The Degraded Reach: Rate and Pattern of Bed and Bank Adjustment of the Colorado River in the 25 km Immediately Downstream from Glen Canyon Dam

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ABSTRACT

The 25-km reach of the Colorado River immediately downstream from Glen Canyon Dam is a classic example of a channel whose bed has degraded and armored in response to flow and sediment regulation caused by a dam. Although the evacuation of bed sediment from this reach was reported upon nearly 30 yrs ago (Pemberton, 1976), the complete array of channel adjustments has not been described previously. This study uses the abundance of historical data available for this river segment and field measurements made in the last decade in a comprehensive analysis of channel change. We add 25 years to the record of previously reported bed elevation measurements, such that the long-term trend in channel bed adjustment can now be understood. These measurements are supplemented with (1) new analyses of long-term records of bed and bank elevation at U. S. Geological Survey stream gaging stations, (2) mapping of historical aerial photographs that depict changes in the channel-side alluvial deposits, and (3) a pre-dam sediment budget for Glen Canyon. These data depict in detail the processes of the transformation of the Colorado River in Glen Canyon from an alluvial sand-bedded river with a large reservoir of fine-sediment storage to a pool-and-riffle, gravel-bed trout stream.

Although bed degradation began when the cofferdam was installed in 1959, the greatest proportion of degradation occurred in 1965 when the U. S. Bureau of Reclamation intentionally released high flows from the dam in a series of pulses intended to scour the reach downstream from the dam. This event evacuated a reach-average of 2.6 m of sediment from the center of the channel. Continued erosion occurred in the downstream half of the study area during emergency power plant-bypass releases of the mid-1980s. There were small adjustments in bed elevation in the 1990s, but the channel bed today is much the same as it was 15 years ago. The total volume of bed sediment evacuated from the study reach is equivalent to one-third the pre-dam annual sediment load and is two orders of magnitude greater than estimated post-dam sediment inputs to the reach. The average size of bed material has increased from 0.2 mm in 1956 to over 20 mm as measured in 1999.

The widespread bed degradation has resulted in the emergence of additional channel controls, which frequently occur at the mouths of tributary canyons. This is evidenced by the development of a stepped low-water longitudinal profile from the smooth profile that existed in the pre-dam era. The magnitude of degradation in riffles decreases with distance downstream from the dam, consistent with general models of bed degradation downstream from dams. The magnitude of sediment evacuation from pools, however, does not decrease systematically, but fluctuates in magnitude and extends much farther downstream.

The alluvial deposits in Glen Canyon include a complex suite of pre- and post-dam fine- and coarse-grained deposits that occur at a variety of elevations above the active river channel. Many deposits are pre-dam remnants, specifically associated with the lowering of the channel. These include pre-dam fine-sediment deposits that are now perched high above the present active channel and mid- and side-channel gravel and cobble bars that occur in segments where degradation was concentrated in one part of the channel, leaving exposed large areas of the pre-dam riverbed. The reach also includes narrow strips of fine-grained post-dam flood deposits. Both pre- and post-dam fine-grained deposits have been colonized and stabilized by invasive exotic riparian vegetation, resulting in a net decrease in bankfull channel width of about 6% throughout the study area.

Some erosion of channel-side deposits has occurred in the study reach, although the magnitude of this erosion is small compared to the evacuation of sediment from the bed. Most of this erosion has been concentrated in a few pre-dam terraces that eroded dramatically for brief periods and have become armored and stabilized. The area of alluvium represented by eddy deposits has not changed significantly, but the elevation of these deposits has decreased resulting in net erosion from eddy storage environments.

INTRODUCTION

Bed degradation is a common response downstream from large dams (Petts, 1979; Galay, 1983;Williams and Wolman, 1984), and the 25-km segment of the Colorado River immediately downstream from Glen Canyon Dam has degraded and armored dramatically in response to the water and sediment regulation (Pemberton, 1976). Although the magnitude, and in some cases, the rate of bed degradation can be predicted with reasonable results in pre-impoundment studies (e.g. Komura and Simmons, 1967; Pemberton, 1976), changes in channel width and the distribution and character of channel-side alluvial deposits are typically more complex and generally less predictable (e.g. Benn and Erskine, 1994; Grams and Schmidt, 2002). Degrading reaches downstream from dams in the semi-arid western United States have been shown to exhibit both trends of increasing and decreasing channel width (Williams and Wolman, 1984). Friedman et al. (1998) demonstrated that channel narrowing was the dominant response in braided reaches downstream from dams in the western Great Plains, while meandering channels had more stable widths, but exhibited a reduced rate of channel migration. Processes of channel narrowing have been described in detail for aggrading reaches (Everitt, 1993) and reaches where the bed is stable (Allred and Schmidt, 1999; Grams and Schmidt, 2002). The specific interaction between stream-bed elevation and channel width was recently investigated by Friedman et al. (1996) who describe channel narrowing subsequent to bed degradation following extreme floods on unregulated Plum Creek, Colorado.

Although the effects of operations of Glen Canyon Dam on channel-side alluvial deposits have been studied in reaches downstream from Lees Ferry (e.g. Schmidt et al., 1999; Hazel et al., 1999), the Glen Canyon reach has been largely excluded from previous geomorphic investigations, because most of these studies have been conducted with the objective of evaluating or monitoring the condition of campsites used by river float trips, which begin at Lees Ferry, or habitat for endangered fish species, which do not occur in the Glen Canyon study area. There are, nevertheless, important resources in

Glen Canyon. Many of these resources may be affected by present and future dam operations. The pre-dam terraces whose shoreward banks are inundated by current dam operations contain many archeological sites that, if eroded, would be permanently lost. Because sport fishing for introduced non-native rainbow trout (*Oncorhynchus mykiss*) is very popular, Glen Canyon receives heavy day and overnight use by boaters traveling upstream from Lees Ferry. They use Glen Canyon sand bars and alluvial terraces for camping and as day-use areas. Tourists enjoy the canyon in one-day float trips from the dam to Lees Ferry. In total, more than 50,000 visitors travel the Colorado River in Glen Canyon each year (U.S. Department of Interior, 1995). Finally, the Glen Canyon trout fishery has become naturalized and the condition of the gravel/cobble bed is, therefore, of concern with regard to spawning habitat.

The richness of data available for the Glen Canyon reach provides the opportunity to investigate several aspects of channel adjustment in detail, illustrating how some elements of channel adjustment can be anticipated and planned for, while others may be unforeseen. In this study, we examine the spatial pattern of bed degradation between 1956 and present, extending the previously reported post-dam record of bed elevation in Glen Canyon by 25 years. The record of changes in bed elevation and channel width are enhanced by integrating, for the first time, post-dam measurements with long pre-dam records of bed elevation at two discharge-measurement cableways that were abandoned shortly after dam closure. We also analyze pre- and post-dam aerial photographs to describe the style, magnitude, and distribution of changes in channel-side alluvial deposits. This analysis of multiple and detailed long-term records of channel form illustrates a comprehensive story of channel adjustment that is rarely told in its entirety.

STUDY AREA

Physiographic Setting

In its course across the Colorado Plateau, the Colorado River has carved a series of canyons, each distinguished by a unique suite of geologic formations exposed in the canyon walls. The most resistant rock formations contribute to canyons with abundant tributary debris fans, large rapids, and steep average gradients (Grams and Schmidt, 1999). Because debris fans exert a dominant influence on many channel attributes, these reaches are typically referred to as debris fan-dominated canyons (Schmidt and Rubin, 1995; Grams and Schmidt, 1999). Canyons cut into less resistant formations tend to have few debris fans, small rapids or riffles, and lower average gradients. These reaches are often referred to as incised meanders, because the river channel typically flows in an entrenched meandering valley (Harden, 1990; Grams and Schmidt, 1999). While Grand Canyon is the largest debris fan-dominated canyon of the Colorado Plateau, Glen Canyon was the longest canyon formed of incised meanders.

The Glen Canyon region includes over 200 km of the Colorado River corridor plus hundreds of tributary canyons stretching from Hite, Utah downstream to Lees Ferry, Arizona (Figure 1). Most of this expansive region is now flooded by Lake Powell, the reservoir formed by Glen Canyon Dam. The subject of this paper is the 25-km of Glen Canyon downstream from the dam. For the first 21 km downstream from the dam, bedrock from river level to the tops of the canyon walls is Triassic/Jurassic Navajo Sandstone, which is also the dominant formation in the flooded portions of Glen Canyon upstream. Bedrock near Lees Ferry, from 21 to 25 km downstream from the dam, includes highly erodible Triassic conglomerates, sandstones, and shales that are stratigraphically below the Navajo Formation. These formations include the Kayenta, Chinle, Shinarump, and Moenkopi. Several small tributaries enter Glen Canyon between the dam and Lees Ferry. Although some of these tributaries have small fans at their mouth, none form debris fans comparable to those that occur in Marble Canyon downstream from Lees Ferry.

Locations in Glen Canyon are commonly referenced by river mile (RM), which by convention is measured in miles upstream from Lees Ferry with a "-" sign to avoid confusion with locations downstream from Lees Ferry. We use the RM convention for place names that can be identified on river guides or maps that use this reference system. However, we report and plot most data in the more convenient format of distance downstream from Glen Canyon Dam, in kilometers. The dam is at RM –15.7 and the Lees Ferry cableway, 25.4 km downstream from the dam, is at RM 0.0.

Streamflow Regulation

There are no significant water-contributing tributaries in the study area between Glen Canyon Dam and the Paria River confluence (Figure 1). The streamflow measured at Lees Ferry is, therefore, representative of the entire study area. A stream gage has been in continuous operation at Lees Ferry since 1921. The gage and streamflow record have been analyzed in detail by Topping et al. (2003). Streamflow regulation at Lees Ferry began with completion of the cofferdam at the Glen Canyon damsite in February 1959. Although the 130 million m^3 storage capacity of the cofferdam (Pemberton, 1976) was too small to control floods, it likely caused reduced sediment concentrations in Glen Canyon. The complete regulation of streamflow in Glen Canyon began with the closure of Glen Canyon Dam in March 1963. Subsequently, the mean annual (2-yr) flood was reduced by 63% from 2407 m^3/s to 892 m^3/s (Topping et al., 2003). The post-dam average flood is essentially the same as the capacity of the Glen Canyon Dam power plant. Flows have exceeded power plant capacity only rarely since 1962 (Figure 2).

Sediment Supply

Like most reservoirs formed by large dams, Lake Powell is a highly efficient sediment trap. Topping et al. (2000) analyzed the record of suspended sediment measurements made at Lees Ferry and determined pre- and post-dam average loads of fine sediment. For those pre-dam years with a complete sediment record, 1949 to 1962, approximately 57 ± 3 million Mg of fine sediment was transported past Lees Ferry each year. Measurements from 1966 to 1970 indicate a post dam mean annual load of 0.24 ± 0.01 million Mg, a reduction of more than 99%. The post-dam sediment load is derived from the bed and banks of the river in the Glen Canyon study reach and ephemeral tributaries that drain the highly erodible Mesozoic sedimentary rock formations.

The post-dam sediment yield from tributaries between Glen Canyon Dam and Lees Ferry has been independently estimated by Webb et al. (2000) using regional sediment yield equations and other empirical methods. They estimated an annual load of

76,000 Mg for the total tributary drainage area of the Glen Canyon study area. Based on analysis of the Escalante River suspended-sediment data (this river drains similar lithologies to those found downstream from Glen Canyon Dam), half of this load is probably sand. Others have estimated the sand content of tributary inflow to be as low as 15% (Randle and Pemberton, 1987).

The difference between the estimated post-dam sediment delivery to the study area and estimated average load at Lees Ferry indicate that a sediment deficit exists for Glen Canyon. While such a deficit has certainly existed throughout the post-dam era, there is uncertainty in its magnitude.

A brief description of the nature of pre-dam sediment transport in Glen Canyon is necessary to provide context for understanding how flow regulation has completely changed the character of this reach of the Colorado River. During the average pre-dam year, sand exported from Glen Canyon accumulated in Marble and upper Grand Canyons during the nine months (July-March) of the year when the discharge was typically lower than about 250 m^3/s (Topping et al., 2000). Then, during the three months of higher discharge during the snowmelt flood (April-June), this stored sand was exported from Marble and upper Grand Canyons. This process led to pronounced annual hysteresis in suspended-sand concentration and grain size at the Grand Canyon gage, located 141 km downstream from Lees Ferry (Topping et al., 2000). Although there were not large changes in the loads of silt and clay, there were substantial differences in the loads of sand as a function of discharge between the Lees Ferry and Grand Canyons gages. This high degree of sensitivity to changes in sediment supply indicate that the amount of background sediment storage in Marble and upper Grand Canyons was small relative to the seasonal change in sediment storage. As the sand concentration decreased during the snowmelt flood, the grain size of the sand in suspension coarsened leading to the deposition of inversely graded flood deposits in Marble and Grand Canyons (Rubin et al., 1998).

Topping et al. (2000) showed that significant increase in the degree of sediment supply limitation appeared to occur near Lees Ferry, thus significantly distinguishing the character of pre-dam sediment supply of Glen Canyon from than of Marble and Grand Canyons. Unlike the Grand Canyon gage, very little hysteresis was evident in either suspended-sand concentration or grain size at the Lees Ferry gage. The seasonal scour and fill in Glen Canyon at Lees Ferry appeared to be controlled mainly by reach geometry and was not substantially influenced by depletion in the upstream supply of sediment during snowmelt floods, as at the Grand Canyon gage. Also, very little change in the bed-sediment grain size occurred during pre-dam snowmelt floods at Lees Ferry, unlike at the Grand Canyon gage, where the bed sediment coarsened substantially during these floods. Moreover, the pre-dam flood deposits sampled in Glen Canyon did not ubiquitously coarsen upward with respect to sand grain size, unlike deposits sampled further downstream in Marble and Grand Canyons. Topping et al. (2000) therefore concluded that the Colorado River behaved much more like an equilibrium sand-bedded channel in Glen Canyon than it did in the more sediment supply-controlled Marble and Grand Canyons. This hypothesis is supported by an analysis of the pre-dam sediment budget for Glen Canyon (Appendix A).

Previous Geomorphic Investigations in Glen Canyon

Annual and seasonal patterns of sediment transport and storage in the Colorado River in Glen Canyon were drastically changed with the completion of the cofferdam at the Glen Canyon damsite on February 11, 1959 and closure of the gates of Glen Canyon Dam on March 13, 1963. Pemberton (1976) summarized bed degradation in Glen Canyon measured between 1956 and 1975, and compared these measurements with predictions made 20 years earlier (U.S. Bureau of Reclamation, 1957). The 1957 study predicted that a gravel bar approximately 6 km downstream from the dam and the riffle at the mouth of the Paria River would act as controls on the depth of bed degradation and its downstream extent. Pemberton (1976) found that the measured net degradation of 9.87 million m^3 in the 25-km study area was only slightly greater than the predicted net degradation of 8.26 million m^3 and that stability had been achieved by 1975 through bed armoring at gravel and cobble bars acting as channel controls. The median size of the armor layer at these bars was equal to or larger than the predicted armoring size

(Pemberton, 1976). Thus, Pemberton (1976) concluded that bed degradation was largely complete by 1975.

The U.S. Geological Survey (USGS) records of discharge measurements made at the Lees Ferry gage (station number 09380000) provide a long record of bed elevation at the downstream end of Glen Canyon. These records were analyzed, in part, by Burkham (1986) and Topping et al. (2000). Burkham (1986) examined a subset of those measurements made between 1924 and 1984 and reported on long-term trends in channel width, cross-section area, mean velocity, and maximum depth. He observed that, prior to 1940, the thalweg annually scoured during the spring snowmelt flood and then returned to the approximate pre-flood elevation during the summer and fall. Beginning in 1942, the thalweg typically did not completely refill to the elevation of the preceding year, resulting in a gradual trend of decreasing average bed elevation from 1942 to 1962 (Burkham, 1986). Burkham (1986) suggested that this trend of decreasing average bed elevation was in response to a trend of decreasing suspended sediment concentrations during this pre-dam period.

The records analyzed by Burkham (1986) show scour of the bed during a May 1965 dam-bypass release, and that this scoured condition persisted through 1984. The analysis of bed elevation from the Lees Ferry discharge measurement notes is, however, complicated by the use of three different cableway locations. Burkham (1986) suggested that the behavior of the sties was similar, based on characteristics of the stage-discharge and velocity-discharge relations among the sites, and therefore treated measurements made at the separate locations as one continuous time series. Because the location of the cableway used for discharge measurements was permanently moved shortly after the 1965 scouring event, the exact response at that location has been unknown.

Topping et al. (2000) analyzed a more complete record of mean bed elevation for one of the three Lees Ferry cableway locations for the pre-dam period 1921 to 1959. Their analysis indicated no trend in mean bed elevation between 1921 and 1929 and a very gradual, but statistically significant, decrease in mean bed elevation from 1929 to 1959. Topping et al. (2000) concluded that this trend was consistent with other lines of evidence indicative of a long-term slight decrease in the pre-dam supply of fine-sediment to the channel.

Williams and Wolman (1984) analyzed data compiled from river segments downstream from large dams throughout the United States in an effort to formulate general models describing downstream channel adjustment. They included the 10 Reclamation monitoring cross-sections in Glen Canyon in their analysis of 287 cross-sections from locations throughout the United States. Williams and Wolman (1984) selected a subset of 114 cross-sections where degradation had occurred and these were used in developing a statistical model that described the general pattern of bed erosion in degrading reaches downstream from dams. They concluded that once degradation began, the rate of continued degradation could be fit to either a logarithmic or hyperbolic function, with time as the independent variable and bed elevation as the dependent variable. This model well described the pattern of bed degradation for five of the Glen Canyon cross-sections, but did not fit the remaining five. Thus, while a logarithmic rate of decrease in bed elevation may fit many degrading cross-sections, there is a high degree of variability that was not explained by a simple mathematical model. In this study, we reanalyze all available data for Glen Canyon, looking at channel response at all measured cross-sections for the period between 1956 and January 2000.

Effects of the operations of Glen Canyon Dam on channel-side alluvial deposits have been extensively studied in reaches downstream from Lees Ferry (see reviews by Webb et al., 1999; Schmidt et al., 2002). These studies have documented (1) no long-term accumulation of sand on the bed since the 1980s, (2) net loss of sand from eddies below the elevation inundated by flows of about 708 m^3/s, (3) aggradation and subsequent erosion of deposits formed during post-dam floods, and (4) net decrease in the total area of eddy deposits since completion of Glen Canyon Dam. These studies have not investigated changes to deposits in Glen Canyon.

Changes in sand storage have been monitored at one eddy-deposited sand bar in Glen Canyon (Beus and Avery, 1992; Kaplinski et al., 1995; Hazel et al., 1999). This sand bar, located 15 km downstream from the dam, was surveyed 39 times between July

12, 1990, and November 2, 2001. Kaplinski et al. (1995) reported that the area and volume of sand above the stage of 142 m^3/s did not change significantly between 1990 and 1995. In their analysis of erosion and deposition during the 1996 controlled flood, Hazel et al. (1999) documented no significant topographic changes above the 566 m^3/s stage and a 7% increase in area and 19% increase in volume above the 142 m^3/s stage at this one site. These areas and volumes of deposition are very small in comparison to the average response measured at sites in Marble Canyon and Grand Canyon (Schmidt et al., 2002).

METHODS

Measurements of the Bed

Bureau of Reclamation Cross-sections

In 1956, the U.S. Bureau of Reclamation established 22 channel cross-sections on the Colorado River between the Glen Canyon damsite and the Paria riffle, just downstream from Lees Ferry (Figure 1). A subset of these cross-sections was resurveyed in 1959, 1965, 1975, 1983, and 1990 (Table 1). Ten cross-sections were selected as monitoring sites following the 1956 survey (Pemberton, 1976), and all of these were measured in all of the years listed above. The Grand Canyon Monitoring and Research Center (GCMRC) resurveyed nearly all of the cross-sections that had been established in 1956. Cross-sections R-0 to R-13 were surveyed January 24-27, 2000, and R-15 to R-20 were surveyed May 10-11, 2000. R-3 could not be located, and R-14 was not surveyed. Ground topography along the cross-sections was surveyed using electronic total stations, and bathymetry along the cross-sections was measured with a boat-mounted SONAR. Positions were surveyed and are reported in Arizona State Plane Coordinates, central zone. Elevations are in meters above sea level (NVGD1929). The minimum bed elevations are listed in Appendix B.

The cross-sections were classified by occurrence in riffle or pool channel type. These channel types were identified in the field and by inspection of the longitudinal profile and cross-section plots. Riffles were identified as segments with below average channel depth and above average surface streamflow velocity. Pools were identified as segments between riffles with larger average depth and lower surface velocity.

Reclamation also collected data describing the size and thickness of bed sediments in Glen Canyon in 1956 (Pemberton, 1976). Bore holes were drilled through the alluvium at seven locations. Drill logs and samples detail the thickness of the overlying fine-grained sediment and the size distribution of the underlying gravels. A jet probe was used to penetrate the fine sediment layer and determine the depth to gravel at an additional nine locations. At each of these locations, the jet probe was used to determine the depth to gravel at multiple positions across the channel. Some of these profiles of the gravel interface were located at or near the monitoring cross-sections. From these data, we reconstructed the longitudinal profile of the sand-gravel interface in Glen Canyon to place the history of bed erosion in the context of bed-material size.

Lees Ferry Gaging Station

We also analyzed the records of bed topography for both the Upper and Lower Cableways of the USGS Gage at Lees Ferry (Figure 1). Water surface elevation has been measured by a recording gage that has been maintained at the same location since January 19, 1923. From 1921 to 1923, water surface was measured at several different staff gages. The details of the gage operations and discharge measurements, including estimates of extreme floods, are described by Topping et al. (2003). Topping et al. (2000) analyzed the record of bed elevation up to 1962. We extend the record to 2000, including changes caused by the closure of Glen Canyon Dam.

Discharge measurements have been made at three different cableway locations (Figure 1). The Upper Cableway was in operation from August 3, 1921, to December 1, 1966. The Lower Cableway was installed in January 1929 and removed in February 1965. From 1929 to 1965, the Upper Cableway was used for most measurements and the Lower Cableway was used primarily during floods when measurements at the Upper Cableway were logistically difficult. The Upper Cableway is located 1.5 km upstream from the gage and is the same cross-section as Reclamation's cross-section R-1. The Lower Cableway was located 0.7 km upstream from the recording gage. Since December

13, 1966, all discharge measurements are made at a third location that is 15 m upstream from the recording gage. We refer to this location as the Lees Ferry cableway. Because of the distance between the Upper Cableway and the recording gage, a staff gage was installed at the Upper Cableway in April 1924 to help constrain stage change during discharge measurements. This gage is known as the "cable gage." For most of the discharge measurements made at the Upper Cableway, stage was measured at both the cable gage and the recording gage.

In his analysis of bed change at Lees Ferry, Burkham (1986) argued that the behavior of the bed at the three cableway locations was similar, and he included measurements made at all of these locations in a single time series. He calculated minimum bed elevation by subtracting the maximum depth, recorded on the discharge measurement notes, from the recording gage height. Thus, bed elevations for measurements made at the Upper Cableway were determined based on the gage height measured 1.5 km downstream. We recalculated the time series of minimum bed elevation separately for measurements made at the Upper Cableway and measurements made at the Lower Cableway, and calculated water surface elevations independently for those locations.

The minimum bed elevations that we report for all Upper and Lower Cableway measurements were calculated as the difference between water surface elevation and maximum depth. Maximum depth was determined by inspection of each USGS discharge measurement note for all 4353 measurements made at both cableway locations from August 3, 1921, to December 1, 1966. Three thousand nine hundred ninety-six measurements were made at the Upper Cableway, 350 were made at the Lower Cableway, and seven were made from a boat before a cableway was constructed. The maximum depths were tabulated with the data analyzed by Topping et al. (2003), which include the date, channel width, cross-sectional area, and recording gage height for each measurement, and the cable gage height when measured. We calculated the water surface elevation for each measurement. The calculation varied depending on whether the measurement was made at the Upper Cableway or the Lower Cableway and whether or not gage height was measured at the cable gage. The details of these calculations are explained in Appendix C.

Minimum bed elevations determined from the 1956 to 2000 Reclamation and GCMRC surveys of R-1 were added to the record derived from USGS gaging notes for the Upper Cableway. The 2000 GCMRC survey of the channel cross-section at the Lower Cableway was included in that time series. Elevations for all measurements were reported relative to sea level (NAVD1929).

Complete cross-sections were plotted for selected dates for the Upper Cableway and the Lower Cableway, to show patterns of erosion and deposition across the entire channel. For these dates, the measured vertical depth and position along the cableway were recorded from the discharge measurement notes. Bed elevations across the entire channel were calculated by the same methods used for calculating the elevations of maximum depth. For most measurements, position along the cableway was recorded relative to the same point. When this was not the case, position along the cross-section was determined by matching stable topography on the left bank of the cross-section at the Upper Cableway and on the right bank of the cross-section at the Lower Cableway.

Mapping of Alluvial Deposits

Mapping From Aerial Photographs

Only a few of the Reclamation cross-sections traverse sections where channel-side deposits occur, and those measurements were not routinely made above the edge of water. Thus, the topography of channel-side alluvial deposits was rarely captured by cross-section measurements, and these data are not useful for systematic analyses of changes in those deposits or the determination of trends in channel width. Yet, changes in the patterns of channel-side deposition represent an important component of channel adjustment. We describe these changes by mapping all alluvial deposits in the study area on one series of pre-dam photographs and five series of post-dam photographs (Table 2).

Surficial geology was mapped on mylar overlays on the aerial photographs, while viewing in stereo to interpret the relative elevations of the deposits. We digitized the mapping into a geographic information system (GIS), using a digitizing tablet coordinated to stable features on the aerial photographs for reference points. Coordinates for the reference points were obtained from digital orthophotographs.

Each deposit was mapped according to depositional setting or facies, elevation category (formative discharge), surface texture, and extent of vegetation cover. The map units are similar to those used by Schmidt and Leschin (1995), Schmidt et al. (1999), and Schmidt et al. (2002). The distinction between pre- and post-dam deposits is also consistent with that of Hereford et al. (2000).

Depositional facies were determined by interpretation of the photographs in stereo and by field inspection. Colorado River alluvial deposits were mapped either as fine-grained eddy sand bars, fine-grained channel-margin deposits, or gravel bars. Eddy sand bars were further subdivided into separation, reattachment, and undifferentiated eddy bars according to the classification scheme proposed by Schmidt and Rubin (1995). Channel-margin deposits are typically linear river-parallel bar and bank deposits, but include all Colorado River alluvium not deposited in eddies (Grams and Schmidt, 1999, their Figure 4.7). Mapping was checked in the field in September 2000. A complete description of the map units is included as Appendix D.

The post-Glen Canyon Dam flow regime and the timing of aerial photographs makes it possible to classify post-dam deposits along the Colorado River into elevation categories according to formative discharge, which in many cases corresponds directly with deposit age. The October 1984 aerial photographs were taken following the 1983 post-dam flood of 2755 m^3/s and the 1984 flood of 1648 m^3/s. Because flows had just dropped from about 708 m^3/s prior to the photographs, that water's edge was visible as a line on the photographs. Deposits below the 708 m^3/s stage were mapped as *fluctuating-flow* deposits (Figure 3). Above this abandoned high-water line were the bare sand deposits from the high flows of 1984, mapped as *high-flow* deposits. The deposits from the 1983 flood were also distinct, and are higher in elevation than the 1984-flood deposits and were mapped as *flood-sand* deposits. Alluvial deposits above the 1983 and 1984 deposits and lacking evidence of deposition in the previous two years were mapped as pre-dam deposits. Pre-dam terrace deposits include the levels mapped as *high tamarisk* *terrace* and *high terrace*. These criteria were used to map the deposits in all of the post-dam photograph series. One additional category was used on the April 1996 photographs, which were taken immediately following the 1996 controlled flood of 1274 m^3/s. These *controlled-flood* deposits were identified by their appearance as freshly reworked deposits on those photographs. Collectively, the high-flow, flood-sand, and controlled-flood deposits are referred to as *post-dam flood* deposits.

Many of the alluvial deposits in Glen Canyon are steeply sloping or have large cutbanks. It is therefore not possible to assign these banks or slopes to a single elevation category with a known formative discharge. Slopes are, therefore, mapped as a separate facies with deposit level identified as the range between the adjacent deposits at the top and bottom of the slope, respectively.

The suite of depositional levels identified in the post-dam period does not exist on the 1952 photographs. Deposits on these photographs fall into three easily distinguished categories: (1) wetted sand, interpreted to have been inundated by the peak discharge preceding the photographs of 450 m^3/s, (2) bare sand reworked by that years flood of 3483 m^3/s, and (3) vegetated terraces. To enable comparison from the pre- to post-dam periods, these deposits have been classified into categories consistent with those used on the post-dam photographs. The wetted sand in 1952 corresponds directly to the post-dam *fluctuating-flow* deposits. The bare sand encompasses a much broader range of formative discharges, and corresponds to both the *fluctuating-flow* and *post-dam flood* categories. We identify the area of pre-dam *low sand* as a range including, at minimum, the area of wetted sand, and at maximum, the area of wetted sand plus one-half the area of bare sand. We identify the area of pre-dam *high sand* similarly, including, at minimum, one-half the area of bare sand, and at maximum, all of the bare sand. Error bars around the midpoints of the extremes indicate these ranges. All the vegetated terraces mapped in 1952 are considered equivalent to the *pre-dam terraces* mapped on the post-dam photographs.

