October 2004

SYSTEM-WIDE CHANGES IN THE DISTRIBUTION OF FINE SEDIMENT IN THE COLORADO RIVER CORRIDOR BETWEEN GLEN CANYON DAM AND BRIGHT ANGEL CREEK, ARIZONA

Final Report

By **John C. Schmidt, David J. Topping, Paul E. Grams,**
and **Joseph E. Hazel**

SYSTEM-WIDE CHANGES IN THE DISTRIBUTION OF FINE SEDIMENT IN THE COLORADO RIVER CORRIDOR BETWEEN GLEN CANYON DAM AND BRIGHT ANGEL CREEK, ARIZONA

FINAL REPORT
Submitted to Grand Canyon Monitoring and Research Center

October 2004

John C. Schmidt[1], David J. Topping[2], Paul E. Grams[1], and Joseph E. Hazel[3]

[1] Department of Aquatic, Watershed, and Earth Resources, Utah State University
[2] U. S. Geological Survey, Flagstaff
[3] Department of Geology, Northern Arizona University

in partial fulfillment of cooperative agreement 1425-98-FC-40-22640 and modifications, between Utah State University and the Grand Canyon Monitoring and Research Center

Report of the Fluvial Geomorphology Laboratory
Deparment of Aquatic, Watershed, and Earth Resources
Utah State University
Logan, Utah 84322-5210

Contents

Abstract
1.0 Introduction . . . 1
1.1 The Importance of a Comprehensive History of Geomorphic Change . . . 3
2.0 Water and Fine-Sediment Fluxes . . . 3
3.0 The Valley of the Colorado River . . . 7
3.1 Longitudinal Profile and Bed-Material Distribution . . . 10
3.2 The Fan-Eddy Complex . . . 13
3.2.1 Longitudinal Distribution of Eddy Deposition Zones . . . 15
3.3 Sedimentology of Fine-Grain Alluvial Deposits . . . 18
4.0 Previous Studies in Fine-Sediment Flux and Storage . . . 20
4.1 Previous Projections of Long-Term Changes in the Fine-Sediment Budget . . . 21
5.0 Changes in the Topography of the Main-Channel Bed . . . 23
5.1 Pre-dam Changes in the Main-Channel Bed, as Measured at the Lees Ferry and Grand Canyon Gages . . . 23
5.2 Post-Dam Changes of the Bed in Glen Canyon . . . 25
5.2.1 Rate and Magnitude of Degradation . . . 31
5.3 Post-dam Changes in the Bed in Marble and Upper Grand Canyons . . . 32
5.3.1 Bed Changes in Marble and Grand Canyons That Are Probably Post-dam . . . 33
5.3.2 Changes at the Grand Canyon Gage between 1963 and 2000 and at the Lower Marble Canyon Gage between 1983 and 2000 . . . 34
5.3.3 Changes in Main Channel Pools Offshore from Eddies between 1992 and 2000 . . . 35
6.0 The History of Fine Sediment Storage at Specific Sites . . . 37
6.1 Badger Creek Rapids . . . 42
6.2 Eminence Break Camp . . . 49
7.0 Long-Term Changes in Fine Sediment Storage Shown by Comparison of Oblique Photographs . . . 61
7.1 Previous Studies . . . 61
7.2 Methods and Results . . . 61
7.2.1 Description of change depicted in some of the photographs . . . 63
8.0 Changes in the Area of Fine-Grained Alluvial Deposits Determine by Aerial Photography Analysis . . . 67
8.1 Methods . . . 67
8.1.1 Accuracy of mapping . . . 72
8.1.2 Metrics used to describe changes in fine-grain deposits among years . . . 74
8.2 Description of the Photograph Series That Were Analyzed . . . 75
8.2.1 Pre-dam conditions of the mid-1930s, 1952, 1954, 1956, 1958 . . . 75
8.2.2 Pulsed high releases of May 1965 . . . 75
8.2.3 Fluctuating flows of June 1973 . . . 75
8.2.4 Bypass and spillway floods of the mid-1980s: October 1984 . . . 76
8.2.5 Resumption of wide-ranging hydroelectricity-generating flows: June 1990 . . . 76
8.2.6 Interim operating criteria: October 1992, May 1993, and March 1996 . . . 76
8.2.7 Effects of the 1996 Controlled Flood: April 1996 . . . 76
8.2.8 Changes in bars after the 1996 Controlled Flood: September 1996 and September 1997 . . . 76
8.3 Changes in the Area of Fine-Grained Alluvial Deposits Determined by Aerial Photograph Analysis . . . 77
8.3.1 Changes in eddy bars . . . 77

8.3.2 Changes in channel-margin deposits. . . . 79
9.0 Analysis of NAU Survey Data, 1990 to 2001 82
9.1 Methods 82
9.2 Changes in Area and Volume in the Post-Dam Flood Zone 82
9.3 Changes in Area and Volume in the Fluctuating Flow Zone 86
9.4 Changes in Volume in the Deep Parts of Eddies, Below the Stage of 227 m^3/s 89
9.5 Long-term Changes Determined from Integration of NAU Data with Aerial Photograph Analysis 90
10.0 An Integrated History of Fine-Sediment in Glen, Marble, and Upper Grand Canyons 91
10.1 Summary 91
10.2 Styles of Change in Eddies 94
10.3 Style of Channel Change 95
10.4 River Processes that Caused Channel Change and Constraints on Rehabilitation Towards Pre-dam Conditions 95
Acknowledgments 96
11.0 Literature Cited 97
Appendices 103

Figures

Figure 1	Map showing the 4 river segments that comprise the study area...	2
Figure 2	Graphs showing instantaneous discharge of the Colorado River at ...	4
Figure 3	Graph showing flow duration curves of the Colorado River at the Lees ...	5
Figure 4	Graph showing pre-dam sand concentrations as a function of water ...	5
Figure 5	Graph showing longitudinal profile of the Colorado River and reach ...	9
Figure 6	Photographs of the Colorado River. ...	9
Figure 7	Maps showing topography of the bed of the Colorado River ...	11
Figure 8	Maps showing the bed of the Colorado River near President Harding Rapid...	12
Figure 9	Photographs of Badger Creek Rapids at River Mile 8...	13
Figure 10	Map showing the distribution of unconsolidated geologic deposits ...	14
Figure 11	Diagram showing the method of calculation of EDZs.	16
Figure 12	Graphs showing cumulative distribution of EDZs in 5 study reaches...	18
Figure 13	Diagram depicting generalized cross section showing geomorphic ...	19
Figure 14	Diagram depicting generalized internal stratigraphy of Grand Canyon ...	20
Figure 15	Photographs showing the Colorado River near the U. S. Geological Survey...	24
Figure 16	Graphs showing bed elevation at the Lees Ferry gage...	26
Figure 17	Graph showing mean bed elevation at the Grand Canyon gage...	27
Figure 18	Map showing Glen Canyon and locations of cross-sections that have been ...	28
Figure 19	Graphs showing minimum bed elevation at cross-sections in Glen Canyon ...	30
Figure 20	Graph showing change in stage at 150 m^3/s, plotted as a function of ...	32
Figure 21	Graph showing bed sediment size distribution for samples in Glen Canyon...	32
Figure 22	Graph showing longitudinal profile of the thalweg and contact of sand and ...	33
Figure 23	Photograph of the Marble Canyon dam site, near River Mile 39.	33
Figure 24	Graph showing mean bed elevation and the discharge of water measured at...	35
Figure 25	Graphs showing (A) measured sediment volume in the 7 largest pools ...	36
Figure 26	Graphs showing normalized sediment volume in 16 main channel pools...	36
Figure 27	Graph showing longitudinal profile of the water surface at Badger Creek ...	37
Figure 28	Photographs showing Badger Creek Rapids. Photographs taken from river...	38
Figure 29	Photographs of Badger Creek Rapids, taken from the cliffs above the rapid...	40
Figure 30	Graphs showing the Colorado River upstream from Badger Creek Rapids...	43
Figure 31	Aerial photographs of Bader Creek Rapids. Flow is from right to left...	44
Figure 32	Photographs of the separation bar on river left downstream from Badger ...	46
Figure 33	Graph showing changes in topography of the separation bar on river left ...	48
Figure 34	Graphs showing changes in the volume of sand on the separation bar on ...	48
Figure 35	Photographs of the riffle and eddy at Eminence Break. Flow is from right ...	50
Figure 36	Maps showing the area of the eddy and patterns of recirculating flow at ...	53
Figure 37	Maps showing changes in topography during the 1996 Controlled Flood ...	55
Figure 38	Graphs showing topographic changes of the separation and reattachment ...	56

Figure 39	Photographs of the Colorado River near Eminence Break camp in different....	58
Figure 40	Graphs showing changes in the area of sand at Eminence Break at different....	60
Figure 41	Photographs depicting the Colorado River channel in 1897 and 1994 near	63
Figure 42	Photographs of Redwall Cavern at River Mile 33.3....	64
Figure 43	Photographs of the river corridor near Saddle Canyon...	65
Figure 44	Photographs of the Colorado River in the Tapeats Gorge, taken from Cape	66
Figure 45	Maps showing types of sand deposits and the topographic levels at which ...	68
Figure 46	Graph showing the area of each eddy bar in the post-dam flood zone...	73
Figure 47	Graphs showing the temporal sequence of the area of the pre-dam ...	77
Figure 48	Graphs showing eddy fill ratios for the 5 study reaches in average pre-dam	79
Figure 49	Graphs showing the temporal sequence of channel-margin deposits in the ...	79
Figure 50	Graphs showing temporal changes in the area and volume of sand above ...	83
Figure 51	Histograms showing the proportional change during indicated time periods...	84
Figure 52	Graph showing temporal changes in the mean and median area of sand ...	85
Figure 53	Graphs showing temporal changes in the area and volume of sand below ...	87
Figure 54	Histograms showing the proportional change during indicated time periods....	88
Figure 55	Graph showing temporal changes in the mean and median area of sand...	89
Figure 56	Graphs showing (A) measured sediment volume over time in the 7 largest ...	92
Figure 57	Graphs showing mean and median area of deposits in the post-dam flood ...	94
Figure 58	Graphs showing the temporal sequence of the area of fluctuating flow zone....	94

Tables

Table 1. Segment characteristics of the Colorado River in Marble and upper Grand Canyons. 8
Table 2. Depth to bedrock in the valley of the Colorado River. 8
Table 3. Characteristics of the 5 reaches in Marble and upper Grand Canyons where fine-grain alluvium was mapped and analyzed in a GIS. The sixth reach was Glen Canyon. 15
Table 4. Estimates of the potential fine-sediment storage volume in 9 EDZs. 17
Table 5. Estimates of the average change in fine sediment thickness in Marble and upper Grand Canyons under various scenarios of seasonal sediment accumulation, relative proportion of accumulation stored in eddies and the main channel, and proportion of the main channel where storage occurs. . . . 28
Table 6. Locations of cross-sections in Glen Canyon indicating which cross-sections were surveyed each year and the dates of those measurements if known. 29
Table 7. Summary of channel cross-section data at Marble Canyon Dam sites. 33
Table 8. Comparison of the area of sand depicted in photographs taken during the Second Powell Expedition and matched by Stephens and Shoemaker (1987). 62
Table 9. Summary of changes in sand bars depicted in historical photo matches taken by Turner and Karpiscak (1980). 62
Table 10. Aerial photographs analyzed in this study. 69
Table 11. Description of units in pre- and post-controlled flood geomorphic maps. 71
Table 12. Areas above 708 m^3/s stage and between 227 and 708 m^3/s stages, as surveyed by NAU and estimated from aerial photographs. 72
Table 13. Error matrix of the agreement between areas surveyed by NAU and estimated by USU. 73
Table 14. Reach-average change in eddy sand bars between pre-dam photographs and the 1990s. 78
Table 15. Eddy deposition zones (EDZs) that increased or decreased in area between average pre-dam conditions and the 1990s. 80
Table 16. Summary of temporal trends in area and volume of sand in two elevation zones at sites measured by NAU. 85
Table 17. Mean and median area of post-dam flood sands above the elevation of the stage of 708 m^3/s at study sites in Marble Canyon. 86
Table 18. Mean and median area of sand in the fluctuating flow zone, below the elevation of the stage of 708 m^3/s and above the stage of 227 m^3/s, at study sites in Marble Canyon. 90
Table 19. Estimates of loss of fine sediment from eddies between the pre-dam era and the 1990s. 91

SYSTEM-WIDE CHANGES IN THE DISTRIBUTION OF FINE SEDIMENT IN THE COLORADO RIVER CORRIDOR BETWEEN GLEN CANYON DAM AND BRIGHT ANGEL CREEK, ARIZONA

By **John C. Schmidt, David J. Topping, Paul E. Grams,** *and* **Joseph E. Hazel**

ABSTRACT

The riverine ecosystem of the Colorado River between Glen Canyon Dam and Bright Angel Creek had less fine sediment on its bed, in eddies, and as channel-margin deposits in 2001 than it did prior to completion of the dam. Changes in dam operations in the 1990s did not arrest this trend.

The decrease in fine sediment storage is documented by comparison of historical oblique photographs, analysis of historical aerial photographs, and field surveys since 1990. The magnitude of the decrease is uncertain. The loss of sand is probably about 25% of the area typically exposed at base flow in pre-dam photographs, but estimates range between 0 and -55%, depending on study reach and method of analysis. There is no indication that the magnitude of decrease is less in the downstream part of the study area. The cumulative loss of eddy sand is about 1 m in thickness but also varies greatly.

Eddies are now the primary storage site of fine sediment. Eddies have always been a very large storage site for fine sediment, but the bed once played a more important role than it does today. The bed has been significantly lowered in Glen Canyon, but the bed has only degraded in pools and ponded backwaters in Marble and Upper Grand Canyons. There is no evidence that fine sediment aggrades on the main channel bed or in the deep parts of eddies for longer than a few weeks to a few months, and these parts of the river respond quickly to changes in flow and sediment transport. These areas evacuate fine sediment during flows typical of the 1990s. Post-dam flood deposits have a longer response time and adjust over a period of years to decades to changes in dam operations. These deposits are only constructed by dam releases that exceed power plant capacity. They are subject to large erosion rates during the first months following flood recession, but erosion rates thereafter decrease. The area of these deposits caused by the 1996 Controlled Flood lasted about 5 years, although some individual deposits remain large today.

1.0 INTRODUCTION

Today's Colorado River in Glen Canyon National Recreation Area and Grand Canyon National Park is heavily used as a recreation corridor. Between 15,000 and 20,000 persons annually float through Marble and Grand Canyons (U. S. Department of the Interior, 1995), and these river trips often are remembered by the participants for the rest of their lives. More than 50,000 people visit Glen Canyon each year, where they primarily fish for rainbow trout (*Oncorhynchus mykiss*) or take scenic boat trips from Glen Canyon Dam to Lees Ferry (U. S. Department of the Interior, 1995). Thousands of hikers and backpackers scramble or walk into Marble and Grand Canyons to enjoy an afternoon visit or an evening camp.

The Colorado River corridor is also a unique riverine ecosystem. Parts of the Colorado River in Glen, Marble, and Grand Canyons are critical habitat for the endemic endangered humpback chub (*Gila cypha*) and razorback sucker (*Xyrauchen texanus*). Riparian vegetation occurs in two distinct zones: one relict of the pre-dam hydrologic conditions and a denser assemblage at lower elevation that is an artifact of the post-dam flow regime. Both vegetation zones constitute habitat for birds and other fauna.

The stream flow that maintains this riverine ecosystem and is the focus of so many people's recreational experience is determined by water releases from Glen Canyon Dam. Today's floods are much smaller and today's base flows are much larger than those which occurred prior to the dam. The existence of the dam also blocks all sediment delivered from the Colorado River upstream from Lake Powell reservoir. When the reservoir is full, stream flow temperature averages 8°C.

These changes to water flow, sediment transport, and water temperature have transformed the geomorphology and ecology of the Colorado River and its alluvial valley (Carothers and Brown, 1991; National Research Council, 1991; U.S. Department of the Interior, 1995; Webb, 1996). Among the geomorphic features affected by the dam's existence and operations are fine-sediment deposits, the size and abundance of which are indicators of the degree to which the post-dam ecosystem has been altered from the pre-dam condition (National Research Council, 1996).

The purpose of this paper is to describe the physical transformation of the channel and alluvial deposits of the Colorado River during the twentieth century in Glen, Marble, and upper Grand Canyons, with emphasis on fine sediment (Fig. 1). The upstream end of the study area is Glen Canyon Dam, located at River Mile –15[1]. The downstream end of the study area is River Mile 87, which is the location of U. S. Geological Survey (USGS) gaging station 09402500 (Colorado River near

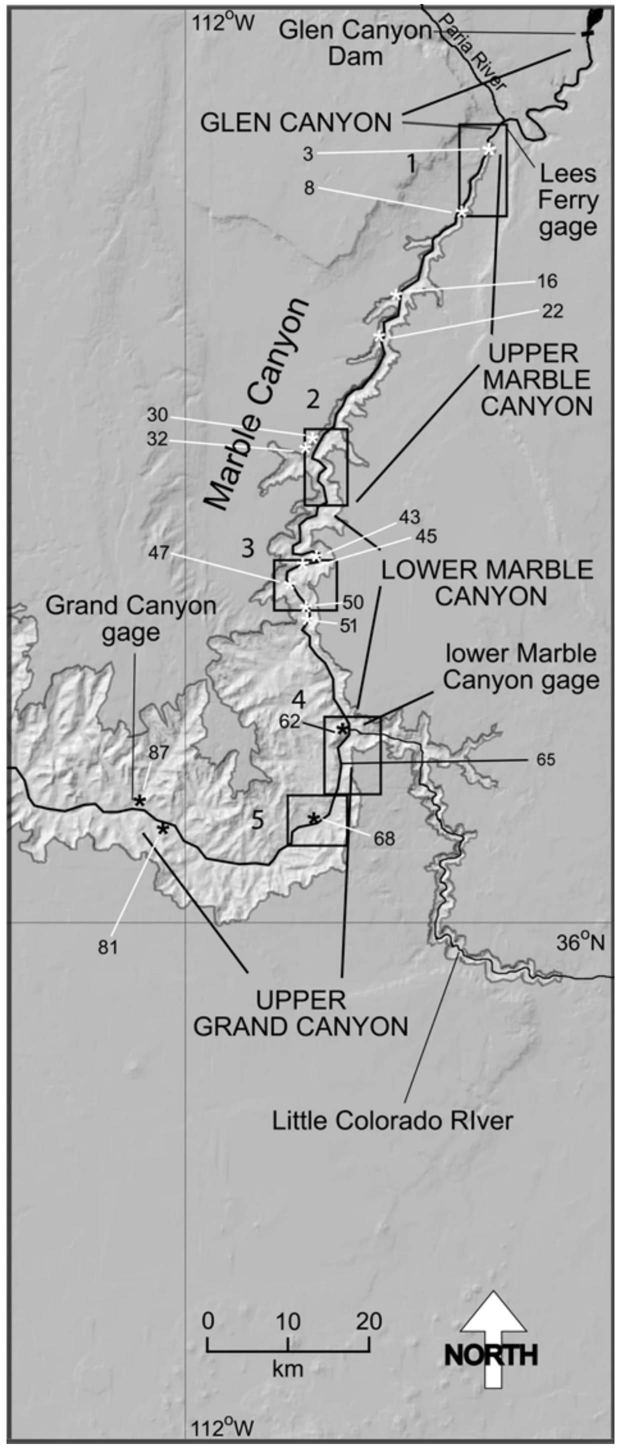


Figure 1. Map showing the 4 river segments (in capital letters) that comprise the study area. Five study reaches where historical aerial photographs were analyzed are shown in boxes: (1) Lees Ferry Reach, (2) Redwall Gorge Reach, (3) Point Hansborough Reach, (4) Tapeats Gorge Reach, and (5) Big Bend Reach. The sixth study reach was all of Glen Canyon. NAU study sites are indicated by *,with location in River Mile.

1 Locations in the study area are described in terms of the distance, in river miles, from Lees Ferry. Distance downstream is positive, and distance upstream is negative. Locations are cited to the nearest 0.1 mile, based on the location system of the Grand Canyon Monitoring and Research Center (GCMRC).

Grand Canyon, Arizona, and referred to hereafter as the Grand Canyon gage). We present evidence from gaging station measurements, channel cross-section surveys, comprehensive hydrographic surveys, sand-bar surveys, historical and modern matched ground-level oblique photographs, and analysis of aerial photographs within a geographic information system (GIS).

1.1 The Importance of a Comprehensive History of Geomorphic Change

Numerous studies have described aspects of the environmental history of the Colorado River in Glen, Marble, and Grand Canyons. These studies generally described the decrease in fine sediment in and along the channel and the increase in riparian vegetation. Each of these studies emphasized analysis of a specific type of data. Burkham (1986) analyzed discharge measurement data at gaging stations. Howard and Dolan (1981), Beus et al. (1985), Schmidt and Graf (1990), and the Sand Bar Studies Group of Northern Arizona University (NAU) reported on topographic surveys of sand bars. Turner and Karpiscak (1980), Stephens and Shoemaker (1987), and Webb (1996) matched ground level photographs spanning a century. Brian and Thomas (1984) and Kearsley et al. (1994) inventoried campsites in the field and on aerial photographs, respectively.

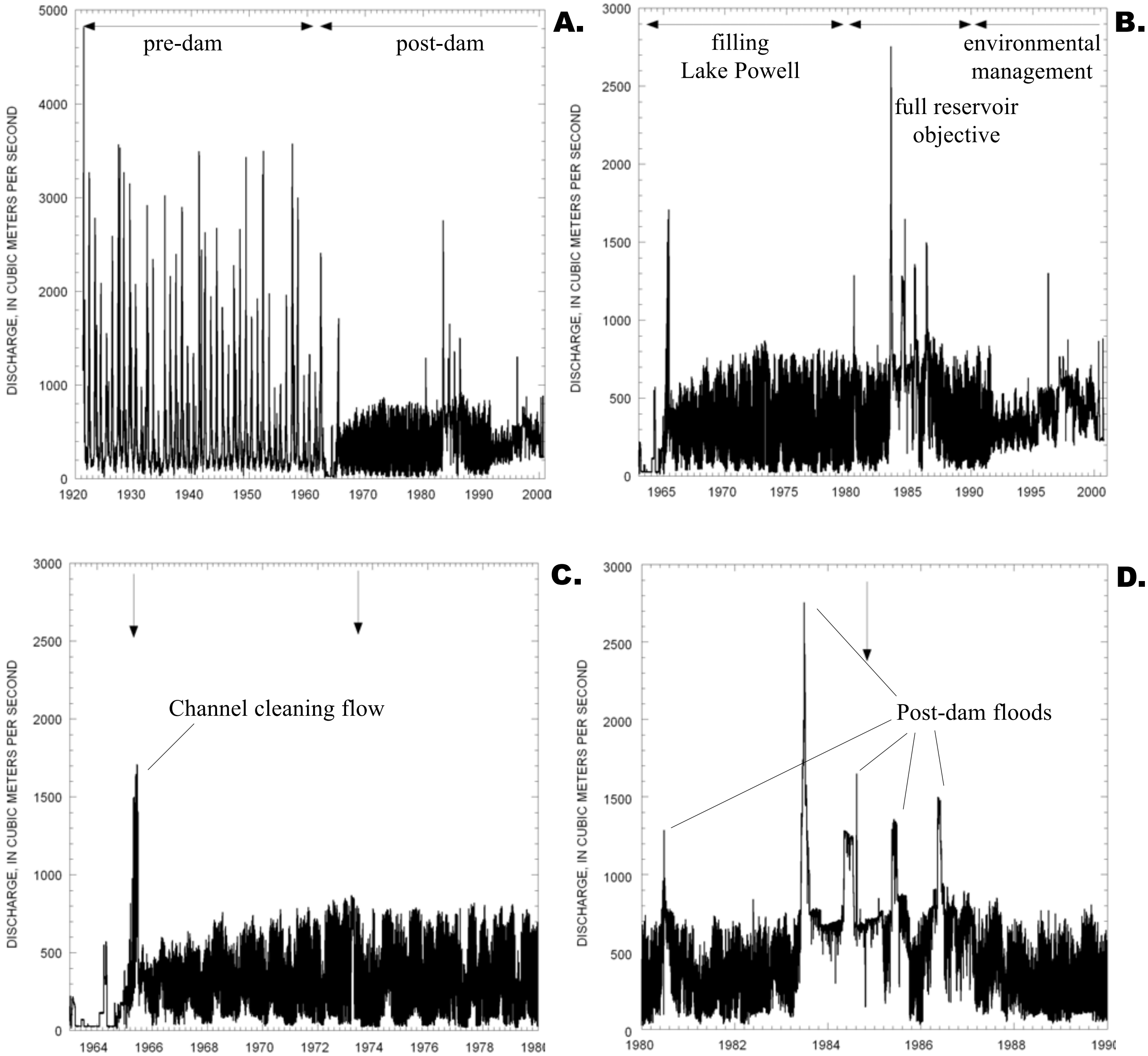
Although each of these studies generally described the same style of environmental change, each analytical technique had limitations of temporal resolution or spatial robustness. These limitations blocked the attempt to assign a magnitude to the decrease in fine-sediment storage in the channel and alluvial valley, and there is no consensus as to the nature of longitudinal trends in channel change.

Comprehensive understanding of the timing, magnitude, style, and spatial extent of channel change in Glen, Marble, and Grand Canyons is essential as a benchmark against which to understand changes in the aquatic and riparian ecosystem and to inform public policy debate about environmental management of Glen Canyon Dam. The attempt to reverse environmental conditions that are determined to be undesirable will partly be founded on a clear understanding of the magnitude of the geomorphic transformation that has occurred downstream from the dam.

2.0 WATER AND FINE-SEDIMENT FLUXES

The fluxes of water and of sand, silt, and clay were highly variable before completion of Glen Canyon Dam (Topping et al., 2000b). The median discharge of the Colorado River at USGS gaging station 09380000 (Colorado River at Lees Ferry, Arizona, and referred to hereafter as the Lees Ferry gage) was 227 m^3/s for the pre-dam period between May 8, 1921, and March 12, 1963, and the range of flows during the year was large (Fig. 2A). The 10% exceedence flow was 1359 m^3/s, and the 90% exceedence flow of 127 m^3/s (Fig. 3) was more than an order of magnitude less (Topping et al., 2003). Prior to completion of the dam, the total annual load of fine sediment was 57 ± 3 million metric tons at the Lees Ferry gage and 83 ± 4 million metric tons at the Grand Canyon gage, based on measurements made after 1944 (Topping et al., 2000b). Between 1949 and 1962, the difference between the annual load of the year of largest transport and the year of smallest transport was one order of magnitude (Topping et al., 2000b). Approximately 40% and 35% of the annual fine sediment load passing the Lees Ferry and Grand Canyon gages, respectively, was sand.

The concentration of sand in suspension and the discharge of water were reasonably well correlated at the Lees Ferry gage, but this correlation was poor at the Grand Canyon gage (Topping et al. 2000a; Rubin and Topping, 2001). At the Grand Canyon gage, concentration was much greater during the rising limb of the spring snowmelt flood than during the flood's recession. The variation in suspended-sand



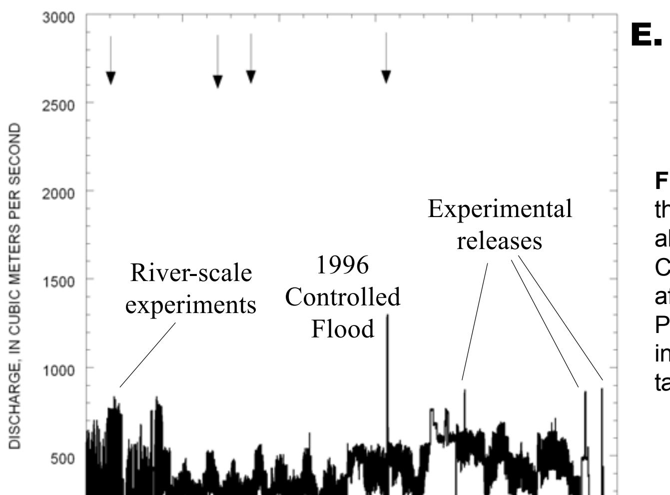


Figure 2. Graphs showing instantaneous discharge of the Colorado River at the Lees Ferry gage (Topping et al., 2003). A. entire period of record. B. Post-dam era. C. Period during which Lake Powell was filled. D. Period after Lake Powell reservoir had filled for the first time. E. Period of modern environmental management. Arrows indicate times when post-dam aerial photographs were taken.

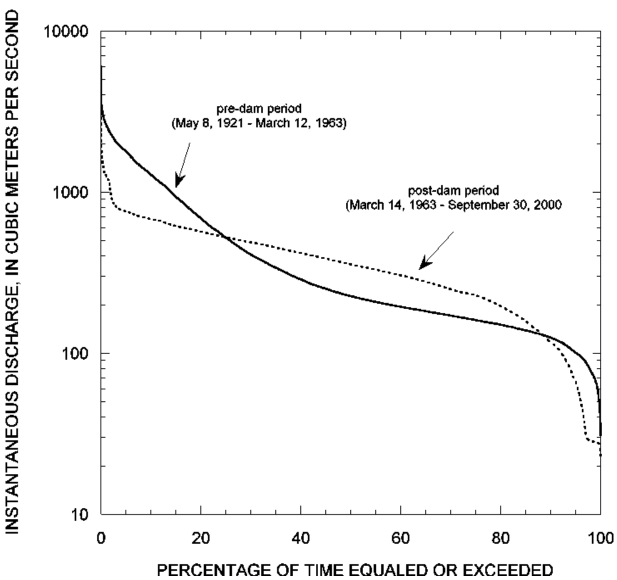


Figure 3. Graph showing flow duration curves of the Colorado River at the Lees Ferry gage for the pre-dam and post-dam periods (Topping et al., 2003).

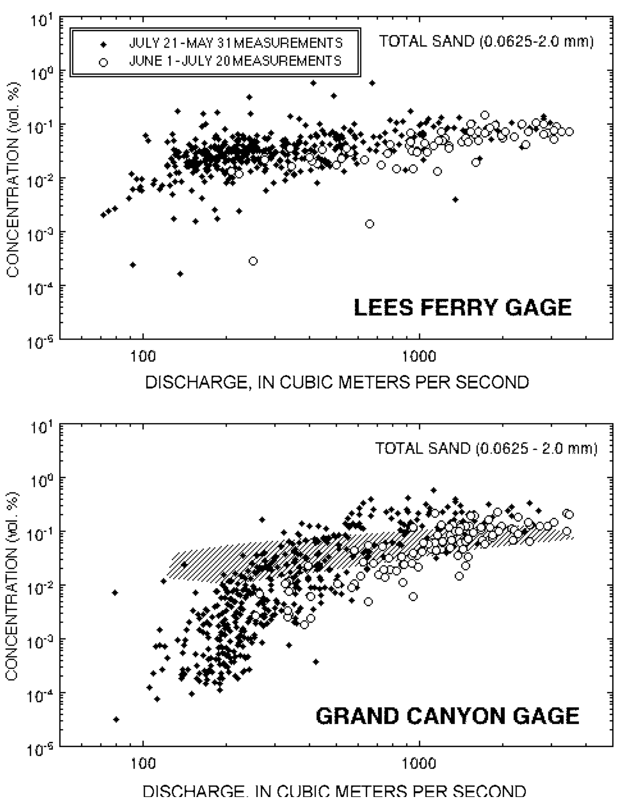


Figure 4. Graphs showing pre-dam sand concentrations as a function of water discharge for the Lees Ferry and Grand Canyon gages. Cross-hatched region overlaying the Grand Canyon gage data indicates the region in concentration-discharge space occupied by the Lees Ferry data. (Topping et al., 2000b, Fig. 4B).

concentration at any given discharge was 2 orders of magnitude at the Grand Canyon gage, whereas this variation was about half an order of magnitude at Lees Ferry.

The relative concentration of fine sediment at the two gages differed between the low-flow and flood-flow seasons. When flows were less than about 250 m^3/s, the concentration of sand in suspension was greater at the Lees Ferry gage than at the Grand Canyon gage (Fig. 4). At flows less than about 150 m^3/s, the concentration of suspended sand at Lees Ferry was about 2 orders of magnitude more than at the Grand Canyon gage. When flows exceeded about 500 m^3/s during the rising limb of the annual spring flood, the concentration of suspended sand at the Grand Canyon gage exceeded that at the Lees Ferry gage. The concentration of sand in suspension at the Grand Canyon gage subsequently decreased to approximately equal the concentration of sand in suspension at the Lees Ferry gage.

These seasonal differences in concentration imply that there was a 9-mth period between July and the following March when sand accumulated, because more sand was delivered into Marble and upper Grand Canyons than was exported downstream (Topping et al., 2000b). This was the period when discharge was mostly less than 250 m^3/s. During the spring snowmelt flood between April and June, the amount of sand exported past the Grand Canyon gage was approximately equal to the amount transported past the Lees Ferry gage plus the amount of sand that had accumulated in the reach since the previous July. Decrease in the concentration of sand in transport past the Grand Canyon gage during the spring flood resulted from depletion of the supply that had accumulated during the preceding low-flow season. Thus, fine-sediment deposits between the gages were eroded and exported downstream during the annual spring snowmelt flood. Presumably, the total amount of sand on the bed and along the banks in Marble and upper Grand Canyons was least immediately upon recession of the snowmelt flood, despite the reworking and deposition of high-elevation flood deposits.

Operations of Glen Canyon Dam greatly reduced the magnitude of floods, increased the magnitude of base flows, and greatly reduced the amount of fine sediment delivered to the river corridor. River flows are dictated by a number of statutes, regulations, and administrative decisions that are collectively known as the Law of the River (MacDonnell et al., 1995). The most important of these "laws" concerns the required annual release of 1.02 x 10^6 ha·m (8.23 x 10^6 ac·ft) of water from Glen Canyon Dam to fulfill obligations to Mexico and the Lower Basin states of Arizona, California, and Nevada. A second tier of considerations concerns maximization of hydroelectric power production by reduction of the magnitude of dam releases to those that can pass through the power-plant turbines; the capacity of the turbines is approximately 900 m^3/s when the reservoir is full. Other considerations that determine the magnitude of base flows include river navigation and fisheries. The median discharge of the Colorado River for the period between March 14, 1963, and September 30, 2000, was 74% higher and the seasonal variation in flows was much less than during the pre-dam period (Topping et al., 2003). The 10% exceedence flow for the post-dam period was about 708 m^3/s, and the 90% exceedence flow was about 125 m^3/s (Fig. 3).

Flow regimes of the post-dam river have changed since 1963, and management of Lake Powell and of water releases from Glen Canyon Dam can be divided into 3 time periods (Fig. 2B). Between 1963 and 1980, the primary objectives were to fill the reservoir and generate hydropower, while still meeting legally defined downstream needs. In 1963 and 1964, the Bureau of Reclamation (Reclamation) sought to quickly increase storage in the reservoir, and dam releases were very low. In May 1965, dam releases occurred as a sequence of discrete pulses wherein flows increased or decreased by 500 to 1000 m^3/s for periods of 1 day to 1 week (Fig. 2C). Engineer's notes in the Reclamation archives refer to the high releases of 1965 as a "channel cleaning" flow. Releases subsequently met annual requirements to downstream users, hydroelectric power production was maximized, and the reservoir gradually filled.

After the reservoir filled for the first time in 1980, dam operations were guided by considerations of dam safety in addition to the traditional constraints of hydroelectric power production and downstream water needs (Fig. 2D). This period included the 4 years between 1983 and 1986 when inflow was unusually large, and dam releases exceeded the capacity of the power plant. We refer to the peak flows of each of these years as post-dam floods. The highest of these occurred on June 29, 1983, and was 2750 m^3/s at the Lees Ferry gage. Between 1984 and 1986, annual peak flows were between 1340 and 1515 m^3/s. Between summer 1986 and summer 1990, dam releases were similar to those of the reservoir-filling period.

The era of environmental management began in summer 1990 during an 18-mth period when dam releases varied for 2-wk periods to facilitate river-scale experiments (Beus and Avery, 1992). The daily range in dam releases was thereafter constrained under administrative rules associated with the Grand Canyon Protection Act (Fig. 2E). A 7-day experimental release of 1274 m^3/s began on March 26, 1996, and is hereafter referred to as the 1996 Controlled Flood. Implementation of the Record-of-Decision for the Environmental Impact Statement for Glen Canyon Dam Operations (U.S. Department of the Interior, 1995) formalized restrictions on the daily range of dam releases. The magnitude of base flows increased throughout this period, and flows less than the pre-dam median of 227 m^3/s occurred rarely. There were 3 short-duration experimental releases of 878 m^3/s flows in November 1997, May 2000, and September 2000.

Sediment supply to the Colorado River in the post-dam era was reduced more than was the capacity of the river to transport that load, and the river has been shifted into a condition of sediment deficit. Operation of the dam has greatly reduced the floods that exported large quantities of fine sediment from Grand Canyon and has eliminated the naturally occurring lower flows that allowed seasonal sediment storage.

Sediment delivery to Marble Canyon decreased by about 99.5-99.6% after completion of Glen Canyon Dam. Transport past the Grand Canyon gage decreased between 81 and 85%, because some fine sediment continues to enter the Colorado River from the Paria and Little Colorado Rivers and from smaller tributaries (Topping et al., 2000a). The role of sediment availability in determining the concentration of suspended sediment at any discharge is now greater than during the pre-dam period.

3.0 THE VALLEY OF THE COLORADO RIVER

The study area consists of four segments: Glen Canyon, upper Marble Canyon, lower Marble Canyon, and upper Grand Canyon. Glen Canyon is the segment between River Mile –15 and River Mile –1, where the river flows through a canyon of Jurassic Navajo Sandstone and upper Triassic Kayenta formation, and between River Mile –1 and +1 where the river flows in a relatively open valley of lower Triassic sedimentary rocks. Upper Marble Canyon begins at River Mile 1, and river-level bedrock is Mississippian to Permian sediments. The downstream end of this segment occurs where the valley widens and approximately occurs at River Mile 40. Lower Marble Canyon extends to the mouth of the Little Colorado River at River Mile 61; river-level bedrock is primarily Cambrian sedimentary rocks. Upper Grand Canyon occurs between River Mile 61 and 87, and river-level rocks include Cambrian sandstones and Proterozoic sedimentary, volcanic, and metamorphic rocks. We use the informal names Tapeats Gorge, Big Bend, and Upper Granite Gorge to refer to the parts of this segment between River Miles 61 and 65, 65 and 77, and 77 and 87, respectively. Finer resolution segmentation of the study area has been proposed (Schmidt and Graf, 1990; Melis, 1997), but is inappropriate for the types of data analyzed here.

Channel width varies in relation to bedrock lithology. The average width of the channel at base flow of 227 m^3/s in Marble and upper Grand Canyon is 86 m. Average channel width of a flood of 2750 m^3/s is 130.9 m, 54% greater than channel width at base flow. The channel is widest where river-level bedrock is shale or inter-bedded shale, sandstone, and limestone. Average channel width at base flow is typically greater than 110 m and is greater than 160 m at flood flow between River Mile 47 and 57 and between River Mile 66 and 73 (Fig. 5). The narrowest parts of the Colorado River are in upper Marble Canyon and Upper Granite Gorge (Table 1). Reach average channel width at base flow is less than 70 m and is less than 100 m at flood flow between River Miles 11 and 31 and between River Miles 78 and 87.

There are 3 types of unconsolidated deposits that are widespread in the valley of the Colorado River: alluvium, colluvium, and eolian deposits (Hereford, 1996; Hereford et al., 1993, 1998, 2000a, 2000b). The depth of these unconsolidated deposits that fill the bedrock trench of the Grand Canyon varies from 0 to 45 m, based on side-scan sonar records, geophysical studies, and borings at proposed dam sites (Table 2). Alluvium includes gravel bars and fine-sediment deposits that occur as terraces and flood plains and gravel bars (Fig. 6). These deposits occur mostly within the active channel and form narrow deposits beyond the channel. Colluvium includes landslide deposits, talus, and debris-flow deposits. Eolian deposits mantle parts of debris fans, high terraces, and talus, especially in lower Marble Canyon and parts of upper Grand Canyon.

Table 1. Segment characteristics of the Colorado River in Marble and upper Grand Canyons

River Mile	Reach-average channel width at base flow (227 m^3/s), in meters[1]	Reach-average channel width at flood stage (2746 m^3/s), in meters[1]	Ratio of base flow channel to flood channel width
Upper Marble Canyon (RM 1-40)	78.1	111.5	0.71
Lower Marble Canyon (RM 40-61)	99.9	164.7	0.61
	Upper Grand Canyon		
Tapeats Gorge and Big Bend (RM 61-77)	101.1	171.0	0.61
Upper Granite Gorge (RM 77-87)	59.3	82.1	0.72

[1] Reach-average width determined from maps of water's edge at indicated discharge. Water surface area at indicated discharge was divided by reach length to determine average width.

Table 2. Depth to bedrock in the valley of the Colorado River

Location	Depth to bedrock, in meters	data source
-15	31.4 [1]	U. S. Bureau of Reclamation Dam Site Boring
39.5	18 [1]	U.S. Bureau of Reclamation, Topping et al., unpubl.
47R	3.7-(11.9,44.8) [2,3]	Qamar and Rubin, unpubl.[4]
51.5L	>13.4 [2]	Qamar and Rubin, unpubl. [4]
52L	>17.1 [2]	Qamar and Rubin, unpubl. [4]
54R	>25.9 [2]	Qamar and Rubin, unpubl. [4]
66L	2.7-9.4 [2]	Qamar and Rubin, unpubl. [4]

[1] borehole
[2] seismic reflection survey
[3] respective depths of (middle, deepest) reflectors
[4] Rubin et al. (1994a)

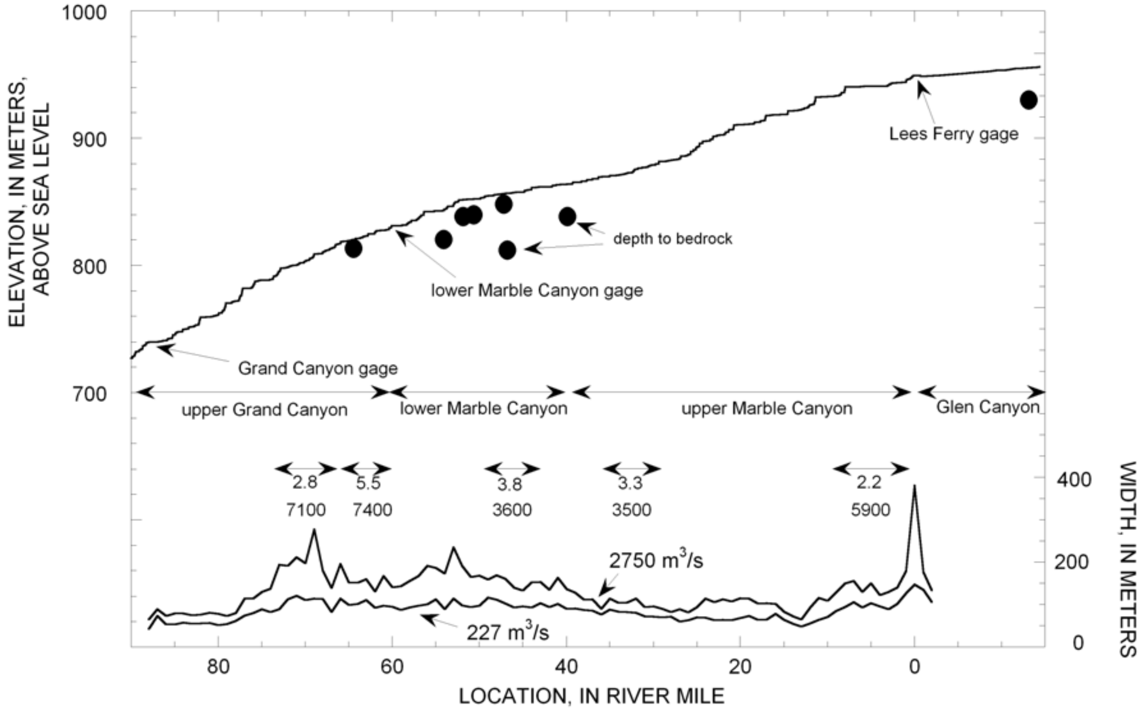


Figure 5. Graph showing longitudinal profile of the Colorado River and reach average channel width at 85 and 2750 m^3/s. The profile data are those collected by the GCMRC and analyzed by Magirl et al. (unpubl. manuscript). Depth to bedrock data are those reported in Table 2. Double bar arrows are the extent of the 5 study reaches shown in Figure 1. The upper number is the number of EDZs (eddy deposition zones) per river km and the lower number is the median area of the EDZs, in square meters.

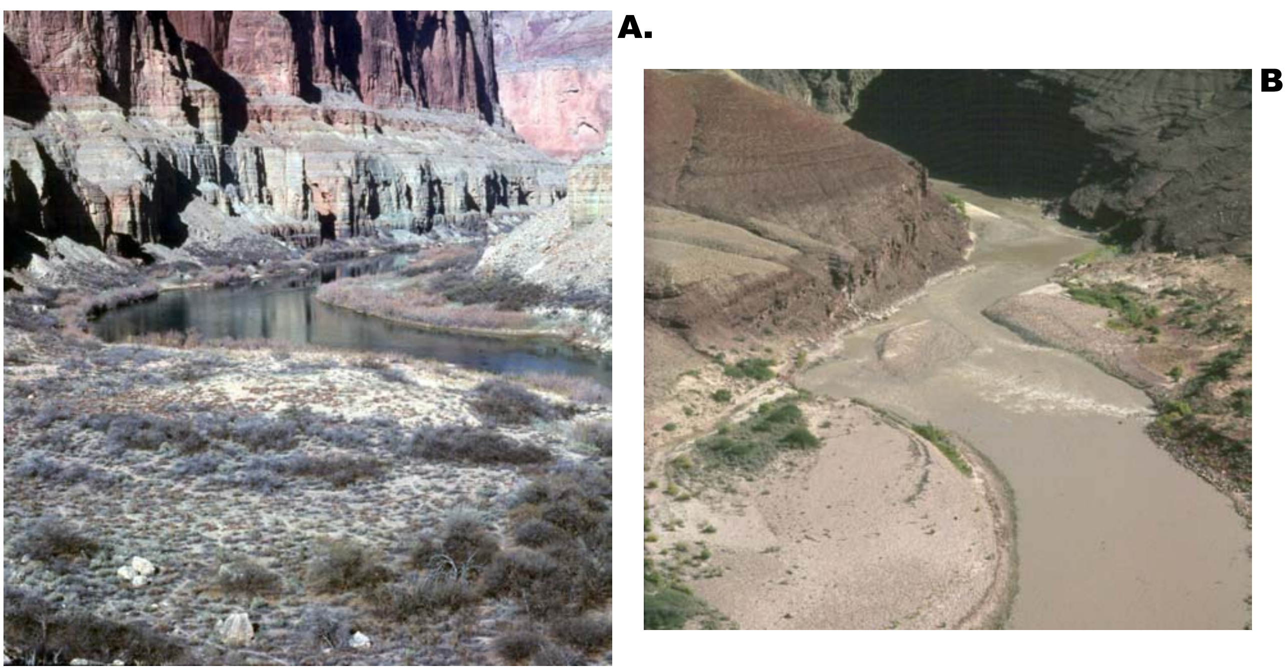


Figure 6. Photographs of the Colorado River. A. Upstream view in lower Marble Canyon across the debris fan at the mouth of Little Nankoweap Creek, near River Mile 52. Valley width is relatively wide here. B. Downstream view immediately downstream from Unkar Rapid in upper Grand Canyon near River Mile 73. Here, the valley abruptly narrows in the upper part of the photograh where the resistant lower part of the Precambrian Dox formation is encountered. The riffle in the center of this photograph occurs where the river flows over the gravel bar at the downstream end of the Unkar fan-eddy complex.

There are few large fine-sediment deposits in the Colorado River valley, because there is little space between the channel and the confining bedrock or colluvium. The amount of space available for fine-sediment deposition is reflected in the difference in channel width between base flow and flood flow. A large difference in these values indicates large available areas for alluvium to be deposited. The base-flow channel width is typically less than 60% of the flood-flow width near Soap Creek Rapid (River Miles 11 to 13), near North Canyon Rapid (River Miles 20 to 22), in lower Marble Canyon (River Miles 50 to 57), and in the Big Bend (River Miles 66 to 74). The base flow channel width is more than 75% of the flood-flow width in upper Marble Canyon between River Miles 13 and 16 and between River Miles 25 and 38.

3.1 Longitudinal Profile and Bed-Material Distribution

The longitudinal profile of the Colorado River in Marble and Grand Canyon is a series of long, flat reaches interrupted by short, steep rapids and riffles that are somewhat less steep (Fig. 5). Leopold (1969) reported that 50% of the total elevation decrease of the river, as surveyed in 1923, took place in only 9% of the downstream distance, and Magirl et al. ("Changes in the water-surface profile of the Colorado River in Grand Canyon, Arizona, between 1923 and 2000," unpubl. manuscript) found that 66% of the total drop, as measured in 2000, occurred in the same distance. The spacing between rapids is determined by the spacing of tributary canyons (Dolan et al., 1978), because debris from each tributary partially blocks the Colorado River. Similar relationships have been identified on other rivers with abundant debris fans (Graf, 1979; Schmidt and Rubin, 1995).

The bed of the Colorado River includes shallow areas at rapids and riffles and deep pools, or scour holes. Deep pools typically occur downstream from rapids but also occur offshore from flow obstructions (Fig. 7, 8). Measurements of bed topography in the past decade demonstrate that significant scour and fill occurs in these pools during post-dam floods.

