Prepared in cooperation with Northern Arizona University and Utah State University

Sandbar Response in Marble and Grand Canyons, Arizona, Following the 2008 High-Flow Experiment on the Colorado River

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COVER:
View looking south (downstream) of the Colorado River and the sandbar at Carbon Canyon (study site 65L in Eastern Grand Canyon) on April 4, 2008. Discharge at the time was about 368 m^3/s. (Photograph by J.E. Hazel, Jr.)

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By Joseph E. Hazel, Jr., Paul E. Grams, John C. Schmidt, and Matt Kaplinski

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Contents

Abstract 1
Introduction 1
Purpose and Scope 3
Physical Setting 3
Units, Place Names, and Study Area 3
The Fan-Eddy Complex 3
Controlled Floods, Tributary Sand Inputs, and Fluctuating Flows 5
Methods 8
Results 11
Overview of Topographic Response 11
Styles of Topographic Response 11
Style 1 12
Style 2 With Net Eddy Erosion 12
Style 2 With Net Eddy Deposition 14
Style 3 14
Spatial Pattern of Topographic Response 19
Longevity: Changes from April to October 2008 21
Campsite Area 23
Comparison of Three High-Flow Experiments: 1996, 2004, and 2008 28
Discussion and Conclusions 29
Acknowledgements 35
References Cited 36
Appendix A. Summary of study sites and types of data collected, Colorado River in Marble and Grand Canyons 40
Appendix B. Basic Data Tables for Studied Sites on Colorado River, Marble and Grand Canyons 46

Figures

1. The Colorado River and Grand Canyon National Park, between Lake Powell and Lake Mead reservoirs 2
2. Geomorphic description of physical setting and boundary definitions for fan-eddy complexes of the Colorado River 4
3. Instantaneous discharge of the Colorado River at USGS streamflow-gaging station (09380000), Lees Ferry, Arizona, for the 2008 calendar year 9
4. Histograms of net sandbar thickness change between February and April 2008 13
5. Relation of proportional sand-volume change above reference stage for each site between February and April 2008 14
6. Comparison of repeat topographic and bathymetric surveys collected at site 172L illustrating Style 1 site response 15
7. Selected daily photographs of the reattachment bar at site 172L 16

8. Areal and volumetric elevation-change distributions from the erosion-deposition map at site 172L shown in figure 6*C* 16
9. Comparison of repeat topographic and bathymetric surveys collected at site 44L illustrating a Style 2 sandbar response 17
10. Selected daily photographs of the sandbars at site 44L 18
11. Areal and volumetric elevation-change distributions from the erosion-deposition map at site 44L shown in figure 9C 19
12. Comparison of repeat topographic and bathymetric surveys collected at 65R illustrating a variant of Style 2 response 20
13. Selected daily photographs of the reattachment bar at site 65R 21
14. Areal and volumetric elevation-change distributions from the erosion-deposition map at site 65R shown in figure 12*C* 24
15. Comparison of repeat topographic and bathymetric surveys collected at site 3L 25
16. Selected daily photographs of the reattachment bar at site 3L 26
17. Areal and volumetric elevation-change distributions from the erosion-deposition map at site 3L shown in figure 15*C* 26
18. Downstream variations at study sites and sediment-transport-flux monitoring reaches in response to 2008 HFE 27
19. Photographic sequence at site 68R showing rapid erosion following the change in fluctuating flow regime at Glen Canyon Dam on April 15, 2008 28
20. Boxplot showing temporal sequence of deposit thickness above the reference stage compared to daily mean discharge following the 2008 HFE 29
21. Histograms showing the distribution of campsite area above the reference stage 30
22. Average campsite area above the reference stage before, after, and about 6 months after the 2008 HFE 31
23. The relation of change in campsite area to change in sandbar area and volume for two time intervals in 2008, pre- to postflood (February-April) and the following 6 months (April-October) 31
24. Cumulative probability distributions of total-site sand volume following the 1996, 2004, and 2008 HFEs 32
25. Boxplots showing normalized sand volumes of all sites within each sediment-transport-flux monitoring reach 33
26. Cumulative probability distributions of sand volume above reference stage following the 1996, 2004, and 2008 HFEs 34

Tables

1. Channel geometry and geomorphic characteristics for selected study sites, Colorado River in Marble and Grand Canyons 6
2. Sediment-transport-flux monitoring stations and reaches of the Colorado River used to compare the 1996, 2004, and 2008 HFEs 11
3. Critical and noncritical recreational campsite reaches of the Colorado River 12
4. Observations of erosion and deposition from repeat photography at sites along the Colorado River in Marble and Grand Canyons 22
Table B1. High-elevation-zone area and volume at four measurement times in 2008 at each study site 46
Table B2. Midelevation zone area and volume at four measurement times in 2008 at each study site 48
Table B3. Low-elevation-zone eddy area and volume, and main-channel volume at four measurement times in 2008 at each study site 50
Table B4. Midelevation zone and high-elevation-zone campsite area measured at four measurement times in 2008 at each study site 52

Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
mile (mi)	1.609	kilometer (km)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
	Area	
square meter (m^2)	10.76	square foot (ft^2)
	Volume	
cubic meter (m^3)	35.31	cubic foot (ft^3)
	Mass	
metric ton (t)	1.102	ton (2,000 lb)
	Flow rate	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)

In this report, horizontal and vertical coordinate information is referenced in meters above the GRS80 ellipse defined by the North American Datum of 1983 (NAD 83). Elevation, as used in this report, refers to NAD83/GRS80 ellipsoid heights and not traditionally defined NAVD88 orthometric heights.

Sandbar Response in Marble and Grand Canyons, Arizona, Following the 2008 High-Flow Experiment on the Colorado River

By Joseph E. Hazel, Jr.[1], Paul E. Grams[2], John C. Schmidt [3], and Matt Kaplinski[1]

Abstract

A 4-day planned release of water at 1,203 cubic meters per second (m^3/s) from Glen Canyon Dam in March 2008 provided an opportunity to analyze channel-margin response at discharge levels above the normal, diurnally fluctuating releases for hydropower plant operations. We compare measurements at sandbars and associated campsites along the mainstem Colorado River, downstream from Glen Canyon Dam, at 57 locations in Marble and Grand Canyons. Sandbar and main-channel response to the 2008 high-flow experiment (2008 HFE) was documented by measuring bar and bed topography at the study sites before and after the controlled flood and twice more in the following 6 months to examine the persistence of flood-formed deposits. The 2008 HFE caused widespread deposition at elevations above the stage equivalent to a flow rate of 227 m^3/s and caused an increase in the area and volume of the high-elevation parts of sandbars, thereby increasing the size of campsite areas. In this study, we differentiate between four response styles, depending on how sediment was distributed throughout each study site. Then, we present the longitudinal pattern relevant to the different response styles and place the site responses in context with two previous high-release experiments conducted in 1996 and 2004. We find that (1) nearly every measured sandbar aggraded above the 227-m^3/s water-surface elevation, resulting in sandbars as large or larger than occurred following previous high flows; (2) reaches closest to Glen Canyon Dam were characterized by a greater percentage of sites that incurred net erosion, although the total sand volume in all sediment-flux monitoring reaches was greater following the 2008 HFE than following previous high flows; and (3) longitudinal differences in topographic response in eddies and in the channel suggest a greater and more evenly distributed sediment supply than existed during previous controlled floods from Glen Canyon Dam.

Introduction

Operations of Glen Canyon Dam affect the downstream geomorphology and associated riverine ecosystem along the Colorado River in Marble and Grand Canyons (fig. 1). One feature of the geomorphic environment is the sand and finer sediment that occurs as eddy bars, channel-margin deposits, and as patches that cover parts of the coarser grained channel bed. These deposits are of interest, because sandbars are an attribute of the pre-dam riverine landscape, are used as campsites, are substrate for riparian plants, create aquatic habitat, and are a source of windblown sand that potentially buries and preserves archaeological sites (Wright and others, 2005; Draut and Rubin, 2008).

Completion of Glen Canyon Dam in 1963 eliminated the supply of fine sediment delivered from the upper Colorado River Basin, decreased the magnitude of annual flood flows, and increased the magnitude of base flows (Howard and Dolan, 1981; Topping and others, 2003; Wright and others, 2005). Collectively, these changes in hydrology and sediment supply caused evacuation of sand from the bed and margins of the river channel, such that the average size of sandbars emergent at base flows in 2001 was at least 25 percent less than before completion of the dam (Schmidt and others, 2004). Other factors, such as vegetation growth (Turner and Karpiscak, 1980), hillslope runoff or burial by debris flows (Melis and others, 1994), eolian processes (Draut and Rubin, 2008), and human activities (Phillips and others, 1986) have also contributed to reductions in the area of exposed bare sand, thereby reducing the area available for camping (Kearsley and others, 1994; Kaplinski and others, 2005).

The Colorado River in Marble and Grand Canyons is currently the subject of a large-scale river rehabilitation program called the Glen Canyon Dam Adaptive Management Program (GCDAMP). A primary goal of the GCDAMP is to maintain or improve the condition of sandbars for their associated

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Figure 1. The Colorado River and Grand Canyon National Park, between Lake Powell and Lake Mead reservoirs. Shown are the locations of Lees Ferry, the topographic survey sites, U.S. Geological Survey gaging stations (with station numbers), and the sediment-transport flux monitoring reaches between the sediment-transport measurement sites.

ecosystem and resource values (U.S. Department of Interior, 1995; National Research Council, 1999). One aspect of the GCDAMP is implementation of an experimental program that evaluates the environmental effects of dam releases (Patten and others, 2001; Wright and others, 2005). On March 6, 2008, a 2.5-day (60-hour) controlled flood of 1,203 cubic meters per second (m^3/s) was released from Glen Canyon Dam (U.S. Department of Interior, 2008). At the time of this release, the river bed had been supplied with fine sediment (sand, silt, and clay) by a series of floods from the Paria River (fig. 1) in fall 2006 and fall 2007. The purpose of the present study is to document the response of eddy bars and some of the associated resource attributes to this flood, termed the 2008 high-flow experiment (2008 HFE). The findings are compared to results from two previous high-flow experiments conducted under differing sand-supply and flow conditions: the longer duration 1996 HFE of 1,275 m^3/s (Webb and others, 1999) and the 2004 HFE of similar magnitude and duration as the 2008 HFE (Topping and others, 2006a).

Purpose and Scope

The principal goals of this study are: (1) evaluation of whether sandbars located throughout the Colorado River in Marble and Grand Canyons gained or lost sand in response to the 2008 HFE, (2) evaluation of the persistence of rebuilt sandbars under normal dam operations over the 6-month period that followed the 2008 HFE, (3) comparison of the river response to the 2008 HFE with the river response to the 1996 and 2004 high flows at common monitoring sites, and (4) evaluation of changes in the area of campsites associated with sandbar changes resulting from the 2008 HFE. Site response was analyzed above and below the 227-m^3/s water-surface elevation (hereafter referred to as the reference stage; sand below this elevation is almost always subaqueous, while sand above this elevation is either always subaerial or within the diurnal fluctuating zone of dam releases associated with peaking hydropower generation). In order to facilitate comparison with data collected during the two previous HFEs, detailed field measurements were made at the long-term study sites measured by Hazel and others (1999) and Kaplinski and others (2005), as well as additional sites, on five survey trips in 2008.