In summary, in developing a comprehensive pre- to post-dam time series, we divided the fine-grained deposits into three elevation categories. The pre-dam *low sand* and the post-dam *fluctuating-flow* deposits correlate and are referred to as *low-elevation* deposits. The pre-dam *high sand* and the *post-dam flood* deposits correlate and are referred to as *high-elevation* deposits. The *terrace* category includes all deposits mapped as terraces on either the pre- or post-dam photographs.

The study area was divided into five 5-km reaches for the purpose of generalizing longitudinal patterns of channel adjustment indicated by the surficial geologic maps. Post-dam average gradient in these reaches varies from 0.0001 to 0.0005 and post-dam average channel width ranges from 156 to 216 m (Table 3).

Characterization of Eddy Deposits

Eddy sand bars are numerous in reaches of the Colorado River downstream from Lees Ferry (Schmidt and Graf, 1990), but also occur within Glen Canyon. Eddies form in channel expansions downstream from constrictions created by flow obstructions. These obstructions are most commonly caused by tributary debris fans but may also be caused by bedrock outcrops and other bank irregularities. Downstream from Lees Ferry, storage in eddies accounts for a significant proportion of the total fine sediment storage area (Schmidt et al., 1999; Schmidt et al., 2002). Because the actual area of recirculating flow is a function of discharge, it is necessary to quantify eddy size by some other objectively defined measure. We use the method described by Schmidt et al. (1999) that defines eddy size based on the historical extent of sand within each eddy for a given reach. This area is the union of all contiguous deposits within a recirculation zone as mapped from all years of available aerial photography. The value of this metric, which we refer to as the eddy depositional zone (EDZ), is a function of both the sand storage condition and the water surface elevation at the time of the aerial photography. Because the same photographs are used throughout a given study reach, this bias is consistently applied. The frequency of large EDZs, defined as those larger than 1000 m^2, varies from 2.2 to 5.0 per km in reaches where detailed mapping has been completed in the first 120 km downstream from Lees Ferry (Schmidt et al., 2002). Their analysis included photographs taken in 1935 that we did not use, because most of Glen Canyon is obscured in shadow. The 1935 photographs were taken at low discharge in the sediment accumulation season when many eddies were filled with sand, and the deposits mapped from these photos contributed significantly to defining the EDZ boundaries. Because we did not use these photographs, the EDZs calculated for Glen Canyon may be expected to be somewhat smaller than in the reaches downstream from Lees Ferry.

Accuracy of the Surficial Geologic Maps

The surficial geologic mapping described above has many sources of error and uncertainty. Errors may be the result of (1) errors in mapping and aerial photograph interpretation, (2) the uncertainty resulting from the width of the hand-drawn line on the aerial photograph, (3) digitizing errors due to operator error, and (4) scale transformation errors resulting from distortion in the aerial photographs. Because of the length of river mapped and the number of years of repeat mapping, errors of the first type are inevitable. These errors were located and edited by an iterative process using two error-checking routines. The other sources of error are addressed in an accuracy assessment that determines confidence levels for the maps.

The first of the error-checking routines is the inspection of erosion-deposition maps for changes in deposits that are either unlikely or impossible. Erosion-deposition maps are made by evaluating every possible change in map unit categories from one year to the next and assigning a new attribute to each of these combinations describing that change. For example, an attribute of "deposition" would be applied in the event the level of a deposit changed from a low-elevation category to a high-elevation category. An erroneous result would occur if a change from a low-elevation deposit to a higher deposit were identified for a period during which no floods occurred that could have inundated a deposit at that level. Unrealistic results of this type were checked by inspecting each of the maps and the original mapping on the photographs.

The second error-checking routine is the analysis of a longitudinal profile for each deposit level. These longitudinal profiles were developed within the GIS by assigning a downstream distance and an elevation to every mapped alluvial deposit. The downstream distance was calculated as the distance from the upstream end of the study area (the base of Glen Canyon Dam) to the centroid of each mapped deposit projected onto the river centerline. The elevation for each deposit was calculated as the average elevation of the contour lines intersecting the respective deposit. In some locations, poor overlay between the topographic map and the surficial geologic maps resulted in inaccurate elevations. For example, a small position error may cause a narrow sliver of steep slope or cliff to intersect an alluvial deposit and significantly alter the calculated average elevation for the deposit. Polygons were examined individually and elevations were interpreted manually where these errors occurred. Water surface elevations from the Reclamation cross-section surveys and the US Geological Survey gage stations were included on the profile.

The longitudinal profile of deposit elevations shows that while there is a range of elevations within each elevation category and some overlap between categories, the categories are generally well separated with distinct mean elevations (Figure 4). The average slopes of each category are similar but converge towards the downstream end of the study area. This convergence is an expected result of the greater magnitude of bed degradation and greater lowering of the stage-discharge relation that has occurred at the upstream end of the study area. Note that the deposits mapped as pre-dam terraces in 1956 plot above the post-dam flood deposits.

Schmidt et al. (2002) estimated error in identification of fluctuating flow and post-dam flood deposits. This was done by comparing the area of sand surveyed (Hazel et al., 1999) with the area measured by mapping from aerial photographs for these two elevation categories. This comparison was made for eight sites where both data are available, including one site in Glen Canyon. Comparisons were possible for multiple dates of overlapping survey and photographic data resulting in 26 comparisons. The total area compared was 166,469 m^2. The variance σ^2 in the comparison between the surveyed area and mapped area was 828,599 m^2. We applied this estimate of variance to the Glen Canyon data to calculate the standard error SE for deposit area in Glen Canyon as

$$SE = \sigma\sqrt{n}$$

where σ is the standard deviation and n is the number of deposits. Individual estimates of the standard error were made for the total area of eddy, channel-margin, and all deposits for each year of mapping (Table 4).

Some of the analyses applied to the surficial geologic maps involve creating overlays between two separate maps and calculating areas of change in attribute labels. The estimate of standard error described above characterizes the uncertainty in the determination of the total area of map units, but does not address the error of individual polygons. We therefore used a method that estimates uncertainty by assuming uniform error around the entire perimeter of every polygon. Sondossi and Schmidt (2001) estimated positional accuracy of mapping similar to that conducted in this study by comparing digitized locations of 56 points with the actual locations of the same points on orthophotograph base maps. These data indicate a mean positional error of 1.6 m, which is approximately the same as the error that would be expected due to the thickness of a 0.3 mm pencil line at the scale of the aerial photographs. We approximated the error for individual polygons as the product of this mean position error and the perimeter of each polygon. The maximum error in a map consisting of a set of individual polygons was then approximated as the sum of the errors of the individual polygons. This error was then expressed as a percentage of the total area of those polygons. Because these percentage errors are large for small polygons, polygons smaller than 500 m^2 were excluded from consideration in the erosion-deposition maps. Applying this method to each of the erosion-deposition overlay maps, the estimated error ranges from 5 to 14% with a gross average of 9%. For simplicity, we applied the maximum estimated error, rounded up to 15% to all erosion-deposition comparisons.

RESULTS

Rate and Magnitude of Bed Degradation

The onset of degradation and the channel cleaning flows

Degradation of the bed in the first 10 km downstream from Glen Canyon Dam began between 1956 and 1959, and by 1965 had progressed downstream to Lees Ferry. During the period of dam construction, degradation rates were high at cross-sections within 5 km from the dam, and cross-sections more than 10 km downstream were mostly stable (Figure 5). The rate of bed degradation accelerated dramatically after 1959, and it is likely that most of this degradation occurred in May 1965. During the first two years of dam operations, releases from Glen Canyon Dam were extremely low to increase the level of Lake Powell. It is unlikely that significant bed lowering took place during this period of low flows. In May 1965, the emergency bypass facilities (jet tubes) were used for the first time in conjunction with the left-bank diversion tunnel. In that month, flows of up to 1645 m^3/s were released in a series of several short spikes (Figure 2). Although the stated purpose of these releases was to test the bypass facilities, it appears that accelerating the process of bed degradation near the dam was a secondary objective. Several Reclamation documents, including a 1957 degradation report, make it clear that degradation of the bed in Glen Canyon was anticipated and incorporated in power plant design (U.S. Bureau of Reclamation, 1957). Moreover, engineer's notes in Reclamation files indicate that the 1965 high releases were intended as a "channel-cleaning" flow designed to scour the bed in Glen Canyon to achieve the optimum tailwater elevation downstream from the dam (Appendix E). Not only did these "channel-cleaning" flows in 1965 scour sediment from Glen Canyon, they also scoured approximately 16 million Mg of fine sediment from Marble and upper Grand Canyons (Topping et al., 2000; Rubin and Topping 2001).

Continued degradation and the magnitude of sediment evacuation

All of the cross-sections in the study area degraded between the beginning of dam construction in 1956 and the most recent survey in 2000. However, the rate of bed lowering decreased markedly following the 1965 channel-cleaning flows. The rate of bed degradation was lowest between 1965 and 1975, when dam releases were maintained at or below power plant capacity. Between 1975 and 1990, most cross-sections were relatively stable but R-10 and R-1 degraded (Figure 5). Most of this degradation probably occurred during the large floods of 1983-86. The 1983 cross-section measurement was made in October, several months after that year's peak discharge. Degradation occurring during the 1983 flood is recorded in the 1975-1983 measurement interval, and degradation occurring during the 1984-86 floods is recorded in the 1983-

1990 measurement interval. Between 1990 and 2000, many of the cross-sections aggraded slightly, during this period dominated by low power plant capacity flows.

At the time of the 1956 cross-section measurements, the bed of the Colorado River in Glen Canyon was mostly sand and the average bed surface size was about 0.2 mm (Figure 6). Underlying the sand at varying depths was a layer of gravel with an average size of about 20 mm. Throughout the study area, the entire thickness of the sand layer and a significant thickness of the underlying gravel have been evacuated (Figure 7). This is shown at those locations where the depth to gravel in 1956 was measured at or near one of the monitoring cross-sections. Up to 7 m in thickness and 50% of the total volume of material evacuated between 1956 and 2000 was derived from the underlying gravel layer.

A total of approximately 10.7 million m^3 of sediment was eroded from the study area (Figure 8), exceeding the volume of degradation predicted at the time of dam construction (Pemberton, 1976) by about 30 percent. In the upstream 10 km, the accumulated volume of degradation has not changed significantly since 1965. At distances greater than 10 km downstream, the volume of degradation increased significantly after 1983 and was concentrated at cross-sections 10 and 11A. In both cases, the degradation occurred along the margins of the channel and not in the thalweg. Thus, continued degradation has evacuated sediment from the reach without affecting the longitudinal profile of minimum bed elevation.

Spatial pattern of bed adjustment and development of the post-dam longitudinal profile

Based on observations in the field and inspection of the cross-sections and the post-dam longitudinal profile, cross-sections were divided into those that occurred in pools and those that occurred at or near riffles. On average, the magnitude of degradation in pools exceeded that measured in riffles by a factor of five. The magnitude of degradation in riffles decreases with distance downstream from the dam. However, the magnitude of degradation in pools does not systematically decrease (Figure 5). This demonstrates that local variation in channel adjustment owing to local variation in channel characteristics can be greater than longitudinal trends in the magnitude of channel adjustment.

The locus of degradation varied considerably among the cross-sections (Figure 9). Riffles tended to degrade differentially across the channel, often leaving part of the bed near its pre-dam elevation, e.g. R-11A. In pools, degradation tended to occur across the width of the channel, resulting in near uniform lowering, e.g. R-7. In nearly all cases, the degradation was contained within the limits of the 1956 channel, thereby resulting in a deeper and narrower channel. Exceptions to this pattern of narrowing occurred at R-11A (Figure 9) and R-4, where bank erosion caused channel widening.

The lowering of the bed has caused large shifts in stage-discharge relations that are greatest near the dam and decrease downstream. The pattern exhibited by these shifts in the stage-discharge relationships are, in fact, a better indicator of degradation of channel controls than the actual measurements of bed topography at the cross-sections. Stage-discharge relations were determined for each cross-section using all measured water surface elevations. Linear trends were fit to each cross-section for periods where the relation remained stable. For cross-sections where there were shifts in the stage-discharge relation, most of the adjustment occurred by 1965, consistent with the period of greatest bed degradation (Figure 10a). Stage-discharge relations at the downstream end of the reach have been stable (Figure 10b). The downstream trend in the stage-discharge adjustment was determined by evaluating the change in stage for a discharge of 150 m^3/s between the pre-1965 period and the post-1965 period. The change in stage decreases from over 2 m at the upstream end of the study area to no significant change at R-1, 24 km downstream (Figure 11).

The downstream limit of adjustment in the stage-discharge relation is about 20.2 km downstream from the dam. The stage-discharge relation decreased at R-4, 20.1 km downstream from Glen Canyon Dam and remained stable at R-2, which is 2.5 km farther downstream. Between these two cross-sections are Cave Canyon and Fall Creek, two tributaries with small debris fans (Figure 1). At low discharges (< 55 m^3/s), there is a small riffle at the mouth of Cave Canyon, which is the channel control for R-4. This riffle is the furthest downstream channel control for which degradation due to dam operations is known to have occurred. The next riffle downstream at Fall Creek may have degraded, but we were unable to reoccupy the cross-section at R-3, to determine whether the stage-discharge relation had changed. The next significant channel control downstream is the riffle opposite the mouth of the Paria River, and stability of the stage-discharge relations at cross-sections downstream from Fall Creek indicate that that channel control has been stable (Figure 11).

Prior to closure of Glen Canyon Dam, the average gradient through the study area was similar across a broad range of discharges (Figure 7). The reach average gradient was 0.00034 and 0.00037 at discharges of 79 and 2067 m^3/s, respectively. The onset of bed degradation, which has been greatest at the upstream end of the study area, caused the reach-average gradient to decrease to between 0.00025 and 0.00028. While reach-average gradient has decreased, differential bed erosion has caused the local gradient to become steeper in some locations and less steep in others.

Magnitude of bed degradation relative to pre-dam scour-and-fill

Upper Lees Ferry Cableway

Combined, the USGS discharge measurements and the Reclamation and GCMRC cross-section surveys provide a 79-yr record of bed elevation for the Upper Lees Ferry Cableway. Our time series differs from that of Topping et al. (2000) by the inclusion of all available post-dam data and from that of Burkham (1986) by segregating the data by measurement location. The time series shows annual scour and fill of up to 7 m and a downward trend in the annual maximum of the minimum bed elevation (Figure 12). This trend begins in about 1940 and was previously identified by Burkham (1986) and Topping et al. (2000). During this period, the bed never scoured lower than 941.5 m, which was the maximum depth of scour measured in 1929. Thus, the 1940 to 1959 trend of decreasing bed elevation is a result of the cross-section failing to completely fill rather than progressively deeper scour. Topping et al. (2000) concluded that this pattern is indicative of a slight pre-dam trend of increasing sediment-supply limitation in Glen Canyon.

Following the large scouring event during the channel-cleaning flows of May 1965, the bed at the Upper Cableway never refilled to pre-dam elevations. The Upper Cableway discharge measurements made between May 1965 and December 1966 show that the elevation of the bed at its maximum fill following the 1965 scouring event was still about 6 m lower than the typical filled-condition bed elevation prior to May 1965. These changes are also recorded in the Reclamation surveys made between 1956 and 1965. Subsequent surveys at this cross-section show that the thalweg at the Upper Cableway has never been higher than 0.3 m above the elevation measured in December 1966. By January 2000, the bed had degraded an additional 2.2 m lower than the lowest elevation measured in 1965. Although the post-dam measurements are infrequent compared to the pre-dam measurements and may miss periods of bed-sediment aggradation, the timing of these measurements suggests that sediment accumulation has not occurred since 1965.

Lower Lees Ferry Cableway

The time series of minimum bed elevation for the Lower Cableway has frequent and wide gaps between measurements. Most Lower Cableway measurements were made at high discharge, and therefore tend to represent the bed in a scoured condition and do not describe the annual refilling of the channel, which occurred during seasons of lower average discharge (Figure 13). During pre-dam floods, the bed typically scoured to an elevation of about 941 m. The few measurements that were made in months other than the snowmelt flood season indicate that the cross-section filled to about 945 m. The January 2000 measurement shows that there has been far less post-dam degradation at the Lower Cableway than 0.8 km upstream at the Upper Cableway. The 2000 measurement was made at a discharge and time of year when the bed at the Lower Cableway was typically at a maximum and is probably representative of the post-dam filled condition. The bed is at approximately the same elevation as pre-dam years during the annual flood. Post-dam erosion has not degraded the bed to below the elevation of pre-dam maximum scour, as has occurred at the Upper Cableway.

Selected plots of the cross-section at the Lower Cableway show that the bed has degraded along much of the channel width, creating a more rectangular cross-section than existed in the pre-dam era (Figure 14). While the thalweg elevation in January 2000 is similar to the elevation during pre-dam floods, there has been 2 to 5 m of erosion along more than 100 m of the cross-section that never scoured during pre-dam floods. Thus, the area of degradation at this cross-section is large even though the depth of degradation is less than for the Upper Cableway.

Channel-width changes at the Lower Lees Ferry Cableway

Measurements made at the Lower Cableway record changes in channel width from 1929 to present. Such a record is not available for the Upper Cableway where channel width has changed owing to rockfall (Topping et al, 2003), but not alluvial deposition or erosion. The Lower Cableway traverses a large sand deposit on the left bank, and changes in channel width at this location resulted from aggradation and degradation of that deposit.

Since the first Lower Cableway measurements in 1929, there have been episodic decreases in channel width, illustrating a pre-dam cycle of deposition and erosion of channel-side deposits. The process of narrowing we describe is similar to that described by Allred and Schmidt (1999) wherein bank-attached bars form or migrate into the cross-section, aggrade and become colonized by riparian vegetation, and are never scoured by subsequent floods. Figure 15 shows the channel width for each discharge measurement plotted in relation to the Lower Cableway water surface elevation. The data are divided into five time periods and describe a progressive decrease in channel width. From May 1929 through most of June 1935, the relation between width and water surface elevation was stable throughout the range of discharges measured. Between June 20, 1935, and May 11, 1936, there was a three-meter decrease in width, establishing a new trend in the relation that was stable through 1938. In June 1938, the channel narrowed by more than 2 m in one day, establishing a new trend at elevations above 952 m. A final episode of narrowing occurred in May 1948. Time series of channel width can only be shown for narrow elevation intervals, which removes the effect of water surface elevation on the measure of channel width (Figure 16). Within these narrow elevation ranges, width is not correlated with stage (Figure 17). The channel narrowed in each year that successive measurements were made at similar water surface elevations. In most cases, the channel partially re-widened that same year or the next year. Since dam closure, the deposit is rarely inundated and is stabilized by riparian vegetation.

A detail of the left bank of the Lower Cableway cross-section illustrates the formation of the sand bar that narrowed the channel (Figure 18). Inundation discharges were determined for each elevation from the stage-discharge relation for the Lower Cableway. The narrowing began with a deposit that first appeared in June 1935 and aggraded the deposit from the 465 m^3/s stage to the 1892 m^3/s stage. The time series of channel width indicates this deposition occurred between June 15 and June 22, 1935 (Figure 16a). The next major episode of deposition occurred the next year between May 8 and May 11, 1936 (Figure 16b). That deposit aggraded the bar to at least the 1477 m^3/s stage (Figure 18). By May 27, 1948, the bar had eroded approximately to the June 14, 1935, level. Two days later, the bar aggraded to the 2147 m^3/s stage, the highest elevation deposit measured at that location on the cross-section. The 1949 to 1957 measurements show the deposit consistently at an elevation somewhat below the elevation of the 1948 deposit, indicating some erosion but an otherwise stable deposit.

The January 24, 2000 measurement by GCMRC indicates that the onshore portion of the deposit aggraded to the 3298 m^3/s stage and that a further offshore part of the deposit aggraded to the 1159 m^3/s stage. In our aerial photograph mapping, the higher-elevation onshore deposit was mapped as high-tamarisk terrace (htt) and the lower elevation deposit was mapped as an undifferentiated post-dam flood deposit (fs/hf). Thus, the htt deposit must have formed during the 1957 and 1958 floods, because those are the only floods that could have aggraded the deposit to that elevation. The lower fs/hf deposit would have been inundated in those years and in 1962, 1965, 1983, and 1984. Because the 1984 aerial photographs indicated recent deposition on this surface, the deposit most likely aggraded to its current elevation during the 1983 and 1984 floods.

Aggradation of the deposit at the Lower Cableway appears to have been initiated with the deposition measured in 1935. Although the period of record prior to the aggradation of the 1935 deposit is short, notes from the Lees Ferry hydrographers log support the conclusion that narrowing began at that time. On June 4, 1935, the hydrographer, Sherman O. Decker, noted channel narrowing in the vicinity of the gage and upstream caused by flash floods that occurred the previous summer:

> "The measurements above 42,000 c.f.s. have been plotting from .06 to .21 [ft] above the rating curve dated 10-15-32. An investigation at the river banks at and above the gage was made and it was found that the extremely heavy runs of last summer had caused several washes which empty in on the right bank and from 100 to 600 ft. above a point opposite the gage, to build deltas out in the river. This narrowed the main river channel and also turned the flow slightly more towards the gage. Since these deltas and a heavy growth of willow have not scoured out it is believed they are, at least partly, responsible for the measurements consistently plotting above the curve."

In addition to noting the deposition and channel narrowing that began in 1934-35, the hydrographer also notes the stabilization of those deposits by willow. Both the 1935 and 1952 aerial photographs show a vegetated deposit in this location, although by 1952 the vegetation was likely dominated by the tamarisk that now cover the deposit.

The total amount of channel narrowing that has occurred at the Lower Cableway between 1935 and 2000 has been about 8 m, all of it occurring on the left bank. This represents a decrease in the width of the river at this location of about 4%. Thus, the major episode of channel narrowing (50 m) reported by Hereford et al. (2000) between the 1920s and 2000 in the vicinity of the Paria River confluence (just downstream from the Lees Ferry gage) did not extend this far upstream on the Colorado River.

Alluvial Deposits in Glen Canyon

Glen Canyon in 1952

Although sheer bedrock walls and steep talus slopes are the most striking feature of the river corridor in Glen Canyon, channel-side alluvial deposits have also been a persistent feature of the fluvial landscape. Aerial photographs taken in 1952 show abundant deposits of bare sand and narrow strips of vegetated flood plain and terrace (Figure 19). Older oblique photographs, including some taken as early as 1889 show a similar landscape (Turner and Karpiscak, 1980; Webb, 1996). Most of the large alluvial deposits occurred on the inside of sharp meander bends, or downstream from these bends. Eddy deposits were much less frequent and generally much smaller than the channel-margin deposits. Averaged for all years of mapping, sand within eddy depositional zones comprises about 11% of the total area of fine-grained alluvium (Table 5). Gravel deposits also occurred, but were less common than sand deposits. In most cases, the gravel bar surfaces had numerous patches of sand and were mapped as mixed sand and gravel. Sand deposits covered approximately 84% of the 122 ha of mapped alluvial deposits; the remaining area was covered by mixed sand and gravel.

Although bare alluvial sand deposits were abundant in 1952, terraces covered with vegetation made up a greater percentage of the alluvial valley. Of the 122 ha of mapped alluvial deposits, 66% were terraces and the remainder were low and high elevation active-channel deposits. The 1952 bankfull channel area was calculated as the sum of the active channel deposits and the wetted channel. This area was divided by the length of the mapped area (25211 m), yielding a reach-average estimate for bankfull channel width of 156 m (Table 6).

Tables summarizing the area of map units for 1952 and each subsequent year of aerial photography are included in Appendix F.

Glen Canyon in 1984-2000

The character and distribution of alluvial deposits changed dramatically following closure of Glen Canyon Dam. The total area of alluvial deposits increased by about 50% (60 ha) between 1952 and 1984, but the proportion of those deposits composed of sand decreased (Figure 20). The increased abundance of gravel and cobble is most dramatic in the upstream 10 km of the study area where these bars were rare in 1952 and abundant in 1984 (Plate 1). The net increase in the area of alluvium, which is mostly gravel, has been accompanied by an increase in the area of dense vegetation on the remaining fine-sediment deposits, resulting in a reduction of the area of bare sand (Figure 20). Although the invasive saltcedar shrub (*Tamarix sp.*) has been present in the region since the 1930s (Clover and Jotter, 1944), there has been a great increase in its abundance since 1952 (Turner and Karpiscak, 1980).

This increase in the abundance of alluvial deposits occurred as active bars and bed sediments became part of the flood plain as a direct result of bed degradation. Because degradation has not been uniform across the channel, but has been concentrated in certain locations, sand and gravel deposits became perched on the channel margins.

The shifts in the stage-discharge relations that occurred throughout most of Glen Canyon resulted in decreased inundation frequencies for deposits that have not changed in elevation. Thus, while sediment has been evacuated from the bed of the river, channel-side deposits, which are relicts from the pre-dam era, are no longer inundated and are preserved by stabilizing vegetation.

Erosion and Deposition of Alluvial Deposits

Erosion and Deposition: 1950s to 1984

The best illustration of channel change is provided by those locations where cross-section surveys and erosion-deposition maps both indicate changes on the banks. It is important to note that the erosion-deposition maps do not provide an objective measure of bed erosion because they only depict deposits that were above the water surface at the time of photography. For example, in the vicinity of R-11A bed degradation occurred across much of the cross-section, but this degradation is not shown in the erosion-deposition map (Figure 21). The maps do capture erosion in locations where channel-side deposits present in 1952 have been replaced with lower elevation deposits or have become part of the river channel. The cross-section measurements document the depth and the timing of erosion while the maps provide the only means of quantifying the spatial extent of the erosion.

The 1952 to 1984 erosion-deposition maps indicate apparent deposition on many of the gravel bars. We refer to this as apparent deposition because the cross-section measurements show that these deposits have not changed in elevation or have in fact degraded (Figure 21). The appearance of deposition in these locations is a result of the shifting stage-discharge relation and we have labeled these deposits as “perched” gravel bars rather than areas of deposition.

Similar changes have occurred at eddy deposits (Figure 22). The 1952 to 1984 erosion-deposition map shows deposition of post-dam flood and fluctuating flow deposits on the right bank in an area that was within the river channel in 1952. Although the 2000 survey does not cover the entire cross-section, it shows the right bank to be at a lower elevation (Figure 9B). These post-dam flood deposits that were within the river channel in 1952 and appear on the erosion-deposition maps as deposition, are lower in elevation than the pre-dam riverbed. This is further evidence that areas of apparent deposition between 1952 and 1984 are the result of channel lowering rather than aggradation.

The channel cross-section data aided our interpretation of the erosion-deposition maps. Areas where the mapping indicated erosion of channel-side sand deposits or terraces are all areas where the cross-section surveys also indicated erosion, although the mapping does not show the majority of the bed degradation, which occurred in the center of the channel. The areas where the mapping indicates “deposition” between 1952 and 1984 are all perched deposits where the cross-section surveys indicate either no topographic change or degradation. Included in this category are sand deposits mapped as fluctuating flow deposits and post-dam flood deposits in 1984 and controlled flood deposits in April 1996. Implicit in these post-dam map units is the classification of these deposits as depositional features relating to preceding high flow events. Thus, these features that may have experienced deposition during some of the post-dam flood events have experienced net degradation or no net change since the pre-dam era. We have no evidence of deposition on any of the perched gravel deposits in the post-dam era, although local deposition on these deposits is possible.

The patterns of change in alluvial features described above are not distributed uniformly throughout the study area (Plates 2 and 3). Erosion of sand bars and terraces has occurred in discrete patches and the area of each of these patches varies greatly in magnitude. The perched sand and gravel deposits also occur in discontinuous patches throughout the study area. The reach-average magnitudes of channel adjustment are similar among four of the five reaches (Figure 23). However, in Reach 2, the area of erosion and the area of perched gravel deposits was more the twice that measured in any of the other reaches. This is the reach with the widest alluvial valley (Table 3) and the greatest area of pre-dam terraces in 1952. Within Reach 2, half of the erosion occurred at one location: the terrace on river left at R-11A. The erosion at this location between 1952 and 1984 was the largest single change measured in the entire study area (Figures 9A and 21). This terrace was the largest fine-grained deposit in the study area in 1952, and the remaining portion of that deposit was still among the largest terraces mapped on the 1984 photographs.

The most pronounced difference between this terrace and other pre-dam terraces that did not erode is its position relative to other channel features and the location of maximum erosion on the channel cross-section. At R-11A, erosion of the bed was greatest on the portion of the cross-section nearest the terrace. As this portion of the channel lowered, the gravel bar on the right bank remained stable, concentrating flow on the left side of the channel. This combination of bed degradation, which increased the relief at the edge of the terrace, and concentration of flow near the terrace probably led to the high rate of erosion of this deposit. In contrast, most of the other terrace deposits are adjacent to lower elevation channel-margin gravel or sand deposits. In these locations, bed degradation has typically been greatest in the center of the channel or on the opposite bank. This is the case just 850 m upstream from R-11A at R-12, where the pre-dam terrace has been stable. This and the other observations suggest that the style and magnitude of change in the alluvial deposits within the study area is controlled by local reach characteristics more strongly than distance downstream from Glen Canyon Dam.

Tables summarizing the changes between aerial photograph intervals are included in Appendix G.

Erosion and Deposition: 1984 to 1996

Changes in the alluvial deposits in Glen Canyon between 1984 and 1996 were small compared to the changes measured between 1952 and 1984. There has been little bank erosion since 1984. Channel-side sand deposits and pre-dam terraces continued to erode slightly (Figure 20). Post-dam high flows resulted in localized areas of deposition between 1984 and 1990 and between March and April 1996. Despite these changes, there was no significant change in the total area of pre-dam terrace, post-dam flood, or fluctuating-flow deposits from 1984 to April 1996 (Figure 20).

