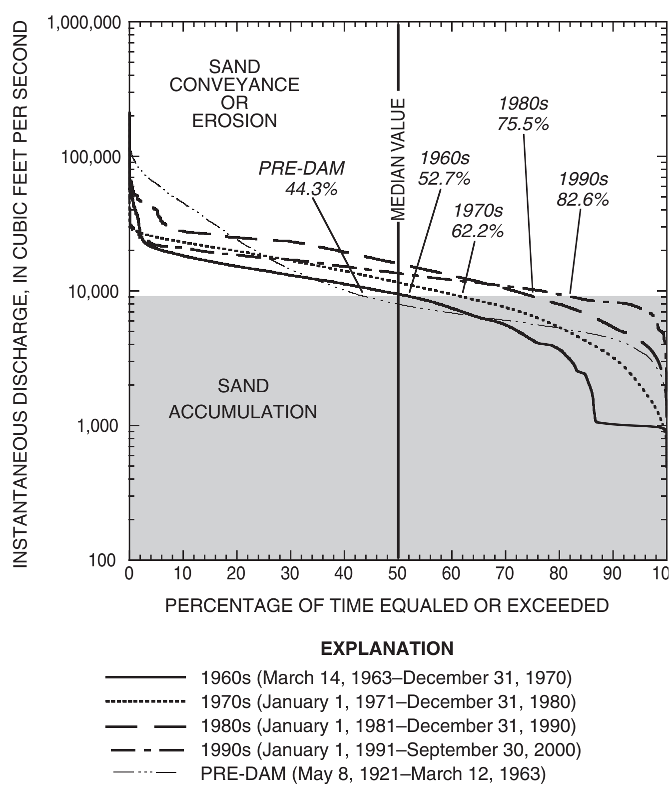

Figure 29. Flow-duration curves for the Colorado River at Lees Ferry from each of the four post-dam decades and the entire pre-dam period. The gray shaded region shows the pre-dam discharge range under which sand accumulated in the reach between the Lees Ferry and Grand Canyon gaging stations, in Marble and upper Grand Canyons. The percentages of time when these discharges were exceeded during each period are indicated in italics.

As a result of the changing operation of Glen Canyon Dam through time, the discharge characteristics of the Colorado River at Lees Ferry have changed substantially during the four decades since closure of the dam; the median discharge has generally increased, and the duration of lower discharges has progressively decreased (fig. 29). Thus, during each decade, as discharges less than 9,000 ft^3/s became less common, the discharge of the river became progressively more conducive to the conveyance of sand through or the erosion of sand from Marble and upper Grand Canyons. The median discharge for the entire post-dam period of March 14, 1963, through September 30, 2000, was 12,600 ft^3/s. During the initial reservoir-filling period of March 14, 1963, through December 31, 1970, the median discharge was 9,490 ft^3/s, and the discharge of the river was greater than 9,000 ft^3/s 52.7 percent of the time. During the 1970s, the median discharge was 11,600 ft^3/s, and the discharge of the river was greater than 9,000 ft^3/s 62.2 percent of the time. During the 1980s, the combination of the wet-weather conditions in the Upper Basin and the full reservoir resulted in the highest decadal median discharge, 15,900 ft^3/s. Discharge of the river during the 1980s was greater than 9,000 ft^3/s 75.5 percent of the time. Due to the constraints placed on dam operations in 1991, the 1990s were the post-dam decade with the most discharges conducive to the conveyance of sand through or the erosion of sand from Marble and upper Grand Canyons. Although the median discharge during the 1990s (13,500 ft^3/s) was less than that during the 1980s, the 1990s had the longest duration of discharges greater than 9,000 ft^3/s (82.6 percent of the time).

In addition to greatly reducing the duration of flood flows and progressively eliminating lower flows, operation of the dam has eliminated the seasonality from the annual hydrograph of the Colorado River (fig. 30). Prior to closure of the dam, the lowest discharge month was January, with a median discharge of 5,140 ft^3/s (fig. 30*A*) and a minimum discharge of 578 ft^3/s (fig. 30*B*), and the highest discharge month was June, with a median discharge of 51,200 ft^3/s (fig. 30*A*) and a maximum discharge of 170,000 ft^3/s (fig. 30*B*). During the post-dam period of record, the highest-discharge month was August, with a median discharge of 16,400 ft^3/s, and the lowest discharge month was October, with a median discharge of 10,200 ft^3/s (fig. 30*A*).

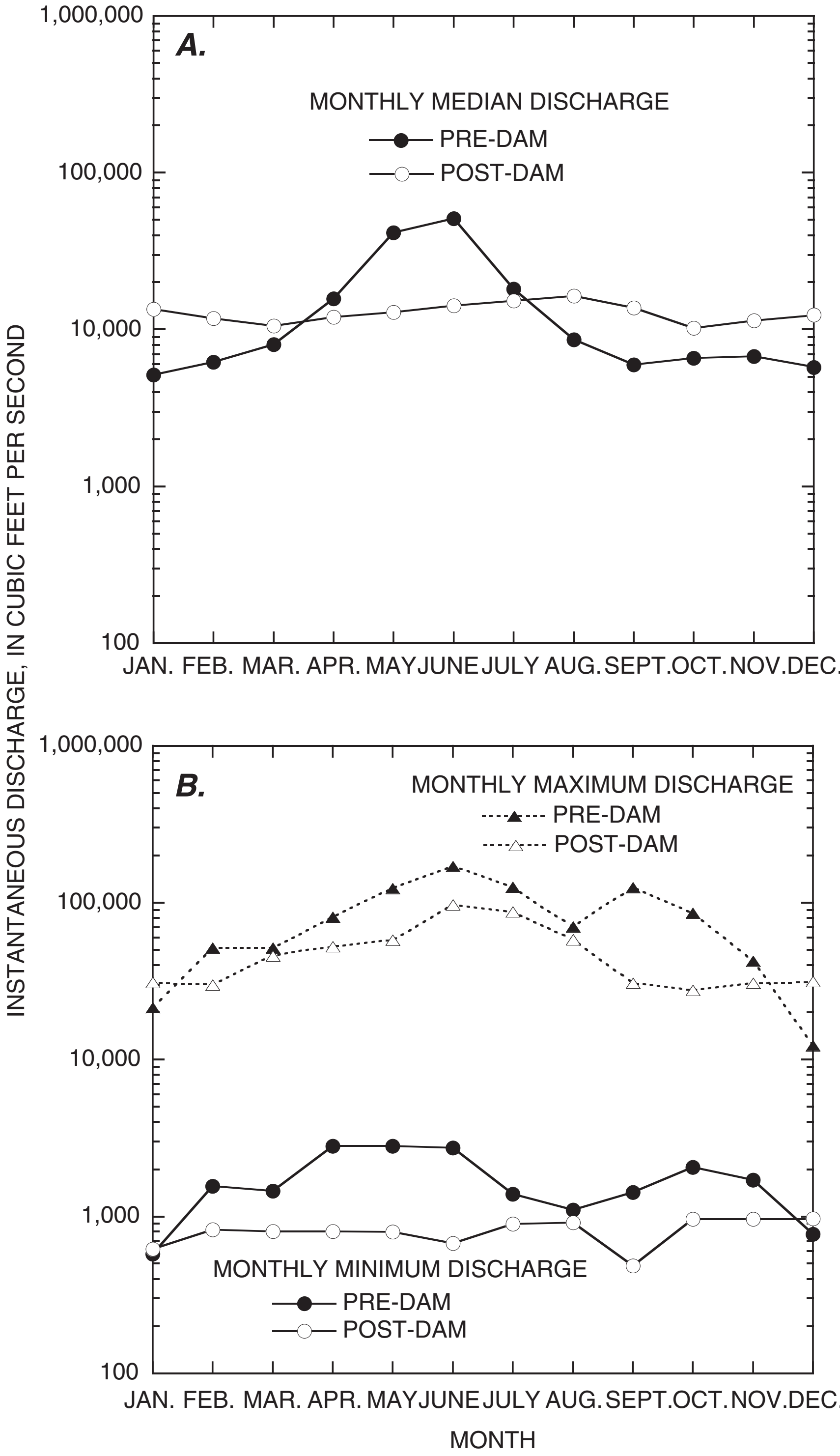

Figure 30. Effects of dam operations on: (*A*) Monthly median discharges of the Colorado River at Lees Ferry. (*B*) Monthly minimum and maximum discharges of the Colorado River at Lees Ferry. All of the post-dam monthly minimum discharges in this figure occurred prior to the constraints placed on dam operations on August 1, 1991.

Thus, operation of the dam has reduced the natural range in the monthly median discharge by a factor of eight. Furthermore, because no post-dam months have median discharges less than 9,000 ft^3/s, operation of the dam has biased all months of the year toward either the conveyance of sand through or the erosion of sand from Marble and upper Grand Canyons.

Operation of Glen Canyon Dam for hydroelectric-power generation has increased the daily range in discharge by a factor of 15.8, with the post-dam median daily range in discharge, 8,580 ft^3/s, actually exceeding the pre-dam median discharge, 7,980 ft^3/s (figs. 22*A* and 25*A*). In addition, dam operations have increased the median daily range in discharge by a factor of 10.6 over the pre-dam decade with the largest daily range in discharge, the 1920s (fig. 25*B*). Because of this increased sub-daily variability in discharge, daily mean discharges are not adequate to characterize the hydrology of the post-dam river. Thus, the post-dam flow-duration curve computed from daily mean discharges underestimates the duration of higher discharges and overestimates the duration of lower discharges (fig. 31). Of the four post-dam decades, the 1970s had the greatest median daily range in discharge, 13,700 ft^3/s, and the 1990s had the smallest median daily range in discharge, 4,940 ft^3/s (fig. 32). The median daily ranges in discharge during the 1960s and 1980s were intermediate to these values at 8,840 ft^3/s and 9,830 ft^3/s, respectively. For comparison, the pre-dam median daily range in discharge was 542 ft^3/s (fig. 32). As in the case of discharge, operation of Glen Canyon Dam has also eliminated the seasonality associated with the daily range in discharge (fig. 33). Operation of the dam for hydroelectric-power generation has increased the daily range in discharge during all but 0.1 percent of all days (fig. 34).

Not only has operation of the dam greatly reduced the duration of lower discharges, it has eliminated low-discharge months (fig. 35). Prior to closure of the dam, minimum discharges could be lower than 5,000 ft^3/s each month of the year (figs. 30*A* and 35*A*), and maximum discharges could be lower than 9,000–10,000 ft^3/s in several or more months each year (fig. 35*B*). After 1965, discharges released from the dam were not held lower than 9,000 ft^3/s for more than 1 month until the summer of 2000, when the discharge released from the dam was held steady at 8,000 ft^3/s from June through early September.

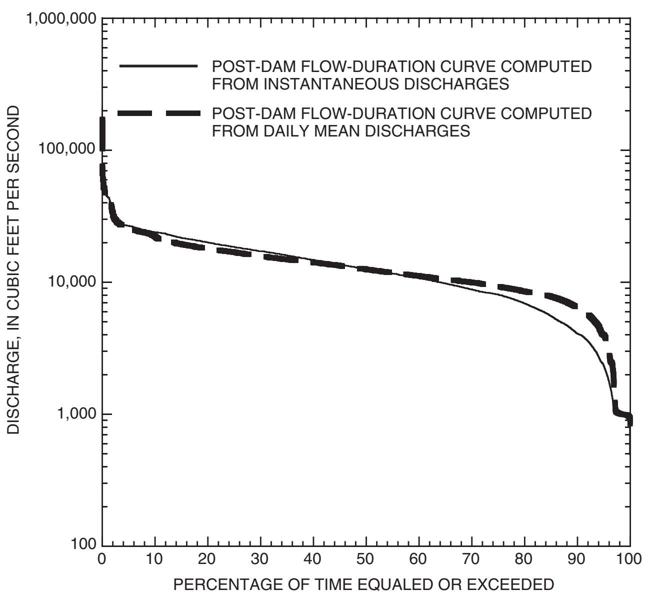

Figure 31. Comparison of the post-dam flow-duration curve computed from instantaneous discharges with the post-dam flow-duration curve computed from daily mean discharges.

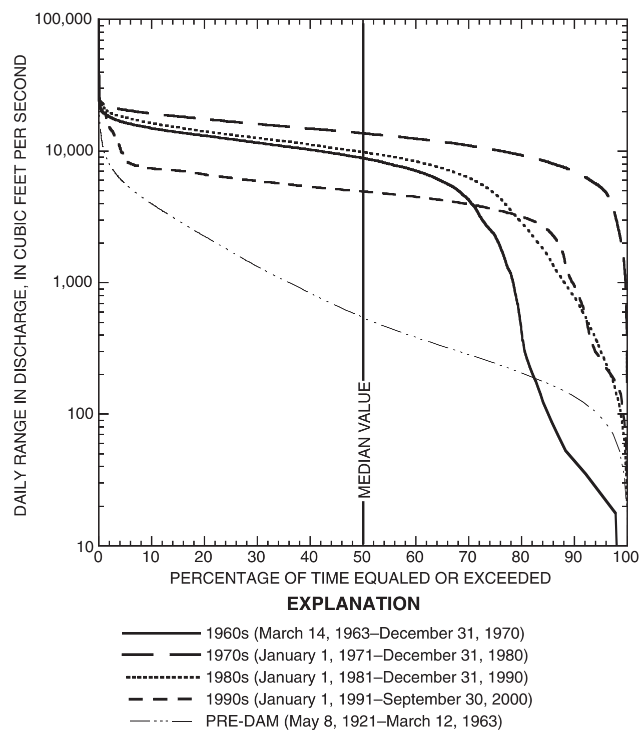

Figure 32. Exceedance curves of the daily range in the discharge of the Colorado River at Lees Ferry for the four post-dam decades and the entire pre-dam period of record.

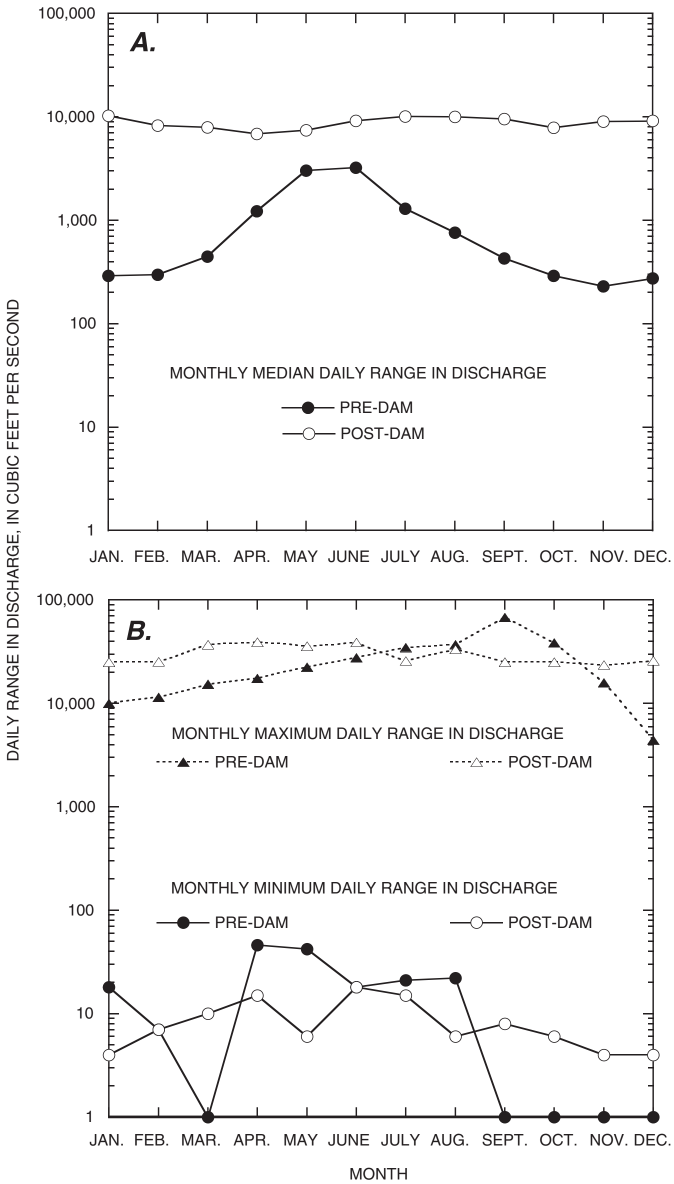

Figure 33. The effects of dam operations on: (*A*) Monthly median daily ranges in the discharge of the Colorado River at Lees Ferry. (*B*) Monthly minimum and maximum daily ranges in the discharge of the Colorado River at Lees Ferry. Daily ranges in discharge plotted equal to 1 indicate that the minimum daily range in discharge during these months was less than the level of detection.

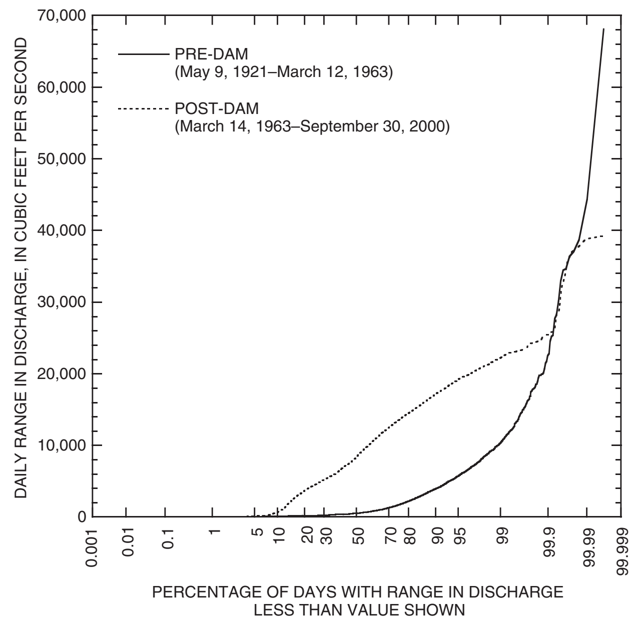

Figure 34. Probability graph of the daily range in the discharge of the Colorado River at Lees Ferry during the pre- and post-dam periods of record. Operation of Glen Canyon Dam has greatly increased the daily range in discharge during most days.

Although the post-dam duration of low discharges decreased after closure of the dam (figs. 22*A* and 29), monthly minimum discharges during the post-dam period prior to August 1, 1991, were actually lower than the monthly minimum discharges during the pre-dam months of February through November (figs. 30*B* and 35*A*). After August 1, 1991, discharges lower than 5,000 ft^3/s could not be released from the dam at any time (fig. 35*A*) and discharges lower than 8,000 ft^3/s could be released from the dam only at night (U.S. Department of the Interior, 1995; National Research Council, 1996). Because of the slightly wetter weather patterns in the Upper Basin during the mid- to late-1990s, a full reservoir, and these new constraints on dam operations, discharges lower than the pre-dam median discharge were no longer a substantial part of the hydrology of the Colorado River downstream from Glen Canyon Dam by the late 1990s. Likewise, by the late 1990s, discharges lower than the maximum pre-dam discharge at which sand accumulated in Marble and upper Grand Canyons (9,000 ft^3/s) were no longer a substantial part of the hydrology of the Colorado River downstream from Glen Canyon Dam.

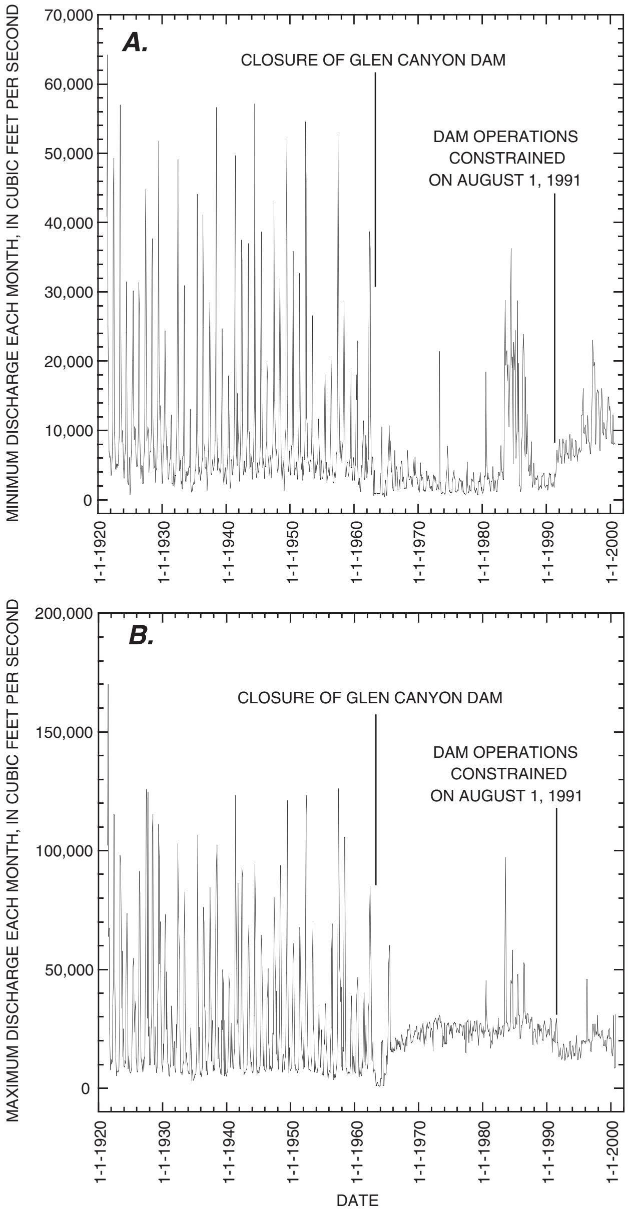

Figure 35. The minimum and maximum discharges of the Colorado River at Lees Ferry each month from May 1921–September 2000. (*A*) Minimum discharge each month. (*B*) Maximum discharge each month.