Physical Setting

Units, Place Names, and Study Area

Measurements are reported in the SI system; however, locations and place names are reported in river miles (RM), downstream from Lees Ferry, Arizona (RM 0). The river-mile convention has long been used as the standard reference system for locations along the Colorado River in Marble and Grand Canyons and was formalized in 2006 (U.S. Geological Survey, 2006). Lees Ferry is located 15.5 miles downstream from Glen Canyon Dam and 1 mile upstream from the mouth of the Paria River and the northeastern boundary of Grand Canyon National Park (fig. 1).

In this report, we refer to Marble Canyon as the reach of the Colorado River between the Paria River and the Little Colorado River, located at RM 61.5 (fig. 1). The Paria River is the primary source of sand to the upstream end of Marble Canyon (Topping and others, 2000). Although Grand Canyon extends downstream to the Grand Wash Cliffs (RM 276), for our purposes we refer to Grand Canyon as the segment downstream from the Little Colorado River and extending to Diamond Creek (RM 226). Place names were derived from Stevens (1990) and Belknap (2001). The “left” and “right” sides of the Colorado River are with respect to assuming the viewer is facing in a downstream direction.

For evaluation of downstream variations in response to the 2008 HFE, we defined five sediment-transport-flux monitoring reaches in Marble and Grand Canyons (fig. 1; table 2). These reaches are demarcated by locations at which tributary sediment inputs occur or mainstem bed sediment, suspended-sediment concentration, and grain size are monitored (Topping and others, 2006b). The fixed sediment-transport measurement sites are: (1) the Colorado River at Lees Ferry gaging station (USGS station number 09380000; RM 0), (2) the RM 30 sediment station, located at the midpoint of Marble Canyon, (3) the Colorado River above Little Colorado River near Desert View gaging station (gage was discontinued) (09383100; RM 61), (4) the Colorado River near Grand Canyon gaging station (09402500; RM 88), (5) the former Colorado River above National Canyon near Supai gaging station (09404120; RM167), and (6) the Colorado River above Diamond Creek near Peach Springs gaging station (09404200; RM 225). In the downstream order in which they occur, we refer to the sediment-transport-flux monitoring reaches as upper Marble Canyon (UMC), lower Marble Canyon (LMC), eastern Grand Canyon (EGC), central Grand Canyon (CGC), and western Grand Canyon (WGC).

The Fan-Eddy Complex

The geomorphic framework of the Colorado River in Marble and Grand Canyons is dominated by an assemblage of channel features termed the fan-eddy complex by Schmidt and Rubin (1995). Debris flows and floods in steep, ephemeral tributaries to the Colorado River deliver large boulders to the Colorado River, some of which cannot be transported by the mainstem (Webb and others, 1989). The bouldery deposits create debris fans that constrict the mainstem channel flow and create rapids (fig. 2*A*). These hydraulic controls define the longitudinal profile of the river and affect flow patterns immediately upstream and downstream from each debris fan (Howard and Dolan, 1981). Immediately upstream from each debris fan is an area of ponded flow, where flow has decelerated, stage has increased, and water-surface slope has decreased so as to create sufficient potential energy to accelerate flow through the constriction, analogous to flow from a

nozzle (Kieffer, 1985). The area of ponded flow may extend upstream a few channel widths to a few kilometers and varies with discharge. Immediately downstream from each debris fan, channel width typically is wider than elsewhere (Schmidt, 1990). Cross-sectional area here is much greater than in the rapid, because channel depth also increases greatly. Much of the increase in depth occurs where a deep scour hole typically develops immediately downstream from the rapid (fig. 2*A*). Lateral recirculating eddies typically form between the boundary of the downstream flowing jet and the channel banks (Schmidt, 1990). Further downstream from the scour hole and lateral recirculating eddies, the channel typically narrows and shallows; this portion of the bed is referred to as the exit slope (fig. 2*A*). The acceleration of stream flow associated with the slight decrease in channel cross-sectional area terminates the downstream length of eddies along the channel banks. A midchannel or bank-attached cobble bar commonly occurs in these areas of somewhat shallow flow. The coarse debris is the result of erosion of the upstream debris fan during pre-dam high flows (Webb and others, 1989). At lower discharges, flow typically passes around the margins of these cobble bars and creates a riffle (fig. 2*A*).

Each of the sites selected to study 2008 HFE sandbar response is in the channel expansion immediately downstream

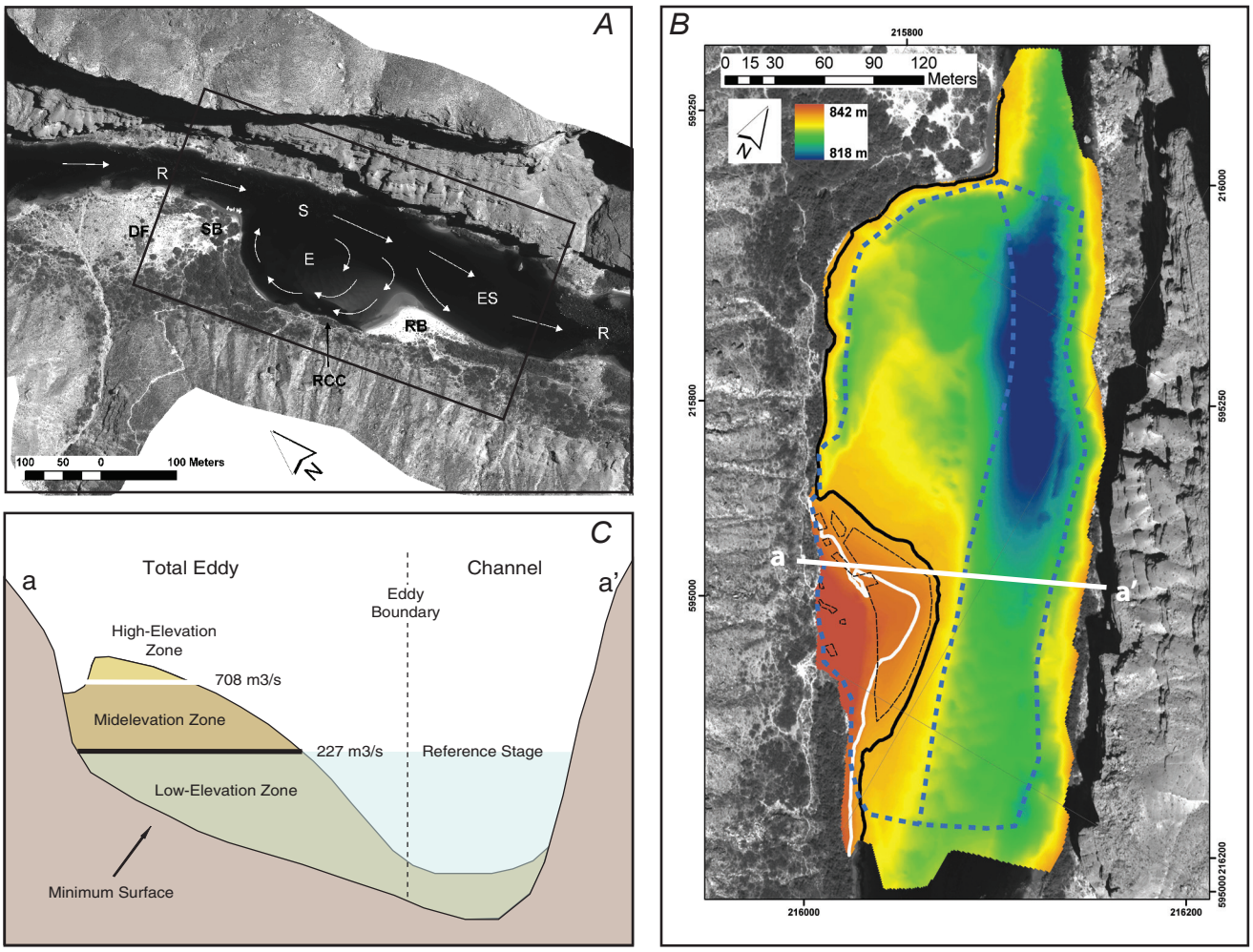


Figure 2. Geomorphic description of physical setting and boundary definitions for fan-eddy complexes of the Colorado River. *A*, Aerial view (May 2002) of a typical fan-eddy complex (listed in table 1 as site 47R) in Marble Canyon at the reference stage (227 m^3/s). DF, tributary debris fan; R, rapid or riffle; S, scour hole; ES, exit slope; E, eddy; RB, reattachment bar; SB, separation bar, RCC, return-current channel. Arrows indicate flow direction. Box insert indicates area shown in *B*. *B,* Digital elevation model (1983 Arizona State Plane in meters, central zone projection) of the same site from the April 1, 2008, survey. The dashed blue line is the computational boundary for the channel expansion, with a dividing line between the eddy and main channel. The solid black and white lines are the stage elevations reached by flows of 227 m^3/s and 708 m^3/s, respectively. These stage elevations separate high-elevation, midelevation, and low-elevation zones within the total eddy. The thin dashed black lines show the surveyed campsite area. Heavy white line is approximate location of schematic cross section a—a' shown in *C*. *C,* Schematic of computational boundaries in a—a' described in the text. Note that a—a' is viewed in an upstream direction.

from the rapid. All sites include the entire bed of the lateral recirculating eddy, and most sites include the bed of the adjacent channel, where the predominant direction of flow is downstream. Although debris fans may become overtopped at high discharges, causing regions of recirculating flow to shrink and eventually disappear, all sites included in this study were eddies with recirculating flow across the full range of discharges that occurred during the study period.

Lower flow velocities in eddies promote deposition from the suspended load. Eddies have the potential to completely fill with sediment (Wiele and others, 1996) and can contain sandbars more than 10 m thick (Rubin and others, 1994). The scour hole and main-channel bed adjacent to eddies may be completely covered with sand, forming subaqueous dune fields 1 to 2 m thick in some locations, while in other locations the bed-sand area is patchy over large regions of the gravel, boulder, and bedrock bed (Anima and others, 1998; Howard and Dolan, 1981; Wilson, 1986; Schmidt and others, 2007; D. Topping, U.S. Geological Survey, written commun., 2009). Much thicker sand deposits, however, can temporarily accumulate in the main channel during tributary flooding (Wiele and others, 1996).