Erosion and Deposition in Eddies

The eddies in Glen Canyon are not uniformly distributed throughout the reach (Figure 1). Based on our surficial geologic mapping, we identified a total of 34 eddy depositional zones between the dam and Lees Ferry, 20 of which are larger than 1000 m^2. In the first four reaches, eddies are rare but those that do occur tend to be large, resulting in a much larger average EDZs than in downstream reaches (Table 5). In Reach 5, there are approximately 2.6 EDZs per km, which is comparable with the frequencies observed in some of the reaches downstream from Lees Ferry. Although there are a few large eddies in Glen Canyon, most eddies are small (Figure 24). The cumulative frequency distribution of EDZs approximates a log-normal distribution, as is the case further downstream (Schmidt et al., 2002).

Like the gravel bars and channel-margin deposits, active eddy bars in Glen Canyon became perched and stabilized with vegetation as a result of bed degradation. Figure 25 shows four nearby EDZs between 14.5 and 16.0 km downstream from Glen Canyon Dam. These four EDZs are among the largest in Glen Canyon. The area of exposed sand has not changed significantly between 1952 and 1984. Most of the area that was mapped as clean sand in 1952 is mapped as a post-dam flood deposit in 1984. These deposits consisted primarily of clean sand in 1952, and were densely covered by vegetation in 1984. Examination of the repeat surveys of R-7 indicated that these bars are currently at a lower elevation than in 1952 (Figure 9B), indicating net loss of sand from the EDZs. Thus, despite negative changes in the volume of sediment stored in eddies, the area of exposed sand has remained remarkably constant.

Changes at these sites are representative of the rest of Glen Canyon (Figure 26). The area of *high-elevation* sand in eddies has decreased slightly since 1984, although this decrease is not within our estimate of error. Meanwhile, the area of low-elevation sand has fluctuated, and neither an increasing nor a decreasing trend are suggested. These patterns are consistent with observations for reaches downstream for this same period (Schmidt et al., 2002).

DISCUSSION

Adjustment of the Bed

The timing of major bed degradation in Glen Canyon is directly related to management decisions made in the operation of Glen Canyon Dam. The episode of most rapid degradation occurred during a series of spike flows released 2 yr after dam closure. Reclamation documents contain calculations that were carried out to predict the amount of bed lowering these flows would be expected to produce, indicating these flows were released with the knowledge and intention of bed lowering. The power plant was designed to operate at maximum efficiency following degradation of the downstream channel, the magnitude of which was predicted by the studies initiated in 1956. The channel-cleaning flows achieved this degradation much sooner than might have occurred under different circumstances. Thus, in the case of Glen Canyon and possibly many other systems, the timing of bed degradation did not follow a natural progression of channel adjustment, but was an engineering decision.

Certainly much of the variability that has been observed in rates of bed degradation downstream from dams (Williams and Wolman, 1986) is related to local geomorphic conditions and bed sediment characteristics (e.g. Xu, 1996). However, management intentions may be also be an important source of variability. The degree of human control over the timing of bed degradation exhibited in Glen Canyon was possible because of the large magnitude of reservoir storage relative to annual runoff. The storage to runoff ratio for the Colorado River upstream from Glen Canyon Dam is approximately 2.3, contrasted to most reservoir storage systems in the United States, which have storage to runoff ratios significantly less than one (Hirsch et al., 1990). For those systems with low storage to runoff ratios, managers have little control over the release pattern and the timing of bed degradation. As the magnitude of storage capacity relative to runoff volume increases, managers have an increasing flexibility with release patterns and, therefore, rates of bed degradation.

The different channel elements in the Glen Canyon reach exhibited different patterns of degradation, both during the period of greatest bed lowering in 1965 and during the period of more gradual degradation and sediment evacuation that followed. At most of the riffles, nearly all of the degradation occurred during the 1965 channel-cleaning flows and the magnitude of that degradation decreased systematically downstream. This is supported by the systematically decreasing shift in stage-discharge relations with distance from the dam. On the other hand, significant bed degradation and sediment evacuation from pools has been variable throughout the reach and has continued through 2000. This difference in behavior between hydraulic controls and the bed at other locations explains the difficulty that has been encountered in efforts to predict the magnitude of degradation based on distance downstream from dams (e.g. Williams and Wolman, 1984). In this study, we have documented degradation of pools more than 6-km downstream from the downstream limit of degradation of channel controls. Schmidt et al. (2002) report pre- to post-dam bed degradation at cross-sections in Marble Canyon more than 60 km further downstream.

Previous investigations of bed adjustment at Lees Ferry (Burkham, 1986; Topping et al., 2000) focused on the role of decreasing supply of fine sediment in causing bed degradation. The data we have analyzed show that both fine and coarse sediment have been evacuated from the bed in Glen Canyon, indicating the sediment imbalance for this reach applies to gravels, cobbles, and sand.

The disparity of degradation rates between riffles and pools has also led to the adjustment of the river's longitudinal profile. Each steep segment in the profile is located at a large gravel bar and the three steepest riffles occur at the mouths of tributaries. These tributaries, Honey Draw, an unnamed tributary at RM -9, and Water Holes Canyon, were identified by Webb et al. (2000) as potentially significant contributors of sediment to the Colorado River by either stream flow. None of these tributaries has a large debris fan, and only Honey Draw has a small debris fan. The development of steep sections and the occurrence of differential erosion demonstrate that the longitudinal profile that has developed as the riverbed eroded must be related to the distribution of the bed sediment grain sizes. This indicates that the largest sediment buried in the bed was located at the mouths of the largest tributaries, which have emerged as channel controls as the finer sediment was evacuated from the bed. Therefore, occurrence of pool and riffle segments exhibited in Glen Canyon appears to be related to the interaction between tributary sediment delivery and mainstem sediment reworking, rather than a display of classic pool-riffle morphology.

The bed lowering that established the modified post-dam water-surface profile and resulted in perched gravel and sand deposits throughout the reach occurred in one brief period, while sediment evacuation from the non-control sections is an ongoing process. The recent post-dam high flows of the 1980s and 1996, which were probably responsible for most of the sediment evacuation from the pools, did not cause further lowering of the bed at channel controls. Based on these observations, it seems that future lowering of the bed at channel controls, causing further shifts in the stage-discharge relations, is very unlikely. Conversely, depending on the rate of tributary sediment delivery and the size of supplied sediment, aggradation of channel controls is a possibility. Aggradation of channel controls has been suggested for debris-fan dominated canyons where floods have been eliminated (Graf, 1980; Webb, 1997). Continued evacuation of sediment from pools should be expected during high power plant releases and floods. It may, therefore, be useful to continue monitoring those cross-sections.

The volume of sediment that has been degraded from the bed in Glen Canyon is large relative to post-dam sediment loads, but small relative to the pre-dam suspended sediment loads. Approximately 18.4 million Mg of sediment has been excavated from the bed of the Glen Canyon Reach (assuming the eroded sediment had a specific gravity of 2.65 and a porosity of 35%). This is 275 times the estimated annual post-dam input of sediment of all sizes from ungaged tributaries in the study area, but just one-third the pre-dam annual load of suspended sediment (sand and finer material) measured at Lees Ferry.

The changing pattern of bed degradation in Glen Canyon is consistent with the transition from incised meander to debris-fan dominated canyon stream type. This study has confirmed that presence of debris fans limits the downstream extent of degradation of channel controls, precluding the possibility of bed-elevation lowering in Marble Canyon and Grand Canyon.

Adjustment of Alluvial Deposits

The pattern of alluvial deposit change in Glen Canyon is consistent with the dramatic bed lowering and reduced sediment budget. The major changes identified between the 1952 and 1984 aerial photographs include approximately equal areas of (1) sand deposit erosion, (2) perched sand deposits, and (3) perched gravel deposits. Erosion of pre-dam terraces also occurred. Because the thickness of erosion of channel-side deposits is known for only a few locations, it is not possible to estimate the volume of that erosion comparable to the estimate of sediment evacuated from the bed. The only well-constrained estimate for magnitude of channel-side deposit erosion is for the terraces, of which there has been about 1.5 million Mg of erosion between 1952 and 1996. This assumes 5 m of erosion, based on the cross-section measurements at R-11A. There has been up to an additional 5 million Mg of erosion on all other channel-side deposits (sand and gravel). This assumes 3 m of erosion from all low-elevation deposits and 2 m of erosion from all high-elevation deposits. These estimates are also based on the cross-section measurements, but are poorly constrained because very few of the repeat cross-section measurements traverse these deposits. All estimates assume a dry sediment weight of 2650 kg/m^3 and a porosity of 35%.

While bed degradation has been progressive, changes in channel-side deposits have been spatially and temporally variable. Comparison between the mapped changes and the cross-section surveys suggests the widespread perching of alluvial deposits accompanied the bed degradation that occurred during the 1965 channel-cleaning flows. The perched deposits are areas that were part of the river's bed in 1952, but are now elevated relative to the bed in the thalweg and the low discharge water surface elevation, owing to degradation concentrated in a portion of the channel. These deposits decrease in abundance in the downstream direction as the degree of degradation-induced shift to the stage-discharge relation decreases. Although the largest changes in the alluvial deposits occurred by 1984, some deposits have eroded or aggraded since 1984.

Although there has been a significant amount of terrace erosion, approximately 75% of the area of pre-dam terraces remains intact. The lower elevation fluctuating-flow and post-dam flood alluvial deposits may be adjusted to the current post-dam flow and sediment regime. Although there has been a significant amount of erosion of these deposits, the rate of erosion has been declining since 1984 and has been balanced by some deposition. The large eddy-deposited sand bars and channel-margin deposits that do exist are largely stabilized by dense thickets of riparian vegetation. Moreover, these deposits are rarely inundated by dam operations and in many cases protected by gravel or cobble armor. The persistence of the few remaining bare sand deposits demonstrates the efficiency of these sediment traps and indicates that the sediment input from the ungaged tributaries in Glen Canyon, however meager, appears to be sufficient to maintain these deposits.

CONCLUSIONS

1. The majority of bed lowering and sediment evacuation occurred during the channel cleaning flows of May 1965. This degradation was anticipated and planned by dam managers.
2. The magnitude of degradation of channel controls decreases systematically downstream from Glen Canyon Dam to a distance of 20.6 km, below which channel controls have been stable.
3. The magnitude of degradation in pools does not vary systematically with distance below the dam.
4. Riffles and channel controls have not degraded significantly since the 1965 channel-cleaning flows, whereas sediment evacuation from pools has continued to present. The total magnitude of sediment evacuation is about 18.4 million Mg, exceeding the predicted magnitude by about 30%.
5. The dropping stage-discharge relations have decreased the inundation frequency of deposits leaving pre-dam channel-side sand deposits and portions of the exhumed gravel bed perched above the range of post-dam normal power plant discharges. This has caused in increase in the area of exposed alluvium and reduction of channel width by about 6%, despite the large magnitude of net sediment evacuation from the reach.

6. Because the perched deposits are rarely inundated and stabilized by vegetation, erosion of these deposits has been limited and highly localized—nearly all of the erosion that was measured occurred at one location.

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TABLES

Table 1. Locations of cross-sections in Glen Canyon indicating which cross-sections were surveyed each year and the dates of those measurements if known.

Section Name	Distance from Dam (km)	1956	1959	1963	1965*	1975*	1983	1990*	2000
R-20	1.0	18-Aug	25-Nov	21-May	Sep 20-30	Jul	19-Oct	Sep	10-May
R-19	1.5	18-Aug		21-May					10-May
Glen Canyon Dam Gage Station Cableway	2.3								10-May
R-18	2.5	18-Aug	24-Nov	22-May	Sep 20-30	Jul	18-Oct	Sep	10-May
R-17	3.4	18-Aug		22-May					11-May
R-16	4.3	15-Aug	23-Nov	22-May	Sep 20-30	Jul	18-Oct	Sep	11-May
R15A	4.6			23-May					11-May
R-15	5.8	15-Aug	30-Nov	23-May	Sep 20-30	Jul	19-Oct	Sep	11-May
R-14	7.5	10-Aug	19-Nov	24-May	Sep 20-30	Jul	19-Oct	Sep	
R-13	8.9	10-Aug		24-May					27-Jan
R-12	9.4	10-Aug		24-May					27-Jan
R-11A	10.3	9-Aug	18-Nov	27-May	Sep 20-30	Jul	20-Oct	Sep	27-Jan
R-11	11.0	9-Aug		27-May					27-Jan
R-10	12.8	9-Aug	17-Nov	27-May	Sep 20-30	Jul	20-Oct	Sep	26-Jan
R-9	14.4	8-Aug							26-Jan
R-8	15.0	8-Aug	12-Nov		Sep 20-30	Jul	20-Oct	Sep	26-Jan
R-7	15.8	8-Aug							26-Jan
R-6	16.8	7-Aug							26-Jan
R-5	18.4	7-Aug	9-Nov		Sep 20-30	Jul	21-Oct	Sep	26-Jan
R-4	20.1	7-Aug							25-Jan
R-3	21.4	6-Aug							
R-2	22.6	6-Aug							25-Jan
R-1 (Old Upper Lees Ferry Cableway)	23.9	6-Aug	4-Nov		Sep 20-30	Jul	21-Oct	Sep	25-Jan
Old Lower Lees Ferry Cableway	24.7								24-Jan
Lees Ferry Cableway	25.4								24-Jan
R-0	27.8	6-Aug	29-Oct		Sep 20-30	Jul		Sep	28-Jan

* Exact measurement date not known.

Table 2. Dates of aerial photographs used in surficial geologic mapping and the discharge at time of photography.

Date	Scale	Discharge (m^3/s)	Portion of Study Area Mapped*
September 14, 1952	1:10,000	290	-13.4 to 0
October 8, 1952	1:10,000	180	-15 to –13.4
October 21, 1984	1:3,000	141	-15 to 0
June 2, 1990	1:4,800	141	-15 to 0
October 11, 1992	1:4,800	226	-15 to –3.2
May 30, 1993	1:4,800	226	-3.2 to 0
March 24, 1996	1:4,800	226	-15 to 0
April 4, 1996	1:4,800	290	-15 to 0

* By river mile within Glen Canyon.

Table 3. Selected characteristics of study area and reaches within study area.

Characteristic	Reach					Study Area
	1	2	3	4	5	
Length (km)	5.2	5.1	4.9	5.0	5.0	25.2
Gradient	0.0005	0.0002	0.0001	0.0003	0.0001	0.0003
Alluvial valley width (m)	175	216	156	194	172	183

Table 4. Estimate of map error for channel-margin, eddy, and all deposits for each year of mapping.

Map year	Deposit	Area of deposits (m^2)	Number of deposits, *n*	Average deposit area (m^2)	Standard error, *SE* (m^2)
1952	cm	913,529	129	7082	10339
1952	eddy	77,850	12	6488	3153
1952	cm &eddy	991,380	141	7031	10809
1984	cm	921,081	434	2122	18963
1984	eddy	94,689	153	619	11259
1984	cm &eddy	1,015,769	587	1730	22054
1990	cm	891,373	475	1877	19839
1990	eddy	107,259	112	958	9633
1990	cm &eddy	998,632	587	1701	22054
1992	cm	900,452	414	2175	18521
1992	eddy	101,162	107	945	9416
1992	cm &eddy	1,001,614	521	1922	20777
Mar-96	cm	1,019,093	402	2535	18251
Mar-96	eddy	113,910	89	1280	8588
Mar-96	cm &eddy	1,133,003	491	2308	20170
Apr-96	cm	1,015,246	373	2722	17580
Apr-96	eddy	103,851	82	1266	8243
Apr-96	cm &eddy	1,119,097	455	2460	19417

Table 5. Summary description of eddy depositional zones in Glen Canyon and the proportion of sand that occurs within these zones.

Characteristic	Reach 1	2	3	4	5	Study Area
All eddies						
Number	2	4	4	4	21	34
Frequency (per km)	0.4	0.8	0.8	0.8	4.2	1.3
Average area (m^2)	5634	1294	14481	6327	3906	5192
Eddy sand storage (%)*	4.5	1.0	26.5	6.3	20.8	11.1
Eddies larger than 1000m^2						
Number	1	1	3	2	13	20
Frequency (per km)	0.2	0.2	0.6	0.4	2.6	0.8
Average area (m^2)	10936	4122	23900	12350	6074	8825

* Percent of all fine-grained alluvium that is within eddy depositional zones, averaged for all years of mapping from aerial photographs.

Table 6. Bankfull channel width, by reach for each year of mapping from aerial photographs.

Date	Reach Bankfull channel width (m) 1	2	3	4	5	Study Area
Sep-52	158	176	137	166	142	156
Oct-84	150	164	123	153	132	144
Jun-90	151	165	125	154	134	146
Oct-92	151	166	126	154	135	146
Mar-96	151	167	126	155	135	147
Apr-96	150	167	126	156	137	147

FIGURE CAPTIONS

Figure 1. Map showing the study area in Glen Canyon. The 5-km reach divisions, cross-section locations, eddies, debris fans, and largest tributaries are also indicated. River mile locations are in miles upstream from the Lees Ferry cableway.

Figure 2. Plot showing annual maximum instantaneous discharge and daily mean discharge of the Colorado River at Lees Ferry, Arizona, 1921 to 2000. Dates of cross-section measurements and aerial photography used in this report are indicated. The inset shows the instantaneous discharge measurements from Lees Ferry for the channel cleaning flows, March to August 1965.

Figure 3. Sketch showing relative elevations of mapped deposits in relation to the pre- and post-dam channel. The approximate stages of the pre-dam average flood (about 2500 m^3/s) and the post-dam average flood (about 850 m^3/s) are shown. Post-dam deposits shown are the flood sand (fs), high-flow sand (hf), controlled flood sand (cf), and fluctuating-flow sand. Vegetation on the fluctuating-flow, post-dam flood, and high-tamarisk terrace deposits is mostly tamarisk, but other riparian species occur. Vegetation on the pre-dam terrace is mostly upland grasses and shrubs.

Figure 4. Longitudinal profile of the elevation of deposits mapped on the 1984 photographs and water surface elevations from cross-section surveys and the Lees Ferry gage.

Figure 5. Minimum bed elevation for measurements made from 1956 to 2000 at the 10 monitoring cross-sections, grouped by riffles (a) and pools (b). The distance below Glen Canyon Dam is indicated for each cross-section.

Figure 6. Bed sediment size distributions for Glen Canyon. The plotted distributions from 1956 include the average of bed surface samples, the average of sand-only samples and the average of bore-hole samples of the underlying gravel layer. The plotted distributions from 1966 include the average of gravel-bar surface (armor) samples, gravel-bar subsurface samples, and sand-only samples. Only the gravel-bar surface was sampled in 1975. The 1999 size-distributions are from samples collected by pipe dredge from a boat at approximately 1 km intervals throughout the study area. The plotted distributions from 1999 include the average of all samples, the average of samples collected on a “smooth bed”, and the one sample collected in an eddy. The 1956-1975 data are from Pemberton (1976).

Figure 7. Longitudinal profile showing thalweg elevation for each of the surveys and elevation of the top of the gravel layer determined by bore hole and jet probe measurements in 1956. Water surface profiles measured before (1956) and after (1966) major bed degradation are also shown. The discharge was 79 m^3/s at the time of the 1956 measurement and at 238 m^3/s at the time of the 1966 measurement.

Figure 8. Plot showing the accumulated volume of bed degradation since 1956 as a function of distance downstream from Glen Canyon Dam. The degraded volume between two adjacent cross-sections is calculated as the average change in cross-sectional area multiplied by the distance between the cross-sections. The intervals are added cumulatively from the dam downstream such that the degradation at the end of the study area is the total amount of degradation. Degradation is calculated between each indicated year and 1956 such that the degradation between two successive measurements is the difference between the curves for those years.

Figure 9. Plots of cross-sections R-11a (A) and R-7 (B) in Glen Canyon for each measurement. The jet probe measurements made in 1956 show the top of the gravel layer at R-11a (A).

Figure 10. Stage-to-discharge relation for cross-sections R-10 (a) and R-1 (b).

Figure 11. Change in stage at a discharge of 150 m^3/s, plotted as a function of distance downstream from Glen Canyon Dam.

Figure 12. Time series of minimum bed elevation for the Upper Cableway of the Lees Ferry gage from August 14, 1921 to December 1, 1966. Upper cableway measurements for which the gage height was measured at the Upper Cableway are distinguished from measurements where only recording gage height was measured at Upper Cableway gage height was calculated. Also plotted are Reclamation and GCMRC surveys of R-1, which is the same location as the Upper Cableway, from 1956 to January 2000.

Figure 13. Time series of minimum bed elevation for the Lower Cableway of the Lees Ferry gage from May 12, 1929 to July 17, 1957.

Figure 14. Selected plots of the entire Lower Cableway cross-section from 1929 to 2000. Degradation of the bed at the thalweg has been much less than at the Upper Cableway, but the bed has degraded across the rest of the channel, changing channel shape.

Figure 15. Plot showing channel width as a function of water surface elevation at the Lower Cableway. The data include all Lower Cableway measurements and are divided into five time periods showing episodic decrease in channel width.

Figure 16. Time series of channel width for two narrow ranges in water surface elevation. Width measured at water surface elevations between 952.0 and 952.4 m are shown in (A), and widths measured at water surface elevations between 951.3 and 951.5 m are shown in (B).

Figure 17. Plot showing the poor correlation between channel width and water surface elevation for the elevation ranges shown in Figure 16, confirming that those trends in width are not related to differences in discharge at the time of measurement. This demonstrates that the discharge increments for which we compare changes in channel width are sufficiently small that the correlation between width and discharge is eliminated.

Figure 18. Detail of the left bank of the cross-section at the Lower Cableway shown in Figure 14. The bed elevations are from USGS discharge measurements.

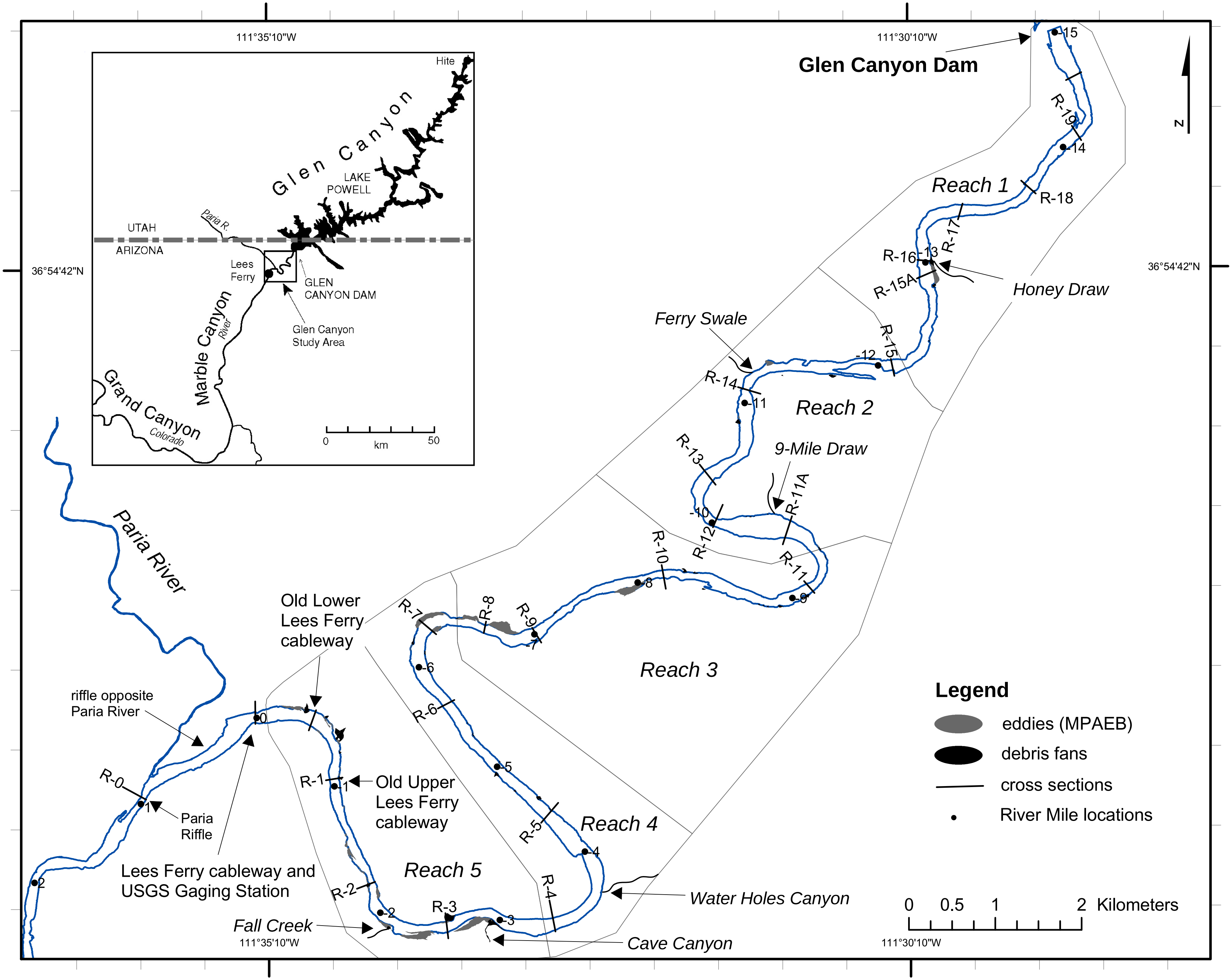
Figure 19. Clips from aerial photographs taken in 1952 (A) and 1984 (B) showing the reach near cross-section R7, about 16 km downstream from Glen Canyon Dam. Note the bare sand bars and narrow strips of vegetation in the 1952 photograph. Stream flow is from right to left.

Figure 20. Time series showing total area of terrace deposits, high- and low-elevation sand deposits, and gravel deposits. The error bars are the standard error except for 1952 where the standard error is exceeded by the uncertainty associated with assigning those deposits to the post-dam elevation categories.

Figure 21. Map showing interpreted changes in the channel-side deposits between 1952 and 1984 at R-11A compared to the location of surveyed changes in topography along the cross-section.

Figure 22. Map showing interpreted changes in the channel-side deposits between 1952 and 1984 at R-7 compared to the location of surveyed changes in topography along the cross-section.
Figure 23. Plot showing longitudinal variation in patterns of erosion and deposition between 1952 and 1984.
Figure 24. Histogram showing the distribution of EDZ size in Glen Canyon.
Figure 25. Maps showing the distribution of deposits in 1952 and 1984 for four large eddy depositional zones in Glen Canyon.
Figure 26. Time series showing total area of post-dam flood, and fluctuating-flow elevation sand in all eddies.