The size of bed material is wide ranging. Bedrock occurs as islands in some places and has been identified on the bed in side-scan sonar images (Anima, et al., 1998). Coarse debris includes boulders that are 10s of meters in diameter that are delivered to the channel by rockfall or debris flow. Debris flows deliver a wide range of sizes; Webb et al. (2000) estimated that boulders larger than 256 mm comprise 14% ± 19%, by weight, of each flow, based on analysis of 41 samples. The percentage of the bed that is bedrock or boulders varies widely; Wilson's (1986) side scan sonar data collected in 1984 showed that 30% of the bed of the Big Bend was boulders and bedrock. The percentage of the bed that was bedrock or boulders was 36%, 62%, and between 42 and 81% in lower Marble Canyon, Upper Granite Gorge, and upper Marble Canyon, respectively (U. S. Department of the Interior, 1988, Table A-2).

Debris flows, as well as stream flow floods, boulder abrasion, and Pleistocene terraces, are the sources of cobbles, between 64 and 256 mm, and pebbles, between 2 and 64 mm, to the bed. Cobbles and pebbles comprise 24% ± 19% and 41% ± 21%, respectively, of debris flows. Cobble bars are common between River Miles 1 and 4, in parts of lower Marble Canyon, and in the Big Bend. Imaging of the bed using video cameras has revealed that much of the bed elsewhere is comprised of cobbles.

Estimates of the proportion of the bed covered by sand vary widely. Howard and Dolan (1981) assumed that 75% of the bed of the study area was sand, but Smith and Wiele (J. D. Smith and S. M. Wiele, "Flow and sediment transport in the Colorado River between Lake Powell and Lake Mead," unpubl. manuscript) predicted that less than 30% of the bed needed to have been covered with sand in order to support a uniform downstream flux of sand during two experimental flows in 1990 and 1991. Rubin et al. (1994a) estimated that the mean thickness of sand in

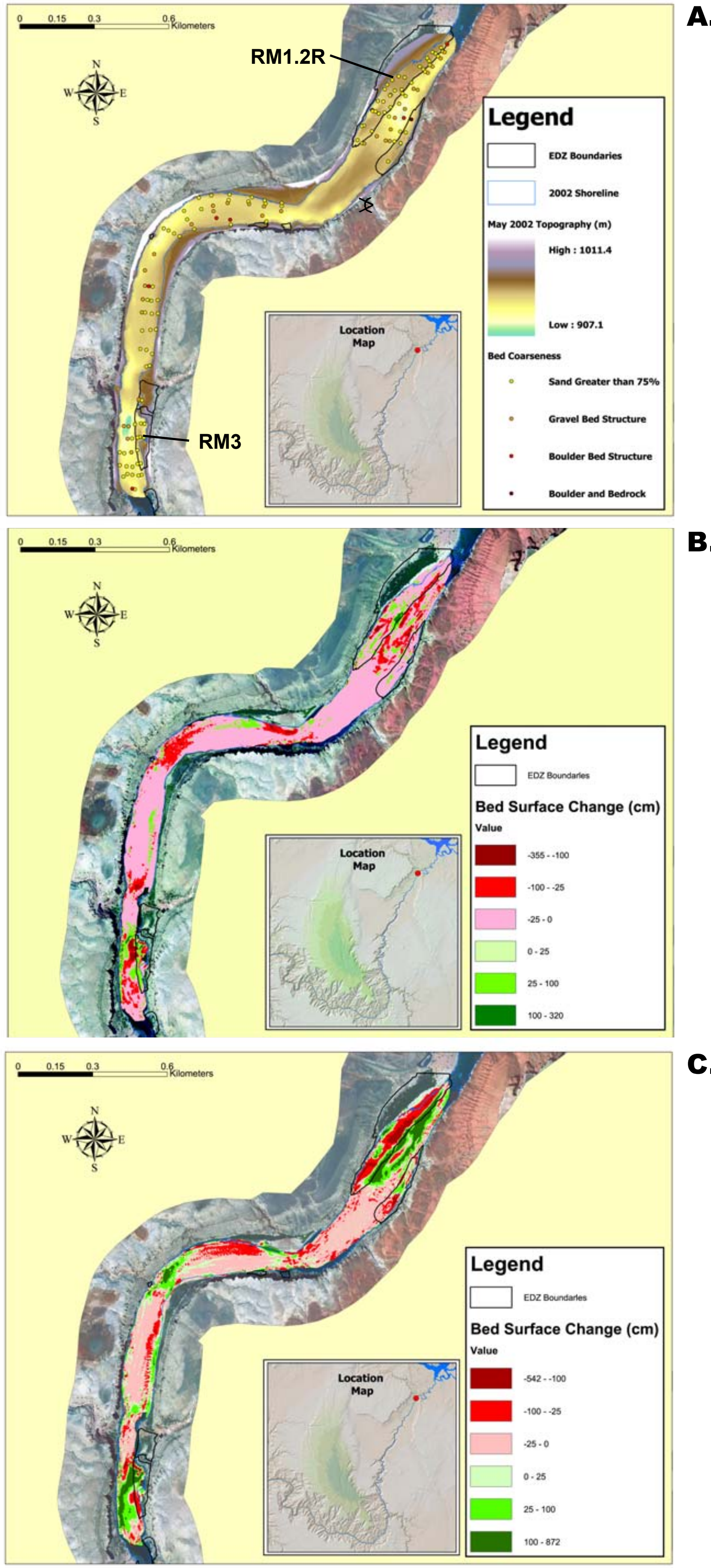
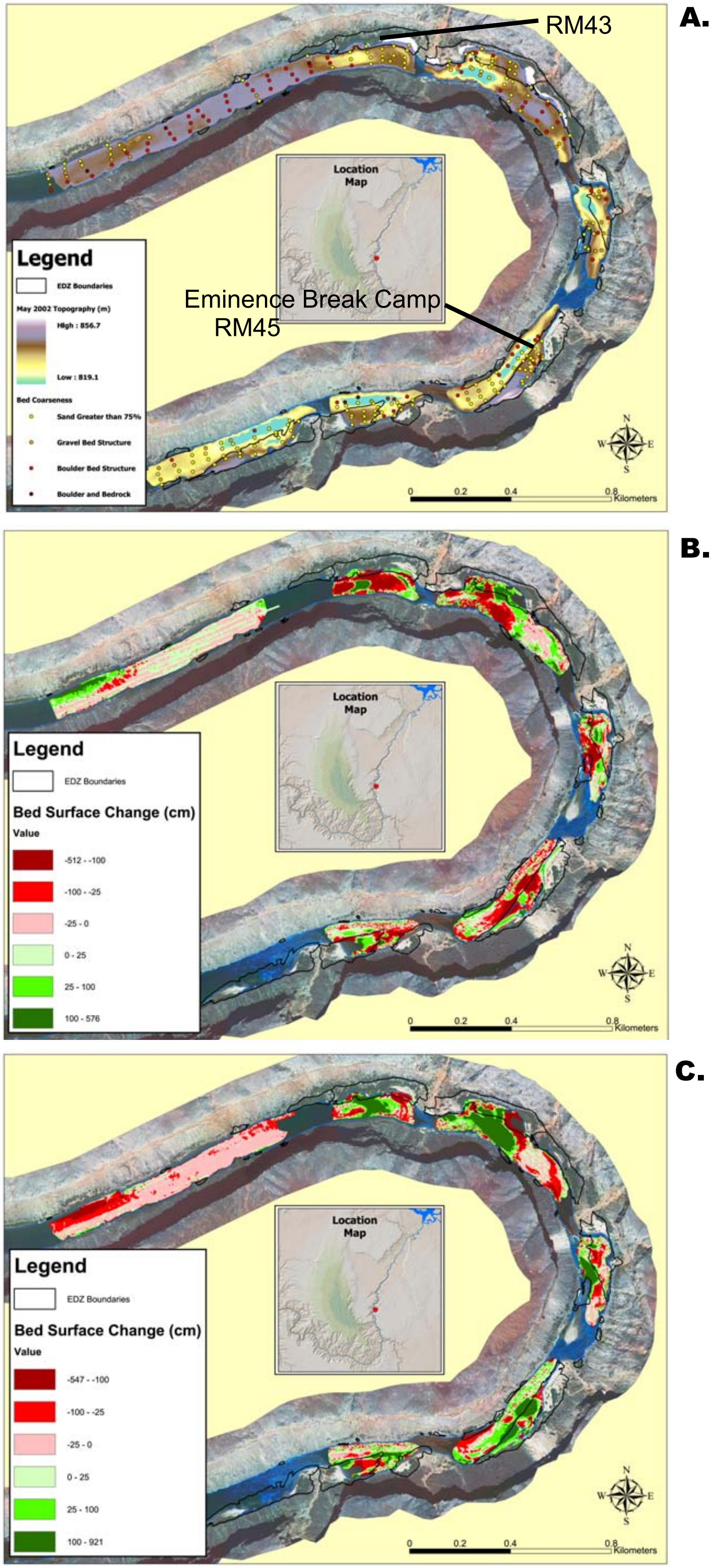


Figure 7. Maps showing topography of the bed of the Colorado River between Paria Riffle and the riffle opposite Cathedral Wash, between River Mile 1 and 2.3. Flow is from top to bottom. A. Bed topography measured in May 2002. B. Change in bed elevation between August 2000 and September 2000. C. Change in bed elevation between September 2000 and May 2002. Note that areas of significant bed elevation change are confined to a relatively small part of the channel. Data from GCMRC and Rubin et al. (unpublished data). RM1.2R is mentioned in the text. Photograph location site of Figure 41 is shown in A( ). RM3 is an EDZ monitored by NAU.

Figure 8. Maps showing the bed of the Colorado River near President Harding Rapid, between River Mile 42 and 45. Flow is from top to bottom. A. Topography in May 2002. B. Change in bed topography between August and September 2000. C. Change in bed topography between September 2000 and May 2002. Note that areas of significant bed elevation change are confined to a relatively small part of the channel. Data from GCMRC and Rubin et al. (unpublished data). RM43 and RM45 are EDZs that are monitored by NAU.



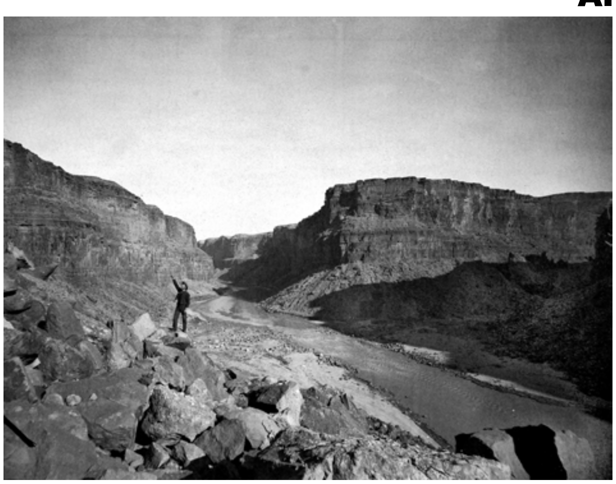
Marble Canyon was "at least a few tens of centimeters and not more than a few meters." Subsequent monitoring using side-scan imaging and underwater cameras showed that the proportion of the bed covered by sand is less than 30% and typically occurs upstream from rapids and adjacent to some eddies (Anima et al., 1998). Schmidt (1999) used a sediment budget to argue that the bed was not a significant source of sand during the 1996 Controlled Flood, and Hazel et al. (J. E. Hazel, Jr., D. J. Topping, J. C. Schmidt, M. Kaplinski, and T. S. Melis, "Downstream effects of a dam on sediment storage in a bedrock canyon: the relative roles of eddy and channel storage in the sediment budget for the Colorado River in Marble Canyon, AZ," unpubl. manuscript) argued that most sand stored in the study area occurs in eddies and not on the channel bed. Data presented in subsequent sections of this report support that conclusion.

3.2 The Fan-Eddy Complex

The distribution of alluvial deposits along the channel edge is determined by the hydraulic patterns created by each fan, and this pattern is similar at each fan (Fig. 9). Schmidt and Rubin (1995) defined the fan-eddy complex as the sequence of hydraulic features that occurs wherever a tributary debris fan partially blocks the flow. The most upstream part of each fan-eddy complex is the ponded backwater upstream from the fan (Fig. 10). The narrow channel and elevated bed of each rapid act as a hydraulic control on flow upstream from the fan, and ponding may extend upstream between a few channel widths to a few kilometers (Kieffer, 1985). The upstream extent of ponding varies with discharge; differences in channel geometry cause some rapids to be drowned at high flow, whereas the degree of hydraulic control at other sites may become increasingly severe (Kieffer, 1988).

Flow separation occurs immediately downstream from most rapids, where the bank angle diverges abruptly from the orientation of the main flow (Schmidt, 1990). A zone of recirculating flow exists along the bank downstream from the point of flow separation. This zone is typically organized into a single recirculating cell with upstream flow along the bank; smaller, secondary cells of recirculation may exist at some sites at some discharges. The length of the recirculating flow zone changes with discharge, and the zone typically gets longer and thinner at high discharge.

A.



B.

Figure 9. Photographs of Badger Creek Rapids at River Mile 8. View is upstream. The rapid is at the center of the photo and the glassy water surface upstream from the rapid is the ponded backwater. Eddies occur on both banks downstream from the rapids and separation bars mantle the downstream parts of both debris fans. The EDZ on river left, including the separation bar, is monitored by NAU as RM8. A. Photograph by Franklin Nims taken on December 28, 1889. B. Photograph by Dave Edwards taken on January 30, 1991. Both photographs are from Webb (1996, fig. 10.2) and are reprinted with permission.

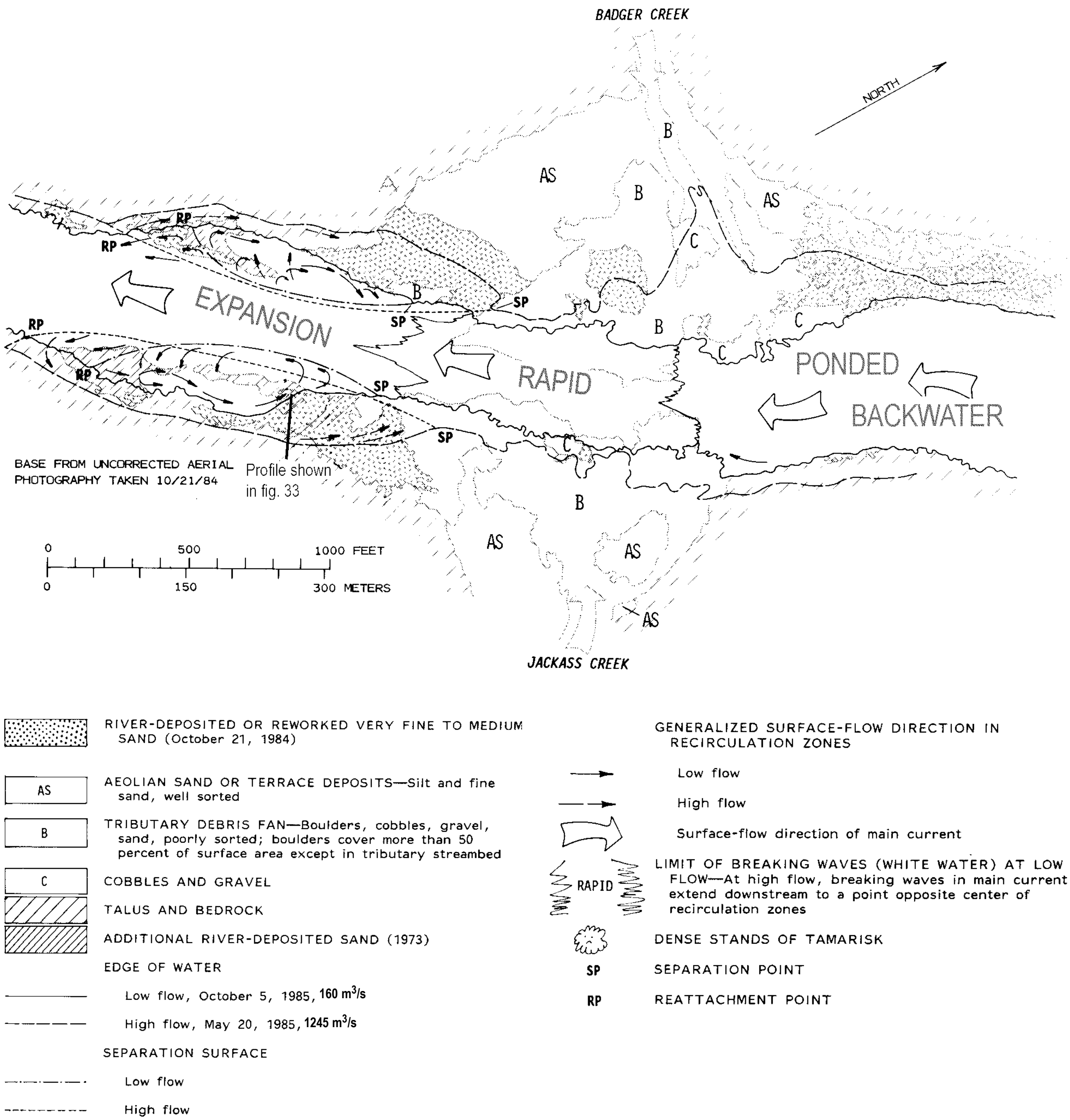


Figure 10. Map showing the distribution of unconsolidated geologic deposits at Badger Creek Rapids. Stippled patterns depict the distribution of fine-grained deposits. Figure is from Schmidt and Graf (1990).

The recirculation zone is an effective trap of the suspended load, and eddy bars composed of sand, silt, and clay typically fill these zones in Marble and upper Grand Canyons. These eddy bars have been subdivided (Schmidt, 1990; Schmidt and Graf, 1990). Separation bars mantle the downstream side of debris fans and occur near the point of flow separation. Reattachment bars underlie the primary eddy cell and are highest near the point of flow reattachment at the downstream end of the recirculation zone. Sedimentary structures in these bars demonstrate that bed form migration directions reflect the recirculating direction of the flow (Rubin et al., 1990, 1994b).

Table 3. Characteristics of the 5 reaches in Marble and upper Grand Canyons where fine-grain alluvium was mapped and analyzed in a GIS. The sixth reach was Glen Canyon.

		Lees Ferry Reach (RM 0-8)	Redwall Gorge Reach (RM 29-35)	Point Hansborough Reach (RM 42-50)	Tapeats Gorge Reach (RM 60-65)	Big Bend Reach (RM 65-72)
Reach length, in kilometers		14	10	10.8	8.0	12.1
Total number of EDZs	all	37	56	81	57	56
	> 1000 m^2	31	33	41	44	34
EDZ frequency, in number per kilometer	all	2.6	5.6	7.5	7.1	4.6
	> 1000 m^2	2.2	3.3	3.8	5.5	2.8
Total area of EDZs, in square meters	all	287,400	167,100	453,460	406,930	414,630
	> 1000 m^2	284,430	157,450	437,120	402,230	407,410
Total EDZ area, in square meters, per kilometer	all	20,500	16,700	42,000	50,900	34,300
	> 1000 m^2	20,300	15,700	40,500	50,300	33,700
Mean size, in square meters	all	7800	3000	5600	7100	7400
	> 1000 m^2	9200	4800	10,700	9100	12,000
Median size, in square meters	all	3900	1400	1000	3000	1500
	> 1000 m^2	5900	3500	3600	7400	7100
Notabley large EDZs (location in River Mile and size in square meters)		1.2R: 67,000		43.6L: 34,300 44.5L: 34,400 47.1R: 43,300 47.6R: 45,000	63.5L: 33,300 64.4L: 34,300	66.1L: 34,500 68.2L: 52,800 71.3L: 38,600 71.7L: 33,500

The highest elevation parts of eddy bars sometimes merge downstream with linear banks of fine-sediment that resemble flood plains. These "channel-margin deposits" typically have levees of low relief and form by movement of suspended sediment away from the main flow, similar to that which occurs on the floodplains of alluvial rivers.

A mid-channel, or bank-attached, cobble bar often exists downstream from the zone of flow recirculation. The debris on this bar has been eroded from the upstream debris fan (Grams and Schmidt, 1999; Pizzuto et al., 1999; Webb et al., 1999; Larsen et al., 2004). At moderate and low discharge, flow typically passes around the margins of these bars and creates a riffle (Fig. 6B).

3.2.1 Longitudinal Distribution of Eddy Deposition Zones

The frequency and size of recirculation zones vary longitudinally due to differences in channel width, valley width, frequency of tributary debris fans, and shape and size of fans. We mapped the distribution of fine sediment in 80 km of the study area (Fig. 1) on 11 aerial photograph series. Mapping was conducted in Glen Canyon (Grams et al., 2004), in the Lees Ferry Reach[2] between Lees

2 The reaches where mapping was conducted and analyzed within a GIS are referred to by specific name, i.e. Lees Ferry Reach and Big Bend Reach, to distinguish them from geographic places, i.e. Lees Ferry and the Big Bend.

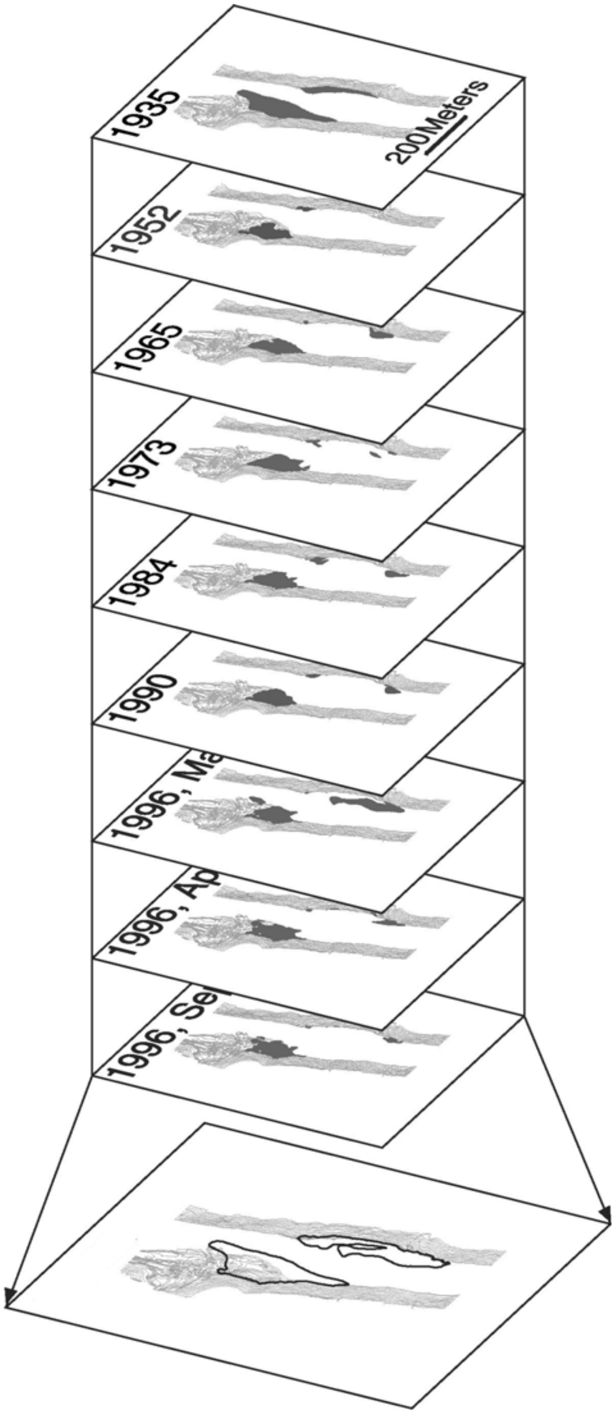


Figure 11. Diagram showing the method of calculation of EDZs. EDZ is shown at bottom of figure.

Ferry and Badger Creek Rapids (Sondossi, 2001), in the Redwall Gorge Reach between Twentynine Mile Rapids and Nautiloid Canyon (Sondossi et al., 2002), in the Point Hansborough Reach near Point Hansborough (Schmidt and Leschin, 1995; Schmidt et al., 1999b), in the Tapeats Gorge Reach between Sixtymile Rapids and Lava Chuar Rapids (Schmidt and Leschin, 1995; Schmidt et al., 1999b), and the Big Bend Reach between Lava Chuar Rapids and Unkar Rapids (Schmidt and Leschin, 1995; Schmidt et al., 1999b) (Table 3). These maps were overlain in a GIS, and the polygon enclosing the area where eddy bars occurred in any of the years of available photography was determined (Fig. 11). This polygon, referred to as the eddy deposition zone (EDZ), is a surrogate for the area of recirculating flow. Although this polygon is smaller than the total area of recirculating flow, it has the advantage of being defined without the necessity of field observations at many discharges, and EDZ areas can be compared among different parts of the study area.

There are 287 EDZs in the mapped reaches in Marble and upper Grand Canyons, of which 183 are larger than 1000 m^2 and for which we measured the area of sand in each aerial photograph series. The average number of EDZs larger than 1000 m^2/km in Marble Canyon is approximately 3, which leads to an estimate that there are approximately 300 EDZs larger than 1000 m^2 in Marble Canyon. The total area of EDZs varies between 16,700 and 50,900 m^2/km. The total area of EDZs in Marble Canyon is about 26,000 m^2/km, which leads to an estimate that there is approximately 2.6 x 10^6 m^2 of EDZ in Marble Canyon. EDZs comprise approximately 20% of the water surface area at the approximate discharge of the pre-dam average flood, because the average width of the channel at 2700 m^3/s in Marble Canyon is about 130 m.

There is more uncertainty in the estimate of these values in upper Grand Canyon, because the distribution of EDZs is unknown in Upper Granite Gorge. The total area of EDZs is approximately 1.3 x 10^6 m^2, based on the actual data for EDZs in the Tapeats Gorge Reach and Big Bend Reach, application of the Big Bend Reach average to the remainder of the Big Bend, and application of the Redwall Gorge Reach average to the Upper Granite Gorge.

Table 4. Estimates of the potential fine-sediment storage volume in 9 EDZs.

EDZ name (NAU designation)	EDZ area, in square meters	Area surveyed by NAU, in square meters	Area of comparison, in square meters	Void volume between the stage of 100 m^3/s and the minimum elevations surveyed by NAU, in cubic meters	Percent overlap between EDZ and area surveyed by NAU	Thickness of void volume, in meters
Cathedral (RM 3)	11,658	8392	7124	25,122	72	3.53
Fence Fault (RM 30)	11,479	9448	4954	8949	82	1.81
South Canyon (RM 32)	10,837	9536	4316	11,877	88	2.75
Anasazi Bridge (RM43)	25,348	11,318	4545	12,412	45	2.73
Eminence Break (RM 45)	80,259	30,377	12,884	34,776	38	2.70
Saddle Canyon (RM 47)	44,977	29,935	21,831	92,797	67	4.25
Crash Canyon (RM 62)	20,103	17,816	14,878	92,787	89	6.24
Carbon (RM 65)	20,253	18,123	10,971	24,451	89	2.23
Tanner (RM 68)	11,476	9422	4269	11,822	82	2.77

Eddies have an enormous capacity to store fine sediment. They have the potential to store as much fine sediment as Topping et al. (2000b) estimated accumulated seasonally prior to completion of Glen Canyon Dam. We determined the composite lowest elevation surface surveyed by NAU in the 1990s in 9 EDZs by integrating all surveys and determining the lowest measured value at each grid node. We subtracted this topographic surface from a flat surface whose elevation is the stage at 100 m^3/s. This flat surface conforms to the lowest stage used in the calculation of EDZs. The difference between these two surfaces is a conservative estimate of the fine sediment storage potential in the eddy. The volume between these two surfaces, divided by the area of comparison, is between 1.8 and 6.2 m (Table 4). The mean thickness is 3.2 m. Application of this thickness to the total estimated area of EDZs yields estimates of 8.32×10^6 and 4.2×10^6 m^3 for the potential storage volume of eddies in Marble and upper Grand Canyons, respectively. The potential storage volume is 13.1×10^6 and 6.5×10^6 metric tons for Marble and upper Grand Canyons, respectively. These values approximate the upper range of seasonal fine-sediment accumulation estimated by Topping et al. (2000b).

There is substantial longitudinal variation in the number and size of EDZs. The frequency of EDZs larger than 1000 m^2 varies twofold among the reaches (Table 3). There are 2.2 EDZs larger than 1000 m^2/km in the Lees Ferry Reach, and there are 5.6 EDZs per kilometer in the Tapeats Gorge Reach. The largest EDZ in these reaches is 67,000 m^2 and occurs immediately downstream from Paria Riffle, at RM 1.2R (Fig. 7). The second largest EDZ is located between Comanche and Tanner Creeks in the Big Bend Reach at RM68.2L; this EDZ is 52,800 m^2 in area. Other large EDZs are Saddle Canyon (RM47.6R; 45,000 m^2) and Triple Alcoves (RM47.1R; 43,300 m^2). Although there are some very large EDZs in the study area, these are so few that they do not account for a large proportion of the total area

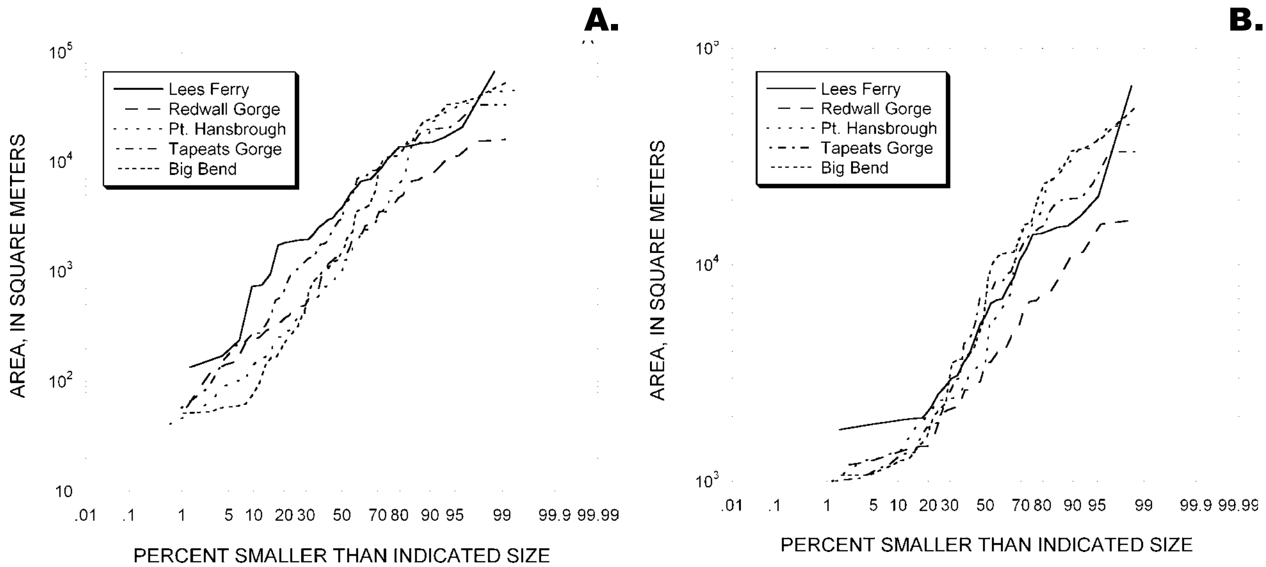


Figure 12. Graphs showing cumulative distribution of EDZs in 5 study reaches. A. distribution of all EDZs. B. distribution for those EDZs larger than 1000 m².

of eddy deposition. The distribution of EDZ sizes is log-normal (Fig. 12), and the mean EDZ area is between 1.3 and 5 times larger than the median (Table 3). EDZs of moderate size have the most significant potential storage area for fine sediment, because the size class with the greatest cumulative area is that between 10,000 and 20,000 m².

The frequency of EDZs is an indication of the proportion of fine-sediment deposits that form in eddies. The frequency of EDZs is low in the Lees Ferry and Big Bend Reaches, and a large proportion of fine sediment occurs as channel-margin deposits. However, the total area of eddy bars also depends on the width of the zone available for fine sediment deposition. The largest total area of EDZs per unit river length occurs in the Tapeats Gorge Reach where EDZs are the most frequent and the baseflow channel width is about 70% of the channel width at flood flow. The smallest total area of EDZs per unit river length is in the Redwall Gorge Reach where EDZs are relatively frequent but the base flow channel is about 77% of the channel width of flood flows.

3.3 Sedimentology of Fine-Sediment Alluvial Deposits

Fine sediment of the Colorado River occurs as terraces and flood plains, and these deposits can be subdivided by facies and by the minimum discharge that inundates their surfaces. The former subdivisions are primarily between eddy bars and channel-margin deposits. The latter subdivisions are grouped as (1) pre-dam flood deposits, (2) post-dam flood deposits, and (3) post-dam fluctuating-flow deposits. The distribution of these deposits in a specific year was mapped near Lees Ferry (Hereford et al., 2000b), Nankoweap Rapids (Hereford et al., 1998), Palisades Creek (Hereford, 1996), and Granite Park (Hereford et al., 2000a).

Pre-dam and post-dam fine-sediment deposits have many similarities. The landforms of both deposits are primarily those of eddy bars or channel-margin deposits (Schmidt and Rubin, 1995). Sedimentary structures are primarily those formed by climbing ripples (McKee, 1938; Rubin et al., 1990). Active eddy bars also include cross-bedding and wave structures;

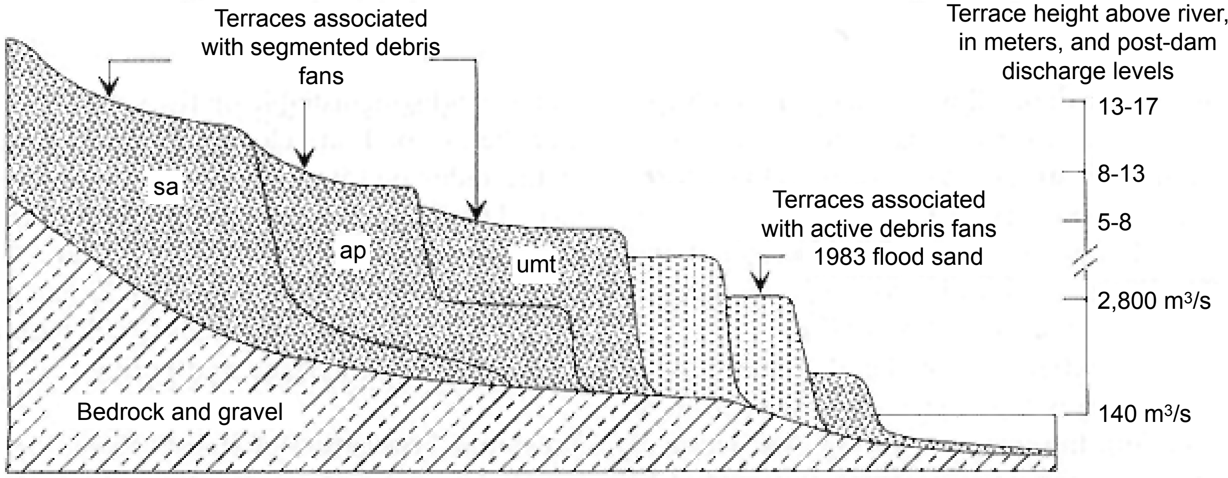


Figure 13. Diagram depicting generalized cross section showing geomorphic and geologic relations of late Holocene terrace-forming alluvium, eastern Grand Canyon. Sa is striped alluvium; ap is alluvium of Pueblo II age; umt is upper mesquite terrace. The unlabeled coarse stippled patterns depict the lower mesquite terrace and the pre-dam terrace at higher and lower positions, respectively. The densely stippled lowest surface are the deposits of the post-dam Colorado River. From Hereford et al. (1996, fig. 8).

levees on the surface of channel-margin deposits are typically composed of a single set of foresets that record the onshore migration of the ridge (Schmidt and Rubin, 1995). Pre-dam flood deposits are primarily composed of poorly sorted silty very-fine sand, and post-dam deposits are primarily composed of very fine and fine sand with less silt. Deposits typically form distinct topographic surfaces, and most surfaces are underlain by discrete deposits separated by erosional unconformities.

Hereford et al. (1993, 1996) identified and determined ages of 5 late Holocene terraces that pre-date completion of Glen Canyon Dam: the striped alluvium, alluvium of Pueblo II age, alluvium of the upper mesquite terrace, alluvium of the lower mesquite terrace, and pre-dam alluvium (Fig. 13). Deposition of the striped alluvium occurred from about 770 B.C. until around A. D. 300. The Pueblo II alluvium accumulated between about A. D. 700 and 1200. The three lower terraces formed during subsequent large floods and are much thinner, generally occupy less area, and are interpreted to represent the progressive decline in the magnitude of large floods (Hereford et al., 1993). The upper mesquite terrace formed between about A. D. 1400 and 1880, and its vegetation is that of the upper riparian zone community and includes mature western honey mesquite (*Prosopis glandulosa*) trees and shrubs in lower Marble Canyon and upper Grand Canyon. The lower mesquite terrace has similar vegetation. This surface had recently been overtopped in a January 1890 photograph, reported by Hereford et al. (1993); thus, the surface must have been inundated by the July 1884 flood of record whose estimated peak discharge was 5935 $m^3/s \pm 850\ m^3/s$ (Topping et al., 2003).

The pre-dam terrace level is a strath terrace established in older alluvium or is underlain by its own alluvium. The dominant vegetation on this terrace includes large, mature, and partially buried saltcedar (*Tamarix ramosissima*). Hereford et al. (1993) stated that this terrace formed during large floods between about 1930 and 1960, based on types of driftwood and other debris. This terrace occurs near Lees Ferry (Hereford et al., 2000b), in the Point Hansborough Reach (Schmidt and Leschin, 1995), near Nankoweap Rapids (Hereford et al., 1998), and in the Big Bend Reach (Hereford et al., 1993; Schmidt and Leschin, 1995).

Post-dam flood deposits were created in 1965, 1980, annually between 1983 and 1986,

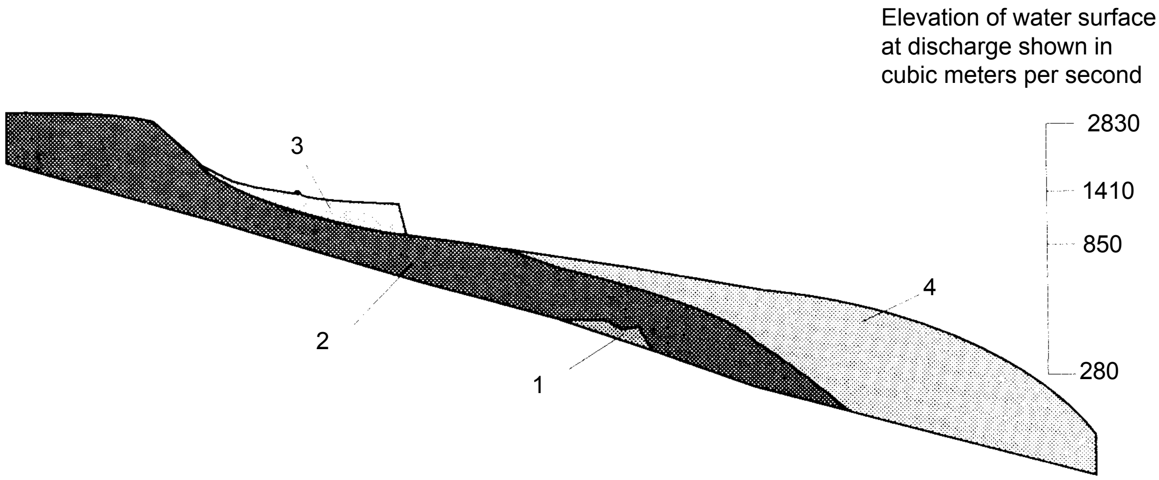


Figure 14. Diagram depicting generalized internal stratigraphy of Grand Canyon reattachment bars as they existed in the late 1980s. 1 is the pre-dam deposit whose upper surface was eroded in 1983. 2 is the flood sand of 1983 and includes fluvial dunes and climbing ripples. 3 is the high flow sand deposited between 1984 and 1986. This deposit was of limited extent and was generally thin and are primarily climbing ripples. 4 are deposits formed by fluctuating flows that occurred after spring 1986. From Rubin et al. (1994b, fig. 3).

and by the Controlled Flood of 1996. The size and characteristics of post-dam flood deposits have changed with time. The 1965 flood deposits may have been reworked in 1980 and were reworked in 1983. Smaller floods of 1984 to 1986 and 1996 reworked the lower parts of the 1983 deposits.

Stratigraphic relations among these flood deposits and the lower elevation fluctuating flow deposits were described by Rubin et al. (1990, 1994b), Schmidt and Graf (1990), and Schmidt and Rubin (1995). These field studies demonstrated that the thickest post-dam flood deposit, occurring beneath a high topographic bench, formed in 1983 and was comprised of well-sorted to very well sorted very-fine to medium sand (Fig. 14). Although the smaller floods of 1984 to 1986 created a distinct bench approximately 1 m lower than the 1983 bench, the underlying deposit of very-fine to medium sand was typically thin. In upper Grand Canyon, floods from the Little Colorado River in winter 1993 (Wiele et al., 1996) formed flood deposits 10s of centimeters to several meters thick. The 1996 Controlled Flood formed new flood deposits of fine to coarse sand that were up to several meters thick near the reattachment points of some eddies. These deposits occurred at approximately the same elevation as those of the period between 1984 and 1986, and it was not possible to distinguish these deposits in mapping conducted after 1996. Rubin et al. (1998) and Topping et al. (1999) found that the 1996 Controlled Flood deposits were inversely graded, consistent with the temporal coarsening of the suspended load of the same flood. Topping et al. (2000a) identified similar patterns in pre-dam flood deposits and in those formed by the experimental release of November 1997. Fluctuating flow deposits are active bars of very fine to fine sand inset into the flood deposits.

4.0 PREVIOUS STUDIES OF FINE-SEDIMENT FLUX AND STORAGE

Changes in the bed and in the size and distribution of fine-sediment deposits along the channel caused by completion of Glen Canyon Dam are ultimately caused by changes in the balance between influx and efflux of fine sediment to and from the study area. Although changes in the flux have been dramatic, the resulting changes to the fine-sediment deposits have been less obvious. Previous studies reached conflicting conclusions about the long-term trends of these changes.

4.1 Previous Projections of Long-Term Changes in the Fine-Sediment Budget

The long-term fate of fine-sediment deposits was anticipated in numerous studies, and conclusions of those studies varied widely from predictions that long-term degradation of fine-sediment deposits was inevitable to predictions that smaller deposits would equilibrate with the greatly reduced post-dam fine-sediment flux. Dolan et al. (1974) linked changes in flux to changes in sediment storage and observed that:

> At Lees Ferry, the median suspended-sediment concentration has been reduced by a factor of about 200. Farther downstream, however, there is less reduction because of additional sediment from tributaries and from the continuing erosion of pre-dam terraces and of the channel bed; at the [Grand Canyon gage] the factor of reduction is about 3.5.

Laursen et al. (1976) described a bleak future for fine-sediment deposits:

> At present, the mean annual capacity of the river to carry beach-building material is about 12 million metric tons per year. The tributaries supply about 2.7 [million] metric tons of beach-building sediment per year. The difference of about 9 million metric tons per year must be obtained through scour of the bed and/or banks. … the beaches … could be in danger of being washed away since the transport capacity of the regulated river is in excess of the amount of beach-building material being supplied from the tributaries … How long they will last cannot as yet be estimated; certainly more than 10 years, probably less than 1000 years; but how much more or less than 100 years is a matter for continued study.

Pemberton (1976) reported on the magnitude and rate of bed degradation in the 25 km of Glen Canyon, as measured between 1956 and 1975. Pemberton (1976) argued that stability had been achieved by 1975 through bed armoring at gravel and cobble bars that act as channel controls.

Howard and Dolan (1981) reached a very different conclusion than Laursen et al. (1976) about the fate of fine-sediment deposits. Howard and Dolan (1981) stated that: “Greatly reduced flood peaks since completion of Glen Canyon Dam have decreased the turbulence generated by rapids and hence transport capacity to the extent that an average of more than 1.5 m of sand has accumulated on the bed of [Marble Canyon and] the Upper Grand Canyon.” The fine-sediment budget of Howard and Dolan (1981) was based on monthly transport data and the assumption that transport relations were stationary and did not change with time. Howard and Dolan (1981) assumed that the bed, and not eddies, was the major repository of sand. They also argued that the trend of bed aggradation at the Grand Canyon gage was representative of the entire river upstream to Lees Ferry.

Despite the projections that sand was accumulating in the riverine ecosystem, the available evidence in the late 1970s and early 1980s indicated that eddy sand bars were slowly being eroded, albeit at slow rates. Howard (1975) established profiles across 20 eddy sand bars, and resurvey of these profiles in the next few years indicated little change (Howard and Dolan, 1979). Therefore, Howard and Dolan (1981) concluded, “During the first ten years since the dam, sandy channel banks have suffered only a very slight erosion, with individual cases of both pronounced erosion and marked deposition.” Some of these sites were resurveyed in 1980 (Dolan, 1981) and two sites were resurveyed in 1982 (Beus et al., 1982). Beus et al. (1985) analyzed these surveys and concluded, “On balance there was slightly more loss than gain suggesting a gradual depletion of beach sand from the terraces studied.”

The view that reduction in transport capacity exceeded reduction in sediment supply and that sand accumulated on the channel bed for multi-year periods prevailed for the next 15 years. Sediment budgets based on sediment-transport measurements made in the mid-1980s were calculated by Andrews (1990). He found that, "A three-fold decrease in mean annual peak water discharge, plus the large contribution of sediment by tributaries, results in a surplus rather than a deficit of sediment."

The potential beneficial role of floods in transferring sand to high elevation was evident from the increase in the number and size of campsites immediately after the 1983 flood. Brian and Thomas (1984) found that the 1983 flood completely eliminated 24 campsites, but that approximately 30% of the remaining campsites aggraded. Erosion was typical in Marble and upper Grand Canyon. The campsites where there was significant aggradation were primarily located in western Grand Canyon. These findings were echoed by Beus et al. (1985) who resurveyed sand bar profiles immediately after the 1983 flood. They found that the 1983 flood created thick new sand deposits at many sites, but they noted that some sites were completely eroded. Beus et al. (1985) assumed that the sites of thick sand deposition were more numerous than those that had eroded and concluded that flood-induced deposition reversed the system-wide progressive erosion trends of the previous 15 years: "A substantial net gain of sand on the 20 beaches [that were surveyed] more than compensated for the previous eight-year loss. Possibly occasional high water 'spills' through the Grand Canyon are desirable to maintain existing campsite beaches."

A significant management implication of the assumed accumulation of sand on the channel bed and beneficial role of floods was that multi-year bed accumulation could be redistributed to the channel edge by floods. Smillie et al. (1993) suggested that accumulation rates could be controlled: "flow fluctuations and corresponding sand transport in the Colorado River can be managed to achieve a balance with long-term average annual sand inputs from the Paria River." This view of sediment management was described in the Final Environmental Impact Statement for Glen Canyon Dam Operations (U. S. Department of the Interior, 1995) and the associated Record of Decision that proposed a sequence of controlled floods that would redistribute fine sediment from the channel bed to the banks (Schmidt et al., 1999a).

Kearsley et al. (1994) adopted an approach similar to that employed by Brian and Thomas (1984) to measure system-wide changes in sand bars. Kearsley et al. (1994) made semi-quantitative measurements of the size of every campsite in Grand Canyon from aerial photographs taken in 1965, 1973, 1984, and 1990. Thus, they did not assume that the 20 sites measured in detail in the field by Beus et al. (1985) were representative of the population of all eddy bars. Their measurements were less precise but more spatially robust than those reported by Howard and Dolan (1981) and Beus et al. (1985). Kearsley et al. (1994) found that there had been more post-dam erosion than identified by other studies: "at least 30% of all campsites decreased in size during the first 10 years of Glen Canyon Dam operations, and 32% of all campsites decreased in size during the next 18 years." They found that the "benefit" of sand aggradation caused by the 1983 flood was short lived, and by 1991 only a few campsites were larger than they had been in 1973.

Webb (1996) compared the size of sand bars in two elevation zones in replications of ground-level photographs originally taken in 1889 and 1890 during the R. B. Stanton expedition, and he found a significant difference in the size of bars in the upstream and downstream parts of the Colorado River corridor. He found that 72% of low water sand bars, defined as those inundated by flows less than the capacity of the Glen Canyon Dam powerplant, had decreased in size during the intervening century. He found that the proportion of sand bars that had eroded decreased downstream, and he found that the proportion of eroded bars was slightly more at low elevation than at elevations that are now only inundated by post-dam floods.

Measurements during the 1996 Controlled Flood demonstrated that the concentration of suspended sediment decreased by approximately one-half during this 7-day event (Topping et al., 1999). This evidence of supply limitation led to recalculation of historical sediment budgets (Topping et al. (2000a, 2000b) and realization that many of the assumptions on which the sediment-related findings of the Environmental Impact Statement for Glen Canyon Dam Operations (U.S. Department of the Interior, 1995) are not valid (Schmidt, 1999; Rubin et al., 2002).

5.0 CHANGES IN THE TOPOGRAPHY OF THE MAIN-CHANNEL BED

Gravel has been eroded from riffles that act as hydraulic controls within 20 km from Glen Canyon Dam, but there is no indication of degradation of gravel and boulders from the rapids that act as channel controls in the next 145 km. There is abundant evidence of extensive erosion of sand from riffles and pools in Glen Canyon, and there is scattered evidence of degradation of pools in Marble and Grand Canyons. The only evidence for sustained accumulation of fine sediment in the study area during the post-dam era was in 1963 and 1964 when dam releases were very low.