Flood Frequency During the Pre-Dam Period

To evaluate the natural frequency of floods on the Colorado River at Lees Ferry, partial-duration and annual flood-frequency analyses were conducted on the pre-dam part of the continuous record of instantaneous discharge (fig. 36). To extend these analyses to larger floods with longer return periods, the 1884 flood and the paleoflood data of O'Connor and others (1994) were also included in these analyses. The base discharge selected for the partial-duration analysis was the instantaneous discharge between May 8, 1921, and March 12, 1963, that was equaled or exceeded only 25 percent of the time, 18,500 ft^3/s (fig. 22*A*). This base discharge was also chosen because it was exceeded about 25 percent of the time during both the pre- and post-dam periods of record. In this section of the paper, the term "flood" is used to describe any discharge above this base discharge. During the pre-dam period between May 8, 1921, and March 12, 1963, 277 floods occurred with peak discharges in excess of 18,500 ft^3/s. The return periods for the pre-dam flood data were computed on the basis of different lengths of record. The return periods for the 277 floods between May 8, 1921, and March 12, 1963, were computed on the basis of their 41.8-year period of record. Because the 1884 flood had the largest peak discharge of any flood at Lees Ferry between June 1884 and March 1963, the return interval for the 1884 flood was computed on the basis of a 78.2-year period of record. The return period of the largest paleoflood identified by O'Connor and others (1994), the ~300,000 ft^3/s paleoflood that left behind the crevice deposit, was recomputed on the basis of the 1,200–1,600-year age of the deposit rather than the 2,307-year period of record used by O'Connor and others (1994).

Inclusion of the data of O'Connor and others (1994) in this flood-frequency analysis first required a reevaluation of the return periods for these paleofloods. O'Connor and others assumed that the 10 paleofloods which left the deposits in Axehandle Alcove that are less than 2,062–2,307 years old (including the historic flood that produced deposit "G1") were equally spaced over 2,307 years. This assumption led O'Connor and others to compute return periods of 200 to 800 years for the eight paleofloods associated with the deposits underlying "G1." During the early part of the 20th century, however, floods observed at the Yuma gaging station on the Colorado River had peak discharges equivalent to those of these eight prehistoric paleofloods. Because the natural June tributary inflow to the Colorado River between Lees Ferry and Yuma was minimal, the peak discharges of these floods at Lees Ferry and Yuma should have been comparable. Between 1903 and 1920, five snowmelt floods at the Yuma gaging station had peak discharges that ranged from either 120,000 to 170,000 ft^3/s (when a coefficient of 0.8 is used to relate the measured surface velocities to the mean velocities, as explained previously) or 135,000 to 190,000 ft^3/s (when a coefficient of 0.9 is used).

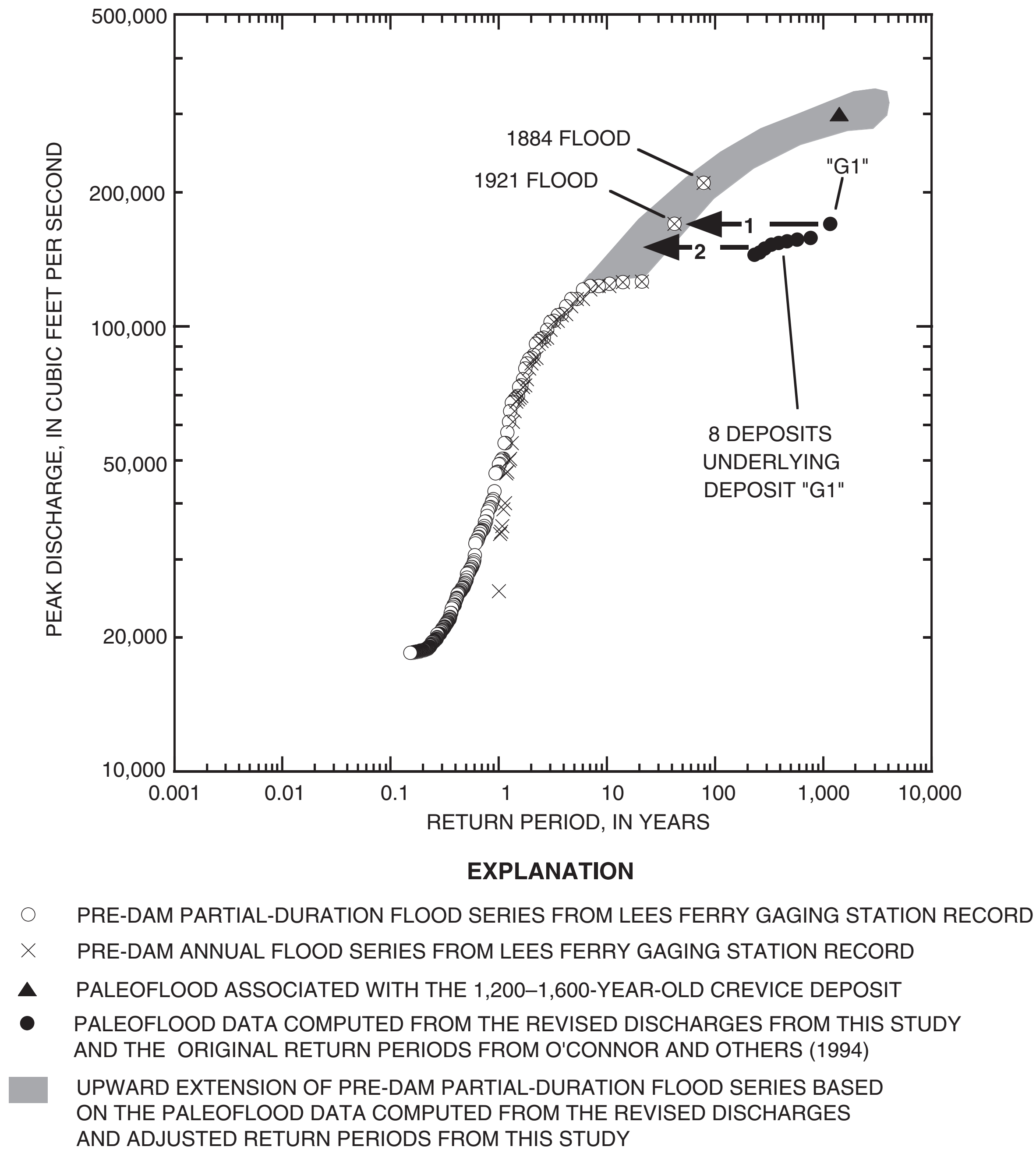

Figure 36. Partial-duration and annual flood-frequency analyses for the pre-dam Colorado River at Lees Ferry. In the partial-duration series, 40 out of the 46 floods with peak discharges in excess of 50,000 cubic feet per second were snowmelt floods. Also included are the paleoflood data of O'Connor and others (1994) recomputed on the basis of the revised discharges from this study. The bold black arrows show the return-period adjustments that should be applied to paleoflood data. Arrow "1" indicates the return-period adjustment that should be applied to the paleoflood associated with deposit "G1" (given that "G1" was likely deposited during the 1921 flood), and arrow "2" indicates the return-period adjustments that should be applied to the paleofloods associated with the eight deposits underlying "G1" (see text for further discussion).

The peak discharges of these five floods at Lees Ferry, therefore, were smaller or equal to the peak discharge of the 1921 flood that likely produced the "G1" deposit, larger than the peak discharges of all post-1921 floods, and were in the same discharge range as the eight paleofloods that left the deposits underlying deposit "G1."

The fact that the eight prehistoric paleofloods and the large 1903–20 floods at the Yuma gaging station were of comparable magnitudes requires that floods of these magnitudes occurred at least twice in the last 200–800 years. Thus, the return-period estimates of O'Connor and others (1994) for the paleofloods are high by a minimum of a factor of two (herein referred to as bounding condition one). Extension of the record of floods at the Lees Ferry gaging station from 1921 back to 1903 through use of the record from the Yuma gaging station, yields return periods for these floods that range from 12 to 60 years (herein referred to as bounding condition two). Therefore, on the basis of these two bounding conditions, the return period for the smallest of the eight paleofloods must range from 12 to 100 years over the last 2,307 years, and the return period for the largest of the eight paleofloods must range from 60 to 400 years over the last 2,307 years. Furthermore, the fact that the 1884 and 1921 floods were larger than the eight paleofloods suggests that the return periods for the eight paleofloods are closer to those computed on the basis of bounding condition two (12 to 60 years). The return-period adjustments that should be applied to the paleoflood data based on this analysis are indicated in fig. 36. Finally, although the paleoflood discharges used by O'Connor and others (1994) were too high and the return periods computed by O'Connor and others were too long, the upward extension of the flood-frequency relationship in fig. 36 is quite similar to that originally proposed in fig. 5 of O'Connor and others (1994); in both analyses, a flood with a peak discharge of 300,000 ft^3/s has a return period slightly longer than 1,000 years.

Comparison of the flood-frequency analyses based on the partial-duration and annual flood series indicates that the analysis based on the annual flood series overestimates the return periods for all pre-dam floods with peak discharges lower than about 60,000 ft^3/s (fig. 36). The partial-duration flood-frequency analysis indicates that, prior to the closure of Glen Canyon Dam, floods with a peak discharge of about 50,000 ft^3/s occurred every year on average, and that floods with a peak discharge of about 125,000 ft^3/s occurred every 8 years on average. This analysis also suggests that, under natural pre-dam hydrology, the return period for the 170,000 ft^3/s 1921 flood was about 40 years, the return period for the 210,000 ft^3/s 1884 flood was about 80 years, and that the return period of a 300,000 ft^3/s flood was slightly longer than 1,000 years (fig. 36).

Effect of the Operation of Glen Canyon Dam on Flood Frequency

To determine the effect of the operation of Glen Canyon Dam on the frequency of floods on the Colorado River, partial-duration and annual flood-frequency analyses were also conducted on the post-dam part of the continuous record of instantaneous discharge (fig. 37*A*). The same base discharge was used in the post-dam partial-duration flood-frequency analysis as in the pre-dam analysis (18,500 ft^3/s). During the post-dam period between March 14, 1963, and September 30, 2000, 5,222 floods had peak discharges in excess of 18,500 ft^3/s. The return periods for these 5,222 post-dam floods were computed on the basis of a 37.6-year period of record. Because operation of Glen Canyon Dam has effectively removed the seasonality from the annual hydrograph of the Colorado River (fig. 30), flood-frequency analysis based on the annual flood series provides a poor characterization of the frequency of floods in the post-dam river (fig. 37*A*). Compared to the return periods computed from the partial-duration flood-frequency analysis, the annual flood-frequency analysis greatly overestimates the return period of all but the three largest post-dam floods.

The effect of the operation of Glen Canyon Dam on the frequency of floods on the Colorado River at Lees Ferry is shown in fig. 37*B*. Operation of the dam has increased the return period for floods with pre-dam return periods in excess of about 6–7 months, and has decreased the return periods for the smallest floods in the analysis (floods with peak discharges of about 18,500 ft^3/s) from 1.8 months to only 2.6 days. The effect of dam operations on the duration of floods with sustained discharge in excess of 18,500 ft^3/s has also been large (fig. 38). The longest four periods of sustained discharge above 18,500 ft^3/s at Lees Ferry have all occurred since the dam was closed. In 1984, discharge exceeded 18,500 ft^3/s for 214.2 consecutive days; in 1997, discharge exceeded 18,500 ft^3/s for 200.7 consecutive days; in 1983, discharge exceeded 18,500 ft^3/s for 175.0 consecutive days; and in 1985, discharge exceeded 18,500 ft^3/s for 138.4 consecutive days. The longest pre-dam period of sustained higher discharge occurred in 1929, when discharge exceeded 18,500 ft^3/s for 129.6 consecutive days.

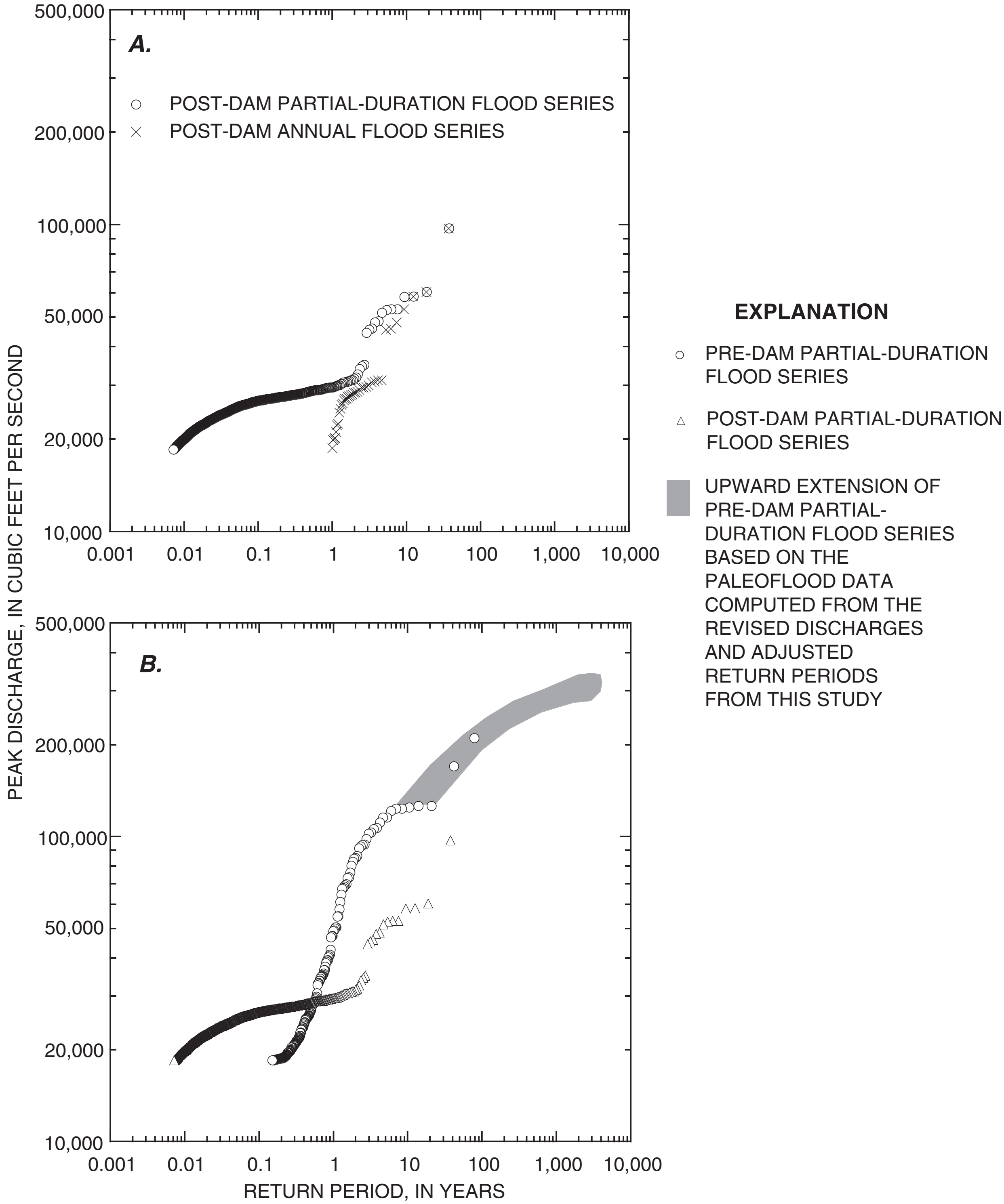

Figure 37. The effect of dam operations on flood frequency on the Colorado River at Lees Ferry. (*A*) Comparison of post-dam partial-duration and annual flood-frequency analyses. The annual flood-frequency analysis grossly overestimates the return periods for most post-dam floods. (*B*) Partial-duration flood-frequency analyses for the pre- and post-dam period.

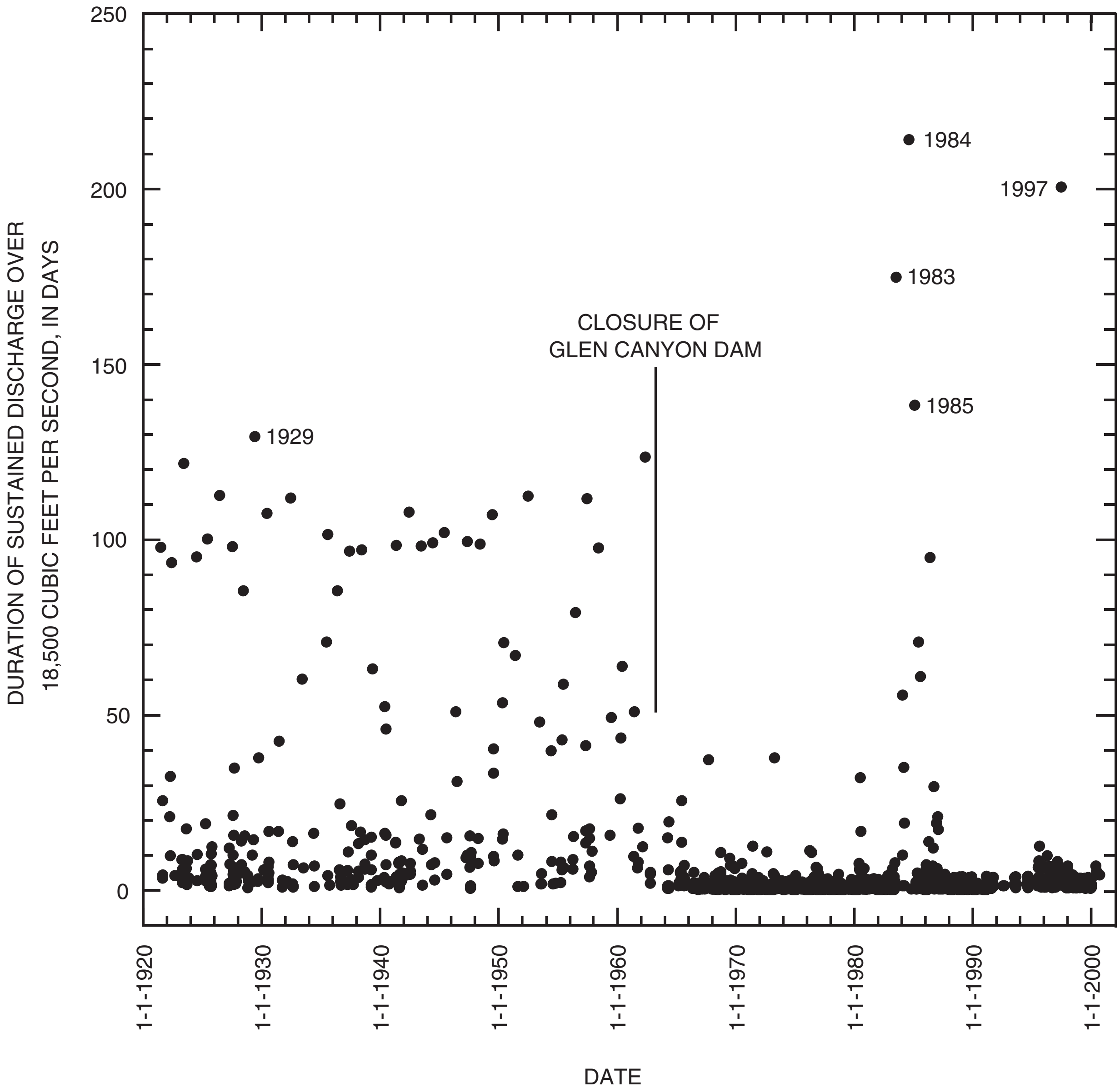

Figure 38. The duration of periods of sustained discharge over 18,500 cubic feet per second (the base discharge used in the flood-frequency analyses).

CONCLUSIONS

Although its geographic location within the Colorado River drainage basin and its accessibility made Lees Ferry a good location for a stream-gaging station, the stage dependence of the location and geometry of the hydraulic control made computations of flood discharges at this gaging station difficult during the pre-dam period. As stage increases, the water-surface profile progressively flattens at the Lees Ferry Gage as the location of hydraulic control shifts downstream. This development of backwatered flow conditions causes a reversal in the curvature of the stage-discharge rating curve, such that, at stages in excess of about 15 ft, discharge is proportional to stage raised to a power of less than one. This reversal in curvature made extrapolation of the stage-discharge rating curve problematic; thus there was considerable uncertainty in the estimated peak discharges of the largest historical floods at Lees Ferry in 1884 and 1921. The USGS originally estimated that these two floods had peak discharges of about 210,000–250,000 and 174,000 ft^3/s, respectively. On the basis of a key assumption now known to be false, the peak discharges of these floods were revised upward by Gatewood and Hunter in 1938 to 300,000 and 220,000 ft^3/s, respectively. The analyses in this paper of the raw data from Lees Ferry (which accounts for the progressive development of backwatered flow conditions in the reach at high stages), of the surveys of high-water marks at the Grand Canyon gaging station and at River-mile 233.7, and of the published data from other upstream and downstream gaging stations, indicate that the most likely peak discharges of the 1884 and 1921 floods at Lees Ferry were 210,000±30,000 ft^3/s and 170,000±20,000 ft^3/s, values close to those originally estimated by the USGS.

The progressive flattening of the water-surface profile at high stages and the consequent downward revision in the peak discharges of these two floods imply that the peak discharges in the 4,500-year paleoflood series of O'Connor and others (1994) need to be revised. The peak discharges of many of the prehistoric floods associated with these paleoflood deposits were, in fact, comparable to the peak discharges of floods during the early part of the 20th century. This observation leads to a minimum reduction of a factor of two in the return periods for these floods estimated by O'Connor and others (1994).

Analyses of the 1921–2000 continuous record of instantaneous discharge provide insight into the pre-dam natural variability in the discharge of the Colorado River, and the hydrologic changes imposed on the Colorado River in Grand Canyon National Park by the construction and operation of Glen Canyon Dam. The continuous record of instantaneous discharge can be either requested from the USGS Grand Canyon Monitoring and Research Center, Flagstaff, Arizona, or obtained electronically at http://www.gcmrc.gov.

Prior to the closure of Glen Canyon Dam in March 1963, the discharge of the Colorado River at Lees Ferry varied substantially over decadal time scales. The median discharge during the driest decade, the 1930s (6,720 ft^3/s), differed from the median discharge during the wettest decade, the 1920s (10,700 ft^3/s), by a factor of 1.6. The median discharge for the entire pre-dam period from May 8, 1921, through March 12, 1963, was 7,980 ft^3/s. Although large floods were common in the pre-dam river, discharges exceeded 18,500 ft^3/s only about 25 percent of the time. Topping and others (2000) showed that sand accumulated substantially in the pre-dam river in Marble and upper Grand Canyons only when the discharge was lower than about 9,000 ft^3/s, and that sand eroded from Marble and upper Grand Canyons when the discharge was higher than about 16,000 ft^3/s. The pre-dam decadal variation in discharge therefore had major implications for sand storage in Marble and upper Grand Canyons; the 1920s were likely the pre-dam decade most dominated by erosion of sand from this reach, and the 1930s were likely the pre-dam decade most dominated by accumulation of sand in this reach.