Sand deposits in eddies have been described and classified by Schmidt (1990) as separation bars, which form near the upstream part of the eddy where flow separates from the bank, and reattachment bars, which form where flow reattaches to the bank (fig. 2*A*). Separation bars mantle the downstream surface of debris fans, but they do not exist downstream from all debris fans. Reattachment bars form a platform projecting upstream into the center of the eddy. A distinct geomorphic characteristic of reattachment bars is the return-current channel, where upstream-directed flow is redirected along the bank (Rubin and others, 1990). This deep channel typically divides the separation bar from the reattachment bar. At lower flows, the return-current channel becomes stagnant as recirculating flow is partially blocked by an emergent reattachment bar. This low-velocity condition can result in suitable habitat for certain native fish (Korman and others, 2004; Schmidt and others, 2007). We use the term “eddy bar” where the unique topography of separation bars and reattachment bars cannot be distinguished or where the distinction is not relevant to the discussion (table 1).

Controlled Floods, Tributary Sand Inputs, and Fluctuating Flows

The 2008 HFE was the third controlled flood released from Glen Canyon Dam with the intention of rebuilding sandbars. The first such experimental flow occurred in 1996 and consisted of a 7-day release of 1,275 m^3/s (see Webb and others, 1999, for details on the 1996 HFE). Sandbar surveys and photographic analyses indicated that sediment was deposited on the channel margin as high-elevation sandbars but that low-elevation sandbars were eroded (Hazel and others, 1999; Andrews and others, 1999; Schmidt and others, 1999). Sandbar deposits formed by the 1996 HFE exhibited upward-coarsening grain size, indicating that the supply of fine sediment was exhausted during the course of the event (Rubin and others, 1998). This finding was supported by sediment budgets constructed for the 1996 high flow that showed eddies were the source for much of the suspended sediment, rather than the sandy bed of the main channel (Schmidt and others, 1999; Hazel and others, 2006a). On the basis of the 1996 findings, researchers concluded that future high-flow experiments should only be conducted under conditions of enriched sand supply such that high flows would result in sandbar deposition, without depleting sand from storage as occurred in 1996 (Rubin and others, 2002).

This concept of sand-enriched high flows was first tested by the second high flow, conducted in November 2004, which was timed to follow a period of sand delivery from the Paria River. Because findings from the 1996 HFE indicated that most deposition occurred in the initial 1 to 2 days of that experiment (Andrews and others, 1999; Schmidt and others, 1999), and on the basis of later sandbar simulations conducted by Wiele and Torrizo (2005) with flow and sand-supply boundary conditions similar to those measured during the 1996 HFE, the 2004 HFE was shorter in duration (2.5 days) and had a slightly smaller peak discharge (1,160 m^3/s). This experiment resulted in an increase of total sandbar area and volume in the upper end of Grand Canyon, but further downstream, where sand accumulation had not occurred, there was a net transfer of sand out of eddies (Topping and others, 2006a). Topping and others (2006a) concluded that in order to achieve increases in total sandbar area and volume throughout a greater proportion of Marble and Grand Canyons, more sand would be required than was available during the 2004 high flow.

The 2008 HFE was released specifically to test the hypothesis that greater antecedent sand supply could result in sandbar building throughout most of Marble and Grand Canyons without depleting more sand than was accumulated by tributary inputs leading up to the event (Topping and others, 2006a). Tributary floods in the Paria River, primarily in October 2006 and August–September 2007, supplied about 3.35±0.34 million metric tons of sand to the Colorado River between the 2004 and 2008 HFEs (D. Topping, U.S. Geological Survey, written commun., 2009). As a result, Marble Canyon contained approximately two to three times more sand than had accumulated before the 2004 high-flow release. In contrast, the year antecedent to the 1996 HFE had the least recorded accumulation of tributary-supplied sand in the Colorado River in Marble and Grand Canyons (D. Topping, U.S. Geological Survey, written commun., 2009).

The 2008 HFE had a similar hydrograph as the 2004 high-flow hydrograph (fig. 3). Beginning on March 4, 2008, releases were increased by 43 m^3/s per hour until hydropower plant capacity (892 m^3/s) was reached, and then each of the four Glen Canyon Dam bypass tubes was opened for a total bypass release of 425 m^3/s by March 6 (U.S. Department of the Interior, 2008). For the 60-hour period that discharge

Table 1. Channel geometry and geomorphic characteristics for selected study sites, Colorado River in Marble and Grand Canyons.

[Site names are from Belknap (2001) and Stevens (1990) or are informally used. **, sites surveyed before and after the 1996 and 2004 HFEs. *, sites surveyed before and after the 1996 HFE. -, not determined because bathymetry data were not collected at the site.]

Site ID[1]	River Mile (RM)[2]	Site Name	Deposit Type[3]	Eddy Size (m^2)[4]	Expansion Ratio[5]		Stage Change[6] (m)
					242 (m^3/s)	1,203 (m^3/s)	
1R	1.2	Paria Beach	U	40,880	2.0	1.5	3.0
3L**	2.5	Cathedral Wash	R	7,610	1.5	1.3	3.4
8L**	8.1	Below Jackass	S	-	1.6	1.5	3.0
9L	8.9		S,R	12,270	1.8	1.4	4.2
16L**	16.6	Hot Na Na Wash	S	8,160	2.1	1.2	3.1
22R**	22.0	Twentytwo Mile	R	7,160	1.5	1.5	5.8
24L	23.6	Lone Cedar	U	-	1.3	1.4	5.0
29L	29.5	Shinumuo Wash	U	-	1.2	1.0	4.8
30R**	30.7	Sand Pile	R	8,520	1.7	1.6	5.0
32R**	31.9	South Canyon	U	11,620	2.8	1.5	2.9
33L	33.3	Redwall Cavern	R	-	-	-	4.7
35L	35.1	Nautiloid	S,R	21,390	2.5	1.4	5.0
41R	41.4	Buck Farm	S,R	42,050	2.9	1.7	4.1
43L**	43.4	Anasazi Bridge	R	8,460	1.7	1.3	4.3
44L**	44.6	Eminence	S,R	26,570	1.9	1.4	4.1
45L	45.0	Willie Taylor Camp	S,R	22,550	1.9	1.4	4.0
47R**	47.6	Lower Saddle	R	28,440	2.6	1.9	3.5
49R	48.8		R	7,640	1.4	1.3	3.8
49L	48.9		S,R	14,470	1.4	1.2	3.8
50R**	50.2	Dinosaur	S,R	8,691	1.0	1.0	3.9
51L**	51.0	Fiftyone Mile Camp	R	31,690	1.6	1.5	3.5
54R	54.6		R	12,370	1.4	1.4	3.4
55R**	55.9	Kwagunt Marsh	R	24,300	1.1	1.4	2.5
56R	56.6	KwaguntBeach	U	-	1.1	0.8	3.1

Table 1. Channel geometry and geomorphic characteristics for selected study sites, Colorado River in Marble and Grand Canyons.—Continued

[Site names are from Belknap (2001) and Stevens (1990) or are informally used. **, sites surveyed before and after the 1996 and 2004 HFEs. *, sites surveyed before and after the 1996 HFE. -, not determined because bathymetry data were not collected at the site.]

Site ID[1]	River Mile (RM)[2]	Site Name	Deposit Type[3]	Eddy Size (m^2)[4]	Expansion Ratio[5]		Stage Change[6] (m)
					242 (m^3/s)	1,203 (m^3/s)	
58L	58.1	Malgosa	R	-	0.9	0.8	3.6
62R**	62.9	Crash Canyon	R	15,920	1.7	1.4	3.9
63L**	63.5		S,R	27,870	3.0	2.1	4.0
65R**	65.2	Carbon	S,R	17,130	1.6	1.2	2.8
65L	65.8		R	12,300	1.6	1.4	2.5
66L	66.1	Palisades Creek	S,R	-	1.8	1.4	2.0
68R**	68.8	Tanner	U	15,950	1.2	1.1	2.4
70R	70.1	Basalt	R	-	2.0	1.7	2.7
81L**	81.8	Grapevine	U	3,410	1.5	1.6	3.7
84R	84.6	Clear Creek	S,R	-	1.3	1.3	4.9
87L**	87.6	Cremation	U	1,150	1.5	1.1	3.8
88R	88.1	Boat Beach	R	3,070	1.2	1.3	3.4
91R*	91.8	91 Mile	S	4,490	1.3	1.2	4.2
93L*	93.8	Granite	U	3,590	1.7	1.8	2.9
104R*	104.4	Upper 104 Mile	R	1,020	1.3	1.0	3.9
119R*	119.4	Big Dune	R	8,930	1.6	1.3	4.6
120R	119.8	119 Mile Camp	R	10,080	1.9	1.3	4.5
122R*	122.7	122 Mile Camp	R	8,240	2.2	2.1	4.2
123L*	123.3	Upper Forster	R	8,050	1.4	1.3	4.0
137L*	137.7	Football Field	R	5,140	1.2	1.2	4.3
139R*	139.6	Fishtail	U	7,190	1.3	1.2	4.5
145L*	145.8	Above Olo	R	1,320	1.4	1.5	5.0
165R	165.7	165 Mile	S,R	5,150	1.1	0.9	4.6
166L	167.2	Lower National	S	-	2.4	1.1	3.6

Table 1. Channel geometry and geomorphic characteristics for selected study sites, Colorado River in Marble and Grand Canyons.—Continued

[Site names are from Belknap (2001) and Stevens (1990) or are informally used. **, sites surveyed before and after the 1996 and 2004 HFEs. *, sites surveyed before and after the 1996 HFE. -, not determined because bathymetry data were not collected at the site.]

Site ID[1]	River Mile (RM)[2]	Site Name	Deposit Type[3]	Eddy Size (m^2)[4]	Expansion Ratio[5]		Stage Change[6] (m)
					242 (m^3/s)	1,203 (m^3/s)	
172L*	172.6	Below Mohawk	R	9,400	1.3	1.3	3.9
183L*	183.3	Below Chevron	R	5,150	1.7	1.6	4.1
194R*	194.6	Hualapai Acres	R	14,140	2.2	2.1	3.8
201R	201.6		R	12,060	2.5	1.4	3.4
202R*	202.3	202 Mile	S,R	15,620	2.7	1.7	3.8
213L*	213.3	Pumpkin Springs	U	3,990	3.1	2.4	5.8
214R	214.5	214 Mile	R	5,250	1.4	1.1	3.8
220R*	220.1	Middle 220	U	2,450	1.4	1.1	3.0
225R*	225.5		R	5,635	2.3	1.8	2.9

[1]The descriptors "L" and "R" denote the location of the emergent sandbar on left and right sides of the river, respectively, facing downstream.

[2]Approximate location based on the river mile centerline (U.S. Geological Survey, 2006) downstream from Lees Ferry (river mile 0), in Grand Canyon National Park.

[3]Deposit type: R, reattachment bar, S, separation bar, U, undifferentiated eddy bar.