FIGURES


Glen Canyon Dam
111°35'10"W
111°30'10"W
36°54'42"N
36°54'42"N
N
Reach 1
Reach 2
Reach 3
Reach 4
Reach 5
Honey Draw
Ferry Swale
9-Mile Draw
Water Holes Canyon
Cave Canyon
Fall Creek
Old Lower Lees Ferry cableway
Old Upper Lees Ferry cableway
Lees Ferry cableway and USGS Gaging Station
riffle opposite Paria River
Paria Riffle
Paria River
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
1
2
R-19
R-18
R-17
R-16
R-15A
R-15
R-14
R-13
R-12
R-11A
R-11
R-10
R-9
R-8
R-7
R-6
R-5
R-4
R-3
R-2
R-1
R-0
Legend
eddies (MPAEB)
debris fans
cross sections
River Mile locations
0
0.5
1
2
Kilometers
Hite
Glen Canyon
LAKE POWELL
UTAH
ARIZONA
Paria R.
Lees Ferry
GLEN CANYON DAM
Glen Canyon Study Area
Marble Canyon
River
Grand Canyon
Colorado
0
km
50

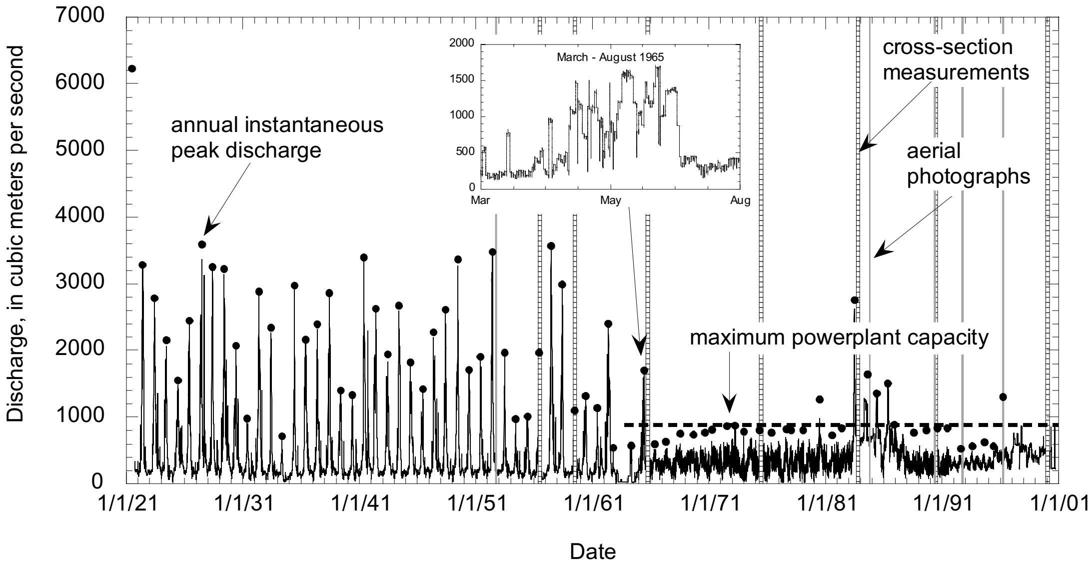

7000
6000
5000
4000
3000
2000
1000
0
Discharge, in cubic meters per second
1/1/21
1/1/31
1/1/41
1/1/51
1/1/61
1/1/71
1/1/81
1/1/91
1/1/01
Date
annual instantaneous peak discharge
March - August 1965
2000
1500
1000
500
0
Mar
May
Aug
cross-section measurements
aerial photographs
maximum powerplant capacity

Figure 2

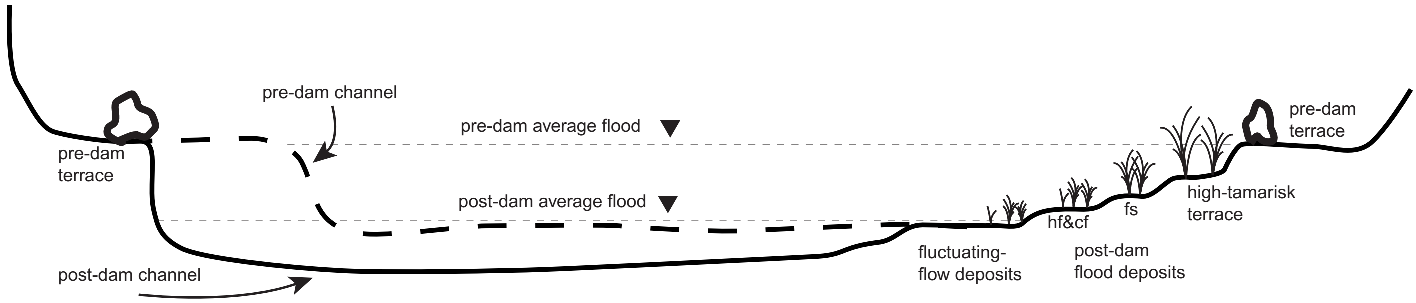
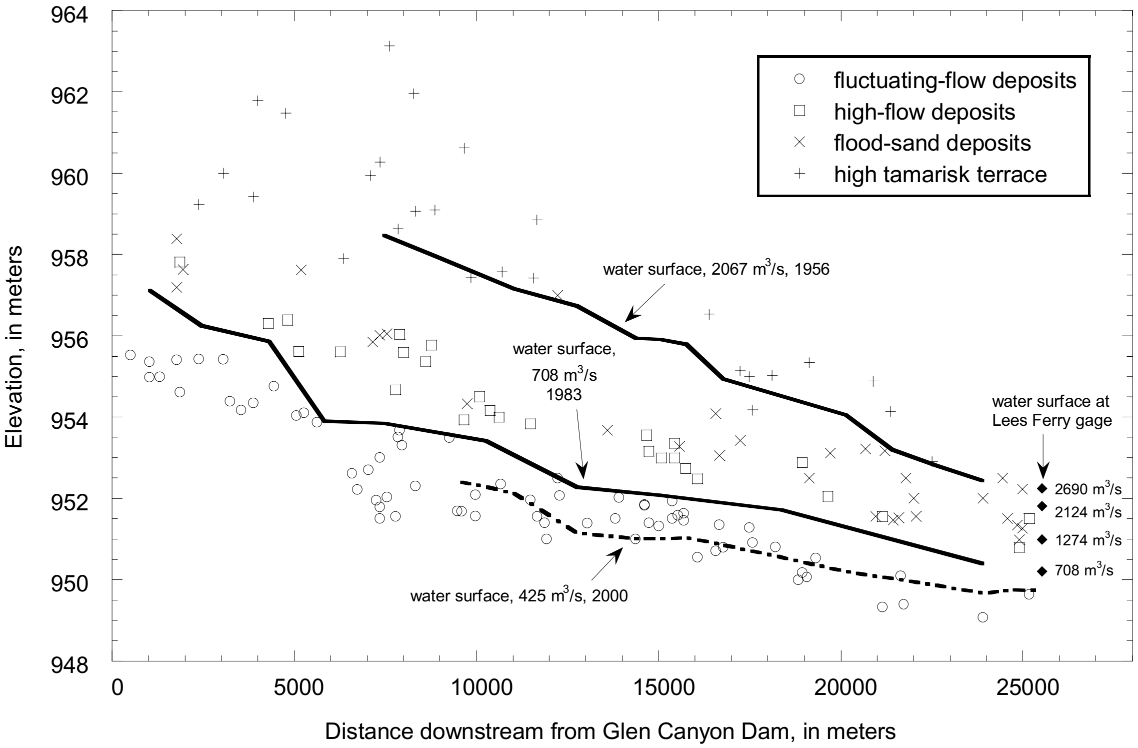

pre-dam channel
pre-dam average flood
post-dam average flood
pre-dam terrace
post-dam channel
pre-dam terrace
high-tamarisk terrace
fs
hf&cf
fluctuating-flow deposits
post-dam flood deposits

Figure 3



964
962
960
958
956
954
952
950
948
Elevation, in meters
0
5000
10000
15000
20000
25000
Distance downstream from Glen Canyon Dam, in meters
○ fluctuating-flow deposits
□ high-flow deposits
× flood-sand deposits
+ high tamarisk terrace
water surface, 2067 m³/s, 1956
water surface, 708 m³/s 1983
water surface, 425 m³/s, 2000
water surface at Lees Ferry gage
◆ 2690 m³/s
◆ 2124 m³/s
◆ 1274 m³/s
◆ 708 m³/s

Figure 4

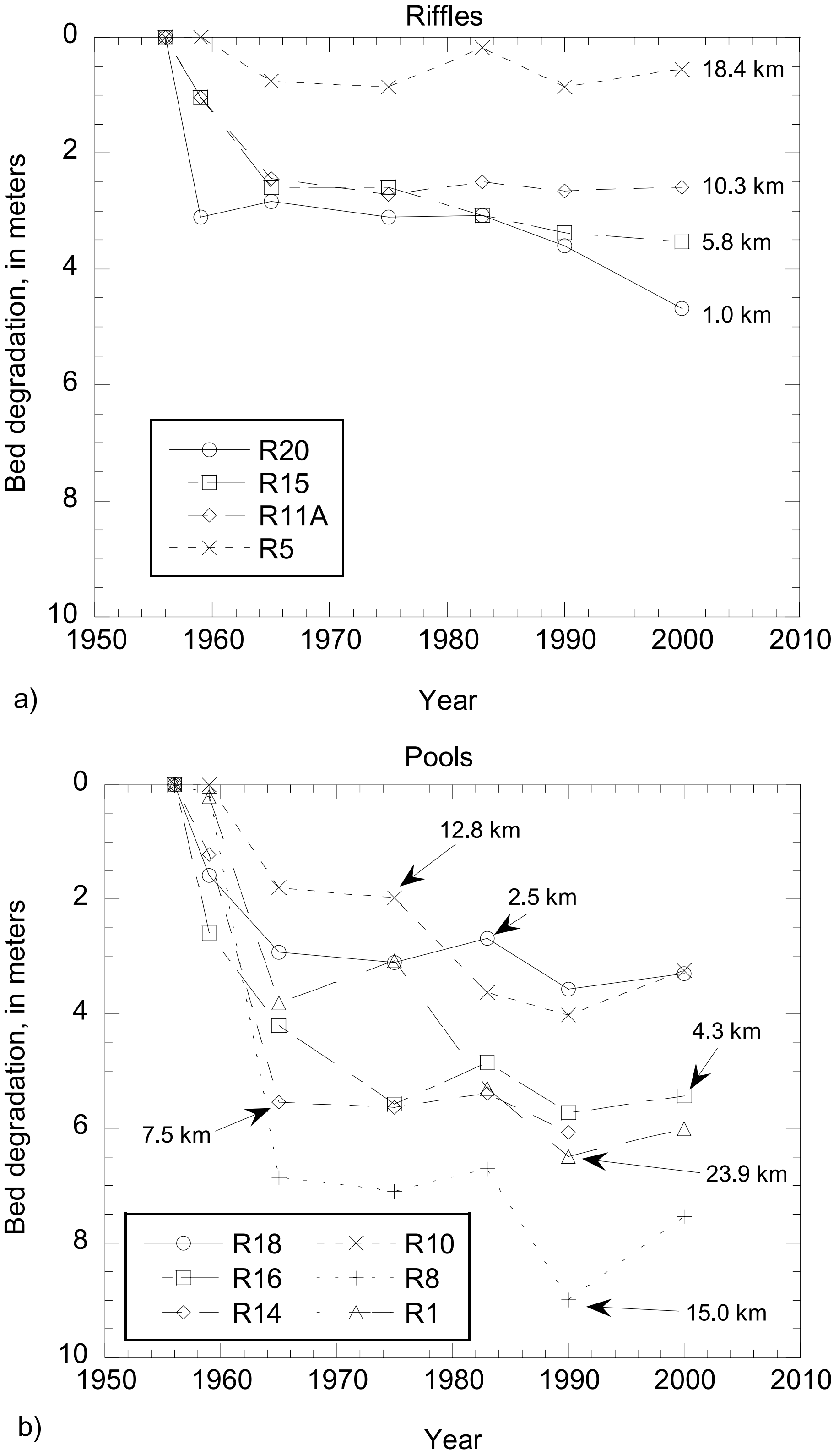

Riffles
Bed degradation, in meters
0
2
4
6
8
10
1950
1960
1970
1980
1990
2000
2010
Year
a)
18.4 km
10.3 km
5.8 km
1.0 km
R20
R15
R11A
R5
Pools
Bed degradation, in meters
0
2
4
6
8
10
1950
1960
1970
1980
1990
2000
2010
Year
b)
12.8 km
2.5 km
4.3 km
7.5 km
23.9 km
15.0 km
R18
R16
R14
R10
R8
R1

Figure 5

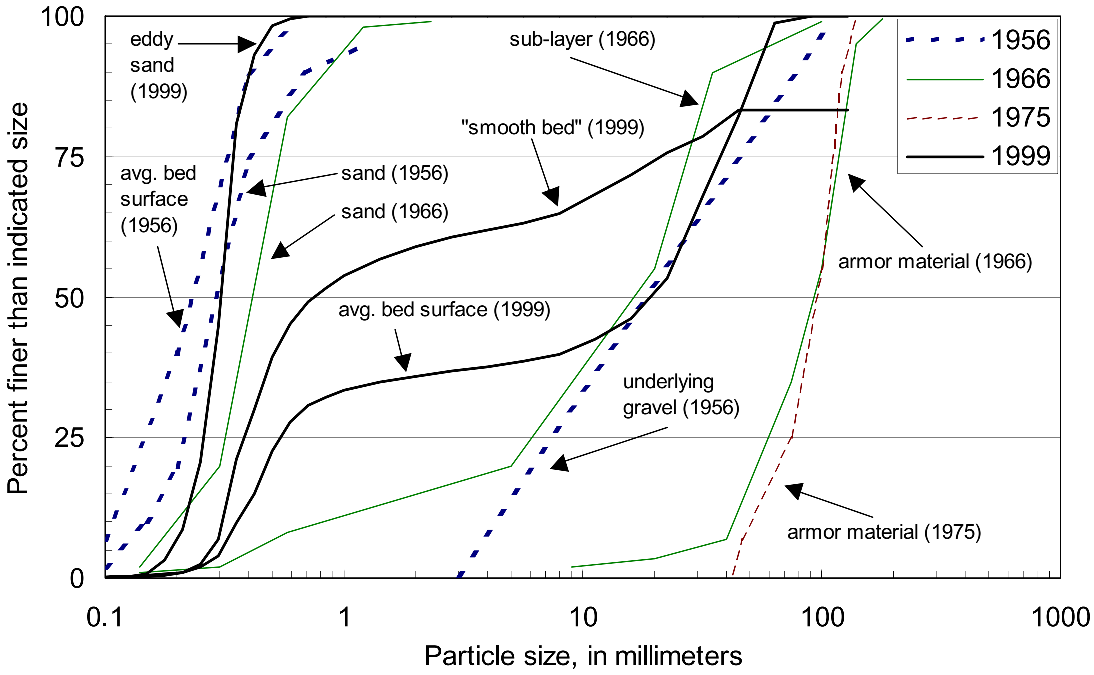
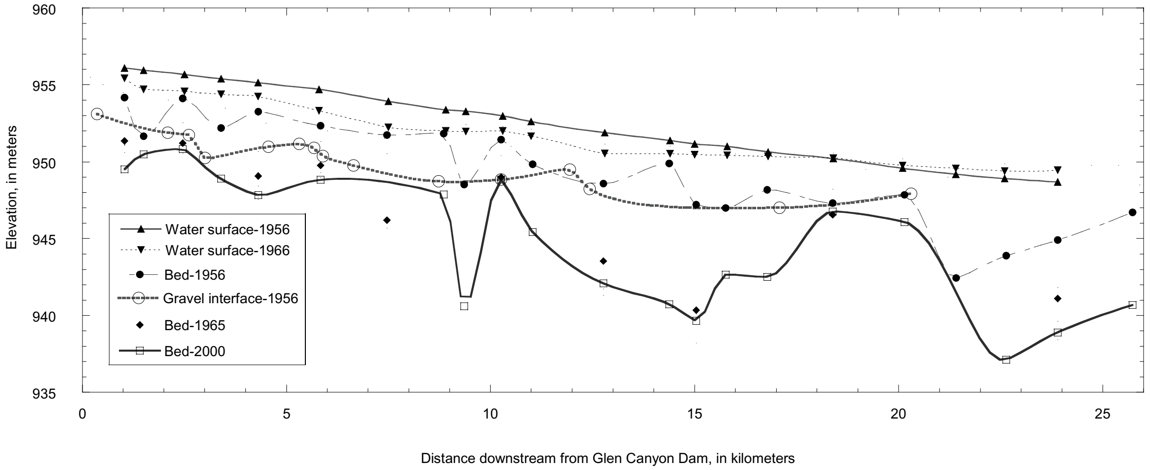

100
75
50
25
0
0.1
1
10
100
1000
Percent finer than indicated size
Particle size, in millimeters
1956
1966
1975
1999
eddy sand (1999)
avg. bed surface (1956)
sand (1956)
sand (1966)
sub-layer (1966)
"smooth bed" (1999)
avg. bed surface (1999)
underlying gravel (1956)
armor material (1966)
armor material (1975)

Figure 6



960
955
950
945
940
935
Elevation, in meters
0
5
10
15
20
25
Distance downstream from Glen Canyon Dam, in kilometers
Water surface-1956
Water surface-1966
Bed-1956
Gravel interface-1956
Bed-1965
Bed-2000

Figure 7

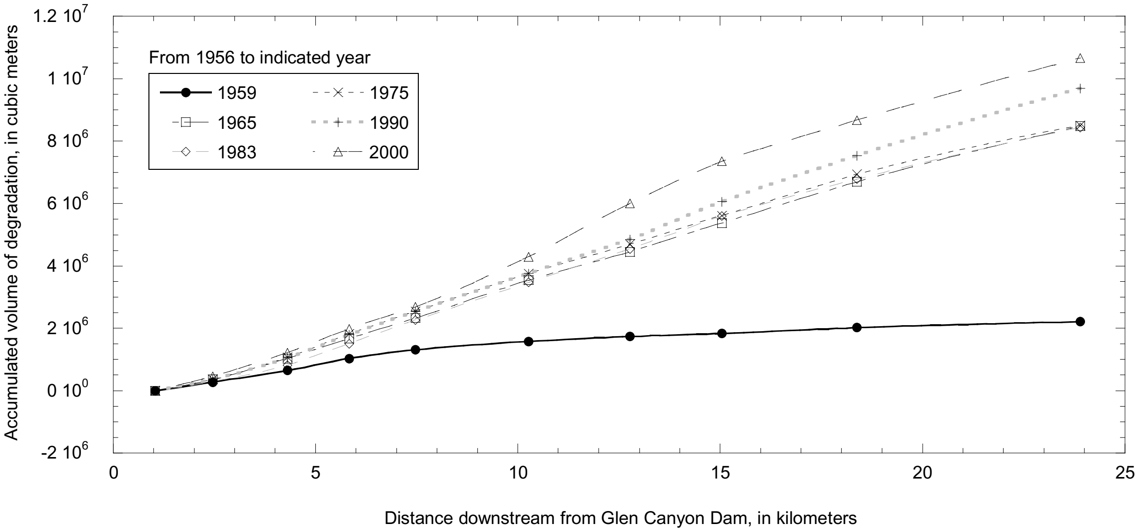
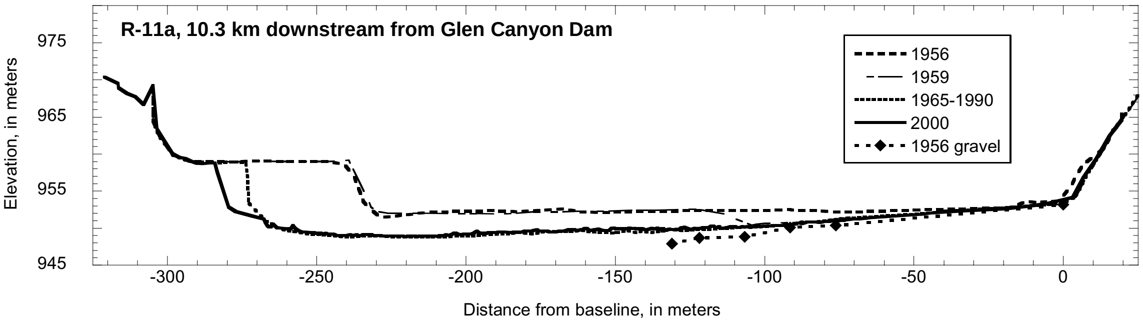
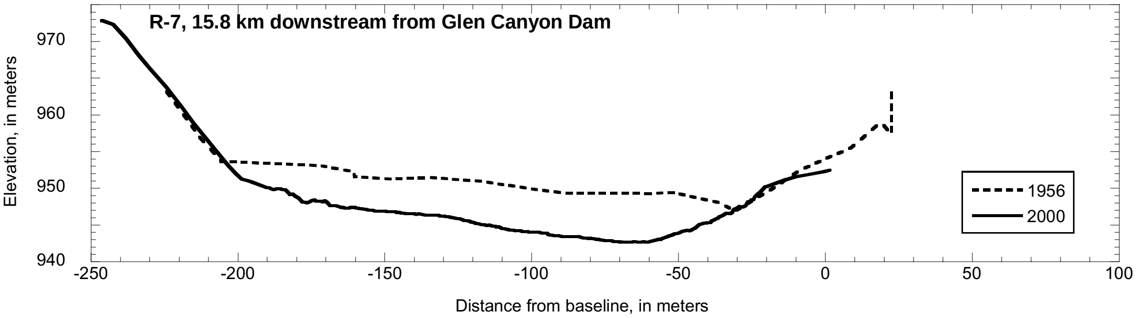

From 1956 to indicated year
1959
1965
1983
1975
1990
2000
Accumulated volume of degradation, in cubic meters
1.2 10^7
1 10^7
8 10^6
6 10^6
4 10^6
2 10^6
0 10^0
-2 10^6
0
5
10
15
20
25
Distance downstream from Glen Canyon Dam, in kilometers

Figure 8

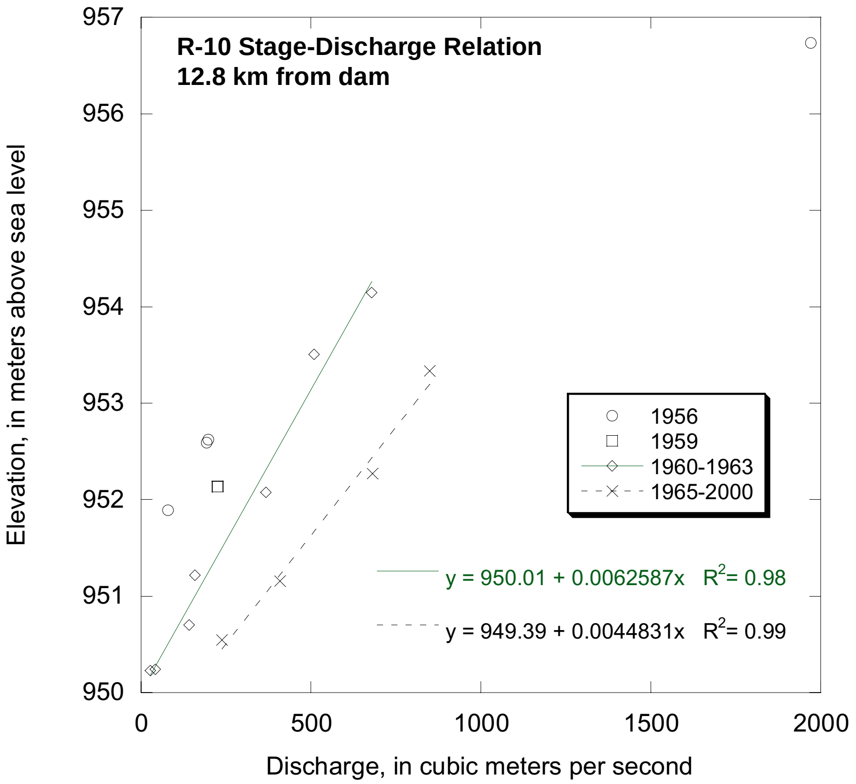

R-11a, 10.3 km downstream from Glen Canyon Dam
1956
1959
1965-1990
2000
1956 gravel
Elevation, in meters
975
965
955
945
-300
-250
-200
-150
-100
-50
0
Distance from baseline, in meters

a)

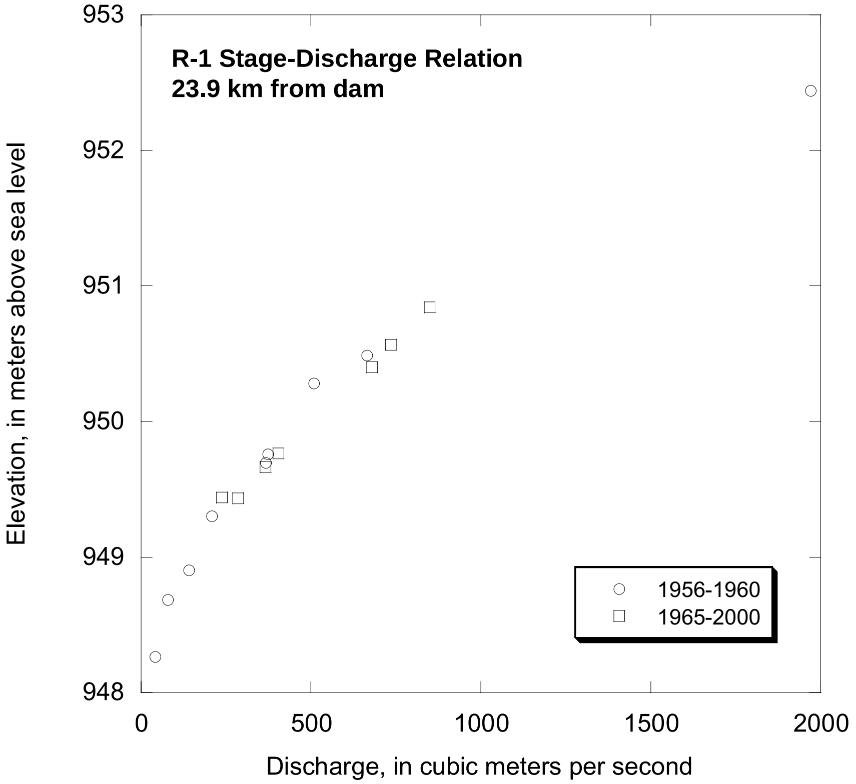

R-7, 15.8 km downstream from Glen Canyon Dam
1956
2000
Elevation, in meters
970
960
950
940
-250
-200
-150
-100
-50
0
50
100
Distance from baseline, in meters

b)

Figure 9


R-10 Stage-Discharge Relation
12.8 km from dam
957
956
955
954
953
952
951
950
0
500
1000
1500
2000
Elevation, in meters above sea level
Discharge, in cubic meters per second
1956
1959
1960-1963
1965-2000
y = 950.01 + 0.0062587x R² = 0.98
y = 949.39 + 0.0044831x R² = 0.99

a)


R-1 Stage-Discharge Relation
23.9 km from dam
953
952
951
950
949
948
0
500
1000
1500
2000
Elevation, in meters above sea level
Discharge, in cubic meters per second
1956-1960
1965-2000

b)

Figure 10

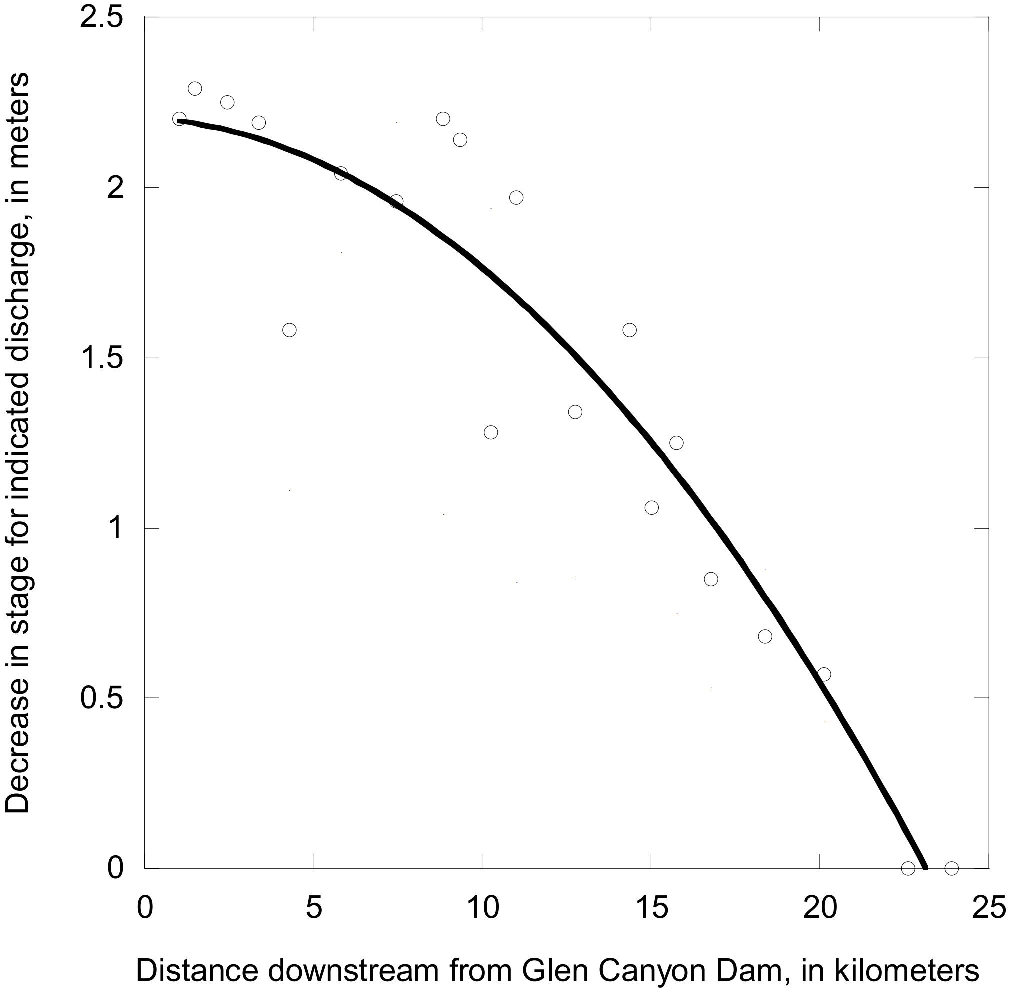

2.5
2
1.5
1
0.5
0
0
5
10
15
20
25
Decrease in stage for indicated discharge, in meters
Distance downstream from Glen Canyon Dam, in kilometers

Figure 11

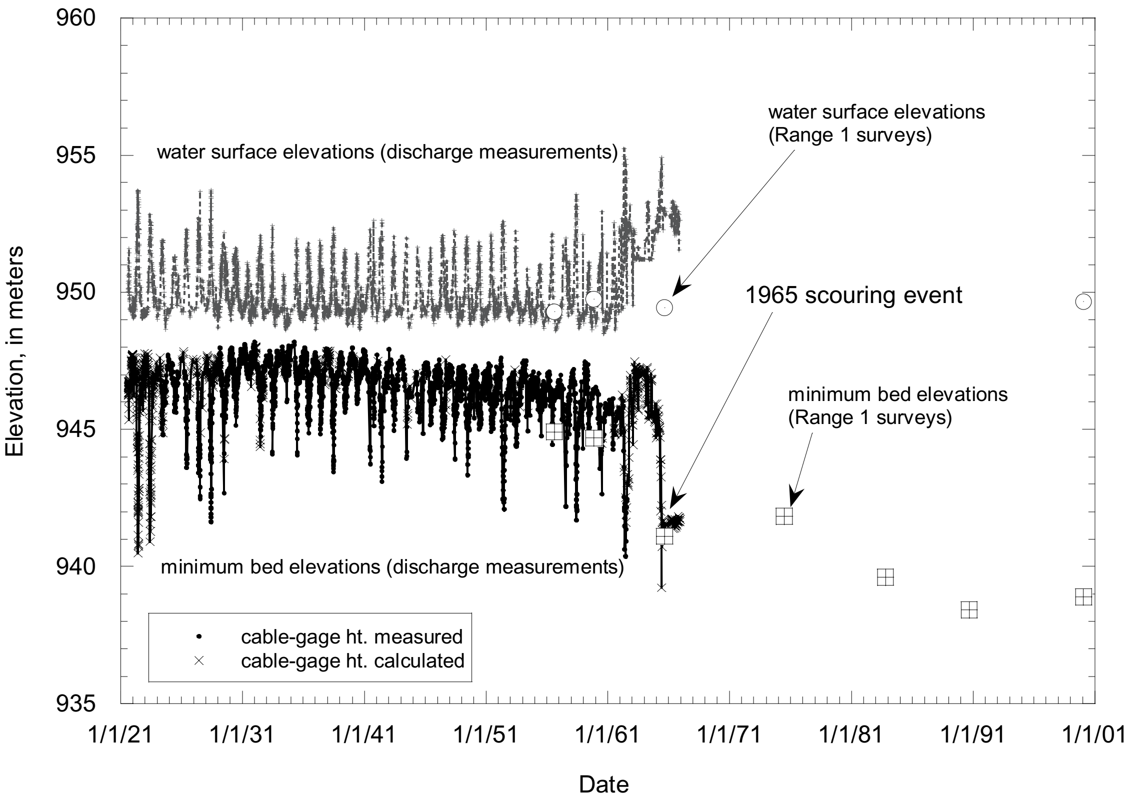

960
955
950
945
940
935
Elevation, in meters
water surface elevations (discharge measurements)
water surface elevations
(Range 1 surveys)
1965 scouring event
minimum bed elevations
(Range 1 surveys)
minimum bed elevations (discharge measurements)
• cable-gage ht. measured
× cable-gage ht. calculated
1/1/21
1/1/31
1/1/41
1/1/51
1/1/61
1/1/71
1/1/81
1/1/91
1/1/01
Date