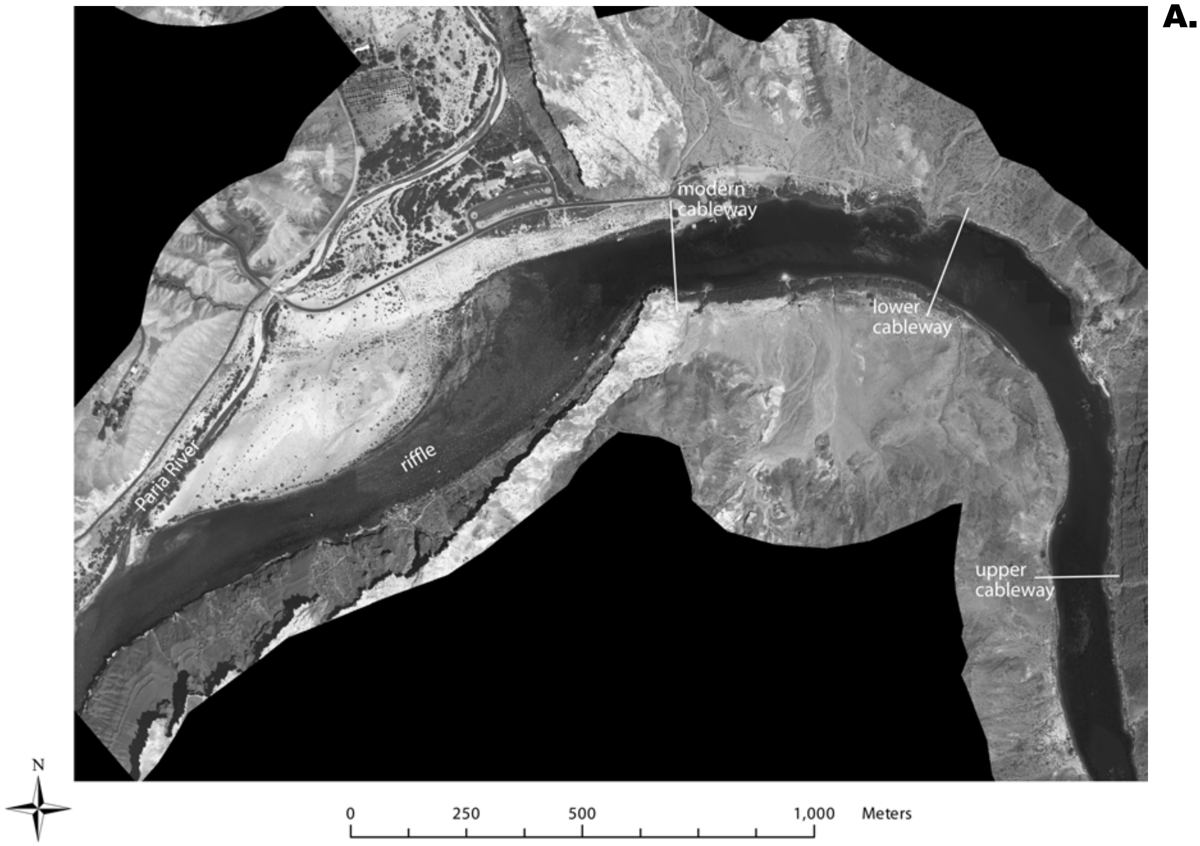
5.1 Pre-dam Changes in the Main-Channel Bed, as Measured at the Lees Ferry and Grand Canyon Gages

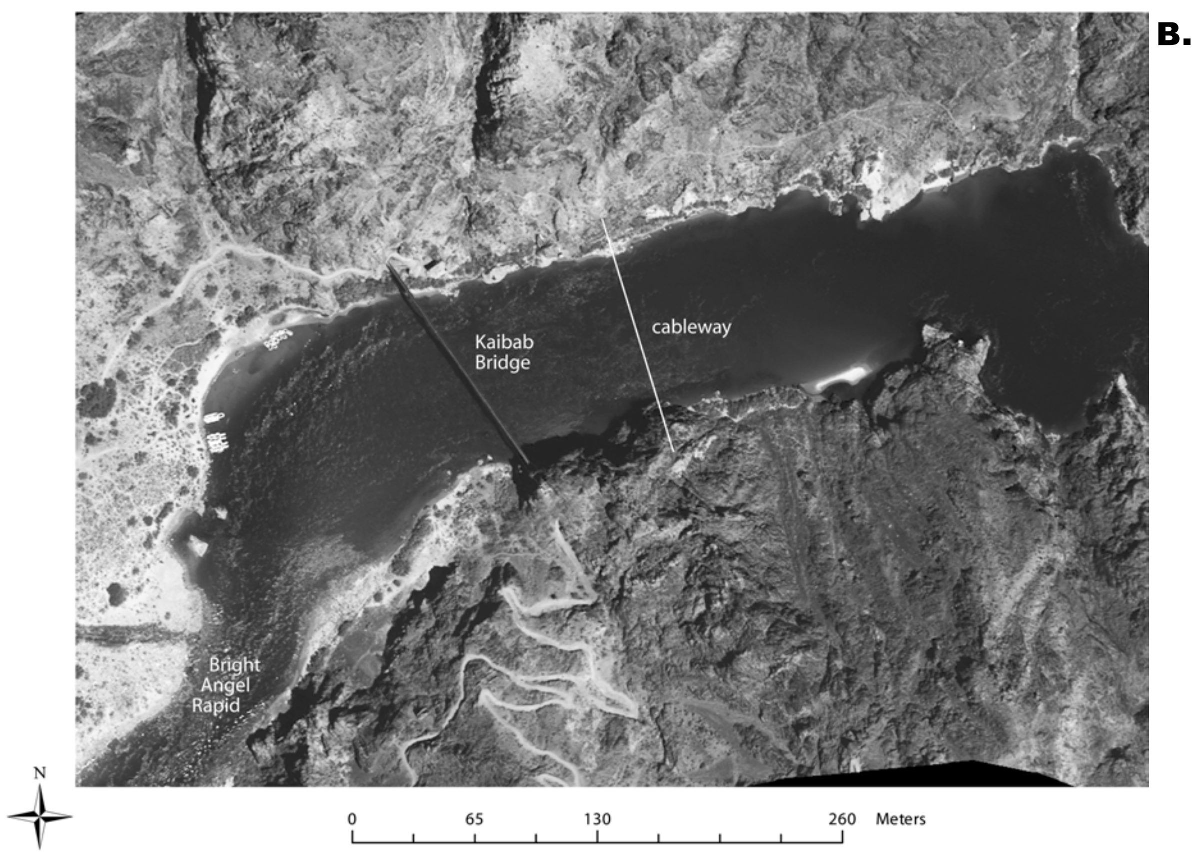
The characteristics of the Colorado River's bed have been measured at the Lees Ferry and Grand Canyon gages since the early 1920s (Fig. 15 A,B), because discharge measurements have been made at these locations. The measurement reaches are a few channel widths in length and include 2 and 3 cableway crossings of the river, respectively. In order to evaluate pre-dam characteristics of the bed, it was necessary to integrate these temporally precise but spatially restricted data with imprecise but spatially extensive estimates of bed change that were deduced from the mass balance calculations of Topping et al. (2000b) and estimates of the area of the bed and of EDZs.

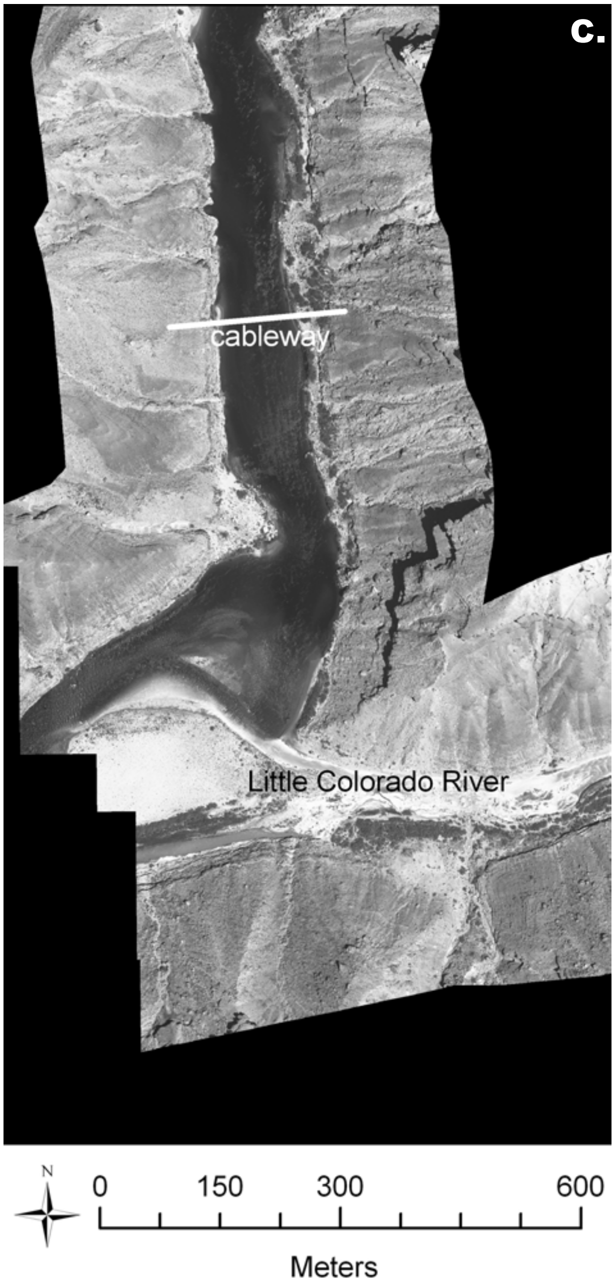
Topping et al. (2000a, b) described hydraulics and sediment transport at the Lees Ferry and Grand Canyon gages. Each gaging reach is a ponded backwater, and the downstream controls are the riffle opposite the Paria River confluence and Bright Angel Rapid, respectively. The magnitude of annual scour and fill was between 1 and 7 m at the Lees Ferry gage and between 1 and 3 m at the Grand Canyon gage. The bed at the Lees Ferry gage scoured during rise of the annual flood, and filling began about 2 weeks after the peak occurred. Filling continued until the pre-flood bed elevation was approximately restored. In contrast, the bed at the Grand Canyon gage initially filled. Scour began about 4 weeks before the annual peak was reached, and scour continued until the channel returned to its approximate pre-flood elevation. The bed remained at this elevation until the next year's snowmelt flood repeated the cycle.

Comparison of the magnitude of scour and fill measured at the gages with predictions of average bed elevation changes estimated under different scenarios of seasonal sediment accumulation, proportion of the accumulation stored in eddies and the main channel, and the proportion of the channel where fine sediment storage occurred indicate that the gages describe bed behavior of a small proportion of the channel. In a year when 7.0×10^6 t of fine sediment accumulated between July and the next March, the average elevation change in eddies would have been about 0.6 m and the average change in bed elevation would have been between 0.2 and 0.5 m, if half of the fine sediment accumulated in eddies and half in the

Figure 15. Photographs showing the Colorado River near the USGS gaging stations in spring 2002 at 227 m^3/s. A. Near the Lees Ferry gage. Flow is from right to left. B. Near the Grand Canyon gage. Flow is from right to left. C. Near the lower Marble Canyon gage. Flow is from top to bottom. North is to the top of each photo.







main channel (Table 5). The range in estimates of bed elevation change depends on how much of the bed is assumed to have stored fine sediment. The smaller value assumes that fine sediment was stored everywhere but in rapids. The larger value assumes that fine sediment was stored in 30% of the main channel. Both predictions are less than was measured at the Lees Ferry and Grand Canyon gages. The only scenarios where annual average bed scour and fill approximate the magnitude measured at the two gages is if 30% of the channel is assumed to have stored fine sediment and 50% or more of all fine sediment is assumed to have accumulated on the bed. Analysis of pre-dam historical photographs, and estimation of the fine-sediment storage potential of eddies, indicates that large fluctuations in sand storage also occurred in eddies, thus indicating that a significant proportion of seasonal storage also occurred there. Thus, it is unlikely that more than 50% of the total fine sediment storage occurred in the channel. It is likely that less than 30% of the channel bed stored significant amounts of sediment.

Despite the different patterns of scour and fill, the two gages had similar long-term trends of degradation (Topping et al., 2000b). There was a small, but progressive, decrease in bed elevation at each gage after each year's snowmelt flood, because the average bed elevation at low flows was never quite as high as that of the previous year. This decrease in bed elevation was progressive between the 1920s and the 1960s (Topping et al., 2000b). The degradation rate was between 2.5 and 3.0 cm/yr for the periods between 1929 and 1944 and between 1945 and 1959, respectively, at the Lees Ferry gage (Fig. 16) and 1.6 cm/yr for the period between 1922 and 1962 at the Grand Canyon gage (Fig. 17). Topping et al. (2000b) argued that progressive degradation was caused by a long-term decrease in the amount of fine sediment supplied from the upper Colorado River basin, rather than a long-term change in flow regime.

5.2 Post-Dam Changes of the Bed in Glen Canyon

The bed of the Colorado River within 5 km from Glen Canyon Dam began to degrade between 1956 and 1959, soon after the cofferdam was constructed. There was extensive degradation of pools and riffles within 20 km from the dam, caused by the 1965 channel cleaning flow. Subsequently, there was little degradation of riffles, but some pools continued to degrade. The net effect of degradation was the transformation of a sand bed to a gravel bed throughout the 25 km of Glen Canyon.

Figure 16. Graphs showing bed elevation at the Lees Ferry gage. A. Time series of minimum bed elevation for the Upper Cableway between 1921 and 1966. Also plotted are Bureau of Reclamation and GCMRC surveys of cross-section R-1, which is the same location as the Upper Cableway, between 1956 and 2000. B. Time series of minimum bed elevation for the Lower Cableway between 1929 and 1957. Figure from Grams et al. (2004, fig. 12, 13).

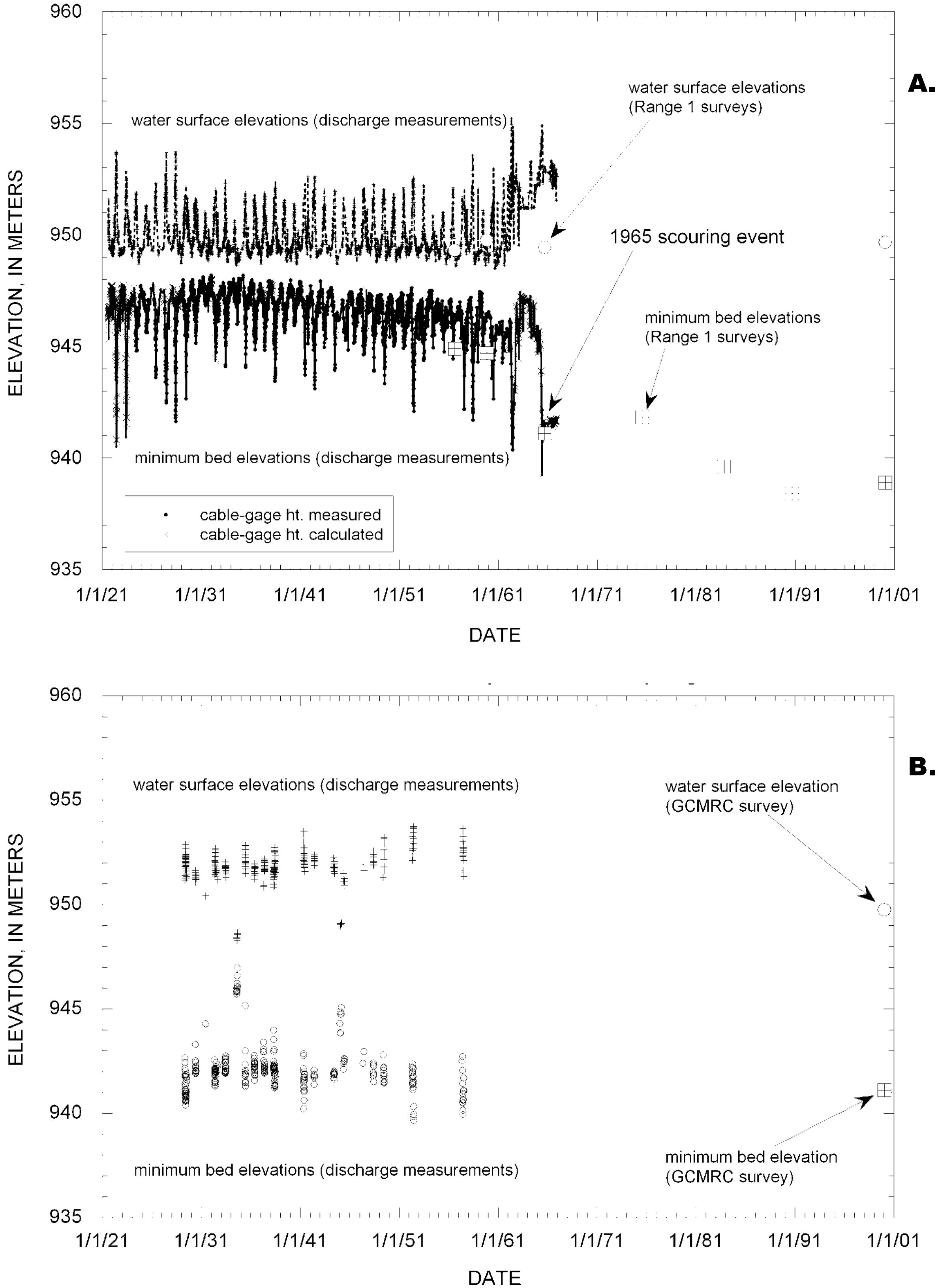


Figure 17. Graph showing mean bed elevation at the Grand Canyon gage. A. entire period of record. B. post-dam era. Mean bed elevation was calculated by dividing cross-section area by width. All elevations adjusted to that of the lower gage. Arrows in B indicate times when configuration of Bright Angel Rapid changed due to debris flow or flash flood.

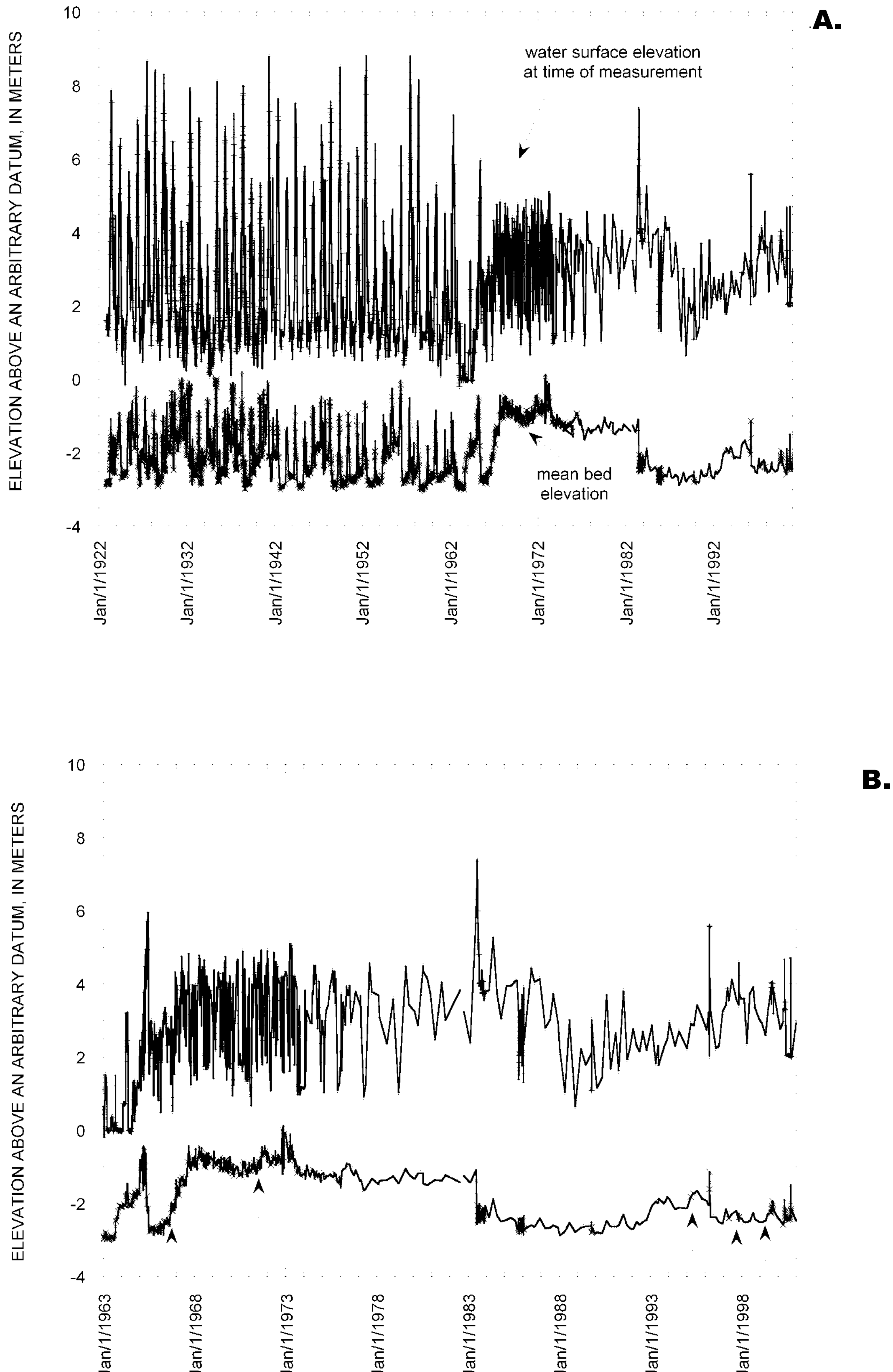


Figure 18. Map showing Glen Canyon and locations of cross-sections that have been measured since 1956 (Grams et al., 2004, fig. 1). River miles locations are in miles upstream from the present Lees Ferry cableway.

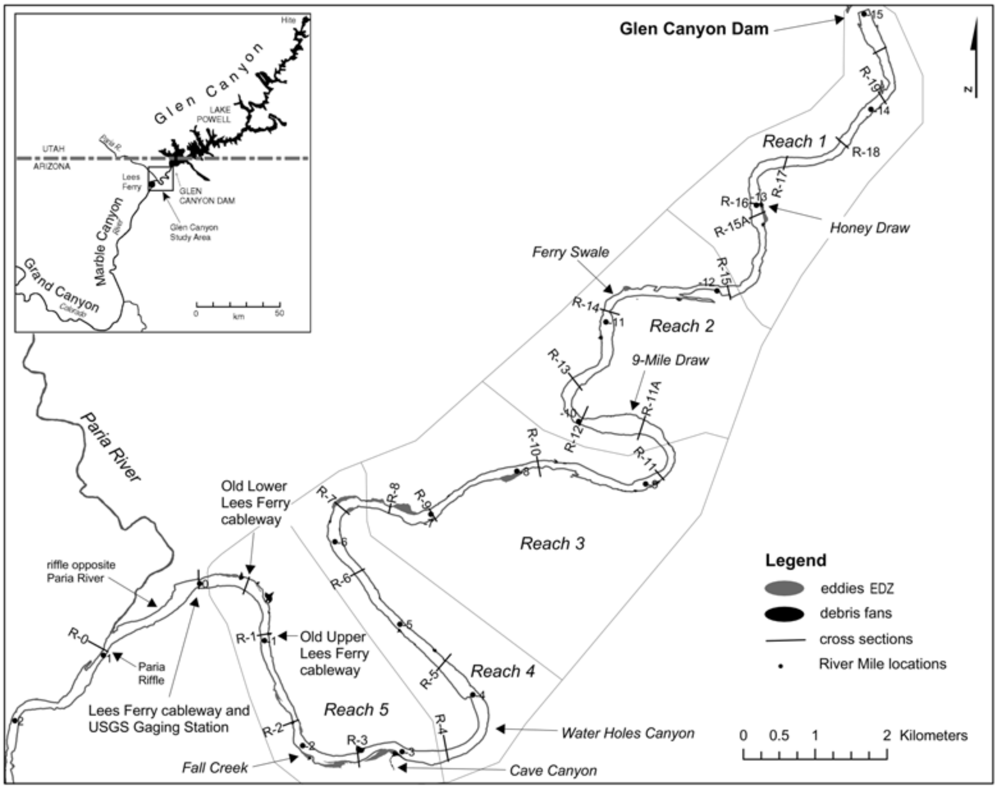


Table 5. Estimates of the average change in fine sediment thickness in Marble and upper Grand Canyons under various scenarios of seasonal sediment accumulation, relative proportion of accumulation stored in eddies and the main channel, and proportion of the main channel where storage occurs. **Bold numbers indicate the most likely scenario for pre-dam seasonal storage of fine sediment.**

Seasonal sediment accumulation, in metric tons	Equivalent volume, in cubic meters[1]	Equivalent thickness, in meters, under three assumptions about the relative proportion of fine sediment stored in eddies and in the main channel and two assumptions about the proportion of the channel that can store fine sediment[2]					
		eddies	channel	eddies	channel	eddies	channel
proportion of the channel that can store fine sediment			[0.9] (0.3)		[0.9] **(0.3)**		[0.9] (0.3)
relative proportion stored in eddies and the main channel		0.1	0.9	**0.5**	**0.5**	0.9	0.1
1,000000	640,000	0.02	[0.04] (0.13)	**0.08**	[0.02] **(0.07)**	0.15	[0.00] (0.01)
7,000,000	4,460,000	0.11	[0.30] (0.91)	**0.57**	[0.17] **(0.51)**	1.03	[0.03] (0.10)
13,000,000	8,280,000	0.21	[0.56] (1.69)	**1.06**	[0.31] **(0.94)**	1.91	[0.06] (0.19)

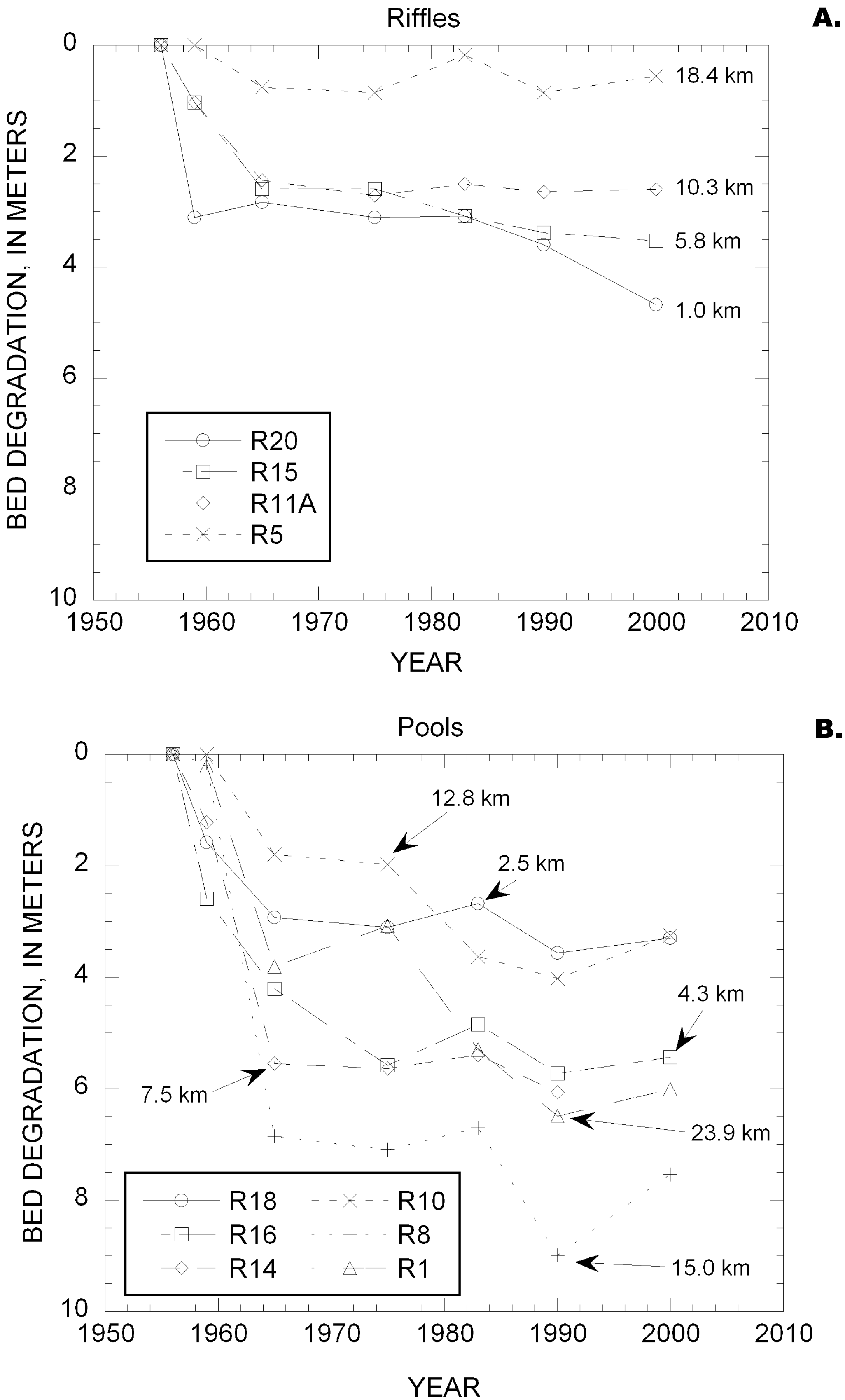
[1] assumes bulk specific weight of fine sediment is 1570 kg/m^3
[2] assumes area of eddies is 3.9×10^6 m^2, and area of channel is 14.7×10^6 m^2

Table 6. 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	20-30 Sep	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	20-30 Sep	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	20-30 Sep	Jul	18-Oct	Sep	11-May
R15A	4.6			23-May					11-May
R-15	5.8	15-Aug	30-Nov	23-May	20-30 Sep	Jul	19-Oct	Sep	11-May
R-14	7.5	10-Aug	19-Nov	24-May	20-30 Sep	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	20-30 Sep	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	20-30 Sep	Jul	20-Oct	Sep	26-Jan
R-9	14.4	8-Aug							26-Jan
R-8	15.0	8-Aug	12-Nov		20-30 Sep	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		20-30 Sep	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		20-30 Sep	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		20-30 Sep	Jul		Sep	28-Jan

* Exact measurement date not known.

Figure 19. Graphs showing minimum bed elevation at cross-sections in Glen Canyon, grouped by (A) riffles and (B) pools (Grams et al., 2004, fig. 5). The location of each cross-section is shown on Figure 18 and the distance downstream from Glen Canyon Dam is indicated.



5.2.1 Rate and Magnitude of Degradation

Data that demonstrate the rate and magnitude of bed degradation are resurvey of 22 cross-sections established by Reclamation in 1956 between Glen Canyon Dam and the riffle at the Paria River confluence, just downstream from Lees Ferry (Fig. 18, Table 6). Reclamation also described the size and depth of bed sediments by boring, or using a jet probe, at 16 locations. Borings and probes extended into the underlying gravel, entirely through the overlying sand. A subset of these cross-sections was resurveyed in 1959, 1965, 1975, 1983, 1990, and 2000 (Grams et al., 2004). Supplemental data about bed degradation was determined by analysis of discharge measurements and the cableways of the Lees Ferry gage.

Degradation of riffles and pools began soon after dam construction began, and there was significant erosion within 7.5 km from the dam by 1959 (Fig. 19). The thalweg of the riffle 1.0 km downstream from the dam was eroded 3 m and pools were eroded 1.25 to 2.5 m. Further downstream, there was no change in bed elevation. Pemberton (1976) suggested that the cofferdam's storage capacity of 3.58×10^7 m^3 was sufficiently large to reduce the concentration of suspended sediment of the 1957 and 1958 spring snowmelt floods, whose peak discharges were 3,567 and 3,001 m^3/s, respectively, thereby reducing the magnitude of fill that would have occurred during flood recession.

The 1965 channel cleaning flow achieved its intended purpose and caused the greatest amount of bed degradation ever measured in the study area. Resurvey of cross-sections in September 1965 indicated that cross-sections in the upstream part of Glen Canyon were further eroded and that cross-sections in the downstream part of Glen Canyon were eroded for the first time. Riffles as far downstream as 18.4 km from the dam were eroded, and the pool at the upper cableway of the Lees Ferry gage was eroded by about 5 m (Fig. 19A). Approximately 5.0×10^6 tons were eroded from Glen Canyon during the 3 mths of these high flows (Topping et al., 2003).

The rate of bed degradation decreased greatly thereafter, and there was some aggradation in the 1990s. The thalweg of pools typically eroded an additional 0.5 to 2.0 m between fall 1983 and fall 1990 and aggraded by less than 1.0 m in the same pools between 1990 and 2000. In some cases, such as at cross-sections 10 and 11A, the channel widened although the thalweg did not degrade further.

Degradation of pools and riffles differed in magnitude and longitudinal pattern. Pools degraded 5 times more than riffles, and the magnitude of degradation was just as large in the downstream end of Glen Canyon as in the upstream end. In contrast, the magnitude of degradation of riffles decreased downstream, and the bed at the riffle immediately downstream from the Lees Ferry gage did not change at all.

There are two implications of the decreasing downstream magnitude of bed degradation at riffles. The first is that the magnitude of shifts in stage-discharge relations decreased downstream. Water surface elevation at 150 m^3/s is now about 2.3 m lower than it was in 1956 near the dam, but there has been no change in water surface elevation at a cross-section 20.2 km downstream from the dam (Fig. 20). The second implication is that the gradient of the Colorado River in Glen Canyon decreased by about 25%. In 1956, the gradient was 0.00034 and 0.00037 at 79 and 2067 m^3/s, respectively, and today the gradient is between 0.00025 and 0.00028.

The cumulative volume of sand and gravel eroded from Glen Canyon was about 10.7×10^6 m^3. In 1956, the D_{50} of the bed was approximately 0.2 mm and the D_{50} of the underlying gravel was about 20 mm (Fig. 21). The entire sand layer of the pre-dam bed was removed, but half of the total degraded bed sediment was gravel (Fig. 22).

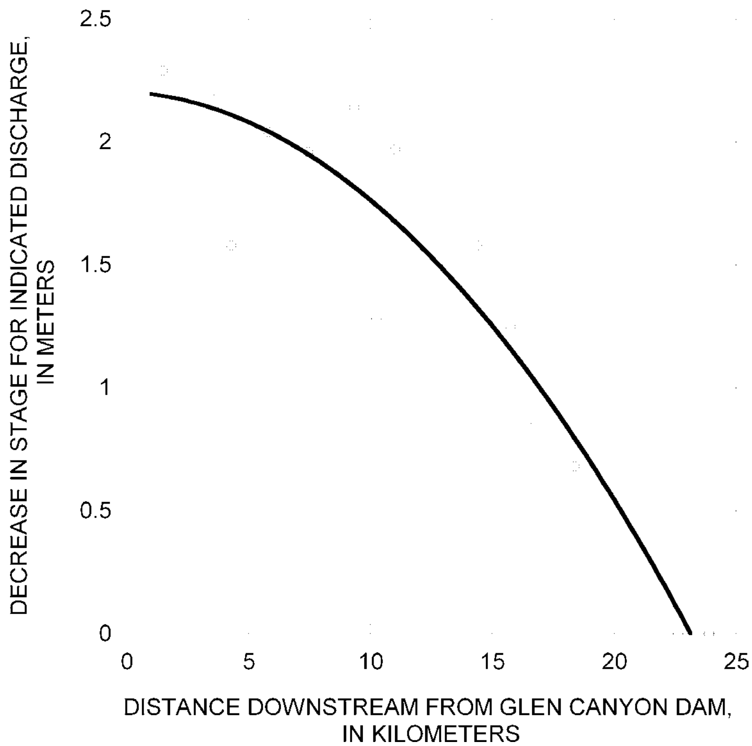
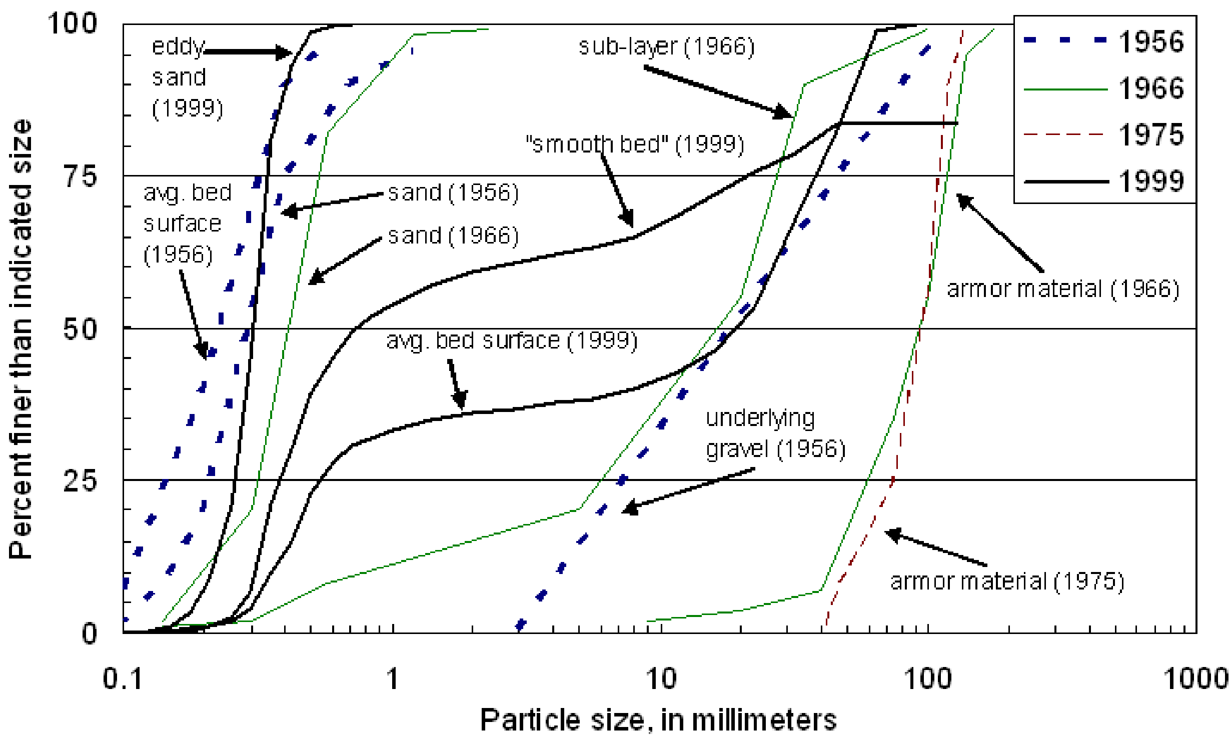


Figure 20. (Left) Graph showing change in stage at 150 m³/s, plotted as a function of distance downstream from Glen Canyon Dam (Grams et al., 2004, fig. 11).

Figure 21. (Below) Graph showing bed sediment size distribution for samples in Glen Canyon. Size in 1956 includes the average of bed surface samples, distinguishing the average of sand samples and the average of bore-hole samples of the underlying gravel. Size in 1966 distinguishes the average size of gravel armor, gravel subsurface, and sand. Size in 1975 is for gravel armor. Samples in 1999 were collected by pipe dredge from a boat at approximately 1-km intervals, and the indicated size is the composite of all samples. Data for 1956 to 1975 are from Pemberton (1976). Figure is from Grams et al. (2004, fig. 6).



5.3 Post-dam Changes in the Bed in Marble and Upper Grand Canyons

There is no evidence for longitudinally consistent changes in stage-discharge relations in Marble and Grand Canyon, because bouldery rapids have not eroded. These rapids act as the hydraulic controls of the water surface profile for the 145 km between the Lees Ferry and Grand Canyon gages. There is some evidence that many rapids aggraded. There is limited evidence that the bed of some pools degraded. There is no evidence of longitudinally extensive multi-year accumulation of fine sediment on the bed.

Figure 22. (Below) Graph showing longitudinal profile of the thalweg and contact of sand and gravel that existed in 1956. Water surface profiles are those surveyed in 1956 at 79 m³/s and 1966 at 238 m³/s (Grams et al., 2004, fig. 7).

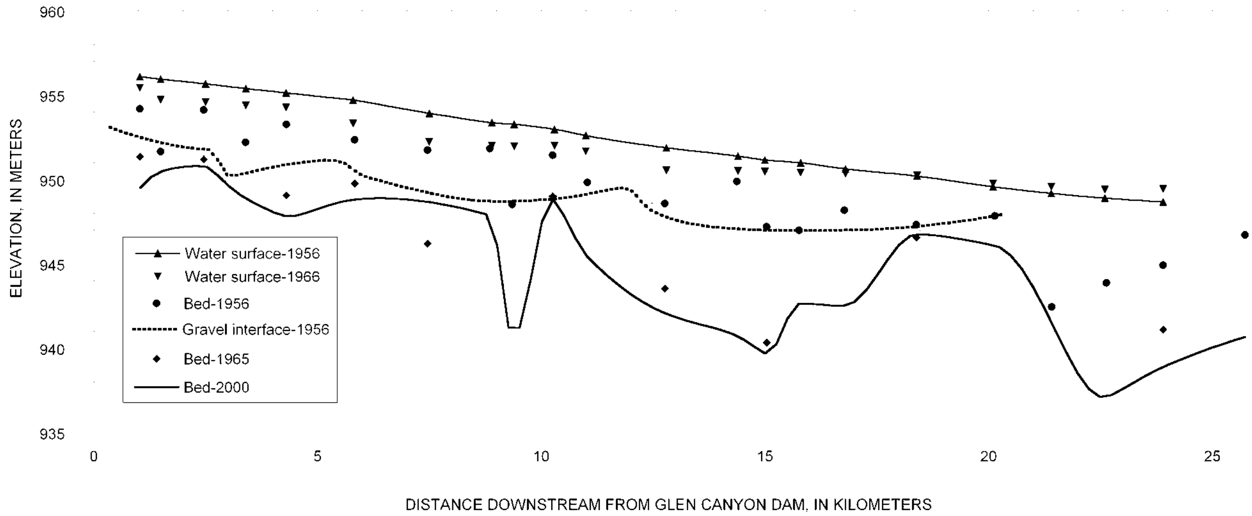


Table 7. Summary of channel cross-section data at Marble Canyon Dam sites

Location	Average change in bed elevation between 1950 and 2000, in meters	Average change in bed elevation between 1998 and 2000, in meters
RM 32.8A	0	
RM 32.8B	+ 0.1	
RM 39.5A	- 0.9	
RM 39.5B	- 1.0	0
RM 39.5C	- 1.0	0
RM 39.5D	- 0.4	+ 0.1

5.3.1 Bed Changes in Marble and Grand Canyons That Are Probably Post-dam

Comparison of the water surface elevation of the Colorado River between Lees Ferry and Lake Mead reservoir in 1923 and 2000 indicates that there was net aggradation of rapids, and that the rate of aggradation probably increased after completion of the dam. Magirl et al. (unpubl. manuscript) compared Light Detection and Ranging (LiDaR) data of the elevation of the Colorado River with that surveyed by the USGS in 1923 and compared the elevations of 145 rapids. They found that 39 rapids aggraded, 16 degraded, and that the average for all measured rapids was an increase in water surface elevation of +0.18 m ± 0.55. Magirl et al. (unpubl. manuscript) argued that aggradation in rapids increased after completion of the dam, based on statistical comparison of the rapids where debris

Figure 23. Photograph of one of the alternative Marble Canyon dam sites, near River Mile 39.5.

flows are known to have occurred since 1963 with those where such events are unknown.

Resurvey of the bed at 6 cross-sections at the 2 alternative sites of the proposed, but never constructed, Marble Canyon Dam site (Fig. 23) show that the Colorado River bed degraded between the 1950s and 2000. Between 1950 and 2000, there was little change in bed sediment at 2 cross-sections at River Mile 32.8 but between 0.4 and 1.0 m of bed sediment were removed from each of 4 cross-sections at River Mile 39.5 (Table 7). These measured changes probably reflect long-term adjustment to the reduced fine-sediment supply to Marble Canyon instead of short-term bed adjustments, because the changes measured between 1950 and 2000 greatly exceeded the measured changes that occurred at the same cross-sections between 1998 and 2000.

5.3.2 Changes at the Grand Canyon Gage between 1963 and 2000 and at the Lower Marble Canyon Gage between 1983 and 2000

Discharge measurements at the Grand Canyon and at U. S. Geological Survey gaging station 09383100 (Colorado River near Desert View, Arizona, and referred to hereafter as the Lower Marble Canyon gage) demonstrate the relative roles played by mainstem sediment mass balance and by nearby tributaries in determining bed elevation in ponded backwaters. These measurements indicate that post-dam multi-year fine-sediment accumulation did not occur except when the channel control immediately downstream had aggraded, the downstream tributary was flooding and thereby increased mainstem stage, or the discharge of the Colorado River was very low for more than 1 year.

Most of the significant increases in mean bed elevation at the Grand Canyon gage occurred immediately following debris flows or flash floods in Bright Angel Creek that presumably aggraded Bright Angel Rapid (Fig. 17). The most significant of these events was the December 1966 debris flow that delivered large boulders to the rapid (Cooley et al., 1977). The bed at the gage aggraded about 1.5 m during the next 9 months. Aggradation of about 0.5 m occurred immediately after a flash flood in July 1971, and an additional 0.5 m of aggradation between November 1972 and January 1973 may be related to this change at Bright Angel Rapid. Short episodes of aggradation occurred in response to 3 flash floods in Bright Angel Creek between 1995 and 1997. The first of these was a +0.35-m shift in the stage-discharge relation at the gage that occurred when the riffle was aggraded by a ~85 m^3/s flood that occurred on March 5, 1995, on Bright Angel Creek (Rihs, 1995). The rapid was aggraded again by coarse sediment from a flash flood on Bright Angel Creek that probably occurred on September 26, 1997, and the stage-discharge relation at the gage shifted +0.2 m. Additional aggradation occurred due to a tributary flood that probably occurred on April 24, 1999, when the stage-discharge relation shifted +0.15 m.

Bed aggradation of about 2.5 m occurred between August 1963 and March 1965 and was unrelated to changes at Bright Angel Rapid, because no floods in Bright Angel Creek were reported. Discharge was typically less than 40 m^3/s during much of this period and only exceeded 500 m^3/s for about 2 wks in spring 1964. There were several floods on the Paria and Little Colorado Rivers during this period and Topping et al. (2000b) estimated that about 4 million tons of fine sediment accumulated in the study area. Bed aggradation at the gage was probably due to accumulation on the bed, because there were no high flows that could have transferred this sediment into eddies.

Significant degradation of the bed occurred in a few weeks in May 1965 and June 1983 during large post-dam floods. Degradation at the gage caused by the former flood was probably a widespread phenomena, because Rubin and Topping (2001) estimated that 17.6 x 10^6 tons were eroded from Marble and upper Grand Canyons in May and June 1965. Much of this sediment had accumulated during the

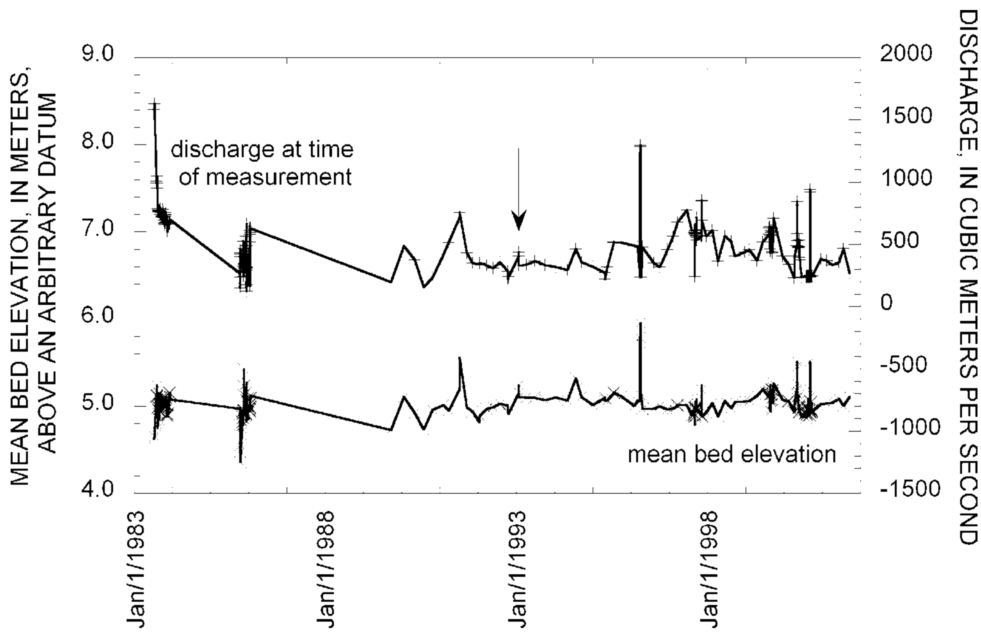


Figure 24. Graph showing mean bed elevation and the discharge of water measured at the Lower Marble Canyon gage cableway between 1983 and 2001. Arrow indicates January 1993 flood in Little Colorado River, located immediately downstream from the cableway.

prior 2 years. Degradation caused by the latter flood was probably related to erosion of boulders in Bright Angel Rapid that caused a long-term shift in the stage-discharge relation. There was a small amount of degradation during the rising limb of the 1996 Controlled Flood, because the stage-discharge relation shifted by –0.35 m. Degradation at a slow rate occurred between 1969 and 1971 and between 1974 and 1983, because Bright Angel Rapid was presumably eroded to some degree.

Similar patterns of aggradation and degradation were measured at the Lower Marble Canyon gage between 1983 and 2000 (Fig. 24). Here, aggradation in the measurement reach occurred during the few days when floods from the Little Colorado River, located approximately 1 km downstream (Fig. 15C), entered the Colorado River. These tributary floods temporarily increased the water-surface elevation at the gage, decreased the velocity, and induced bed aggradation. Ponding of the flow was measured on January 22 and 23, 1993, during a flood from the Little Colorado River, when the stage-discharge relation shifted +0.64 m. Although not measured at the time, a flood from the Little Colorado River that occurred on January 12, 1993, probably shifted the stage-discharge relation by approximately 1 m, because this flood exceeded the January 23 peak by about 40%. These ponding events caused bed aggradation of about 0.3 m under the cableway, and the bed did not degrade to its pre-1993 elevation again until August 1997.