During the pre-dam era, the discharge of the river was fairly steady over sub-daily time scales, with a median daily range in discharge of only 542 ft^3/s. Therefore, daily mean discharges provide a reasonable characterization of the hydrology of the pre-dam river. An exception is the summer thunderstorm season, when the daily range in discharge was observed to exceed 30,000 ft^3/s, but these extreme daily ranges occurred on average only during 1 day in every 3 years. Daily ranges in discharge were larger than 10,000 ft^3/s only during 1 percent of all pre-dam days. The median daily range in discharge was greatest during the June part of the snowmelt flood (3,230 ft^3/s). The decadal daily range in discharge was somewhat correlated with the decadal discharge. As in the case of discharge, the median daily range in discharge during the driest decade, the 1930s (516 ft^3/s), differed from the median discharge during the wettest decade, the 1920s (808 ft^3/s), by a factor of 1.6.

The operation of Glen Canyon Dam has removed the seasonality from discharge and from the daily range in discharge. Dam operations have removed flood flows and base flows, and dam operations for hydroelectric power generation have introduced wide-ranging daily fluctuations in discharge that are relatively consistent throughout the year. The changes that dam operations have imposed on the hydrology of the Colorado River at Lees Ferry exceed anything in the quasi-natural pre-dam period of record.

As for the pre-dam river, discharge and the daily range in discharge have varied substantially over decadal time scales in the post-dam river as dam operations have evolved in response to the filling of Lake Powell reservoir and to growing concern about the effects of dam operations on the downstream Colorado River ecosystem. From the 1960s to the 1990s, the median discharge of the Colorado River at Lees Ferry increased from 9,490 ft^3/s to 13,500 ft^3/s. During the wettest post-dam decade, the 1980s, the median discharge of the Colorado River at Lees Ferry was 15,900 ft^3/s, only slightly higher than that during the 1990s. During the four post-dam decades, discharges under which sand can accumulate in Marble and upper Grand Canyons have progressively disappeared. During the 1960s, discharge was greater than 9,000 ft^3/s 52.7 percent of the time; during the 1970s, discharge was greater than 9,000 ft^3/s 62.2 percent of the time; during the 1980s, discharge was greater than 9,000 ft^3/s 75.5 percent of the time; and during the 1990s, discharge was greater than 9,000 ft^3/s 82.6 percent of the time. Through time, the post-dam river has been progressively dominated by discharges that erode sand, and base flows have disappeared. Discharges most likely to erode sand from Marble and upper Grand Canyons occurred during the 1990s.

Dam operations for power generation have increased the median daily range in discharge by a factor of 15.8 relative to the pre-dam median daily range in discharge. The post-dam median daily range in discharge, 8,580 ft^3/s, actually exceeded the pre-dam median discharge of 7,980 ft^3/s. As a result of this increase in the sub-daily variability in discharge, daily mean discharges no longer provide an adequate characterization of the hydrology of the Colorado River. The decade with the largest daily range in discharge was the reservoir-filling decade of the 1970s, when the median daily range in discharge was 13,700 ft^3/s (a factor of 25.2 greater than the pre-dam median daily range in discharge). The decade with the smallest daily range in discharge was the 1990s, when the median daily range in discharge was 4,940 ft^3/s (a factor of 9.1 greater than the pre-dam median daily range in discharge). Relative to the pre-dam period of record, dam operations for hydroelectric-power generation have increased the daily range in discharge during all but 0.1 percent of all days. Prior to closure of the dam, the daily discharge range exceeded 10,000 ft^3/s on only about 1 percent of all days. During the post-dam period, the daily discharge range exceeded 10,000 ft^3/s on about 43 percent of all days.

The operations of Glen Canyon Dam also have altered the frequency of floods on the Colorado River at Lees Ferry. Prior to closure of the dam, the average recurrence intervals were 1 year for floods with peak discharges of 50,000 ft^3/s, and 6 years for floods with peak discharges of 120,000 ft^3/s. Although dam operations have maintained the pre-dam frequency of floods with peak discharges of about 29,000 ft^3/s, the frequency of floods with peak discharges greater than this value has been reduced, whereas the frequency of floods with peak discharges less than this value has been increased. For example, the 2-year flood during the pre-dam period was 85,000 ft^3/s whereas the 2-year flood during the post-dam period was 31,500 ft^3/s. Because of this increase in the frequency of smaller "floods," the annual flood series is inadequate to characterize the flood-frequency distribution in the post-dam river. During the pre-dam period of record, the average recurrence interval for floods with peak discharges of 20,000 ft^3/s was 97 days. After closure of the dam, these 20,000-ft^3/s floods increased in frequency by a factor of 27, so that their recurrence interval is now 3.6 days. In addition to increasing the frequency of these lower floods, operation of the dam has also resulted in the longest periods of sustained high discharge; all four of the longest periods of sustained discharge in excess of 18,500 ft^3/s occurred after closure of the dam.

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APPENDIX A: List of Accession, Box, and Location Numbers where the U.S. Geological Survey Data used in this Study are Stored in the Federal Records Centers

Access to these data must be requested through the District Chief, Arizona District, USGS,Tucson, Arizona.

Files Stored in the Federal Records Center in Laguna Niguel, California

1921–37 Colorado River at Lees Ferry surface water records file: Accession # 57-78-0006, Box # 2 of 2, Location # MB053635

1921–34 Colorado River at Lees Ferry gage height observations: Accession # 57-68A-0138, Box # 6 of 6, Location # SB214830

1923–48 Colorado River at Lees Ferry stage-recorder charts: Accession # 57-55A-584, Box # 5 of 34, Location # RB4957

1949–56 Colorado River at Lees Ferry stage-recorder charts: Accession # 57-60-336, Box # 16 of 48, Location # SB025762

1966–70 Colorado River at Lees Ferry annual technical files and stage-recorder charts: Accession # 57-74A-1590, Box # 1 of 59, Location # MB8995

1971–72 Colorado River at Lees Ferry stage-recorder charts: Accession # 57-76A-5301, Box # 1 of 39, Location # YB34320

1973 Colorado River at Lees Ferry annual technical file and stage-recorder chart: Accession # 57-76A-5301, Box # 1 of 39, Location # YB34320

1974–77 Colorado River at Lees Ferry annual technical files and stage-recorder charts: Accession # 57-82-0004, Box # 1 of 4, Location # MB047919

1978–79 Colorado River at Lees Ferry annual technical files and stage-recorder charts: Accession # 57-94-0030, Box # 13 of 13, Location # SB13994

1980 Colorado River at Lees Ferry annual technical file and stage-recorder chart: Accession # 57-94-0030, Box # 1 of 13, Location # SB13994

1981 Colorado River at Lees Ferry annual technical file and stage-recorder chart: Accession # 57-94-0030, Box # 13 of 13, Location # SB13994

1982–89 Colorado River at Lees Ferry annual technical files and stage-recorder charts: Accession # 57-94-0030, Box # 1 of 13, Location # SB13994

1990 Colorado River at Lees Ferry annual technical file and stage-recorder chart: Accession # 57-96-0010, Box # 3 of 4, Location # BT2670

1921–28 Colorado River at Lees Ferry discharge measurement notes: Accession # 57-55-0584, Box # 10 of 58, Location # BT000964

1929–31 Colorado River at Lees Ferry discharge measurement notes: Accession # 57-55-0584, Box # 11 of 58, Location # BT000964

1932–34 Colorado River at Lees Ferry discharge measurement notes: Accession # 57-55-0584, Box # 12 of 58, Location # BT000964

1935–37 Colorado River at Lees Ferry discharge measurement notes: Accession # 57-55-0584, Box # 13 of 58, Location # BT000964

1938–41 Colorado River at Lees Ferry discharge measurement notes: Accession # 57-55-0584, Box # 14 of 58, Location # BT000964

1942–48 Colorado River at Lees Ferry discharge measurement notes: Accession # 57-55-0584, Box # 15 of 58, Location # BT000964

1949–57 Colorado River at Lees Ferry discharge measurement notes: Accession # 57-60-0336, Box # 3 of 48, Location # ST007405

1921–28 Colorado River at Lees Ferry discharge measurement notes: Accession # 57-55-0584, Box # 10 of 58, Location # BT000964

1930–34 Colorado River at Lees Ferry sediment records: Accession # 57-78-0005, Box # 1 of 26, Location # MT016349

1948–53 Colorado River at Lees Ferry sediment records: Accession # 57-78-0005, Box # 1 of 26, Location # MT016349

1954–59 Colorado River at Lees Ferry sediment records: Accession # 57-78-0005, Box # 2 of 26, Location # MT016349

1960–76 Colorado River at Lees Ferry sediment records: Accession # 57-78-0005, Box # 3 of 26, Location # MT016349

1891–37 Colorado River at Yuma surface water records file: Accession # 57-78-0006, Box # 2 of 2, Location # MB053635

Files Stored in the Federal Records Center in Denver, Colorado

1921–26 Colorado River at Lees Ferry discharge revision, original computations: Accession # 57-64A-0423, Box # 3 of 24, Location # 62480

1921–26 Colorado River at Lees Ferry annual technical files: Accession # 57-64A-0423, Box # 2 of 24, Location # 62479

1927–50 Colorado River at Lees Ferry annual technical files: Accession # 57-64A-0423, Box # 3 of 24, Location # 62480

1951–60 Colorado River at Lees Ferry annual technical files: Accession # 57-66A-0574, Box # 21 of 27, Location # 225838

1961–65 Colorado River at Lees Ferry annual technical files: Accession # 57-70B-117, Box # 13, Location # 904128

1957–60 Colorado River at Lees Ferry stage-recorder charts: Accession # 57-67A-0261, Box # 3 of 13, Location # 327910

1961-–65 Colorado River at Lees Ferry stage-recorder charts: Accession # 57-70A-117, Box # 1, Location # 904104

Colorado River near Grand Canyon gaging station reconnaissance and construction reports: Accession # 57-64A-0423, Box # 1 of 24, Location # 62478

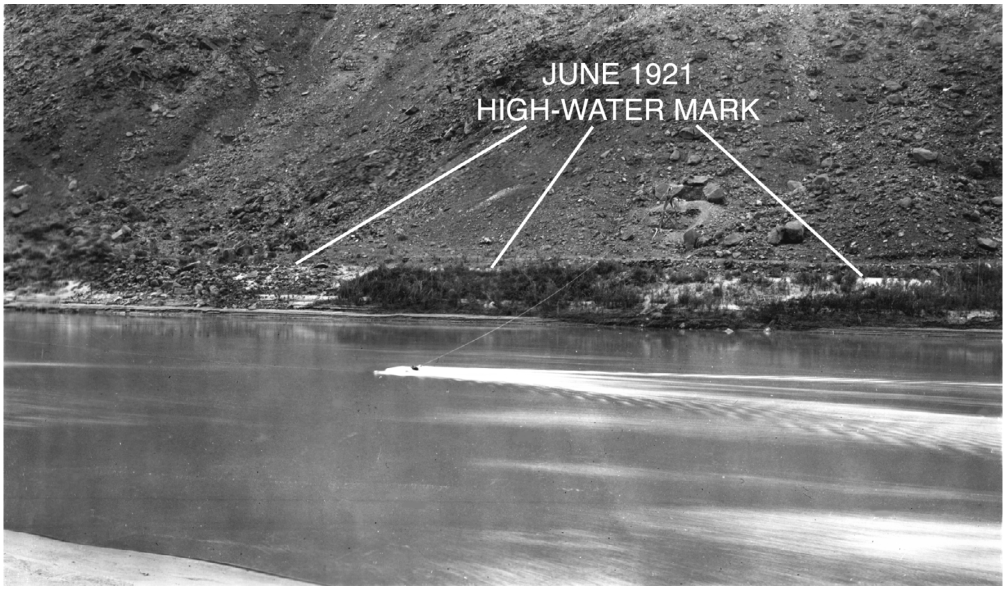
1941 Paria River at Lees Ferry annual technical file: Accession # 57-66A-0574, Box # 2 of 27, Location # 225819

APPENDIX B: Important Events in the History of the Lees Ferry Gaging Station

May 8, 1921	E.C. LaRue installed a temporary inclined staff gage on the right bank (fig. 1*C*). This gage is herein referred to as the "LaRue Gage." This gage was not graduated and was read twice daily by measuring down with a tape from a nail used as a reference point. H.A. Schenck (Chief of Surveys, Southern California Edison Company) later told Roger C. Rice (District Engineer, USGS) that the slope of this gage was approximately 2:1 (which corresponds to an angle of about 26°34′). E.C. LaRue later said that he thought the slope of the gage was closer to 32°. The first reading of stage was made at 6:00 p.m.
June 12–13, 1921	The LaRue Gage was overtopped by water between 5 p.m. on June 12 and 6:00 a.m. on June 13. Frank T. Johnson, the observer, continued to measure the stage twice daily after the gage was overtopped by "pegging" up the slope above the gage. This method consisted of inserting a stick at the edge of water and then later measuring the change in stage on the stick and inserting a new stick at the new edge of water. G.S. Stevens (in a memorandum dated March 15, 1924, in Appendix D) later estimated that the first two "pegged" measurements, because of their much larger magnitude, were probably measurements up the sloping bank and were not vertical measurements.
June 13, 1921	Roger C. Rice (USGS) drafted a letter to H.W. Dennis (Construction Engineer, Southern California Edison Company) detailing the plan of cooperation between the USGS and the Southern California Edison Company for the establishment of the Lees Ferry gaging station. Under this agreement, the USGS would serve in a general advisory capacity, provide all current-meter equipment, and would process all of the data collected at the site. The Southern California Edison Company would then assume responsibility for the cost of all gage-related construction, and would pay two resident hydrographers to make gage-height observations, discharge measurements, and perform maintenance.
June 18, 1921	Peak of the June 1921 flood occurred at 2:00 p.m. Frank T. Johnson marked the high-water elevation as the top of nail in vertical board on the south side of the road near a wash. As the flow receded, Johnson continued to record the stage twice daily by "pegging" down the slope.
June 21, 1921	H.A. Schenck (Southern California Edison Company) and Roger C. Rice (USGS) met in Flagstaff, Arizona, to discuss the details of establishing the Lees Ferry gaging station.
June 22, 1921	Arrangements were made with the Flagstaff Lumber Company to furnish the material for the A-frames and cable car for the discharge-measurement cableway. Arrangements were made with P.S. Solberg, 309 South Beaver Street, Flagstaff, to do the carpentry.
June 23, 1921	H.A. Schenck and Roger C. Rice visit Lees Ferry with survey party. Elevation of high-water mark near the future site of the permanent Lees Ferry Gage at the dugway was determined. They approved the location for the discharge measurement cableway that was previously selected by E.C. LaRue. This location is marked as the "Upper Cableway" in fig. 1*C*, and is herein referred to as the Upper Cableway.
June 23, 1921	Jerry Johnson told Roger Rice that the peak stage of the 1884 flood was 2 ft higher than the peak stage of the 1921 flood.
June 24, 1921	The flow receded to below the top of the LaRue Gage. Frank T. Johnson found that the lower part of the gage had broken loose and that the top part had rotated out of position. He installed a new temporary inclined staff gage, with a new slope of 24°35′. This gage became known as the "Number 1 Gage." Johnson stated that he thought the reference-point nail for the Number 1 Gage was at the same elevation as the reference point for the LaRue Gage, but he was not completely sure of his observation. G.C. Stevens later estimated in a memorandum dated November 22, 1923 (Appendix D), that the reference point for the new

	Number 1 Gage was probably 2.65 ft lower than that for the LaRue Gage. Based on information presented in Appendix D, the reference point for the Number 1 Gage was most likely about 3.65 ft lower than that for the LaRue Gage.
June 24, 1921	Due to the high velocities encountered at Lees Ferry during the snowmelt flood, the decision was made to use heavier lead weights than normal when making discharge measurements. One 100-pound weight and one 50-pound torpedo-shaped weight were thus ordered from W. and L.E. Gurley, Troy, New York. At that time, the USGS only had weights lighter than 30 pounds in stock. Also, a special winch was designed to handle the heavier weights. Because of the heavier equipment, the cable and cable car were also designed to be larger.
June 25, 1921	First reading on the new Number 1 Gage made by Frank T. Johnson at 7 a.m.
June 25, 1921	F.S. Solberg of the Flagstaff Lumber Company informed Schenck and Rice that the wooden A-frame for the Upper Cableway would be completed by July 8, 1921.
June 28, 1921	Temporary inclined staff gage installed on the right bank just above the ferry crossing (fig. 1*C*). This gage was known as the "Number 2 Gage" and had a slope of 24°20′. The first stage measurement on this gage was made at 4:30 a.m. The Number 2 Gage was read twice daily until 6:00 a.m. on August 11, when it was ordered removed by E.C. LaRue. The datum of this gage was never tied into the datums of the other gages.
July 7, 1921	Temporary inclined staff gage installed on the left bank near the large rock below the Upper Cableway site. This gage was known as the "Number 3 Gage" and was at the site of the higher-water inclined sections of the future "Number 4 Gage" (fig. 1*C*). The first stage measurement on this gage was made at 7:45 a.m. The Number 3 Gage was read twice daily until 9:05 a.m. on August 11, when it was ordered removed by E.C. LaRue. The datum of this gage was never tied into the datums of the other gages.
July 25, 1921	Southern California Edison Company began construction of the Upper Cableway for measuring discharge.
August 3, 1921	Temporary inclined staff gage installed on the left bank near the Number 3 Gage. This gage was first read at 6:10 a.m. and became known as the "Number 4 Gage" (fig. 1*C*).
August 3,1921	First discharge measurement made from the Upper Cableway.
August 5, 1921	Temporary inclined staff gage installed at the end of the dugway (fig. 1*C*). This gage became known as the "Dugway Gage" and was located immediately upstream from the future permanent Lees Ferry Gage. The datum of the Dugway Gage was the same as the future Lees Ferry Gage.
August 9, 1921	W.E. Johnson replaced Frank T. Johnson as the gage observer.
August 11, 1921	Number 2 and Number 3 Gages ordered removed by E.C. LaRue.
August 14, 1921	First dependable stage measurement made at the Dugway Gage at 8:50 a.m.
September 19, 1921	Eyebolt failed on Upper Cableway and cable car fell in river at 3:00 p.m. with I.G. Cockcroft and Elmer Johnson aboard. Cockcroft and Johnson swam to shore. Johnson was not a strong swimmer and used the car top as a life preserver.
September 21, 1921	Cable reattached and cable car placed back on cable (fig. B1). Discharge measurements were not made from the cable again until December 3, 1921. Discharge from October 4 through November 30 was measured from a boat at the Upper Cableway cross-section.

A.



B.

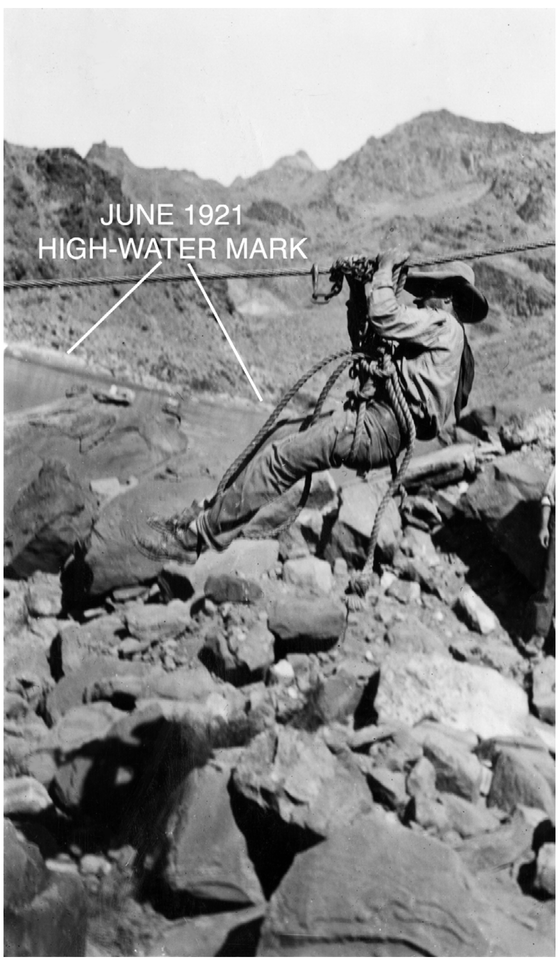
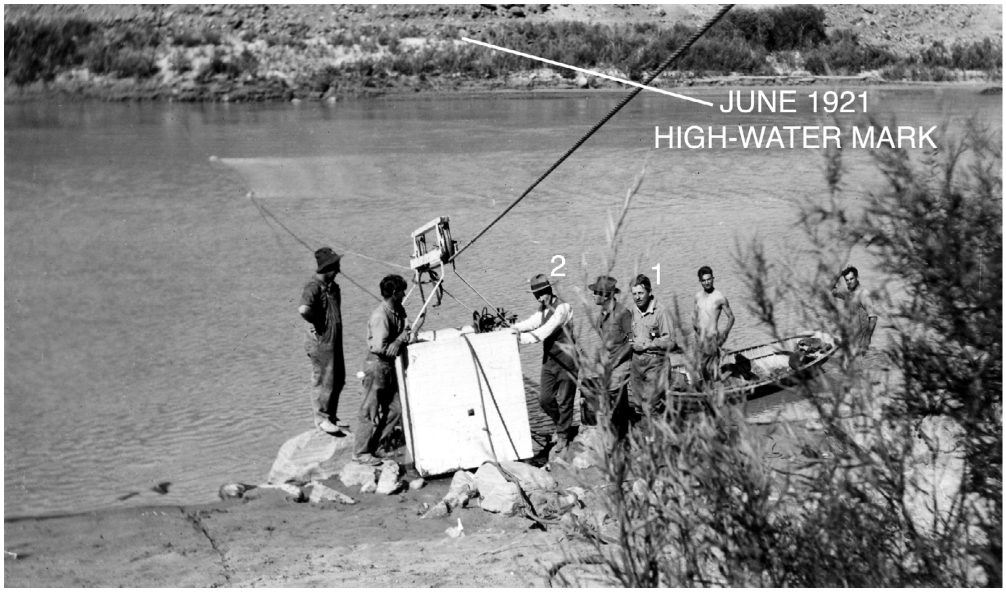


Figure B1. Repairs to the Upper Cableway and the high-water marks from the 1921 flood (photographs by R.C. Rice, U.S. Geological Survey, September 20, 1921). (*A*) View from the right bank of the cable and cable car in the river in the morning. High-water marks from the June 1921 flood are visible on the left bank. Source of this and the photographs in figs. B1*B*–B3*D*, and B4–B6: 1921–37 Surface Water Records File, Colorado River at Lees Ferry, Arizona, file stored at the Federal Records Center in Laguna Niguel, California, in Accession No. 57-78-0006, Box 2 of 2, Location No. MB053635. (*B*) Downstream view from the right bank of Sid Wilson attaching the chain come-along to the cable. High-water marks from the June 1921 flood are visible on the left bank in the background.