[4]Eddy size determined by a fixed boundary between the main channel and eddy located at the base of the eddy sandbar.

[5]Average channel width in expansion with associated eddy divided by average channel width in nearest upstream or downstream constriction. Channel width determined using the method for generating cross-sections by Magirl and others (2008).

[6]Difference in water-surface elevation between the 227-m^3/s and 1,203-m^3/s stage (Hazel and others, 2006b).

exceeded 1,175 m^3/s at the USGS streamflow-gaging station at Lees Ferry (09380000; fig. 1), beginning at 0600 hours (Pacific Standard Time) on March 6 and ending at 1830 hours on March 8, the mean discharge was 1,203 m^3/s. The down-ramp rate was 43 m^3/s per hour until the normal hydropower plant releases scheduled for March were reached. In the first month following the 2008 HFE, diurnal peak flows were between 325 and 390 m^3/s, with daily fluctuations of 142–227 m^3/s. On April 15, 2008, releases were increased to diurnal peak flows of 425–462 m^3/s. In summer, monthly discharges were higher, with diurnal peaks flows of 500–530 m^3/s and daily fluctuations of 200–227 m^3/s. In September and October 2008, there was a steady release regime of 354 m^3/s. These major changes in flow regime allow comparison of sandbar stability under relatively lower fluctuating flows associated with normal spring operations (typically referred to as the modified low fluctuating flow dam operation) followed by the response after higher summer operations.

Methods

Repeated high-resolution topographic surveys were made on five river trips in 2008 (fig. 3). Each measurement site is located in the downstream part of a fan-eddy complex (fig. 2A). Sixty-two emergent sandbars, consisting of reattachment and/or separation bars, were surveyed down to the 227-m^3/s stage at 57 sites (appendix A). Three study sites were not surveyed on the February 2008 river trip (50R, 56R, and 62R), and we utilized data collected in October 2007 as the pre-2008 HFE site condition at these sites. Subaerial topography

and campsite areas were surveyed with Topcon GTS-313 and Topcon GPT-2003 electronic total stations.

Bathymetry was measured and analyzed at 40 sites on the February and April trips with a multibeam sonar system installed on a 7-m motorized raft (appendix A). These measurements expanded the survey area to include the bed of the eddy and adjacent main channel, such that the entire area of sand and water ever inundated since 1990 was included in the survey. Typically, the longitudinal extent of each bathymetric survey was from the downstream end of the rapid or riffle to approximately one to two channel widths downstream of the eddy that existed at the time of the survey.

The combined topographic and bathymetric data have a positional accuracy better than 0.10 m and elevation accuracy that varies from 0.05 m or less for points acquired by total station to 0.10 m or less for bathymetric points. Point data were referenced to the Arizona State Plane NAD83, Arizona Central (FIPS 202) coordinate system, in meters, using established benchmarks. Specific details and error analysis of the topographic surveying techniques and the multibeam system are described by Hazel and others (2008) and Kaplinski and others (2009), respectively.

The topographic and bathymetric point data for each study site were combined, and digital elevation models (DEMs) at 1-m resolution were constructed by building triangulated irregular networks (TINs) using Delaunay triangulation (McCullagh, 1988). Changes in topography were determined by subtracting the pre-2008 HFE DEM from the post-2008 HFE DEM to generate erosion-deposition maps. Kaplinski and others (2009) reported an average uncertainty of 5 percent in topographic surfaces generated using the same methods used in this study.

The topographic surfaces were used to compute sand deposit volume within the two geomorphic settings that occur in the channel expansion: the eddy and the bed of the adjacent channel (fig. 2*B*). Because the size and exact position of the eddy change as a function of discharge, a fixed eddy boundary was delineated. This boundary divides the eddy from the main channel at the base of the eddy sand deposit (fig. 2*B*). Thus, the eddy for computational purposes includes all deposits separated from the main channel within the region between the separation and reattachment points of the eddy. Hereafter, we use "total eddy" to refer to this computational area. Sandbar deposits above the reference stage outside the eddy were not surveyed; thus the main-channel environment consists entirely of sand deposits below the 227-m^3/s water-surface elevation. To examine the entire site or channel-expansion response, we refer to the combined total eddy and main channel volumes as "total site sand volume." However, it is not possible to report absolute sand volumes, because depths to the gravel, boulder, or bedrock substrate are known only for a very few locations (Rubin and others, 1994). Thus, the sand volumes reported in this study are computed by determining the volume of sand above a synthetically constructed minimum surface

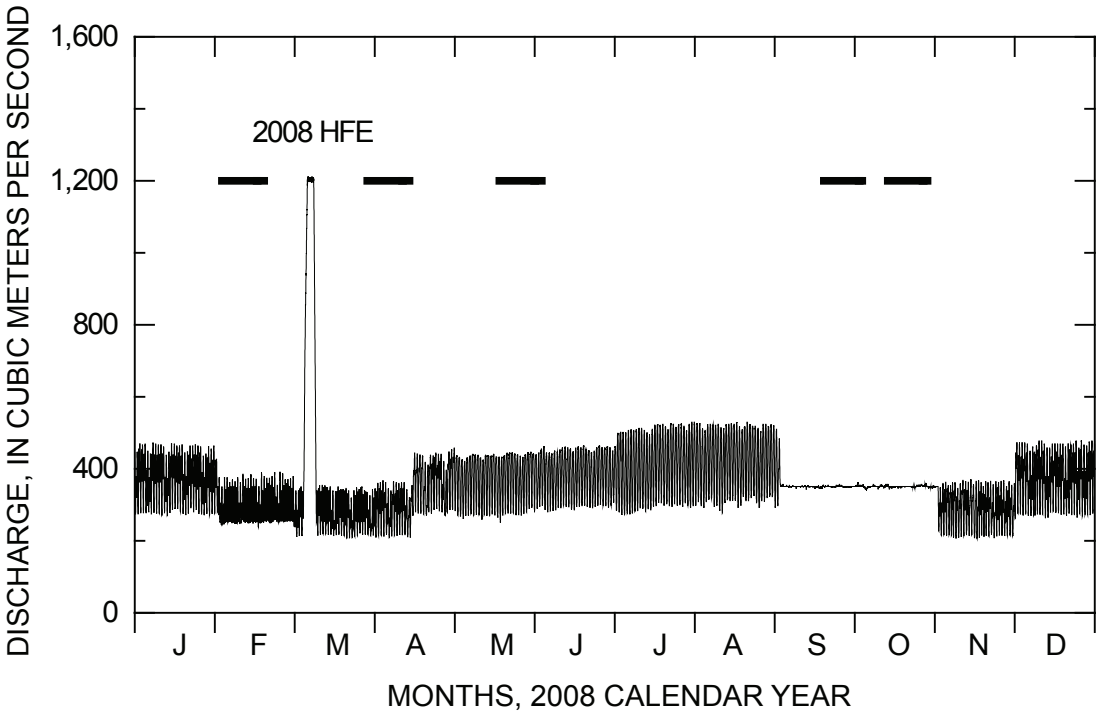


Figure 3. Instantaneous discharge of the Colorado River at USGS streamflow-gaging station (09380000), Lees Ferry, Arizona, for the 2008 calendar year. The solid, horizontal lines indicate the times of survey river trips.

(fig 2*C*). The minimum surface was computed by determining the lowest sandbar elevation ever measured for each 1-m grid cell using all surveys for each study site, including all measurements made from 1990 to 2008. The minimum sandbar surface thus separates sediment that has never changed for the period of monitoring (below the minimum surface) from sediment that has been active during the period of monitoring. The minimum surfaces used in this report are an update of the minimum surfaces computed and described by Hazel and others (2006a). We also computed maximum sandbar surfaces with the same method in order to determine the percentage of the total eddy area filled at any given time by an eddy sandbar. Thus, we defined a reference eddy sand-storage volume for each site as the maximum volume of sand that can possibly be stored within the eddy below the maximum surface.

To examine sandbar response within the total eddy computational area, we differentiate between three elevation zones (figs. 2*B* and *C*). The low-elevation zone is defined as the volume of sand between the calculated minimum surface and the elevation of the reference stage of 227 m^3/s. The midelevation zone is the region between the reference stage and the water surface elevation at a higher topographic level defined as the elevation reached by a discharge of 708 m^3/s. The high-elevation zone includes the region above the 708-m^3/s water-surface elevation. We refer to the combined mid- and high-elevation zones as sand storage above the reference stage. These elevation zones were selected because 227 m^3/s represents the lowest discharge typical of normal hydropower plant operations and 708 m^3/s represents the highest discharge of normal daily hydropower plant operations. The stage elevations for flows of 227 and 708 m^3/s were derived from the stage-discharge relations of Hazel and others (2006b). At some sites that had not been surveyed previously, new relations were computed using similar methods.

The thickness of sandbars resulting from the 2008 HFE was determined from the change in sand volume over a defined area for each site within four bins that increase in spatial scale: high-elevation sand (within the eddy), sand above reference stage (within the eddy), total sand within the eddy, and total sand within the study site. To determine total sand thickness in eddies and total sand thickness within entire study sites, the total volume change at all zonal elevations within an eddy and the combined eddy and channel were divided by the measured area of the respective zones. Because the portion of the sandbar exposed above the reference stage occupies a small percentage of the overall eddy area, high-elevation sand thickness and the thickness of the sand above the reference stage were determined by dividing the volumetric change by the area of the maximum sandbar surface (that is, an estimate for the maximum potential sandbar area was computed with the same method as the minimum surface).

Post-2008 HFE bar stability was evaluated by comparing sandbar thickness above the reference stage at a 36-site subset of the study sites collected in May 2008 to surveys at the same sites collected in September and October 2008 (appendix A). In order to calculate erosion rates, we divided volume change above the reference stage by the number of days between successive surveys at each site. To observe short-term changes at the sites and also to help interpret longer term changes, a combination of remote analog and digital cameras were utilized to collect repeated daily oblique images at 32 of the sites (appendix A).

To evaluate sandbar response in comparison with suspended-sand concentration, the study sites were grouped into reaches of similar sand concentration during the 2008 HFE (table 2), based on proximity to the fixed sediment-monitoring stations and also to measurements of suspended-sand concentration collected longitudinally during the 2008 HFE (D. Topping, U.S. Geological Survey, written commun., 2009). A subset of the study sites were analyzed for comparison of the 2008 HFE results with results from the two previous HFEs in 1996 and 2004. For comparing total sand volume, there were 29 sites where sufficient data were collected in 1996 and 2008 to make comparisons (table 1). Of these sites, 10 sites in UMC, LMC, and EGC were also surveyed in 2004 (table 1). For comparisons of sand volume above reference stage, there were 38 sites that could be compared between 1996 and 2008 and 22 sites in UMC, LMC, and EGC that could be compared between 2004 and 2008. To compare sand volumes following the 2008 HFE, the measured values were normalized as the ratio of sand volume measured following each of the HFEs to the sand volume measured immediately before the 1996 HFE. This method of normalizing the data is consistent with the method used when analyzing such data for the 1996 HFE (Hazel and others, 1999) and the 2004 HFE (Topping and others, 2006a). These normalized data were used to compute cumulative probability distributions and median response for each of the reaches of similar suspended-sediment concentration corresponding to the sediment-flux monitoring reaches (fig. 1).