5.3.3 Changes in Main Channel Pools Offshore from Eddies between 1992 and 2000

Annual measurements of 16 main channel pools between 1992 and 2000 by NAU further confirm that there has been no system-wide accumulation of fine sediment during the era of environmental management. In fact, these data indicate that there was probably a progressive loss of bed sediment. Many of these pools scoured during the 1996 Controlled Flood, remained scoured during the experimental releases of 1997, and filled when dam releases decreased in 1998 (Fig. 25). The average trend in bed elevation between 1992 and 2000 is negative ($p=9.8x10^{-4}$). This loss of sediment included gravel as well as sand, because pipe-dredge samples from these pools included both.

The data from each of the 16 pools were also normalized and averaged into one time series, because each pool is only a few channel

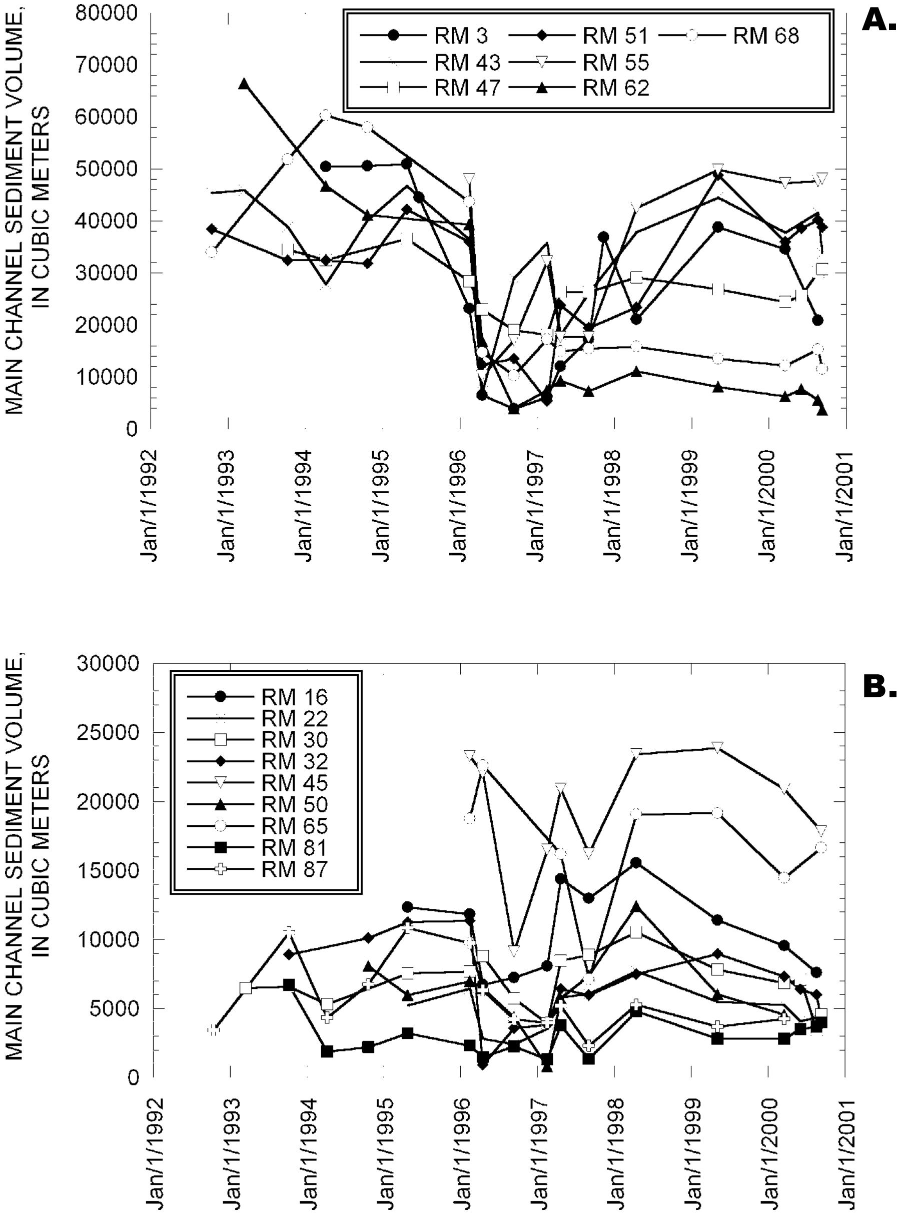


Figure 25. Graphs showing (A) measured sediment volume in the 7 largest pools measured by NAU. (B) Measured sediment volume in the 9 smallest pools.

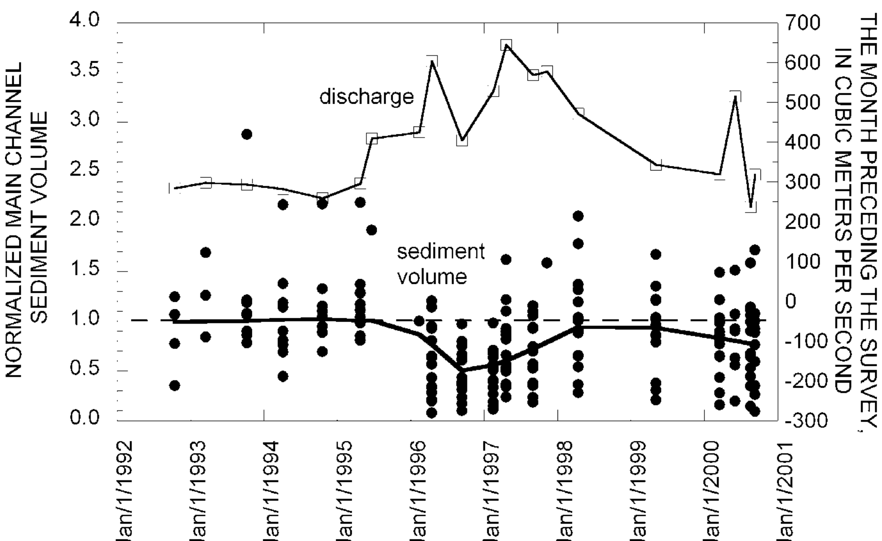


Figure 26. Graphs showing normalized sediment volume in 16 main channel pools and the mean discharge during the month preceding each survey. The data from each site were normalized by dividing the measured volume during each survey by that measured in the pool during the February 1996 survey. The thick solid line is a smoothed curve fit to the data.

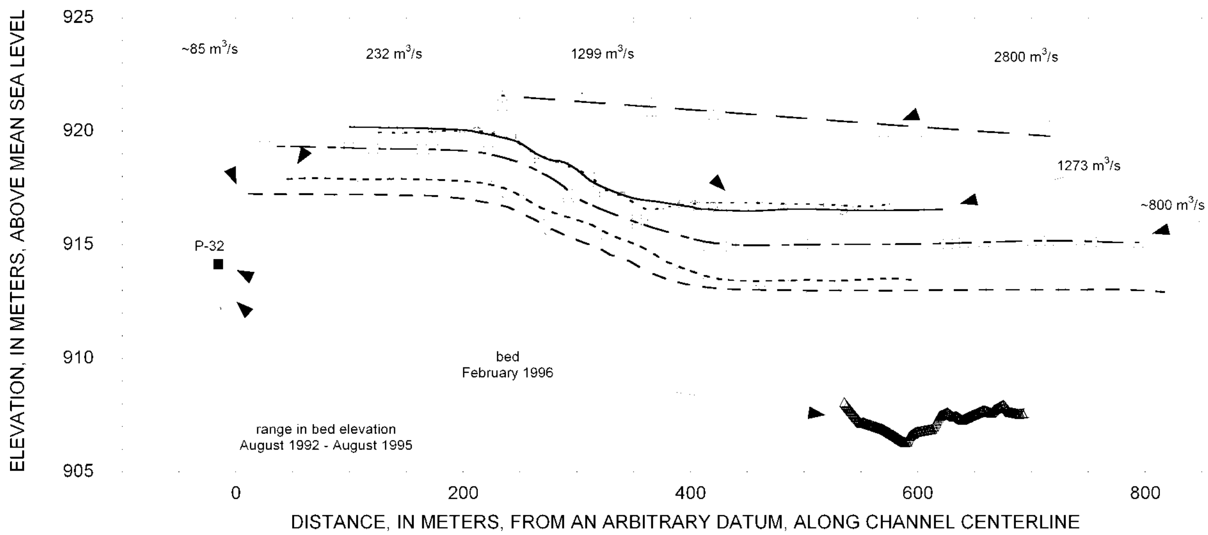


Figure 27. Graph showing longitudinal profile of the water surface at Badger Creek Rapids at 3 discharges, surveyed in 1985 by J. C. Schmidt, and at 2 discharges, surveyed in 1996 by NAU. Elevations are those surveyed at the water's edge, and the flat or adverse slope downstream from the rapids is that of the upstream flowing eddies that occur along both banks. Discharge at time of measurement is based on unit values measured at Lees Ferry gage: 1299 m^3/s determined from high water marks of the 1996 Controlled Flood; 1273 m^3/s surveyed on May 19, 1985; ~800 m^3/s surveyed July 31, 1985; 232 m^3/s surveyed March 22, 1996; ~85 m^3/s surveyed October 5, 1985. Water surface at 2800 m^3/s based on field surveys of the estimated water's edge determined from a June 1952 photograph (Fig. 29A). Bed elevations measured by NAU on February 15, 1996, and at cross-section P32 by Graf et al. (1995, 1997).

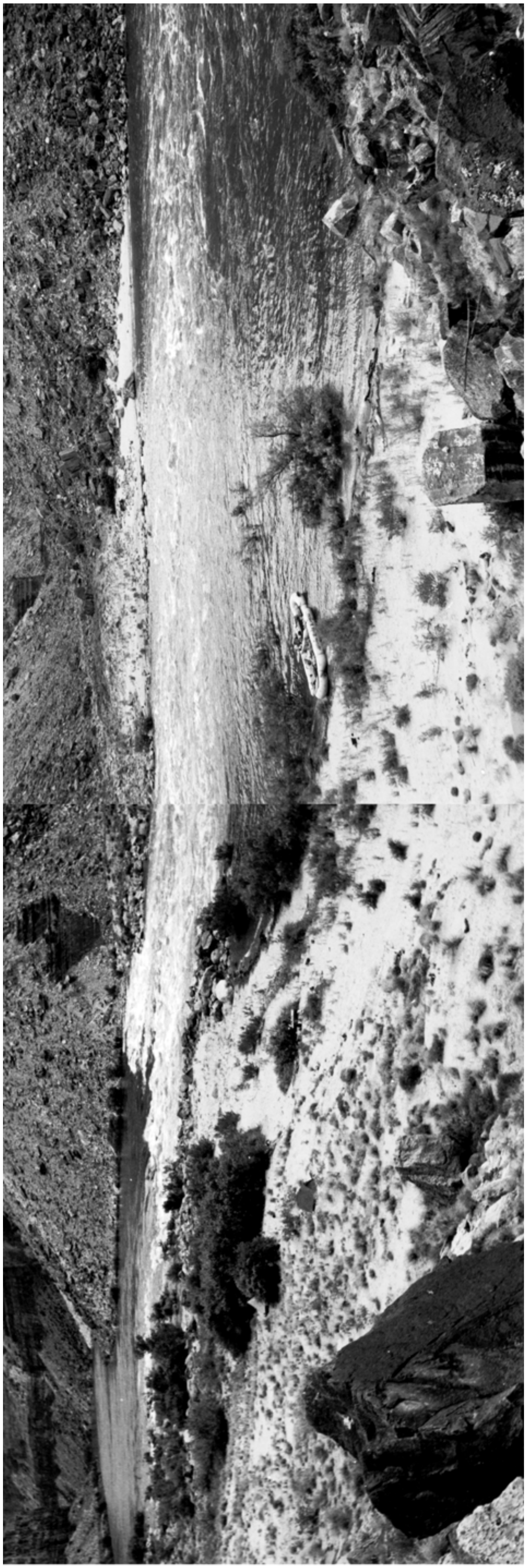
widths in length and channel geometry effects produce substantial scatter in temporal patterns of specific sites. The average trend indicates that pools tend to scour during increasing discharge and to fill during decreasing discharge (Fig. 26). This behavior is similar to that observed in the ponded backwater immediately upstream from the Grand Canyon gage during the 1996 Controlled Flood (Topping et al., 2000b), and to that observed during pre-dam floods in the ponded backwater of the Lees Ferry gage (Colby 1964, Howard and Dolan 1981, Topping et al., 2000a).

Resurvey of monumented cross-sections between 1992 and 1999 also did not indicate accumulation of fine sediment on the bed (Flynn and Hornewer, 2003). Most of these cross-sections were located downstream from the Paria and Little Colorado Rivers; others were located elsewhere between Glen Canyon Dam and Lava Falls Rapid, which is downstream from the study area. Most of these cross-sections describe the main channel in ponded backwaters, but some describe the main channel pool downstream from small rapids and a portion of the adjacent eddy. Flynn and Hornewer (2003) found that 61 of 83 cross-sections had a net loss of bed sediment and only 19 had a net gain. Of 57 cross-sections located within 10 km downstream from the Paria or Little Colorado Rivers, 55 had a net loss of bed sediment. The only time these cross-sections filled was immediately following tributary floods, and the duration of main channel aggraded conditions was short.

6.0 THE HISTORY OF FINE SEDIMENT STORAGE AT SPECIFIC SITES

Temporally detailed records of sand bar volume were reconstructed for a few sites in the study area, based on integrating data from aerial and oblique photographs and field surveys. These data illustrate the processes that lead to aggradation and degradation of fine sediment. The description of Badger Creek Rapids emphasizes flow characteristics and the characteristics of sand deposits during the pre-dam and post-dam eras. The description of Eminence Break camp emphasizes patterns of long- and short-term bar change.

A.

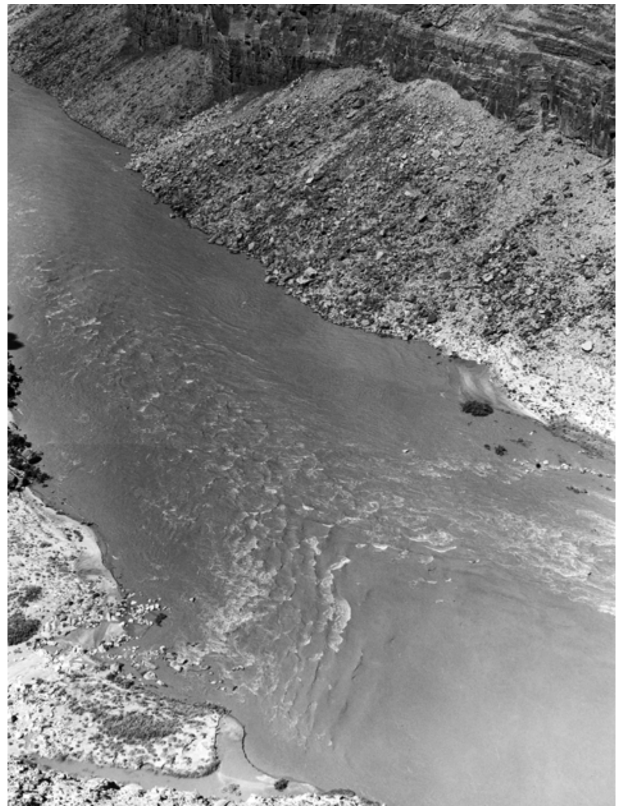


B.

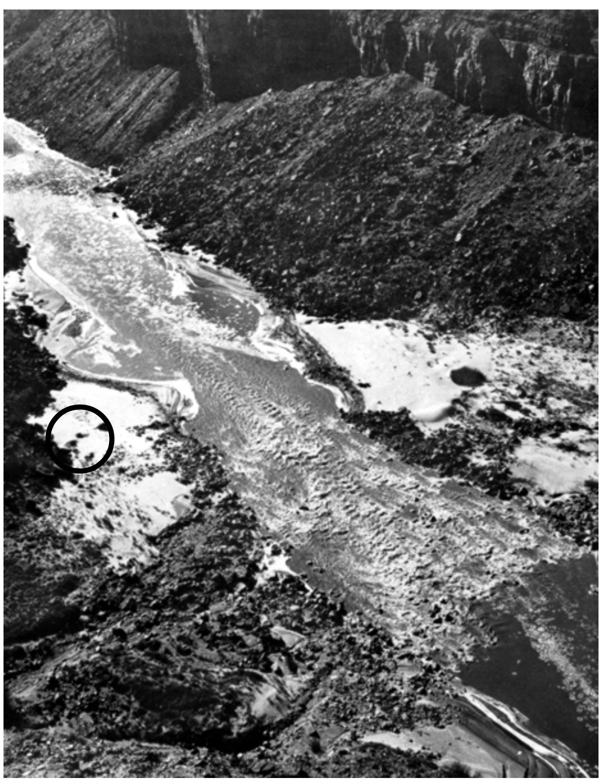
C.

Figure 28. Photographs showing Badger Creek Rapids. Photographs taken from river right. Flow is from left to right. Jackass Creek enters the Colorado River on the opposite bank and Badger Creek enters the Colorado River at the extreme left side of the photograph. The sand in the foreground and on the opposite bank are separation bars that mantle the respective debris fans. Most of the bare sand upslope from the water's edge in May 1985 (A) was deposited during the flood of 1983. At low flow, there are many exposed boulders in the rapid, and the rapid is much shorter. Tail waves extend further downstream at higher flows. Areas shoreward from the tail waves are eddies; waves that originate from the tail waves propagate across the eddies, and breaking waves create a foreshore at the water's edge of the separation bars. A. May 19, 1985, 1200 hrs, 1273 m^3/s. B. July 30, 1985, 1630 hrs, between 839 and 851 m^3/s. C. January 11, 1986, 1100 hrs, between 52 and 67 m^3/s.

Figure 29. Photographs of Badger Creek Rapids, taken from the cliffs above the rapid on river left. Flow is from right to left. Note the extensive areas of bare sand on the separation bars on river left and river right in pre-dam photographs. Some talus blocks on the separation bar on river left were exposed in 1972 and more were exposed in 1991. Reattachment bars were more extensive in pre-dam photographs and did not exist in 1991. Prominent talus block described in Fig. 34A is circled in B, C, F, G. Photos are stake 705, archives of R. H. Webb, U. S. Geological Survey, Tucson. A. June 19, 1952, taken by R. S. Leding, National Park Service (Photograph 2297, Grand Canyon National Park archives). B. January 2, 1954, at approximately 125 m^3/s. Taken by P. T. Reilly (photograph R-44-1). C. July 1956. taken by Tad Nichols. D. August 1964. Taken by Tad Nichols. E. October 1968. Taken by Tad Nichols. F. August 21, 1972 photograph taken by R. M. Turner, U. S. Geological Survey. Boat in rapid is 6.7 m long. (Turner and Karpiscak, 1980, fig. 36B). G. October 4, 1991, photograph taken by R. H. Webb (stake 705B).



A.



B.

C.

D.

E.

F.

G.

6.1 Badger Creek Rapids

Badger Creek Rapids is the first significant challenge in river navigation downstream from Lees Ferry (Fig. 9) and is considered of moderate difficulty (Belknap, 1969; Stevens, 1983). The rapids are technically challenging at low discharge when large boulders must be avoided. At high discharge, these boulders are submerged, and the rapids are much easier to navigate. Water surface elevation (Fig. 27) was measured and photographs (Fig. 28) were taken on May 19, July 31, and October 5, 1985, at approximately 1273, 800, and 85 m^3/s, respectively. A photograph taken on June 19, 1952, at about 2800 m^3/s depicts flow conditions at approximately the pre-dam mean annual flood (Fig. 29A). Water surface elevation in the rapids drops between 3.6 and 4.1 m in a distance of approximately 200 m, and the water surface slope in the rapids is between 0.015 and 0.020. The total fall in the rapid is less at higher discharges, because the stage proportionally increases to a greater degree in the channel expansion downstream from the rapid then in the ponded backwater upstream from the rapid. The speed of rowing rafts in the steep parts of the rapids at low flow was between 4.0 and 4.5 m/s in October 1985.

The basic configuration of the rapids and associated sand bars have not changed in the past 100 yrs, but there have been minor topographic changes. Debris flow deposits at the mouths of Jackass and Badger Creeks constrict the Colorado River channel from river left and river right, respectively, and boulders form the bed of the rapids. The channels of these ephemeral tributaries presently enter the Colorado River in the upstream half of the rapids, but the broad fan shape of the debris fans (Fig. 10) is evidence that these tributaries have changed course over time. Webb (1996) determined that a debris flow occurred here between 1897 and 1909, and Webb et al. (2002) reported a debris flow in Jackass Creek on August 19, 1994. There is relatively little difference between the water surface profiles surveyed in the mid 1980s and 1996 (Fig. 27), indicating that the 1994 debris flow did not significantly aggrade the rapid. The distal parts of the debris fan are truncated by the Colorado River, and the banks of the Colorado River opposite the rapids are steep. The width of the rapids is confined within these banks at flows less than about 1270 m^3/s; the flow has overtopped these banks at 2800 m^3/s.

Channel width decreases between 10 and 35% between the ponded backwater and the rapid. Because flow depth also decreases, mean section velocity upstream from the rapids is much less than in the rapid. These low velocities provide an opportunity for fine sediment to be deposited on the channel bed and along the banks. Sand was dredged from the bed of the ponded backwater during two research trips in the late 1990s. Short-term changes in fine-sediment storage on the bed were measured by repeated bed surveys in the early 1990s across the ponded backwater. Bed elevations changed by about 4 m between August 26, 1992, and January 11, 1994, and by about 2 m between January 11, 1994, and August 30, 1995 (Fig. 30). The banks of the ponded backwater are sand that forms several distinct levels that are collectively about 50 m wide.

Flow separation downstream from the rapids occurs along both banks where the debris flow deposits do not impinge on the flow (Fig. 10). The point of flow separation moves onshore and upslope at higher discharges, and the separation bars are inundated by the upstream part of the eddy. Once the banks of the rapids are overtopped, such as at discharges comparable to the pre-dam mean annual flood stage, parts of the separation bar may be inundated by downstream flow (Fig. 29A).

The topography and stratigraphy of the separation bars is greatly affected by surface waves that originate from the tail waves of the rapid and obliquely break at the shore of the bar; these waves and the resulting near shore

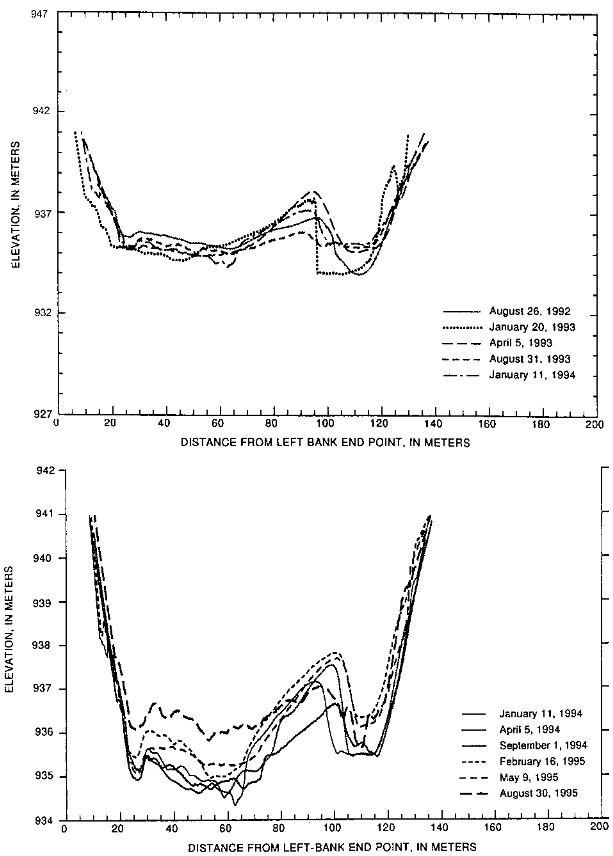


Figure 30. Graphs showing the Colorado River upstream from Badger Creek Rapids in the ponded backwater at cross-section P-32. Orientation is looking downstream. Changes in the bed reflect temporary changes in storage of sand, because sand was excavated from the bed by pipe dredges. A. Changes in the bed between August 26, 1992, and January 11, 1994 (Graf et al., 1995). B. Changes in the bed between January 11, 1994, and August 30, 1995 (Graf et al., 1997).

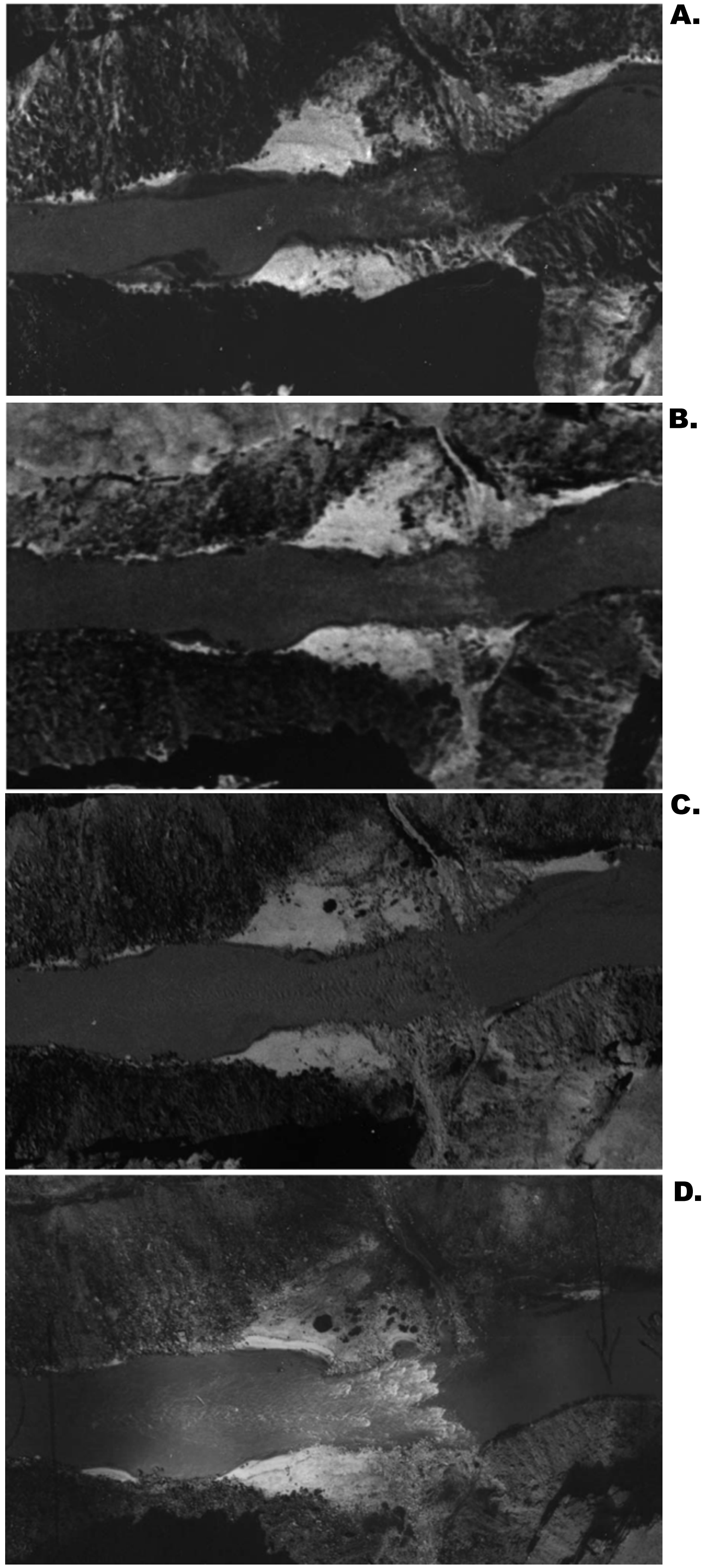
topography give Grand Canyon sand bars their popular name, "beaches." The height of these waves on the separation bar on river left was 6 to 18 cm at about 1270 m^3/s in May 1985 and between 18 and 34 cm at about 840 m^3/s in July 1985; waves broke onshore every 15 to 30 sec. These waves create a foreshore and ridge and runnel topography characteristic of ocean shorelines, and these waves have the potential to significantly rework fluvial sand bars (Bauer and Schmidt, 1993). Nearshore flow velocities were between 0.1 and 0.5 m/s in May and July 1985. Waves entrained and transfered sand from the swash zone offshore into eddy currents, and the sand was subsequently redistributed within the eddy or transported back into the main downstream flow.

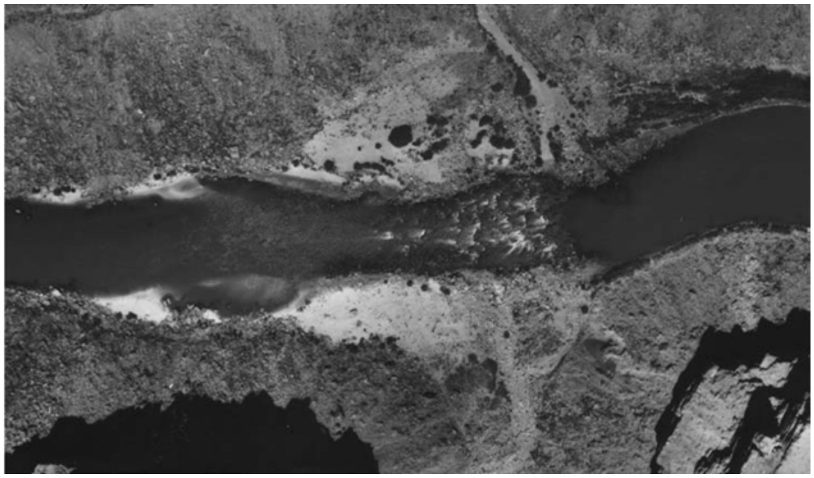
Reattachment bars once filled all or parts of the eddies, and these bars projected in an upstream direction from the reattachment point. The point of flow reattachment occurs where the talus banks impinge on the flow, about 300 m downstream from the separation point, although flow reattachment location changes with flow. At 2800 m^3/s, the tail waves of the rapid extend far into the flow expansion and appear to be further to river left than at lower discharges. This shift in the location of the main thread of flow causes the reattachment point to shift onshore and may lead to scour of part of the reattachment bar at discharges comparable to the pre-dam mean annual flood (Schmidt, 1990).

There is a rich photographic history of the rapid and its nearby sand bars, because the canyon rim is easily accessed. There are many photographs of boats running this rapid. The large separation bars immediately downstream from the rapids were often used as campsites. Interviews with former river runners (Webb et al., 2002) indicate that these bars were large and often used as campsites. Georgie White regularly used the sand bar on river right as her first night's camp, and the bar accommodated large river parties (J. C. Schmidt interview of Joan Nevills Staveley, September 1994). In the 1950s, the eddy on river left was typically "full of sand" and the long sandy shoreline was often used by anglers fishing for catfish (J. C. Schmidt interview of Bob Rigg, September 1994). John Cross II reported that the sand bar on river left could easily accommodate 2 large boating parties in the 1960s (J. C. Schmidt interview, September 1994).

The photographs taken of Badger Creek Rapids indicate that the separation bars were extensive and suggest annual reworking during the pre-dam era. The upslope extent of bare sand in each photograph was higher in years when the preceding flood was large (Fig. 29, 31). Parts of these bars included aeolian dunes at the upstream and onshore edges of the main bars. Sand extended to the water's edge at low flow, except for small aggregations of exposed

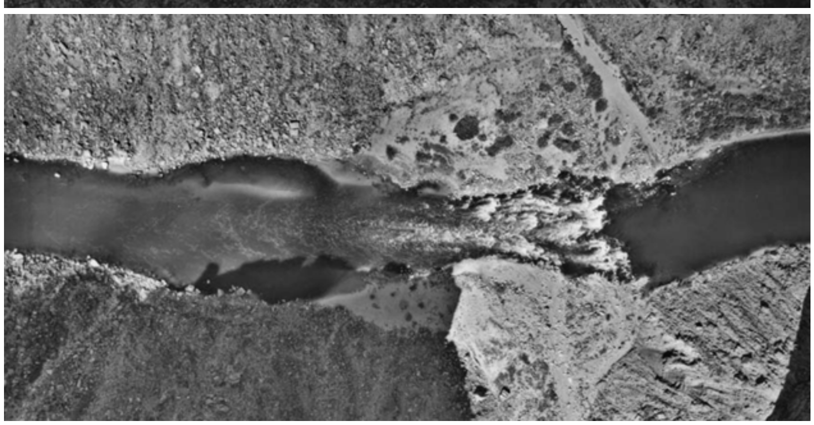
Figure 31. Aerial photographs of Bader Creek Rapids. Flow is from right to left. A. Photo 3-284, taken sometime in the mid-1930s at between 85 and 170 m^3/s. B. Photo 6306, taken sometime in the mid-1930s at between 85 and 170 m^3/s. C. Photo GS-WG 11-141, taken September 25, 1952, at between 252 and 315 m^3/s. D. Photo USGS 011 taken May 14, 1965, at between 710 and 796 m^3/s. E. Photo USGS 023WRD taken June 16, 1973, at between 75 and 170 m^3/s. F. Photos GCES-1-192 and GCES-1-194 taken October 21, 1984, at between 148 and 150 m^3/s. G. Photo GCES 13-10 taken March 24, 1996, at 227 m^3/s. H. Photo GCES 13-9 taken April 4, 1996 at 227 m^3/s. (I on page 46.)



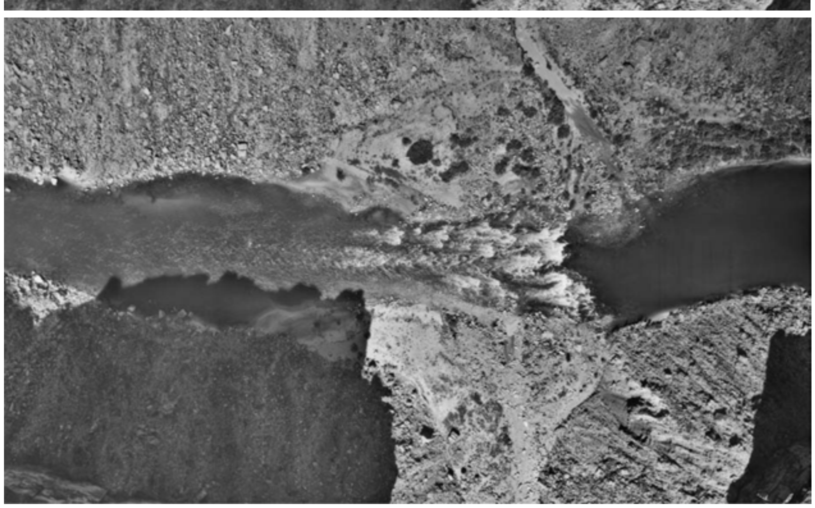


E.

F.

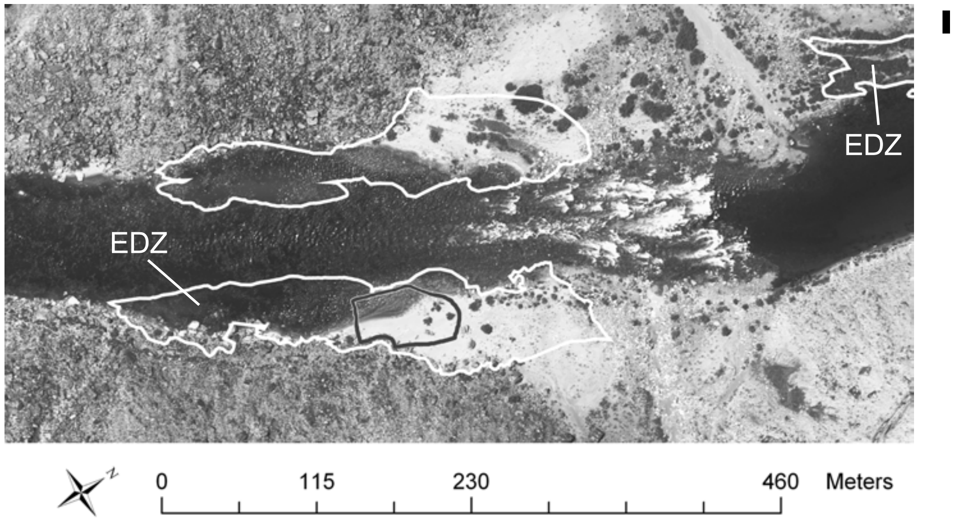


G.



H.

Figure 31, Continued. I. Digital photograph taken between May 24 and June 5, 2002, at 227 m³/s. EDZ boundaries computed from the area of sand in all aerial photographs. Boundary of area surveyed by NAU (site RM8) is also shown in black border.

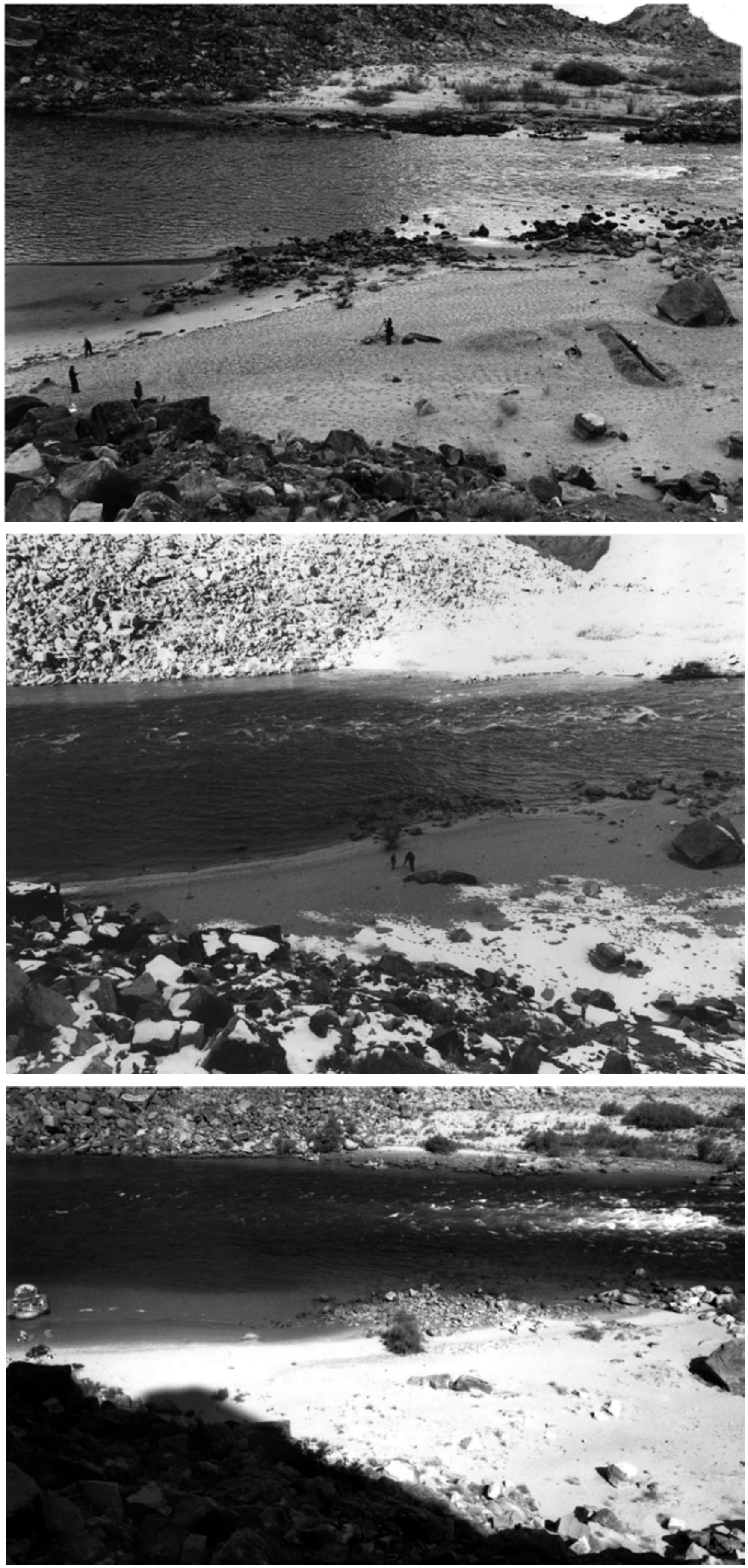


boulders that are probably the distal parts of the underlying debris flow deposits. The bars were also extensive in the early part of the post-dam era, based on the photographs taken in 1964, 1968, 1972, and 1973; saltcedar had become established on river right by 1972. Reattachment bars typically filled the eddies offshore and downstream from the separation bars, and these reattachment bars were typically between 1 and 3 m lower than the separation bars. Parts of these bars were emergent in 1972 and in all prior photographs,

The first significant change in sand distribution that is evident from the photographs is the loss of reattachment bars that occurred before October 1984, because there are no such bars in that aerial photograph (Compare Fig. 31E, F). Very small reattachment bars were redeposited in the 1990s, (Fig. 31G, H, I), but their size was not comparable to that of the 1970s. Erosion of these reattachment bars comprises a significant decrease in sand storage. NAU measured the bed topography of both eddies in February 1996. Comparison of the bed topography with the EDZs indicates that approximately 2.3 and 3.6 m of sand were removed from the river right and river left eddies, respectively. The maximum thickness of sand eroded was 4 m and 6 m on river right and river left, respectively.

During the 1980s and 1990s, the high parts of the separation bars inundated by post-dam floods were eroded and more talus blocks and debris flow boulders were exposed (compare Fig. 32A with subsequent photographs). Erosion of these high areas was progressive

Figure 32. Photographs of the separation bar on river left downstream from Badger Creek Rapids. A. July 8, 1973 (Weeden photograph 1-5) . B. January 11, 1986 (Schmidt et al., 1989, fig. A-5). C. January 12, 1989 (Schmidt et al., 1989, fig. A-5). D. August 3, 1991 (R. H. Webb photograph stake 2018A).



B.

C.

D.

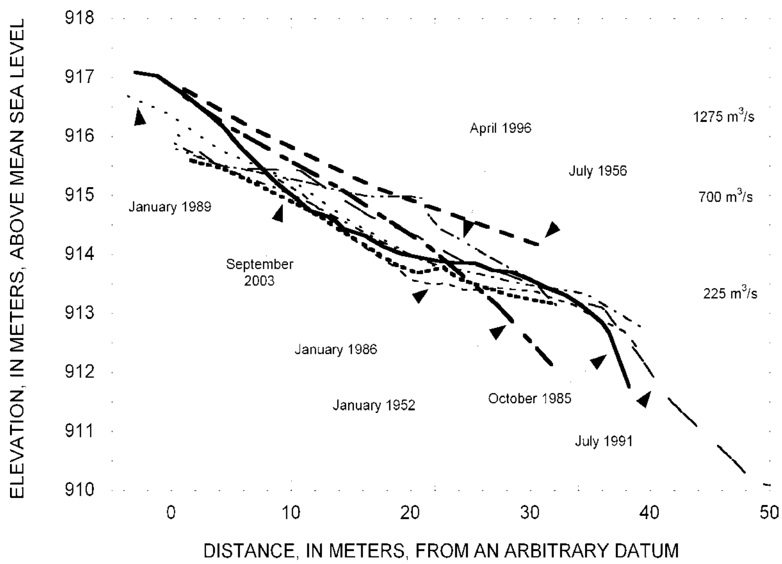


Figure 33. Graph showing changes in topography of the separation bar on river left between the 1950s and September 2003. Stage of indicated discharge is shown. See Figure 10 for location of profile. Thick long-dashed lines are topography reconstructed from oblique photographs in the 1950s. Thick solid line is that surveyed on October 5, 1985, and a thick dashed line is that surveyed in September 2003. The topography upslope from station 10 has progressively lowered since 1985 with total change between 0.5 and 1 m. The 1996 Controlled Flood significantly aggraded the bar near station 20, but the beach berm that was formed was subsequently eroded and topography in 2003 is the lowest it ever was during the measurement period in most of the profile.

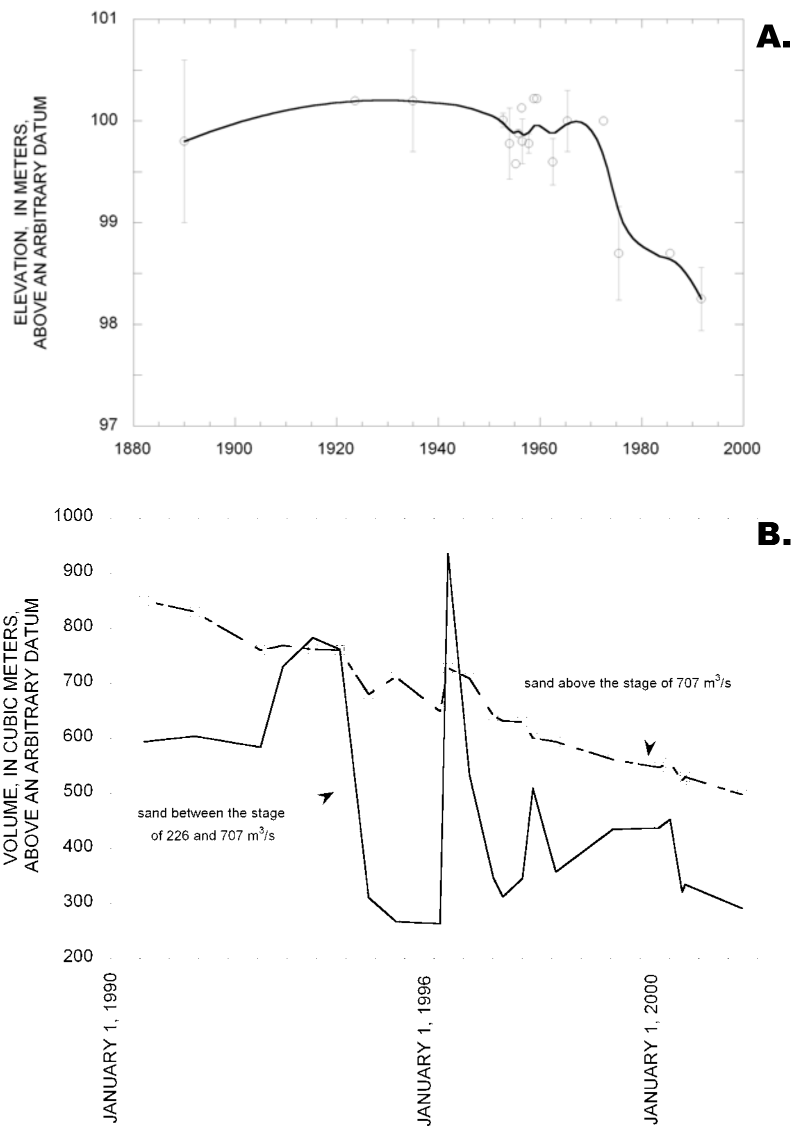


Figure 34. Graphs showing changes in the volume of sand on the separation bar on river left at Badger Creek Rapids. A. Elevation of sand near a large talus block that was only inundated once since completion of Glen Canyon Dam. Here, erosion has been progressive. The location of the talus block is shown on Fig. 29. B. Volume of sand in that part of the bar surveyed by NAU (Fig. 31I). The area above the stage of 707 m³/s is approximately the post-dam flood zone and the area between the stage of 226 and 707 m³/s is the fluctuating flow zone.

and was not reversed. Erosion partly occurred by wind deflation, because the high areas were eroded by more than 0.5 m after 1986 yet were not inundated (Fig. 33). The sand surface surrounding a large talus block near the upstream edge of the separation bar is now approximately 2 m lower than in the early 1970s (Fig. 34A).

The topography of the low parts of the separation bars has been more variable, but the 2003 field survey indicates that the bar was the lowest measured since the mid-1980s (Fig. 33). The total volume of sand surveyed by NAU (Fig. 31I) was less in 2003 than at any time since those surveys began in 1991 (Fig. 34B). The 1996 Controlled Flood deposited approximately 0.3 m of sand on the lower part of the separation bar on river left, based on surveys, excavation of a trench, and recovery of scour chains, and some areas were temporarily restored to pre-dam elevations (Fig. 33A). However, this deposit was completely eroded by 2003. In summary, there is much less sand here today than before construction of the dam. There was nearly complete loss of the reattachment bars and widespread deflation of the high part of the separation bars. The low parts of the separation bars were not progressively eroded, there have been short periods of aggradation, and the low parts of these bars were relatively low in 2003.