C.



D.

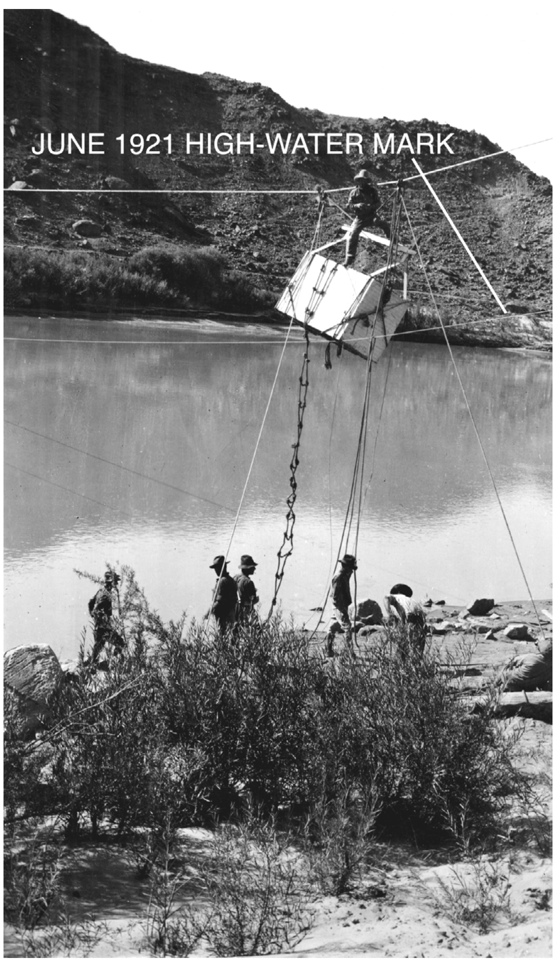


Figure B1—*Continued.* Repairs to the Upper Cableway and the high-water marks from the 1921 flood (photographs by R.C. Rice, U.S. Geological Survey, September 20, 1921). (*C*) View from the right to the left bank of the cable car rescued from the river. High-water marks from the June 1921 flood are visible below the level of the road on the left bank. Numbered are: 1. H.W. Dennis (Southern California Edison Company) and 2. R.Q. Grant (U.S. Weather Bureau). (*D*) View from the right bank of Sid Wilson reattaching the cable car to the Upper Cableway. High-water marks from the June 1921 flood are visible below the level of the road on the left bank.

September 21, 1921	Dugway Gage was permanently installed and consisted of a vertical low-water section from 0 ft to 9.5 ft, inclined middle section from 8 ft to 21 ft, and a high-water section from 21 ft to 28 ft. Elevation of the peak of the June 1921 flood was found to be 26.5 ft on this new gage (fig. B2). First stage measurement made at 6:25 p.m. The datum of the Dugway Gage was 3,106.16 ft above the NGVD1929.
September 24–29, 1921	New Number 4 Gage was permanently installed. This gage replaced the old temporary Number 4 Gage on the large rock in the channel and the inclined Number 3 Gage on the left bank. This gage consisted of a vertical low-water section attached to the large rock in the channel near the left bank below the Upper Cableway, and five higher-elevation inclined sections on the left bank. Vertical section read from 3 ft to 15 ft, and inclined sections read from 12.5 ft to 33.5 ft (fig. B3). Elevation of the road on the left bank was at a stage of 27 ft. Photographs indicate that, at the Number 4 Gage, this road was just above the elevation of the peak stage of the June 1921 flood. The datum of the Number 4 Gage was 3,106.82 ft above the NGVD1929.
September 25–26, 1921	Number 1 Gage was permanently installed and consisted of a vertical low-water section from 10.15 ft to 13.55 ft and an inclined higher-water section that extended from 13.5 ft to 23 ft. Low-water section was located about 117 ft downstream from the inclined section (fig. B4). Elevation of the peak of the June 1921 flood was found to be 30.89 ft on the Number 1 Gage. The datum of the Number 1 Gage was 3,102.60 ft above the NGVD1929.
September 29, 1921	Old temporary Number 4 Gage on rock was removed.
September 30, 1921	The USGS computed daily mean discharge through this date from the stages measured at the Number 1 Gage. Because of uncertainties in how the stages measured on the LaRue Gage related to those measured on the Number 1 Gage, no daily mean discharges were published by the USGS prior to June 13, 1921.
October 1, 1921	The USGS computed daily mean discharge after this date from the stages measured at the Dugway Gage.
June 7, 1922	I.G. Cockroft and Elmer Johnson measured the elevation of two high-water marks from the June 1921 flood at the Lonely Dell Ranch. The first of these marks was "about 8 inches above the ground on post of fence near bottom wire" and was shown to Cockcroft and Elmer Johnson by Jerry Johnson. The corrected NGVD1929 elevation of this high-water mark was 3,132.64 ft, which equals 26.48 ft above the datum of the Dugway Gage. This high-water mark was only 0.02 ft lower than that measured on the left bank at the Dugway Gage. The second of these high-water marks was at the high-water edge of the alfalfa field near the fence and road. This high-water mark was traced to be within 50 ft of the original gage on the Paria River (this gage was one meander upstream, about 1,970 ft, from the current Paria River gage). The high-water mark consisted of small pieces of drift and grass. The corrected NGVD1929 elevation of this high-water mark was 3,132.61 ft, which equals 26.45 ft above the datum of the Dugway Gage. This mark was only 0.05 ft lower than that measured at the Dugway Gage. These high-water marks were located between 0.6 and 1.2 miles diagonally downstream on the right bank of the Colorado River, and up the Paria River valley. In a streamwise coordinate system, these marks would be located about 0.3 miles downstream from the Dugway Gage. Therefore, the slope of the water surface in the reach immediately below the Dugway Gage was approximately 0.00001 to 0.00003 during the peak of the 1921 flood.

A.

B.

Figure B2. The Dugway Gage and the high-water mark from the 1921 flood (photographs by R.C. Rice, U.S. Geological Survey, September 22, 1921). (*A*) Downstream view of the vertical low-water section (on right) and inclined middle section (on left) of the Dugway Gage. (*B*) Downstream view of the inclined middle section of Dugway Gage.

C.

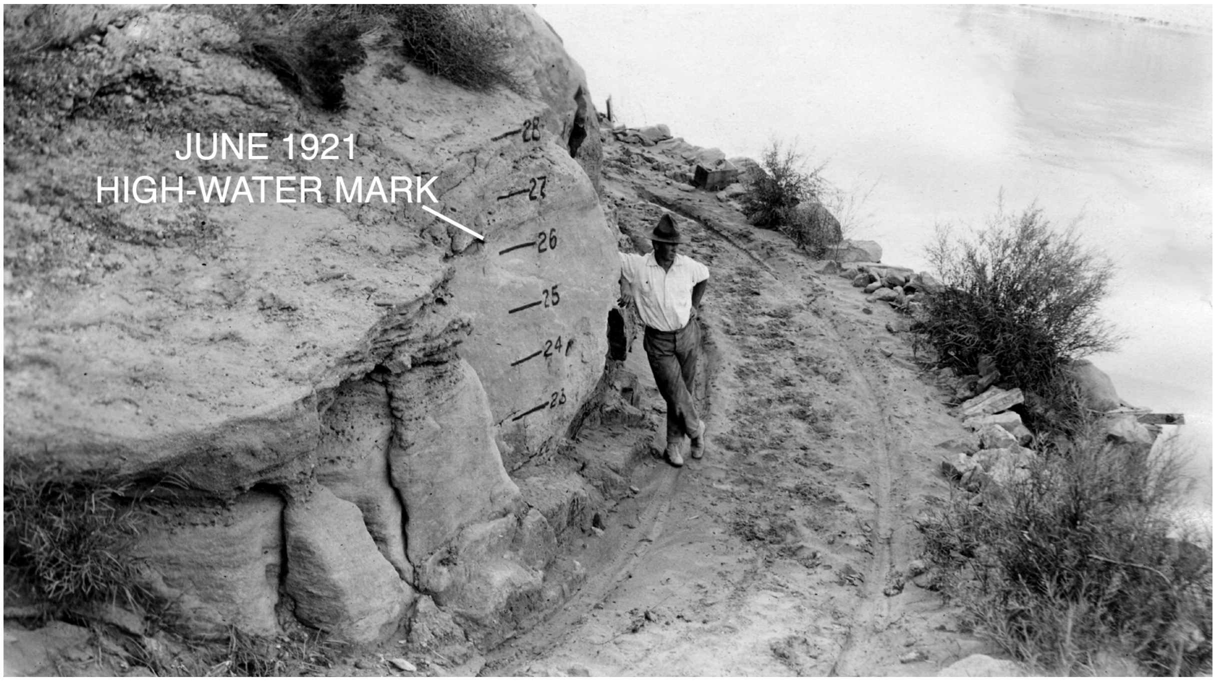


Figure B2—*Continued.* The Dugway Gage and the high-water mark from the 1921 flood (photographs by R.C. Rice, U.S. Geological Survey, September 22, 1921). (*C*) Downstream view of the high-water section of Dugway Gage painted on cliff next to dugway road. I.G. Cockcroft standing next to gage. High-water mark from the June 1921 flood visible on the cliff at a stage of 26.48 feet on the gage (determined by levels on June 7, 1922). This stage equals an elevation of 3,132.64 feet above the NGVD1929.

June 7, 1922	I.G. Cockcroft and Elmer Johnson first tied the elevation of the July 7, 1884, flood peak into the Dugway Gage. The 1884 flood was the most recent flood prior to the June 1921 flood that was larger than the 1921 flood. The high-water mark was a crotch in a peach tree at the Lonely Dell Ranch (on river right below the Dugway Gage) from which Jerry Johnson rescued a cottontail rabbit. The corrected NGVD1929 elevation of this mark was 3,136.90 ft, which equals 30.74 ft above the datum of the Dugway Gage. The elevation of the stump of this tree near Johnson's house was checked by levels by W.E. Dickinson on September 22, 1924. On April 13, 1938, J.S. Gatewood estimated that the peak stage of the 1884 flood would have been at a stage of about 31.5 ft on the Dugway Gage. However, because the water-surface slope during the 1921 flood was between 0.00001 and 0.00003 between the Dugway Gage and the Lonely Dell Ranch, and it is likely that the water-surface slope was even lower during the 1884 flood (because of flattening of the water surface in this reach with increasing stage, as shown in this study), the peak stage of the 1884 flood was probably no more than 31 ft on the Dugway Gage.
August 10, 1922	I.G. Cockcroft installed a new vertical low-water section for the Dugway Gage to replace the old one that had "torn loose." Cockcroft stated that the "new vertical reads 1/2 tenth lower." Roger C. Rice stated that Cockcroft probably installed this new staff gage slightly lower than the original one so that the readings on it and on the lower end of the inclined middle section would agree. Although the original vertical low-water and inclined upper sections were installed relative to the same datum, stage readings tended to be about 0.05 ft lower on the original vertical low-water section than on the inclined middle section.

A.

B.

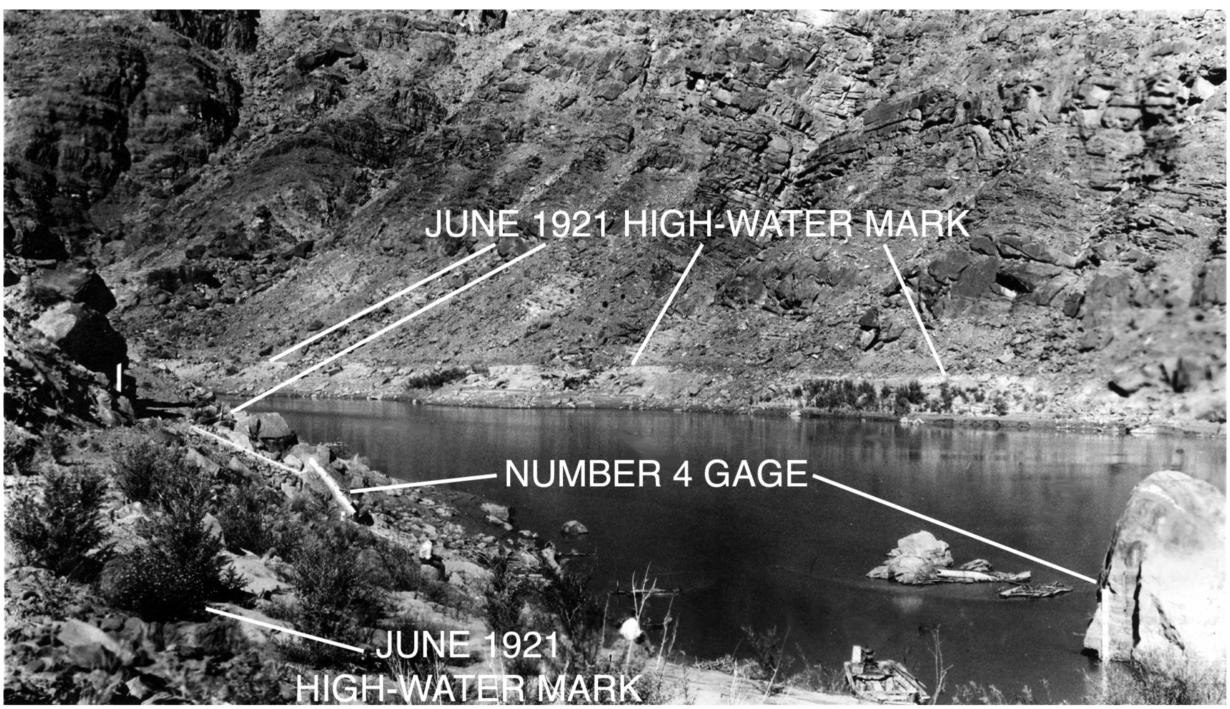


Figure B3. The Number 4 Gage and the high-water marks from the 1921 flood. (*A*) October 2, 1921, downstream view of the of the Upper Cableway left-bank A-frame and the Number 4 Gage. Position of inclined sections of Number 4 Gage on the left bank indicated; vertical low-water section of the Number 4 Gage is on the large rock in the river near the left bank. High-water marks from the June 1921 flood are visible on both banks. (This photograph and those in parts *B* through *D* taken by R.C. Rice of the U.S. Geological Survey.) (*B*) October 2, 1921, downstream view of the Number 4 Gage and high-water marks from the June 1921 flood. Inclined upper sections of the gage are on the left bank; vertical low-water section is on the rock to the right. Two people and a boat are visible in the foreground for scale.

C.

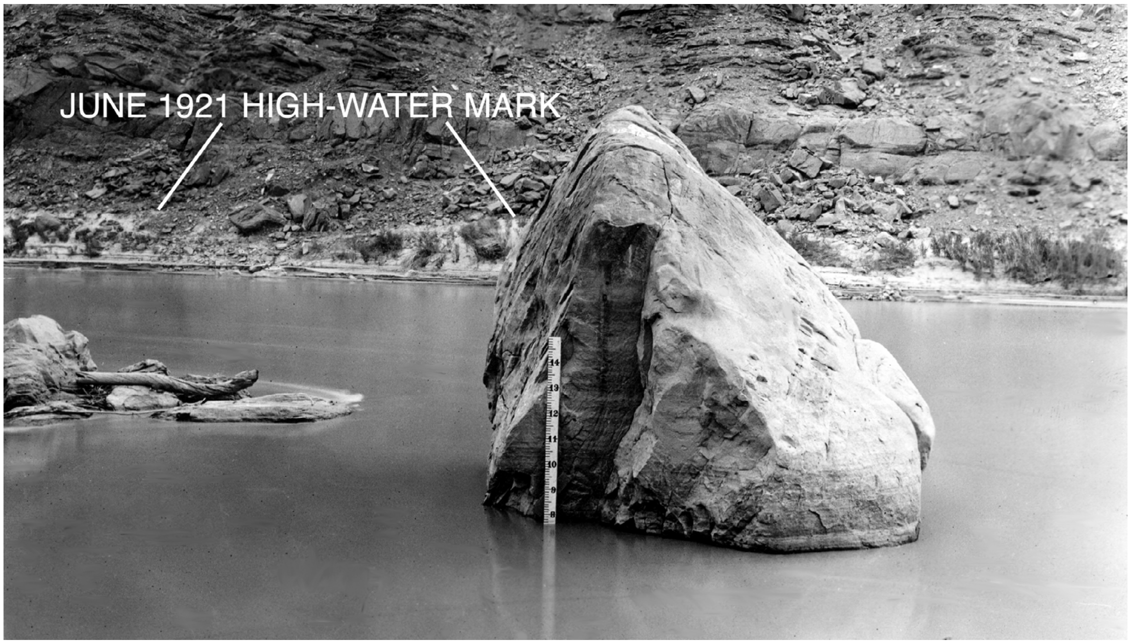


Figure B3—*Continued.* The Number 4 Gage and the high-waters mark from the 1921 flood. (*C*) October 2, 1921, view of the vertical low-water section of the Number 4 Gage on the rock. High-water marks from June 1921 flood are visible on the right bank.

September 20, 1922	Last regular stage measurement made at the Number 4 Gage at 7:20 a.m.
October 10– December 16, 1922	The concrete gagehouse and stilling well for the permanent Lees Ferry Gage were built immediately downstream from the Dugway Gage. The new Lees Ferry Gage and the Dugway Gage both have the same datum.
January 19, 1923	An Au-fuzee continuous water-stage recorder was installed.
September 1, 1923	USGS takes over full control of the Lees Ferry gaging station from the Southern California Edison Company.
September 22, 1923	Last stage measurement made at the Number 4 Gage.
April 1924	Inclined slope gage installed on the left bank at the Upper Cableway. This gage was known as the "Cable Gage." Gage read from 13.5 ft to 34 ft (fig. B5). Gage was used to help constrain the change in stage during discharge measurements at the Upper Cableway (which was 1 mile upstream from the recorder gage). Gage was tied into a benchmark near the Number 4 Gage on April 24, 1924. The original datum of the Cable Gage was 3,109.40 ft above the NGVD1929.
April 17, 1924	Inclined upper section of the Number 1 Gage replaced.
June 1, 1924	New inclined upper section of the Number 1 Gage tied into the old Southern California Edison Company benchmark.
August 26–27, 1924	New vertical low-water section installed about 20 ft offshore from the new inclined upper section of the Number 1 Gage. This new vertical section was anchored to the offshore side of a large rock, and was tied in with a rod and level to the datum of the Number 1 Gage.

D.

E.

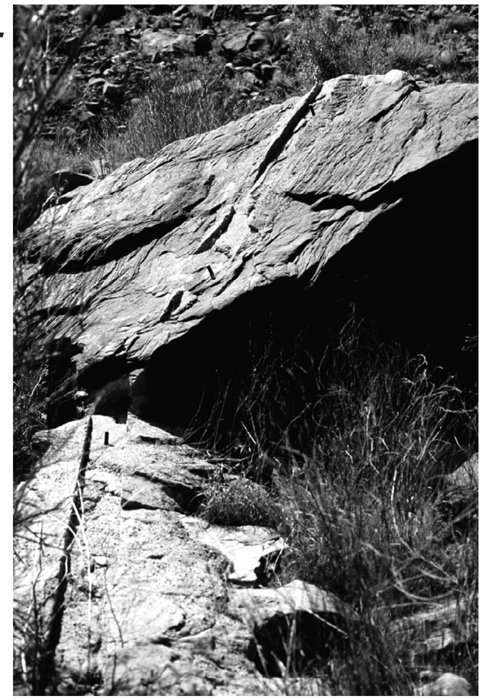
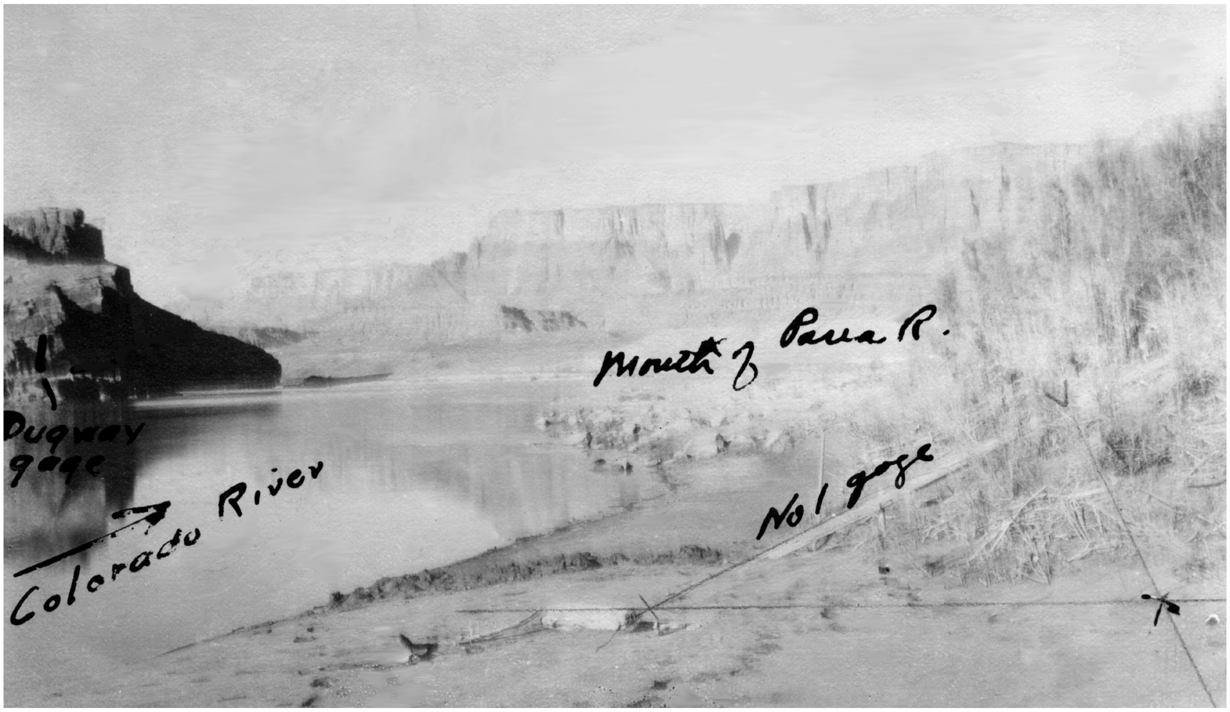


Figure B3—*Continued.* The Number 4 Gage and the high-waters mark from the 1921 flood. (*D*) October 2, 1921, view of the inclined upper sections of the Number 4 Gage. Analysis of figs. B1*D*, 3*A*, and 3*B* indicates that the peak stage of the June 1921 flood was at about the elevation of the road in this photograph. This elevation equals a stage of 27 feet on the Number 4 Gage, which equals an elevation of 3,133.9 feet above the NGVD1929. (*E*) May 25, 1999, view of the remnants of the inclined portion of the Number 4 Gage. Photograph taken by D.J. Topping (U.S. Geological Survey)

October 12, 1924	Cable Gage reconstructed and remarked. Datum of gage was lowered 10 ft. New datum of the Cable Gage was 3,099.40 ft above the NGVD1929.
October 5, 1925	Backwatered flow conditions develop in the Colorado River at the Lees Ferry Gage as a result of a large flood on the Paria River. The stage of the Colorado River at the Lees Ferry Gage increased by as much as 1 ft as a result of the Paria River flood entering the Colorado River just downstream from the gage. Backwatered flow conditions lasted 2 hours before an increase in the discharge of the Colorado River increased the stage above 11 ft at the Lees Ferry Gage.
October 12, 1925	Floating logs tore out vertical low-water section of the Number 1 Gage. Gage useless below 13.5 ft.
October 19, 1925	Last stage measurement made at the Number 1 Gage at 6:00 a.m.