Figure 12

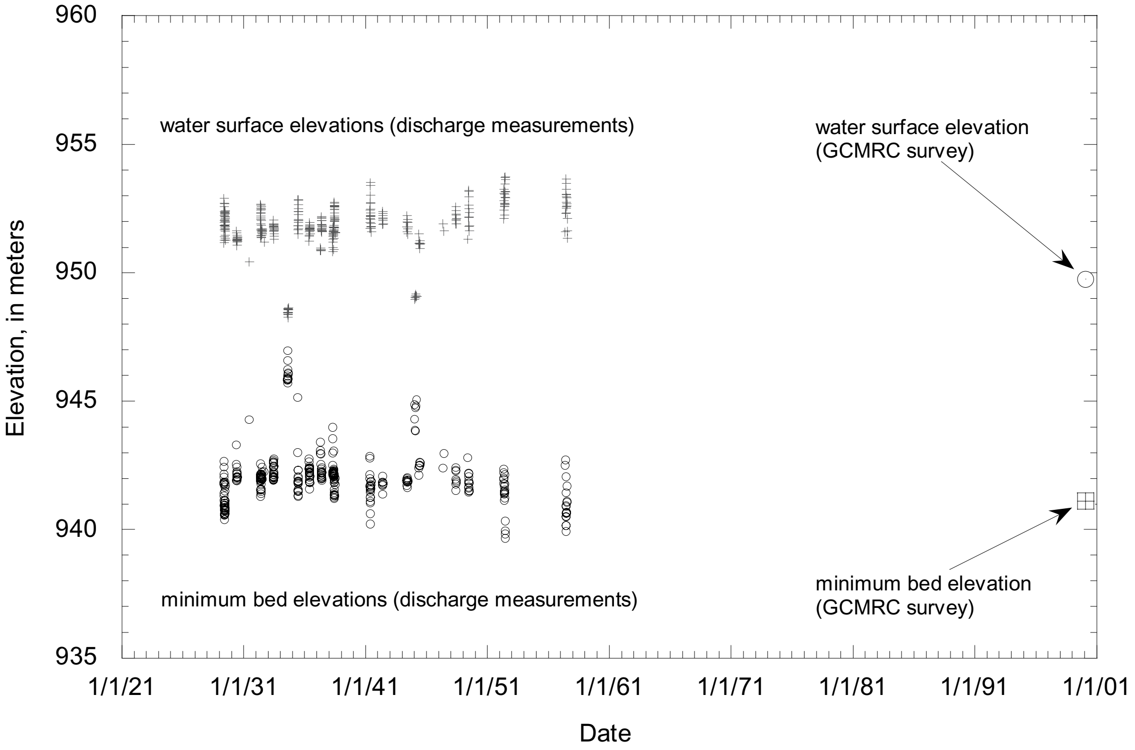

960
955
950
945
940
935
Elevation, in meters
water surface elevations (discharge measurements)
water surface elevation
(GCMRC survey)
minimum bed elevations (discharge measurements)
minimum bed elevation
(GCMRC survey)
1/1/21
1/1/31
1/1/41
1/1/51
1/1/61
1/1/71
1/1/81
1/1/91
1/1/01
Date

Figure 13

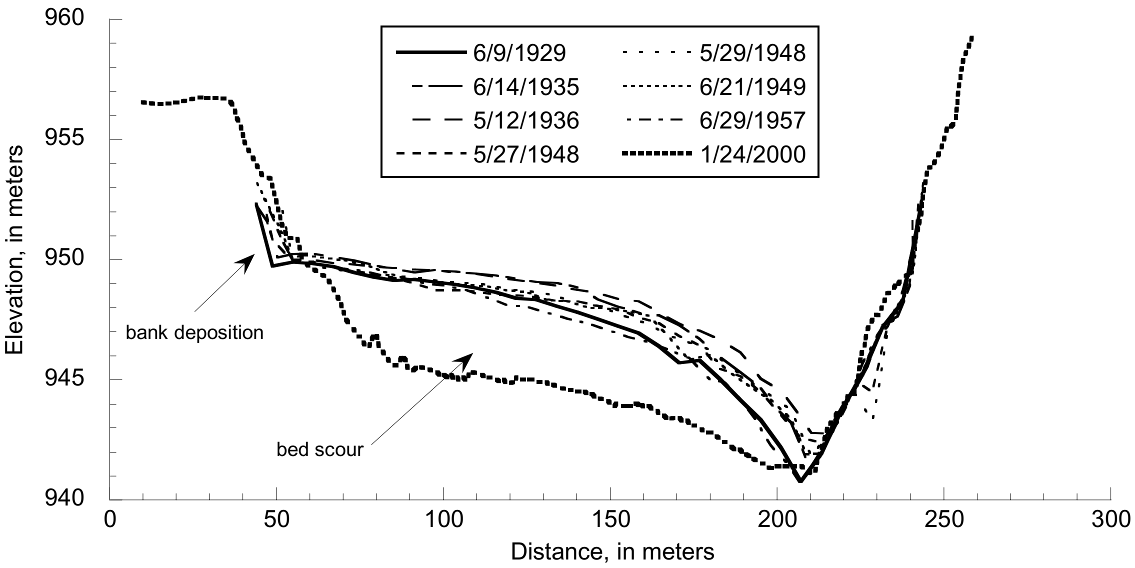
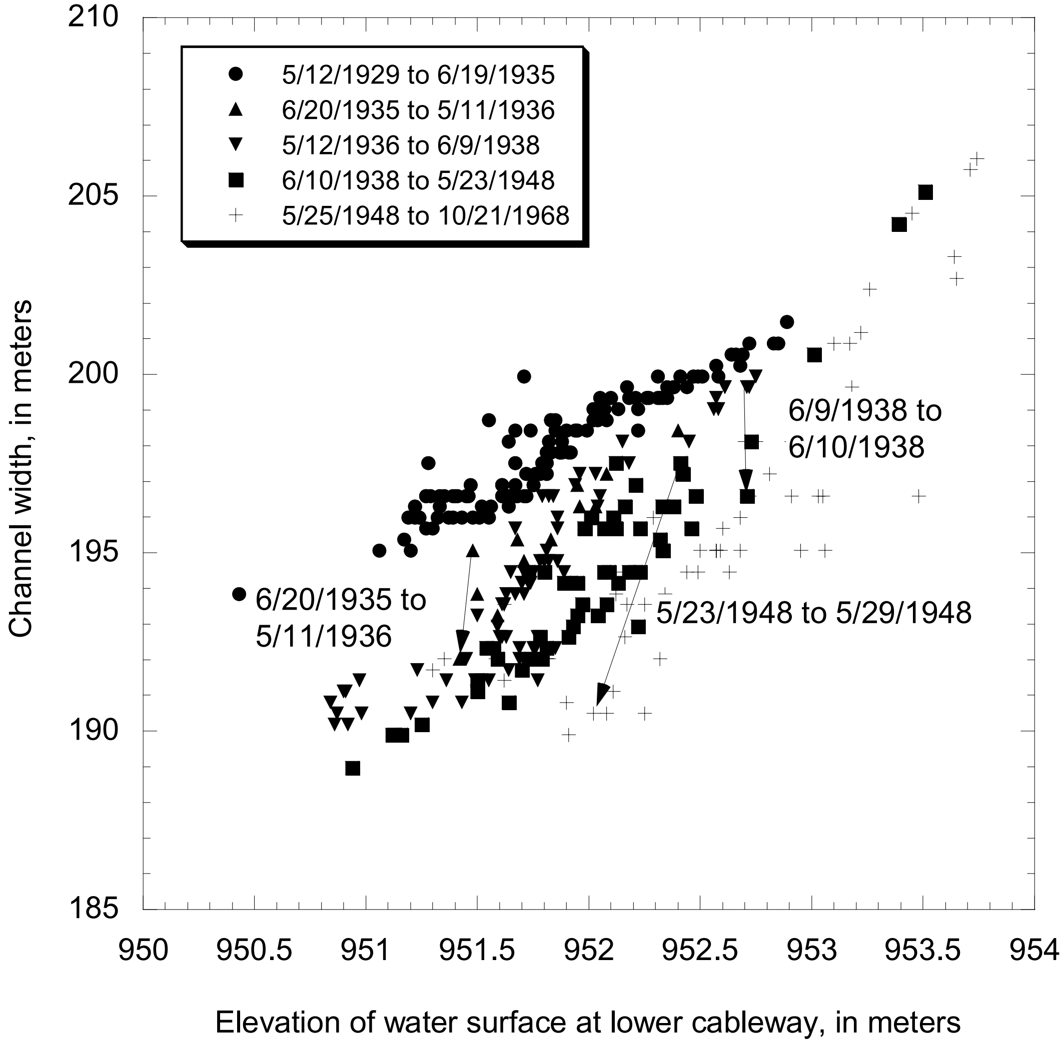
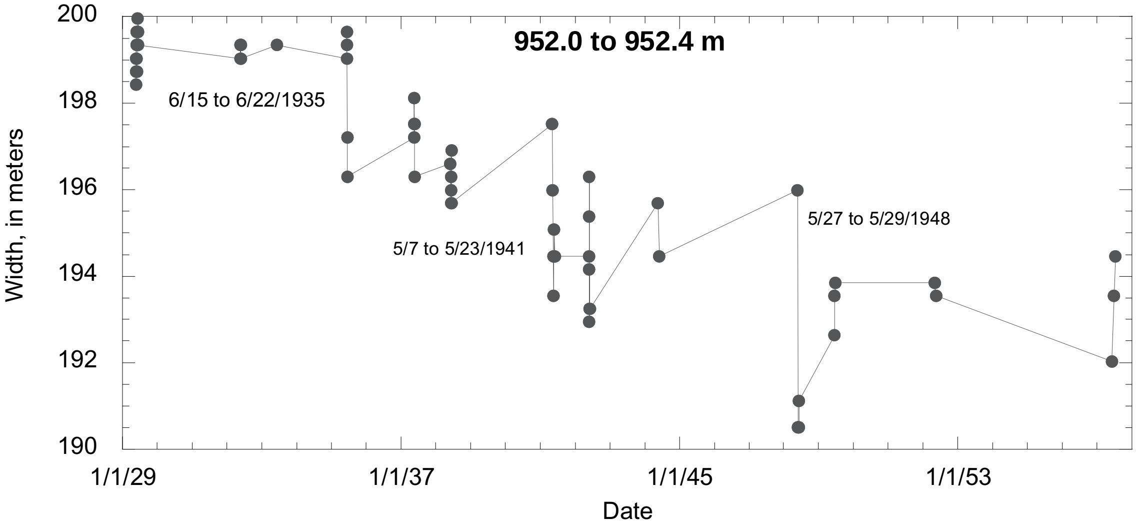

960
955
950
945
940
0
50
100
150
200
250
300
Elevation, in meters
Distance, in meters
6/9/1929
6/14/1935
5/12/1936
5/27/1948
5/29/1948
6/21/1949
6/29/1957
1/24/2000
bank deposition
bed scour

Figure 14

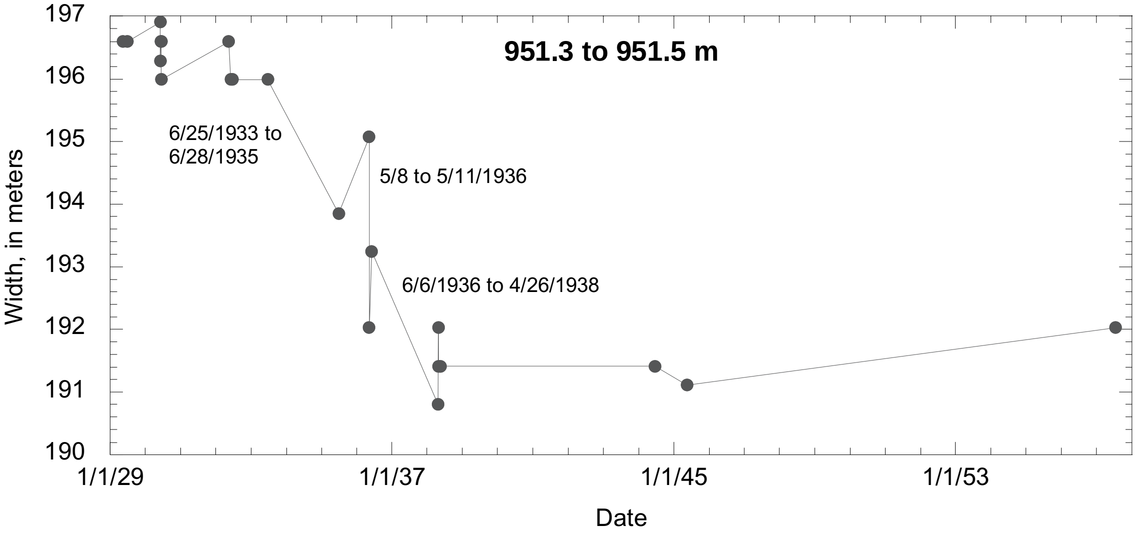


210
205
200
195
190
185
950
950.5
951
951.5
952
952.5
953
953.5
954
Channel width, in meters
Elevation of water surface at lower cableway, in meters
● 5/12/1929 to 6/19/1935
▲ 6/20/1935 to 5/11/1936
▼ 5/12/1936 to 6/9/1938
■ 6/10/1938 to 5/23/1948
+ 5/25/1948 to 10/21/1968
6/20/1935 to 5/11/1936
6/9/1938 to 6/10/1938
5/23/1948 to 5/29/1948

Figure 15

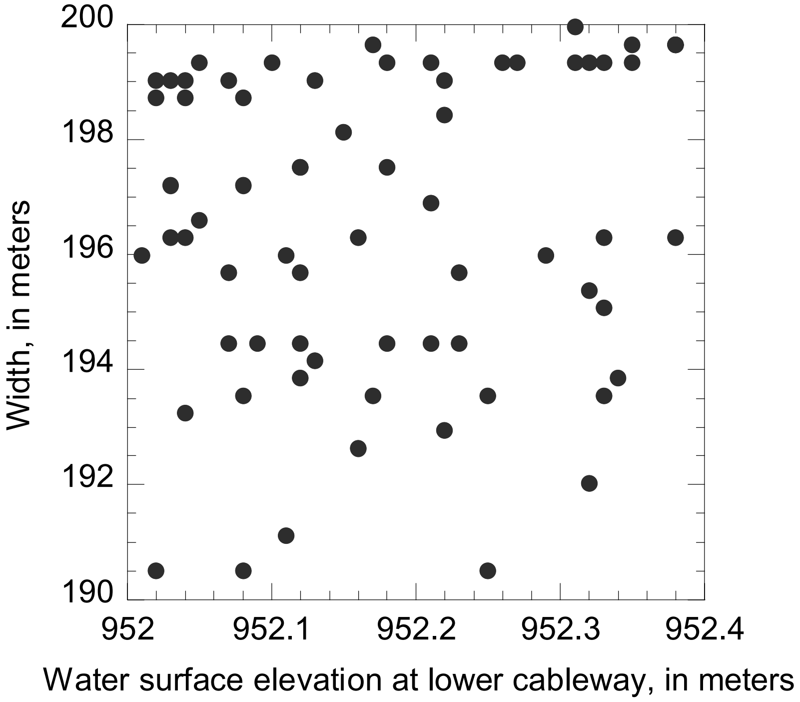

952.0 to 952.4 m
Width, in meters
Date
200
198
196
194
192
190
1/1/29
1/1/37
1/1/45
1/1/53
6/15 to 6/22/1935
5/7 to 5/23/1941
5/27 to 5/29/1948

a)


951.3 to 951.5 m
Width, in meters
Date
197
196
195
194
193
192
191
190
1/1/29
1/1/37
1/1/45
1/1/53
6/25/1933 to
6/28/1935
5/8 to 5/11/1936
6/6/1936 to 4/26/1938

b)

Figure 16



200
198
196
194
192
190
Width, in meters
952
952.1
952.2
952.3
952.4
Water surface elevation at lower cableway, in meters

Figure 17

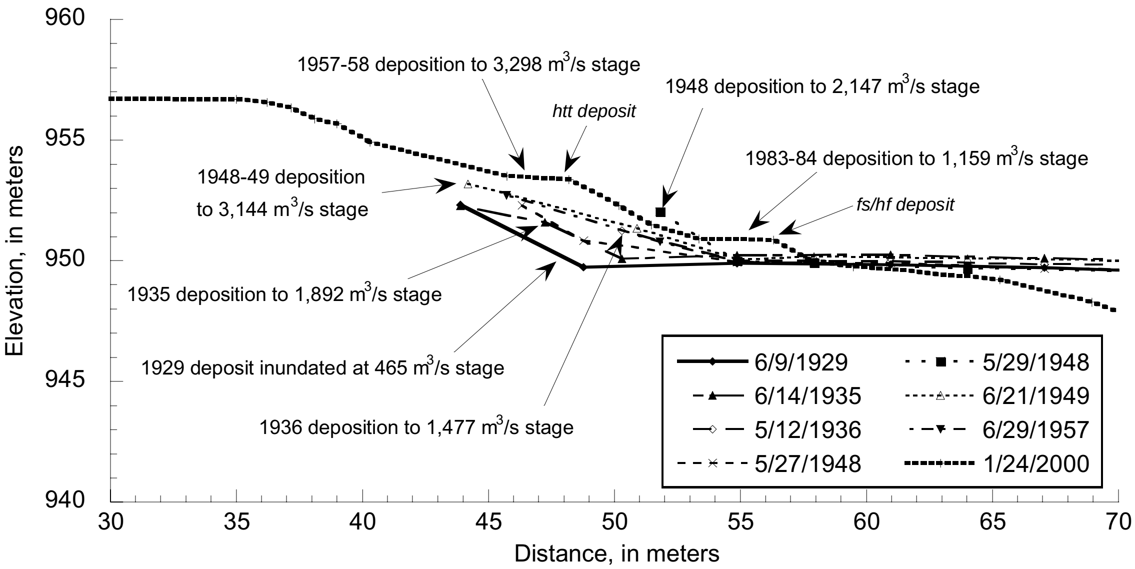
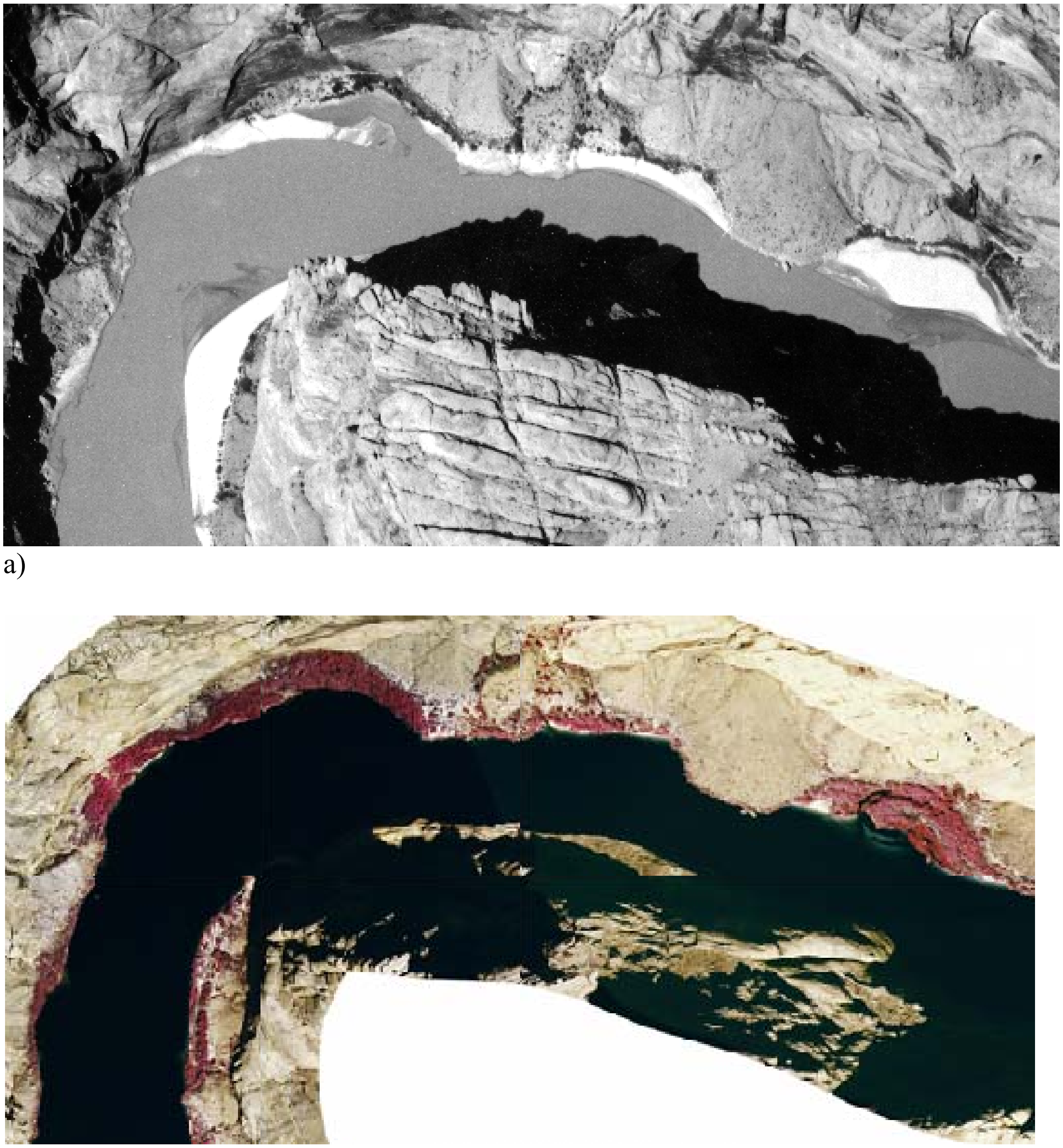

960
955
950
945
940
Elevation, in meters
30
35
40
45
50
55
60
65
70
Distance, in meters
1957-58 deposition to 3,298 m3/s stage
htt deposit
1948 deposition to 2,147 m3/s stage
1983-84 deposition to 1,159 m3/s stage
fs/hf deposit
1948-49 deposition to 3,144 m3/s stage
1935 deposition to 1,892 m3/s stage
1929 deposit inundated at 465 m3/s stage
1936 deposition to 1,477 m3/s stage
6/9/1929
6/14/1935
5/12/1936
5/27/1948
5/29/1948
6/21/1949
6/29/1957
1/24/2000

Figure 18



a)

b)

Figure 19

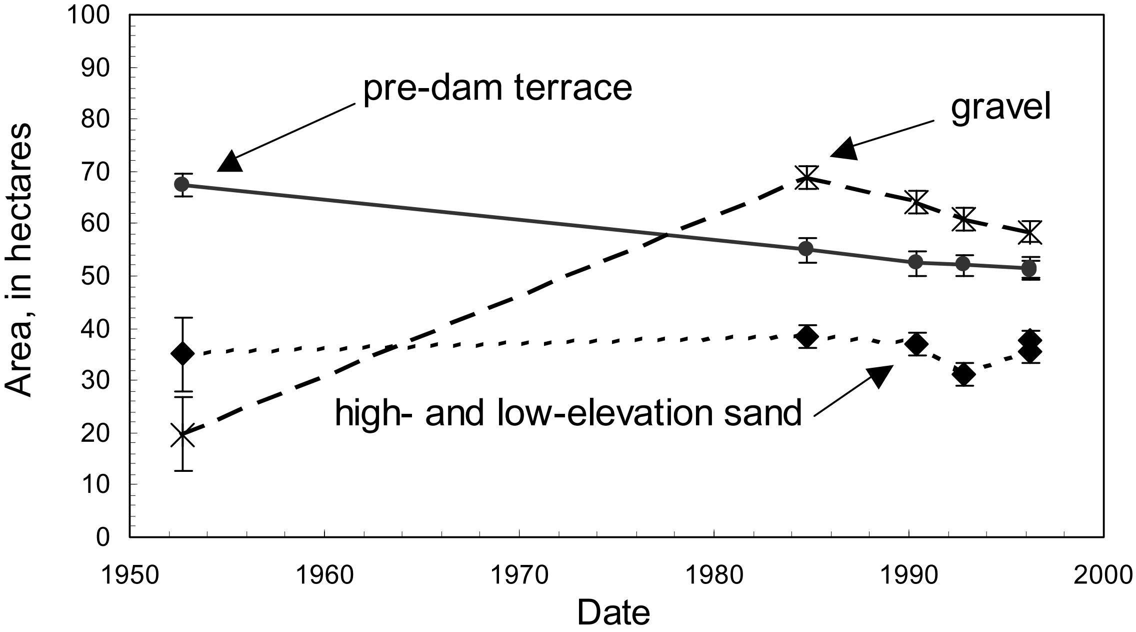

100
90
80
70
60
50
40
30
20
10
0
Area, in hectares
1950
1960
1970
1980
1990
2000
Date
pre-dam terrace
gravel
high- and low-elevation sand

Figure 20

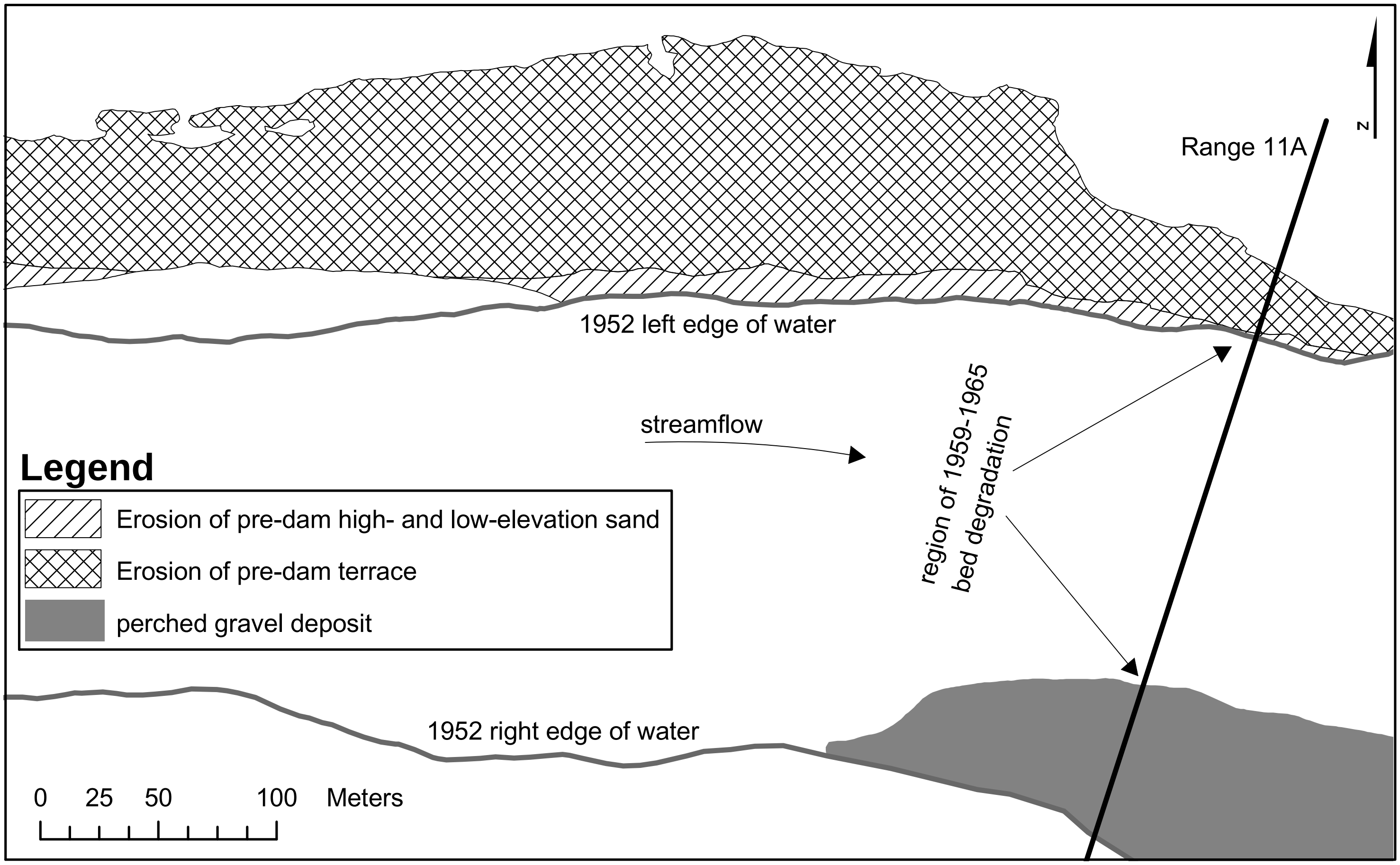

Range 11A
N
1952 left edge of water
streamflow
region of 1959-1965
bed degradation
Legend
Erosion of pre-dam high- and low-elevation sand
Erosion of pre-dam terrace
perched gravel deposit
1952 right edge of water
0
25
50
100
Meters