6.2 Eminence Break Camp

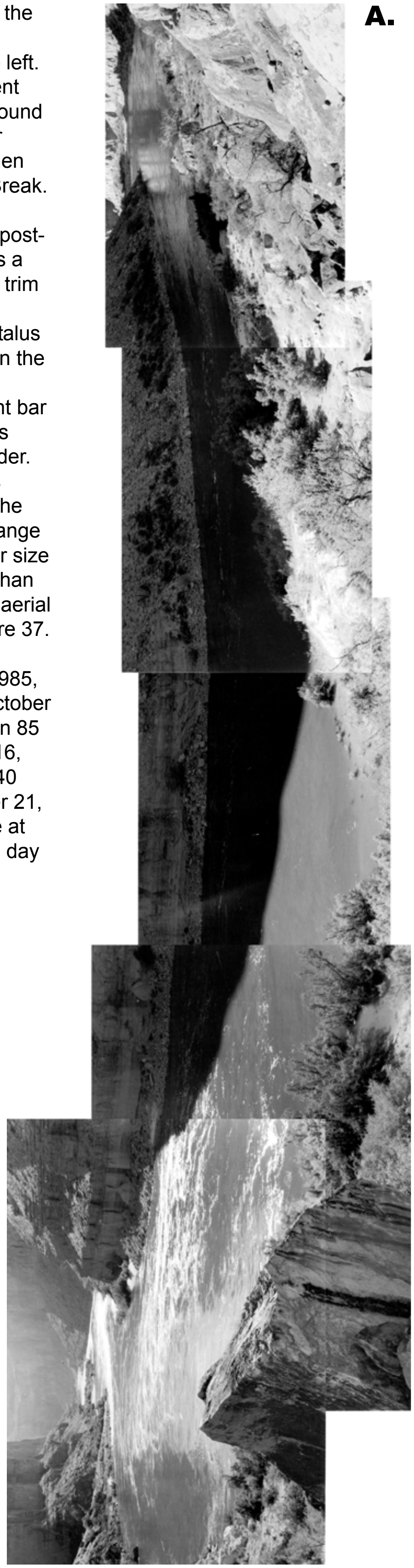
Downstream from River Mile 40, Marble Canyon widens. There are large debris fans, river gradient flattens, and few rapids present navigational difficulty. Sand bars are large in lower Marble Canyon, and campsite opportunities are abundant. One such large camp is an unnamed fan-eddy complex downstream from President Harding Rapid near where the Eminence Break fault cuts across the left canyon wall. This camp is informally called Eminence Break camp.

One typically enters the riffle of this fan-eddy complex near the left bank where the main current has been steered by a large cobble bar on river right (Fig. 35). This bar is only submerged during large releases from the Glen Canyon Dam power plant or post-dam floods. The flow area upstream from the riffle is probably not much larger than in the riffle itself, but the orientation of the flow in the riffle is oblique to the shoreline. This divergence of flow direction and shoreline causes the point of flow separation to occur relatively far upstream along the fan shoreline, and the separation bar covers a large part of the debris fan (Fig. 36). The elevation drop in the riffle is between 0.12 and 0.15 m, which is much less than Badger Creek Rapids. There have not been any significant changes in the debris fan or the gravel bar upstream from the fan, and the present tributary channel through the debris fan developed between the mid-1930s and 1952.

The eddy immediately downstream from the debris fan is very large (Schmidt 1990), and a deep scour hole now exists in the main channel, offshore from the eddy (Fig. 8A). The eddy exists at all discharges between base flow and the pre-dam mean annual flood, based on field observations of surface currents and sedimentologic evidence (Schmidt and Graf, 1990; Leschin and Schmidt, 1995). The direction of surface currents was mapped in the field during the 1996 Controlled Flood, and these measurements show that the eddy increased in length by 24% as discharge increased from 227 to 1275 m^3/s. At base flow, there is a single recirculating cell with many areas of weak or stagnant flow. At 1275 m^3/s, smaller secondary cells of recirculating current exist between the debris fan and the primary eddy.

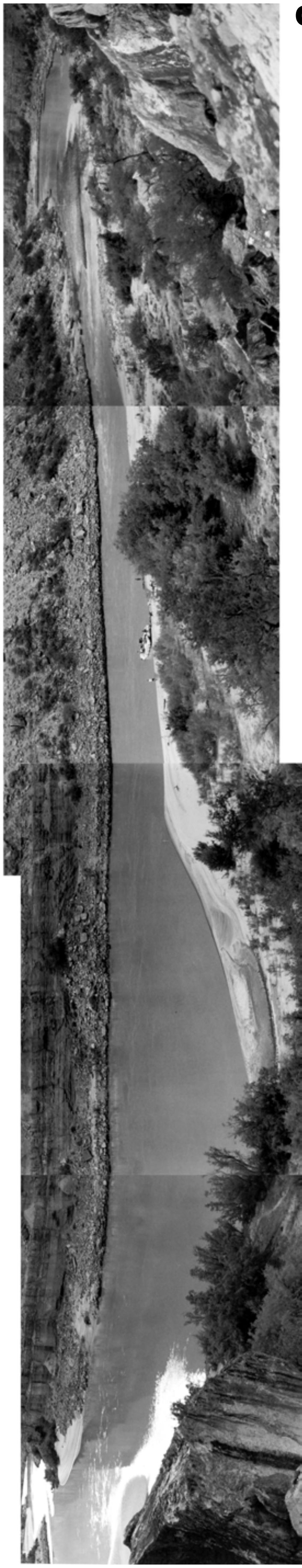
Aerial photographs and frequent topographic surveys since the mid-1980s show that the areas of erosion and deposition during post-dam floods are similar from event to event. Aggradation of the separation and reattachment bars occurs near the shoreline, and erosion occurs further offshore. The net change in the entire eddy depends on the

Figure 35. Photographs of the riffle and eddy at Eminence Break. Flow is from right to left. Flow emerges from President Harding Rapids, sweeps around Point Hansborough, over or around a cobble bar, and then into the riffle at Eminence Break. The May 1985 photograph depicts conditions during a post-dam flood when the stage is a few meters below the lower trim line of the pre-dam riparian vegetation on the opposite talus slope. The separation bar in the foreground is a popular campsite. The reattachment bar that is further downstream is behind the foreground boulder. The position of this bar was remarkably stable through the late 1980s despite a wide range of dam releases, but the bar size is much smaller and lower than was the bar in the pre-dam aerial photographs shown in Figure 37. A. May 25, 1985, 1600 hrs, ~1175 m³/s. B. August 5, 1985, 1000 hrs, ~800 m³/s. C. October 12, 1985, 1730 hrs, between 85 and 125 m³/s. D. January 16, 1986, 1700 hrs, between 340 and 400 m³/s. E. December 21, 1992. Mean daily discharge at the Lees Ferry gage on this day was 317 m³/s.

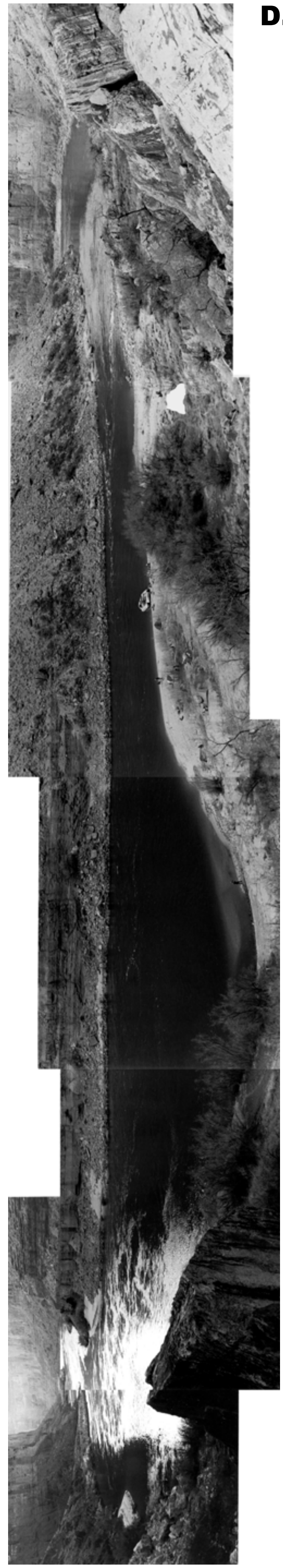


A.

B.



C.

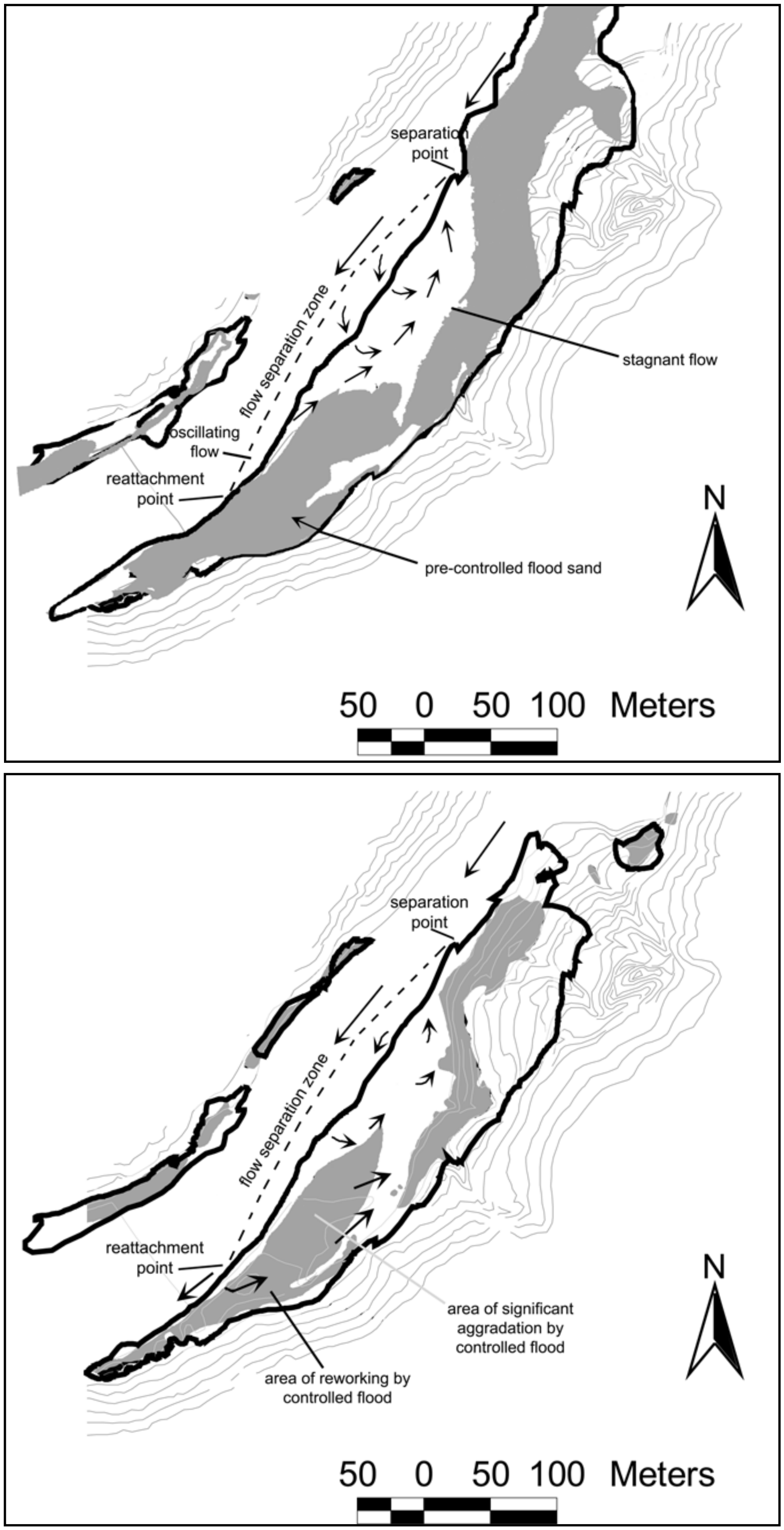


D.

Figure 35, Continued.
E. December 21, 1992.
Mean daily discharge at the Lees Ferry gage on this day was 317 m^3/s.

E.

Figure 36. Maps showing the area of the EDZ and patterns of recirculating flow at (A) 225 m^3/s and (B) 1275 m^3/s, as mapped before and during the 1996 Controlled Flood. Shaded areas indicate the area of emergent sand at 225 m^3/s before the flood and deposits created by that flood, respectively (adapted from Grams and Schmidt, 1999).



relative size of the onshore deposition and the offshore erosion. Daily measurements of bed topography during the 1996 Controlled Flood showed that the aggradation rate was typically less than 1 m per day in most of the eddy (Fig. 37). However, a large subaqueous slump occurred on the first day of the flood; more than 3 m of sand was eroded from the middle of the eddy. Deposition during the subsequent 6 days was typically less than 1 m per day, and the areas of deposition changed from day to day. The area-weighted deposition and area-weighted erosion rates were approximately the same: about 0.3 m/day (Schmidt, 1999). Thus, the initial large amount of erosion on the first day of the flood was not replenished, and the 1996 Controlled Flood caused a net loss of approximately 25,000 m^3 of sand from the eddy (Andrews et al., 1999). Nevertheless, there was a net increase of 1760 m^3 of sand above the stage of 225 m^3/s (Andrews et al., 1999).

A similar pattern of bed change was measured between August and September 2000 caused by the experimental release of September 2000. More than 1 m of sand was eroded from the center of the eddy, but nearshore deposition of less than 1 m occurred near the reattachment point. Low flows between September 2000 and May 2002 typically caused deposition in the areas that had been previously eroded (Fig. 37).

Reworking of flood deposits occurs at low flow and when the bars are subaerially exposed (Fig. 38). Redistribution of sand by canyon winds may be locally extensive; aeolian dunes formed on the separation bars between 1988 and 1996. There is wide variability in the magnitude and style of adjustment of the subaqueous parts of the bars during periods when flows do not exceed 890 m^3/s, however. Although the typical style of bar adjustment has been bank retreat along the entire face of the separation bar, there have been short periods of aggradation. The size and shape of the reattachment bar changes greatly from year to year.

Figure 37. Maps showing changes in topography during the 1996 Controlled Flood and between August 2000 and May 2002 at Eminence Break. Outlined area is EDZ. Topographic changes in A are those during rise of the 1996 Controlled Flood, those of B-G occurred during +6 flood, and those in H on flood recession. I shows changes caused by experimental release in late summer 2000.
A. Topography of March 26, 1966, (Day One of Controlled Flood) and shaded areas depicting topographic change since previous day.
B. Topography of March 27, 1996 (Day Two) and shaded areas depicting topographic change since previous day.
C. Topography of March 28, 1996 (Day Three) and shaded areas depicting topographic change since previous day.
D. Topography of March 29, 1996 (Day Four) and shaded areas depicting topographic change since previous day.
E. Topography of March 30, 1996 (Day Five) and shaded areas depicting topographic change since previous day.
F. Topography of March 31, 1996 (Day Six) and shaded areas depicting topographic change since previous day.
G. Topography of April 1, 1996 (Day Seven) and shaded areas depicting topographic change since previous day.
H. Topography of April 2, 1996 (Day Eight) and shaded areas depicting topographic change since previous day.
I. Topography of September 2000 and shaded areas depicting topographic change since August 2000.
J. Topography of September 2000 and shaded areas depicting topographic change to May 2002.

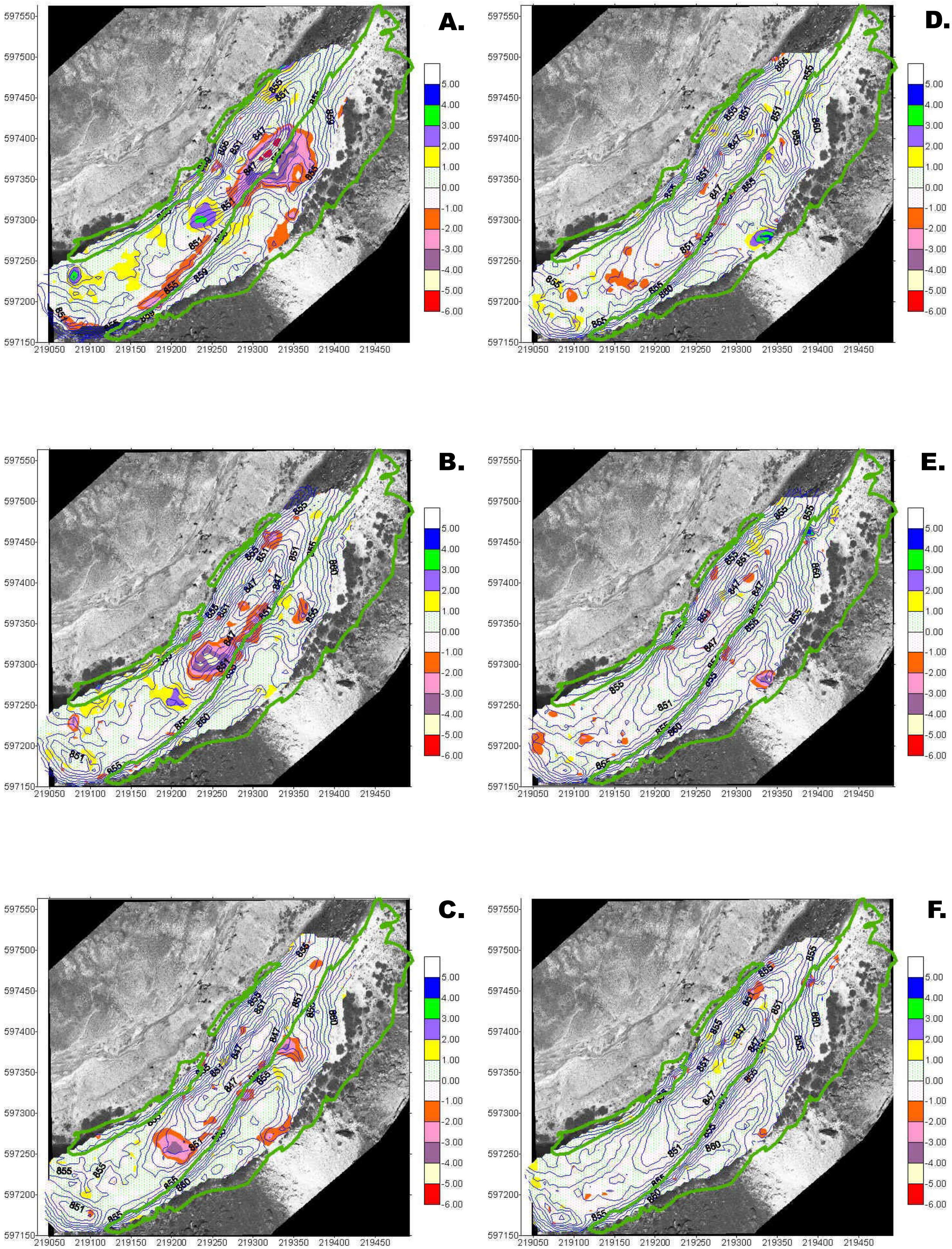

A.
B.
C.
D.
E.
F.
5.00
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00

Figure 37, Continued.

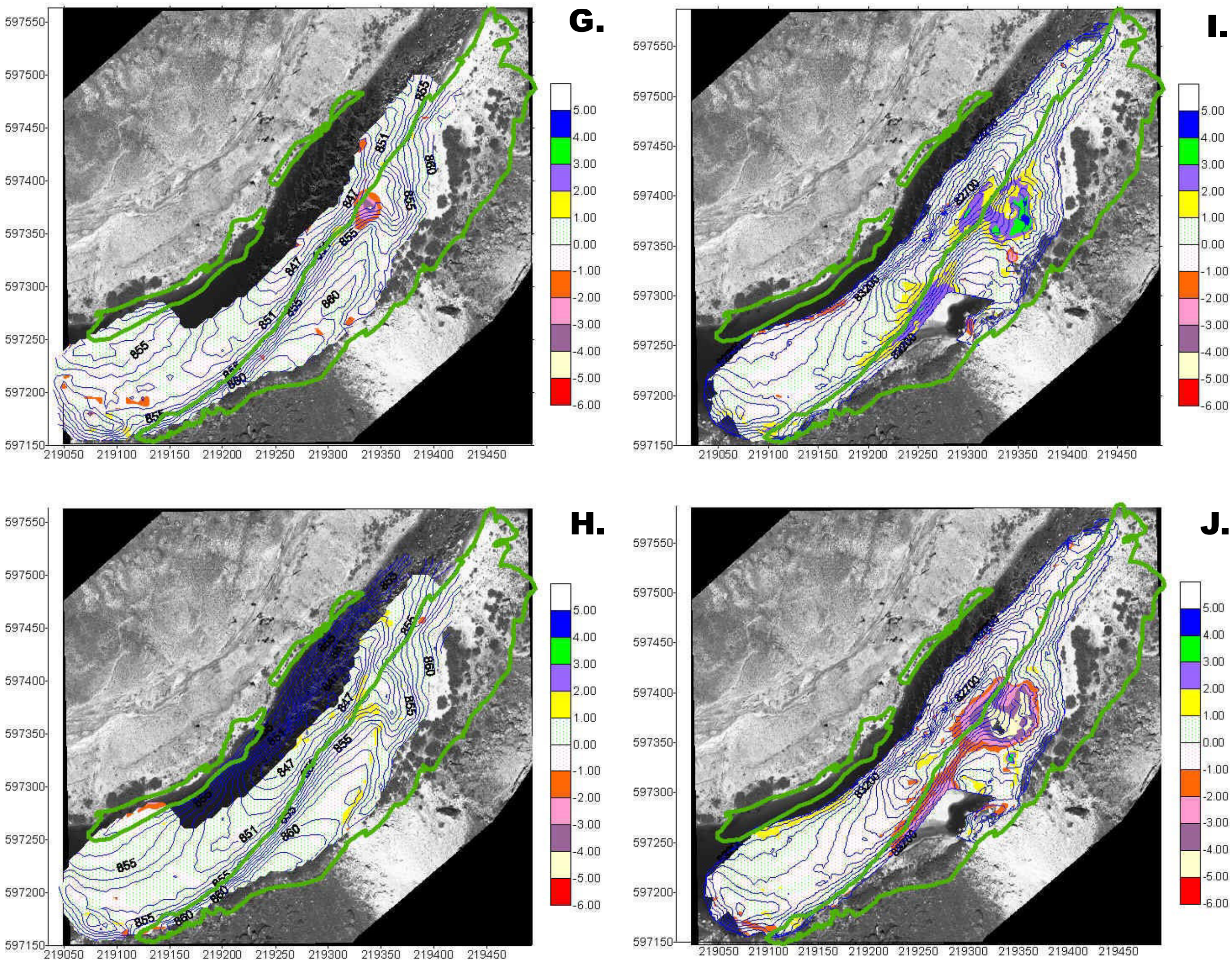
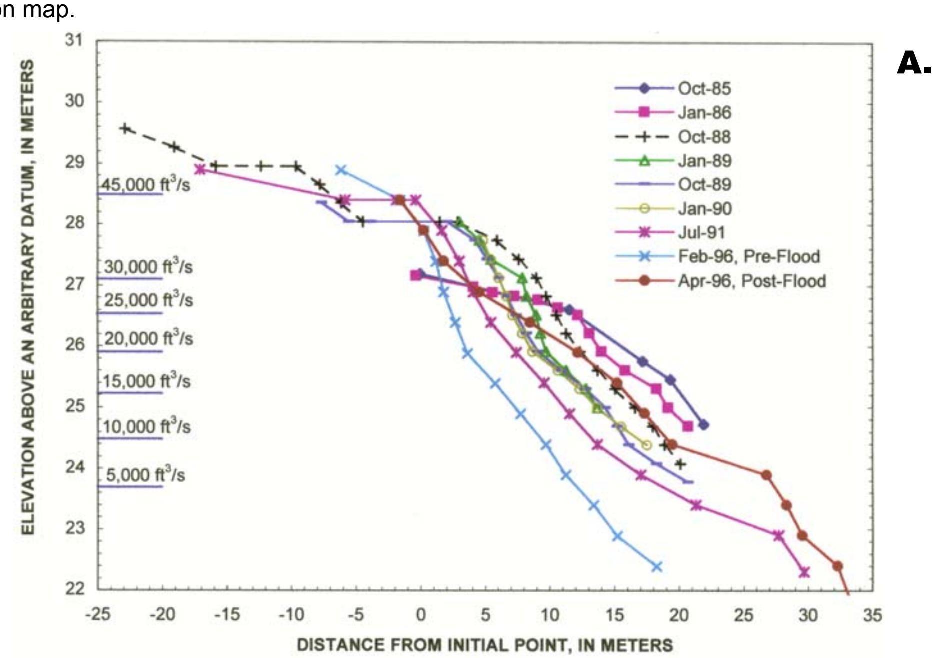
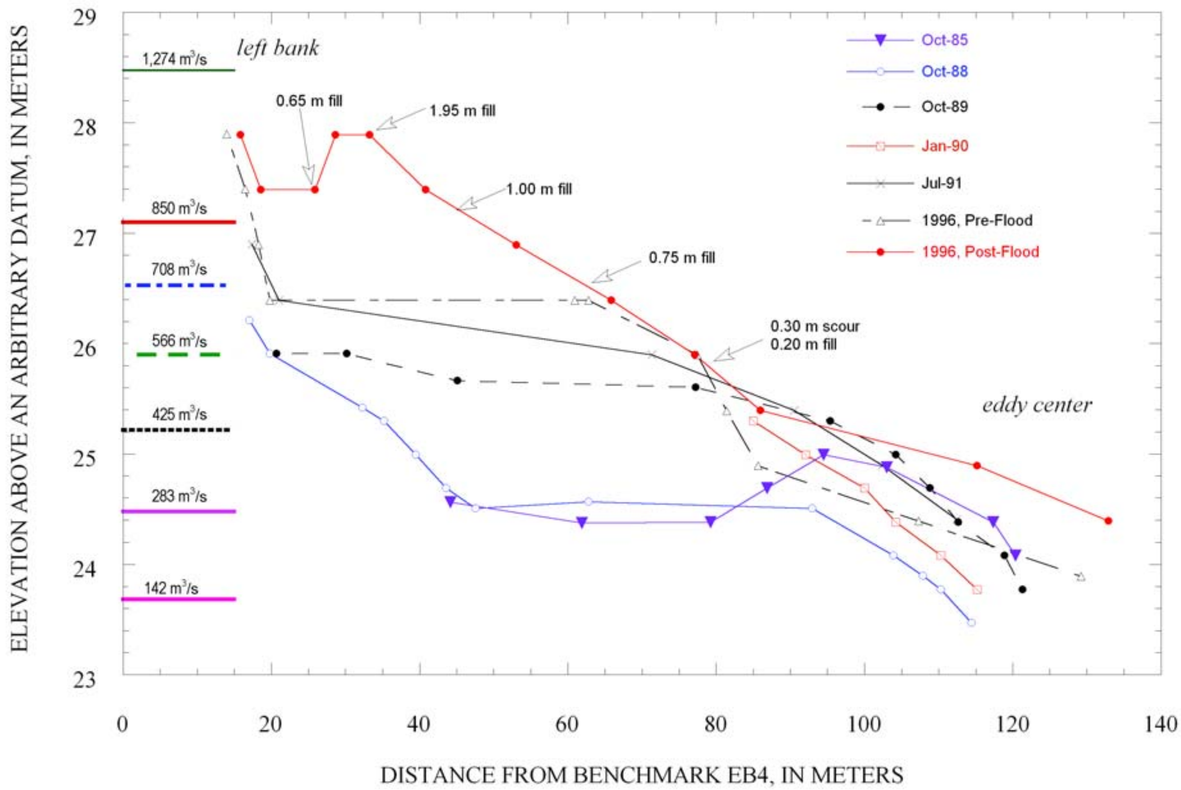


Figure 38. Graphs showing topographic changes of the separation and reattachment bars at Eminence Break since 1985. Note progressive bank retreat in A between October 1985 and February 1996. Increase in elevation on shore from Station 0 between 1985 and February 1996 is an aeolian dune. Note large fluctuations in elevation of reattachment bar. A. Changes along a profile of the separation bar. B. Changes along a profile of the reattachment bar. C. Location map.

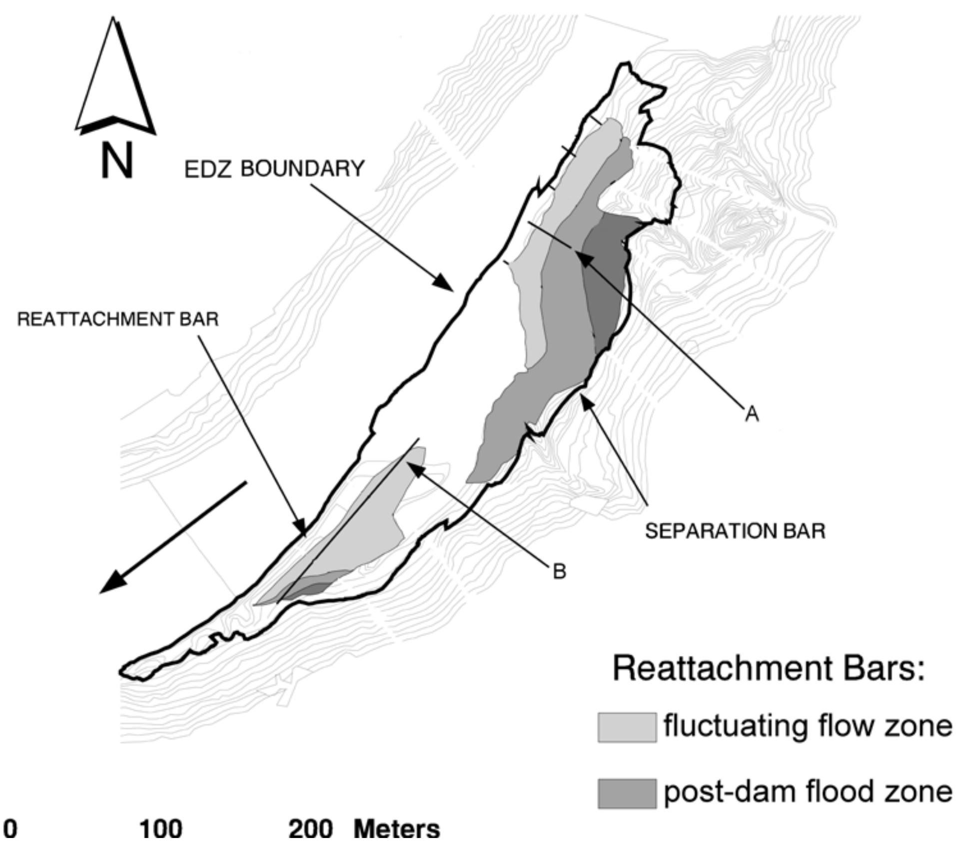


B.



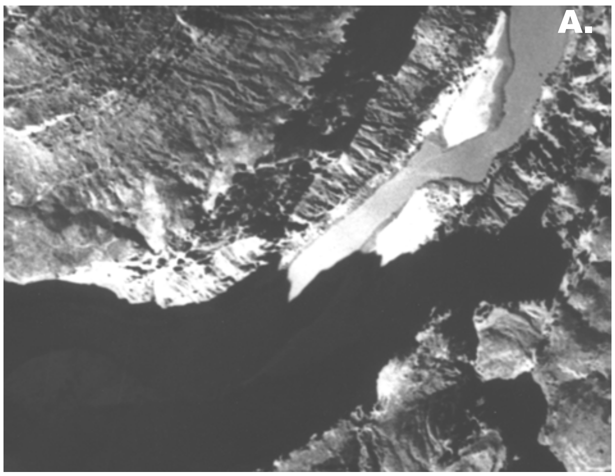
ELEVATION ABOVE AN ARBITRARY DATUM, IN METERS
DISTANCE FROM BENCHMARK EB4, IN METERS
left bank
eddy center
1,274 m³/s
850 m³/s
708 m³/s
566 m³/s
425 m³/s
283 m³/s
142 m³/s
0.65 m fill
1.95 m fill
1.00 m fill
0.75 m fill
0.30 m scour
0.20 m fill
Oct-85
Oct-88
Oct-89
Jan-90
Jul-91
1996, Pre-Flood
1996, Post-Flood

C.

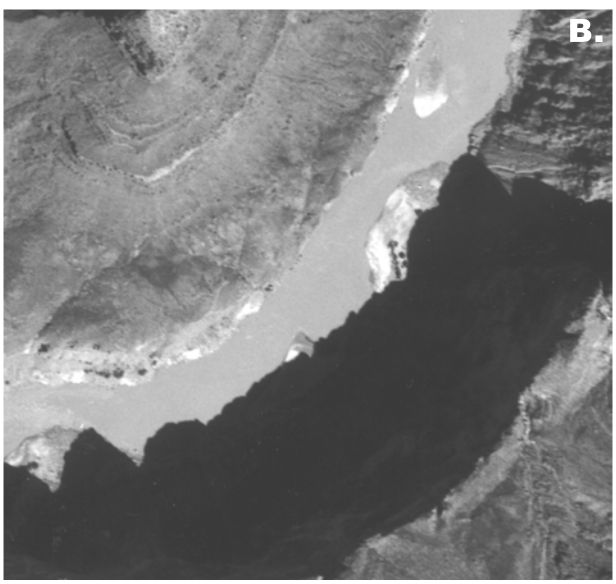


N
EDZ BOUNDARY
REATTACHMENT BAR
A
SEPARATION BAR
B
Reattachment Bars:
fluctuating flow zone
post-dam flood zone
0 100 200 Meters

Figure 39. Photographs of the Colorado River near Eminence Break camp in different years. Note the longer area of reattachment bars in the 1930s (A) and 1950s (B, C) than in any post-dam photograph. A. Photo GC-3?-8434, taken sometime in the mid-1930s at between 85 and 170 m^3/s. B. Photo GS-WG 9-206, taken September 24, 1952, at between 320 and 380 m^3/s. C. Photo GC 56-93-3, taken July 9, 1956, at between 328 and 342 m^3/s. D. Photo USGS 0091 WRD taken May 14, 1965, at between 710 and 796 m^3/s. E. Photo USGS 0124WRD taken June 16, 1973, at between 200 and 303 m^3/s. F. Photos GCES-2-187 and GCES-2-188 taken October 21, 1984, at between 148 and 150 m^3/s. G. Digital photograph taken between May 24 and June 5, 2002, at 227 m^3/s. EDZs are indicated.

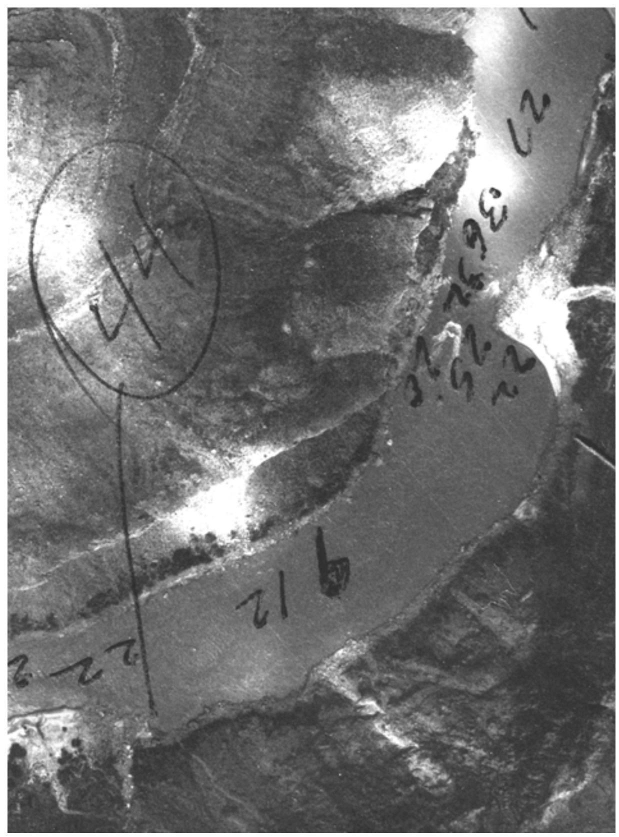


A.



B.

C.



D.

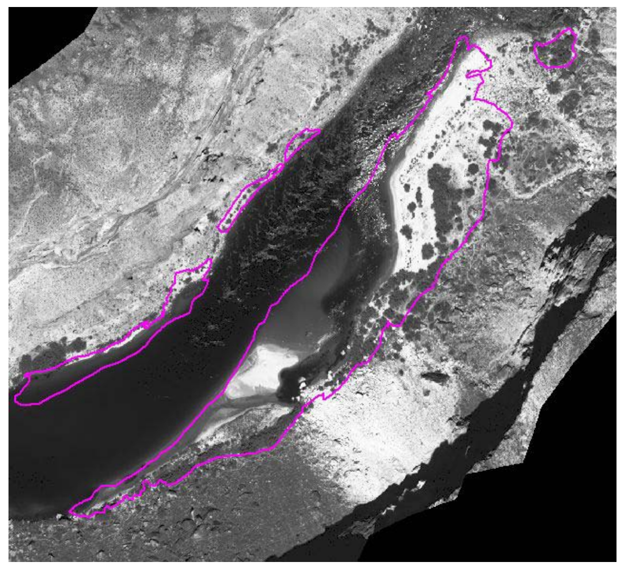
Aerial photographs taken since the 1930s demonstrate that the separation and reattachment bars have been persistent parts of the river landscape (Fig. 39). The separation bar has changed little in size since the 1930s. However, the reattachment bar has decreased in area; the entire bed of the eddy was an emergent sand bar at low flow in the 1930s, but there is only a small, well-defined reattachment bar today.

Available photographs and maps show that riparian vegetation now covers large areas of the separation bar that were formerly bare sand. Riparian shrubs, especially saltcedar,

have increased in number at this site. Some of the largest individual saltcedar plants that exist today can be identified on the 1952 and 1956 aerial photographs, and may have been small plants in the 1930s. The area of saltcedar and willow on the separation bar is larger in each of the post-dam photographs than in any of the pre-dam photographs.

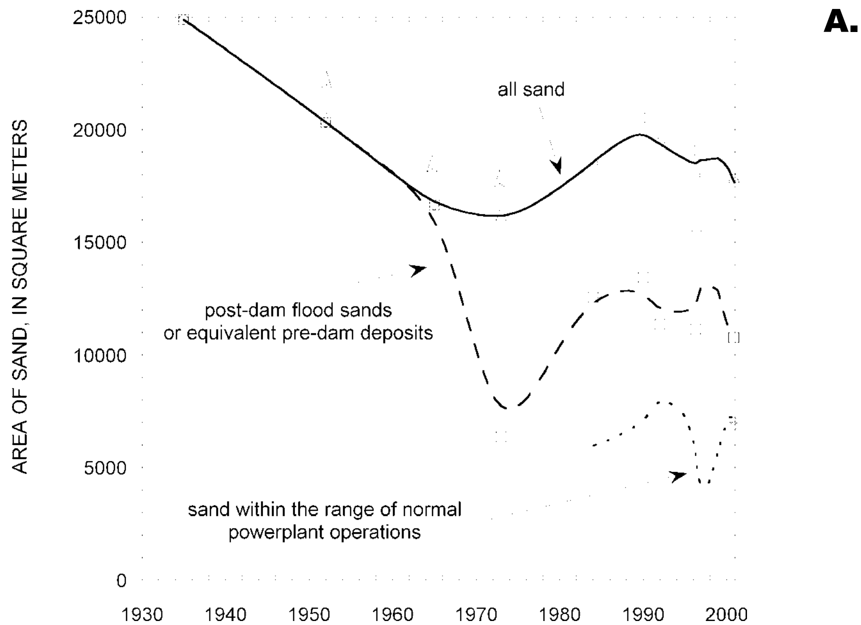
The largest area of exposed sand was in the 1930s when the entire sand bed of the eddy was emergent at base flow (Fig. 39A). The discharge at the time of this photograph was very low, and bare sand extended continuously downstream from the debris fan. There was little relief to this surface and no indication of a primary eddy return current channel separating higher separation and reattachment bars. The bar surface was probably about 1 m above base flow stage. There probably was no recirculating flow at the time of this photograph, because there was no abrupt change in the downstream angle of the banks. The separation bar was partially vegetated upslope from this expanse of sand; it is impossible to interpret the topography of the reattachment bar because of dark shadows.

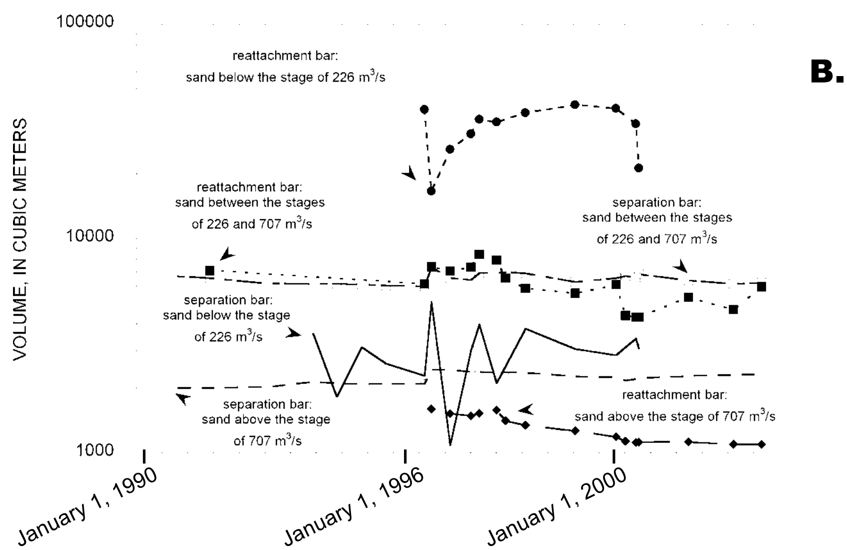

F.


G.

The area of sand at Eminence Break decreased greatly between the 1930s and today. The amount of sand photographed above water level since 1952 has fluctuated between about 16,000 and 20,000 m^2 (Fig. 40A); the area of exposed sand measured in the 1930s photograph was 25,000 m^2. The total area of sand at base flow was larger in 1952, 1965, and 1973 than in subsequent years of photography. At the time of aerial photography in 1952 and 1956, the central part of the eddy was inundated at between 320 and 380 and between 328 and 342 m^3/s, respectively (Fig. 39B, C); separation and reattachment bars were distinct. The reattachment bars were larger in those photographs than in any post-dam photograph, despite the high discharge that was more than twice that at the time of any post-dam photograph. The area of sand

Figure 40. Graphs showing changes in the area of sand at Eminence Break at different elevations in different years. A. Changes in the area of sand, based on mapping of aerial photographs. Vertical arrows with open heads indicate that the area is likely larger than the plotted point, because water stage was significantly higher than at the times other serial photographs were taken. B. Volume of sand in different elevation zones, measured by NAU. Above stage of 707 m³/s is post-dam flood zone. Between stages of 226 and 707 m³/s is fluctuating flow zone. Below 226 m³/s is inundated at base flow.





above normal power-plant operations decreased greatly in the first decade after the dam was completed and subsequently fluctuated in size.

The volume of sand in the post-dam flood zone changed little since 1990 on the separation bar but steadily decreased on the reattachment bar since 1996 (Fig. 40B). Sand in the fluctuating flow zone of the reattachment bar was largest in the years immediately following the 1996 Controlled Flood, but there was erosion of sand in this zone recently. Sand in this zone on the separation bar changed little since 1990. Large year-to-year variations in the amount of sand stored below the stage of base flow were measured during the same period.

7.0 LONG-TERM CHANGES IN FINE SEDIMENT STORAGE SHOWN BY COMPARISON OF OBLIQUE PHOTOGRAPHS

7.1 Previous Studies

Further evidence that there has been a decrease in sand at high elevations throughout the study area is provided by comparison of historical photos with exact matches taken during the past decade. Our findings are consistent with those of Webb (1996) and Webb et al. (2002). Webb (1996) found that sand deposits upstream from River Mile 125 had eroded but that deposits further downstream had not changed much. He reported that there had been extensive erosion of low-elevation sand bars in Glen Canyon, finding that 94% of sand bars inundated by post-dam floods were smaller in the 1990s than they had been in 1889 and 1890. Webb (1996) also found that 83% of similar elevation sand deposits in upper Marble Canyon were smaller during the same time interval.

Webb et al. (2002) interviewed the "Old Timers", individuals who had rafted through Grand Canyon prior to completion of Glen Canyon Dam:

> Most of the Old Timers lamented the current status of sand bars in Grand Canyon, particularly in Marble Canyon (miles 0 to 61); they often pointed to sand bars and noted how small they were. The Old Timers remarked on the severe beach erosion in the reach downstream from Nankoweap Rapid (river mile 53-54) and at the mouth of the Little Colorado River (mile 61.5L) …Nichols commented on the reduction in sand bars at the mouth of the Little Colorado River …
>
> Cross II, who ran the river frequently in the years after closure of Glen Canyon Dam, described the slow, progressive loss of sand bars in Marble Canyon through the 1960s. He believed that wind erosion and human impacts, not large clear-water releases such as the 1965 high flows, were the dominant reasons for the sand bar erosion from 1963, through about the mid-1970s. He used the separation bar at Soap Creek Rapid (mile 11.3) as an example of a campsite that, from his memory, just gradually blew away.
>
> Rigg thought that the sand-bar erosion downstream from Nankoweap Creek was probably the greatest of any place in Grand Canyon. What formerly was a sand-lined channel is now a reach lined with gravel bars.

Matched oblique photography taken in the late 1960s and early 1970s did not reveal extensive decreases in area of sand, indicating that the rate of bar change was slow at that time. Stephens and Shoemaker (1987) matched photographs taken during the second Powell Expedition, spanning the period between 1872 and 1968. In many cases, differences in water stage precluded the opportunity to compare changes of sand in the fluctuating flow zone, but there were some decreases in sand in the post-dam flood zone. Ten images were compared in the study area. There was less high elevation sand in 3 of these images and in no case was there more sand in 1968 than in 1872 (Table 8). Turner and Karpiscak (1980) matched 13 images between Lees Ferry and Bright Angel Creek for which the size of sand deposits was compared. These photo matches span the interval between early to mid-20th century to the early 1970s (Table 9). There was relatively little change in sand deposits detectable in these matches, but there was a large increase in the area of riparian vegetation.

7.2 Methods and Results

We compared 79 photo matches, most of which were provided by R. H. Webb from his extensive photoarchives (Appendix A). Some of these photos had been analyzed previously by Webb (1996) and Webb et al. (2002). We examined each photo match and located the site by river mile and by EDZ. We qualitatively assessed the volume of fine

Table 8. Comparison of the area of sand depicted in photographs taken during the Second Powell Expedition and matched by Stephens and Shoemaker (1987). NA means no analysis is possible.

Camera Station	location	Change in sand in post-dam flood zone	Change in sand in fluctuating flow zone
820	Mouth of Tiger Wash	NA	less
445	Near Shinumo Wash	NA	NA
849	Below Redwall Cavern	less	NA
850	Below Redwall Cavern	same	same
854	Below Saddle Canyon	same	same but more riparian vegetation
856	Little Nankoweap Creek	same	same but more riparian vegetation
894	Immediately above LCR	less and more riparian vegetation	NA
766	Gravel island at LCR	less	NA
885	LCR	NA	NA
451	Above Lava Chuar Rapid	less	NA
858	Above Lava Chuar Rapid	same but more riparian vegetation	NA
605	Near Escalante Creek	same but more riparian vegetation	NA
866	Near Escalante Creek	same but more riparian vegetation	NA
449	Sockdolager Rapids	NA	NA

Table 9. Summary of changes in sand bars depicted in historical photo matches taken by Turner and Karpiscak (1980)

		Change in sand in post-dam flood zone	Change in sand in fluctuating flow zone
35	4-Mile Wash	Same but more riparian vegetation	NA
36	Badger Creek Rapid	~ 2 m of deflation of separation bars	NA
37	Above Soap Creek Rapids	Same but more riparian vegetation	NA
38		Same but more riparian vegetation	NA
39	24 $^{1}/_{2}$ Mile rapids	NA	less
40	Above Silver Grotto	NA	NA
41	Vaseys paradise	NA	less
42	Redwall Cavern	same	same
43	Triple Alcove	Same but more riparian vegetation	NA
44	Below Nankoweap	Same but more riparian vegetation	Less; more gravel
45	LCR confluence	NA	more
47	Above Lava Canyon rapid	Same but more riparian vegetation	NA
48	Above Hance rapid	Same but more riparian vegetation	NA
49	Above Grapevine Rapid	NA	NA
50	Bright Angel debris fan	same	same

sediment visible near water's edge (fluctuating flow zone) and in the post-dam flood zone. Changes in sand in the post-dam flood zone were evaluated in 51 images; there was more sand in the recent photo in 2 of these matches and less sand in 16 matches. There was no apparent change in the other 33 matches. Changes in sand in the fluctuating flow zone were evaluated in 58 images; there was more sand in 3 images and less sand in 31 images. There was no apparent change is the other 24 images. These results are consistent with those reported by others and indicates that, on average, there was more sand on the banks and in the eddies of the Colorado River before Glen Canyon Dam was completed than exists today.

7.2.1 Description of change depicted in some of the photographs

A photograph match of channel-margin and mid-channel bars near River Mile 1.6 spans the period between 1897 and 1994 and shows that high banks of unconsolidated sand once lined the channel during the low flow season (Fig. 41). The 1897 photograph was taken at a very low discharge; December was a month of low discharge in the pre-dam river. Discharge at the time of the photograph was perhaps as low as 150 m^3/s, because the mid-channel bar in the foreground of the photograph is exposed. The vertical banks of sand in 1897 were probably more than 2 m high, and the top of the bare sand bar extended to elevations inundated in the post-dam era by flows that exceed the capacity of the power plant. The mid-channel gravel bar in the foreground had a sand bar extending from its lee, and there is no sand in the channel at this location today. The channel-margin bar is now inundated by power-plant flows, and a narrow linear bank of sand exists along the bedrock wall; this sand deposit is only inundated by post-dam floods. Much of this bar is now composed of gravel derived from the small tributary on the right, and the gravel is derived from eroding Pleistocene terraces that overlie the Kaibab Limestone of the canyon rim.