A.



B.

Figure B4. The Number 1 Gage (photographs by R.C. Rice, U.S. Geological Survey, September–October 1921). (*A*) Downstream view of the inclined higher-water section of the Number 1 Gage on about September 20, 1921. This was the gage built by the observer, Frank T. Johnson, after the crest of the June 1921 flood. It was read by taping down from a nail used as a reference point. The trench was dug to connect the gage to the river. The vertical low-water enamel section had not yet been installed when this picture was taken. Peak stage of the June 1921 flood was measured at 30.89 feet on this gage. This stage equals an elevation of 3,133.50 feet above the NGVD1929. (*B*) October 3, 1921, downstream view of the vertical low-water section of Number 1 Gage installed by Roger C. Rice on September 25, 1921. Elmer Johnson, assistant gage observer and hydrographer, standing next to gage. Location of Dugway Gage on the left bank is indicated.

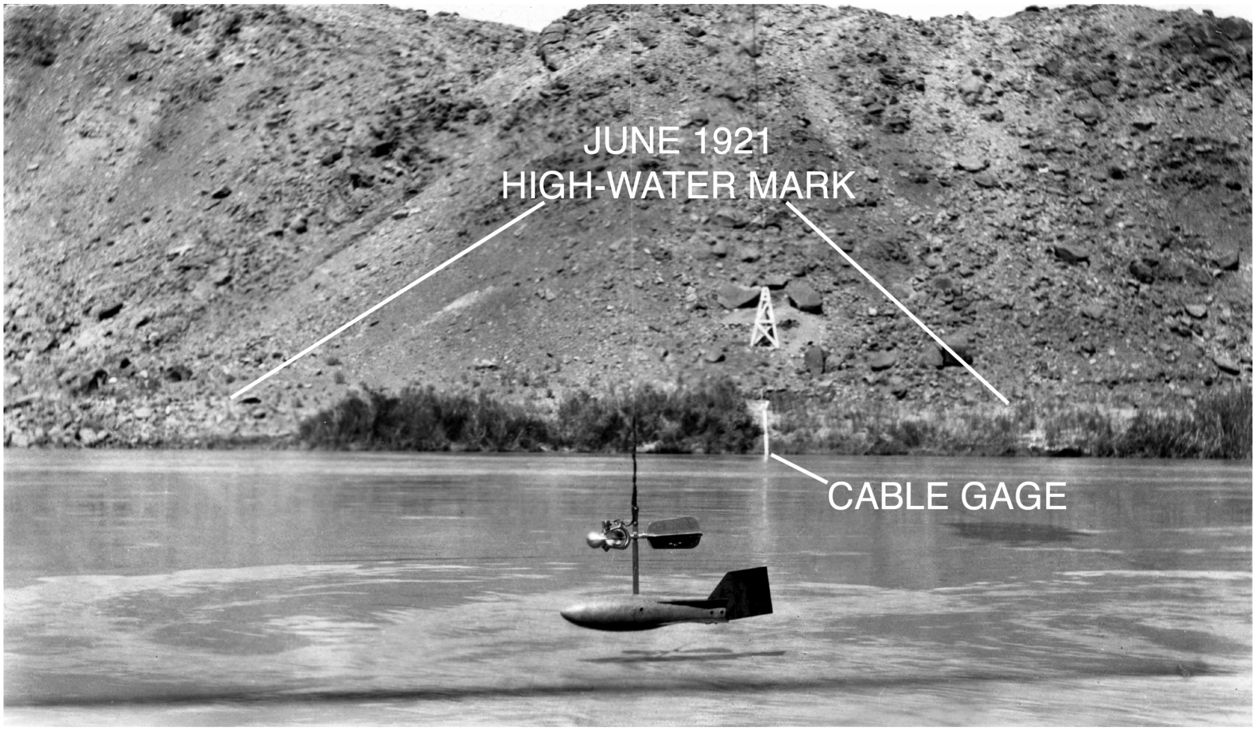


Figure B5. The right- to left-bank view of the Upper Cableway showing the Cable Gage on the left bank (appears as a vertical white stripe below the left-bank A-frame). High-water marks from the June 1921 flood are still visible 3 years after the flood (compare with same high-water marks photographed in September 1921 in fig. B1*A*). High-water marks from the June 1921 flood appear to be just above the elevation of the top of the Cable Gage. This elevation equals a stage of approximately 34.5 feet on the Cable Gage, which equals an elevation of 3,133.9 feet above the NGVD1929. Also shown in the foreground is a Price current meter and 75-lb weight suspended from the cable car. Tail of weight bent slightly upward after sounding rocky bottom. (Photo taken by W.E.Dickinson, U.S. Geological Survey, May 1924).

January 1929	Lower Cableway completed at wider section between the Upper Cableway and the Lees Ferry Gage for making more accurate discharge measurements during periods of higher water (fig. 1*C*). The section chosen was about twice as wide as the section at the Upper Cableway. Work on this project commenced with the pouring of the concrete anchorages in December 1927 and construction of the A-frames in January 1928. Cable was finally erected in January 1929 when the river was low enough to allow easier stringing of the long cable across the channel. Originally, it was hoped that the river would completely freeze over, making the cable stringing easier. In January 1929, the job was completed when the river at the chosen cross-section was restricted to only a narrow channel along the right bank, with the remainder of the channel occupied by a wide sand bar.
March 1929	Upper Cableway was replaced and left A-frame of the Upper Cableway was raised 3 ft and set on two concrete piers.
March 1929	The dugway road area between the gage house and the cliff was filled with rocks to prevent drift from lodging in the opening and endangering the stilling well and gage house during periods of high water. This was possible because the road to the old ferry crossing was no longer used after the construction of the Navajo Bridge across the Colorado River, 4.3 miles downstream.

March–September 1929	Too much water was computed passing the Lees Ferry gaging station relative to the Grand Canyon gaging station (minus the inflow from the Paria River, Moenkopi Wash, and the Little Colorado River) during this period (unpublished USGS memorandum dated December 30, 1929, by W.E. Dickinson; Appendix C). This problem was worse during higher flows. On average 2.7 percent too much water was computed passing Lees Ferry during water year 1929. Although no correction was made to the water-year 1929 record, discharges at the Lees Ferry gaging station during subsequent years would be reduced to equal those at the Grand Canyon gaging station when this type of discrepancy occurred. Although no official reason for this discrepancy was determined, this discrepancy started after the rock fill was placed between the gage and the cliff, and after the Upper Cableway was replaced. This discrepancy also also started with the use of different current meters.
August 2, 1929	Backwatered flow conditions develop in the Colorado River at the Lees Ferry Gage as a result of a large flood on the Paria River. The stage of the Colorado River at the Lees Ferry Gage increased by slightly more than 1 ft as a result of the Paria River flood entering the Colorado River just downstream from the gage. This event was the largest backwatering event ever recorded at the Lees Ferry Gage due to a Paria River flood. Backwatered flow conditions lasted 8 hours before an increase in the discharge of the Colorado River raised the stage to greater than 13.9 ft at the Lees Ferry Gage.
October 1, 1929	The first suspended-sediment samples were collected at Lees Ferry. Samples were collected at three locations across the cross-section; no mention was made of which cableway was used, but it was probably the Lower Cableway. Sampler used was the old Colorado River Sampler described in Howard (1930, 1947).
February 1930	Rock fill extended up to the level of the gage house platform (fig. B6).
May–June 1930	Suspended-sediment laboratory notes for these 2 months state that the samples were weighed in Washington, D.C. All subsequent samples were probably analyzed on site at the sediment laboratory at Lees Ferry (fig. 1*C*).
May 24, 1932	Memorandum by J.S. Gatewood describing the suspended-sediment program states that samples are taken at three positions across the Lower Cableway. The preferred stations are at 700, 600, and 450 ft from the left-bank endpoint of the cable, except during extremely low water, when station 450 ft is dry. When this occurs, the stations are shifted to the right. Samples are not taken every day, but only when someone has to cross the Lower Cableway for some other reason. Hydrographer at Lees Ferry, using a balance, weighs all of the empty and full bottles, and empty and full filter papers.
June 11, 1932	Lower inclined section of the Cable Gage washed out during a period of high water. It was replaced on June 11 with a new temporary section consisting by a 2"x6"x12’ timber on which feet and tenths were marked by saw marks and paint. The section of the gage replaced extended from 18.5 ft to 25.5 ft. Section below this was also free, but was still below water.
September 11, 1932	Lower inclined section of the Cable Gage permanently repaired during the early part of September, with levels run on September 11. The new section extends from 16 ft to 25 ft on the slope. From 13.5 ft to 16 ft, the gage is attached to a vertical post driven as far as possible down into the bank.
May–June 1933	Both wooden A-frames on the Lower Cableway were replaced with steel A-frames. Steel landing towers were built at the left end of the Upper Cableway and at both ends of the Lower Cableway.

Figure B6. March 1933 downstream view of the Lees Ferry Gage and the high level of the rock fill placed behind the gage in 1929–30. The inclined middle section of the old Dugway Gage is in the foreground; compare to view in fig. B2*B*. (Photo taken by the U.S. Geological Survey.)

December 16, 1933	Suspended-sediment sampling program discontinued at Lees Ferry.
March 1941	Staff gage installed on the right bank of the Colorado River, 1.5 miles downstream from the Lees Ferry Gage (fig. B7). This gage was downstream from the gravel bar and downstream from the riffle below the Paria River. The USGS referred to this gage as both the "Lower Paria Gage" and the "staff gage on the Colorado River below the mouth of the Paria River." This gage is herein referred to as the "Lower Staff Gage." It consisted of five enamel sections reading from 0 ft to 16 ft fastened to 2"x6" timber bolted to the vertical rock cliff. The original survey of this gage (a 4-mile circuit of levels) conducted in 1941 determined that the datum of the gage was 3,094.05 ft above the NGVD1929. Resurvey of the gage benchmark by Grand Canyon Monitoring and Research Center staff in the 1990s indicated that the actual datum of this gage was 3,093.98 ft above the NGVD1929.
November 10, 1942	Suspended-sediment sampling program restarted at Lees Ferry. Samples on this day were collected by both throwing the sampler out from the bank and by deploying the sampler from a boat.
November 12, 1942	First suspended-sediment sample collected from the cable. After this date, each suspended-sediment measurement consisted of only one vertical in the cross-section. Measurements were collected typically every 2 days through the end of September 1944.
September 29, 1944	Suspended-sediment sampling program discontinued at Lees Ferry. This date marks the end of the use of the old Colorado River Sampler at Lees Ferry.
December 19, 1944	A large rockfall covered the right-bank anchor of the Upper Cableway. This rockslide caused about 20–25 ft of permanent channel narrowing at the cableway cross-section (fig. 7*C* in Topping and others, 2000). Rock was removed from the cable during February and March 1945. Cable was stretched somewhat, but otherwise appeared undamaged.
March 29, 1945	Excess sag due to the rockfall removed from the Upper Cableway.
October 1, 1947	Daily suspended-sediment sampling program started at Lees Ferry. All samples were collected using the new D-43 depth-integrating sampler. Samples were collected at four stations across the cross-section at the Lower Cableway. The preferred stations were at 330, 510, 620, and 730 ft from the left-bank endpoint of the cable. Frequently, the station at 330 ft was dry. All samples were processed for concentration in the field laboratory at Lees Ferry using standard evaporation procedures. Grain-size analyses were performed on single-vertical samples episodically collected in the center of the channel starting in July 1949. These samples were processed for grain size at the laboratory in Albuquerque, New Mexico.
November 1947	New sediment laboratory at Lees Ferry completed.
February 14, 1951	Suspended-sediment sampling program moved to the Upper Cableway. All samples continued to be collected using a D-43 sampler. Each measurement consisted of three samples collected at centroids of equal discharge across the cross-section.
April 1, 1951	The methodology of collecting the subset of suspended-sediment samples processed for grain-size analysis was changed. Grain-size analyses were now performed on a composite of the three samples collected at centroids of equal discharge across the cross-section.

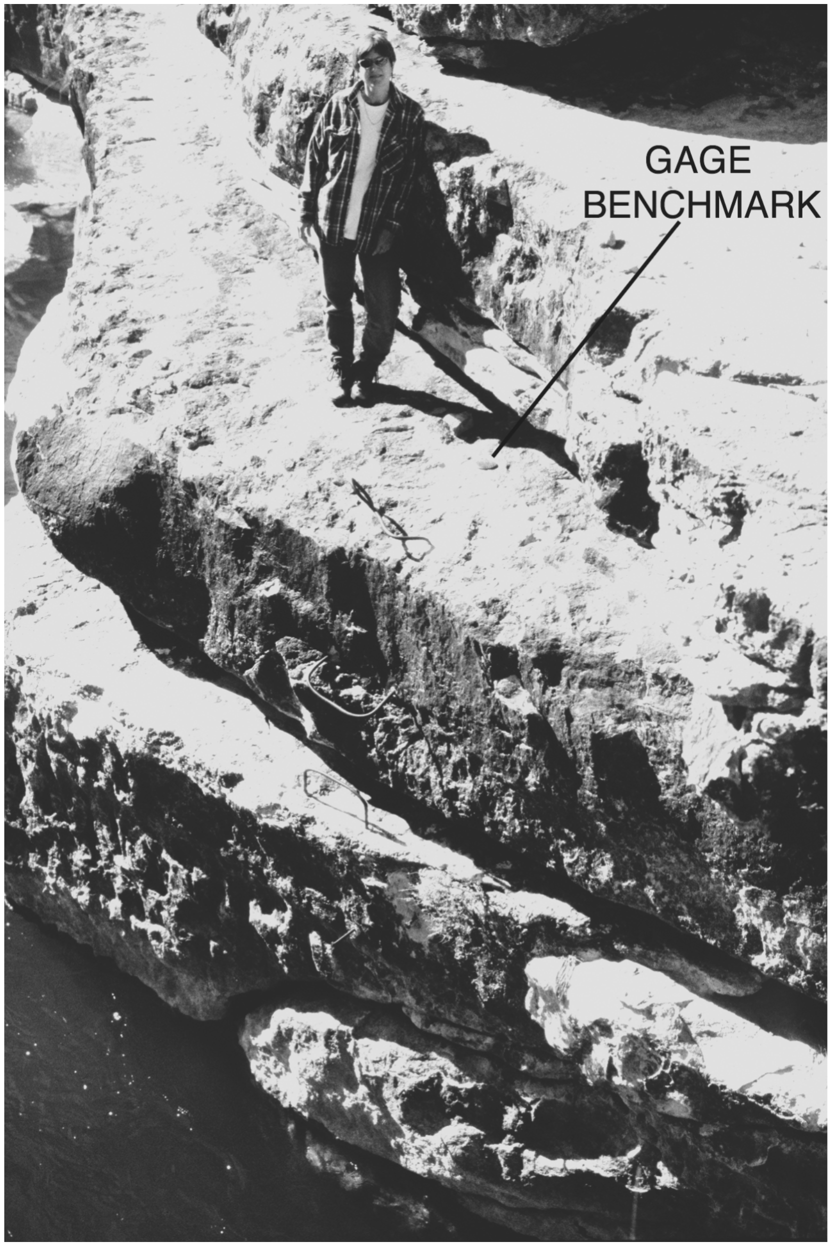


Figure B7. November 13, 2000, downstream view of the remnants of the Lower Staff Gage. Note the ladder rungs attached to the cliff; the Lower Staff Gage was located immediately to the right of this ladder. Stage of the gage benchmark was 17.5 feet on the Lower Staff Gage. (N.J. Hornewer, U.S. Geological Survey, shown for scale, photograph taken by D.J. Topping, U.S. Geological Survey.)

September 21, 1951	Replaced Au stage recorder with a new Stevens A35BT stage recorder.
June 1954	Replaced Stevens A35BT stage recorder with a Stevens A35B stage recorder.
July 1, 1957	Memorandum from Dean Tidball (USGS resident Hydrographer at Lees Ferry) to J.M. Stow (USGS District Chemist, Albuquerque, N.M.) stating that the D-43 sampler was inadequate to sample the entire flow depth at Lees Ferry during higher flows. Tidball wrote, "The D-43 sampler available here proved inadequate for the proper sampling of the Colorado River during its higher stages this year and we were obliged to take some samples to only one half the actual depth at two or three cable stations part of the time. At stages [discharges] under 100,000 ft^3/s we managed to go to full depth at two of the stations. One of these, [the] station [at] 540 [ft from the left-bank endpoint of the cable], required a very fast travel rate for the sampler and due to the difficulty in locating the bottom, resulted in the sampler dragging enough [on the bottom] to collect an excessive amount of silt [all sand, silt, and clay was referred to as silt by the chemists and some hydrographers during this era] on several occasions."
January 8–9, 1958	Hydraulic cable car powered by a gasoline engine installed at the Upper Cableway to allow use of a 300-lb sounding weight during discharge measurements.
Spring 1958	A P-46 point-integrating suspended-sediment sampler was used for the first time at Lees Ferry for routine sampling during higher flows. This sampler was an improvement over the D-43 because it was designed for sampling in deeper, higher-velocity flows, and the nozzle could be opened and closed.
February 11, 1959	Cofferdam completed at Glen Canyon damsite 15.5 miles upstream from the Lees Ferry Gage.
March 13, 1963	Closure of Glen Canyon Dam reduced discharge in the Colorado River at Lees Ferry to 1,000 ft^3/s.
June 12, 1963	Because of excessive sediment in suspension at the Upper Cableway, suspended-sediment samples were collected from a boat near the Lower Cableway from June 12, 1963, through July 10, 1963. Samples collected at 1,000 ft^3/s after July 10, 1963, were collected by wading near the Lees Ferry Gage.
1964	Buildup of aquatic growth on the hydraulic control during spring and summer due to the clear water released from Glen Canyon Dam first observed to cause an increase in roughness in the discharge measurements. Most suspended-sediment samples were once again collected from the Upper Cableway.
October 1965	A D-49 suspended-sediment sampler was now used instead of a D-43 sampler.
February 1965	Lower Cableway disassembled and reinstalled 50 ft upstream from the Lees Ferry Gage. This new cableway is herein referred to as the "Modern Cableway."
April–June 1965	The P-46 suspended-sediment sampler was used during the higher flows released from Glen Canyon Dam during these months.
August 13, 1965	Daily suspended-sediment sampling program discontinued at Lees Ferry.
October 1965	Suspended-sediment samples now collected on a weekly basis at Lees Ferry.
October 30, 1965	First discharge measurement made at Modern Cableway 50 ft upstream from the Lees Ferry Gage.
December 1, 1966	Last discharge measurement made at the Upper Cableway.
February 2, 1967	Digital stage recorder installed in the gage house. This recorder replaces the old Stevens analog chart recorder as the primary stage record.

October 1967	Weekly suspended-sediment sampling program moved from the Upper Cableway to the Modern Cableway. Upper Cableway disassembled sometime after this date.
August 4, 1976	Residency of the USGS hydrographer at Lees Ferry discontinued.
1977	Gravel pit operating on the gravel bar at the mouth of Paria River.
January 4– February 3, 1977	New boat ramp built at Lees Ferry. This reduced the size of an eddy that existed in the right portion of the channel under the cableway.
March 10, 1977	Installation of Convertible Data Collection Platform (CDCP) in gage house. The antenna and two solar panels used to recharge the CDCP batteries were mounted on a mast on the gage house roof. The site address was 16C225534 and the transmission interval was 3 hours.
October 1977	Suspended-sediment sampling frequency changed from weekly to monthly.
April 17, 1982	Cableway struck by helicopter. Pilot and two passengers killed, another hospitalized. No serious damage to cable or support structure.
February 8, 1984	USGS removed gasoline engine and other hydraulic gear from cable car.
November 12, 1986	LaBarge DCP was replaced with a Handar 524 DCP.
March 26, 1987	Wildfire burned 21 acres of tamarisk in the vicinity of the right-bank A-frame of the Modern Cableway. Cable car burned beyond repair, landing platform destroyed by fire, A-frame paint damaged, cable undamaged.

APPENDIX C: December 30, 1929, Memorandum of W.E. Dickinson

File: COLORADO RIVER AT LEES FERRY, ARIZ., 1929.

Colorado River - 1929

Study of Discrepancies.

There is a consistent discrepancy between Lees Ferry and Grand Canyon records for all stages above low-water, the upper discharge being shown larger than the lower.

For purposes of comparison, Lees Ferry, Paria, Grand Falls, and Moenkopi have been combined. The combined record has then been compared with Grand Canyon assuming a time interval of one day during low water and one-half day during high water.