Campsite area as measured in this study is the area of the sandbar that can be used as a kitchen or a place to sleep. We adopted the criteria of Kearsley and Warren (1993) in defining campsite area as that part of the sandbar with no more than an 8 degree slope and little or no vegetation. Slope angle was estimated by observation in the field. Points were surveyed that outline the perimeter of each camping area, as well as points surrounding features to exclude from the camping area, such as trees, bushes, and rocks (Kaplinski and others, 2005). The perimeter points were then used to define polygons of campsite area. Plan areas of the campsite area TIN models were summarized for high-elevation and midelevation zones.

The campsite measurements were analyzed by their occurrence in “critical” and “noncritical” camping reaches. A critical reach was defined by Kearsley and Warrren (1993) as any contiguous stretch of the river in which the number of available campsites is limited because of geologic characteristics, high demand, or other logistical factors. Noncritical reaches were defined as any stretch of the river in which campsites are plentiful and little competition occurs for the majority of sites. There are presently more than 220 actively used river campsites in the Grand Canyon National Park

Table 2. Sediment-transport flux-monitoring stations and reaches of the Colorado River used to compare the 1996, 2004, and 2008 HFEs.

[RM, approximate location based on the river mile centerline (U.S. Geological Survey, 2006) downstream from Lees Ferry (river mile 0) in Grand Canyon National Park. The descriptors "L" and "R" denote the location of the emergent sandbar on left and right sides of the river, respectively, facing downstream.]

Reach	Sedinent-transport flux monitoring reach (RM)	Corresponding reach of similar suspended- sediment concentration (RM)	Upstream and downstream study site used for comparison among high flows	
			Total site sand volume	Sand volume above reference stage
Upper Marble Canyon	0–30	15–40	22R–32R	16L–32R
Lower Marble Canyon	30–61	40–65	43L–65R	43L–65R
Eastern Grand Canyon	61–87	65–130	68R–123L	68R–123L
Central Grand Canyon	87–166	130–180	137L–172L	137L–172L
Western Grand Canyon	166–225	180–225	194L–225R	183L–225R

inventory of camps between Lees Ferry and Diamond Creek (http://www.nps.gov/grca/parkmgmt/riv_camp-atlas.htm). The number of campsites per river mile in noncritical reaches is about twice that in critical reaches (table 3). Sixteen of the sandbar monitoring sites chosen for campsite monitoring in this study are located within critical reaches, and 21 occur in noncritical reaches.

Results

Overview of Topographic Response

Deposition in the high-elevation zone occurred at nearly every study site. The volume of sand in this zone increased by more than 5 percent at 48 of the 57 sites surveyed (appendix B, table B1). The median change in high-elevation deposit thickness was 0.21 m, and virtually all sites aggraded to some extent (fig. 4*A*). Nearly every measured eddy bar aggraded above the reference stage; however, the changes were more variable in the midelevation zone than observed in the high-elevation zone (appendix B, table B2). As a result, the median change in sand thickness above the reference stage was 0.26 m, but the changes from site to site were more variable (fig. 4*B*).

Because of substantial variability in the low-elevation eddy zone and on the bed of the main channel (appendix B, table B3), the total eddy sand thickness change ranged from -1.88 to 1.13 m (fig. 4*C*). Fifty percent of the sites had a total eddy sand thickness change of 0.10 m or greater. In many cases, net deposition above the reference stage in eddies was approximately balanced by net erosion below the reference stage. Sandbar thickness change was also computed for each site, including above and below reference stage for all parts of the channel and eddies. Total site changes were highly variable, ranging from -2.27 to 0.80 m, with a median of 0.06 m (fig. 4*D*).

Styles of Topographic Response

The widespread deposition at all high-elevation sites and at most sites in the midelevation zone, and the variability in the low-elevation eddy zone and on the bed of the main channel, resulted in increases or decreases in total-site sand volume. Therefore, we examined the exchange between high- and low-elevation areas of each study site by comparing the transfer of sand above and below the reference-stage elevation. These responses were categorized into four styles of topographic change depending on the combination of (A) net change in sandbar volume within the eddy boundary above reference stage and (B) net change in volume for the entire site, including the channel and eddy below reference stage (fig. 5). The Style 1 response consisted of net increase in

volume (deposition) at all elevations above and below reference stage, and this style characterized 45 percent of the study sites. The Style 2 response consisted of net decrease in volume (erosion) in the eddy and channel below reference stage and net deposition in the eddy above base flow stage. This was the second most common response and occurred at 37 percent of the sites. The Style 3 response occurred where there was net erosion at all elevations above and below reference stage; this style characterized 16 percent of the measurement sites. The Style 4 response consisted of net erosion above reference stage and net deposition below reference stage. In the following section, we present examples of these response styles to illustrate some of their characteristics and show how erosion and deposition were distributed across individual sites. Because response Style 2 included some sites where there was net erosion across the channel and eddy and some sites where there was net deposition, an example of each case is included. Style 4 response was weak (nearly, a Style 1 response) and occurred at only 1 site; therefore, that response style is not discussed in detail.

Style 1

The most common 2008 HFE response (Style 1) was one in which sand deposition increased the sand volume both above and below reference stage. In all of these sites there was net deposition in the eddy and in the entire study site. An example is 172L, where the post-2008 HFE volume at low elevation exceeded the pre-2008 HFE volume by 11 percent and the post-2008 HFE volume above reference stage exceeded the pre-2008 HFE volume by 29 percent (based on values reported in appendix B). The changes at this site are broadly representative of this style of response, although the magnitudes of proportional changes were greater at some sites (fig. 5). In February 2008, a reattachment bar was present and the bar surface was covered by tamarisk (*Tamarix ramosissima*) near the talus slope and by arroweed (*Pluchea sericea*) along the shoreline (fig. 7*A*). In the high-elevation zone, the bar was eroding along a steep cutbank at the downstream end. The return-current channel was well defined at high elevation but nonexistent at flows in the low range of typical diurnal dam operating releases. Dunes present on the bed in the channel indicate that the bed was either sand or fine gravel. At the time of the February 2008 survey, the bar volume was 66 percent of the reference eddy-storage volume at the site.

Deposition by the flood was greatest on the sandbar platform (fig. 6*B*). Much of the vegetation that had colonized the bar surface was buried beneath 1 to 2 m of sand (fig. 7*C*). Further upstream, there was deposition at low elevation, increasing the elevation of the bar platform. A distinct return-current channel separated the new deposit from the bank, as shown by the location of the 227-m^3/s stage elevation in figure 6*B*. The post-2008 HFE sandbar increased to 85 percent of the total eddy-storage volume above reference stage.

The areal and volumetric change distributions calculated from the erosion-deposition map at 172L are shown in figure 8. These changes are represented as histograms that show the area of the bed and volume of sand associated with each increment of bed elevation change. A unimodal distribution of change, in which 5,800 m^2 of the total eddy was increased 0.25 to 1.0 m in elevation (62 percent of the eddy computational area), was also observed, as shown in figure 8*A*. A large part of the channel, about 5,600 m^2, increased by 0.25 to 0.5 m in elevation (64 percent of the channel computational area). Because the change in sand volume is the product of elevation change and the area over which that change occurred, the greatest volume of deposition occurred where the elevation increased between 0.75 and 1.0 m, and the greatest deposition in the channel occurred where the elevation increased 0.25 to 0.5 m. There was a total of 3,657 m^3 of net deposition in the eddy and 1,595 m^3 of net deposition in the channel. The site as a whole gained 5,252 m^3 of sand (all reported values are listed in the tables contained in appendix B).

Table 3. Critical and noncritical recreational campsite reaches of the Colorado River (modified from Kearsley and Warren, 1993.

Reach number	Reach name	Number of campsites per mile[1]	River mile	
			Starting	Ending
1	Noncritical	0.5	0	11
2	Critical	1.1	11	41
3	Noncritical	1.5	41	77
4	Critical	0.9	77	116
5	Noncritical	1.7	116	139
6	Critical	0.7	139	164
7	Noncritical	1.1	164	226

[1]Primary campsites originally inventoried by Kearsley and Warren (1993) and still considered active by Grand Canyon National Park (http://www.nps.gov/grca/park-mgmt/riv_camp-atlas.htm).

Style 2 With Net Eddy Erosion

There were many sites where sand deposited above the reference stage but erosion occurred below that elevation. At some of these sites, both the eddy and channel environments were dominated by erosion, while at others there was net deposition in the eddy with a larger magnitude of net erosion in the adjacent channel. The changes at Eminence Break (44L) illustrate the Style 2 response for sites where there was net

erosion within the eddy even though deposition occurred in mid- and high-elevation zones (fig. 9).

A large separation bar mantled the Eminence Break debris fan. In February 2008, the separation bar had two distinct topographic levels: the sand below the stage of 708 m^3/s gradually sloped toward the river; higher parts of the separation bar were partially vegetated, with scattered dunes (fig. 10*A*). The reattachment bar at the midelevation zone had a large platform, and there was a well-defined return channel shoreward from the sandbar (fig. 9*A*). The high-elevation zone of the reattachment bar was thickly vegetated and sloped steeply down to the midelevation surface. In the main channel, there was a scour hole adjacent to the eddy. At the time of the February 2008 survey, the volume of the eddy bars increased by 62 percent of the reference eddy-storage volume.