Not all sand bars have decreased dramatically in size, as illustrated by the photograph match at Redwall Cavern, located at River Mile 33. Freeman photographed this reattachment bar on August 8, 1923, and the area of sand was extensive (Fig. 42). Discharge was about 540 m^3/s at the time of the photograph, based on measurements at the Lees Ferry gage. A 1-m high vertical cutbank occurred at water's edge and former shorelines occurred up slope. Webb's match, taken on September

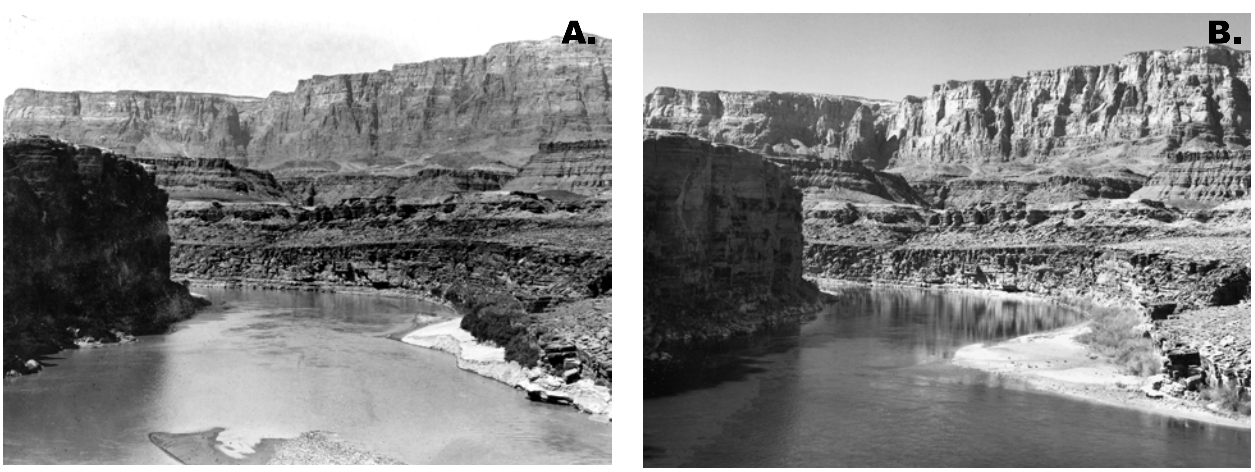


Figure 41. Photographs depicting the Colorado River channel in 1897 and 1994 near River Mile 1.9. The location of the photograph view is shown in Figure 7, and the view is downstream. Note the large amount of sand on river right. A. Photograph taken by G. W. James on December 1, 1897. B. Photograph taken by R. H. Webb on February 24, 1994. Stake 2800.

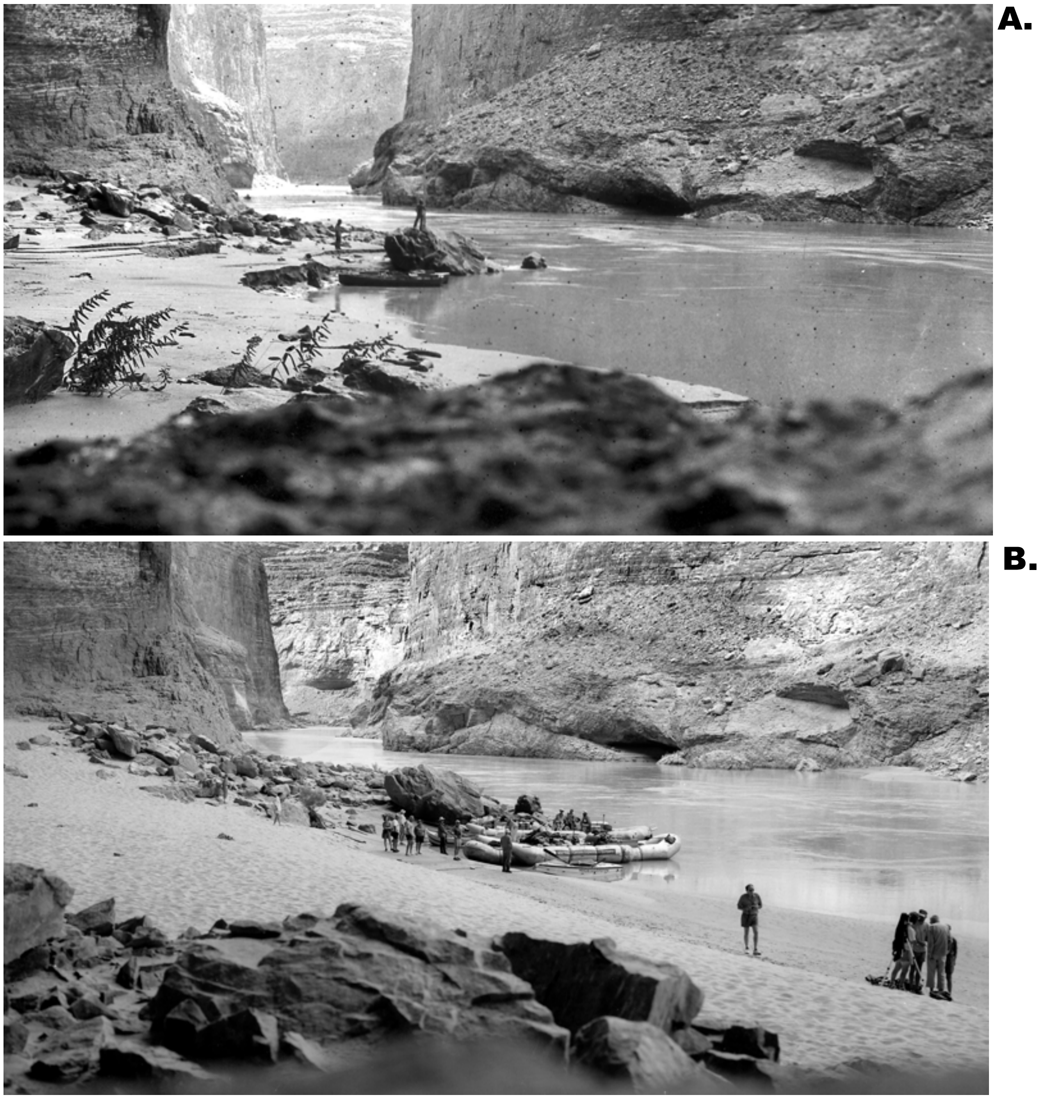


Figure 42. Photographs of Redwall Cavern at River Mile 33.3. A. August 8, 1923, taken by Freeman. Mean daily discharge at the Lees Ferry gage on this day was 538 m^3/s. B. September 10, 1994, taken by Webb. Stake 676. Instantaneous discharge at the Lees Ferry gage on this day was between 230 and 357 m^3/s.

10, 1994, depicted a gradually sloping shoreline, but the approximate volume of sand at this site is similar to that photographed in 1923. Examination of several other photos taken at Redwall Cavern indicate that there was relatively little fluctuation in the size of this sand bar.

Several matches of a 1923 photograph beneath Triple Alcoves looking downstream by E. C. LaRue depict the interplay of effects associated with changes in flow regime and invasion of riparian vegetation. These photographs illustrate the extent to which bare sand was overgrown by saltcedar in the 1970s and early 1980s and the slight scour and fill in densely vegetated areas caused by the floods of the mid-1980s. The 1923 photograph shows a small debris fan with bare sand bars upstream and downstream (Fig. 43). The eddy downstream from the debris fan was nearly filled by a sand bar; the central part of the eddy was low-elevation wet sand and the distant deposit was a high-elevation reattachment bar. R. M. Turner's match of this site on October 8, 1982, showed that only the sand in the immediate foreground was still bare, and all other sand was overgrown with saltcedar. New sand deposits from the 1983 flood can be seen in an October 20, 1983, photograph, and some of these deposits covered areas that had been

Figure 43. Photographs of the river corridor near Saddle Canyon. The view is downstream and was taken beneath Triple Alcoves, near River Mile 47.0.. The photo site is R. H. Webb stake 798. A. 1923 photograph taken by E. C. LaRue. Discharge was between 500 and 600 m^3/s. B. 1976, photograph by R. M. Turner. C. October 8, 1982, when instantaneous discharge at the Lees Ferry gage was between 234 and 488 m^3/s. D. October 20, 1983, when instantaneous discharge at the Lees Ferry gage was between 678 and 748 m^3/s. E. August 15, 1984, when instantaneous discharge at the Lees Ferry gage was between 1029 and 1220 m^3/s. F. 1990 match by R.H. Webb.

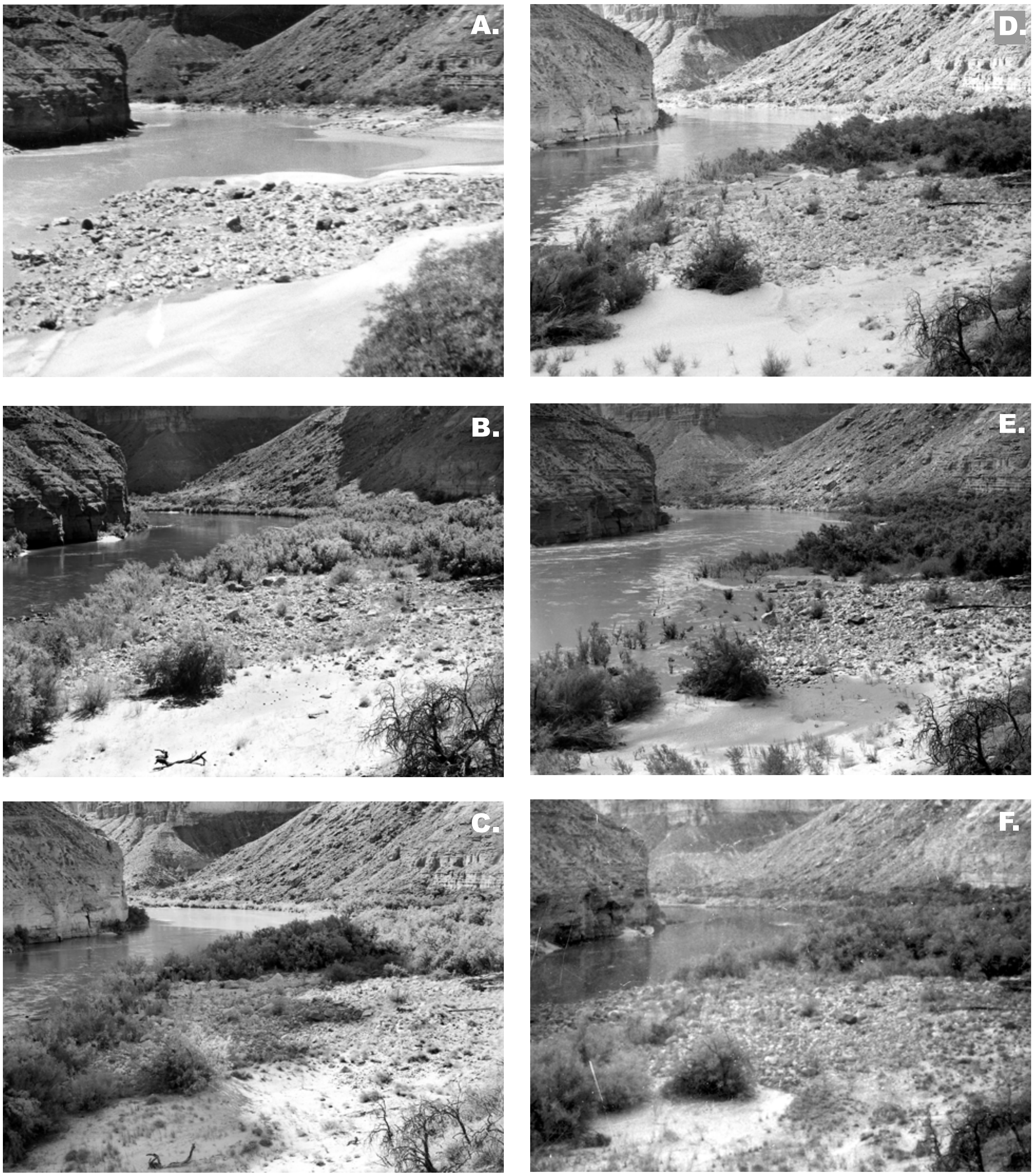
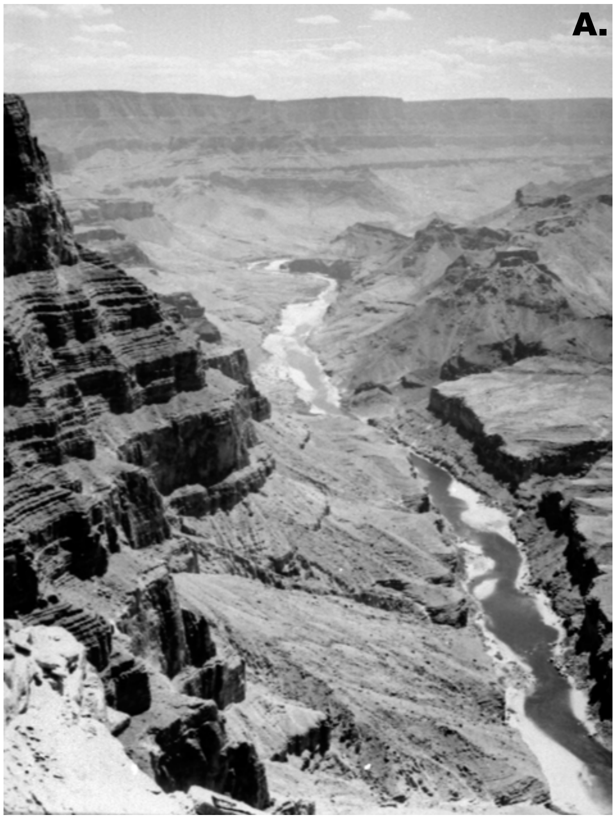
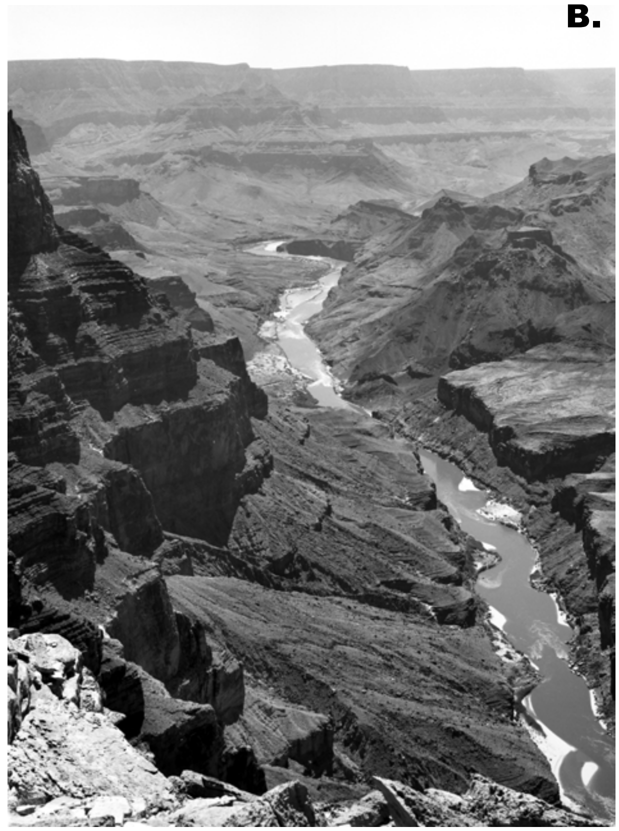
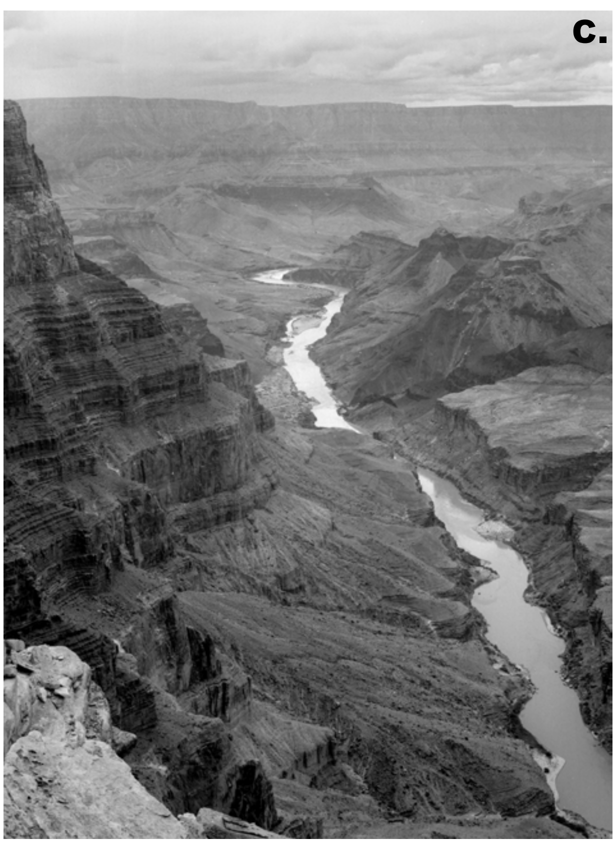


Figure 44. Photographs of the Colorado River in the Tapeats Gorge, taken from Cape Solitude. The view is downstream. A. Blaisdell photograph taken on July 13, 1963, when the mean daily discharge at the Grand Canyon gage was 37 m^3/s. B. R. H. Turner match taken September 2, 1973, when mean daily discharge at the Grand Canyon gage was 219 m^3/s. C. R. H. Webb match taken May 24, 1992, when mean daily discharge at the Grand Canyon gage was 268 m^3/s.







dense saltcedar groves in 1982. A photograph taken on August 15, 1984, depicted water stage at between 1000 and 1200 m^3/s. Releases from the dam had been as high as 1585 m^3/s a few days before this photograph was taken, and wet sand extended about 0.5 m above the stage at the time of the photograph. Thus, most of the sand photographed in 1983 was in the post-dam flood zone.

Blaisdell's photograph of the Tapeats Gorge from Cape Solitude taken in July 1963 depicted the river at extremely low flow: discharge was only about 37 m^3/s at the time of the photograph (Fig. 44). The river banks in 1963 were continuously lined by sand or debris flow deposits, and there are few eddies. Higher water levels at the time of the 1973 and 1992 photographs make it difficult to compare with the conditions in 1963, but the 1992 photograph seemed to depict less sand than in 1973.

8.0 CHANGES IN THE AREA OF FINE-GRAINED ALLUVIAL DEPOSITS DETERMINED BY AERIAL PHOTOGRAPH ANALYSIS

Rich temporal records of sand bar change at specific sites have the advantage of describing detailed attributes of bar adjustment. However, these detailed analyses can only be described at a few places. Thus, uncertainty arises about the representativeness of these temporal patterns. Aerial photograph analysis provides the opportunity to place detailed descriptions of sand bar change at a few places into a larger spatial context. Inspection of aerial photographs allows measurement of every sand deposit, albeit with greater imprecision. Temporal resolution is sacrificed, because there are relatively few years when aerial photographs were taken, and imprecision is introduced because of the poor quality of some photographs. Another limitation of aerial photograph analysis is that changes in the area of sand deposits do not necessarily reflect changes in volume of sand deposits; the former are readily measured on aerial photographs yet the latter values are necessary for calculating sediment budgets. Nevertheless, conclusions drawn from analysis of aerial photographs are spatially robust because of the large sample size, and conclusions based on robust data can be used to infer changes in sand volume. In this section, we analyze changes in the distribution of sand deposits as detected from analysis of aerial photographs. We show that the loss of pre-dam sand evident at specific sites and from comparison of historical oblique photographs is widespread. Today's Colorado River corridor has much less sand along its margins than did the river prior to completion of Glen Canyon Dam.

8.1 Methods

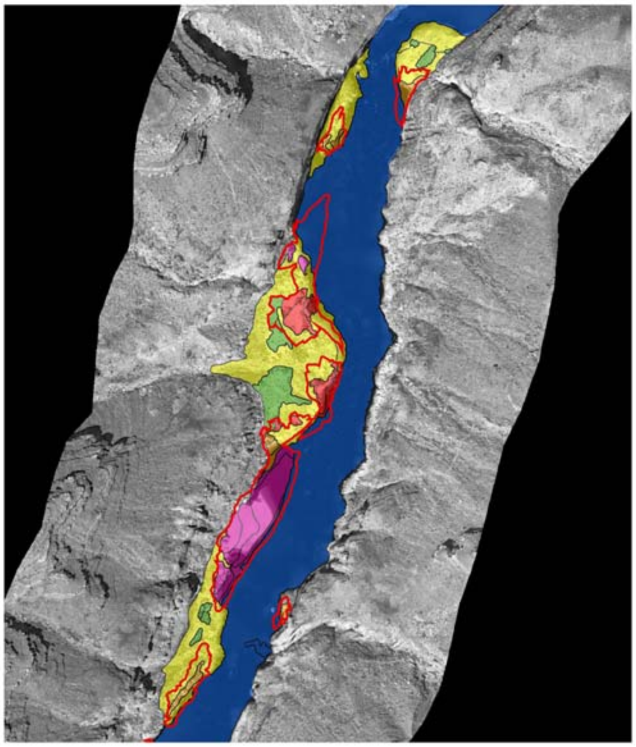
We measured the area of fine sediment in 5 study reaches (Fig. 1). These study reaches were mapped by Leschin and Schmidt (1995), Schmidt et al. (1999b), Sondossi (2001), and Sondossi et al. (2002). The data comprise a census of all sand deposits in the 5 study reaches, and issues associated with estimating population characteristics from sampling data are eliminated. Fine-sediment deposits were mapped on transparent overlays of aerial photographs. Aerial photographs taken between the mid-1930s and fall 1997 were analyzed; photographs taken after April 1996 were only analyzed in some reaches (Table 10). Map units (Table 11) were adapted from Hereford (1996). Coarse-sediment deposits were not mapped on those large-scale photographs that were of poor clarity.

Fine-sediment deposits were distinguished as channel-margin deposits or eddy bars (Fig. 45). The latter were distinguished by characteristic topographic features described by Schmidt and Graf (1990), Rubin et al. (1990), and Schmidt and Rubin (1995), and these bars were subdivided into separation or reattachment bars where appropriate.

Fine-sediment deposits were also distinguished by formative discharge, defined as the smallest discharge that inundates a specific level. The classification by formative discharge was based on the relative elevation of different sand deposits, field observations of the location of water's edge made by the senior author since 1984, inspection of October 1984 and April 1996 photography when higher elevation deposits had recently been inundated, and model predictions of stage. Post-dam flood deposits were subdivided into flood sands of 1983, high flow sands of 1984, 1985 and 1986, and the deposits of the 1996 Controlled Flood.

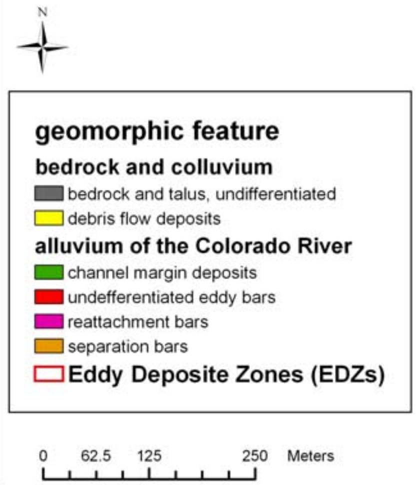
Inspection of the October 1984 photographs was especially helpful in defining formative discharge, because there had been nearly 2 months of steady discharge at about 1275 m^3/s in spring 1984, and flows were reduced quickly to 675 m^3/s in June. Thereafter, discharge was approximately 675 m^3/s for about 80 days prior to the days of photography

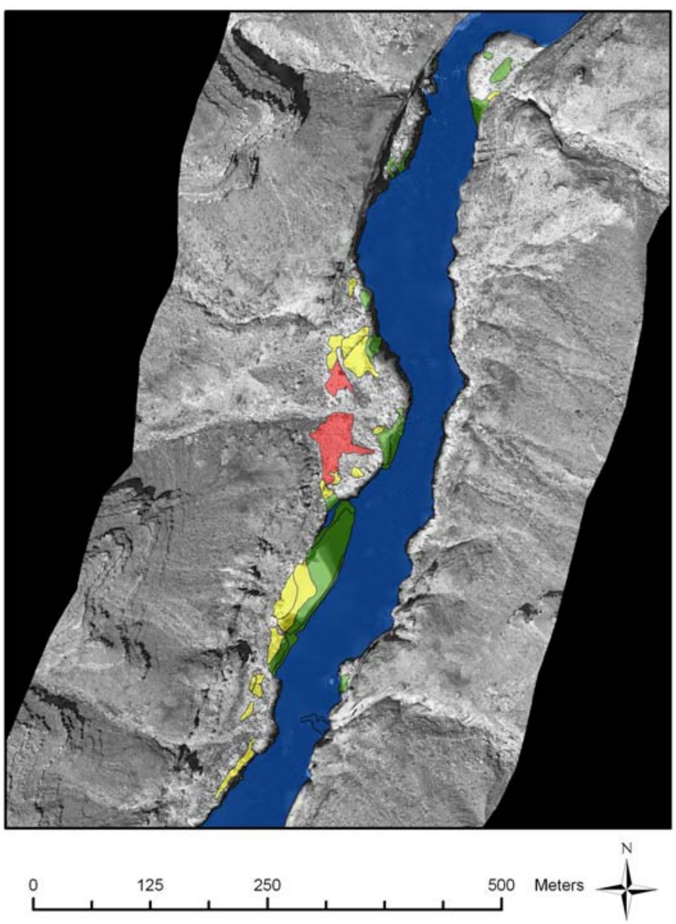
Figure 45. Maps showing types of sand deposits and the topographic levels at which they occur in the Redwall Gorge Reach. Flow is from top to bottom. Mapping such as this was analyzed within a GIS in order to determine historical change in sand deposits. RM30 is an EDZ monitored by NAU.



A.

A. Surface deposits, as they existed in October 1984. See legend for map units and Table 11 for unit descriptions.





B.

B. Formative discharge of fine sediment deposits.

- red is pre-dam flood zone.
- yellow is post dam flood zone.
- green is fluctuating flood zone.

Table 10. Aerial photographs analyzed in this study

Date	Agency and Series	Reach	Discharge at the time of photography, in cubic meters per second
Mid-1930's	3-282 to 3-284 6298 to 6299 6305-6306	Lees Ferry	85-170
	138 to 141	Redwall Gorge	
	143 to 147 8433 to 8436	Point Hansbrough	
	100 to 107 152 to 153	LCR[3]	
April 16, 1949	389 to 392 VT55RTM532311AD	LCR	674[2]
September 24, 1952	9-211 to 9-213	Redwall Gorge	320-380[1]
September 24, 1952	9-205 to 9-208	Point Hansbrough	320-380[1]
September 25, 1952	11-93 to 11-94 11-113 to 11-114 11-138 to 11-142	Lees Ferry	252-315[1]
October 8, 1952	20-52 to 20-54	Lees Ferry	174-179[1]
August 18, 1954	7-68 to 7-71 GS-VCF	LCR	121-156[1] 119[2]
September 14, 1954	8-117 to 8-119	LCR	240-275[1] 269[2]
July 9, 1956	95VV17PLR17/461	Point Hansbrough	328-342[1]
July 9, 1956	129 to 133 VV17PLR17/461	LCR	328-342[1] 357[2]
September 21, 1958	2-25 to 2-29 2-41 to 2-42	Lees Ferry	186-201[1]
May 14, 1965	USGS 001-012	Lees Ferry	710-796[1]
May 14, 1965	USGS 061-070	Redwall Gorge	710-796[1]
May 14, 1965	USGS 080-099	Point Hansbrough	710-796[1]
May 14, 1965	USGS 113-136	LCR	710-796[1] 705[2]
June 16, 1973	USGS 002-022	Lees Ferry	75-303[1]
June 16, 1973	USGS 075-091	Redwall Gorge	75-303[1]
June 16, 1973	USGS 114-135	Point Hansbrough	75-303[1]
June 16, 1973	USGS 153-183	LCR	75-303[1] 280[2]
October 21, 1984	GCES 1-115 to 1-194	Lees Ferry	148-150[1]

[1]Range of instantaneous discharge at the Lees Ferry gage for that day (Topping et al., 2003)
[2] Mean daily discharge at the Grand Canyon gage
[3] LCR includes Tapeats Gorge Reach and Big Bend Reach

Continued on following page.

Table 10, Continued.

Date	Agency and Series	Reach	Discharge at the time of photography, in cubic meters per second
October 21, 1984	GCES 2-86 to 2-125	Redwall Gorge	148-150[1]
October 21, 1984	GCES 2-176 to 2-221	Point Hansbrough	148-150[1]
October 22, 1984	GCES	LCR	150-711[1] 164[2]
June 2, 1990	GCES 11-1 to 13-17	Lees Ferry	137-138[1]
June 2, 1990	GCES 23A-1 to 25-8	Redwall Gorge	137-138[1]
June 2, 1990	GCES 29-2 to 32-10	Point Hansbrough	137-138[1]
June 2, 1990	GCES 37-10 to 50-5	LCR	137-138[1] 170[2]
October 11, 1992	GCES 34-4 to 37-9	Point Hansbrough	227
	GCES 42-11 to 48-7	LCR	227
May 30, 1993	GCES 33-1 to 37-6	Point Hansbrough	227
	GCES 42-11 to 48-7	LCR	227
March 24, 1996	GCES 11-1 to 13-17	Lees Ferry	227

[1]Range of instantaneous discharge at the Lees Ferry gage for that day (Topping et al., 2003)
[2] Mean daily discharge at the Grand Canyon gage
[3] LCR includes Tapeats Gorge Reach and Big Bend Reach

when flow was decreased to 150 m^3/s. The shoreline of the higher flows is obvious on the aerial photographs. The zone between 150 and 675 m^3/s was mapped as the fluctuating flow zone; fluvial bed forms occur on many of these deposits. Sand deposits whose base terminated in the fluctuating flow zone and whose flat upper surface was recently reworked alluvial sand were mapped as high flow sands of 1984. Some riparian vegetation was uprooted or covered by the sand in this zone. Other vegetation was bent down, providing evidence of local flow directions during inundation. Elsewhere, higher deposits of bare sand deposited in 1983 were evident and mapped as flood sands of 1983. These deposits had some small plants growing from their surface but generally retained the appearance of recent reworking.

The map units applicable to the 1984 photographs, and subsequent years, could not be applied to the earlier photograph series. Map units in earlier photograph series were distinguished as submerged, wet, bare, and upper sands. Submerged and wet sand units were identified by the same criteria as used for the post-1984 photographs. The bare sand areas were distinguished as dry sand deposits composed of unvegetated, nearly uniform white sand. The upper sand category was applied to the high, vegetated areas.

Sand deposits in the fluctuating flow zone could not be compared among all of the photograph series, because discharge was high in some years and low in others. There was a large difference in stage at different places in the 1973 photograph series, because dam releases varied between 75 and 300 m^3/s; thus, fluctuating flow deposits were not compared among reaches in 1973. Dam releases were held at constant base flow when photographs were taken in 1984 and subsequent years, which allowed comparison among reaches. However, there were small differences in stage among the photo series because base flows were between about 150 m^3/s in 1984 and 1990 and approximately 227 m^3/s in 1992 and

Table 11. Description of units used in pre- and post-controlled flood geomorphic maps

Deposits between 1984 and 1996
submerged sand at 226 m^3/s 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 electomagnetic wavelength used for photography, and the depth and turbidity of the river at the time of photography.
wet sand, inundated at between 226 and 550 m^3/s 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 submerged deposits.
fluctuating-flow sand, inundated at between 550 and 890 m^3/s Very-fine- to fine-grained sand with widely ranging colors of light gray, brown, and reddish brown. The deposits are typically separated from the river by a single scarp and slope smoothly down into wet or submerged deposits or directly into the river. Well-defined bedforms are occasionally visible.
Little Colorado River (LCR) flood sand, inundated at less than 990 m^3/s Mainstem alluvial deposits of the winter 1993 LCR flood occurs only downstream from the LCR confluence. Deposits are higher in elevation than fluctuating-flow sand. In the 1993 photos, these deposits have no new vegetation growing on them but may extend into previously vegetated areas.
high flow sand, inundated at between 890 and 1400 m^3/s Medium- to very-fine grained sand, with some silty layers. Deposited by 1984-1986 Glen Canyon Dam bypass releases. High-flow deposits are typically separated from adjacent fluctuating-flow deposits by a cutbank. Dune bedforms are sometimes present and are distinct from the smaller and sharper bedforms that occur on fluctuating-flow deposits.
flood sand of 1983, inundated at between 1400 and 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. Deposited by the 1983 spillway flood. Internal structures include ripples, climbing ripples, cross-laminations, and planar bedding. Smooth, planar sand deposits present in the 1984 aerial photos and higher in elevation than high-flow deposits were mapped as flood sand. The 1983 peak stage is often indicated by a driftwood line.
1996 Controlled-flood deposits (interpreted from aerial photos taken immediately after flood recession)
submerged sand at between 226 and 385 m^3/s 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, and the turbidity of the river at the time of photography.
wet sand, inundated at between 226 and 550 m^3/s 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 submerged deposits.
perched wet sand, inundated at greater than 550 m^3/s Fine-grained sand that appears wet in photos but is located far from the river. In some cases, occurs at locations known to be more than a vertical meter from the water surface at the time of photography.
controlled-flood sand, inundated at between 550 and 1274 m^3/s Coarse- to fine-grained sand appearing clean and fresh in photos. Deposit forms are generally sharp and well-defined. Deposits are typically lighter colored than the nearby older fine-grained deposits. In some vegetated areas and in some low-velocity areas deposits may appear wet or darker due to higher silt content.

Table 12. Areas above 708 m^3/s stage and between 227 and 708 m^3/s stages, as surveyed by NAU and estimated from aerial photographs.

		Post-dam flood deposits, in square meters		Fluctuating flow zone, in square meters	
Site	Year	NAU	Photos	NAU	Photos
-6 Mile	1990	3025.9	3159.5	2871.2	2737.6
	1992	4065.2	3853.6	1705.5	1917.2
	3/1996	3217.7	3524.1	1376.2	1069.8
	4/1996	4132.3	4033.9	1151.5	1249.9
RM3	1990	2874.4	2645.2	1254.1	1483.3
	3/1996	847.7	659.8	632.8	820.7
	4/1996	1235.4	719.0	950.0	1466.4
RM8	1990	2339.9	2546.5	2159.5	1952.9
	3/1996	1430.7	1613.1	2354.0	2171.6
	4/1996	1429.4	998.7	2046.3	2477.0
RM32	1990	2471.9	1853.6	1371.0	1989.3
	3/1996	2978.6	2612.6	928.4	1294.5
	4/1996	2410.5	750.6	1048.7	2708.6
RM43	1990	2899.3	949.7	3545.0	5494.7
	1992	2034.7	1034.8	4007.5	5007.4
	3/1996	2697.6	972.3	3463.4	5188.8
	4/1996	1627.1	796.5	4203.3	5033.9
RM45	1990	2245.1	1622.0	8106.4	8729.5
	1992	2238.8	2422.1	7619.7	7436.4
	3/1996	8699.4	5778.8	7599.0	10519.7
	4/1996	5544.4	3194.8	5440.6	7790.2
RM47	1990	7619.0	7476.0	5393.9	5536.8
	1992	4957.0	5335.7	2999.3	2620.6
	3/1996	3373.2	3509.1	4494.3	4358.4
	4/1996	3612.2	1745.6	3051.2	4917.8
RM65	1993	2321.8	916.4	4367.3	5772.7

subsequent years. To minimize the confounding influence of discharge, we evaluated long-term trends in the area of pre-dam and post-dam flood deposits in some analyses, because the area of these deposits was unaffected by discharge at the time of photography.

8.1.1 Accuracy of mapping

The accuracy of mapping and GIS analyses depends on mistakes in photogeologic interpretation and error due to digitizing and transformation within the GIS. The scale, extent of dark shadows, and image quality vary greatly among the photos (Fig. 31, 39); the photograph series from the mid-1930s, 1965, and 1973 were especially poor. The mid-1930s photographs were the most difficult to use, yet these images are unique because they are the earliest depiction of the distribution of sand at very low discharge. The photographs taken in 1984 are of the smallest scale and highest quality.

We assessed errors by comparing the area of sand surveyed by NAU in overlapping areas with the area measured from aerial photographs for post-1990 photographs in order to determine the accuracy of the GIS data to predict the surveyed area of sand in the post-dam flood zone and the fluctuating flow zone. We compared the area at 8 sites at between 1 and 4 survey dates for a total of 26 comparisons (Table 12). The overall accuracy of the GIS mapping from these 26 comparisons is 84.8% (Table 13), meaning that approximately 85% of the area mapped in the GIS as either

Table 13. Error matrix of the agreement between areas surveyed by NAU and estimated by USU.

		Area, in square meters, surveyed by NAU		
		Fluctuating flow zone	Post-dam flood zone	**Total**
Area, in square meters, mapped from aerial photographs	Fluctuating flow zone	60,701	3753	**64,454**
	Post-dam flood zone	21,628	80387	**102,015**
	Total	**82,329**	**84,140**	**166,469**
		Percentage of total area, as surveyed by NAU		
		Fluctuating flow zone	Post-dam flood zone	**Total**
Percentage of total area, as mapped from aerial photographs	Fluctuating flow zone	36.46%	12.99%	**49.46%**
	Post-dam flood zone	2.25%	48.29%	**50.54%**
	Total	**38.72%**	**61.28%**	**100.00%**

Overall accuracy = 84.8%

post-dam flood deposits or fluctuating flow deposits was the same as surveyed by NAU.

There was no evidence that the errors of the GIS data were related to different individuals who conducted the mapping [i.e., reaches mapped by Leschin and Schmidt (1995), Schmidt et al. (1999b), Sondossi (2001), and Sondossi et al. (2002)], because qualitative comparisons showed that the magnitude and distribution of the residuals of the two groups were not different. Furthermore, there was no statistically significant difference between the slopes and intercepts of the regression relations between NAU and GIS data for the 2 observer groups. We, therefore, performed a comprehensive error analysis of all 26 data points, and we applied the estimated errors to the post-dam flood deposits and fluctuating flow deposit data.

A perfect estimation of eddy bar area in a specific elevation zone would result in a 1:1 relationship between the area as determined from aerial photograph interpretation and as surveyed by NAU (Fig. 46). Based on the

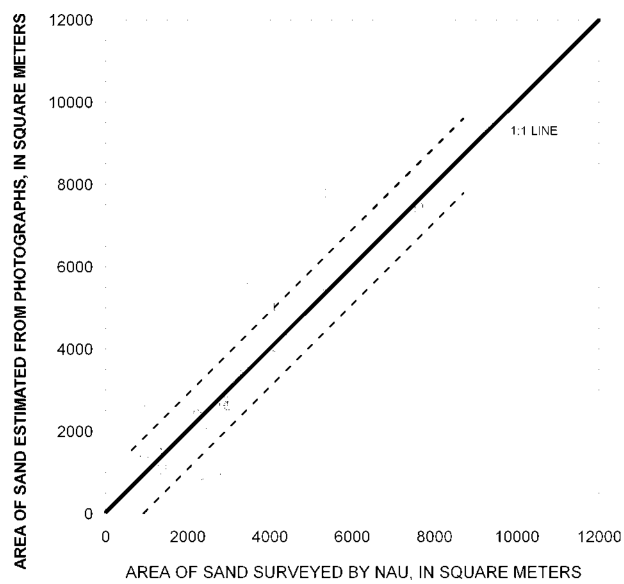


Figure 46. Graph showing the area of each eddy bar in the post-dam flood zone, above the stage of 708 m^3/s (squares) and in the fluctuating flow zone, between 227 and 708 m^3/s (circles) as measured by NAU and from aerial photographs at different sites and in different years.

assumption that the areas surveyed by NAU equal the expected values of our observed GIS estimates, we calculated the differences between the surveyed area and the area in the GIS for each comparison. The differences represent the error about the 1:1 line of our estimates relative to the NAU data, and we used these differences to compute the variance of our area data. The estimated variance of individual area measurements in our comparison was 828,600 m^2. The standard error of the GIS measurements of each of these sites (standard error of an individual area measurement) was 910 m^2, the square root of the variance.

To compute the measurement error for each specific reach, we computed the variance of the total area as the variance of individual sand bars multiplied by the number of eddy bars in that reach. We calculated the standard error of the total eddy area for that reach by calculating the square root of the reach specific variance. This standard error of total area was divided by the reach length or by the number of eddies in order to determine the error bars of 1 standard error for the total area of sand per unit length, or mean eddy size, respectively. For example, error bars associated with estimates of the area of eddy bars per unit reach length, in square meters per linear meter, were computed by dividing the standard error of total eddy area in each reach by the reach length. In the case of photograph series taken in 1973 and earlier, the large scale and dark shadows increase imprecision and inaccuracy, and we assumed that the errors were twice that computed for photographs taken in 1984 and later years.

8.1.2 Metrics used to describe changes in fine-grain deposits among years

We report the mean and median area of discrete deposits and the area of all sand and of sand in the pre-dam and post-dam flood zones. We also report the total area of these deposits per unit river distance for each photograph series. We determined the proportion of each EDZ filled by fine sediment. This proportion, called the fill ratio, is the area of sand normalized to the area of the EDZ.

We adopted several strategies to compensate for the greater inaccuracy of measurements of pre-dam photographs and the differences in discharge at the times of the photographs. Differences in discharge at the time of photography, in the length of time between the onset of the sediment accumulation season and the time of photography, and in the magnitude of each year's snowmelt and monsoon floods were sufficiently great that it was impossible to determine a trend in the area of sand between the 1930s and the 1950s. Therefore, we averaged pre-dam measurements from the 1930s and 1950s and compared these values with the average area calculated for 3 recent post-dam years (1990, March 1996, and April 1996). These estimates of change in sand area between the pre-dam and post-dam eras are conservative, because the 1950s era photographs were taken at approximately twice the discharge of the 1990s era photography and are thus biased to show smaller bars. The average for the 1990s included the distribution of sand immediately after the 1996 Controlled Flood, despite the fact that these high sand deposits only persisted for a few years.

We also estimated change in sand bars between the pre-dam era and the 1990s by inventorying every EDZ larger than 1000 m^2 and defined significant change between the two periods as that which exceeded the error of each measurement. We term this method the EDZ inventory method. We calculated significant erosion if

$$A_{pre} - SE > A_{90s} + SE \qquad (1)$$

where A_{pre} is the average area of sand in the years of pre-dam photography, A_{90s} is the average area of sand in 1990, March 1996, and April 1996, and SE is the standard error of aerial photograph measurements. Significant deposition occurred if:

$$A_{pre} + SE < A_{90s} - SE \qquad (2)$$

Thus, the EDZ inventory metric is a relatively conservative indicator of change, because we only counted those EDZs whose net change exceeded 1 standard error of the pre-dam average deposit size and 1 standard error of the average deposit size in the 1990s.

8.2 Description of the Photograph Series That Were Analyzed

8.2.1 Pre-dam conditions of the mid-1930s, 1952, 1954, 1956, 1958

These aerial photographs described conditions at different discharges, following different magnitude peak snowmelt floods, and after different durations of fine-sediment accumulation. The date of the mid-1930s photographs is unknown. The photographs appear to have been taken in late fall. The discharge was very low and comparable to the discharge at the time of the 1984 and 1990s photography. Eddies were typically filled with sand in these photographs, mid-channel bars were covered by a veneer of sand, and there was little riparian vegetation.

Photographs taken in the 1950s were taken between July and October. Of these, discharge at the time of photography was greatest on September 24, 1952, and July 9, 1956 (Table 10). The antecedent conditions prior to the 1952 photography would have produced a larger expanse of bare sand in the pre-dam flood zone than the 1956 photographs, because the September 1952 flows followed an unusually large spring flood that peaked at 3,482 m^3/s. Also, flow at the time of the 1952 photography was augmented by tributary inflows that had increased by about 150 m^3/s during the previous week and would have created new sand bars. In contrast, the magnitude of the 1956 annual snowmelt peak flow was 1,971 m^3/s and the photographs were taken at the beginning of the fine-sediment accumulation season; thus, sand bars would be smaller at this time.

Photographs taken on September 25, 1952, August and September 1954, and September 1958 were taken at 100 to 150 m^3/s less than the other 1950s photos and therefore more sand was exposed. The snowmelt peak flow of 1954 was unusually low, 971 m^3/s, and the area recently reworked by flood-induced scour and fill was comparable to the post-dam maximum power-plant capacity. The fine sediment accumulation season had progressed longer in the October 1952 photographs and least in the August 1954 photographs.

8.2.2 Pulsed high releases of May 1965

Pulsed high releases from Glen Canyon Dam significantly scoured the bed in Glen Canyon in 1965. There was net export of fine sediment from the study area and large transport rates had the potential to deposit post-dam flood deposits in Marble and upper Grand Canyons. Discharge at the time of these photographs exceeded 700 m^3/s, and sand in the fluctuating flow zone was submerged. Bare, wet sand bars in these photographs had likely formed by flows that had peaked at about 1500 m^3/s 2 weeks before the photographs were taken. The scale of these photographs is relatively large, and the photographs are of poor resolution. It was difficult to delineate most small sand deposits, and there was substantial imprecision in distinguishing post-dam and pre-dam flood deposits.

8.2.3 Fluctuating flows of June 1973

Instantaneous discharge at the Lees Ferry gage varied between about 85 and 800 m^3/s at the time these photographs were taken. Shadows and low water stage indicated that the photographs were taken in the morning in upper Marble Canyon, prior to the daily increase in discharge. Thus, discharge in the Lees Ferry Reach was probably approximately 100 m^3/s but may have been nearly 800 m^3/s in the Point Hansborough and Tapeats Gorge Reaches. Delineation of the base of the post-dam flood zone was estimated as the upper boundary of bare, reworked sand in the Lees Ferry and Redwall Reaches; we assumed that bare sand was reworked by the stage of the high ebb of daily discharge fluctuations. We assumed that all sand above water's edge in the Point Hansborough, Tapeats Gorge, and Big Bend Reaches was in the post-dam flood zone. The scale of these photographs was relatively large, and the photographs were of poor resolution. It was difficult to delineate most small sand deposits, and there was substantial imprecision in distinguishing fluctuating flow and post-dam flood deposits.

8.2.4 Bypass and spillway floods of the mid-1980s: October 1984

These aerial photographs were the smallest in scale of all the years mapped, and unconsolidated deposits were mapped with better precision. These photographs depict the distribution of sand in the fluctuating flow zone and two parts of the post-dam flood zone.

8.2.5 Resumption of wide-ranging hydroelectricity-generating flows: June 1990

Discharge at the time of these false-color infrared photographs was approximately the same as at the time of the 1984 photography. The interval between October 1984 and June 1990 included floods in 1985 and 1986 and wide-ranging fluctuating power plant flows after June 1986. Interpretation of the causes of changes in sand area between 1984 and 1990 was complicated by the intervening flow regime that included two floods and periods of large power plant fluctuations.

8.2.6 Interim operating criteria: October 1992, May 1993, and March 1996

Several photograph series were taken in the 1990s. During this period, flows never exceeded power plant capacity in Marble Canyon, but a large flood in the Little Colorado River in winter 1993 (Wiele et al., 1996) created a mean daily discharge of about 855 m^3/s on January 13. There was high suspended-sand transport in Grand Canyon. Discharge at the times of these photographs was higher than during the 1984 and 1990 photographs. Schmidt and Leschin (1995) measured significant increases in eddy bar area in upper Grand Canyon following the 1993 floods, and small decreases in bar area occurred upstream from the Little Colorado River. The sizes of bars in the Lees Ferry and Redwall Gorge Reaches were only mapped in March 1996 because of the minor degree of bar change measured further downstream. Thus, the changes that occurred between June 1990 and March 1996 reflected a 1.5-year period of experimental flows and a 5.5-year period of constrained power plant flows.

In March 1996, deposits upstream from the Little Colorado River were not significantly different from June 1990. The only notable difference was that more vegetation was established on post-dam flood deposits. Clearly-defined cutbanks had become established between the post-dam flood and fluctuating flow zones.

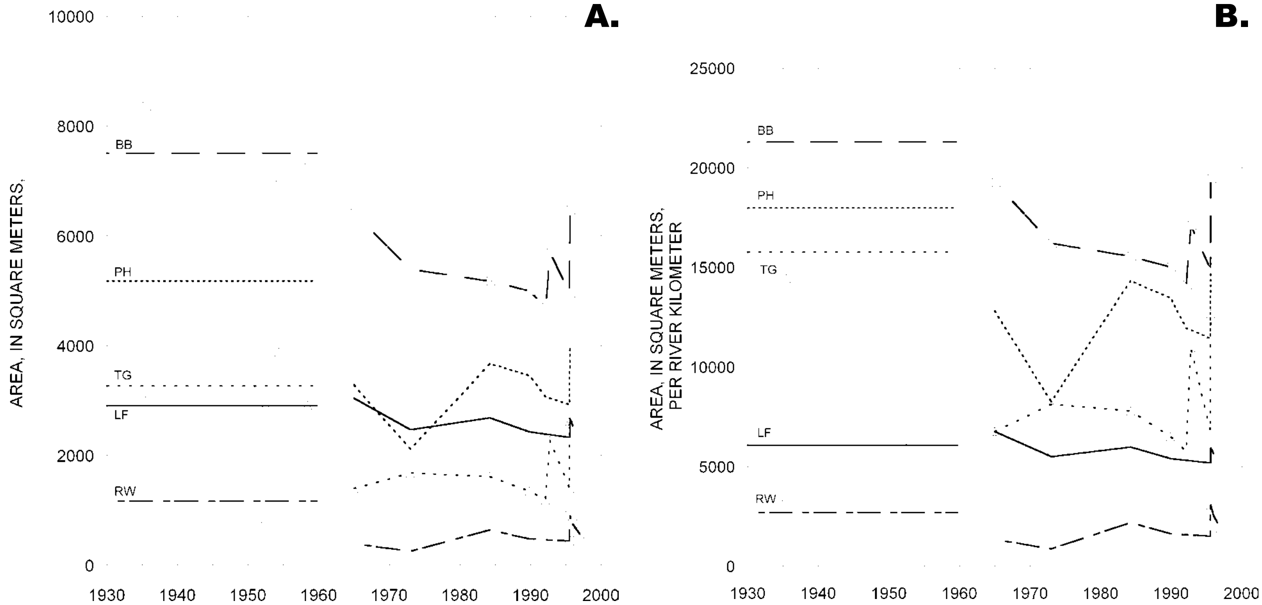
8.2.7 Effects of the 1996 Controlled Flood: April 1996

These photographs were taken 11 days after the March 1996 photographs. During the intervening period, the 7-day Controlled Flood occurred. The photographs depict large reworked sand deposits that partly bury riparian vegetation in places. Although pre-dam deposits and most of the 1983 flood sands were not inundated, all deposits from the floods that occurred between 1984 and 1986 floods were inundated. All vegetation growing on these surfaces was pushed down by water flow, uprooted, or buried. Drift-wood lines were used to estimate the maximum stage of the Controlled Flood. Discharge at the time of these photographs varies from reach to reach, because dam releases had not yet receded to 227 m^3/s in each reach.