Hydrographs show this comparison:

Various comparable periods have actually been totaled and differences in day-second-feet, and percentage computed.

October to February shows an average increase of 275 second-feet, while March to September shows an average decrease of 925 second-feet. The average decrease for the year is shown to be 425 second-feet instead of an increase which might be expected to be probably not less than 300 second-feet, thus the discrepancy may be considered to be 725 second-feet or about 2.7 percent, for the year.

Detailed comparison for certain periods follows:

L.F. etc.	Mar. 6 - 21	306,460	d.s.f.	
G.C.	Mar. 7 - 22	303,200		
		3,260	d.s.f.	
	16 days	204	s.f.	1.1%
		504	s.f.	2.6%

L.F. etc.	April 2 -15	408,700		
G.C.	Apr.2(½) to 16(½)	399,250		
		9,450	d.s.f.	
	14 days	675	s.f.	2.3%
		975	s.f.	3.3%

L.F. etc.	Apr.15 to May 2.	566,600		
G.C.	Apr.15(½) to May 3(½)	552,900		
		13,700	d.s.f.	
	18 days.	760	s.f.	2.4%
		1,060	s.f.	3.4%
L.F. etc.	May 2 to July 16	5,065,600		
G.C.	May 2(½) to July 17(½)	4,953,600		
		112,000	d.s.f.	
	76 days.	1,475	s.f.	2.2%
		1,775	s.f.	2.7%
L.F. etc.	May 18 to June 3	1,533,100		
	May 18(½) to June 4(½)	1,485,900		
		47,200	d.s.f.	
	17 days.	2,780	s.f.	3.1%
		3,080	s.f.	3.4%
L.F. etc.	June 3 to 22	1,725,300		
G.C.	June 3(½) to 23(½)	1,691,250		
		34,050	d.s.f.	
	20 days	1,700	s.f.	2.0%
		2,000	s.f.	2.3%
L.F. etc.	July 16 to Aug 26.	1,434,500		
G.C.	July 16(½) to Aug 27(½)	1,396,700		
		37,800	d.s.f.	
	42 days	900	s.f.	2.6%
		1,200	s.f.	3.5%
L.F. etc.	Aug.26 to Sept.19	604,400		
G.C.	Aug.26(½) to Sept.20(½)	582,500		
		21,900	d.s.f.	
	25 days	875	s.f.	3.6%
		1,175	s.f.	4.9%
L.F. etc.	Sept. 19 - 29.	355,200		
G.C.	Sept.19(½) to 30(½)	350,250		
		4,950	d.s.f.	
	11 days	450	s.f.	1.4%
		750	s.f.	2.3%

W.E.D.
12-30-29.

-2-

APPENDIX D: Relationship between the Datums of the LaRue and Number 1 Gages

Stages measured on the LaRue Gage prior to it being destroyed during the June 1921 flood were related to the datum of the Number 1 Gage through a three-step process. First, the January 25, 1922, analysis of Roger C. Rice (below) was used for the receding-limb portion of the 1921 flood record, when Frank Johnson "pegged" down the slope. Second, the November 22, 1923, analysis of G.C. Stevens (below) was used for the rising-limb portion of the 1921 flood record, when Frank Johnson "pegged" up the slope after the LaRue Gage was overtopped by water. Third, comparison of the instantaneous discharge record at Lees Ferry with the discharge records from upstream and downstream gaging stations (fig. 18) suggests that Frank Johnson accumulated an error in stage of approximately 1 ft while he "pegged" up the slope during the rising limb of the 1921 flood. In this study, we have distributed this error equally among Johnson's measurements. When combined with the November 22, 1923, analysis of G.C. Stevens, this distributed 1-ft error suggests that the reference point for the LaRue Gage was 3.65 ft higher than the reference point for the Number 1 Gage.

January 25, 1922, memorandum of Roger C. Rice

COLORADO RIVER AT LEE FERRY, ARIZONA, 1921.

LA RUE STAFF GAGE: Original staff gage installed May 8, 1921 on right bank above the mouth of Paria River. Readings made with tape reading distance down from nail R.P. on slope to water surface. (La Rue gage at same location and probably same datum as No. 1 slope gage installed June 24, 1921.)

On June 13, 1921, the water went over the top of the inclined gage and observer, Frank T. Johnson, "pegged" back on right bank as the stage rose, recording each reading in the gage book as additional vertical height above the last reading. On June 18, 2 p.m. the river reached its crest and then began to fall. Observer then "pegged" down again until the top of the old inclined staff gage was exposed. He found that the bottom of the inclined gage had broken loose, and from best recollection it is believed that the top of the inclined gage was still in the same place, the gage having swung about this point and was no longer in the original position of slope 2:1 as originally set. On June 24, 1921, observer rebuilt the inclined gage at same location but probably not at same slope as originally set. It is believed that the elevation of the R.P. was unchanged or at approximately the same elevation. This assumption appears to be borne out in the graphic interpretation of the method used during the high stages (Figure 1.) Beginning June 25, 1921, all readings down the slope from the R.P. were made by observer and recorded in gage book in feet and inches.

On September 26, 1921, Roger C. Rice, District Engineer, and I. G. Cockroft, ran a closed line of levels from this gage, called "No. 1 gage" and tied in the highwater mark set by Frank Johnson, which was described as "Top of nail in board, vertical, on south side of road near wash, said to be highwater mark June 18, 1921 and set by Frank Johnson." This elevation was found to be G. Ht. 30.89 feet on No. 1 gage datum, datum of low water section, enameled gage face. The elevation of the nail R.P. used since the June, 1921 highwater was found to be elevation of G. Ht. 22.99 feet. Foot marks on the inclined gage section were also set, and their distance down from the R. P. determined, from which a gage relation table was developed.

With these data, and the original record of the gage observer, it was found necessary to adjust the "pegged" readings up and back as noted on Figure 1.

COLORADO RIVER AT LEE FERRY, ARIZONA, 1921.
LA RUE GAGE: (CONT'D)

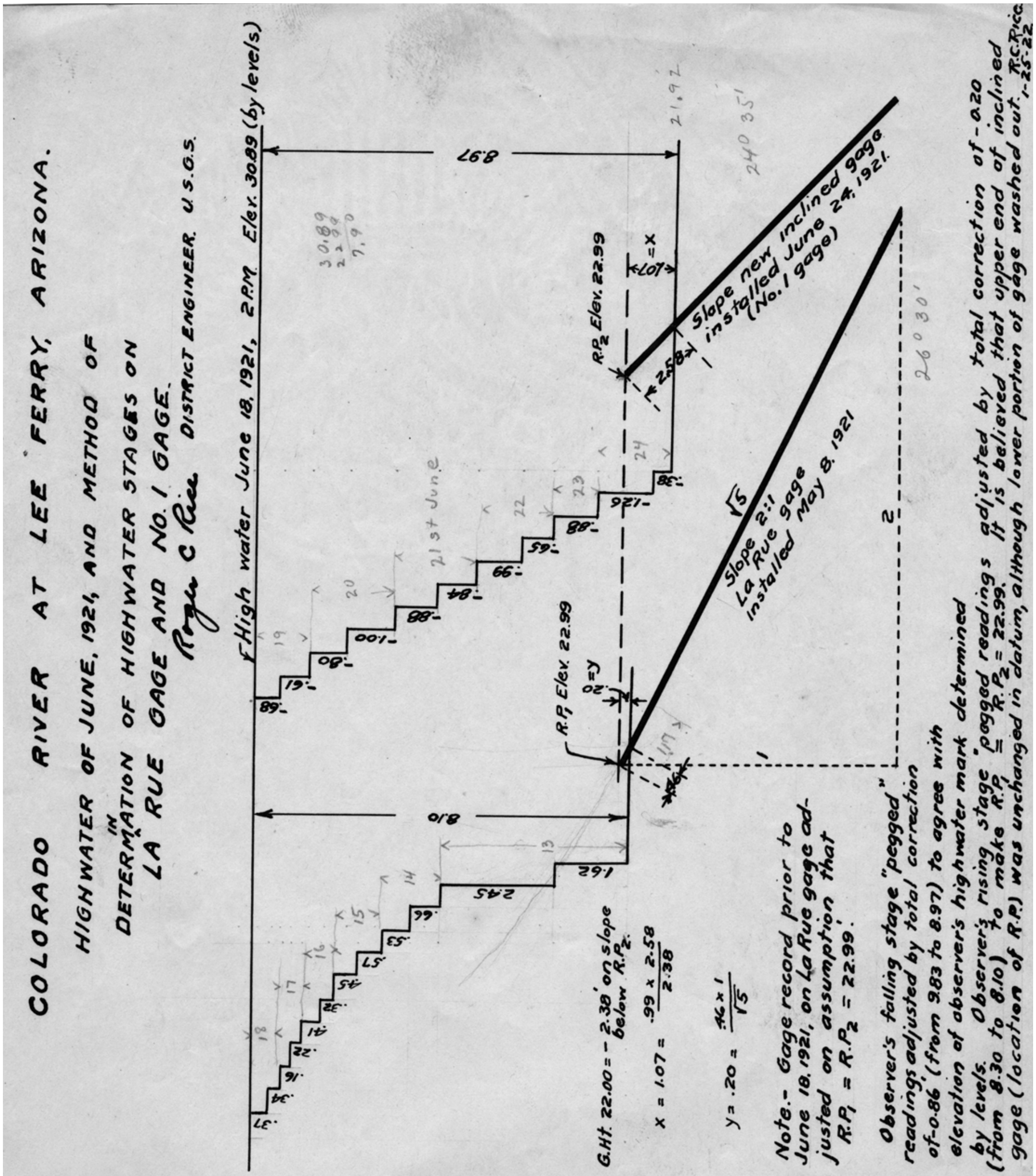
On June 24, 1921, 6 p.m. the observer read the water stage by two methods, (1) from his "pegged" reading and (2) from distance down the slope from R.P.

Distance down from R.P. was -2' 7"" or 2.58 feet, or Gage height 21.92 feet as determined later from levels (Sept, 26, 1921)

Observer's "pegged" readings from this elevation to highwater were adjusted -.86 foot, to make the gage height of the high water of June 18, 1921 agree with the elevation of 30.89 feet as determined by levels on September 26, 1921.

Observer's "pegged" readings from this highwater of June 18 to the elevation recorded June 12, at 5 p.m. ~~xxx~~ were adjusted ~~x20~~ -.20 foot, in order that the elevation of R.P. used for La Rue gage should be the same as R.P. used for what we call No. 1. gage. This is on the assumption that the R.P. elevation of the La Rue gage and No. 1 gage were the same as above explained. If this assumption is not true, then the R.P. for La Rue gage would be at elevation 22.79 feet.

Roger C. Rice,
January 25, 1922.


COLORADO RIVER AT LEE FERRY, ARIZONA.
HIGHWATER OF JUNE, 1921, AND METHOD OF DETERMATION IN OF HIGHWATER STAGES ON LA RUE GAGE AND NO. 1 GAGE.
Roger C Rice
DISTRICT ENGINEER. U.S.G.S.
High water June 18, 1921, 2 P.M. Elev. 30.89 (by levels)
8.97
8.10
R.P.1 Elev. 22.99
R.P.2 Elev. 22.99
Slope new inclined gage installed June 24, 1921. (No. 1 gage)
Slope 2:1 La Rue gage installed May 8. 1921
G.Ht. 22.00 = -2.38' on slope below R.P.2
x = 1.07 = .99 x 2.58 / 2.38
y = .20 = .46 x 1 / √5
Note.- Gage record prior to June 18, 1921, on La Rue gage adjusted on assumption that R.P.1 = R.P.2 = 22.99.
Observer's falling stage "pegged" readings adjusted by total correction of -0.86 (from 9.83 to 8.97) to agree with elevation of observer's highwater mark determined by levels. Observer's rising stage "pegged readings adjusted by total correction of -0.20 (from 8.30 to 8.10) to make R.P.1 = R.P.2 = 22.99. It is believed that upper end of inclined gage (location of R.P.) was unchanged in datum, although lower portion of gage washed out.
R.C.Rice 1-25-22

November 22, 1923, memorandum of G.C. Stevens

COLORADO RIVER AT LEES FERRY, 1921.

Stage records during flood of 1921.

I have made a different interpretation of the records obtained by the so-called "LaRue gage" which was used from May 8 to June 13. (See Mr. Rice's memo. and sketch dated Jan. 25, 1922).

The procedure is to work back from the No. 1 gage which was installed June 24. The R. P. of this gage and the crest of the flood on June 18 were tied in by levels in September, 1921. The pegged readings between June 18 and 24 are therefore reliable and I have accepted Mr. Rice's interpretation of this part of the record.

The pegged readings for June 13 to 18, show on June 13, two readings of much greater magnitude than any of the others. These were the first pegged readings after the water rose above the LaRue gage and I suggest that they were measurements <u>along a slope</u> up from the R. P. of the gage and not vertical measurements. If we start from the crest stage of June 18, gage height 30.89, and work back the following results are obtained.

June	18	2 p.m.			30.89	
	18	6 a.m.	deduct	0.38	30.51	
	17	6 p.m.	"	.35	30.16	
	17	5.30 a.m.	"	.17	29.99	
	16	5.30 p.m.	"	.23	29.76	
	16	5 a.m.	"	.42	29.34	
	15	5.30 p.m.	"	.33	29.01	
	15	6 a.m.	"	.46	28.55	
	14	5 p.m.	"	.58	27.97	
	14	5.30 a.m.	"	.54	27.43	
	13	5 p.m.	"	.67	26.76	
	13	6 a.m. (2.5-1.67).447	=	.37	26.39	
	(a)	(1.67 x .447)	=	.75	25.64	(a)
	12	5 p.m. (22.79 + 2.65)			25.44	
	12	5.30 a.m. (22.46 + 2.65)			25.11	

(a) This computation gives elevation of R. P. of LaRue gage and is (25.64 - 22.99) or 2.65 feet higher than used by Mr. Rice. The readings for previous days may now be obtained by adding 2.65 feet to the heights obtained by Mr. ~~LaRue~~ Rice.

The rating table for No. 1 gage was applied to the gage heights thus obtained and daily discharge found which is somewhat less than obtained by Mr. Rice by adding an arbitrary correction of 3.2 feet. The daily discharge is shown to be too small however when compared with the combined discharge of Green River at Little Valley and Colorado River at Fruita. The hydrographs for these records cross each other on June 13. It appears, therefore, that the records for the LaRue gage are not correctly interpreted and daily discharge for Lees Ferry cannot be computed prior to June 13, 1921.

The gage heights obtained by the procedure outlined appear on form 9-192-a for 1921, for No. 1 gage.

G.C.S. 11/22/23

APPENDIX

Discussed this question at considerable length with LaRue and Holbrook. LaRue's opinion is that slope of original gage was about 32 degrees instead of 2 to 1. No proof however. There are, therefore, 3 doubtful points (1) Was original reference point at same elevation as that on later gage? (2) Slope of original gage and (3) How were the two large readings of June 13 made, vertical or slope measurements.

Conclusion reached that stages before June 13 cannot be correlated with later stages on No. 1 gage from information available. Make discharge record begin on June 13. Some doubt, of course, about correct stage on June 13 as used in preparing discharge for that day.

G.C.S. 3/15/24

copy sent WED Mar 31, 1924

APPENDIX E. Days with Disagreement Greater than or Equal to 5 Percent between the Daily Mean Discharge Computed from the Continuous Record of Instantaneous Discharge and the Published Daily Mean Discharge

Appendix E. Days with disagreeament greater than or equal to 5 percent between the daily mean discharge computed from the continuous record of instantaneous discharge and the published daily mean discharge

[MST, Mountain Standard Time; ft^3/s, cubic foot per second; %, percent]

Date	Disagree-ment (percent)	Published discharge (ft^3/s)	Computed discharge (ft^3/s)	Reason for disagreement
6-13-1921	-7.8	153,000	141,000	Peak discharge of the June 1921 flood was revised as part of this study. The published daily mean discharges for this period were computed using the 1938 revised rating curve of Gatewood and Hunter (rating curve 5-03-38). In this study, discharges prior to June 26, 1921, were computed using the stage-discharge rating curve in fig. 13.
6-14-1921	-11.8	169,000	149,000	
6-15-1921	-15.7	185,000	156,000	
6-16-1921	-18.3	197,000	161,000	
6-17-1921	-19.1	204,000	165,000	
6-18-1921	-21.5	214,000	168,000	
6-19-1921	-19.4	201,000	162,000	
6-20-1921	-16.4	177,000	148,000	
6-21-1921	-12.5	152,000	133,000	
6-22-1921	-7.8	129,000	119,000	
6-23-1921	-7.0	114,000	106,000	
7-26-1921	+8.6	26,600	28,900	The daily mean stage measured on July 26, 1921, was 0.09 ft higher than that measured on July 25, 1921, and was 0.22 ft higher than that measured on July 27, 1921. The published daily mean discharge on July 25, 1921, was 27,700 ft^3/s, and the published daily mean discharge on July 27, 1921, was 26,600 ft^3/s. Therefore, the discharge on July 26, 1921, could not have equaled 26,600 ft^3/s and should have been slightly higher than 27,700 ft^3/s. No discharge measurements were made on this day to justify the published value of 26,600 ft^3/s.
7-30-1921	+15.3	26,200	30,200	The daily mean stage on July 30, 1921, was 0.59 ft less than that measured on July 29, 1921, and 0.52 ft greater than that measured on July 31, 1921. The published daily mean discharge on July 29, 1921, was 33,200 ft^3/s, and the published daily mean discharge on July 31, 1921, was 25,500 ft^3/s. Therefore, the daily mean discharge on July 30, 1921, should have been closer to 33,200 ft^3/s than 25,500 ft^3/s. No discharge measurements were made on this day to justify the published value of 26,200 ft^3/s.
9-15-1921	+5.0	10,000	10,500	On this day, the measured discharge was 10,400 ft^3/s and the stage varied by only 0.08 ft. The daily mean discharge calculated from the continuous record of instantaneous discharge is much closer to the measured value than is the published daily mean discharge.
10-2-1921	-5.9	11,800	11,100	Staff gage readings at 7:35 and 17:40 MST yield a daily mean stage of 8.85 ft for the day. This was the stage value used to compute the published daily mean discharge. The real daily mean stage was probably lower than 8.85 ft, however, because the reading on October 1, 1921, at 18:15 was 7.73 ft and the reading on October 3, 1921, at 8:15 was 7.93 ft. In this study, linear interpolation was used between the time of all four of these gage readings in the computation of the daily mean discharge.
1-13-1922	+8.7	3,900	4,240	Ice
1-14-1922	+22.7	3,700	4,540	Ice
1-15-1922	+16.2	3,700	4,300	Ice
1-16-1922	+9.5	4,110	4,500	Ice
1-17-1922	+7.8	4,110	4,430	Ice
1-29-1922	+9.9	4,430	4,870	Ice

Appendix E. Days with disagreeament greater than or equal to 5 percent between the daily mean discharge computed from the continuous record of instantaneous discharge and the published daily mean discharge—*Continued*

Date	Disagree-ment (percent)	Published discharge (ft^3/s)	Computed discharge (ft^3/s)	Reason for disagreement
2-03-1922	+11.4	5,020	5,590	Ice
7-11-1922	-5.6	27,000	25,500	In this study, discharge was computed on this day using the stage-discharge rating curve and shifts of Gatewood and Hunter. Measured discharge on this day was 25,500 ft^3/s, a value in agreement with the value computed from the continuous record of instantaneous discharge. The published daily mean discharge was computed using a different rating curve without shifts.
8-25-1922	-5.7	19,300	18,200	Staff gage readings at 8:25, 11:30, and 19:20 MST yield a daily mean stage of 10.15 ft for the day. This was the stage value used to compute the published daily mean discharge. The real daily mean stage was probably lower than 10.16 ft, however, because the reading on August 24, 1922, at 18:55 was 8.92 ft, and the reading on August 26, 1922, at 6:50 was 10.10 ft. In this study, linear interpolation was used between the times of these five gage readings to compute the daily mean discharge.
6-12-1923	+5.1	70,400	74,200	In this study, discharge was computed on this day using the stage-discharge rating curve and shifts of Gatewood and Hunter. The published daily mean discharge was computed using a different rating curve without shifts.
6-13-1923	+5.9	69,900	74,000	In this study, discharge was computed on this day using the stage-discharge rating curve and shifts of Gatewood and Hunter. Measured discharge on this day was 74,300 ft^3/s, a value in close agreement with the value computed from the continuous record of instantaneous discharge. The published daily mean discharge was computed using a different rating curve without shifts.
4-12-1924	+6.0	38,500	40,800	In this study, discharge was computed on this day using the stage-discharge rating curve and shifts of Gatewood and Hunter. Measured discharge on this day was 42,200 ft^3/s. The daily mean discharge of 40,800 ft^3/s computed from the continuous record of instantaneous discharge is only 3.3% lower than the measured value of 42,200 ft^3/s. The published daily mean discharge was computed using a different rating curve without shifts.
4-13-1924	+5.2	40,600	42,700	In this study, discharge was computed on this day using the stage-discharge rating curve and shifts of Gatewood and Hunter. The published daily mean discharge was computed using a different rating curve without shifts.
9-13-1924	+7.9	9,640	10,400	Day should have been subdivided during the computation of the published daily mean discharge. Subdivision of the day into four periods would have brought the daily mean discharge into close agreement with the value computed from the continuous record of instantaneous discharge.
12-24-1924	+12.4	3,400	3,820	Ice
12-25-1924	+14.3	2,800	3,200	Ice
12-26-1924	-13.3	1,500	1,300	Ice
12-28-1924	+13.3	1,200	1,360	Ice
12-30-1924	-11.1	1,350	1,200	Ice
1-01-1925	+23.3	1,500	1,850	Ice
1-02-1925	-5.0	2,400	2,280	Ice
1-24-1925	-5.3	4,900	4,640	Ice
1-28-1925	-6.5	4,900	4,580	Ice
1-31-1925	+6.9	5,800	6,200	Ice
2-01-1925	+7.8	6,000	6,470	Ice

Appendix E. Days with disagreeament greater than or equal to 5 percent between the daily mean discharge computed from the continuous record of instantaneous discharge and the published daily mean discharge—*Continued*