Figure 21

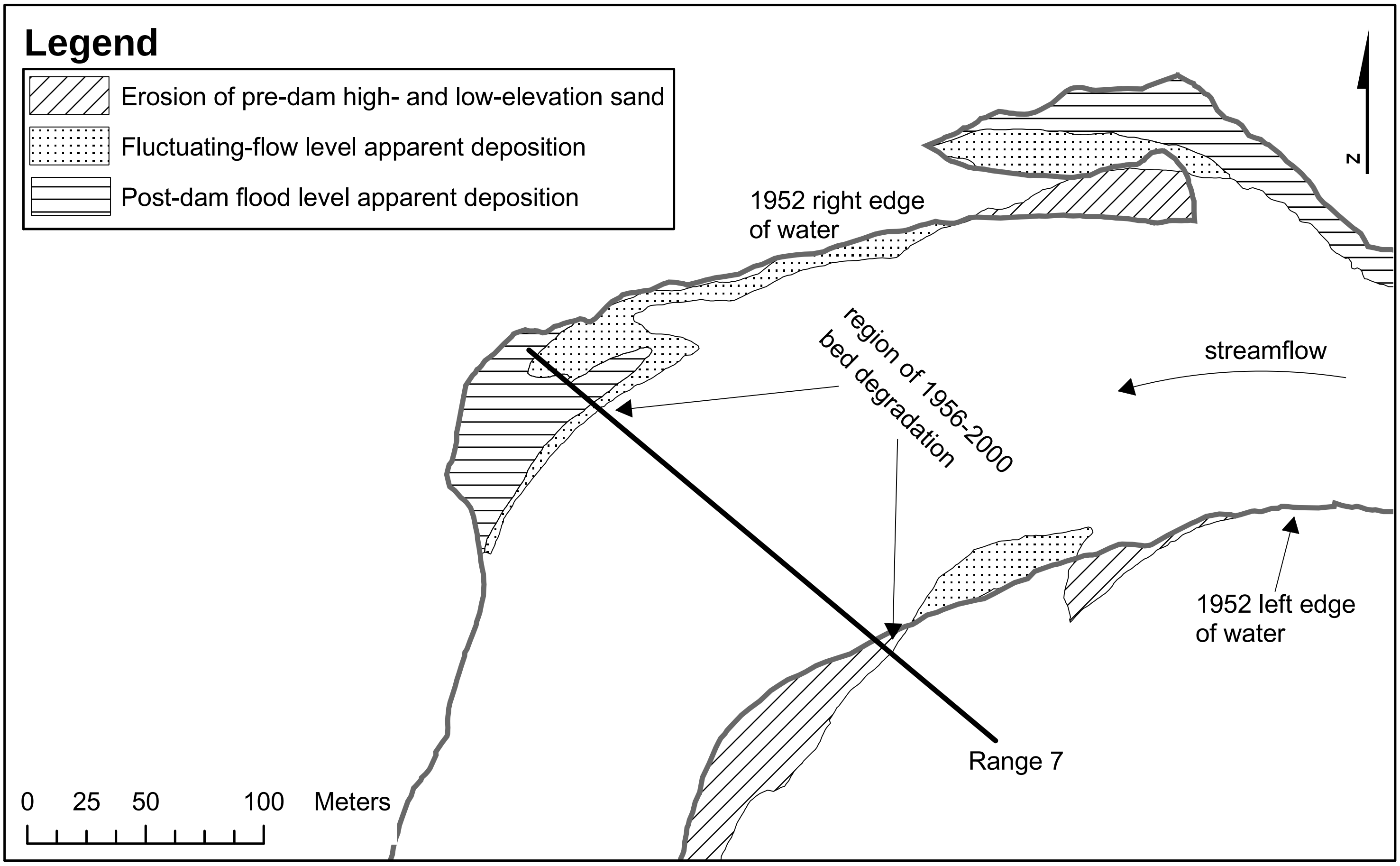
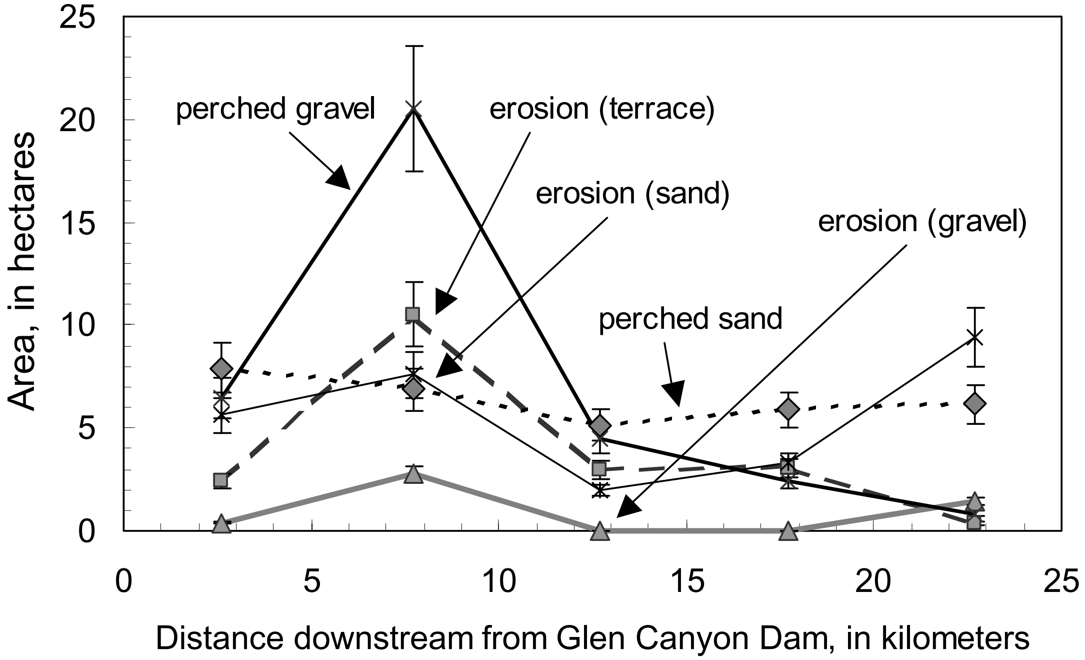

Legend
Erosion of pre-dam high- and low-elevation sand
Fluctuating-flow level apparent deposition
Post-dam flood level apparent deposition
N
1952 right edge of water
region of 1956-2000 bed degradation
streamflow
1952 left edge of water
Range 7
0 25 50 100 Meters

Figure 22



25
20
15
10
5
0
Area, in hectares
0
5
10
15
20
25
Distance downstream from Glen Canyon Dam, in kilometers
perched gravel
erosion (terrace)
erosion (sand)
erosion (gravel)
perched sand

Figure 23

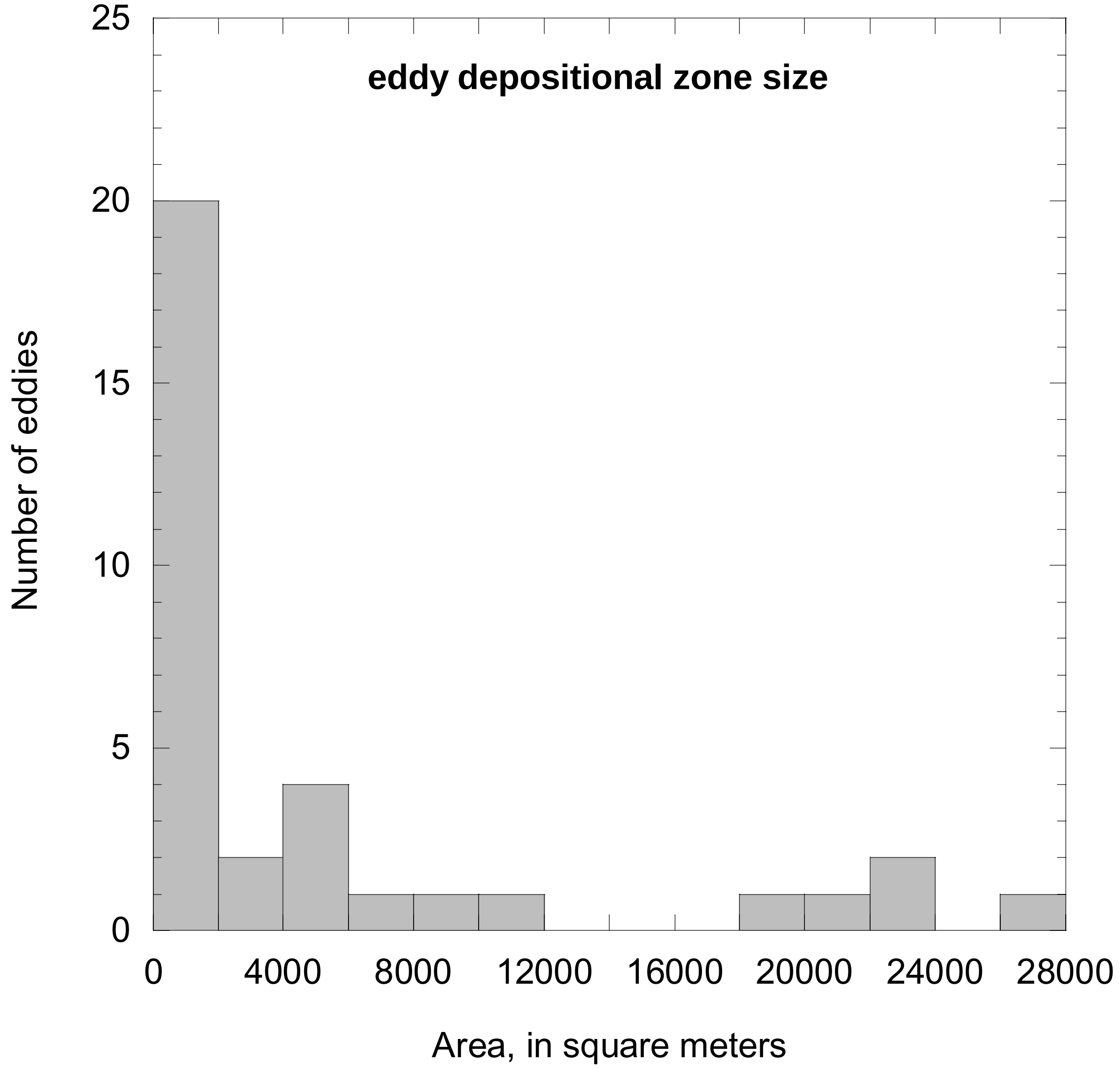

eddy depositional zone size
Number of eddies
0
5
10
15
20
25
0
4000
8000
12000
16000
20000
24000
28000
Area, in square meters

Figure 24

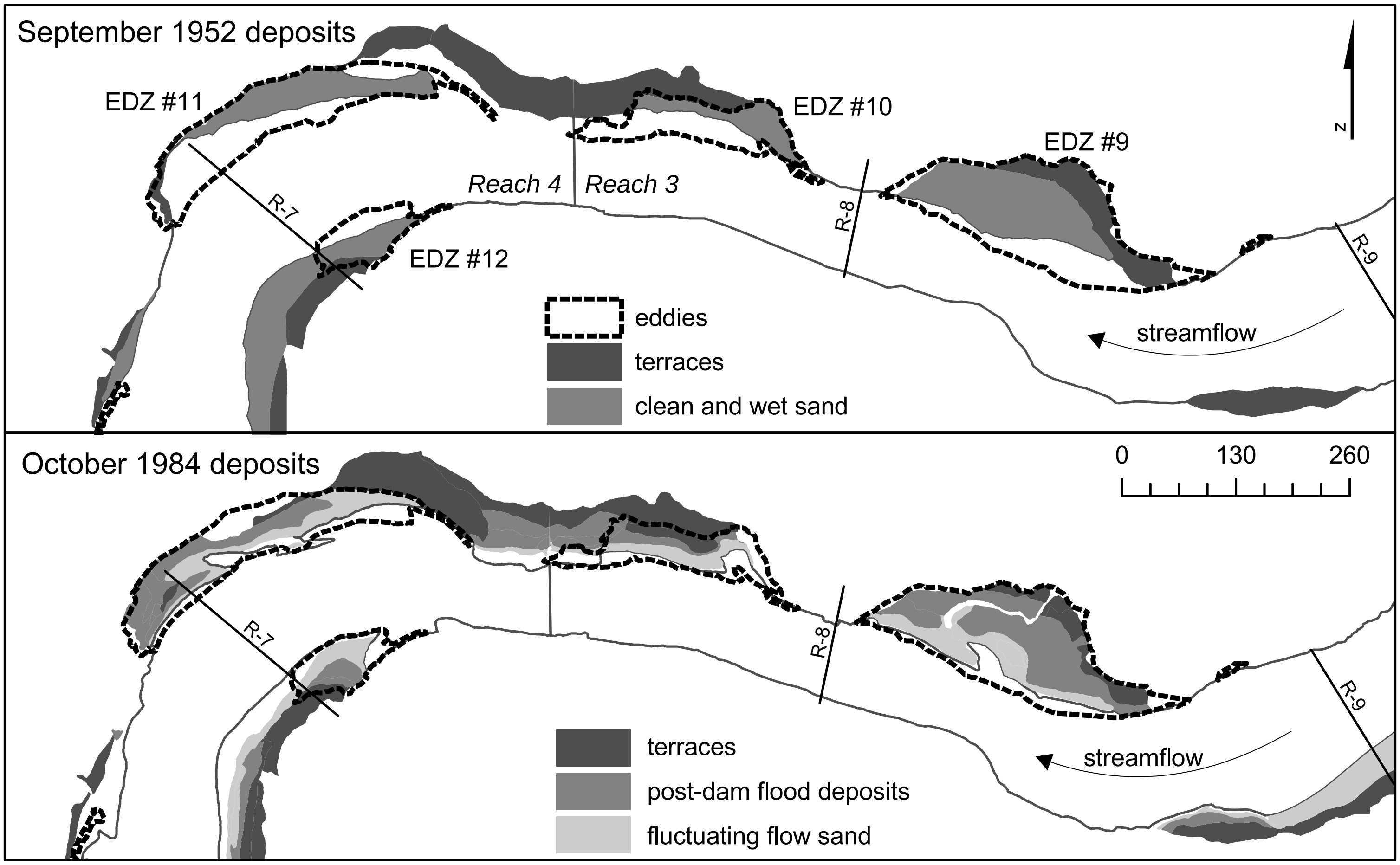

September 1952 deposits
EDZ #11
EDZ #10
EDZ #9
EDZ #12
N
Reach 4
Reach 3
R-7
R-8
R-9
eddies
terraces
clean and wet sand
streamflow
October 1984 deposits
0
130
260
m
R-7
R-8
R-9
terraces
post-dam flood deposits
fluctuating flow sand
streamflow

Figure 25

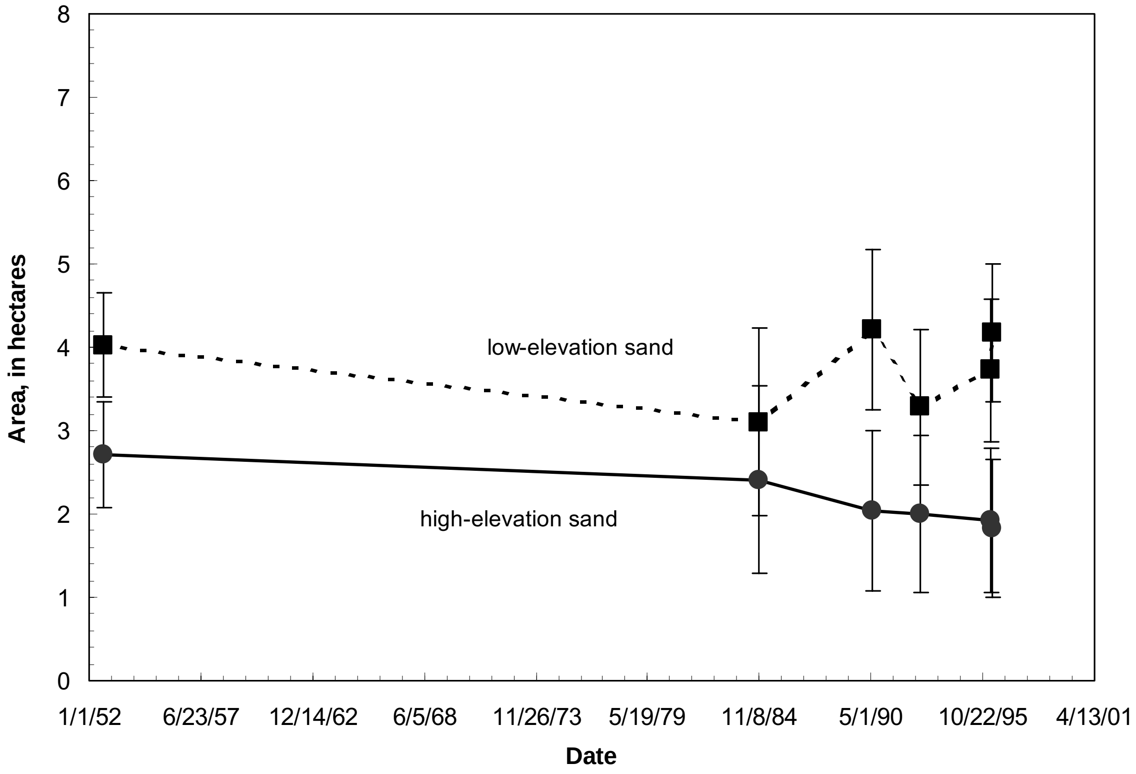

8
7
6
5
4
3
2
1
0
Area, in hectares
low-elevation sand
high-elevation sand
1/1/52
6/23/57
12/14/62
6/5/68
11/26/73
5/19/79
11/8/84
5/1/90
10/22/95
4/13/01
Date

Figure 26

APPENDICES

Appendix A: Pre-dam Sediment Transport and Storage in Glen Canyon

Sediment-transport data used to construct the budgets

The only period for which a sediment budget can be constructed for 273-km long Glen Canyon reach of the Colorado River prior to the construction of Glen Canyon Dam is from October 1948 through September 1958, when the USGS measured suspended-sediment concentration on a daily basis at the 3 major stream gages that bracketed this reach (Figure A1). During 1951-1953, the USGS also measured suspended-sediment concentration at a stream gage on the lowermost portion of the Escalante River, one of the major Glen Canyon tributaries; and during 1948-1954, suspended-sediment concentration was also measured on a daily basis at the stream gage at the mouth of the Dirty Devil River, the major tributary that marks the head of Glen Canyon. Near the upstream end of Glen Canyon, daily suspended-sediment concentration was measured at the Colorado River at Hite, UT gage (USGS station # 09335000) from October 1, 1948 through September 30, 1958. From May 17, 1951 through September 30, 1958, 240 of these samples were analyzed for grain size. The Hite gage was located on the Colorado River just downstream from the mouth of White Canyon, and approximately 8 km downstream from the current Hite Marina on the Lake Powell reservoir and 11 km downstream from the mouth of the Dirty Devil River. At the lower end of Glen Canyon, daily suspended-sediment concentration was measured at the Colorado River at Lees Ferry, AZ gage (USGS station # 09380000) from October 1, 1947 until August 13, 1965. Completion of the cofferdam at the Glen Canyon damsite on February 11, 1959 resulted in a small impoundment of the Colorado River. Thus, post-1958 data from the Lees Ferry gage ceased to provide a measure of the natural sediment-transport and storage conditions within Glen Canyon. During the period of overlap with the Hite grain-size analyzed suspended-sediment record (May 1951-September 1958), 298 of the suspended-sediment samples collected at the Lees Ferry gage were analyzed for grain size. The largest tributary joining the Colorado River in Glen Canyon is the San Juan River.

During the period of overlap with the Hite and Lees Ferry sediment records, suspended-sediment concentration was measured on a daily basis in the San Juan River at the "near Bluff, AZ" gage (USGS station # 09379500), except during the period from June 2, 1951 through December 7, 1952, when very few suspended-sediment data were collected. This gage is located at the village of Mexican Hat, UT, and is 183 km upstream from the confluence with the Colorado River. During the period of overlap with the Hite grain-size analyzed suspended-sediment record, 183 of the suspended-sediment samples collected at the near Bluff gage were analyzed for grain size. The second largest tributary joining the Colorado River in Glen Canyon (but far smaller than the San Juan River) is the Escalante River. Suspended-sediment concentration was measured on this river at the Escalante River at mouth, near Escalante, UT gage (USGS station # 09339500) on a quasi-daily basis from March 1951 through September 1953. This gage was located about 8.2 km upstream from the mouth of the river. Between October 1, 1951 and September 11, 1953, 65 suspended-sediment samples from this gage on the Escalante River were analyzed for grain size. Immediately upstream from Glen Canyon, suspended-sediment concentration was measured at the mouth of the Dirty Devil River at the Dirty Devil River near Hite, UT gage (USGS station # 09333500) on a daily basis from July 1948 through June 1954. This gage was located about 4.2 km upstream from the mouth of the river.

Methods used to construct the budgets

As shown in Topping et al. (2000), the seasons of greatest tributary sediment supply to the Colorado River are July-October and January-April, and the season of greatest sediment transport in the Colorado River is the snowmelt-flood period of April-June. Thus, both calendar years (January through December) and water years (October-September) are inappropriate time periods over which to compute annual sediment budgets in the pre-dam Colorado River system. To solve this problem, Topping et al. (2000) developed the "sediment-year" convention. This convention is also adopted in this study. Sediment years extend from July 1 of the preceding year through June 30 of the current year. For example, sediment-year 1950 extends from July 1, 1949 through

June 30, 1950. In this study, annual sediment budgets were constructed for Glen Canyon for the period of sediment-data overlap among the 3 main gages, sediment-years 1950-1951 and 1953-1958. Because of the major gap in the suspended-sediment data from the San Juan River, no sediment budget could be constructed for sediment-year 1952.

Because the period of sediment record for the Escalante River was much shorter than at the 3 main gages on the Colorado and San Juan Rivers, and the area of other tributaries is large (16,900 km^2), we had to develop a method to estimate the annual and monthly sediment loads from the total 21,500 km^2 area of Glen Canyon tributaries (inclusive of the Escalante River basin) that contribute sediment to the lowermost 183 km of the San Juan River below the near Bluff gage and the 262 km of Glen Canyon between the Hite and Lees Ferry gages. Estimating the combined annual sediment load of these tributaries was a 3-step process.

The first step in estimating the annual tributary sediment contribution was to estimate the annual sediment yield per km of these tributaries based on the sediment loads measured at the lower ends of the Escalante and Dirty Devil Rivers in the early 1950s. This approach is justified based on the fact that the topography and geology of these 2 drainage basins is similar to the topography and geology of the drainages of the other Glen Canyon tributaries. During its 2-year period of sediment record, the 4,600 km^2 Escalante River basin contributed 1.5 million Mg per year to the Colorado River, and during its 5-year period of sediment record, the 11,300 km^2 Dirty Devil River basin contributed 5.1 million Mg per year to the Colorado River. Sediment yields based on these loads are 330 Mg/km^2/yr for the Escalante River basin and 450 Mg/km^2/yr for the Dirty Devil River basin. To extend the period of sediment record for the Escalante River to the full 5 years of streamflow record at Escalante River at mouth gage, sand loads and silt and clay loads were computed using sediment rating curves fit to the grain-size analyzed suspended-sediment data. This “sediment-rating-curve” approach suggests that the Escalante River basin contributed about 2 million Mg of sediment per year to the Colorado River during the 1950s. The sediment yield for the Escalante River basin based on this extension of the period of record is 430 Mg/km^2/yr.

The second step in estimating the annual tributary sediment contribution was to determine the total annual sediment load based on the sediment yields from the Escalante and Dirty Devil basins and to compare this load to the total Glen Canyon tributary sediment contribution measured during the 1986 sediment survey of the Lake Powell reservoir by Ferrari (1988). The mean annual sediment yield of the Glen Canyon tributaries during the 1950s based on the data from the Escalante and Dirty Devil drainage basins is 440 Mg/km^2. This corresponds to a total mean annual load from all of the Glen Canyon and lower San Juan River tributaries of about 9 million Mg per year. Ferrari (1988) indicated that about 14% of the sediment stored in the Lake Powell reservoir was being stored within the tributary-canyon portions of the reservoir, with the Dirty Devil River canyon containing the greatest amount of the tributary-derived sediment (about 30-40%). Thus, the amount of sediment stored in the tributary canyons downstream from the old Hite gage (below the Dirty Devil River, North Wash, and White Canyons) is probably about 10% of all of the sediment stored in the Lake Powell reservoir. This estimate does not include the amount of tributary-derived sediment that was being stored in either the Colorado River channel or San Juan River portions of the reservoir. Correction for the additional tributary-derived sediment stored in these portions of the reservoir and the tributary sediment supplied between the near Bluff gage and the head of the reservoir in the San Juan River canyon, suggests that, of all of the sediment stored in Lake Powell, about 15% was probably derived from tributaries that enter the Colorado and San Juan Rivers between the Hite and near Bluff gages and the Lees Ferry gage. Fifteen percent of the measured sediment load of the Colorado River at Lees Ferry during sediment-years 1950-1958 corresponds to about 10 million Mg per year. This value is used in this study for the combined annual sediment load of the Glen Canyon tributaries.

The third step in estimating the annual tributary sediment contribution was to estimate the tributary sediment contribution during each of the 9 sediment years from 1950 to 1958. This was done by setting the combined sediment load of the Glen Canyon tributaries each year to be proportional to that measured on the Paria River at Lees Ferry, the closest tributary with a complete sediment record during the 1950s (see Figure 9a in Topping et al., 2000). During each year, a similar process was used to estimate the monthly sediment load of the tributaries. The combined sediment load of the Glen Canyon tributaries each month was set to be proportional to the monthly mean load measured on the Escalante River.

The uncertainties applied to the measurements used in the Glen Canyon sediment annual and monthly sediment budgets were estimated based on Appendix B in Topping et al. (2000). Topping et al. (2000) listed the 6 major sources of uncertainty associated with determinations of suspended-sediment load of the Colorado River and its tributaries. Based on their analysis, we have assigned the following uncertainties to the measured monthly and annual sediment loads: (1) 5% for the Colorado River at Hite and Lees Ferry gages, (2) 5% for the San Juan River near Bluff gage, and (3) 20% for the Escalante River at mouth, near Escalante gage. Comparison of the Escalante River sediment record with the sediment-rating-curve extended record indicates that the uncertainty in the extended Escalante River sediment record is about 70%. The uncertainty assigned to the monthly and annual estimated loads of the Glen Canyon tributaries is 50%.

Analysis of annual and seasonal pre-dam sediment budgets for Glen Canyon

Closure of Glen Canyon Dam reduced suspended sediment transport at Lees Ferry by more than 99%, from 57 ± 3 million Mg to 0.24 ± 0.01 million Mg annually (Topping et al., 2000). Of the fine sediment (sand, silt, and clay) supplied to Glen Canyon during the average pre-dam year, approximately 58% was from the Colorado River upstream from the Hite gage, 25% was from the San Juan River upstream from Mexican Hat (the near Bluff gage), and 17% was from the other Glen Canyon tributaries (Figures A1 and A2a). During sediment-years 1950-1951, 1953-1958, the mean annual supply of fine sediment from the Colorado River upstream from Hite was 34±2 million Mg. Analysis of the grain-size analyzed suspended-sediment data indicates that approximately 20-25% of this amount (or about 6-9 million Mg) was sand. During sediment-years 1950-1951, 1953-1958, the mean annual supply of fine sediment from the San Juan River upstream from Mexican Hat was 15±1 million Mg. Analysis of the grain-size analyzed suspended-sediment data indicates that approximately 35-40% of this amount (or 5-6 million Mg) was sand. During sediment-years 1950-1951, 1953-1958, the mean annual supply of fine sediment from the other Glen Canyon tributaries is estimated to have been approximately 10±5 million Mg. Analysis of the grain-size analyzed suspended-sediment data from the Escalante River gage suggests that approximately 55-60% of this amount (or about 3-9 million Mg) was sand. During sediment-years 1950-1951, 1953-1958, the mean annual export of fine sediment from Glen Canyon past the Lees Ferry gage was 59±3 million Mg. Analysis of the grain-size analyzed suspended-sediment data indicates that approximately 35-40% of this amount (or 20-25 million Mg) was sand. Thus, of the sand that was ultimately supplied to Marble Canyon from Glen Canyon, approximately equal amounts were supplied by the Colorado River upstream from Hite, the San Juan River upstream from Mexican Hat, and the other Glen Canyon tributaries.

Comparison of the annual supply of fine sediment to and export of fine sediment from Glen Canyon indicates that, in most years, the amount of fine sediment exported from Glen Canyon equaled the amount supplied within the uncertainties in the sediment budget (Figure A2b). Given the uncertainties in the sediment budget, only in sediment-year 1954 (the year with the lowest discharges) did the annual supply exceed the annual export of fine sediment, and only in sediment-year 1957 (the year with the highest discharges) did the annual export exceed the annual supply of fine sediment. Interestingly, there appear to be years with large snowmelt floods (Figure A2c) in which the export did not exceed the supply of fine sediment, for example sediment-year 1958.