Flood deposition was greatest on the downstream part of the reattachment bar, and erosion occurred in the upstream part of the eddy (fig. 9*B*). Deposition occurred on both bars at mid and high elevations. The return-current channel was widened and deepened through scour (note the new location of the 227-m^3/s stage elevation in figure 9*B*). Deposition on the eddy bar above reference stage increased sand volume to 80 percent of the reference eddy-storage volume. However, the 2008 HFE eroded more sand than was deposited at the site, because as much as 6 m of sand eroded from the low-elevation eddy zone by scour of the upstream reattachment bar (fig. 9*C*). In the main channel, there was erosion of sand adjacent to the scoured area of the eddy and sand deposition on the pool exit slope associated with growth of a dune field (fig 10*B*)

The distribution of elevation change in figure 11*A* shows a bimodal distribution, with widespread, relatively low-magnitude deposition (0.25-1.0 m) over an area of ~11,000 m^2 (42 percent of the total eddy area). The erosion of the upstream reattachment bar resulted in a smaller area (~7,500 m^2) with a depth of scour ranging from 1 to 5 m. In contrast, growth of the dune field on a large region of the channel bed (~11,500 m^2) increased the sand elevation by 0.25 to 1.5 m

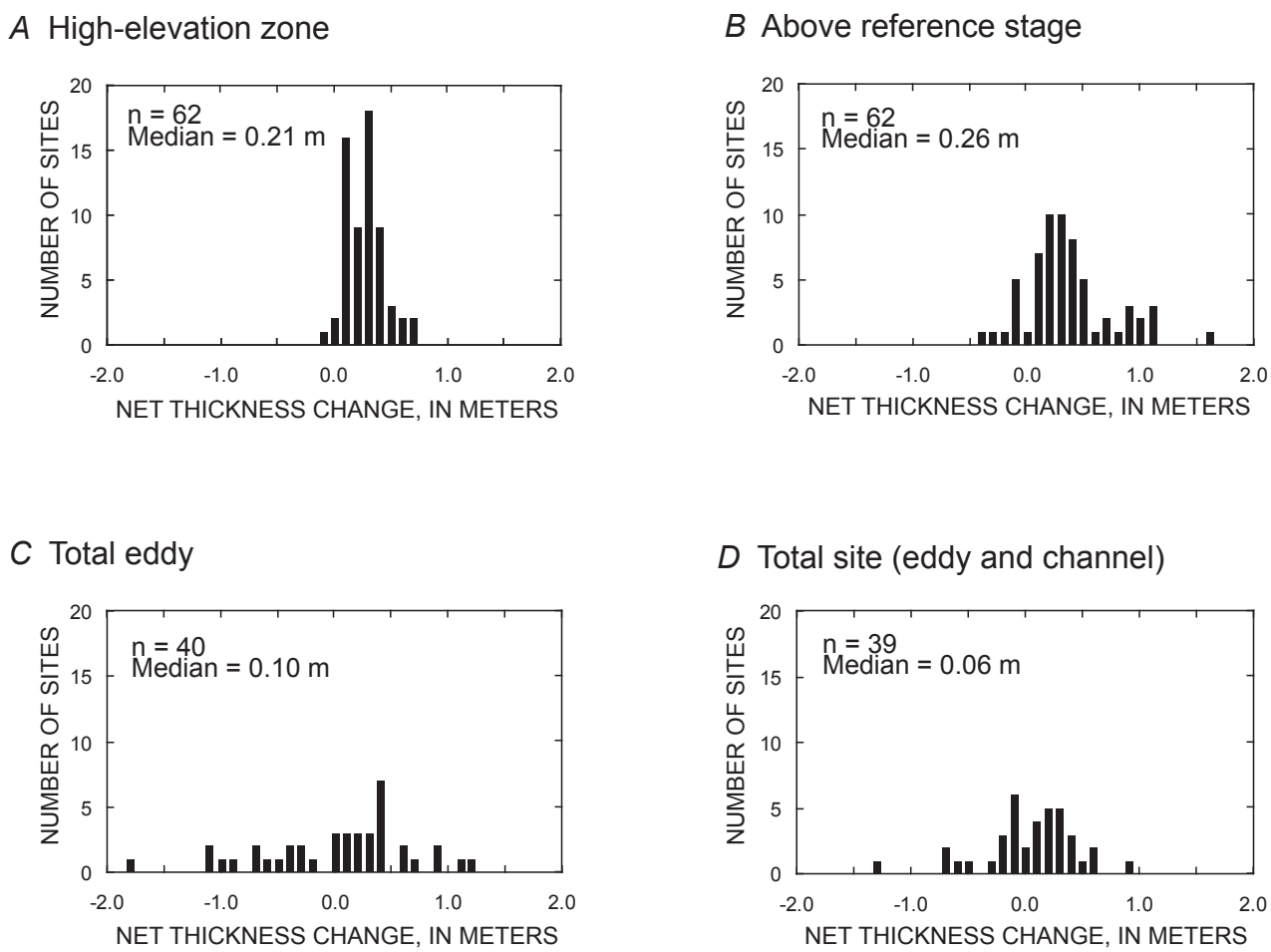


Figure 4. Histograms of net sandbar thickness change between February and April 2008. *A*, High-elevation zone. *B*, Above reference stage. *C*, Total eddy. *D*, Total site (combined eddy and channel).

(66 percent of the channel area; fig. 11*B*). Because erosion of more than 6 m from the eddy was greater than the volume of sand deposited in the channel, the balance was toward net erosion at the site. There was a total of 13,132 m^3 of net sand erosion in the eddy and 4,115 m^3 of net deposition in the channel, resulting in total site erosion of 9,017 m^3.

Style 2 With Net Eddy Deposition

A different variant of Style 2 is one in which there was net deposition in eddies (fig. 5). The changes at site 65R are typical of this style, where high-elevation eddy deposition exceeded low-elevation erosion (fig. 12). At 65R, low-elevation erosion reduced the volume of sand by 24 percent (based on values reported in appendix B) and deposition above the reference stage increased the volume of sand by about 300 percent. In February 2008, the separation bar was characterized by a zone of interspersed sand and boulders on the downstream end of the debris fan. A popular camp was located on a flat and level area on the downstream end of the separation bar. Only the highest part of the reattachment bar at the downstream end of the eddy was exposed at typical dam operating releases. A cutbank 2 to 3 m high separated the high-elevation sand deposit from the midelevation bar. A large reattachment bar occupied most of the low-elevation zone in the eddy (fig. 12*A*).

Deposition was greatest in the downstream part of the eddy, where as much as 3 m of elevation increase occurred on the bar crest and platform, along and in front of the steep cutbank (fig. 12*C*). At this formerly low-elevation part of the eddy, the return-current channel was partially filled with sand as the reattachment bar aggraded toward the bank. Further upstream, a deeper return channel was excavated where more than 2 m of sand eroded from the upstream part of the reattachment bar. The deposition increased the eddy reference storage volume to 68 percent of maximum, and an extensive, uniform reattachment bar platform occupied a large region of the eddy above reference stage (fig. 13*A*).

Widespread, relatively high-magnitude deposition (1.0-3.25 m) occurred over approximately 6,000 m^2 of the total eddy area (fig. 14*A*). Erosion also occurred over a similar-sized area of the eddy, but the erosion was to a depth of 0.25-2.0 m (on average, less than the deposition), resulting in net eddy deposition. In the channel, moderate erosion (0.75-1.25 m) occurred over 7,500 m^2 (83 percent of the channel area) of the bed (fig. 14*B*). As at most other sites, erosion in the low-elevation zone of the eddy was accompanied by net erosion in the channel. There was a total of 5,294 m^3 of net deposition in the eddy and 5,975 m^3 of net erosion in the channel, so the total site response was a net loss in sand volume of 681 m^3. Nonetheless, both separation and reattachment bars substantially aggraded.

Style 3

Changes at site 3L illustrate the Style 3 response (fig. 15), wherein there was net erosion of both the eddy and main channel. At the time of the first survey in February 2008, the bar occupied 47 percent of the eddy. The highest part of the bar was at the downstream end of the eddy, and a well-defined return-current channel existed between a large reattachment-bar platform and the channel bank (figs. 15*A*, 16*A*). The channel bed shallowed downstream from the scour hole, and dunes covered much of the channel bed downstream from the eddy.

Nearly the entire reattachment bar was inundated by the 2008 HFE (fig. 16*B*), and the topography of the bar and channel was significantly modified (fig. 15*B*). The only area of deposition was at the downstream

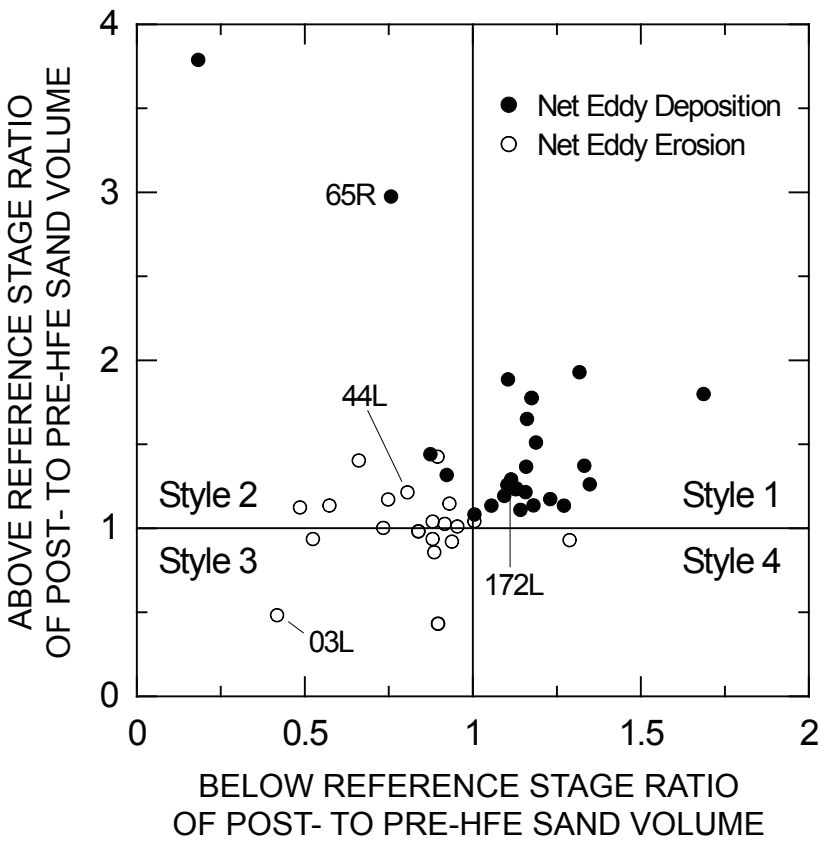


Figure 5. Relation of proportional sand-volume change above reference stage (combined high-elevation and midelevation eddy zones) to below reference stage (combined low-elevation eddy and channel zones) for each site between February and April 2008. The four response styles (Styles 1, 2, 3, and 4) and specific example sites described in the text are shown. Also indicated is net total-eddy deposition or fill as indicated by the net thickness changes shown in figure 4*C*.