Date	Disagree-ment (percent)	Published discharge (ft^3/s)	Computed discharge (ft^3/s)	Reason for disagreement
2-02-1925	+8.2	6,500	7,030	Ice
2-03-1925	-11.6	8,500	7,510	Ice
2-05-1925	-17.4	8,500	7,020	Ice
1-22-1926	+5.0	5,350	5,620	Ice
1-23-1926	+5.3	5,300	5,580	Ice
1-24-1926	+5.5	5,100	5,380	Ice
12-29-1926	+5.4	2,800	2,950	Ice
12-27-1928	+6.4	3,300	3,510	Ice
8-07-1929	-5.0	65,500	62,200	In this study, discharge was reduced by 3.5% during July 16 through August 26, 1929, on the basis of W.E. Dickinson’s December 30, 1929, memorandum (Appendix C). Prior to this reduction, the daily mean discharge computed from the continuous record of instantaneous discharge was only 2% lower than the published value. See text for justification of this reduction.
9-06-1929	-5.6	32,300	30,500	In this study, discharge was reduced by 4.9% during August 26 through September 19, 1929, on the basis of W.E. Dickinson’s December 30, 1929, memorandum (Appendix C). Prior to this reduction, the daily mean discharges computed from the continuous record of instantaneous discharge were within 5% of the published values on these days. See text for justification of this reduction.
9-07-1929	-5.7	29,700	28,000	
9-08-1929	-6.2	30,800	28,900	
9-09-1929	-6.0	40,200	37,800	
9-10-1929	-5.6	41,100	38,800	
9-11-1929	-5.4	35,400	33,500	
9-14-1929	-5.1	25,700	24,400	
1-08-1931	-5.6	4,100	3,870	Ice
1-11-1931	-5.7	4,200	3,960	Ice
1-12-1931	-7.1	4,200	3,900	Ice
1-13-1931	-6.1	4,100	3,850	Ice
1-14-1931	-6.0	4,200	3,950	Ice
1-15-1931	-6.8	4,400	4,100	Ice
1-16-1931	-5.6	4,500	4,250	Ice
1-17-1931	-8.7	4,600	4,200	Ice
1-18-1931	-6.4	4,500	4,210	Ice
12-20-1931	+8.3	1,800	1,950	Ice
12-21-1931	+5.6	2,150	2,270	Ice
12-22-1931	+6.3	2,400	2,550	Ice
1-25-1932	+6.9	3,750	4,010	Ice
12-31-1932	-5.0	2,600	2,470	Ice
1-01-1933	-5.9	3,700	3,480	Ice
1-05-1933	-10.8	3,800	3,390	Ice

Appendix E. Days with disagreeament greater than or equal to 5 percent between the daily mean discharge computed from the continuous record of instantaneous discharge and the published daily mean discharge—*Continued*

Date	Disagree-ment (percent)	Published discharge (ft^3/s)	Computed discharge (ft^3/s)	Reason for disagreement
1-06-1933	+10.9	3,200	3,550	Ice
1-08-1933	+6.1	3,100	3,290	Ice
1-09-1933	+7.5	3,200	3,440	Ice
1-13-1933	-5.3	4,900	4,640	Ice
1-16-1933	-8.9	4,700	4,280	Ice
1-25-1933	-5.4	5,200	4,920	Ice
2-08-1933	+5.5	4,000	4,220	Ice
2-11-1933	-5.0	2,400	2,280	Ice
2-12-1933	-6.2	2,600	2,440	Ice
2-13-1933	-6.2	4,200	3,940	Ice
1-22-1935	+9.4	4,250	4,650	Ice
1-23-1935	+10.0	3,700	4,070	Ice
1-24-1935	+6.8	2,950	3,150	Ice
9-30-1935	-6.0	20,000	18,800	Stage-discharge rating curve was read incorrectly during the computation of the published daily mean discharge. Instead of computing the discharge associated with a daily mean stage of 10.05 ft, the discharge associated with a stage of 10.30 ft was computed.
1-14-1937	+8.0	3,000	3,240	Ice
1-15-1937	-13.6	2,790	2,410	Ice
1-31-1937	-11.1	4,240	3,770	Ice
2-18-1937	+10.2	10,800	11,900	Discharge was copied incorrectly during the computation of the published daily mean discharge; 11,800 ft^3/s was incorrectly copied as 10,800 ft^3/s.
8-28-1937	-5.7	4,240	4,000	Stage-discharge rating curve was read incorrectly during the computation of the published daily mean discharge. Instead of computing the discharge associated with a daily mean stage of 6.40 ft, the discharge associated with a stage of 6.50 ft was computed.
3-15-1940	-5.2	7,140	6,770	Daily mean stage was incorrectly written on the stage-recorder chart as 7.67 ft instead of 7.57 ft during the computation of the published daily mean discharge.
8-03-1940	-6.1	3,300	3,100	Daily mean stage was incorrectly computed as 6.10 ft instead of 6.08 ft, and the shift was incorrectly applied as +0.05 ft instead of -0.03 ft during the computation of the published daily mean discharge.
4-06-1944	+5.7	10,600	11,200	Day was subdivided incorrectly during the district review of the original computations. Day was originally subdivided into five periods, yielding a daily mean discharge of 10,950 ft^3/s. During district review, the day was subdivided into only three periods, yielding a daily mean discharge of 10,600 ft^3/s. The value of 11,200 ft^3/s computed from the continuous record of instantaneous discharge is only 2.3% higher than the original value of 10,950 ft^3/s.
2-06-1949	-6.0	4,840	4,550	Ice
2-07-1949	-8.0	4,860	4,470	Ice
2-10-1949	-5.1	5,460	5,180	Ice
2-11-1949	-7.2	6,240	5,790	Ice
2-12-1949	-5.2	5,930	5,620	Ice

Appendix E. Days with disagreeament greater than or equal to 5 percent between the daily mean discharge computed from the continuous record of instantaneous discharge and the published daily mean discharge—*Continued*

Date	Disagree-ment (percent)	Published discharge (ft^3/s)	Computed discharge (ft^3/s)	Reason for disagreement
1-04-1950	+7.0	5,400	5,780	Ice
1-05-1950	+7.4	5,400	5,800	Ice
1-06-1950	+8.1	5,300	5,730	Ice
1-07-1950	+5.6	5,000	5,280	Ice
1-08-1950	+7.4	4,700	5,050	Ice
11-11-1952	-6.0	6,130	5,760	Daily mean stage was incorrectly written on the stage-recorder chart as 7.29 ft instead of 7.19 ft during the computation of the published daily mean discharge. See fig. 19.
1-01-1963	+5.3	2,250	2,370	Ice
1-12-1963	+5.4	2,800	2,950	Ice
1-13-1963	-12.5	1,600	1,400	Ice
1-14-1963	-6.0	3,000	2,820	Ice
1-22-1963	-9.2	1,300	1,180	Ice
1-24-1963	+15.0	700	805	Ice
9-01-1964	-25.6	1,800	1,340	During the computation of the published daily mean discharge, this day was subdivided using the wrong mean stage for the hours between 0:00–6:00 MST. The mean stage for these 6 hours was incorrectly recorded as 6.20 ft instead of 5.20 ft. Use of a 5.20 ft stage for 0:00–6:00 MST would have resulted in a daily mean discharge of 1,390 ft^3/s, a value only 3.7% higher than the value computed from the continuous record of instantaneous discharge.
1-21-1965	+8.8	7,250	7,890	Time correction of +100 minutes was not applied during the computation of the published daily mean discharge. Application of this time correction would have resulted in a daily mean discharge of 8,010 ft^3/s, a value only 1.5% higher than the value computed from the continuous record of instantaneous discharge.
1-22-1965	-9.3	7,110	6,450	Time correction of +100 minutes was not applied during the computation of the published daily mean discharge. Application of this time correction would have resulted in a daily mean discharge of 6,370 ft^3/s, a value only 1.5% lower than the value computed from the continuous record of instantaneous discharge.
3-09-1965	-7.2	6,570	6,100	Published daily mean discharge was computed incorrectly. The mean discharge for the first 12 hours of the day was computed as 5,090 ft^3/s, and the mean discharge for the second 12 hours of the day was computed as 7,050 ft^3/s. The average of these two numbers is 6,070 ft^3/s. Instead, a value of 6,570 ft^3/s was written in the final computations.
4-22-1965	+5.6	12,500	13,200	Time correction of -45 minutes was not applied during the computation of the published daily mean discharge. Application of this time correction would have resulted in a daily mean discharge of 13,500 ft^3/s, a value only 2.3% higher than the value computed from the continuous record of instantaneous discharge.
12-03-1965	+6.5	9,450	8,840	Day was subdivided incorrectly during the computation of the published daily mean discharge. Day was only subdivided into three periods, resulting in the published daily mean discharge of 9,450 ft^3/s. Subdivision of the day into five periods would have brought the daily mean discharge into close agreement with the value computed from the continuous record of instantaneous discharge.
12-05-1965	+6.0	7,150	6,720	Day should have been subdivided during the computation of the published daily mean discharge.

Appendix E. Days with disagreeament greater than or equal to 5 percent between the daily mean discharge computed from the continuous record of instantaneous discharge and the published daily mean discharge—*Continued*

Date	Disagree-ment (percent)	Published discharge (ft^3/s)	Computed discharge (ft^3/s)	Reason for disagreement
12-31-1965	-5.2	6,500	6,160	During the computation of the published daily mean discharge, this day was subdivided using the wrong mean stage for the hours between 13:00–24:00 MST. The mean stage for these last 11 hours of the day was recorded as 7.05 ft when it was actually closer to 7.80 ft. Use of a 7.80 ft stage for the last 11 hours of the day would have resulted in a daily mean discharge of 6,200 ft^3/s, a value only 0.6% lower than the value computed from the continuous record of instantaneous discharge.
1-26-1966	-11.4	12,300	10,900	During the computation of the published daily mean discharge, this day was subdivided using the wrong mean discharge for the hours between 3:00–10:00 MST. The mean stage for these 7 hours was written as 7.37 ft on the stage-recorder chart. This corresponded to a discharge of 5,790 ft^3/s on the stage-discharge rating curve in use on January 26, 1966. The incorrect discharge used for these 7 hours was 11,200 ft^3/s during the original computation. Use of the correct mean discharge for 3:00–10:00 MST would have resulted in a daily mean discharge of 10,800 ft^3/s, a value only 0.9% lower than the value computed from the continuous record of instantaneous discharge.
8-07-1966	-7.6	10,600	9,790	During the computation of the published daily mean discharge, this day was subdivided using the wrong mean stage for the hours between 6:00–12:00 MST. The mean stage for these 6 hours written on the stage-recorder chart was 8.16 ft, instead of the correct value of 7.16 ft. Use of a 7.16 ft stage for these 6 hours would have resulted in a daily mean discharge of 9,500 ft^3/s, a value only 3.0% lower than the value computed from the continuous record of instantaneous discharge.
10-09-1966	-9.6	8,120	7,340	During the computation of the published daily mean discharge, a mathematical error was made in the averaging process. The average of the mean discharges for the four periods into which the day was subdivided is 7,310 ft^3/s, not the 8,120 ft^3/s value written on the stage-recorder chart.
10-24-1966	+5.8	8,340	8,820	During the computation of the published daily mean discharge, this day was subdivided incorrectly (into only three periods). Subdivision of the day into four periods would have resulted in a daily mean discharge of 8,500 ft^3/s, a value only 3.6% lower than the value computed from the continuous record of instantaneous discharge.
10-31-1966	+7.8	10,300	11,100	During the computation of the published daily mean discharge, this day was subdivided using the wrong mean stage for the hours between 3:00–12:00 MST. The mean stage for these 9 hours written on the stage-recorder chart was 6.88 ft, when, according to the chart, it was closer to 7.13 ft. Use of a 7.13 ft stage for these 9 hours would have resulted in a daily mean discharge of 11,000 ft^3/s, a value only 0.9% lower than the value computed from the continuous record of instantaneous discharge.
11-06-1966	+9.1	4,600	5,020	During the computation of the published daily mean discharge, this day was subdivided using the wrong mean stage for the hours between 0:00–12:00 MST. The mean stage for these 6 hours written on the stage-recorder chart was 6.79 ft, when, according to the chart, it was closer to 7.05 ft. Use of a 7.05 ft stage for these 12 hours would have resulted in a daily mean discharge of 4,930 ft^3/s, a value only 1.8% lower than the value computed from the continuous record of instantaneous discharge.
1-27-1967	+6.6	9,850	10,500	During the computation of the published daily mean discharge, this day was subdivided incorrectly (into only three periods). Subdivision of the day into four periods would have resulted in a daily mean discharge of 10,500 ft^3/s, a value in perfect agreement with the value computed from the continuous record of instantaneous discharge.

Appendix E. Days with disagreeament greater than or equal to 5 percent between the daily mean discharge computed from the continuous record of instantaneous discharge and the published daily mean discharge—*Continued*

Date	Disagree-ment (percent)	Published discharge (ft^3/s)	Computed discharge (ft^3/s)	Reason for disagreement
2-02-1967	-11.5	12,200	10,800	During the computation of the published daily mean discharge, this day was subdivided using the wrong mean stage for the hours between 3:00–12:00 MST. The mean stage for these 9 hours written on the stage-recorder chart was 8.92 ft, when, according to the chart, it was closer to 8.00 ft. Use of a 8.00 ft stage for these 9 hours would have resulted in a daily mean discharge of 10,800 ft^3/s, a value in perfect agreement with the value computed from the continuous record of instantaneous discharge.
6-01-1967	-5.5	10,900	10,300	Published daily mean discharge was copied incorrectly from the final computations. Daily mean discharge written in the final computations in the annual technical file was 10,100 ft^3/s.
11-19-1967	-16.4	5,420	4,530	During the computation of the published daily mean discharge, the daily mean discharge was copied incorrectly from the stage-recorder chart. Daily mean discharge written on the stage-recorder chart was 4,520 ft^3/s; daily mean discharge copied into the final computations was 5,420 ft^3/s. The 5 and the 4 were transposed when the number was copied.
1-24-1970	+6.1	4,590	4,870	Lower intakes in the gage stilling well were plugged on January 24 and 25, 1970. During the computation of the published daily mean discharge, these days were subdivided using estimated mean stages that were probably too low for parts of each day.
1-25-1970	+5.1	2,530	2,660	
2-08-1970	+7.7	3,100	3,340	Lower intakes in the gage stilling well were plugged. During the computation of the published daily mean discharge, the day was subdivided using an estimated mean stage for the hours of 4:00–21:00 MST that was probably too low.
3-11-1971	-7.8	11,600	10,700	Error of unknown origin in the published daily mean discharges for March 11 and 12, 1971. Published record for March 10, 1971, through March 13, 1971, has too much water passing Lees Ferry relative to the gaging station immediately below Glen Canyon Dam. Mean of the published discharges at the gaging station below Glen Canyon Dam for March 9, 1971, through March 12, 1971, is 10,200 ft^3/s, mean of the published discharges at Lees Ferry for March 10, 1971, through March 13, 1971, is 10,800 ft^3/s. In this study, instantaneous discharges were computed using stages from the time-corrected stage-recorder graph record on these days. The mean discharge for March 10, 1971, through March 13, 1971, computed from the continuous record of instantaneous discharge is 10,400 ft^3/s (a value only 2.0% higher than 10,200 ft^3/s).
3-12-1971	-6.3	11,200	10,500	
11-07-1971	+5.3	7,560	7,960	Published daily mean discharge on this day was based on stages digitally recorded every 2 hours. The discharge on this day, however, was more variable than could be captured by the 2-hour punch data. Daily mean stage determined from the stage-recorder graph was 7.75 ft; daily mean stage determined from the bi-hourly digital stage record was 7.69 ft. This stage difference corresponds to a discharge error of about -460 ft^3/s.
12-16-1973	+5.4	3,330	3,510	Published daily mean discharge on this day was based on stages digitally recorded every 2 hours. The discharge on this day, however, was more variable than could be captured by the 2-hour punch data. Daily mean stage determined from stage-recorder graph was 6.14 ft; daily mean stage determined from the bi-hourly digital stage record was 6.07 ft. This stage difference corresponds to a discharge error of about -140 ft^3/s.
3-01-1974	-22.4	11,000	8,540	Published daily mean discharge was copied incorrectly from the final computations. The daily mean discharge written in the final computations in the annual technical final was 8,400 ft^3/s.

Appendix E. Days with disagreeament greater than or equal to 5 percent between the daily mean discharge computed from the continuous record of instantaneous discharge and the published daily mean discharge—*Continued*

Date	Disagree-ment (percent)	Published discharge (ft^3/s)	Computed discharge (ft^3/s)	Reason for disagreement
4-23-1975	+5.1	8,750	9,200	Digital recorder error. Digital stage recorder was erratic the entire month of April 1975. Values recorded on the digital recorder on this day were especially erratic. Because the stages recorded on the stage-recorder graph seemed more correct, these stages were used in this study to compute discharges on this day.
12-26-1976	+5.1	4,530	4,760	Gage was silted in on this day. During the computation of the published daily mean discharge, this day was subdivided by hand using the wrong mean stage for the hours between 14:00–21:00 MST. The mean stage for these 7 hours written on the chart was 6.80 ft, when, according to the chart, it was closer to 6.95 ft. Use of a 6.95 ft stage for these 7 hours would have resulted in a daily mean discharge of 4,640 ft^3/s, a value only 2.5% lower than the value computed from the continuous record of instantaneous discharge.
3-08-1977	+10.5	7,320	8,090	Published daily mean discharge was determined by subdividing the record on the stage-recorder chart instead of using the digital record. Daily mean discharge from the digital recorder was 8,110 ft^3/s, only 0.2% greater than our value of 8,090 ft^3/s. During hand subdivision, the wrong mean stage was used for the hours between 3:00–12:00 MST. The mean stage for these 9 hours written on the chart was 5.55 ft, when, according to the chart, it was closer to 6.55 ft. Use of a 6.55 ft stage for these 9 hours would have resulted in a daily mean discharge of 8,010 ft^3/s, a value only 1.0% lower than the value computed from the continuous record of instantaneous discharge.
3-30-1977	+5.1	8,580	9,020	Published daily mean discharge was computed from the digital record mistakenly using only the stages measured from 16:00–24:00 MST.
7-31-1977	+37.6	12,500	17,200	Digital record for this day was lost by the USGS. Based on the stage-recorder chart record, the daily mean discharge computed from the continuous record of instantaneous discharge seems to be correct. The stage-recorder chart record indicates that daily mean discharge for this day should be close to that on July 30, 1977 (i.e., 17,100 ft^3/s).
11-24-1977	-6.0	3,150	2,960	The published daily mean discharge was computed from the stage-recorder chart record. During hand subdivision of the record, a mean stage of 5.50 ft was used for the hours of 6:00–12:00 MST, when the mean stage for these 6 hours was closer to 5.75 ft.
11-29-1977	-14.0	6,410	5,510	Published daily mean discharge was based only on the digital record for the hours of 14:00–24:00 MST. Daily mean discharge using the stage-recorder chart record for 0:00–14:00 MST and the digital record for 14:00–24:00 MST was written on the printout of the digital record as 5,390 ft^3/s. This value was not copied into the final computations.
3-07-1979	+12.7	1,100	1,240	Gage was silted in during many hours on March 7 through 25, 1979. The published daily mean discharges for this period were thus determined by hand subdivision of the stage-recorder chart record. During this process, time corrections of 1–2 hours were not applied, leading to the errors in the published record.
3-08-1979	-10.3	1,260	1,130	
3-11-1979	-16.8	1,170	973	
3-12-1979	+12.6	1,030	1,160	
3-18-1979	+17.3	878	1,030	
3-25-1979	-7.0	1,150	1,070	

Appendix E. Days with disagreeament greater than or equal to 5 percent between the daily mean discharge computed from the continuous record of instantaneous discharge and the published daily mean discharge—*Continued*

Date	Disagreement (percent)	Published discharge (ft^3/s)	Computed discharge (ft^3/s)	Reason for disagreement
12-27-1979	+10.5	11,400	12,600	Digital recorder malfunction or digital tape read incorrectly during the computation of the published daily mean discharge. Digital record abruptly lost 13.5 hours between 13:00 and 16:00 MST on December 27, 1979. Digital record from 16:00 MST on December 27, 1979. through 13:00 MST on January 3, 1980, was 13.5 hours behind the stage-recorder chart record. Digital record then abruptly regained the 13.5 hours it lost at 13:00 MST on January 3, 1980. Based on comparison with the record from the Grand Canyon gaging station, the stage-recorder chart record for this period was probably correct. In this study, therefore, discharges for this period were computed by using the time-corrected stage-recorder chart record.
12-29-1979	+80.4	4,790	8,640	
12-30-1979	-14.2	2,530	2,170	
12-31-1979	+64.3	2,130	3,500	
1-01-1980	-48.7	2,650	1,360	
1-02-1980	-26.1	8,560	6,330	
10-09-1980	+7.2	15,300	16,400	Published daily mean discharge was computed using the stage-recorder graph record. Values written on the chart using two different subdivisions were 16,000 and 16,400 ft^3/s. These values were copied incorrectly into the final computations as 15,300 ft^3/s.
3-26-1982	+9.8	12,200	13,400	Digital recorder malfunction between 19:00–21:00 MST. Stage value recorded at 19:00 was 6.53 ft, when it should have been 9.53 ft; stage value recorded at 20:00 was 6.74 ft when it should have been 9.74 ft; stage value recorded at 21:00 was 7.36 ft, when it should have been 10.06 ft.
7-09-1982	+27.6	12,300	15,700	Published daily mean discharge was computed by hand subdivision of the stage-recorder chart record. During hand subdivision, the wrong mean stage was used for the hours between 12:00–24:00 MST. The mean stage for these 12 hours was written as 9.5 ft, when, according to the chart, it was closer to 10.5 ft.
3-02-1983	+22.5	12,900	15,800	Digital recorder malfunction from 13:00 MST on March 2, 1983, through 5:00 MST on March 3, 1980. Stage values in the digital record between these times were determined incorrectly by linearly interpolation.
3-03-1983	+5.3	13,200	13,900	
4-10-1983	-6.2	16,100	15,100	Digital recorder malfunction. Published daily mean discharge was computed by hand using an incorrect weighted mean stage of 9.87 ft for the day. Daily mean stage was 9.67 ft, weighted daily mean stage should have been closer to 9.7 ft.
6-03-1986	-8.5	44,500	40,700	Digital recorder malfunction from 1:00-13:00 MST. Digital stage record is 1.13 ft too high between 5:00 and 9:00 MST. Stages in the digital record were linearly interpolated between the correct value at 1:00 MST and the incorrect value at 5:00 MST, and between the incorrect value at 9:00 MST and the correct value at 13:00 MST.