8.2.8 Changes in bars after the 1996 Controlled Flood: September 1996 and September 1997

Analysis of conditions 6 months after the Controlled Flood were made in the Lees Ferry and Redwall Gorge Reaches. Discharge at the time of these photographs was the same as at the time of the March 1996 photos, and comparison between these two photo series pro-

Figure 47. Graphs showing the temporal sequence of the area of the pre-dam and post-dam flood zones between 1930s and 2001. A. Mean area of sand in EDZs. B. Total sand in this zone in EDZs per river kilometer. BB is Big Bend Reach. LF is Lees Ferry Reach. PH is Point Hansborough Reach. RG is Redwall Gorge Reach. TG is Tapeats Gorge Reach.



vided a measure of redistribution of sand deposited by the 1996 Controlled Flood. The recent flood deposits retained much of their fresh appearance, but bank retreat had reduced the size of many of the flood deposits. Analysis of conditions in September 1997 were made in the Redwall Gorge Reach.

8.3 Changes in the Area of Fine-Grained Alluvial Deposits Determined by Aerial Photograph Analysis

Comparison of the distribution of fine sediment in aerial photographs yields a spatially robust picture consistent with historical accounts and matched historical oblique photographs. The evidence indicates that there is less sand along the banks and in the eddies of the Colorado River today than there was before completion of Glen Canyon Dam.

8.3.1 Changes in eddy bars

There was more sand along the Colorado River in the 1930s and 1950s than in subsequent years, although the estimate of the magnitude of change differs among the various metrics. Nevertheless, every metric indicates that the era of modern environmental management of the dam has not restored sand conditions in the river corridor to those of the pre-dam era.

The decrease in sand area from pre-dam to post-dam eras occurred in narrow and wide reaches. Wide valleys initially had larger sand deposits. The greatest average area of flood zone sand deposits was in the Big Bend Reach where the valley is widest (Fig. 47). The area of flood zone sand deposits in the Big Bend Reach was about 6 times more than the area in the Redwall Gorge Reach where the valley is very narrow. The total area of sand in the Point Hansborough Reach, also very wide, was also large in the pre-dam era.

Completion of the dam caused erosion of these deposits in 4 of the 5 study reaches; the area of flood deposits in May 1965 was less than the pre-dam average. In the wide Point Hansborough and Big Bend Reaches, subsequent erosion of flood deposits occurred between May 1965 and June 1973.

Post-dam floods typically increased the

Table 14. Reach-average change in eddy sand bars between pre-dam photographs and the 1990s

	EDZ inventory	mean	median
Lees Ferry			
All sand above water surface	-8%	-26%	-21%
Pre-dam and post-dam flood zone	-4%	-9%	-17%
Redwall Gorge			
All sand above water surface	+1%	-4%	+10% [1]
Pre-dam and post-dam flood zone	-1%	-47%	-55%
Point Hansborough			
All sand above water surface	-17%	-17%	+5% [1]
Pre-dam and post-dam flood zone	-20%	-25%	-17%
Tapeats Gorge			
All sand above water surface	-17%	-34%	-39%
Pre-dam and post-dam flood zone	-17%	-45%	-50%
Big Bend			
All sand above water surface	-12%	-17%	-4%
Pre-dam and post-dam flood zone	-14%	-23%	-38%

[1] Median values are strongly affected by the number of EDZ included in the data base. In the case of some of the pre-dam photographs, dark shadows and poor resolution prevented identification of all sand deposits. Inspection of other data for the same reaches indicates that increases in median area probably did not occur.

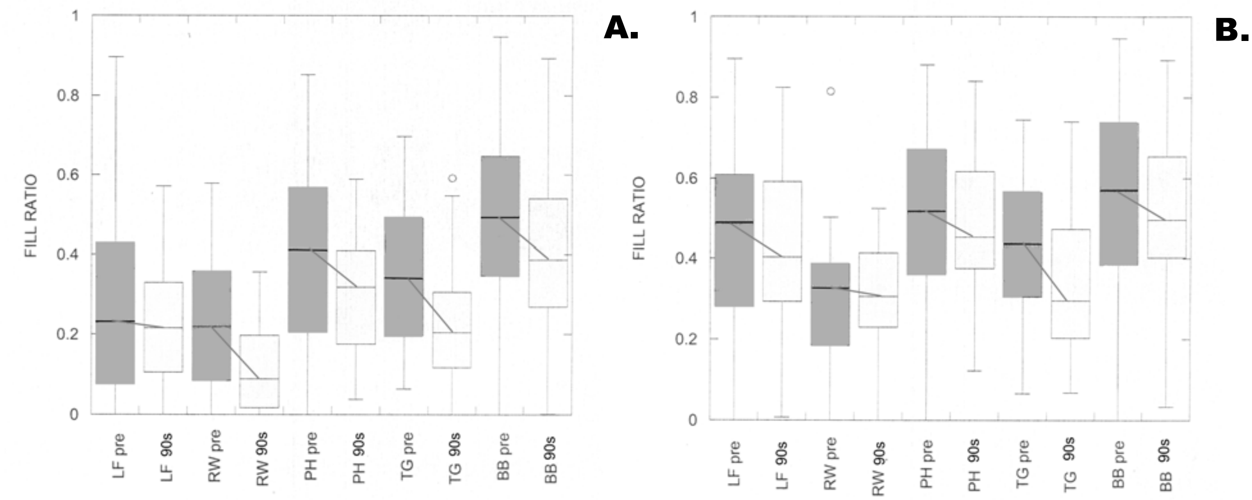
area of sand in the post-dam flood zone. There was an increase in the area of these deposits between June 1973 and October 1984 in the Point Hansborough Reach. The Little Colorado River floods of winter 1993 caused a significant increase in the area of flood zone deposits in the Tapeats Gorge and Big Bend Reaches, both of which are downstream from the Little Colorado River. The 1996 Controlled Flood caused a significant increase in the area of these deposits.

Reductions in the range of daily flow fluctuations in the 1990s did not stop erosion of post-dam flood deposits. There were significant decreases in the area of sand in this zone between 1990 and 1992 in the Point Hansborough Reach and between 1993 and March 1996 in the Tapeats Gorge and Big Bend Reaches.

Results of the EDZ inventory indicate that the area of sand in the post-dam and pre-dam flood zone was between 1% and 20% less in the 1990s than in the pre-dam photographs (Table 14). The EDZ inventory results indicate that the total area of sand in the 1990s was between +1% and –17% of the average pre-dam condition. For both metrics, the greatest change occurred in the wide Point Hansborough and Big Bend Reaches and in the narrow Tapeats Gorge Reach.

Although reach-average trends were computed, specific sites sometimes responded in ways counter to the behavior typical of nearby sites. Despite the reach-average erosional trend, a few EDZs aggraded in the post-dam flood zone or the total area of sand in an EDZ increased. There were 9 EDZs with significant erosion and 2 with significant aggradation in the Point Hansborough Reach (Table 15). Fifteen EDZs had significant

Figure 48. Graphs showing eddy fill ratios for the 5 study reaches in average pre-dam conditions (dark tone) and in the 1990s (light tone). Each plot includes box-and-whisker plots in which the box indicates the interquartile range and the inner line is the median value. A. Post dam flood zone. B. All sand above water level.



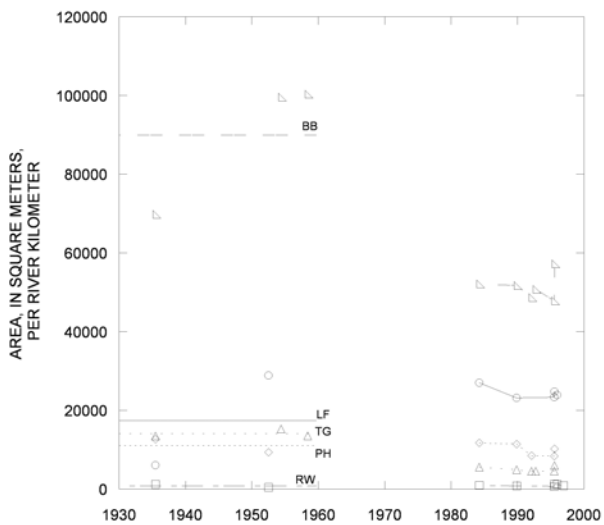


Figure 49. Graphs showing the temporal sequence of channel-margin deposits in the combined post-dam flood zone and the fluctuating flow zone in study reaches.

erosion in the Tapeats Gorge Reach, and no EDZs had significant aggradation. The difference between the number of EDZs with significant erosion and aggradation was even greater in the case of all exposed sand, regardless of elevation.

Comparison of the difference in the mean and median area of flood zone deposits in pre-dam and 1990s photographs indicates larger magnitude changes than does the EDZ inventory, because small differences in more EDZs were included in calculation of these metrics.

The mean area of flood zone deposits and the area of all sand decreased between 9% and 47% and between 4% and 34%, respectively (Table 14). Change in median size of bars was more variable but indicated similar magnitudes of change.

The reach average eddy fill ratio, or proportion of the EDZ filled with sand, also decreased between the pre-dam era and the 1990s. Flood zone sands typically were filled to between 20% and 50% of their EDZ in the pre-dam photographs and all sand, regardless of elevation, filled between 30% and 55% of the EDZs (Fig. 48). In the 1990s, these fill ratios decreased to between 10% and 40% and between 30% and 50%, respectively.

8.3.2 Changes in channel-margin deposits

Channel-margin deposits are also smaller today than they were before completion of Glen Canyon Dam (Fig. 49). The temporal trends in the area of post-dam flood zone and fluctuating flow zone deposits are similar to those of eddy bars, in the sense that the post-dam flood zone deposits decreased in size during periods without floods and increased in area in response to the 1996 Controlled Flood. However, the size of channel-margin deposits in April 1996 was equal or less than the area

Table 15. Eddy deposition zones (EDZs) that increased or decreased in area between average pre-dam conditions and the 1990s.

			All sand above water surface		Post-dam and pre-dam flood zone	
Location, in river mile (EDZ number)	Name of site	Eddy deposition zone area, in square meters	Decrease in area, in square meters	Increase in area, in square meters	Decrease in area, in square meters	Increase in area, in square meters
		Lees Ferry				
1.1R (4)	Below Paria Riffle	67,000	22,100		7,700	
1.3L (5)		14,000	4,200			
2.4L (9)		7,000			500	
2.5L (10)	Above Cathedral Wash (NAU)	11,800	500		600	
2.8R (12)	Cathedral Wash	8,800	600			
4.1L (19)	Four Mile Wash	14,400	800			
5.9R (30)	Six Mile Wash	14,900	1,500			
6.0L (31)	Six Mile Wash	10,500	800			
6.6R (32)		13,800				300
7.0L (33)		20,900	1,600			
7.5L (34)		6,900		2,300		1,200
8.1R (36)	Badger	15,200	2,300		2,200	
8.1L (37)	Jackass (NAU)	16,900	1,300		500	
		Redwall Gorge				
29.8R (2)		8,200			200	
30.7R (8)	Fence Fault (NAU)	11,500		100		
33.6R (34)		5,000			300	
34.2L (47)		6,800		300		100
34.6R (53)		1,700	100			
		Point Hansborough				
43.3L (9)	Anasazi Bridge (NAU)	25,300	7,000		7,000	
43.5L (10)		34,000	8,500		4,600	
43.8L (14)		16,000				2,400
44.0L (16)	President Harding	23,500	6,300		1,400	
44.4L (21)	Eminence Break (NAU)	34,400	2,200		7,400	

44.8L (27)		28,300	1,000		2,500	
45.1L (31)		29,400	1,800		5,900	
46.8R (55)		7,400	100			
47.0R (58)	Triple Alcoves	43,300	6,000[1]			6,000[1]
47.5R (63)	Saddle Canyon	45,000	9,800		14,700	
48.5L (74)		14,500	700			
48.6L (77)		17,400		900		
48.6R (78)		14,600	700		2,000	
48.8R (79)		14,700	300		1,200	
		Tapeats Gorge				
60.2L (2)	Below Sixtymile Rapid	23,900	6,900		5,800	
60.4L (3)		13,600	4,500		3,000	
60.6R (5)		7,500	0		100	
60.6L (6)		4,500			100	
60.8L (7)		19,600	4,400		3,100	
61.3L (11)		10,600	1,200		1,200	
62.3L (25)		11,600	2,200		2,000	
62.4R (26)		9,100	100		1,000	
62.6R (28)		14,800			100	
62.9R (29)	Crash Canyon (NAU)	20,100	3,600		600	
63.5L (34)		33,200	3,500		3,200	
63.8R (38)		8,500	600			
64.0L (39)		15,200	700		800	
64.2L (40)		17,900	200			
64.3L (43)		33,300	500		1,400	
64.6L (45)		18,800	2,500		1,600	
64.7R (46)		8,300	100		800	
		Big Bend				
66.0L (60)		34,500	14,300		16,400	
66.7R (62)		11,300	1,100		1,200	
66.7L (63)		27,100	3,600		3,600	
67.3L (67)		24,700	200		600	
68.1L (73)		52,600	7,600		8,200	
68.8R (76)	Tanner (NAU)	11,500				1,300
69.7L (82)		11,000	800			
70.1L (86)		13,000	4,400		4,800	
71.3L (102)		38,600				1,900
71.6L (106)	Cardenas marsh	33,600				2,600
72.4R (108)		11,400				1,800
72.7L (113)	above Unkar	15,400	100			

[1] Pre-dam condition solely based on 1952 mapping.

of these deposits in 1984, whereas post-dam flood zone deposits in eddies were significantly larger in April 1996 than in 1984. The magnitude of decrease in the area of fluctuating-flow deposits within channel-margin deposits was much larger than for eddy deposits.

9.0 ANALYSIS OF NAU SURVEY DATA, 1990 TO 2001

NAU began measurement of eddy bar topography at 12 sites in Marble Canyon and 2 sites in upper Grand Canyon in September 1990 (Beus and Avery, 1992). Other sites were subsequently added to the protocol, and the NAU survey program included 20 separation or reattachment bars in 17 eddies in the study area in 2001. Sites were typically surveyed at least annually, and these data are an invaluable record of bar change that has been measured with great precision.

These data provide excellent temporal resolution in describing bar change during the era of environmental management. These measurements demonstrate that there has been a progressive decline in the volume of sand stored in eddies since 1990. These measurements illustrate the magnitude and style of changes associated with the post-dam era and the variation from site to site in the magnitude of sediment storage change.

9.1 Methods

We report the time series of area and volume of each study site in the post-dam flood zone and the fluctuating flow zone, as well in the deep parts of eddies below base flow stage of 227 m^3/s. The latter category could not be determined by aerial photograph analysis.

9.2 Changes in Area and Volume in the Post-Dam Flood Zone

The temporal sequence of change in the area and volume of sand above the stage of 708 m^3/s was generally similar from site to site (Fig. 50). The area and volume of sand in this zone decreased or did not change between September 1990 and February 1996, increased at all sites in response to the 1996 Controlled Flood, and decreased at nearly every site between April 1996 and October 2001 (Table 16). The magnitude of change was typically small, except at RM 62 where there was a large amount of erosion between March 1993 and October 1993. This site is located 2 km downstream from the Little Colorado River and significantly aggraded during the 1993 floods. In Marble Canyon, mean and median bar area decreased 9 and 15%, respectively (n=12), but there were sites where the proportional decrease in area was much larger (Fig. 51). The mean area of sand in this zone in February 1996 was significantly less than the area in 1990, based on a paired sign test ($\alpha = 0.05$). This nonparametric test was employed, because the distribution of areas of sand in the study sites was not normally distributed. The mean and median area of sand for the sites in Marble Canyon was 1327 and 1088 m^2, respectively, in September 1990 (Table 17) and was 1208 and 922 m^2, respectively, in February 1996 (Fig. 52).

Between February 1996 and April 1996, the area and volume of post-dam flood deposits increased at every site (Fig. 50), although the magnitude of this increase varied greatly from place to place (Fig. 51 B, E). In general, the magnitude of increase was greatest in lower Marble Canyon and least in upper Marble Canyon. The mean and median bar area in this elevation zone increased 88 and 91% (n=14), respectively, for sites in Marble Canyon (Fig. 52), but the increase in area and volume exceeded 100% in some cases (Fig. 51). The difference in mean area between February and April 1996 was statistically different (Table 17). The proportional changes were similar for area and volume in this elevation zone.

After recession of the 1996 Controlled Flood, the area and volume of sand declined at

Figure 50. Graphs showing temporal changes in the area and volume of sand in post-dam flood zone above the stage of 708 m³/s at 17 study sites in Marble and upper Grand Canyon. A. Area of sites in upper Marble Canyon. B. Area of sites in lower Marble Canyon. C. Area of sites in upper Grand Canyon. D. Volume of sites in upper Marble Canyon. E. Volume of sites in upper Marble Canyon. F. Volume of sites in upper Grand Canyon.

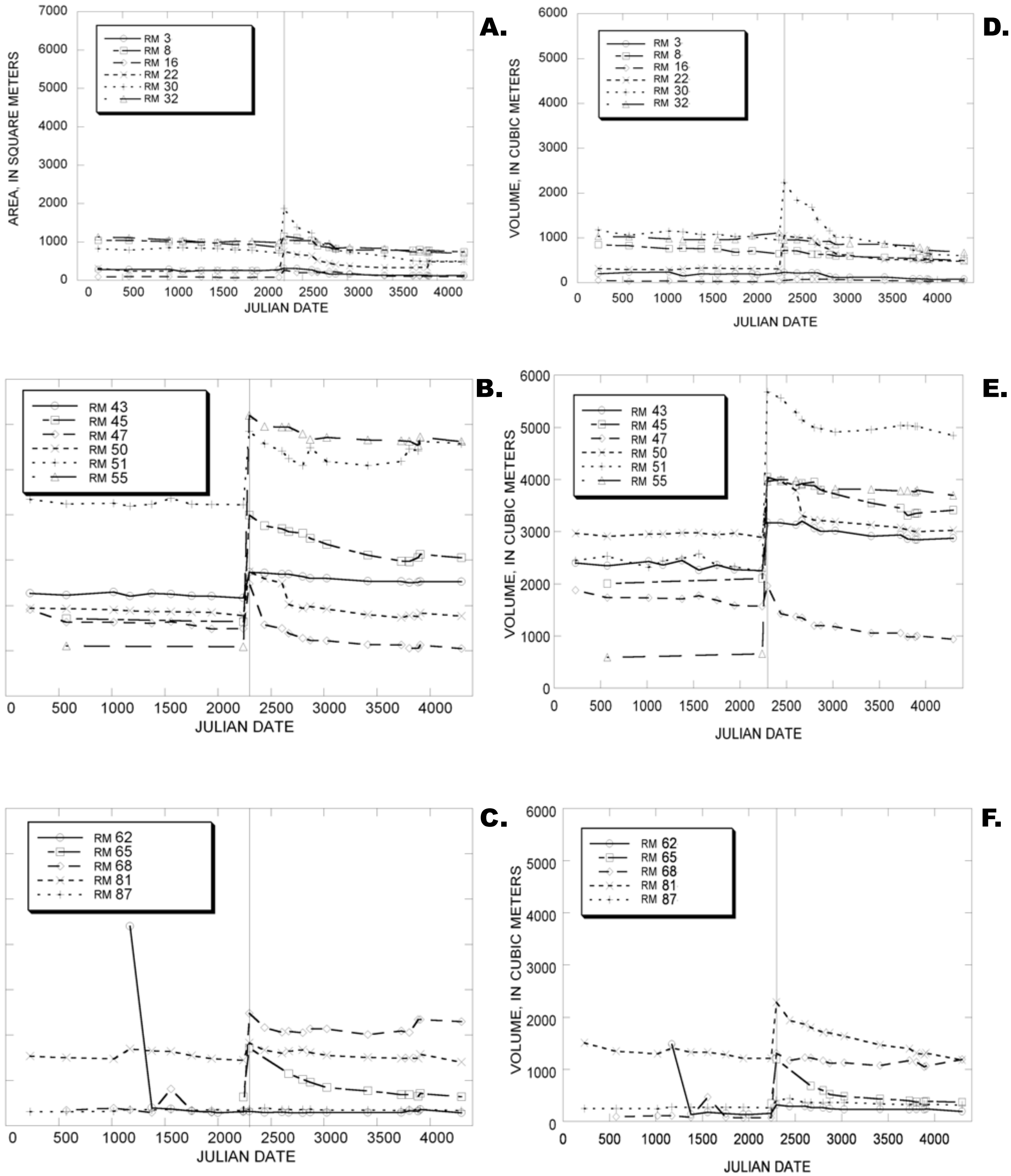


Figure 51. Histograms showing the proportional change during indicated time periods in the area and volume of sand in post-dam flood zone above the stage of 708 m³/s at study sites in Marble Canyon. A. Changes in area between September 1990 and February 1996. B. Changes in area between February 1996 and April 1996. C. Changes in area between April 1996 and October 2001. D. . Changes in volume between September 1990 and February 1996. E. Changes in volume between February 1996 and April 1996. F. Changes in volume between April 1996 and October 2001.

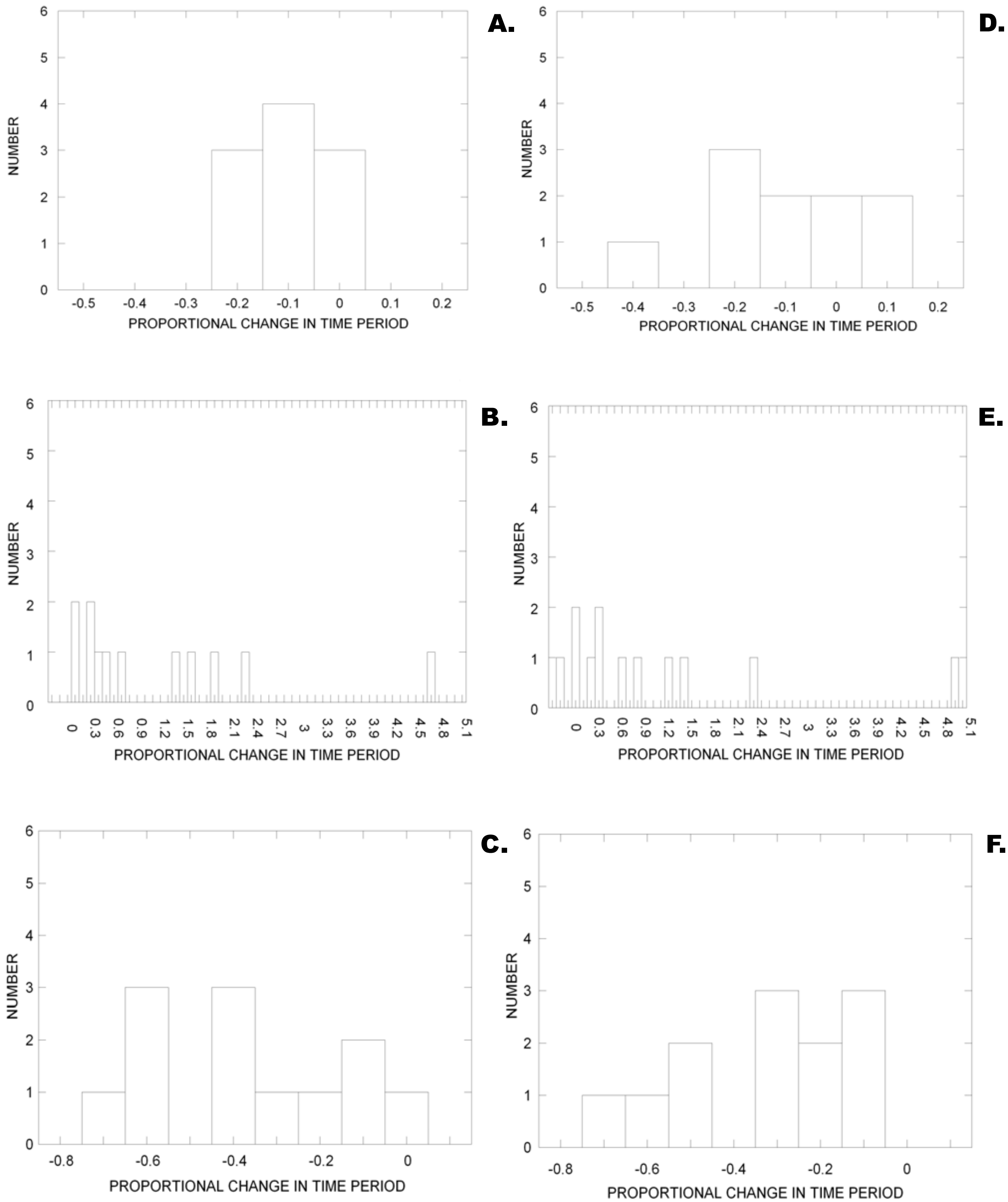


Table 16. Summary of temporal trends in area and volume of sand in two elevation zones at sites measured by NAU. Sites listed in each category had statistically significant ((α = 0.05) increases (+) or decreases (-).

	Pre-flood Period (September 1990 to February 1996)		Post-flood (April 1996 to 2001)	
	area	volume	area	volume
Post-dam flood zone (above the stage of 708 m^3/s)	RM8 (-) RM16 (-) RM32 (-) RM47 (-)	RM8 (-) RM16 (-) RM22 (-) RM47 (-) RM81 (-)	RM3 (-) RM8 (-) RM16 (-) RM22 (-) RM30 (-) RM32 (-) RM43 (-) RM45 (-) RM47 (-) RM50 (-) RM55 (-) RM65 (-) RM81 (-) RM87 (-)	RM3 (-) RM8 (-) RM16 (-) RM22 (-) RM30 (-) RM32 (-) RM43 (-) RM45 (-) RM47 (-) RM50 (-) RM51 (-) RM55 (-) RM62 (-) RM65 (-) RM68 (-) RM81 (-) RM87 (-)
Fluctuating flow zone (between the stages of 227 and 708 m^3/s)	RM22 (+) RM30 (-) RM47 (-) RM51 (-)	RM68 (+) RM16 (-) RM30 (-) RM32 (-) RM43 (-) RM47 (-) RM50 (-) RM51 (-) RM81 (-)	RM3 (+) RM22 (+) RM55 (+) RM87 (+) RM16 (-)	RM22 (+) RM15 (-) RM30 (-) RM32 (-) RM45 (-) RM50 (-) RM81 (-)

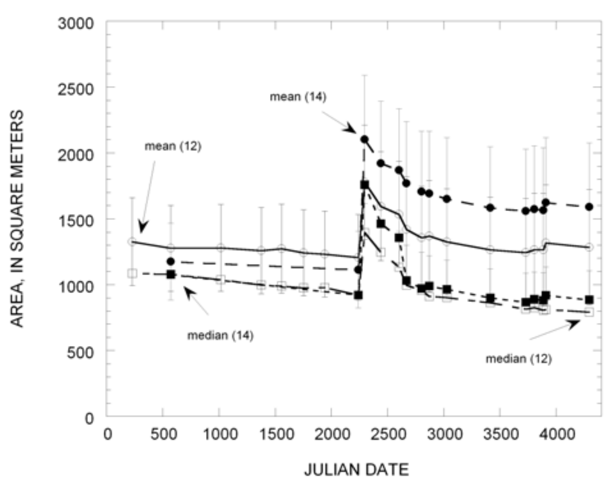


Figure 52. Graph showing temporal changes in the mean and median area of sand above the stage of 708 m^3/s at study sites in Marble Canyon for sample sizes of 12 and 14 study sites. Error bars are one standard error about the mean.

all sites, and the rate of decrease typically declined with time. The negative temporal trends of area and volume for the period between April 1996 and October 2001 were statistically significant at 14 and 17 sites, respectively (Table 16). The mean and median bar area in this elevation zone decreased 24 and 50%, respectively, for the period between April 1996 and October 2001 (Table 17). The mean area and volume in this elevation zone was significantly less in October 2001 than in April 1996, based on paired sign tests. Post-flood erosion eliminated as much as 75% of the area of 1996 deposits at some sites, but there was little change elsewhere (Fig. 51C, F).

Table 17. Mean and median area of post-dam flood sands above the elevation of the stage of 708 m^3/s at study sites in Marble Canyon

Julian Date	Date	Mean area, in square meters (n=12)	Standard error of the mean, in square meters (n=12)	Median area, in square meters (n=12)	Mean area, in square meters (n=14)	Standard error of the mean, in square meters (n=14)	Median area, in square meters (n=14)
231	September 1990	1327	336	1088			
572	July 1991	1277	326	1079	1175	292	1079
1018	October 1992	1281	329	1038			
1376	October 1993	1260	328	998			
1558	April 1994	1273	337	990			
1754	October 1994	1243	327	976			
1941	April 1995	1233	326	978			
2241	February 1996	1208	325	922	1114	290	922
2295	April 1996	1777	435	1397	2103	486	1760
2440	September 1996	1595	413	1246	1922	469	1463
2603	February 1997	1535	404	1135	1869	466	1358
2668	April 1997	1421	400	997	1770	469	1033
2801	September 1997	1358	392	958	1706	460	972
2871	November 1997	1370	423	912	1692	473	991
3027	April 1998	1325	403	902	1651	465	965
3413	May 1999	1266	400	863	1585	463	902
3729	March 2000	1244	409	816	1558	469	869
3805	June 2000	1266	429	827	1574	480	891
3886	August 2000	1266	428	807	1566	475	882
3907	September 2000	1317	441	810	1625	491	920
4295	October 2001	1286	437	792	1590	485	887

Note: Paired sign tests show the following significant differences in means: day 231 – day 2241, day 231 – day 2295, day 2241 – day 2295, and day 2295 - day 4295. The mean eddy area on day 231 is not significantly different from the mean area on day 4295. Paired sign tests on the volume in this elevation zone show the following significant differences: day 2241 – day 2295, day 2295 – day 4295.

9.3 Changes in Area and Volume in the Fluctuating Flow Zone

The time series of change in the area and volume of sand in the fluctuating flow zone was variable from site to site, but the dominant style was erosion (Fig. 53). Between September 1990 and February 1996, many bars decreased in volume in this zone (Table 16), and the proportional decrease varied between 5 and 65% (Fig. 54). The mean and median area of surveyed bars in Marble Canyon in September 1990 was 2867 and 1868 m^2, respectively, and the mean and median areas of these same bars in February 1996 was 2242 and 1707 m^2, respectively, a decrease of 22 and 9%, respectively (Fig. 55). These areas are not significantly different, based on a paired sign test (Table 18).

Figure 53. Graphs showing temporal changes in the area and volume of sand in the fluctuating flow zone, below the stage of 708 m³/s, and above the stage of 227 m³/s at 17 study sites in Marble and upper Grand Canyon. A. Area of sites in upper Marble Canyon. B. Area of sites in lower Marble Canyon. C. Area of sites in upper Grand Canyon. D. Volume of sites in upper Marble Canyon. E. Volume of sites in upper Marble Canyon. F. Volume of sites in upper Grand Canyon.

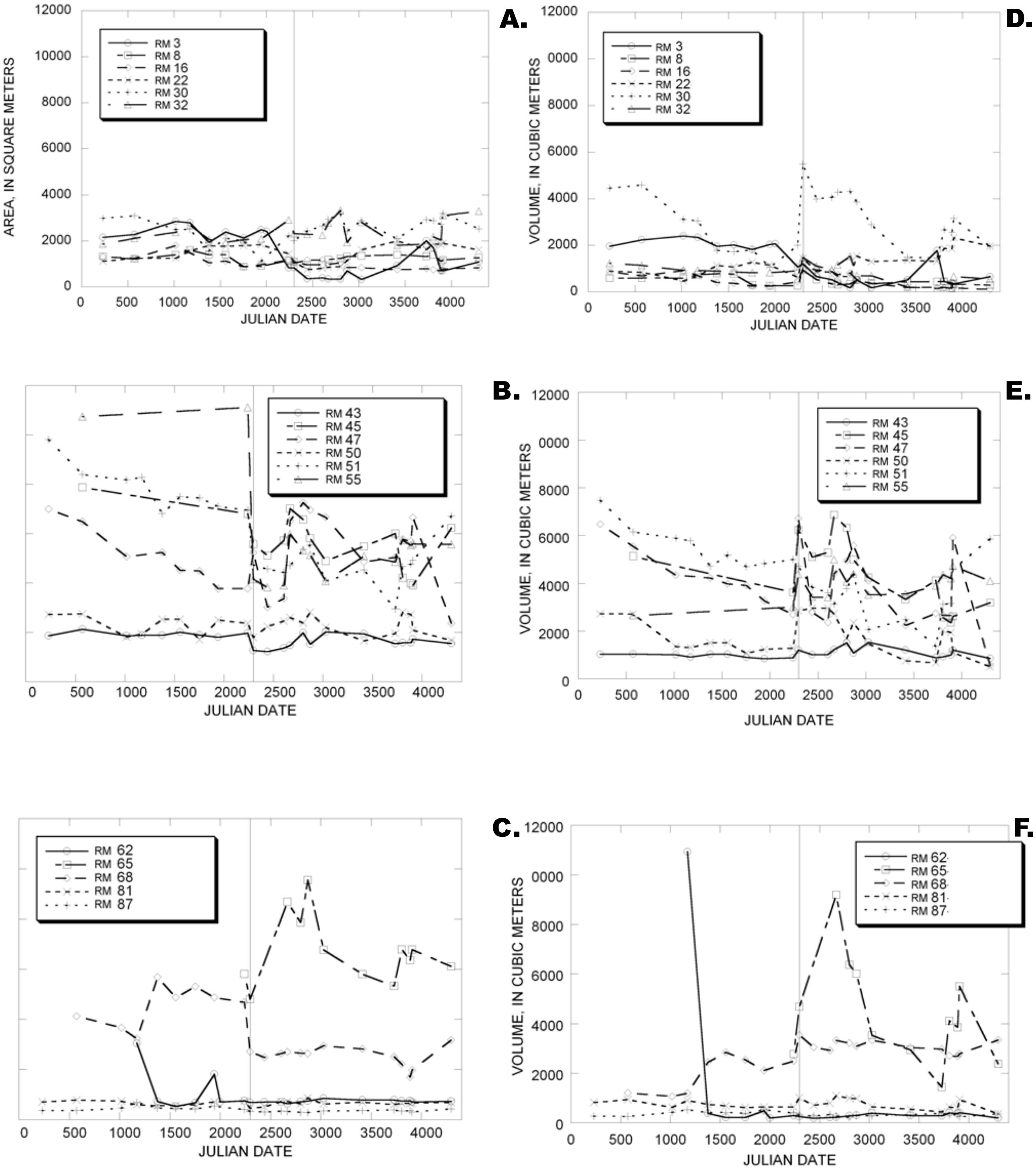


Figure 54. Histograms showing the proportional change during indicated time periods in the area and volume of sand in the fluctuating flow zone, below the stage of 708 m^3/s and above the stage of 227 m^3/s, at study sites in Marble Canyon. A. Changes in area between September 1990 and February 1996. B. Changes in area between February 1996 and April 1996. C. Changes in area between April 1996 and October 2001. D. Changes in volume between September 1990 and February 1996. E. Changes in volume between February 1996 and April 1996. F. Changes in volume between April 1996 and October 2001.

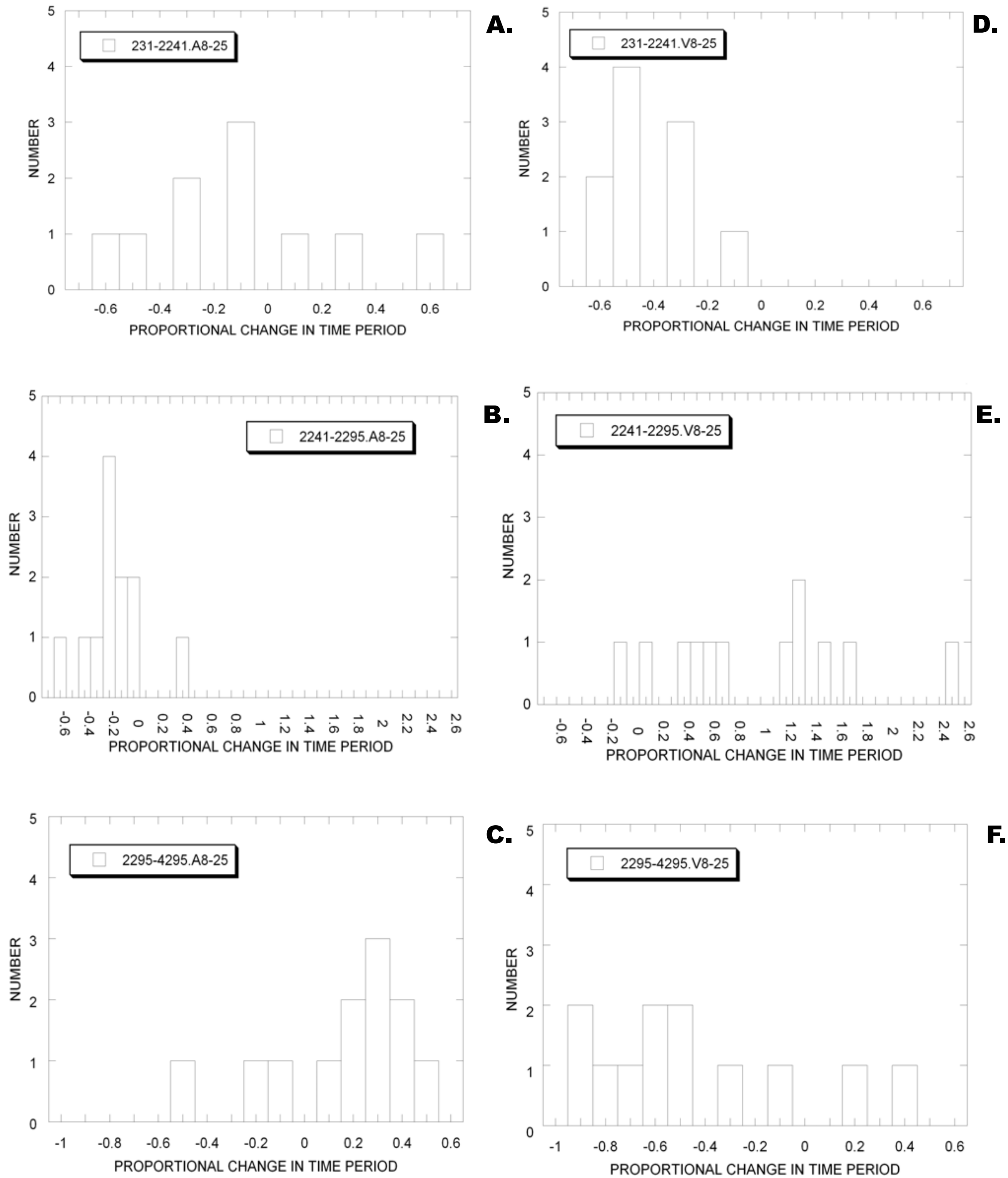
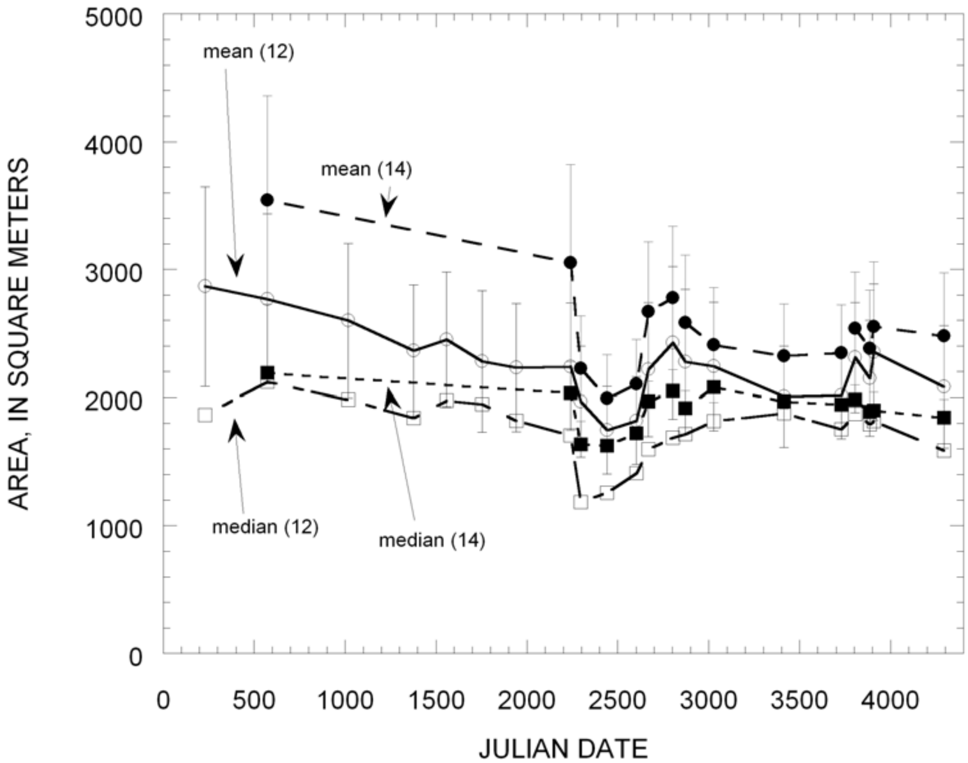


Figure 55. Graph showing temporal changes in the mean and median area of sand in the fluctuating flow zone, below the stage of 708 m³/s and above the stage of 227 m³/s, at study sites in Marble Canyon for sample sizes of 12 and 14 study sites. Error bars are one standard error about the mean.



The 1996 Controlled Flood caused the area in this zone to greatly decrease and the volume of fine sediment to increase (Fig. 54B, E). The mean and median area of bars in this elevation zone in Marble Canyon decreased by 44 and 19%, respectively (Fig. 55), and some sites decreased in area by more than 60%. The mean area in this elevation zone was significantly less in April than February 1996. In contrast, 11 of 12 sites increased in volume in this elevation zone, and 6 of these sites increased by more than 100%. However, the mean volume of sand in this zone before and after the flood were not significantly different, because the variance among the sites was so large.

After recession of the Controlled Flood, the area of sand in this elevation zone typically increased, and the volume of sand decreased in Marble Canyon. The mean bar area increased by 11% and the median increased by 13% in Marble Canyon, but 10 of 12 measurement sites decreased in volume of sand in this elevation zone. There were statistically significant increases in the area of sand in this elevation zone for the period between April 1996 and October 2001 at 4 sites and statistically significant negative trends in volume at 6 sites (Table 16).

9.4 Changes in Volume in the Deep Parts of Eddies, Below the Stage of 227 m³/s

The deep parts of 16 eddies surveyed by NAU also eroded during the 1990s. The volume of the 7 largest surveyed sites in 2000 was typically less than in 1992 (Fig. 56). There was no obvious trend for the small eddies that were surveyed. This part of the eddies tended to scour with increasing discharge and fill with decreasing discharge, based on normalizing the deep eddy survey data and combining these data into one time series. This style of response to floods was similar to that measured in pools in the main channel.

Table 18. Mean and median area of sand in the fluctuating flow zone, below the elevation of the stage of 708 m^3/s and above the stage of 227 m^3/s, at study sites in Marble Canyon

Julian Date	Date	Mean area, in square meters (n=12)	Standard error of the mean, in square meters (n=12)	Median area, in square meters (n=12)	Mean area, in square meters (n=14)	Standard error of the mean, in square meters (n=14)	Median area, in square meters (n=14)
231	September 1990	2867	1868	1868			
572	July 1991	2770	663	2124	3543	816	2192
1018	October 1992	2600	603	1983			
1376	October 1993	2368	512	1843			
1558	April 1994	2454	526	1978			
1754	October 1994	2283	553	1951			
1941	April 1995	2233	501	1822			
2241	February 1996	2242	495	1707	3051	770	2036
2295	April 1996	1969	434	1184	2227	411	1639
2440	September 1996	1746	342	1260	1997	339	1627
2603	February 1997	1820	341	1411	2106	349	1722
2668	April 1997	2218	523	1599	2672	545	1970
2801	September 1997	2427	595	1688	2778	562	2053
2871	November 1997	2280	564	1715	2584	529	1918
3027	April 1998	2243	502	1818	2411	447	2080
3413	May 1999	2008	394	1878	2324	408	1972
3729	March 2000	2020	341	1754	2350	371	1946
3805	June 2000	2312	429	1873	2540	441	1986
3886	August 2000	2152	452	1795	2384	455	1892
3907	September 2000	2355	530	1816	2553	509	1902
4295	October 2001	2083	477	1588	2481	493	1845

Note: Paired sign tests show the following significant differences in mean area: day 231 – day 2295, day 2241 – day 2295, and day 2295 - day 4295. The mean eddy area on day 231 is not significantly different from the mean area on day 4295. Paired sign tests on the volume in this elevation zone show the following significant differences: day 231- day 2241.

9.5 Long- term Changes Determined from Integration of NAU Data with Aerial Photograph Analysis

The NAU survey data were combined and a synthetic surface was calculated representing the highest elevation surveyed since 1990. This surface was compared with the EDZ for the same site in the same manner that a synthetic minimum surface was compared to estimate the potential fine-sediment storage volume (Table 3). We assumed that the upper surface of the EDZ was either the stage of 100 m^3/s or the same as the synthetic maximum surface derived from NAU data. The difference between the two surfaces is representative of the magnitude of loss that occurred between the pre-dam era and the 1990s when NAU conducted its surveys.

The magnitude of loss is between 0.6 and 2.2 m at 9 sites; the mean of the sites is 1.2 m (Table 19). There are eddies with large sand losses in each part of the study area, and there is no indication that the magnitude of sand loss decreases downstream. The average magnitude of loss is approximately 40% of the potential fine-sediment storage volume, which is within the range of a typical year of low to average seasonal accumulation of fine sediment (Topping et al., 2000b).

Table 19. Estimates of loss of fine sediment from eddies between the pre-dam era and the 1990s.

EDZ name	NAU site designation	Void volume between the stage of 100 m3/s and the maximum elevations surveyed by NAU, in cubic meters	Thickness of void volume, in meters[1]
Cathedral	RM3	1129	1.18
Fence Fault	RM30	634	0.83
South Canyon	RM32	1556	1.04
Anasazi Bridge	RM43	3074	1.28
Eminence Break	RM45	3079	0.81
Saddle Canyon	RM47	24801	2.20
Crash Canyon	RM62	3394	0.98
Carbon Canyon	RM65	2881	1.31
Tanner	RM68	684	0.57

[1] Void volume / area of comparison. Area of comparison is the same as reported in Table 4

10.0 AN INTEGRATED HISTORY OF FINE-SEDIMENT IN GLEN, MARBLE, AND UPPER GRAND CANYONS

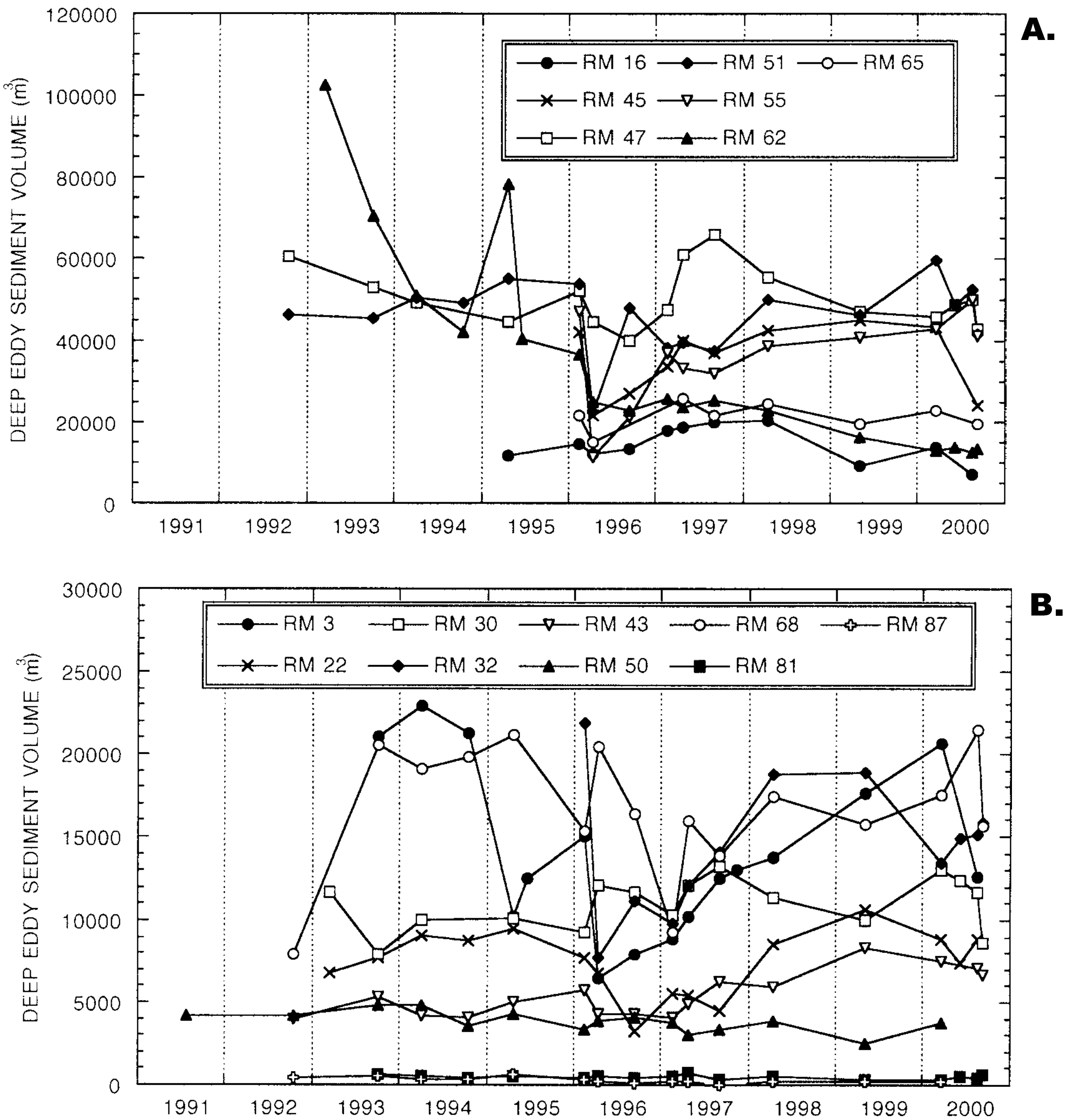
10.1 Summary

Abundant evidence demonstrates that there is less fine sediment on the channel bed and in eddies of the Colorado River than there was before completion of Glen Canyon Dam. During the pre-dam era, riparian vegetation was confined to the upper parts of the pre-dam flood zone, and river trips through Grand Canyon conducted at moderate and low discharge saw expansive fine-sediment deposits along the shoreline that filled parts of eddies. These deposits provided abundant camping opportunities and grit in bed rolls and camp food, as described by early river runners. The decrease in fine sediment occurred in response to reduction in the amount of fine sediment delivered to the Colorado River ecosystem; sediment delivery to Marble Canyon was reduced by more than 99%. This large reduction occurred, because the sediment retention capability of Lake Powell is tremendous.