During the average pre-dam year, sand exported from Glen Canyon accumulated in Marble and upper Grand Canyons during the nine months (July-March) of the year when the discharge was typically lower than about 250 m^3/s (Topping et al., 2000). Then, during the three months of higher discharge during the snowmelt flood (April-June), this stored sand was exported from Marble and upper Grand Canyons. This process led to the observed annual hysteresis in suspended-sand concentration and grain size at the Grand Canyon gage (Topping et al., 2000). To determine whether similar seasons of sediment accumulation and sediment erosion existed in the pre-dam Glen Canyon, a similar seasonal sediment budget was constructed for the average pre-dam year. This was done by first determining the monthly mean supply and export of fine sediment (with uncertainties) during sediment–years 1950-1951 and 1953-1958 (Figure A3a). Then, the mean monthly supply and export of fine sediment were differenced and integrated (with accumulated uncertainties) to determined the amount of fine sediment in storage at the end of each month during the average pre-dam year (Figure A3b).

Similar to the findings of Topping et al. (2000) in Marble and upper Grand Canyons, a season of fine-sediment accumulation and storage and a season of fine-sediment depletion are evident in pre-dam Glen Canyon. Fine sediment rapidly accumulated in pre-dam Glen Canyon during July-August and remained in storage through the month of April. Then, this stored sediment was partially depleted during the snowmelt-flood months of May and June. The chief difference between pre-dam Glen Canyon and pre-dam Marble and upper Grand Canyons was the length of the season of accumulation and storage. In Glen Canyon the season of sediment accumulation and storage was 10 months long, whereas in Marble and upper Grand Canyons it was nine months long. In Glen Canyon, almost all of the accumulation occurred during the month of August. In Marble and upper Grand Canyons, accumulation was also greatest during the month of August, but continued through the winter to the following March. Finally, the degree of fine-sediment depletion during the snowmelt flood appears to have been slightly less in Glen Canyon than in Marble and upper Grand Canyons.

Downstream changes in the pre-dam loads of silt & clay and sand through Glen Canyon

Topping et al. (2000) showed that, though there were not large changes in the loads of silt and clay, there were substantial differences in the loads of sand as a function of discharge between the Lees Ferry and Grand Canyons gages. At discharges less than about 250 m3/s, more sand was being supplied to Marble Canyon from Glen Canyon than was being exported past the Grand Canyon gage. At lower discharges, this difference in sand loads became extremely large. At about 100 m3/s, at least one order of magnitude more sand was being supplied to Marble Canyon from Glen Canyon than was being exported past the Grand Canyon gage. At higher discharges, the situation reversed. During the early portion of the snowmelt flood, up to one-half order of magnitude more sand was being exported past the Grand Canyon gage than was being supplied to Marble Canyon from Glen Canyon. The amount of background sediment storage in Marble and upper Grand Canyons was apparently small relative to the seasonal change in sediment storage. Thus, depletion of the sand seasonally stored in Marble and upper Grand Canyons led to the development of the pronounced hysteresis in suspended-sand concentration and grain size at the Grand Canyon gage. Eventually, the amount of sand exported during the snowmelt flood decreased to approximately equal the amount supplied to Marble Canyon from Glen Canyon. As the sand concentration decreased during the snowmelt flood, the grain size of the sand in suspension coarsened leading to the production of inversely graded flood deposits in Marble and Grand Canyons (Rubin et al., 1998; Topping et al., 2000).

Topping et al. (2000) showed that Glen Canyon appeared to be different than both Marble and Grand Canyons, and that an increase in the degree of sediment supply limitation appeared to occur near Lees Ferry. Unlike the Grand Canyon gage, very little hysteresis was evident in either suspended-sand concentration or grain size at the Lees Ferry gage. The seasonal scour and fill in Glen Canyon at Lees Ferry appeared to be controlled mainly by the reach geometry and was not substantially influenced by depletion in the upstream supply of sediment during snowmelt floods, as at the Grand Canyon gage. Also, very little change in the bed-sediment grain size occurred during pre-dam snowmelt floods at Lees Ferry, unlike at the Grand Canyon gage, where the bed sediment coarsened substantially during these floods. Furthermore, unlike downstream in Marble and Grand Canyons, the pre-dam flood deposits sampled in Glen Canyon downstream from the dam did not ubiquitously coarsen upward with respect to sand grain size. Thus, to determine if the Colorado River really did behave much more like an alluvial equilibrium channel in Glen Canyon than it did in the more sediment supply-controlled Marble and Grand Canyons, we compared the loads of silt & clay and sand at the upstream and downstream ends of Glen Canyon as a function of discharge (Figure A4). This analysis is similar to that in Topping et al. (2000, their Figure 4). Both the loads of silt and clay and the loads of sand were found to be similar at the upper and lower ends of Glen Canyon at all discharges.

Unlike downstream in Marble and upper Grand Canyons, at any given discharge, the amount of sand being exported from Glen Canyon past the Lees Ferry approximately equaled the combined amount of sand being supplied from the Colorado River upstream from Hite and the San Juan River upstream from Mexican Hat (Figure A4). Though, at lower flows, there was a slight tendency for the average amount of sand exported to be slightly less than the average amount of sand being supplied, this difference was tiny compared to that observed in Marble and upper Grand Canyons. Similarly, though, at higher flows, there was a slight tendency for the average amount of sand exported to be slightly higher than the average amount of sand being supplied, this difference was also tiny compared to that observed in Marble and upper Grand Canyons.

Though the seasonal sediment budgets indicates that there were seasons of sediment accumulation and storage and seasons of sediment erosion in Glen, Marble, and Grand Canyons, the amount of sediment in background storage in Glen Canyon was apparently vast compared to that in Marble and Grand Canyons. Therefore, although the seasonal changes in sediment in storage were as large or larger than observed in Marble and upper Grand Canyons, these seasonal changes in sediment storage had very little impact on the seasonal loads of sand. Very little hysteresis in sand concentration or grain size developed during the snowmelt floods in Glen Canyon. Because of the vast reservoir of fine sediment in storage, the pre-dam Colorado River in Glen Canyon, as hypothesized by Topping et al. (2000), did behave essentially as an equilibrium alluvial channel.

Figure Captions

Figure A1. Map of the pre-dam Glen Canyon region and the Glen Canyon study area for this report. Locations of the USGS streamflow gages (open circles) discussed in the text are indicated.

Figure A2. (a) Annual fine-sediment (i.e., sand, silt, and clay) loads of the Colorado River at Hite, of the San Juan River near Bluff (gage located at Mexican Hat), of the Escalante River at mouth (based on daily sediment-concentration measurements), of the Escalante River at mouth (computed based on sediment rating curves), of the Glen Canyon tributaries (estimated), and of the Colorado River at Lees Ferry. Error bars indicate the uncertainties in the loads. (b) Annual fine-sediment supply to and export from the pre-dam Glen Canyon, with uncertainties. In all but 2 years, the supply and export of fine sediment were equal within the uncertainties in the sediment budget. (c) Instantaneous water discharge of the Colorado River at Lees Ferry during the period of the sediment budget.

Figure A3. (a) Mean supplies and export of fine sediment each month (with uncertainties) during the average pre-dam year (computed from sediment-years 1950-1951, 1953-1958). The monthly supply of fine sediment from the Glen Canyon tributaries was based on the suspended-sediment data from the Escalante River at mouth gage. Note that August is, by far, the month with the greatest tributary supply. (b) Amount of fine sediment in storage after each month (with uncertainties) in Glen Canyon and Marble and upper Grand Canyons during the average pre-dam year. The Marble and upper Grand Canyons figure is from Topping et al. (2000). The values in the Glen Canyon figure were computed by differencing and integrating the data in (a), with the uncertainties propagating through the analysis.

Figure A4. (a) 1951-1958 silt and clay loads of the Colorado River at Lees Ferry as a function of instantaneous streamflow. The cross-hatched area indicates the region in load-discharge space of the combined silt and clay-loads of the Colorado River at Hite and the San Juan River near Bluff. Note that this region occupies the same space as the Colorado River at Lees Ferry data, indicating that the silt and clay loads did not change by very much through Glen Canyon. (b) 1951-1958 sand loads of the Colorado River at Lees Ferry as a function of instantaneous streamflow. Open circles show data collected during the peak and recessional limb portions of the snowmelt flood, diamonds show data collected during the rest of the year. Note that there is little hysteresis in these data. The cross-hatched area indicates the region in load-discharge space of the combined sand-load data from the Colorado River at Hite and the San Juan River near Bluff. Note that this region essentially occupies the same space as the Colorado River at Lees Ferry data, indicating that the sand loads did not change by very much through Glen Canyon, though there is a slight tendency for the sand loads to decrease slightly through Glen Canyon during lower discharges, and to increase slightly through Glen Canyon during higher discharges. (c) For comparison with b, at the same scale, 1951-1958 sand loads of the Colorado River at the Grand Canyon gage as a function of instantaneous streamflow. Open circles show data collected during the peak and recessional limb portions of the snowmelt flood, and diamonds show data collected during the rest of the year. Arrows show the direction of the pronounced hysteresis in the sand-load data from the Grand Canyon gage. The cross-hatched region indicates the region in load-discharge space of the sand-load data from the Colorado River at Lees Ferry.

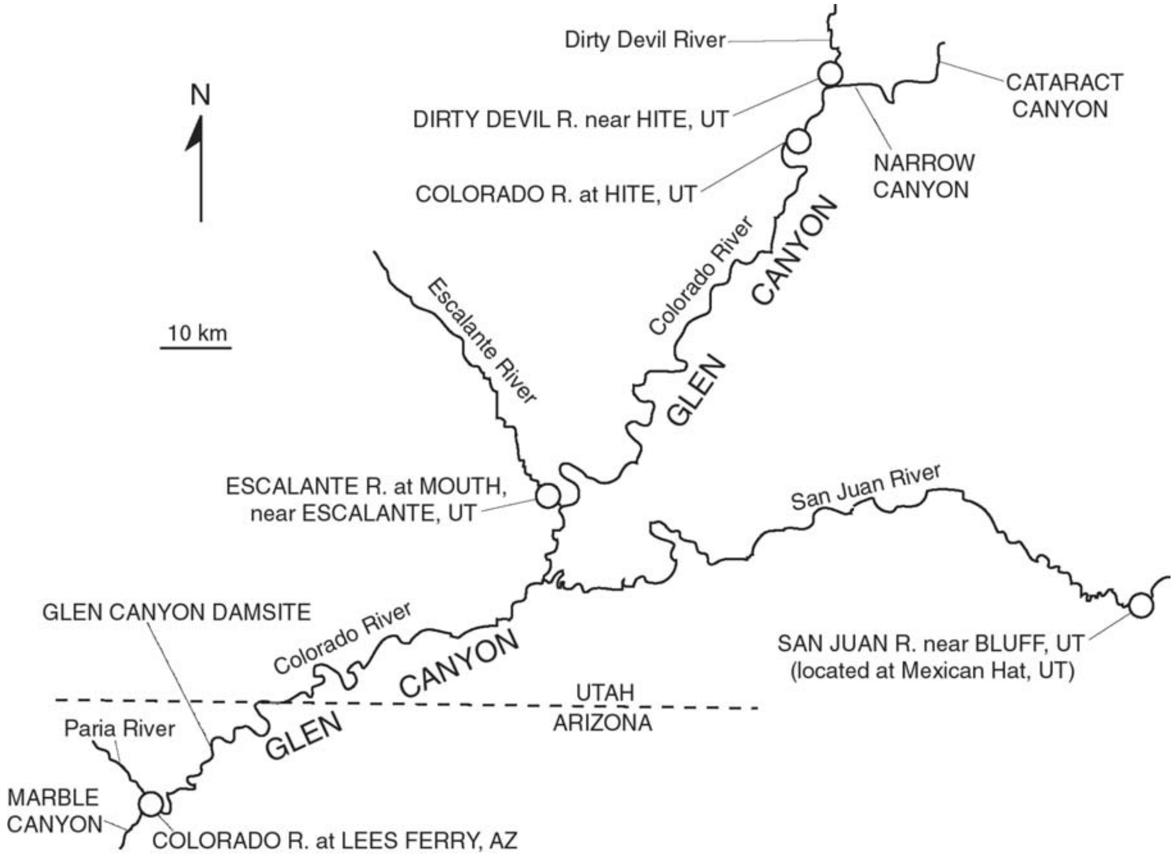

Dirty Devil River
DIRTY DEVIL R. near HITE, UT
COLORADO R. at HITE, UT
CATARACT CANYON
NARROW CANYON
N
10 km
Escalante River
Colorado River
GLEN CANYON
ESCALANTE R. at MOUTH, near ESCALANTE, UT
San Juan River
SAN JUAN R. near BLUFF, UT (located at Mexican Hat, UT)
GLEN CANYON DAMSITE
Colorado River
GLEN CANYON
UTAH
ARIZONA
Paria River
MARBLE CANYON
COLORADO R. at LEES FERRY, AZ

Figure A1

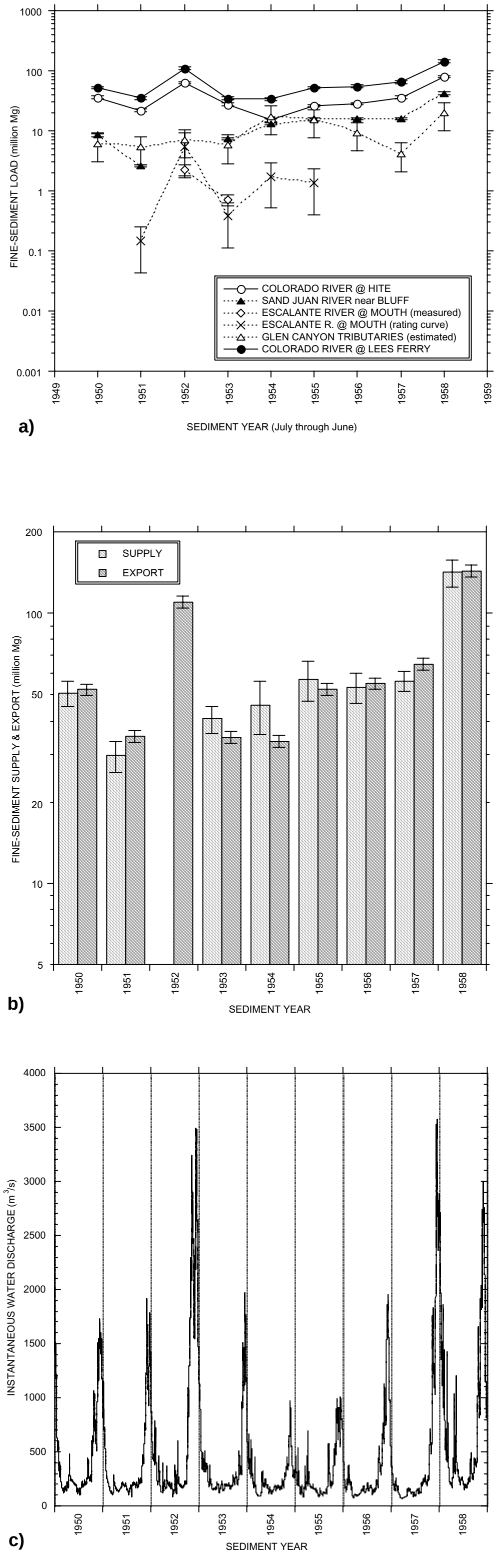
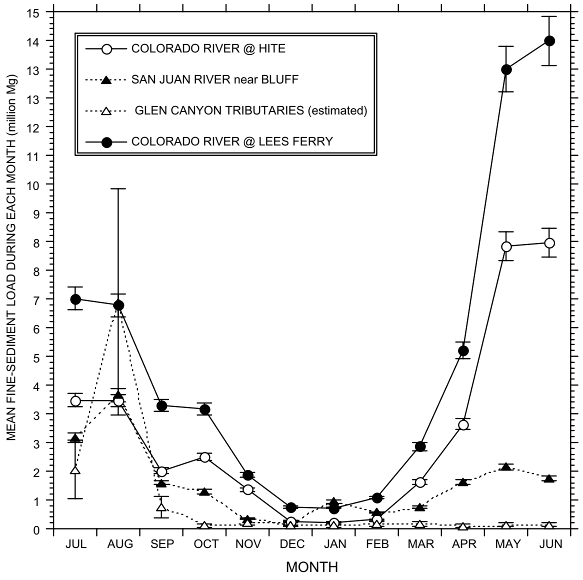
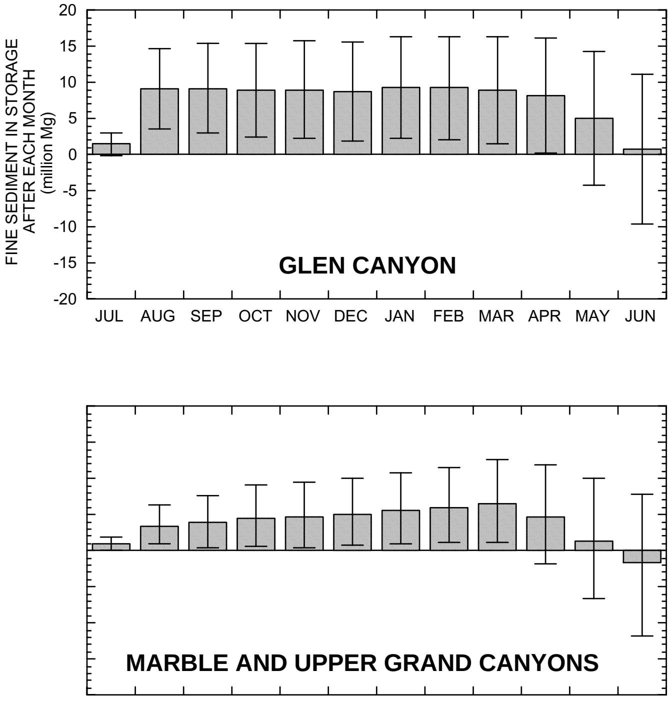

a)
FINE-SEDIMENT LOAD (million Mg)
1000
100
10
1
0.1
0.01
0.001
COLORADO RIVER @ HITE
SAND JUAN RIVER near BLUFF
ESCALANTE RIVER @ MOUTH (measured)
ESCALANTE R. @ MOUTH (rating curve)
GLEN CANYON TRIBUTARIES (estimated)
COLORADO RIVER @ LEES FERRY
1949
1950
1951
1952
1953
1954
1955
1956
1957
1958
1959
SEDIMENT YEAR (July through June)
b)
FINE-SEDIMENT SUPPLY & EXPORT (million Mg)
200
100
50
20
10
5
SUPPLY
EXPORT
1950
1951
1952
1953
1954
1955
1956
1957
1958
SEDIMENT YEAR
c)
INSTANTANEOUS WATER DISCHARGE (m^3/s)
4000
3500
3000
2500
2000
1500
1000
500
0
1950
1951
1952
1953
1954
1955
1956
1957
1958
SEDIMENT YEAR

Figure A2



COLORADO RIVER @ HITE
SAN JUAN RIVER near BLUFF
GLEN CANYON TRIBUTARIES (estimated)
COLORADO RIVER @ LEES FERRY
MEAN FINE-SEDIMENT LOAD DURING EACH MONTH (million Mg)
15
14
13
13
12
11
10
9
8
8
7
6
5
4
3
3
2
1
0
JUL
AUG
SEP
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
MONTH

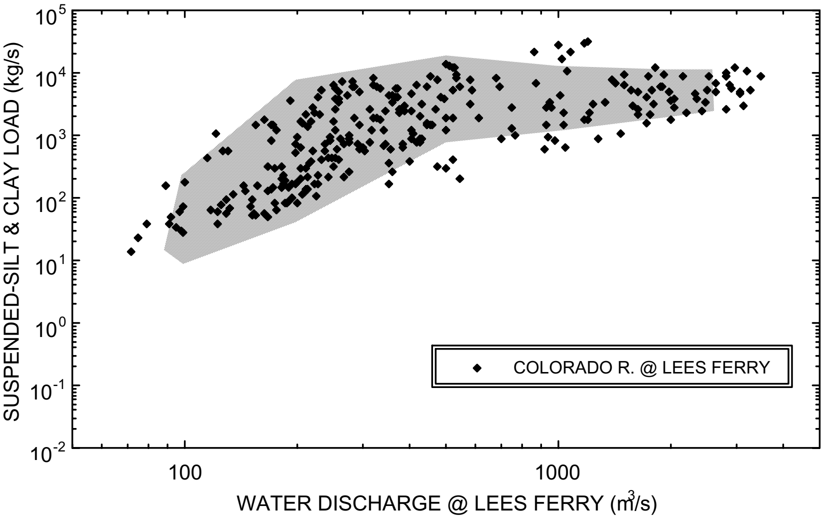
(a)



FINE SEDIMENT IN STORAGE AFTER EACH MONTH (million Mg)
20
15
10
5
0
-5
-10
-15
-20
GLEN CANYON
JUL
AUG
SEP
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
MARBLE AND UPPER GRAND CANYONS

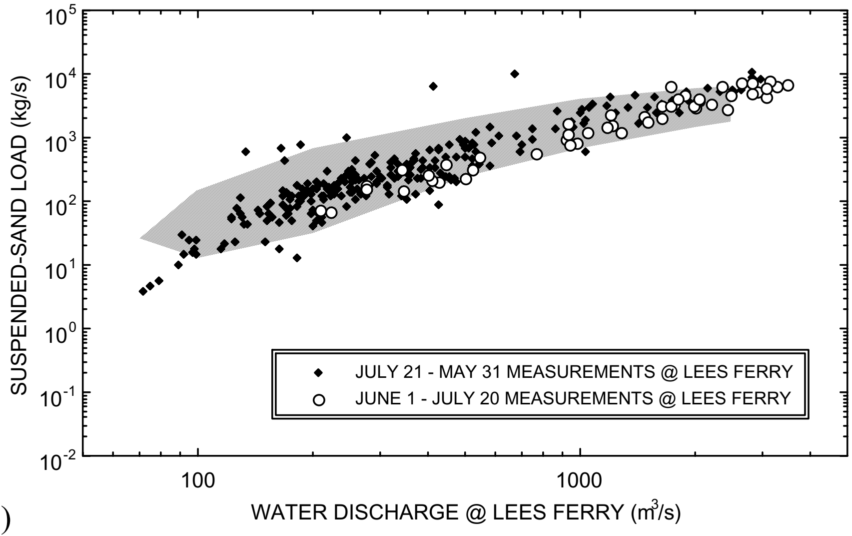
(b)

Figure A3



SUSPENDED-SILT & CLAY LOAD (kg/s)
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
◆ COLORADO R. @ LEES FERRY
100
1000
WATER DISCHARGE @ LEES FERRY (m^3/s)

(a)



SUSPENDED-SAND LOAD (kg/s)
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
◆ JULY 21 - MAY 31 MEASUREMENTS @ LEES FERRY
○ JUNE 1 - JULY 20 MEASUREMENTS @ LEES FERRY
100
1000
WATER DISCHARGE @ LEES FERRY (m^3/s)

(b)

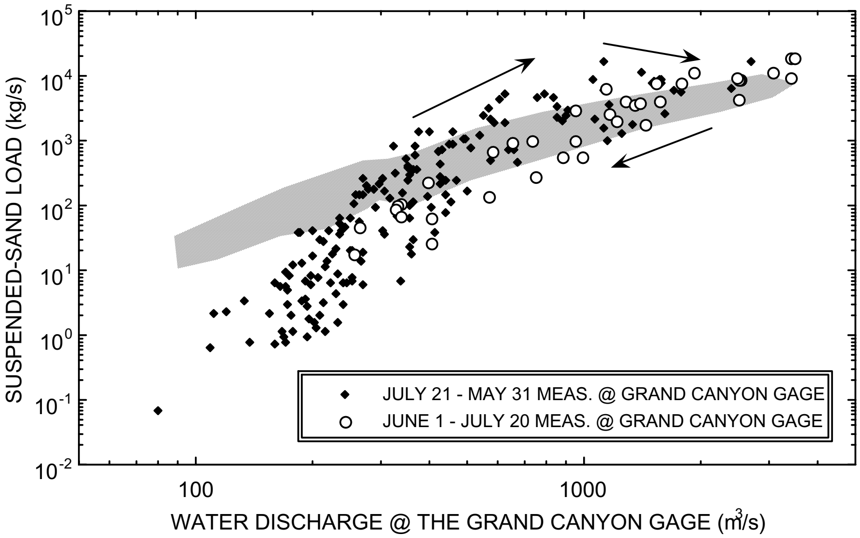

(c)
SUSPENDED-SAND LOAD (kg/s)
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
100
1000
WATER DISCHARGE @ THE GRAND CANYON GAGE (m³/s)
◆ JULY 21 - MAY 31 MEAS. @ GRAND CANYON GAGE
○ JUNE 1 - JULY 20 MEAS. @ GRAND CANYON GAGE

Figure A4

Appendix B: Minimum bed elevation for each measurement at each of the Glen Canyon cross-sections

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	Distance	Minimum bed elevation for indicated year (m)						
Section	(km)	1956	1959	1965	1975	1983	1990	2000
R20	1.0	954.18	951.07	951.34	951.07	951.10	950.58	949.50
R19	1.5	951.65						950.48
R18	2.5	954.12	952.53	951.19	951.01	951.44	950.55	950.82
R17	3.4	952.20						948.90
R16	4.3	953.26	950.67	949.06	947.69	948.42	947.53	947.83
R15	5.8	952.35	951.31	949.76	949.76	949.27	948.97	948.82
R14	7.5	951.74	950.52	946.19	946.10	946.34	945.67	
R13	8.9	951.83						947.88
R12	9.4	948.51						940.60
R11A	10.3	951.44	950.40	949.00	948.72	948.94	948.78	948.84
R11	11.0	949.82						945.43
R10	12.8	945.34	948.57	943.54	943.36	941.71	941.32	942.09
R9	14.4	949.88						940.73
R8	15.0	947.20	947.05	940.34	940.10	940.49	938.21	939.66
R7	15.8	946.98						942.65
R6	16.8	948.17						942.53
R5	18.4	947.32	948.20	946.56	946.47	947.14	946.47	946.76
R4	20.1	947.84						946.08
R3	21.4	942.44						
R2	22.6	943.88						937.13
R1	23.9	944.91	944.70	941.10	941.83	939.61	938.42	938.90
R0	25.7	946.71						940.68

Appendix C: Calculation of water-surface elevations and stage-discharge relations for the Lees Ferry Upper and Lower Cableways.

Upper Cableway

For most measurements made at the Upper Cableway, the gage height was recorded at the cable gage, located at the Upper Cableway. For those measurements, water surface elevation is based on the datum of that gage. The cable gage datum was 947.745 m (NAVD1929) from April 26 to October 12, 1924, and 944.697 m (NAVD1929) from October 12, 1924, to December 1, 1966, which was the last Upper Cableway measurement (Topping et al., in revision). Minimum bed elevation was then calculated from the water surface elevations,

$$MBE_{uc} = WSE_{uc} - D_{max}, \tag{1}$$

where MBE_{uc} is minimum bed elevation at the Upper Cableway, in meters (NAVD1929), WSE_{uc} is the water surface elevation at the Upper Cableway, in meters (NAVD1929), and D_{max} is the maximum depth across the cross-section, in meters.

There were 858 measurements made at the Upper Cableway for which water surface elevation at the cable gage was not recorded, including all measurements made before the cable gage was installed, occasional measurements made after the gage was installed, and all measurements after July 30, 1962. For these measurements, we estimated the water surface elevation at the Upper Cableway using regression relations between the cable gage height and the recording gage height. To minimize errors associated with changes in the relationship between water surface elevation at these two locations, we developed separate regressions for discrete time periods. The period of data used for each regression varies depending on the length of time for which a stable relation between the gages could be established. The root-mean square error for all regressions is 0.99 or better.

Lower Cableway

Water surface elevation was never measured directly at the Lower Cableway. For most measurements made at the Lower Cableway, only the water surface elevation at the recording gage is known. It was therefore necessary to estimate the water surface elevation at the lower cable by interpolating between the measured water surface elevations at the Upper Cableway and the recording gage. A correlation was developed between water surface elevation at the recording gage and the water surface elevation at the cable gage for all measurements when stage was measured at both locations. Although there is some scatter in the relation, a 2nd order polynomial,

$$GH_{uc} = 43726.6 - 91.1788 * GH_{rg} + 0.0485802 * GH_{rg}^{2} \quad (3)$$

fits the data with an R^2 of 0.98. Using this relation, we calculated water surface elevation at the Upper Cableway for each of the measurements made at the Lower Cableway. The water surface elevation at the Lower Cableway (WS_{lc}) was then estimated by linear interpolation between the recording gage and the Upper Cableway.

$$WS_{lc} = GH_{rg} + (D_{lc}/D_{uc}) * (GH_{uc} - GH_{rg}), \quad (4)$$

where D_{lc} is the distance from the recording gage to the Lower Cableway (700 m) and D_{uc} is the distance from the recording gage to the Upper Cableway (1500 m).

For elevations below 950.8 m, there has been no shift in the stage discharge relation since 1929, and a single relation was used to calculate discharge for any elevation in this range (Figure B1). The data were best fit by the following third order polynomial with $R^2 = 0.99$,

$$WS_{lc} = 948.69 + 2.5754\text{x}10^{-3}Q - 7.3718\text{x}10^{-7}Q^{2} + 1.1961\text{x}10^{-10}Q^{3} \quad (6)$$

For elevations above 950.8 m, separate linear fits were applied to measurements made before and after June 19, 1935. For the period from May 12, 1929, through June 19, 1935, the water surface elevations were calculated as,

$$WS_{lc} = 949.55 + 1.0836\text{x}10^{-3}Q, \quad (7)$$

with $R^2 = 0.97$. For the period from June 20, 1935 to present water surface elevations were calculated as,

$$WS_{lc} = 949.52 + 1.1643\text{x}10^{-3}Q, \quad (8)$$

with R2 = 0.98.