APPENDIX F: Monthly Flow-Duration Curves Computed from the Continuous Record of Instantaneous Discharge

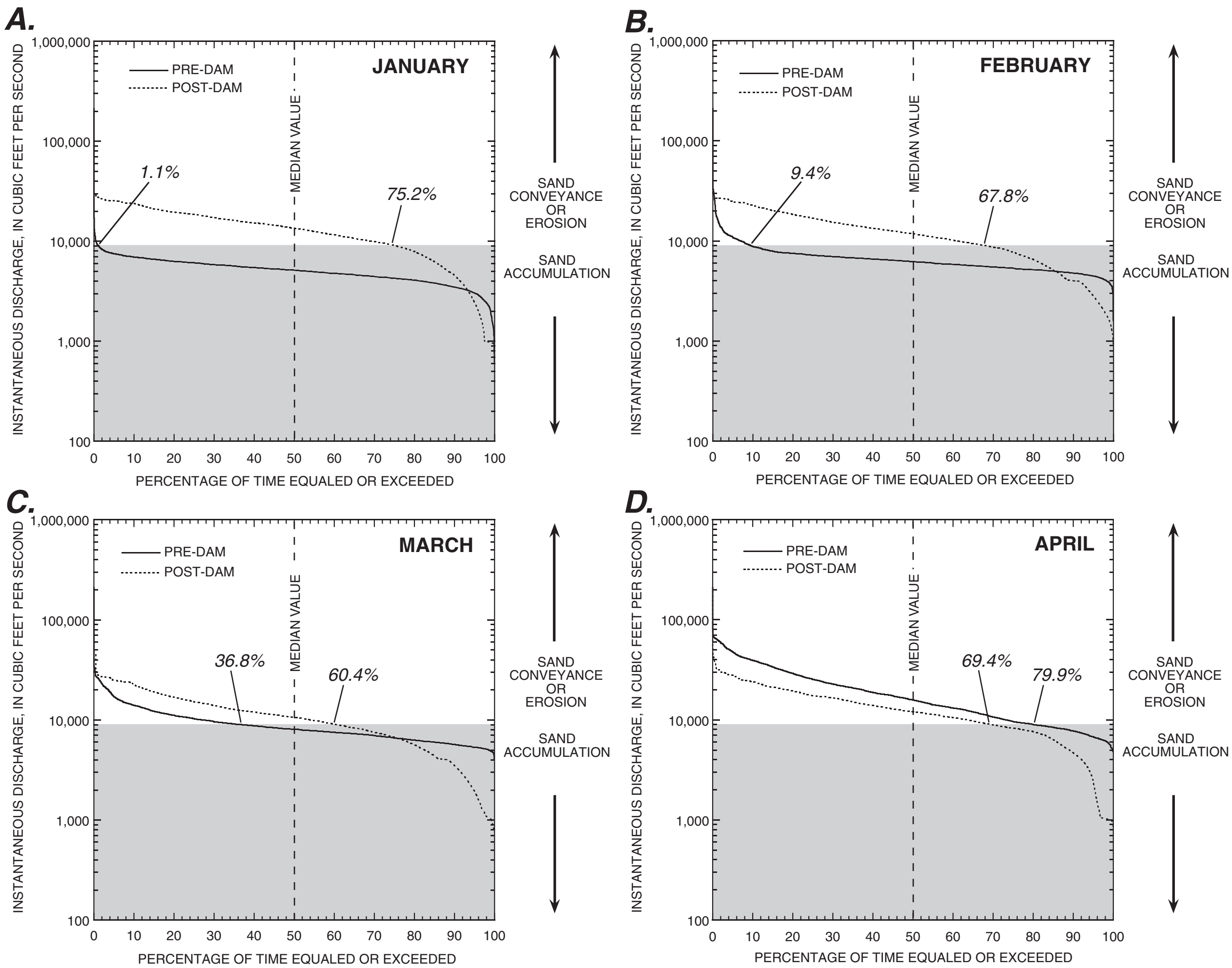


Figure F1. The monthly flow-duration curves for the pre- and post-dam periods of record for the Colorado River at Lees Ferry. The gray shaded region shows the pre-dam discharge range under which sand accumulated in the reach between the Lees Ferry and Grand Canyon gaging stations, in Marble and upper Grand Canyons (Topping and others, 2000). The percentages of time each month when these discharges were exceeded during the pre- and post-dam periods are indicated in italics. (*A*) January. (*B*) February. (*C*) March. (*D*) April.

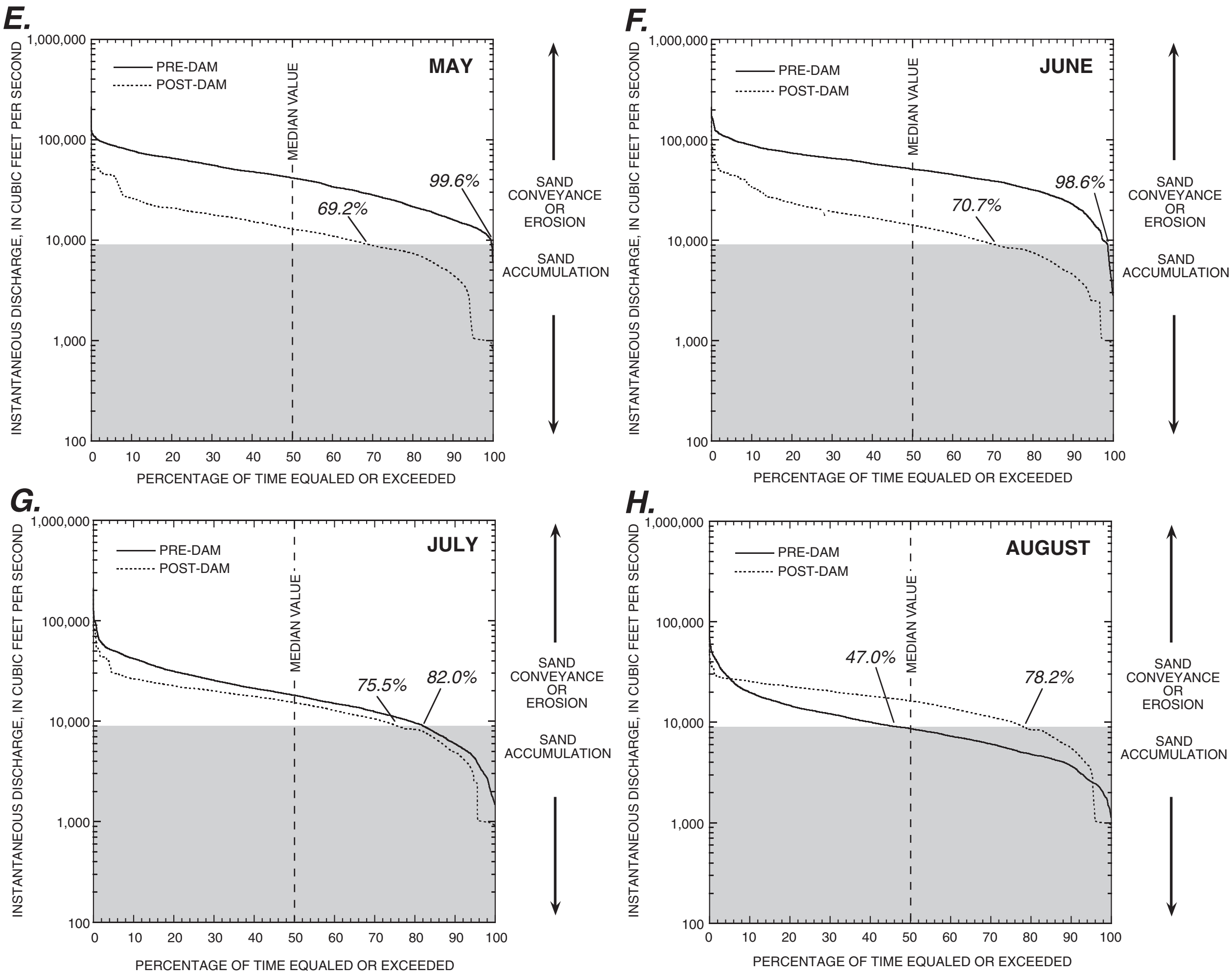


Figure F1—*Continued.* Monthly flow-duration curves for the pre- and post-dam periods of record for the Colorado River at Lees Ferry. The gray shaded region shows the pre-dam discharge range under which sand accumulated in the reach between the Lees Ferry and Grand Canyon gaging stations, in Marble and upper Grand Canyons (Topping and others, 2000). The percentages of time each month when these discharges were exceeded during the pre- and post-dam periods are indicated in italics. (*E*) May. During May in the pre-dam period, discharges under which sand accumulated in Marble and upper Grand Canyons were exceeded 99.6 percent of the time. May was the pre-dam month of greatest erosion in Marble and upper Grand Canyons (Topping and others, 2000, fig. 10*C*). (*F*) June. During this month in the pre-dam period, discharges under which sand accumulated in Marble and upper Grand Canyons were exceeded 98.6 percent of the time. June was the pre-dam month of second greatest erosion in Marble and upper Grand Canyons (Topping and others, 2000, fig. 10*C*). (*G*) July. During this month in the pre-dam period, discharges under which sand could likely accumulate in Marble and upper Grand Canyons were exceeded 75.5 percent of the time; during July in the post-dam period, these discharges were exceeded 82.0 percent of the time. Although this suggests that sand should have been eroded, minor amounts of sand did accumulate in Marble and upper Grand Canyons during both the pre- and post-dam months of July because of the increased sediment supply from tributaries during this month (Topping and others, 2000, fig. 10). (*H*) August. Because this month is the month of greatest tributary sediment supply, and was characterized by low to moderate discharges during the pre-dam period, August was the pre-dam month of greatest sediment accumulation in Marble and upper Grand Canyons (Topping and others, 2000, fig. 10).

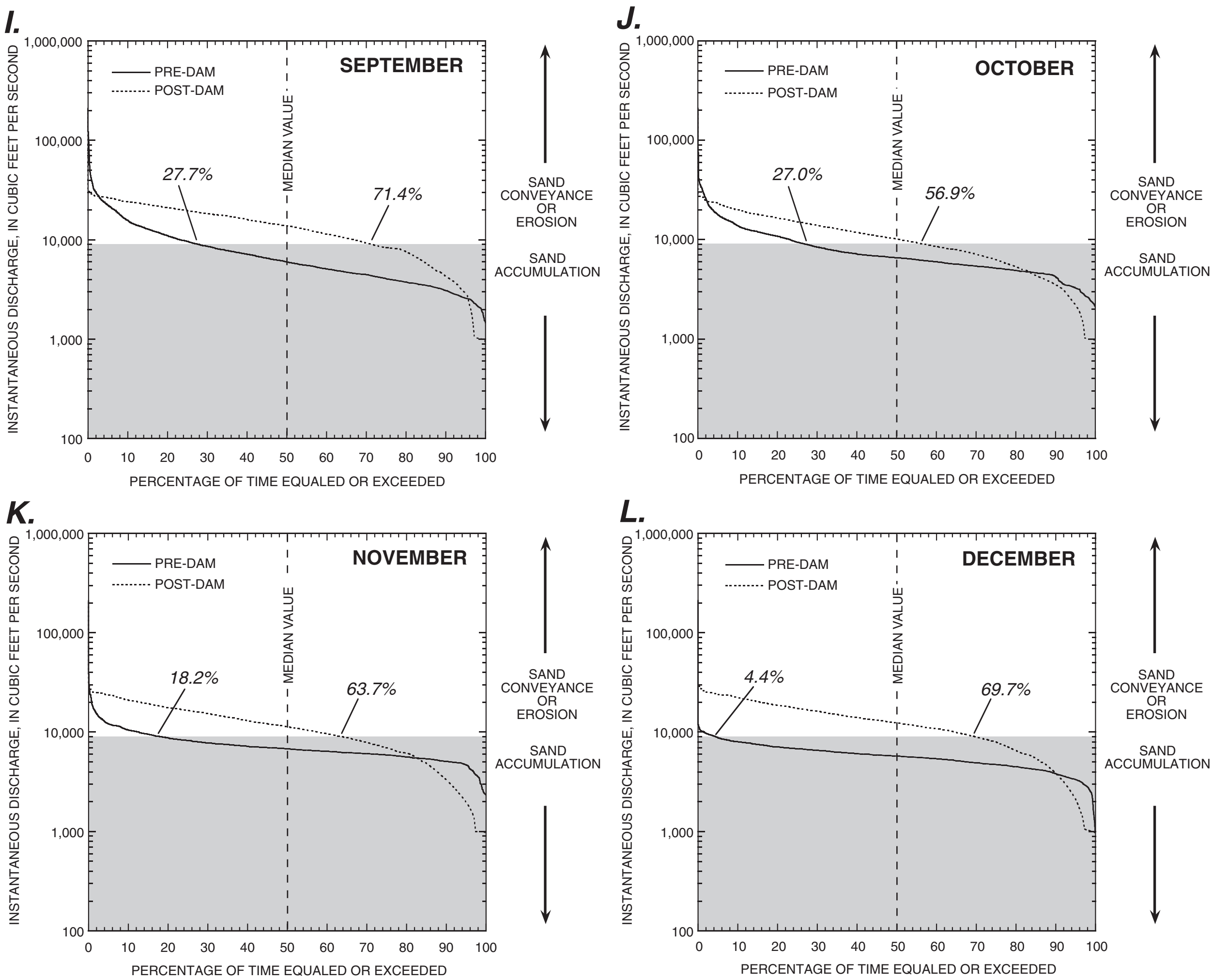


Figure F1—*Continued.* Monthly flow-duration curves for the pre- and post-dam periods of record for the Colorado River at Lees Ferry. The gray shaded region shows the pre-dam discharge range under which sand accumulated in the reach between the Lees Ferry and Grand Canyon gaging stations, in Marble and upper Grand Canyons (Topping and others, 2000). The percentages of time each month when these discharges were exceeded during the pre- and post-dam periods are indicated in italics. (*I*) September. (*J*) October. (*K*) November (*L*) December.

APPENDIX G: Monthly Exceedance Curves of the Daily Range in Discharge Computed from the Continuous Record of Instantaneous Discharge

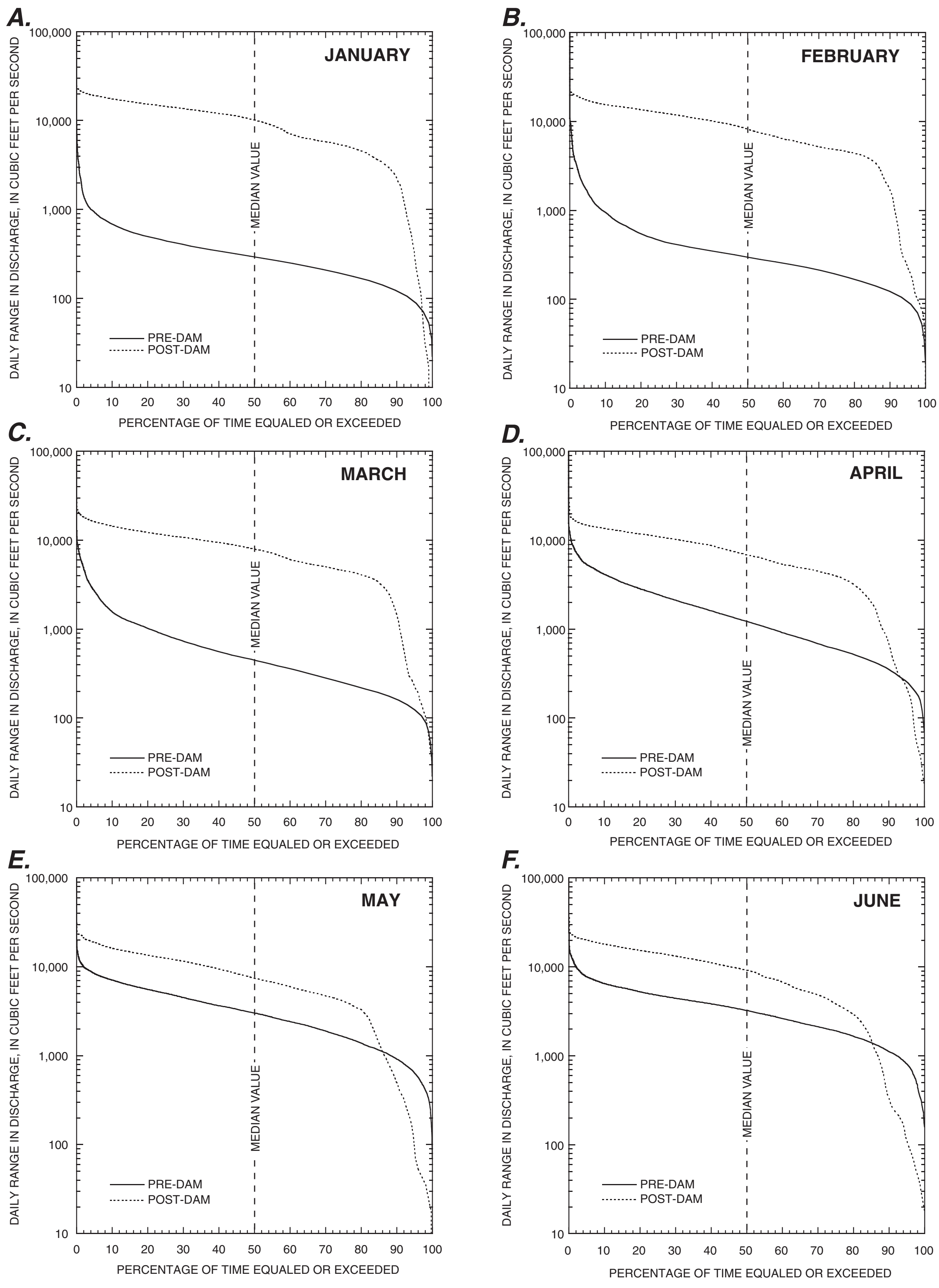


Figure G1. Monthly exceedance curves of the daily range in the discharge of the Colorado River at Lees Ferry for the pre- and post-dam periods. (*A*) January. (*B*) February. (*C*) March. (*D*) April. (*E*) May. (*F*) June.

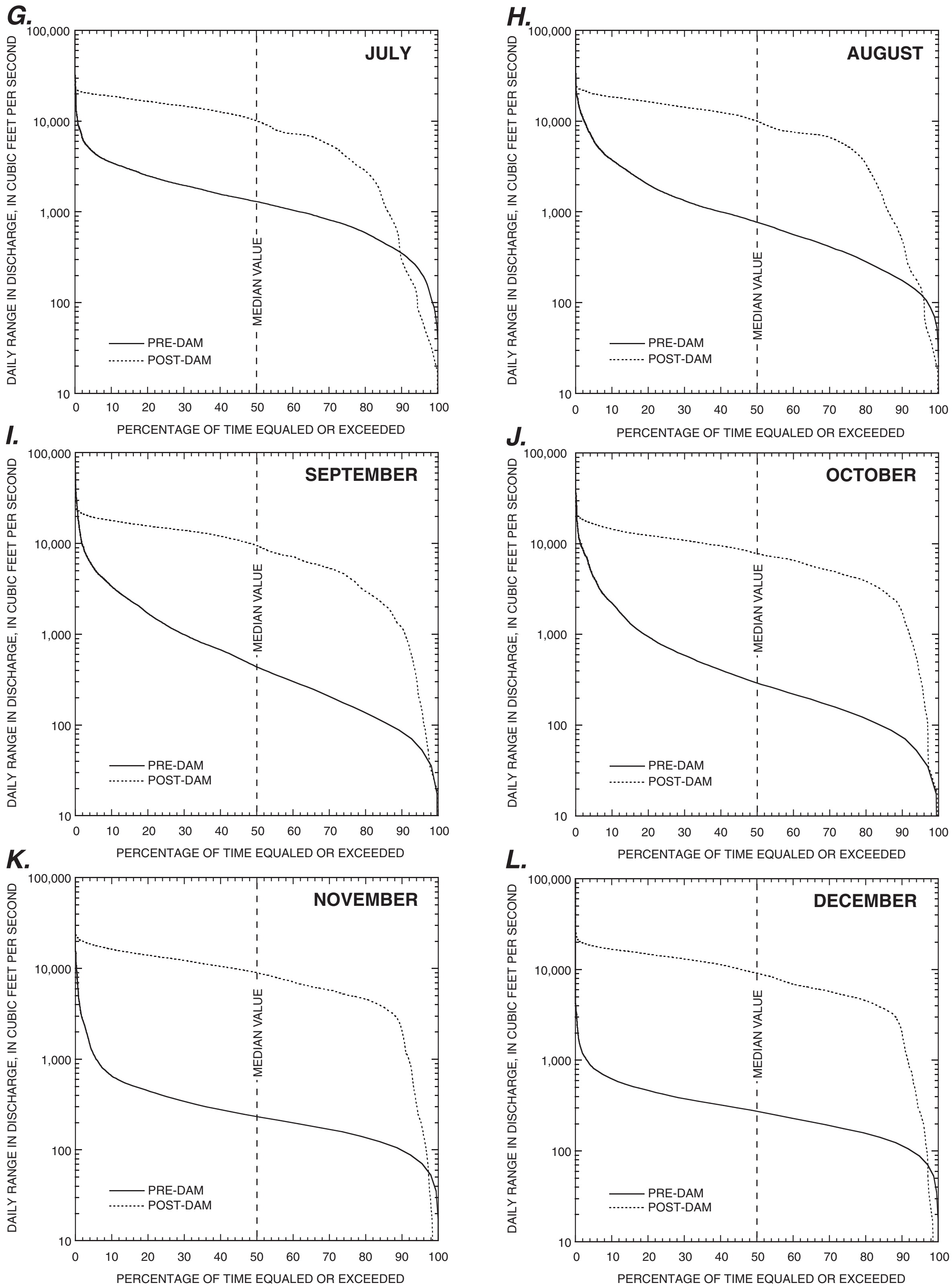


Figure G1—*Continued.* Monthly exceedance curves of the daily range in the discharge of the Colorado River at Lees Ferry for the pre- and post-dam periods. (*G*) July. (*H*) August. (*I*) September. (*J*) October. (*K*) November. (*L*) December.