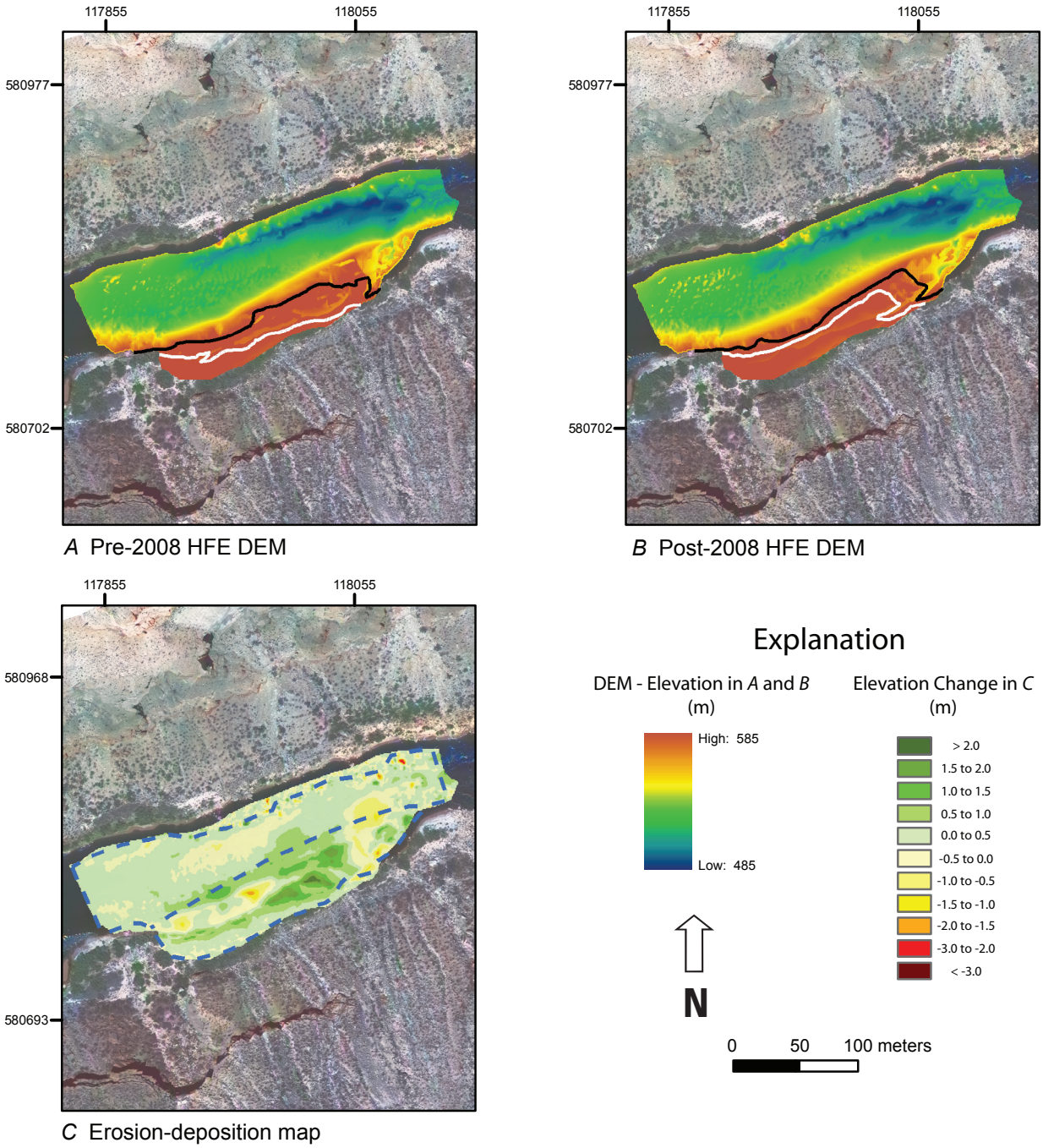


Figure 6. Comparison of repeat topographic and bathymetric surveys collected at site 172L illustrating Style 1 site response. *A*, Pre-2008 HFE digital elevation model (DEM). *B*, Post-2008 HFE DEM. C, The DEMs were differenced against each other to produce a map of spatially distributed elevation change. The solid black and white lines in *A* and *B* are the stage elevations reached by a flow of 227 m^3/s and 708 m^3/s, respectively. The dashed blue line in *C* is the computational boundary described in figure 2. Flow in the main channel is right to left. The maps are inset on 2002 aerial photography. Northing and easting on the map projection is 1983 Arizona State Plane, central zone.

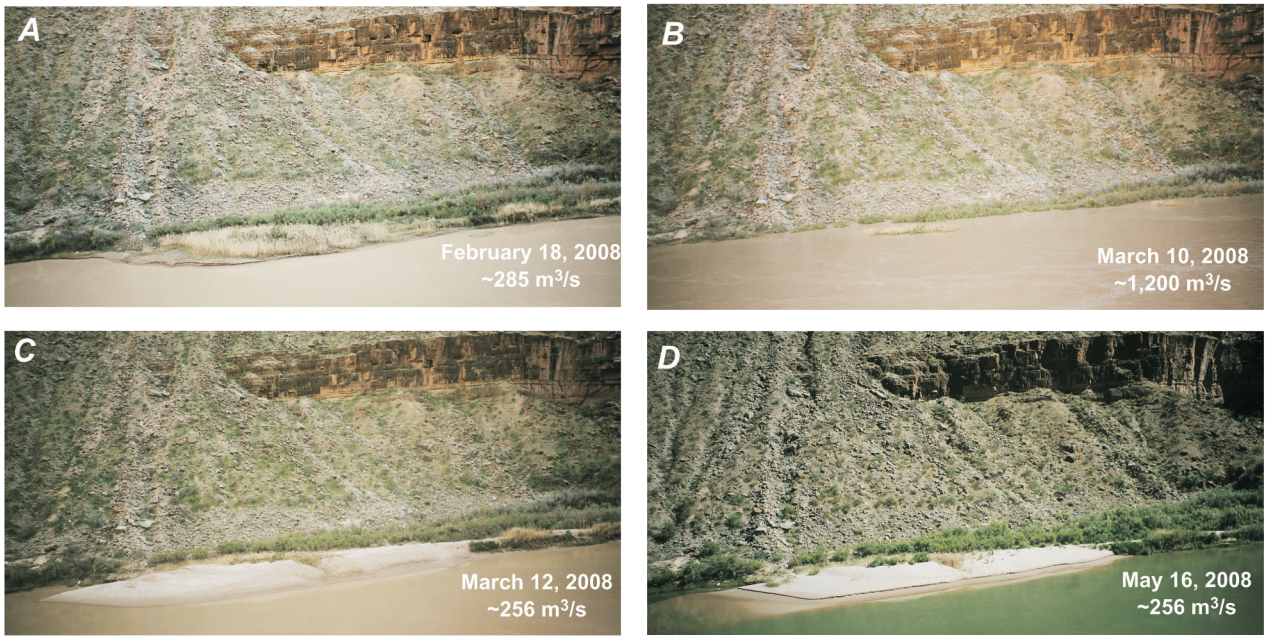


Figure 7. Selected daily photographs of the reattachment bar at site 172L. Flow in main channel is from left to right. The date and estimated discharges based on travel time between USGS stream-flow gaging stations on the Colorado River are given for each. *A,* A large, vegetated mid and high-elevation bar is present. *B*, The extent and height of site inundation by the 2008 HFE is shown. *C*, Post-HFE deposition. *D,* The bar was relatively stable after the onset of a higher flow regime (April 15, 2008).

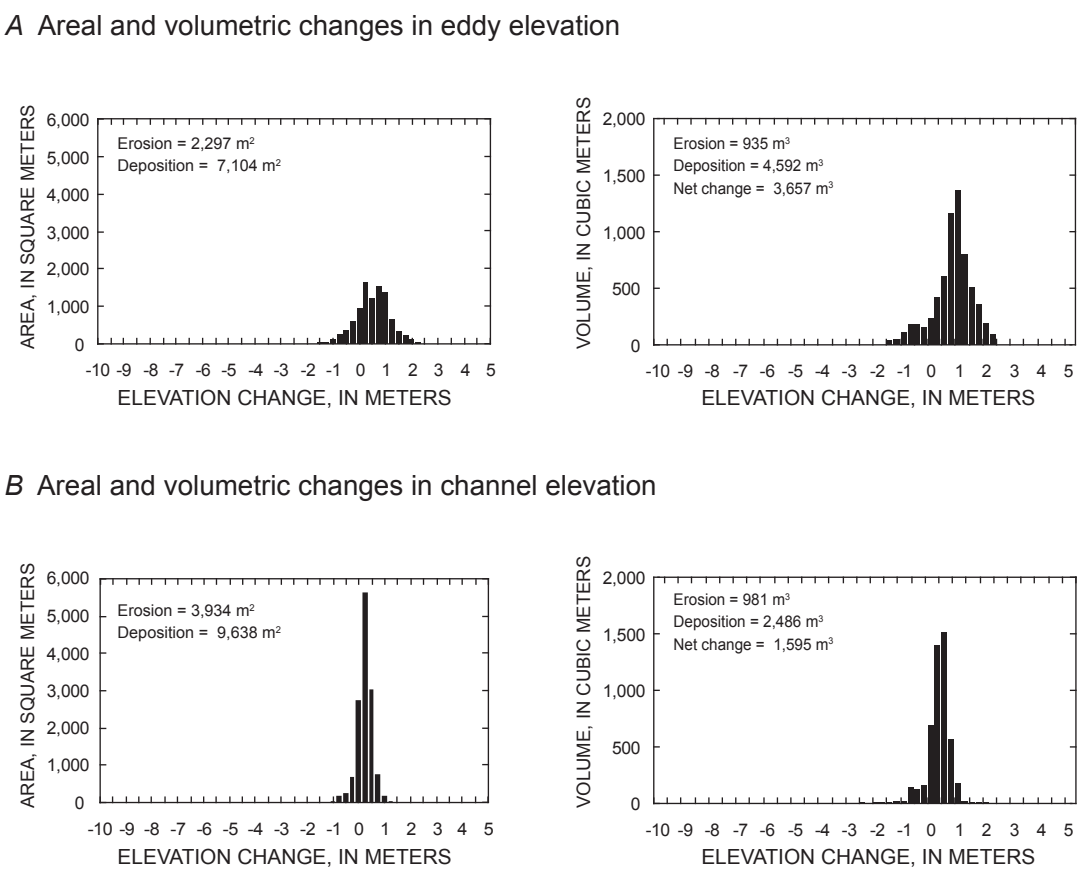


Figure 8. Areal and volumetric elevation-change distributions from the erosion-deposition map at site 172L shown in figure 6*C*. *A*, Total eddy. *B*, Main channel.