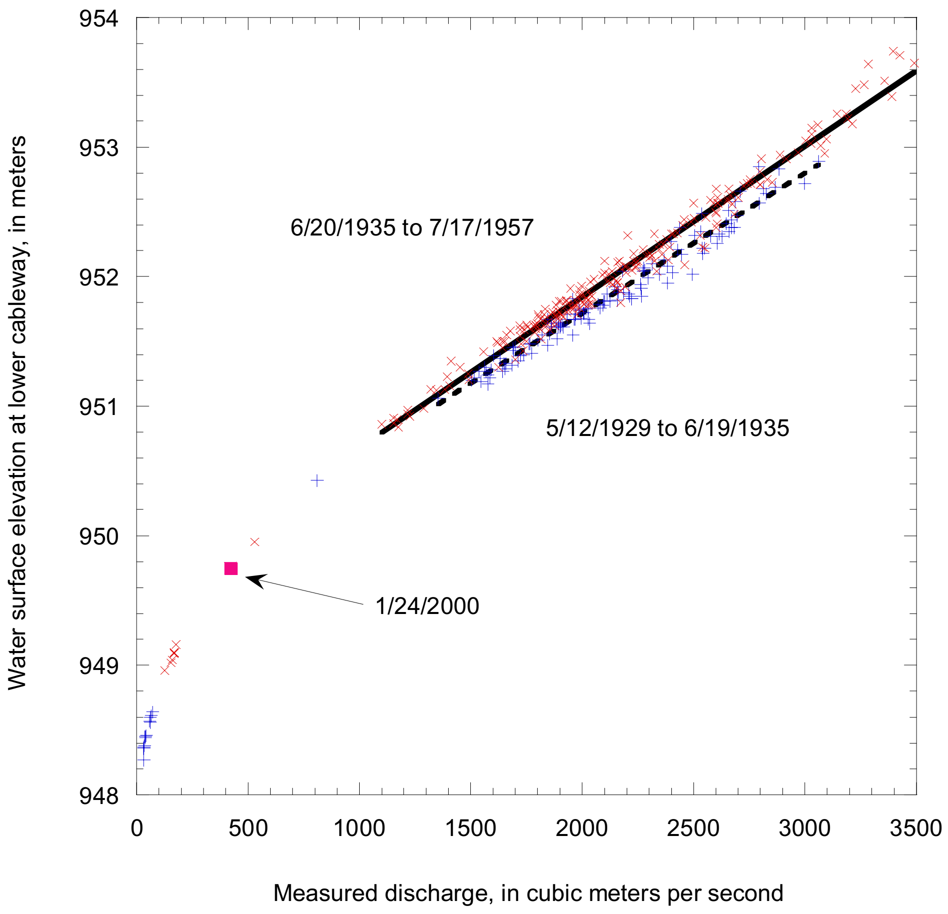


Figure C1. Rating curve showing water surface elevation as a function of discharge at the Lower Cableway from 1929 to 1957. The data were divided into two time periods and fit to separate linear relations for elevations above 950.8 m. At elevations below 950.8 m, there is no shift in the rating relation. The elevation measured in 2000 fits on this relation.

Appendix D: Description of Map Units

DEPOSIT TYPE

Alluvial Deposits

sb	**Separation bar:** Separation bars are recirculating-flow deposits that consist of very fine to fine-grained sand and are located immediately downstream from constrictions caused by debris fans or talus cones. When visible on aerial photographs, subaqueous bedforms have slipfaces facing upstream. The highest part of these bars is typically at the upstream end of the deposit.
rb	**Reattachment bar:** Reattachment bars are recirculating-flow deposits that typically consist of fine- to medium-grained sand. They are located downstream from channel constrictions and have a return-current channel on the shoreward side of the deposit. Bedforms on these deposits typically indicate upstream and onshore current directions. The highest part of these bars is typically at the upstream end of the deposit.
eb	**Undifferentiated eddy bar:** These are recirculating-flow sand deposits that are located from a channel constriction that may be formed by a debris fan, talus cone, bedrock outcrop, or sharp meander bend. They lack distinguishing characteristics of separation or reattachment bars.
cm	**Channel margin deposit:** These are sand deposits that occur in long, narrow bands parallel to the river with occasional levee topography.
sl	**Steep slopes:** These are typically the eroding banks of channel-margin deposits. They are given a hyphenated level designation with the adjacent up-slope deposit listed first and the adjacent down-slope deposit listed second.
gv	**Gravel:** unconsolidated clasts ranging in size from cobbles to boulders, in some cases including sand matrix. Clasts are sub-rounded to rounded. Gravel deposits occur as mid-channel islands or channel-side deposits.
tc	**Tributary channels:** These are deposits contained within the active channel of tributaries to the Colorado River. Deposit texture may be sand, gravel, cobble, or boulder. When sand, these deposits generally appear darker than nearby mainstem deposits.

Non-Alluvial Deposits

river	**Colorado River Channel**
df	**Debris fan:** Debris fans consist of poorly sorted cobbles and boulders, derived from local sedimentary rocks. The clasts are angular to sub-angular, made up mainly of sandstone, shale, mudstone, and limestone. These deposits occur at the mouths of steep tributaries or drainage channels and are typically fan-shaped.
gully	**Gully:** Deeply incised tributary drainage channels.
talus	**Talus:** Cobble to boulder sized angular deposits forming cones at the base of bedrock.
slpwsh	**Slopewash:** Gently sloping colluvium.
rock	**Boulder:** These are individual boulders large enough to be recognized on the aerial photographs.
br	**Bedrock:** Bedrock outcrop.
bridge	**Highway bridge:** The bridge over the Colorado River below Glen Canyon Dam.
dam	**Glen Canyon Dam**
splway	**Spillway:** The spillway outlet structures immediately downstream from Glen Canyon Dam.
developed	**Developed:** Heavily impacted areas. May include roads, parking lots, and structures.
rock	**Boulder:** These are individual boulders large enough to be recognized on the aerial photographs.
shadow	**Shadow:** Areas of deep shadow on aerial photograph, precluding mapping.

Eolian Deposits

es	**Eolian sand:** These are fine sand deposits with dune-like features, commonly found on pre-dam sand deposits.

DEPOSIT LEVEL

Pre- and post-dam alluvial deposits mapped on 1984 and later photographs

ff(sub)	**Fluctuating flow level (submerged) (1984-1996);** Coarse- to fine-grained sand, underwater, and visible on aerial photos. Extent of deposits is partially dependent on the quality of each aerial photo, the angle of the sun in the photo, the distribution of shadows in each photo, the electromagnetic wavelength used for photography, and the depth and clarity of the river at the time of photography. There is poor resolution of submerged deposits for some reaches in the 1984 photographs because of the high turbidity in the river at that time. There is excellent delineation of the submerged deposits in the 1992 and 1993 photos.
ff(w)	**Fluctuating flow level (wet) (1984-1996);** Coarse- to fine-grained sand with some silt and clay. These deposits appear darker on aerial photos than adjacent or nearby subaerial deposits of similar type. This level typically occurs adjacent to the river or to a **ff(sub)** deposit at elevations within 1 m of the water surface at the time of photography.
ff	**Fluctuating flow level (1984-1996; formative discharge: 890 m^3/s or less);** Silty, very-fine- to fine-grained sand with widely ranging colors of light gray, brown, and reddish brown. Exposed thicknesses may exceed 1 m. On aerial photography these deposits appear as clean or sparsely vegetated. They are low-elevation deposits with only a single small scarp between them and the river or are smoothly sloping into **ff(w)-** or **ff(sub)-** deposits or directly into the river. In photos from 1992 and 1993 there may be young vegetation covering the area farthest from the shoreline. The precipitous lowering of the river level just two days prior to the 1984 photography resulted in diagnostic rills appearing on the riverward side of many **ff** deposits. Well-defined bedforms are visible on some **ff**-level deposits especially in 1984 photos.
hf	**High flow level (1984-1986; formative discharge: 890-1400 m^3/s):** Medium- to very-fine grained sand, with some silty layers, silt and clay drapes over bar surfaces and in return channels. Saltcedar knocked over in the 1983 flood is commonly sprouting new sapling growth. Modern debris such as plastic bottles, lighters, and processed lumber is present in the deposits. Identification on aerial photos is typically dependent upon the appearance of the deposit in the 1984 photos. In that set of photos a number of features are useful for identifying **hf** deposits. **Hf** deposits are darker than and generally have Munsell gray scale values half a unit less than adjacent **ff** deposits. This is true whether the deposits are both in shadow or both in sunlight. The color difference between **hf** and **fs** deposits is more variable. **Hf** deposits, viewed stereoscopically, appear at

	higher elevations than **ff** deposits and at lower ones than **fs** deposits. Commonly, there are 2 cutbanks between the **hf** deposit and the river. One of these is developed in the **hf** deposit and other is in the adjacent **ff** deposit. Less commonly there is a cutbank between the **hf** deposit and an adjacent **fs** deposit. A high-water mark defined by features such as color differences, textural differences, or possibly a drift line is often visible between the **hf** deposit and adjacent **fs** deposit. Typically, a high-water mark is visible between an **hf** deposit and an adjacent **ff** deposit. Dune bedforms are sometimes present and are distinct from the sharper and generally smaller bedforms often evident on the **ff** deposits. All bedforms are assumed to have been developed while the bars were submerged and active. Vegetation covering **hf** deposits is dominated by trees and/or large bushes. This vegetation often has a water-swept appearance. Aerial photos from 1990, 1992, and 1993 rarely show any of these features. Some small **hf** deposits are identifiable on the basis of longitudinal correlation.
fs	**Flood level of summer 1983 (1983; formative discharge: 1400-2700 m^3/s):** Medium- to very-fine-grained sand, very well-sorted to well-sorted, distinctive very light gray with some salt- and-pepper coloring. Internal structures include ripples, climbing ripples, cross-laminations, and planar bedding. Plastic bottles, processed lumber, and other modern-era debris are found buried in this level. Photo identification is best done using 1984 photos. Any smooth, planar sand deposit in that set of photos that fails to meet the criteria for a lower level, is mapped as **fs**. Cutbanks developed in **fs** deposits are rarely as sharp as those found in **hf** or **ff** deposits. Color as a guide to distinguish **fs** deposits is not reliable. Mature trees are the dominant vegetation present on **fs** deposits. Some grasses or young bushes may sparsely cover an **fs** deposit in 1984. There is often a driftwood line on the shoreward side of an **fs** deposit.
htt	**Pre-dam high Tamarisk terrace (pre-1963; formative discharge: greater than 2700 m^3/sec):** Silty, very-fine grained sand. This is the lowest of the sand deposits associated with pre-dam river flows. Mature saltcedars with partially buried trunks are the typical vegetation. The deposits are distinguished on the 1984 photographs by its proximity to but higher elevation than **fs** deposits. **Htt** deposits are correlative with pre-dam alluvium of Hereford (1993).
ht	**Pre-dam high terrace (pre- 1963; formative discharge: greater than 2700 m^3/sec):** Silty, very-fine grained sand; typically heavily vegetated. This unit contains a minimum of two distinct levels, both higher in elevation that **htt** deposits.

Pre-dam alluvial deposits mapped on 1952 photographs

w	**Wet active sand:** Sand deposits that appear darker on aerial photos than adjacent or nearby subaerial deposits of similar type. This level typically occurs adjacent to the river or to a **sub** deposit.
c	**Clean active sand:** Sand deposits that are typically bare sand at a level that is near the river. Vegetation is absent or very sparse. They may correlate in elevation with post-dam deposits from the **ff** to **fs** levels.
lt	**Low Terrace (pre-dam active channel or flood plain):** These are sand deposits distinguished from **a** by the presence of some vegetation. They are higher than **a** and lower than **t** and most likely correlate with the post-dam **hf** and **fs** levels.
t	**Terrace (pre-dam flood plain):** These are high-elevation deposits that have not been inundated since closure of Glen Canyon Dam. Most of these deposits correlate to the **htt** level mapped in the 1984 and later photographs. In the 1952 photographs, vegetation, presumably tamarisk is visible on these deposits.
ht	**High Terrace (pre-dam terrace or flood plain):** These are high-elevation deposits that have not been inundated since closure of Glen Canyon Dam. Most of these deposits correlate to the **ht** level mapped in the 1984 and later photographs. In the 1952 photographs, vegetation is visible on these deposits.

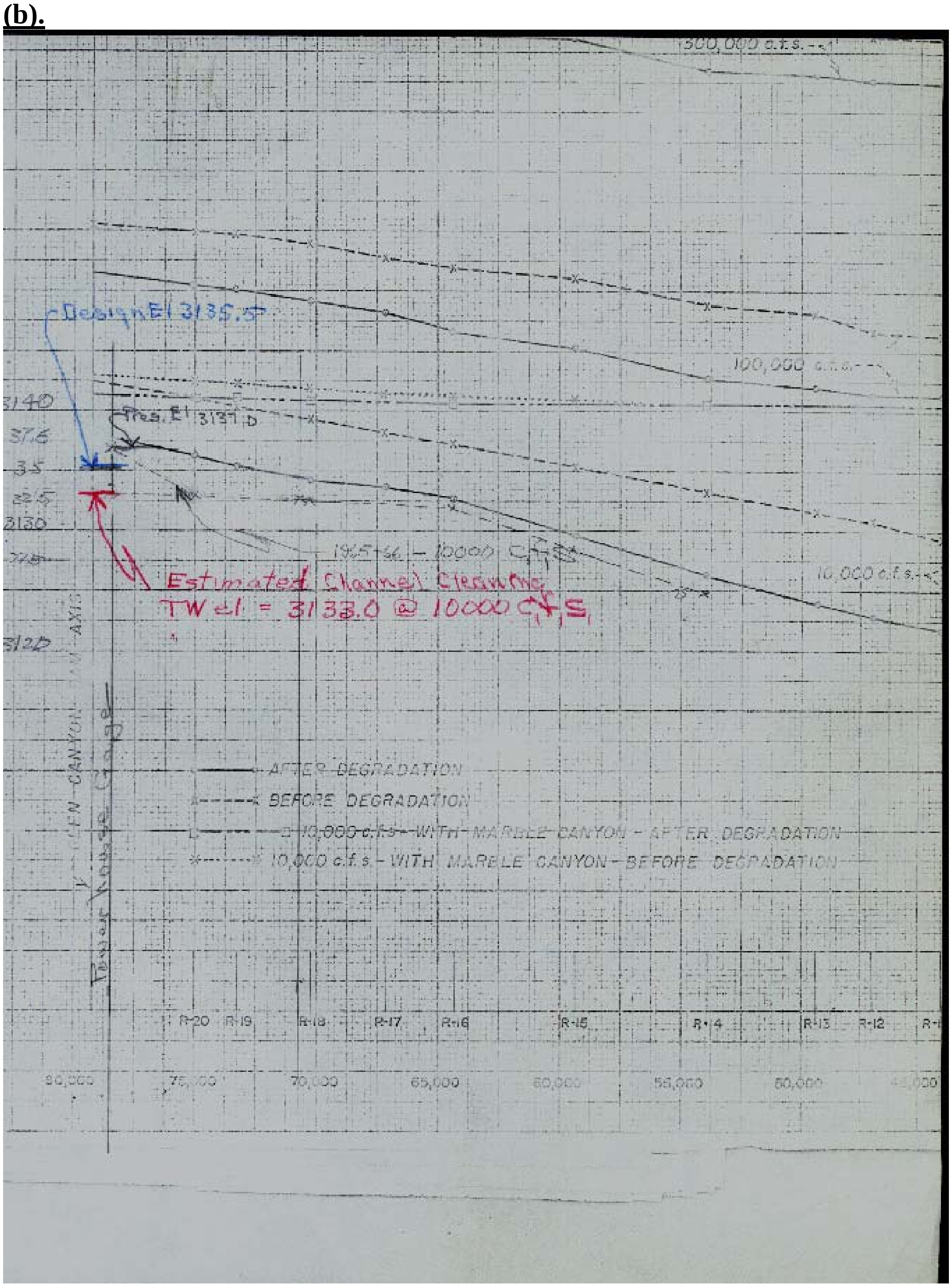
Non-alluvial deposits

NA	**Not Applicable:** This level designation is used for all non-mainstem deposits and features.
river	**Colorado River:** The level designation used for the Colorado River when no submerged deposits are visible.

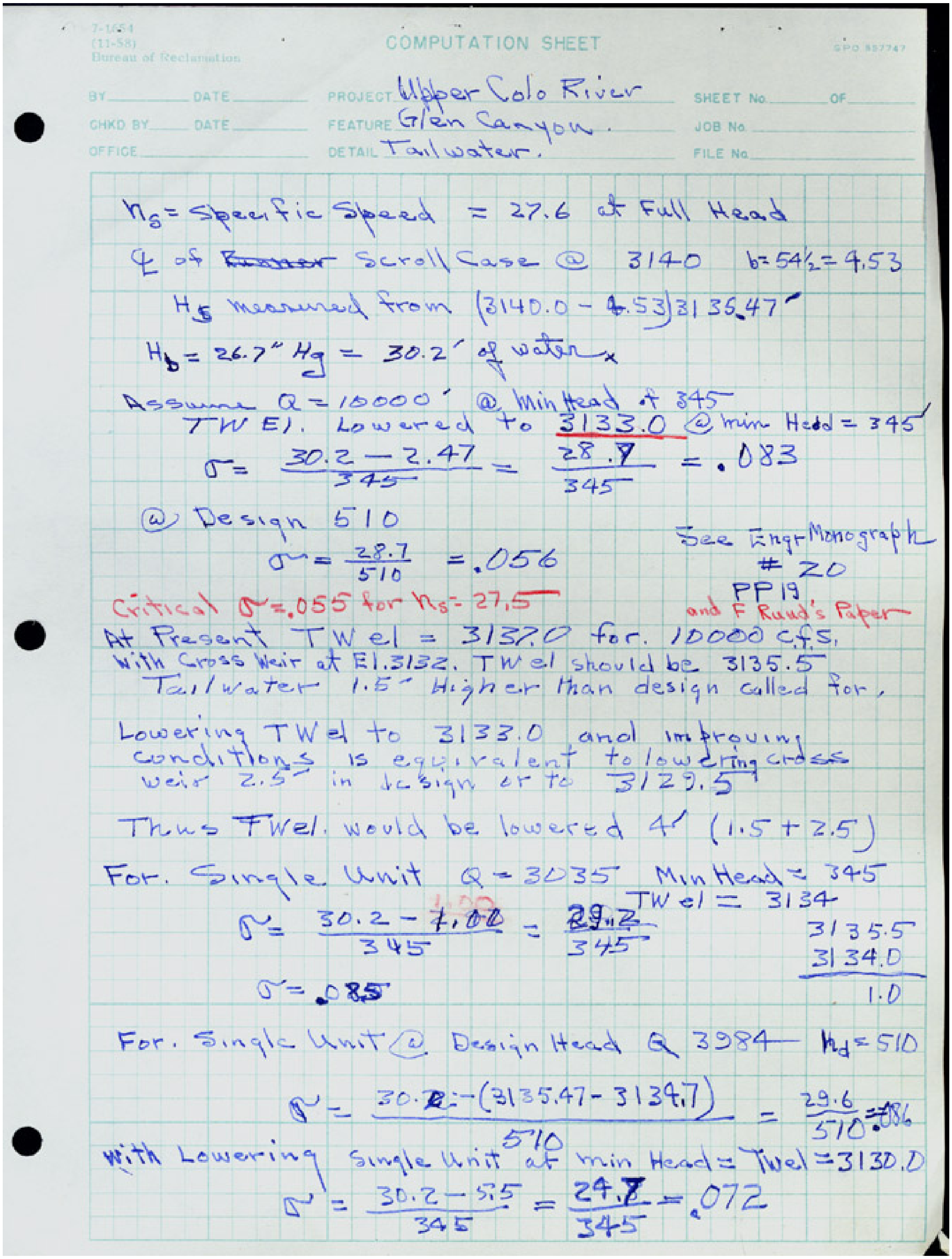
VEGETATION COVER

bare	**Clean and bare sand:** Deposit is dominated by bare sand, vegetation covering less than 10-20% of the deposit surface.
v	**Vegetated:** Deposit is mostly covered by dense vegetation.
pv	**Partially vegetated:** Vegetation cover ranges from greater than 10-20% to about 60%.

Appendix E: Bureau of Reclamation Documents. Diagram of the bed elevation immediately below the dam with handwritten notes indicating the "present" elevation, the "design" elevation, and the estimated "channel-cleaning" thalweg elevation (a). Computation sheet describing the effects of thalweg, "TW" lowering (b).



(a)



7-1654
(11-58)
Bureau of Reclamation

COMPUTATION SHEET

GPO 857747

BY ____ DATE ____ PROJECT Upper Colo River SHEET No. ____ OF ____
CHKD BY ____ DATE ____ FEATURE Glen Canyon. JOB No. ____
OFFICE ____ DETAIL Tailwater. FILE No. ____

n_s = Specific Speed = 27.6 at Full Head

℄ of ~~Runner~~ Scroll Case @ 3140 b = 54½ = 4.53

H_s measured from (3140.0 − 4.53) 3135.47′

H_b = 26.7″ Hg = 30.2′ of water

Assume Q = 10000′ @ Min Head of 345

TW El. Lowered to 3133.0 @ min Head = 345′

$$\sigma = \frac{30.2 - 2.47}{345} = \frac{28.7}{345} = .083$$

@ Design 510

$$\sigma = \frac{28.7}{510} = .056$$

Critical σ = .055 for n_s = 27.5

See Engr Monograph # 20 PP 19 and F Rund's Paper

At Present TW el = 3137.0 for. 10000 c.f.s.
with Cross Weir at El. 3132. TW el should be 3135.5
Tailwater 1.5′ Higher than design called for.

Lowering TW el to 3133.0 and improving conditions is equivalent to lowering cross weir 2.5′ in design or to 3129.5

Thus TWel. would be lowered 4′ (1.5 + 2.5)

For. Single Unit Q = 3035 Min Head = 345
TW el = 3134

$$\sigma = \frac{30.2 - 1.00}{345} = \frac{29.2}{345}$$

3135.5
3134.0
1.0

σ = .085

For. Single Unit @ Design Head Q 3984 H_d = 510

$$\sigma = \frac{30.2 - (3135.47 - 3134.7)}{510} = \frac{29.6}{510} = .086$$

With Lowering Single Unit at min Head = TWel = 3130.0

$$\sigma = \frac{30.2 - 5.5}{345} = \frac{24.7}{345} = .072$$

(b)

Appendix F: Area of deposits from surficial geologic maps. All values are in square meters per unit channel length.

Date / feature	Reach					
Sep-1952	1	2	3	4	5	Study Area
Sand (low elevation)	4.2	7.4	5.4	15.1	11.5	8.7
Sand (high elevation)	1.0	4.7	5.4	12.1	2.9	5.2
Sand (terrace)	17.3	40.1	18.9	27.9	29.4	26.7
Gravel and sand	7.7	16.7	3.8	0.0	10.2	7.7
Gravel	0.0	0.0	0.3	0.0	0.0	0.1
River	145.9	161.4	128.1	143.4	117.8	139.5
Debris fan	0.4	3.5	2.1	2.9	7.0	3.2
Non-alluvial	3.3	0.1	0.0	0.3	0.5	0.9

Oct-1984	1	2	3	4	5	Study Area
Sand (low elevation)	7.3	6.4	11.4	11.6	4.9	8.3
Sand (high elevation)	6.1	6.1	4.2	7.0	11.0	6.9
Sand (terrace)	14.6	30.8	15.1	24.3	24.2	21.8
Gravel and sand	11.8	35.1	16.2	18.7	3.0	17.0
Gravel	12.0	30.8	4.4	1.3	2.7	10.3
River	119.4	99.6	93.3	120.6	116.8	110.0
Debris fan	0.9	1.0	1.6	1.5	7.4	2.5
Non-alluvial	8.7	0.5	1.7	0.8	22.1	6.8

Jun-1990	1	2	3	4	5	Study Area
Sand (low elevation)	7.1	6.8	9.6	8.2	6.3	7.6
Sand (high elevation)	6.5	5.3	5.8	7.6	10.1	7.0
Sand (terrace)	14.2	29.0	14.7	22.7	23.3	20.8
Gravel and sand	16.5	32.7	14.0	19.9	1.0	16.9
Gravel	11.8	24.7	4.0	0.9	1.2	8.6
River	116.7	111.7	95.3	124.0	119.6	113.5
Debris fan	1.6	1.0	1.6	1.7	7.8	2.7
Non-alluvial	0.2	0.4	1.7	1.0	22.7	5.2

Oct-1992	1	2	3	4	5	Study Area
Sand (low elevation)	6.4	3.7	7.2	6.1	4.7	5.6
Sand (high elevation)	7.3	5.9	4.2	6.8	9.7	6.8
Sand (terrace)	13.8	28.6	14.5	23.0	23.3	20.6
Gravel and sand	19.5	25.1	11.6	17.1	3.8	15.5
Gravel	6.9	28.8	6.0	1.1	0.0	8.6
River	115.9	113.6	100.7	129.6	114.1	114.9
Debris fan	0.8	1.2	1.8	1.4	8.2	2.7
Non-alluvial	0.3	1.2	1.5	1.1	18.6	4.5

Mar-1996	1	2	3	4	5	Study Area
Sand (low elevation)	6.4	4.7	8.4	7.1	7.1	6.7
Sand (high elevation)	7.1	7.4	5.0	7.4	9.6	7.3
Sand (terrace)	12.9	28.1	14.3	22.9	24.2	20.5
Gravel and sand	18.6	28.2	9.6	19.4	8.1	16.8
Gravel	4.7	21.9	3.4	1.7	0.0	6.4
River	115.3	112.8	96.5	119.4	109.8	110.8
Debris fan	1.0	1.1	1.9	1.6	7.9	2.7
Non-alluvial	0.7	0.4	1.5	1.6	22.6	5.3

Apr-1996	1	2	3	4	5	Study Area
Sand (low elevation)	7.2	6.3	8.3	9.2	7.1	7.6
Sand (high elevation)	7.3	7.3	5.1	7.1	9.7	7.3
Sand (terrace)	12.8	27.9	13.7	22.9	24.0	20.2
Gravel and sand	18.2	34.8	11.5	23.2	12.8	20.2
Gravel	6.4	23.7	3.7	1.9	0.5	7.3
River	112.9	107.8	92.9	116.7	105.9	107.3
Debris fan	0.8	0.9	1.7	1.1	7.9	2.5
Non-alluvial	1.3	0.5	2.9	1.9	22.5	5.8

Appendix G: Interpreted changes between each aerial photograph interval. All values in hectares.

September 1952 to October 1984 — Reach

Description	1	2	3	4	5	Area Total
Perched Sand	7.9	6.9	5.1	5.9	6.1	6.4
Erosion of Sand	8.8	18.3	5.2	8.2	10.7	10.2
Erosion of Gravel	0.4	2.7	0.0	0.0	1.4	0.9
Perched Gravel	6.5	20.5	4.5	2.4	0.8	7.0
Error	0.0	0.0	0.0	0.0	0.0	0.0
No change	140.4	160.3	131.8	167.6	143.4	148.7

October 1984 to June 1990 — Reach

Description	1	2	3	4	5	Area Total
Deposition of Sand	0.2	0.5	1.0	0.2	0.0	0.4
Erosion of Sand	2.4	4.1	3.0	3.5	2.0	3.0
Erosion of Gravel	0.5	1.0	1.4	0.4	0.2	0.7
Perched Gravel	7.9	2.2	0.5	0.3	0.2	2.3
Error	0.0	0.5	0.0	0.0	0.0	0.1
No change	155.7	198.3	140.6	180.2	157.1	166.5

June 1990 to October 1992 — Reach

Description	1	2	3	4	5	Area Total
Deposition of Sand	0.2	0.0	0.1	0.2	0.0	0.1
Erosion of Sand	3.4	6.0	2.2	1.9	0.1	2.7
Erosion of Gravel	0.3	1.4	0.2	0.7	0.0	0.5
Perched Gravel	0.6	4.5	1.8	0.2	0.2	1.4
Error	0.6	0.3	0.4	1.2	0.4	0.6
No change	161.4	195.4	142.9	178.0	157.2	167.1

October 1992 to March 1996 — Reach

Description	1	2	3	4	5	Area Total
Deposition of Sand	0.0	0.0	0.4	0.0	0.1	0.1
Erosion of Sand	3.0	0.7	0.7	1.3	0.9	1.3
Erosion of Gravel	1.2	0.8	0.0	0.0	0.0	0.4
Perched Gravel	0.1	0.0	0.0	0.0	0.0	0.0
Error	0.2	0.1	0.0	0.1	0.1	0.1
No change	159.6	205.8	144.8	182.9	156.3	170.0

March 1996 to April 1996 — Reach

Description	1	2	3	4	5	Area Total
Deposition of Sand	0.1	0.2	0.5	0.7	0.2	0.3
Erosion of Sand	0.4	0.1	0.1	0.7	0.2	0.3
Erosion of Gravel	0.0	0.0	0.0	0.0	0.0	0.0
Perched Gravel	0.3	0.3	0.0	0.1	0.0	0.1
Error	0.2	0.1	0.0	0.3	0.0	0.1
No change	162.7	207.1	144.3	184.9	164.0	172.7