The rate at which fine sediment was removed from Glen, Marble, and upper Grand Canyons was determined by the changing patterns of water release from Glen Canyon Dam and fine-sediment influx from tributaries downstream from the dam – primarily the Paria and Little Colorado Rivers. Bed degradation in Glen Canyon occurred immediately after construction of the cofferdam, because Glen Canyon is upstream from the Paria River and there was no significant sediment delivery from tributaries in this segment. Bed degradation within 7.5 km downstream from Glen Canyon Dam was significant by 1959, as measured by resurvey of channel cross-sections (Fig. 19). Riffles and pools degraded, and the entire bed near Glen Canyon Dam lowered. No changes in the bed or the banks in Marble or upper Grand Canyons were measured during the construction period.

The immediate response to completion of the dam was accumulation of fine sediment on the bed downstream from Lees Ferry between August 1963 and March 1965. Bed aggradation was measured at the Grand Canyon gage, where mean bed elevation increased 1.5 m (Fig. 17). Dam releases were less than 40 m^3/s during much of this period and only exceeded 400 m^3/s for 2 weeks in spring 1964 (Fig. 2). Blaisdell's 1963 photograph of the Tapeats Gorge shows that most eddy bars were emergent at these very low flows (Fig. 44A); thus the only place for fine sediment to accumulate was on the main channel bed. Blaisdell's photograph, and one taken of Badger Creek

Figure 56. Graphs showing (A) measured sediment volume over time in the 7 largest eddies surveyed by NAU. Five of these contained less fine sediment in 2000 than in the early 1990s. (B) measured volume in the 9 smallest eddies surveyed by NAU. Five of these contained less fine sediment in their last survey than in the first survey.



Rapids in 1964 (Fig. 29D), show that there were extensive flood deposits along the edge of eddies, remnants of unregulated floods that had occurred in the late 1950s and early 1960s.

Pulsed high releases from the dam in May and June 1965 accomplished their purpose of "channel cleaning." Approximately 5.0 x 10^6 tons of fine sediment was removed from riffles and pools throughout Glen Canyon. There is no evidence for degradation of rapids or riffles in Marble and upper Grand Canyons, however. Thus, the 17.6 x 10^6 tons removed from these segments must have come from main channel pools and eddies. There was less fine-sediment in the flood zone in May 1965 than during the pre-dam era (Fig. 47), based on aerial photograph analysis. Thus, the first pulses of high releases eroded some of the pre-dam flood deposits as well as eroding fine sediment at lower elevations. Nevertheless, there were still large areas of fine sediment in the flood zone when the pulsed releases ended, based on an oblique photograph taken in 1968 at Badger Creek Rapids (Fig. 29).

It is impossible to determine the relative proportion of fine sediment removed from the main channel and from eddies in 1965. Calculation of average bed elevation change in eddies and the main channel under various scenarios of fine sediment flux and storage location suggest that half of the fine sediment may have been removed from the bed and half from eddies (Table 5).

There are so few data about pre-dam channel characteristics away from rapids that it is difficult to generalize about long-term post-dam bed changes, but the evidence suggests widespread loss of sand. Resurveys at the proposed Marble Canyon Dam sites, measurements at the Grand Canyon gage, and comparison of the pre-dam distribution of eddy bars with modern bed topography (Table 4) indicate that pools that once scoured during the annual snowmelt flood and refilled during the fine sediment accumulation season are now permanently devoid of fines. Elsewhere, pre-dam aerial photographs depict mid-channel bars covered entirely or in part with sand; today, the surface of these bars is typically cobbles or coarse gravel.

Between summer 1965 and summer 1983, flood deposits in Marble and upper Grand Canyon gradually were eroded. In general, however, there were still expansive sand deposits in Grand Canyon in the mid-1970s, as evidenced by aerial photographs and the ground-level matches of Turner and Karpiscak (1980). Old time river runners described and topographic surveys of the late 1970s measured slow, but progressive, erosion. Analysis of aerial photographs also indicates a decrease in the area of post-dam flood deposits in the Point Hansborough and Big Bend Reaches between 1965 and 1973. There was no indication that fine sediment accumulated on the main channel bed, except due to local changes in channel controls.

The floods that occurred between 1983 and 1986 significantly reworked flood deposits in the Colorado River ecosystem and probably removed large amounts of fine sediment from the deep parts of eddies and from the main channel. Deposition in the post-dam flood zone in 1983 was large in places, based on sedimentologic descriptions in the late 1980s and an inventory of campsites conducted in fall 1983. The floods of 1984 to 1986 reworked the 1983 floods deposits and did not typically create thick new deposits of their own. Post-dam flood deposits subsequently were eroded between 1986 and spring 1996. In upper Grand Canyon, the winter 1993 floods in the Little Colorado River temporarily replenished eddy bars and channel-margin deposits.

The Controlled Flood restored much of the area of sand in the post-dam flood zone, but these deposits were subsequently eroded. There is no evidence that the main channel bed was a significant source of sand to mainstem transport during this flood. Such redistribution from the channel to eddies had been the guiding paradigm of the Controlled Flood (Schmidt et al., 1999a). Thus, the bed had been stripped of sand by 1996, a significant change from its more important role as a temporary storage site of sand in the pre-dam era.

Today's river corridor also has less sand than it did in the mid-1980s or in the beginning of the era of modern environmental river management. Integration of the detailed measurements by NAU with measurements from aerial photographs indicates that the area of post-dam flood deposits in 2003 was smaller than the area of these deposits in 1984 or 1990 (Fig. 57). Integration of these data for sand in the fluctuating flow zone indicates that the area in 2003 was less than in 1990 and probably less than in 1984 (Fig. 58). Imposition of the modern era of environmental dam management that began by constraining the range of fluctuating flows in 1991 did not slow the erosion of sand from Marble or upper Grand Canyons. Eddy bars and channel-margin deposits continue to erode. Thus, the objective of maintaining the volume of fine sediment in the riverine ecosystem was not achieved.

The magnitude of cumulative loss of fine sediment from eddies is approximately 25%, but this estimate remains imprecise. Various methods of historical analysis yield different

Figure 57. Graphs showing mean and median area of deposits in the post-dam flood zone since 1984 as determined from aerial photographs and by NAU. A. Mean area. B. Median area of sand in eddies. NAU (n=12) and NAU (n=14) are two samples of the population of sand bars in Marble Canyon surveyed by NAU. BB is Big Bend Reach. LF is Lees Ferry Reach. PH is Point Hansborough Reach. RG is Redwall Gorge Reach. TG is Tapeats Gorge Reach.

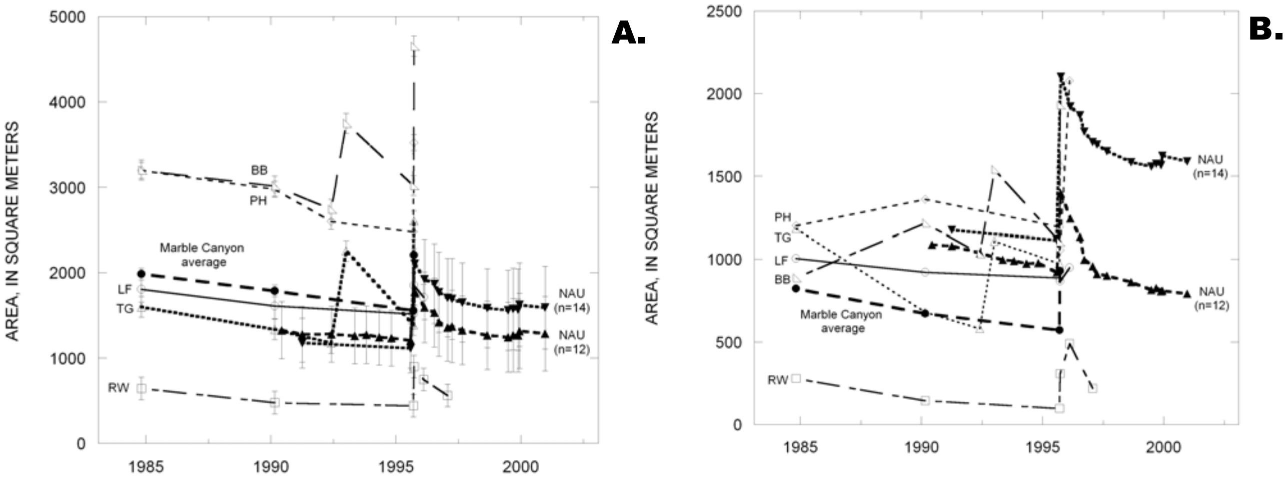
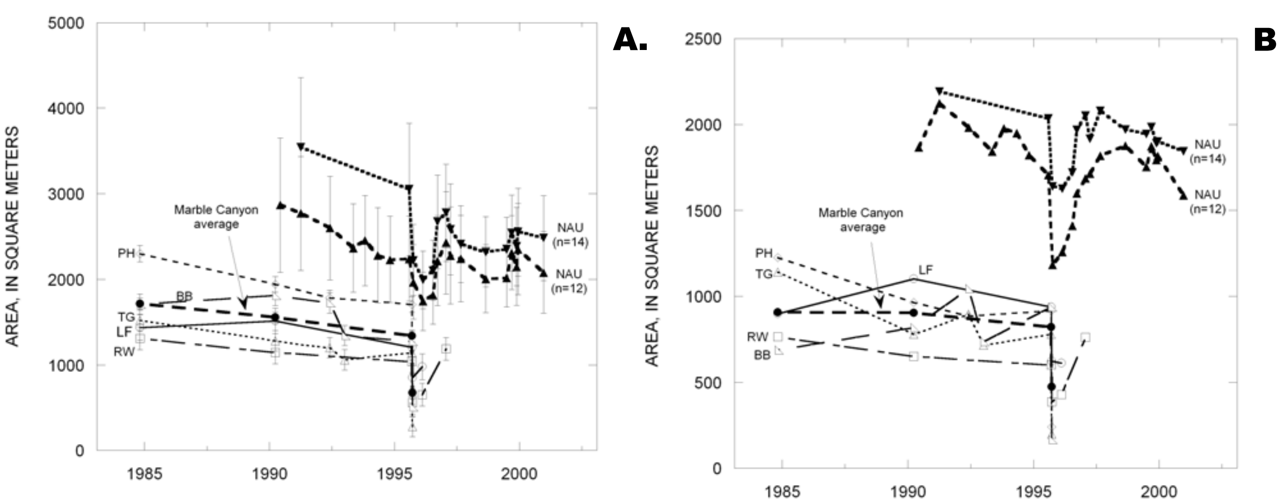


Figure 58. Graphs showing the temporal sequence of the area of fluctuating flow zone between 1984 and 2001as determined from aerial photographs and by NAU. A. Mean area of sand. B. Median area of sand in eddies. BB is Big Bend Reach. LF is Lees Ferry Reach. PH is Point Hansborough Reach. RG is Redwall Gorge Reach. TG is Tapeats Gorge Reach. NAU (n=12) and NAU (n=14) are two samples of the population of sand bars in Marble Canyon surveyed by NAU.



estimates of cumulative loss between the pre-dam era and the era of modern environmental management. Estimates of reach average change in eddy bar area (Table 14) vary between 0 and -55%, but most metrics in most reaches decreased between -10 and -30%. In the 1990s, eddy sand above base flow typically fills between 30 and 50% of the EDZs. Estimates of the volume of sand lost from eddies is limited to 9 sites where the EDZ was compared with the maximum elevation of sand surveyed in the 1990s. This comparison indicates that more than 1 m of sand has been lost from eddies of the study area, if representative of the entire study area, this volume is comparable to the annual pre-dam seasonal sediment accumulation of an average year.

10.2 Styles of Change in Eddies

Erosion of fine sediment in the fluctuating-flow zone tends to occur in some eddies and not elsewhere and has occurred in some reaches and not elsewhere. In contrast, changes in post-dam flood zone deposits carry the strong temporal signature of each flood event. Aggradation of sand in the post-dam flood zone was measured during each flood of the mid-1980s, although the volume of sand involved in deposition during the by-pass floods that occurred between 1984 and 1986 was much less than the volume of sand deposited in 1983 (Rubin et al., 1994b). Although the area of post-dam flood deposits was larger in April 1996, immediately after the 1996 Controlled Flood, than in October 1984, there probably was a long term loss of sand in this elevation between 1983 and 2001. We base this conclusion on the fact that the October 1984 photographs were taken more than 4 months after recession of the 1984 by-pass floods. Measurements by NAU show that the post-dam flood deposits decreased in area by about 4% in the first 5 months following recession of the 1996 Controlled Flood. Thus, it is more appropriate to compare the area of deposits in October 1984 with those photographed in September 1996. There is also not a significant difference between the mean area of post-dam flood deposits measured by NAU in 1990 and October 2001. Essentially, all of the positive benefit of newly-deposited high-elevation flood deposits during the 1996 Controlled flood was removed from the study area by 2001.

Our findings demonstrate that post-dam flood deposits have a longer response time in adjusting to operations of Glen Canyon Dam than do fluctuating flow deposits, because these deposits are infrequently inundated. It took about 5 years to reduce the area of these deposits back to their pre-1996 magnitude. It is uncertain what the average area of these deposits was in the mid-1980s, but available data indicate that post-dam flood deposits were much larger in summer 1983 and may have been larger immediately after recession of the by-pass floods of 1984, 1985, and 1986.

10.3 Style of Channel Change

Erodibility of bed material in channel controls determined the style of channel change in the study area. The style of channel change was very different in Glen Canyon in comparison to Marble and upper Grand Canyon. The difference is due to the fact that gravel in bars that act as channel controls in Glen Canyon were entrained, but boulders in rapids that act as controls in Marble and upper Grand Canyons were not entrained. Thus, the entire bed was lowered in Glen Canyon, although pools were degraded more than riffles. Local stage discharge relations shifted in Glen Canyon, such that the same discharge reaches lower elevations (Fig. 20), but the same did not occur in Marble and upper Grand Canyons. The evidence for bed degradation downstream from Lees Ferry was only in eddies, pools, and ponded backwaters. Scenarios of the location of seasonal fine-sediment accumulation also suggest loss of fine sediment from the bed, but accumulation of coarse debris continues in rapids. Bed lowering in Glen Canyon led to abandonment of some formerly active alluvial surfaces and to net channel narrowing. In contrast, evacuation of fine sediment from eddies and the post-dam flood zone, without any systematic bed incision, effectively widened the channel.

10.4 River Processes that Cause Channel Change and Constraints on Rehabilitation Towards Pre-dam Conditions

The Colorado River channel was re-worked by fluvial, ground-water, colluvial, and aeolian processes. Measurements during post-dam floods and experimental releases in the 1990s indicate that the main channel in ponded backwaters and pools typically scours during peak flows; in some cases, pools immediately scour as the flood rises, such as at the Lees Ferry gage, and elsewhere the bed fills before scouring, such as at the Grand Canyon gage. In either case, scoured pools subsequently fill during periods of fine sediment inflow from tributaries and sustained low flows of the Colorado River. Flows sufficiently low to result in bed aggradation did not occur after March 1965, and the magnitude of base flows increased in the era of environmental management in the 1990s. There was no evidence of sustained fine sediment accumulation on the channel bed anywhere in the study area in the 1990s.

Since the bed is no longer a repository of fine sediment, post-dam floods that are released from Glen Canyon Dam deliver no fine sediment to the study area. Thus, fine sediment available for transport is only derived from the interstices of the cobble bed, the remaining areas of fine sediment in pools, and eddies. Sediment budgets calculated for the 1996 Controlled Flood and experimental releases of the late 1990s indicate that eddies are the primary storage site for fine sediment in the modern Colorado River ecosystem.

Estimates of the proportion of fine sediment stored in the channel and in eddies in the pre-dam era (Table 4) indicates that the main channel was a more important storage site in years of large seasonal accumulation. Nevertheless, eddies were also a large component of sediment storage in the pre-dam era. Eddies accumulated fine sediment during the 9-month accumulation season and were evacuated of fine sediment during the snowmelt flood. The snowmelt flood also reworked and maintained the deposits of the flood zone by depositing fine sediment that had been transported from the upper basin during that specific flood or which had been entrained from the bed and the deep parts of the eddies of the study area. Post-dam floods only entrain fine sediment where it remains on the bed and from eddies, and post-dam sediment transport is primarily derived from the low parts of eddies. New post-dam flood deposits in the downstream part of Grand Canyon are probably derived from eroded eddies in upper Marble Canyon.

There are abundant data that demonstrate that post-dam flood deposits are significantly reworked by colluvial and aeolian processes. Debris flows, hillslope-derived runoff, and wind gradually or episodically erode exposed sand deposits. The rate of removal depends on local canyon geometry and weather. In the absence of floods, post-dam flood deposits are gradually removed, such as has occurred in upper Marble Canyon (Fig. 50). Floods may progressively become a less effective tool in rebuilding post-dam flood deposits, but post-dam floods are the only mechanism to maintain flood-zone deposits in the face of a range of processes that rework these deposits when they become emergent. Thus, floods are best timed to occur immediately after tributary influxes.

The fate of fine sediment deposits in the Colorado River ecosystem is bleak, because post-dam sediment transport is derived from a progressively declining bank account of fine sediment. The supply of fine sediment needed to support deposition along the channel edge during floods primarily comes from erosion of the deep parts of eddies, and these areas are not being replenished during periods of low flows. Thus, amount of fine sediment in eddies at all elevations continues to decline.

ACKNOWLEDGEMENTS

Sara Goeking, Fluvial Geomorphology Laboratory, Utah State University, oversaw the development and editing of the GIS data bases and compilation of spatial statistics. Michael Breedlove, David Galbraith, and Jairo Hernandez helped assemble some of the figures. Robert H. Webb, USGS, graciously contributed numerous photographs. Ted Melis, Scott Wright, Robert S. Anderson, and Randy Parker provided numerous helpful comments on an earlier draft. This report was assembled by Lael Gilbert. This project was inspired by numerous guides and river citizens who share a common passion for the river.

11.0 LITERATURE CITED

Andrews, E. D. 1990. The Colorado River; a perspective from Lees Ferry, Arizona: in Wolman, M. G., and Riggs, H. C., eds., Surface Water Hydrology. Geological Society of America, The Geology of North America, vol. O-1, 304-310.

Andrews, E.D., Johnson, C.E., Schmidt, J.C., and Gonzales M. 1999. Topographic evolution of sand bars, in Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The 1996 Controlled Flood in Grand Canyon: Washington, D.C., American Geophysical Union, Geophysical Monograph 110, p 117-130.

Anima, R.J., Marlow, M.S., Rubin, D.M., and Hogg, D.J., 1998. Comparison of sand distribution between April 1994 and June 1996 along six reaches of the Colorado River in Grand Canyon, Arizona: U.S. Geological Survey Open-File Report 98-141, 33 p.

Bauer, B. O., and Schmidt, J. C. 1993. Waves and sandbar erosion in the Grand Canyon: applying coastal theory to a fluvial system. Annals of the Association of American Geographers 83(3): 475-497.

Belknap, W., III. 1969. Grand Canyon river guide. Boulder City, NV, Westwater Books.

Beus, S.S., and Avery, C.C., 1992. The influence of variable discharge regimes on Colorado River sand bars below Glen Canyon Dam: Draft final report to Glen Canyon Environmental Studies.

Beus, S.S., Carothers, S.W., and Avery, C.C. 1985. Topographic changes in fluvial terrace deposits in Grand Canyon. Journal of the Arizona – Nevada Academy of Science 20: 111-120.

Beus, S. S. et al. 1982. A study of beach profiles as a measure of erosion, in Beus, S. S. and Carothers, S. W., eds., Colorado River Investigations I. Flagstaff, Northern Arizona University and Museum of Northern Arizona report submitted to Grand Canyon National Park, 131 p.

Brian, N. J., and Thomas, J. R. 1984. 1983 Colorado River beach campsite inventory. Grand Canyon National Park report.

Burkham, D.E. 1986. Trends in selected hydraulic variables for the Colorado River at Lees Ferry and near Grand Canyon, Arizona—1922-1984. Glen Canyon Environmental Studies Report No. PB88-216098, 58 p.

Carothers, S.W. and Brown, B.T., 1991, The Colorado River through Grand Canyon. Tucson, The University of Arizona Press, 235 p.

Colby, B.R., 1964, Scour and fill in sand-bed streams: U.S. Geological Survey Professional Paper 462-D, 32 p.

Cooley, M. E., Aldridge, B. N., and Euler, R. C. 1977. Effects of the catastrophic flood of December 1966, North Rim area, eastern Grand Canyon, Arizona. U. S. Geological Survey Professional Paper 980, 43 pp.

Dolan, R. 1981. Analysis of the erosional trends of the sedimentary deposits in Grand Canyon. Manuscript report submitted to U. S. Bureau of Reclamation, Water and Power Resources Service, Durango, 22 p.

Dolan, R., Howard, A., and Gallenson, A. 1974. Man's impact on the Colorado River in the Grand Canyon. American Scientist 62: 392-401.

Dolan, R., Howard, A., and Trimble, D. 1978. Structural control of the rapids and pools of the Colorado River in the Grand Canyon. Science 202: 629-631.

Flynn, M.E., and Hornewer, N.J. 2003. Variations in sand storage measured at monumented cross sections in the Colorado River between Glen Canyon Dam and Lava Falls Rapid, northern Arizona, 1992-1999. U. S. Geological Survey Water-Resources Investigations Report 03-4104,39 p.

Graf, J.B., Marlow, J.E., Fisk, G.G., and Jansen, S.M.D., 1995, Sand-storage changes in the Colorado River downstream from the Paria and Little Colorado Rivers, June 1992 to February 1994: U.S. Geological Survey Open-File Report 95-446, 61 p.

Graf, J.B., Marlow, J.E., Rigas, P.D., and Jansen, S.M.D., 1997. Sand-storage changes in the Colorado River downstream from the Paria and Little Colorado Rivers, April 1994 to August 1995: U.S. Geological Survey Open-File Report 97-206, 41 p.

Graf, W. L. 1979. Rapids in canyon rivers. Journal of Geology 87: 533-551.

Grams, P. E., and Schmidt, J. C. 1999. Integration of photographic and topographic data to develop temporally and spatially rich records of sand bar change in the Point Hansbrough and Little Colorado River confluence study reaches. Final Report to the Grand Canyon Monitoring and Research Center.

Grams, P. E. and Schmidt, J. C. 1999. Geomorphology of the Green River in the eastern Uinta Mountains, Dinosaur National Monument, Colorado and Utah, in A. J. Miller and A. Gupta, eds., Varieties of Fluvial Form. John Wiley & Sons, 81-111.

Grams, P.E., Schmidt, J.C., Topping, D.J., and Goeking, S. 2004. 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: Logan, Utah State University final report to the Grand Canyon Monitoring and Research Center, 111 p.

Hereford, R. 1996. Map showing surficial geology and geomorphology of the Palisades Creek area, Grand Canyon National Park, Arizona. U. S. Geological Survey Miscellaneous Investigations Series Map I-2449.

Hereford, R., Burke, K.J., and Thompson, K.S., 1998. Quaternary geology and geomorphology of the Nankoweap Rapids area, Marble Canyon, Arizona. U. S. Geological Survey Geologic Investigations Series Map I-2608.

Hereford, R., Burke, K. J., and Thompson, K. S. 2000a. Quaternary geology and geomorphology of the Granite Park area, Grand Canyon, Arizona. U. S. Geological Survey Geologic Investigations Series I-2662.

Hereford, R., Burke, K. J., and Thompson, K. S. 2000b. Map showing Quaternary geology and geomorphology of the Lees Ferry area, Arizona. U. S. Geological Survey Geologic Investigations Series I-2663.

Hereford, R., Fairley, H. C., Thompson, K. S., and Balsom, J. R. 1993. Surficial geology, geomorphology, and erosion of archeologic sites along the Colorado River, eastern Grand Canyon, Grand Canyon National Park, Arizona. U. S. Geological Survey Open-File Report 93-517, 46 p.

Hereford, R., Thompson, K. S., Burke, K. J., and Fairley, H. C. 1996. Tributary debris fans and the late Holocene alluvial chronology of the Colorado River, eastern Grand Canyon, Arizona. Geological Society of America Bulletin 108(1): 3-19.

Howard, A.D. 1975. Establishment of benchmark study sites along the Colorado River in Grand Canyon National Park for monitoring of beach erosion caused by natural forces and human impact. University of Virginia Grand Canyon Study Technical Report No. 1, 182 p.

Howard, A., and Dolan, R. 1979. Changes in the fluvial deposits of ther Colorado River in the Grand Canyon caused by Glen Canyon Dam, in Lin, R. M., ed., Proceedings of the First Conference on Scientific Research in the National Parks. Transactions and Proceedings No. 5. U. S. National Park Service, p. 845-851.

Howard, A., and Dolan, R. 1981. Geomorphology of the Colorado River in the Grand Canyon. Journal of Geology 89: 269-298.

Kearsley, L. H., Schmidt, J. C., Warren, K. D. 1994. Effects of Glen Canyon dam on Colorado River sand deposits used as campsites in Grand Canyon National Park, USA. Regulated Rivers: Research and Management 9: 137-149.

Kieffer, S. W. 1985. The 1983 hydraulic jump in Crystal Rapid: implications for river-running and geomorphic evolution in the Grand Canyon. Journal of Geology 93: 385-406.

Kieffer, S. W. 1988. Hydraulic maps of major rapids, Grand Canyon, Arizona. U. S. Geological Survey Miscellaneous Investigations Series Map I-1897.

Larsen, I. J., Schmidt, J. C., and Martin, J. A. 2004. Debris fan reworking during low magnitude floods in the Green River canyons of the eastern Uinta Mountains, Colorado and Utah. Geology 32(4): 309-312.

Laursen, E.M., Ince, S., and Pollack, J. 1976. On sediment transport through Grand Canyon. Proceedings of the Third Federal Interagency Sedimentation Conference. Denver, 4-76 to 4-87.

Leopold, L. B. 1969. The rapids and the pools – Grand Canyon, in The Colorado River region and John Wesley Powell. U. S. Geological Survey Professional Paper 669, 131-145.

Leschin, M. F., and Schmidt, J. C. 1995. Description of map units to accompany maps showing surficial geology and geomorphology of the Point Hansborough and Little Colorado River confluence reaches of the Colorado River, Grand Canyon National Park, Arizona. Flagstaff, Bureau of Reclamation Glen Canyon Environmental Studies report, 6 p. and plates.

MacDonnell, L. J., Getches, D. H., and Hugenberg, W. C., Jr. 1995. The law of the Colorado River: coping with severe sustained drought. Water Resources Bulletin 31(5): 825-836.

Magirl, C. S., Webb, R. H., and Griffiths, P. G. ——, Changes is the water-surface profile of the Colorado River in Grand Canyon, Arizona between 1923 and 2000. manuscript submitted to Water Resources Research.

McKee, E. D. 1938. Original structures in Colorado River flood deposits of Grand Canyon. Journal of Sedimentary Petrology 8(3): 77-83.

Melis, T. S. 1997. Geomorphology of debris flows and alluvial fans in Grand Canyon National Park and their influence on the Colorado River below Glen Canyon Dam, Arizona. PhD thesis, University of Arizona, 490 p.

National Research Council. 1991. Colorado River ecology and dam management, Proceedings of a symposium, May 24-25, 1990, Santa Fe, New Mexico. Washington, D. C., National Academy Press.

National Research Council. 1996. River resource management in the Grand Canyon. Washington, D. C., National Academy Press, 226 p.

Pemberton, E. L. 1976. Channel change in the Colorado River below the Glen Canyon Dam. Proceedings of the Third Federal Inter-agency Sedimentation Conference. Denver, 5-61 to 5-73.

Pizzuto, J. E., Webb, R. H., Griffiths, P. G., Elliott, 1. G., and Melis, T. S. 1999. Entrainment and transport of cobbles and boulders from debris fans, in Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The 1996 Controlled Flood in Grand Canyon. Washington, D.C., American Geophysical Union, Geophysical Monograph 110: 53-70.

Rihs, J. 1995. Analysis of the March 1995 Bright Angel Creek flood event, Grand Canyon National Park. National Park Service report, 9 p.

Rubin, D.M., Anima, R.J., and Sanders, R. 1994a. Measurements of sand thicknesses in Grand Canyon, Arizona, and a conceptual model for characterizing changes in sand-bar volume through time and space. U.S. Geological Survey Open-File Report 94-597, 9 p.

Rubin, D.M., Nelson, J.M., and Topping, D.J. 1998. Relation of inversely graded deposits to suspended-sediment grain-size evolution during the 1996 flood experiment in Grand Canyon. Geology 26: 99-102.

Rubin, D.M., Schmidt, J.C., Anima, R.A., Brown, Kristin, M., Hunter, R.E., Ikeda, H., Jaffe, B.E., McDonald, R., Nelson, J.M., Reiss, T.E., Sanders, R., and Stanley, R.G., 1994b. Internal structure of bars in Grand Canyon and evaluation of proposed flow alternatives for Glen Canyon Dam: USGS Open-File Report 94-594, 56 p.

Rubin, D.M., Schmidt, J.C., and Moore, J.N. 1990. Origin, structure, and evolution of a reattachment bar, Colorado River, Grand Canyon, Arizona. Journal of Sedimentary Petrology 60: 982-991.

Rubin, D. M., and Topping, D. J. 2001. Quantifying the relative importance of flow regulation and grain-size regulation of suspended-sediment transport (a), and tracking changes in bed-sediment grain size (b). Water Resources Research 37:133-146.

Rubin, D. M., Topping, D. J., Schmidt, J. C., Hazel, J., Kaplinski, M., and Melis, T. S. 2002. Recent sediment studies refute Glen Canyon Dam hypothesis. Eos 83(25): 273-278.

Schmidt, J. C. 1990. Recirculating flow and sedimentation in the Colorado River in Grand Canyon, Arizona. Journal of Geology 98: 709-724.

Schmidt, J.C. 1999. Summary and synthesis of geomorphic studies conducted during the 1996 controlled flood in Grand Canyon, in Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The 1996 Controlled Flood in Grand Canyon. Washington, D.C., American Geophysical Union, Geophysical Monograph 110: 329-342.

Schmidt, J. C., Andrews, E. D., Wegner, D. L., Patten, D. T., Marzolf, G. R., and Moody, T. O. 1999a. Origins of the 1995 controlled flood in Grand Canyon, in Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The 1996 Controlled Flood in Grand Canyon. Washington, D.C., American Geophysical Union, Geophysical Monograph 110: 23-36.

Schmidt, J.C., and Graf, J.B. 1990. Aggradation and degradation of alluvial sand deposits, 1965 to 1986, Colorado River, Grand Canyon National Park, Arizona: U.S. Geological Survey Professional Paper 1493, 74 p.

Schmidt, J. C., Grams, P. E., and Leschin, M. F. 1999b. Variation in the magnitude and style of deposition and erosion in three long (8-12 km) reaches as determined by photographic analysis, in Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The 1996 Controlled Flood in Grand Canyon. Washington, D.C., American Geophysical Union, Geophysical Monograph 110: 185-203.

Schmidt, J. C., Kepes, A. J., and Hanson, M. A., 1989. Topographic changes of alluvial sand bars, Lees Ferry to Bright Angel Creek, Colorado River, Grand Canyon National Park. Middlebury College Grand Canyon Study Technical Report No. 89-1 submitted to Grand Canyon National Park, 58 p.

Schmidt, J. C., and Leschin, M. F. 1995. Geomorphology of post-Glen Canyon Dam fine-grained alluvial deposits of the Colorado River in Point Hansbrough and Little Colorado River confluence study reaches in Grand Canyon National Park, Arizona: final draft report for the U. S. Bureau of Reclamation, Glen Canyon Environmental Studies.

Schmidt, J. C., and Rubin, D. M. 1995. Regulated streamflow, fine-grained deposits, and effective discharge in canyons with abundant debris fans, in Costa, J. E., Miller, A. J., Potter, K. W., and Wilcock, P. R., eds., Natural and anthropogenic influences in fluvial geomorphology. Washington, D. C., American Geophysical Union Geophysical Monograph 89: 177-194.

Smillie, G. M., Jackson, W. L., and Tucker, D. 1993. Colorado River sand budget: Lees Ferry to Little Colorado River. Washington, D. C., National Park Service Technical Report NPS/NRWRD/NRTR-92/12, 11 p.

Sondossi, H.A. 2001. Historical analysis of the geomorphology of sand bars along the Colorado River in Upper Marble Canyon, Arizona. Unpublished master’s thesis, Utah State University, 138 p.

Sondossi, H.A., Schmidt, J.C., Goeking, S.A., and Grams, P.E. 2002. Historical change in the geomorphology of sand bars in Redwall Gorge. Report and maps submitted to the Grand Canyon Monitoring and Research Center.

Stephens, H. G., and Shoemaker, E. M. 1987. In the footsteps of John Wesley Powell. Boulder, CO, Johnson Books.

Stevens, L. 1983. The Colorado River in Grand Canyon, a guide. Flagstaff, Red lake Books.

Topping, D. J. 1997. Physics of flow, sediment transport, hydraulic geometry, and channel geomorphic adjustment during flash floods in an ephemeral river, the Paria River, Utah and Arizona. Unpublished doctoral dissertation, Department of Geological Sciences, University of Washington. 405 p.

Topping, D.J., Rubin, D.M., Nelson, J.M., Kinzel, P.J., III, and Bennett, J.P. 1999. Linkage between grain-size evolution and sediment depletion during Colorado River floods, in Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The 1996 Controlled Flood in Grand Canyon. Washington, D.C., American Geophysical Union, Geophysical Monograph 110: 71-98.

Topping, D.J., Rubin, D.M., Nelson, J.M., Kinzel, III, P.J., and Corson, I.C. 2000a. Colorado River sediment transport 2. Systematic bed-elevation and grain-size effects of sand supply limitation. Water Resources Research 36: 543-570.

Topping, D.J., Rubin, D.M., and Vierra, Jr., L.E. 2000b. Colorado River sediment transport 1. Natural sediment supply limitation and the influence of Glen Canyon Dam. Water Resources Research 36: 515-542.

Topping, D. J., Schmidt, J. C., and Vierra, L. E., Jr. 2003. Discharge of the Colorado River at Lees Ferry, Arizona, during the 1884 flood and between May 8, 1921, and September 30, 2000: construction and analysis of a continuous record of instantaneous discharge. U. S. Geological Survey Professional Paper 1677.

Turner, R. M. and Karpiscak, M. M. 1980. Recent vegetation changes along the Colorado River between Glen Canyon Dam and Lake Mead, Airzona. U. S. Geological Survey Professional Paper 1132, 125 p.

U. S. Department of the Interior, 1988. Glen Canyon environmental studies final report. Salt Lake City, Bureau of Reclamation, Upper Colorado Region, 84 pp and appendices (NTIS No. PB88-183348/AS).

U.S. Department of the Interior. 1995. Operation of Glen Canyon Dam, Final Environmental Impact Statement. Salt Lake City, Utah, Bureau of Reclamation, 337 p.

Webb, R. H. 1996. Grand Canyon, a century of change. Tucson, The University of Arizona Press, 290 p.

Webb, R. H., Griffiths, P. G., Melis, T. S., and Hartley, D. R. 2000. Sediment delivery by ungaged tributaries of the Colorado River in Grand Canyon, Arizona. U. S. Geological Survey Water-Resources Investigations Report 00-4055, 67 p.

Webb, R. H., Melis, T. S., Griffiths, P. G., and Elliott, J. G. 1999. Reworking of aggraded debris fans, in Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The 1996 Controlled Flood in Grand Canyon. Washington, D.C., American Geophysical Union, Geophysical Monograph 110: 37—51.

Webb, R. H., Melis, T. S., and Valdez, R. A. 2002. Observations of environmental change in Grand Canyon, Arizona. U. S. Geological Survey Water-Resources Investigations Report 02-4080, 33 p.

Wiele, S.M, Graf, J.B., and Smith, J.D., 1996. Sand deposition in the Colorado River in the Grand Canyon from flooding of the Little Colorado River. Water Resources Research, v. 32, p. 3579-3596.

Wilson, R. P. 1986. Sonar patterns of Colorado River bed, Grand Canyon, in Proceedings of the Fourth Federal Interagency Sedimentation Conference. Water Resources Council, Sedimentation Committee, p. 5-133 to 5-142.

Appendix A: Comparison of Oblique Historical Photographs

RM	EDZ #	Site Name	Stake	Original Photographer	Number	Month	Day	Year	Subject	Matches	Δ high sand	Δ low sand	Comments
1.6		low fan/gv bar below Paria eddy	2800	James, G.W.				1897	cm sand	2/24/94	same	less	similar area of sand but lower in elev.
3.5			2011	Bell, W.	II,6			1872	cm/eddy sand	4/19/91	same	same	more cm sand and veg in 1991; more veg on sand
4		4-Mile Wash	2753	James, G.W.				1897	cm sand	2/24/94			
4.2	19	4-Mile Wash	704	Leding, R.S.		10	21	1952	cm/eddy sand	8/21/72, 6/11/75	same	NA	more sand on veg; smaller eddy bar
29.4		Silver Grotto	2644	Stanton (Nims)	319	7	16	1889	df/sand veneer	2/23/1993, 3/28/99	less	NA	dense tamarisk
30.3	5	GCMRC cableway site	2249	LaRue	369	8	7	1923	river and rocks		NA	NA	
30.4	6	Camp for gage and LISST	2525b	Stanton	323	1	14	1890	s,df	1/2/92	less	more	
30.4	6	Camp for gage and LISST		Grams		3	29	1999	SAME BAR BUT **NOT** A MATCH TO STANTON 2525				
30.6	7	Fence Fault	2250	Stanton (Nims)	322	7	16	1889	df/sand veneer	1/2/92	same	less	
30.6	7	Fence Fault camp	1703	LaRue	368	8	7	1923	df/sand veneer	3/29/99	same	NA	
30.7	7, 8	Fence Fault Camp and NAU 30-mile site	2525a	Stanton	324	1	14	1890	s,df	1/2/92	less	same	
30.8	9	Fence Fault	2729	Stanton (Nims)	321	7	16	1889	small fan on RL	2/23/93	NA	same	
31.7	17	South Canyon	2526	Stanton (Nims)	325	7	17	1889	df and rb	1/2/1992, 3/30/99	more	more	
31.8	NA	South Canyon	2566	Stanton (Nims)	326	7	17	1889	side canyon	2/13/1992, 3/30/99	less	NA	
31.8	17	South Canyon	2731	Fahrni		7	24	1934	recent df/rb				
31.9	18	South Canyon		NPS (Laursen)	19	8	6	1976	s,df	3/30/99	same	same	
31.9	18	South Canyon	2308	Stanton (Nims)	327	7	17	1889	sb and eddy	2/3/1991, 3/30/99	less	same	
31.9	18	South Canyon		NPS	I-42			1974	sb	3/30/99	same	same	
31.9	18	South Canyon		NPS	I-41			1974	sb	8/4/85, 3/30/99	more	more	
31.9	18	South Canyon		NPS	I-40			1974	sb	8/4/85, 3/30/99	same	NA	
31.9	18	South Canyon		NPS	I-40&41			1974	sb panorama	8/4/85, 3/30/99			
32.0	cm	above Vasey's	674	LaRue		8	8	1923	cm		less	less	
32.1	20	near Vasey's	2527	Stanton (Nims)	328	7	17	1889	s,rocks	1/3/92	NA	same	
32.2		below Vasey's	1418	Stanton (Nims)	329	7	17	1889	df and grv island	1/20/90	NA	NA	
32.5		Below Vasey's	2076	Stanton	330	1	15	1890	talus	1/3/92	NA	NA	

33.3		Redwall Cavern	3092	Kolb		11	13	1911	rb	2/23/95, 3/30/99	same	same	dense low elev veg
33.3		Redwall Cavern		NPS (Laursen)	24	8	6	1976	RB	3/30/99	NA	less	
33.3		Redwall Cavern	676	Freeman	173	8	8	1923	rb and df	6/28/72, 3/17/74, 8/14/84, 9/10/94, 3/30/99	less	same	
33.3		Redwall Cavern	2201	LaRue	378	8	8	1923	rb	10/9/91, 3/30/99	same	same	
33.3		Redwall Cavern		NPS (Laursen)	20	8	6	1976	rb	3/30/99	NA	less	
33.3		Redwall Cavern		NPS (Laursen)	21	8	6	1976	sand	3/30/99	NA	less	
33.3		Redwall Cavern	2863	Nichols		7		1951	rb	9/10/94, 3/30/99	NA	less	
33.3		Redwall Cavern	2927	Nichols		7		1951	rb	9/10/94, 3/30/99	NA	NA	
33.3		Redwall Cavern	1419b	Stanton	331	1	15	1890	df	1/3/92, 3/30/99	NA	less	
33.5	35	below Redwall Cavern	1419a	Stanton	332	1	15	1890	sb	1/20/1990, 1/3/92, 3/30/99	NA	less	
34.0		obscure		Hillers	849	8	21	1872	s,rocks	9/4/68	NA	NA	
34.0		obscure	3093	Hillers	850	8	21	1872	s,rocks	9/4/68, 2/23/95	NA	same	new veg 65-95
35.0		Below Nautiloid	2309	Stanton	1/15/	1	15	1890	df	2/3/91	NA	NA	
35.0		Below Nautiloid	2981	Kolb				1911	s,df	199?	NA	same	
36.0		36-Mile Rapid	1564	Stanton	1/16/	1	16	1890	s,br	2/3/91	NA	less	
36.0		36-Mile Rapid	1563	Stanton	1/16/	1	16	1890	s,df	2/3/91	NA	less	
36.4		Below 36-Mile	2805	Freeman		8	9	2023	br,talus	2/26/94	NA	NA	
37.0		above Tatahatso	2864	Kolb		8	9	1923	s,rocks	9/10/94	NA	same	
38.0		obscure	1734a	Stanton	1/16/	1	16	1890	sb	2/3/91, 4/1/99	less	less	
38.0		obscure	1734b	Stanton	1/16/	1	16	1890	s,rocks	2/3/91, 4/1/99	less	less	
39.0		Marble Canyon Dam Site	1565a	Stanton	339	1	16	1890	cm	2/3/91, 4/2/99	less	NA	
39.0		Marble Canyon Dam Site	1565b	Stanton	1/16/	1	16	1890	s,rocks	2/23/93, 4/2/99	less	NA	
39.0		Aerial Marble Canyon Dam Site		Bureau of Reclamation	195?				cm		NA	less	
41.0		Buckfarm		NPS	25	8	7	1976	s	4/2/99	NA	less	
41.0		Buckfarm		NPS	26	8	7	1976	rb	4/2/99	NA	less	
41.3	NA	Bert's Canyon	2865	Stanton	341	1	16	1890	s	9/10/94	same	less	lots more veg onshore side of bars; bar erosion offshore
43.4	9	Anasazi Bridge Camp	1735b	Nims/Stanton	343	1		1890	rb	2/23/93	NA	NA	lots more veg onshore side of rb
43.4	9	Anasazi Bridge Camp	1735a	Nims/Stanton	344	1	16	1890	rb	2/3/91	NA	NA	lots more veg on high sand

43.9		above President Harding	677	LaRue	387	8	10	1923	eddy bar	6/28/72,8/23/72,10/7/82, 10/19/83	same	same	shows same camp as stake 1421, EC#12, shows increasing veg on sand
43.9		above President Harding	677a	LaRue							same	same	lots more riparian veg
43.9		above President Harding	677b	LaRue							same	same	
43.9	14	above President Harding	678a,b	LaRue	386	8	10	1923	eddy bar	6/28/72	same	same	shows same camp as stake 1421, EC#12, shows increasing veg on sand, match view is obscured by veg
43.9	14	above President Harding		Freeman, L.R.	335	23 ?		1923 ?			same	NA	President's camp - above Pt. Hansbrough. BIG SAND
44.1		PH Rapid EC #14	1420b	Nims/Stanton	346	1		1890	sb, rb	2/3/91	same	less	sb has less sand rb not present in 1991
44.9	27		2732	Nims/Stanton	347	1		1890	›, eb in backgrour	2/23/93	same	less	EC#24, more veg on sb in 1993
46.5			798										
47	55, 58		798a,b	LaRue	390	8	11	1923		9/17/76,10/8/82, 10/20/83,8/15/84,11/17/90	less	same	EC#61&67; 1976 photo shows lots more veg on EC#67 (and on df), 1984 photo shows high water
47.2	58	Abv Saddle	1736b	Nims/Stanton	349	1		1890	n eb in background		same	less	much more vegetation at high elevation; mid channel island now gone
48.8			2311	Nims/Stanton	350	1		1890	m sand EC#96&9	2/4/91	NA	NA	match too dark
59			2251b	Nims/Stanton	369	1		1890	eddy bars	1/5/92	same	less	more veg on eddy bars
59.7			2929	Nichols				1957	rapid	9/12/94			notes say sand erosion, original not in file
60.7			1569a	Nims/Stanton	370	1		1890	sb, rb	2/5/91	same	same	lots more veg on sb, rb very similar, water higher in 1991 than in 1890
60.7			1569b	Nims/Stanton	371	1		1890	›ground, rb in bac	2/5/91	same	same	veg on rb and sb, similar sizes
61.4			1427a	Nims/Stanton	375	1		1890	ds side of conflue	1/23/90			bar similar but now has veg.
61.5			730	Blaisdell, J.	NPS 4288	7	13	1963	ıs from confluence	9/2/73, 5/24/92	less	less	close-up of mi 60 to confluence
61.5			731	Blaisdell, J.	NPS 4283	7	13	1963	ls from confluence	9/2/73, 5/24/92	less	less	
62.6			2314a	Nims/Stanton	377	1		1890	s from Crash at g	2/5/91	less	less	more sand on us side of gb in 1991 but 1890 water is higher; new df in foreground; more sand in 1991 us from small fan
62.6			2314b	Nims/Stanton	376	1	?	1890	Crash eddy	2/5/91	less	less	no sand in eddy in 1890; more sand on ds end in 1890 than in 1991, water higher in 1991 photo
63.7			2315	Nims/Stanton	379	1		1890	›ddy bar on river	2/5/91	same	same	more veg on bar water higher in 1991 photo
65			10929	LaRue	409	8	14	1923			same	same	
65.5			1434a	Nims/Stanton	384	1		1890	›ek, lg eddy abv F	1/24/90	same	less	lots more veg. On sand bars
65.5			1434b	Nims/Stanton	383	1		1890	›f eddy us from P	2/6/91	same	less	lots more veg on eb, water higher in 1991 than in 1890
65.5			1434c	Nims/Stanton	385	1		1890	›lw. Palisades on	1/24/90,2/6/91	same	less	more veg on sb and rb, water higher in 1991 than in 1890

65.5	1431b	Nims/Stanton	382			1890	gb blw Palisades	2/7/91	same	less	
65.5		Nims/Stanton	381	1	21	1890					smaller cm sand bar more veg
65.5	1431c	Nims/Stanton	380	1		1890	s from Palisades,	2/7/91	same	less	bar and cm covered by veg., rb had rcc but in 1991 does not
65.5	1080	Hillers	858			1872	blw. Palisades on	9/9/68,6/29/72,7/31/74,10/11/82,10/22/83,1/23/90	same	same	more open sand in 1872 all matches show all covered by veg.
66.3	1437	Nims/Stanton	388	1		1890	big sand beach	1/24/90	NA	NA	view entirely blocked by new tamarisk
66.3	1436	Nims/Stanton	387	1		1890	shown in stake 1	1/24/90	NA	less	view mostly blocked by new tamarisk
68.5	2316a	Nims/Stanton	393	1		1890	Tanner Site	2/8/91	same	NA	1890 shows sand with some veg, more veg in 1991; too distant for measurements
71.3	1440	Stanton	396	1		1890	denas marsh and	1/25/90	same	same	shows open sand bar at marsh site
72.7	1442	Stanton	400	1		1890	looking us at ec c	1/26/90	same	NA	shows veg on eb sand