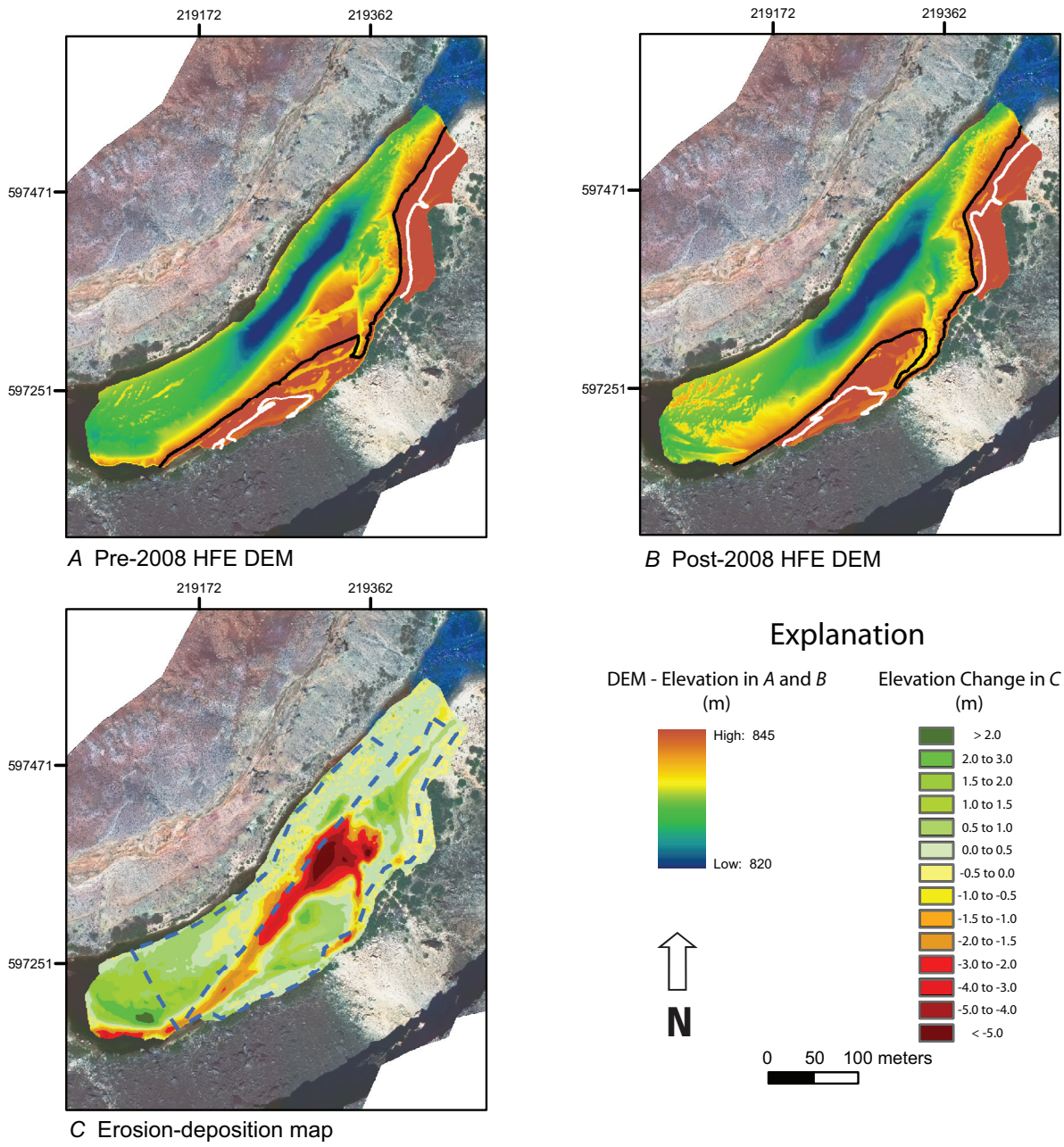


Figure 9. Comparison of repeat topographic and bathymetric surveys collected at site 44L illustrating a Style 2 sandbar response. *A,* Pre-HFE digital elevation model (DEM). *B,* Post-HFE DEM. *C,* The DEMs were differenced against each other to produce a map of spatially distributed elevation change. The solid black and white lines in *A* and *B* are the stage elevations reached by a flow of 227 m^3/s and 708 m^3/s, respectively. The dashed blue line in *C* is the computational boundary described in figure 2. Flow in the main channel is from upper right to lower left. The maps are inset on 2002 aerial photography. Northing and easting on the map projection is 1983 Arizona State Plane, central zone.

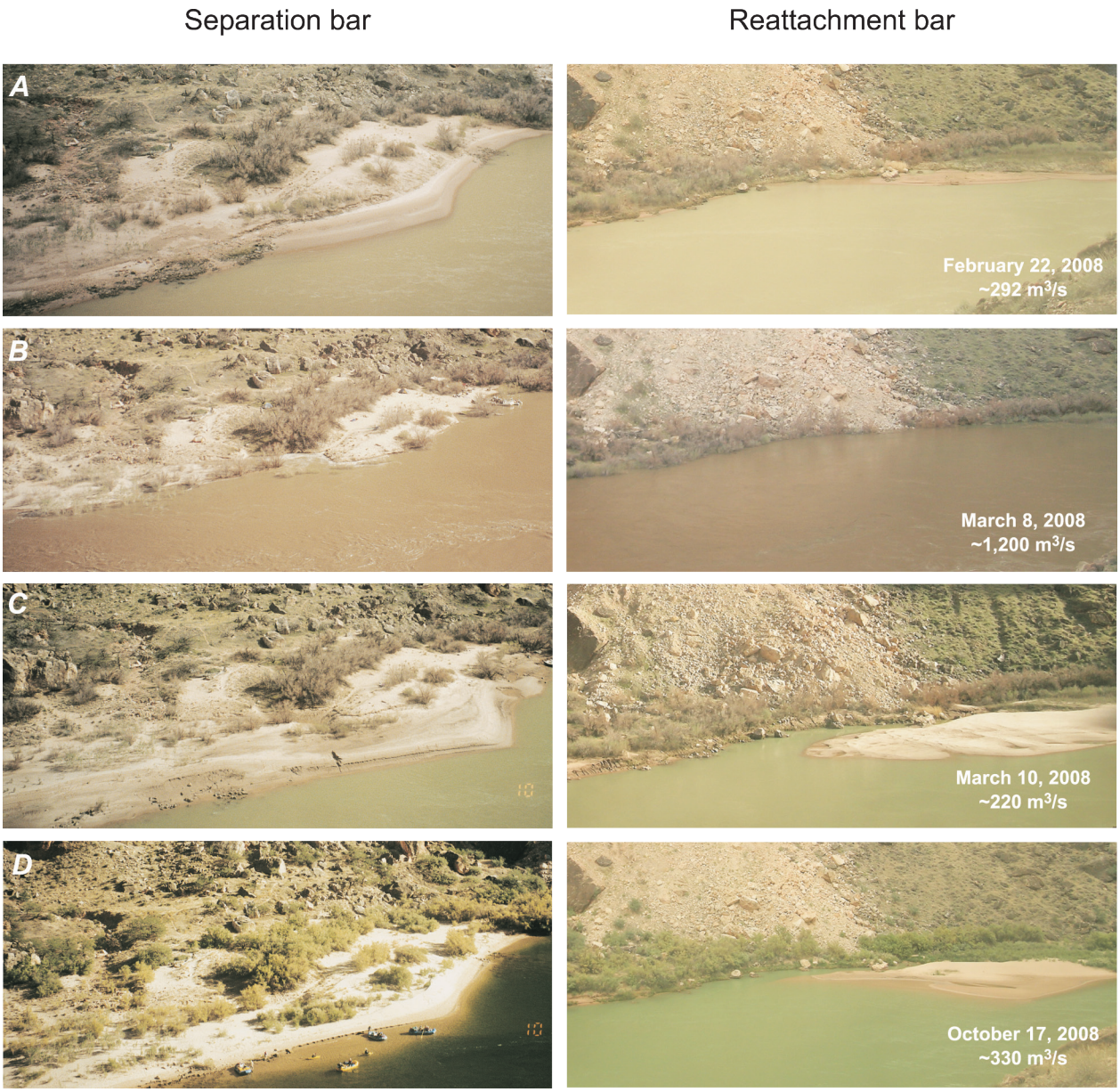


Figure 10. Selected daily photographs of the sandbars at site 44L. In each sequence the separation bar is shown on the left and the reattachment bar is to the right. Flow in main channel is from left to right. The indicated discharges are estimates based on travel time between USGS stream-flow gaging stations on the Colorado River. *A*, Pre-2008 HFE. Note the rocky shoreline on the upstream end of the separation bar and thick vegetation at high-elevation on the reattachment bar. *B,* The extent and height of site inundation by the 2008 HFE is shown. *C,* Post-2008 HFE response. *D,* Erosion in the following months.

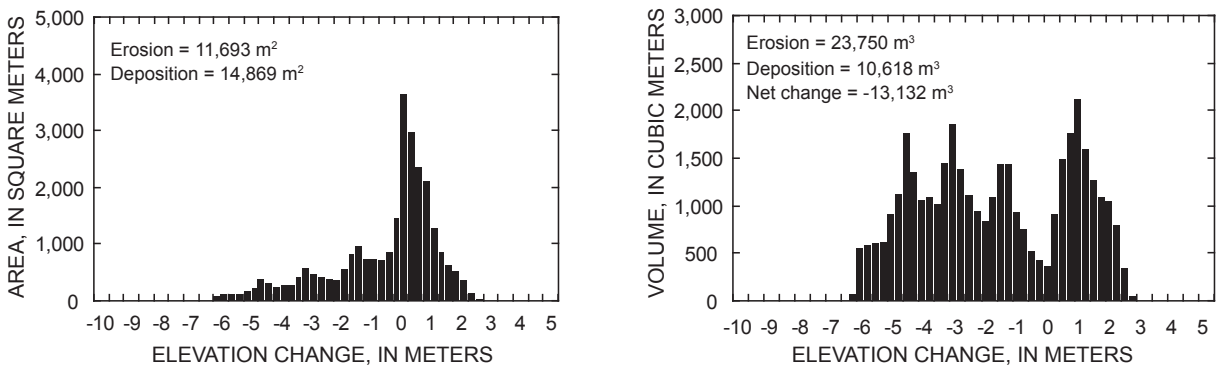
end of the eddy and in the adjacent channel, where more than 2 m of sand deposited (figs. 15*C*, 16*C*). Erosion occurred elsewhere, especially in the upstream half of the eddy and in parts of the channel (fig. 15*C*). Scour of the reattachment-bar platform occurred to a depth of more than 5 m, resulting in a decrease in volume of sand above reference stage of 1,165 m^3. The volume of sand in the eddy above reference stage decreased to 23 percent of maximum. The adjacent main channel was also scoured to depths exceeding 5 m. The scour hole at the upstream end of the site deepened and lengthened. Erosion also occurred at the exit slope, where much of the dune field was removed (fig. 15*B*).

The distributions of areal and volumetric change show that in nearly equal areas of the eddy (~2,000 m^2) there was as much as 5.5 m of erosion and 2 m of deposition (fig. 17*A*). In contrast, a larger part of the channel, about 6,500 m^2 was eroded about 3 to 5 m, and there was 1 to 2 m of sand deposited over a smaller area of the bed (fig. 17*B*). The greatest volume of sediment eroded from the eddy occurred where there was erosion of between 5 and 6 m of sand, and the greatest aggradation occurred where there was deposition of more than 1.5 m of sand. A scour depth of more than 3 m occurred over 43 percent of the entire site area, above and below reference stage. There was a total of 13,860 m^3 of net erosion in the eddy and 40,131 m^3 of net erosion in the channel, and the site as a whole lost 53,991 m^3 of sand.

Spatial Pattern of Topographic Response

The three primary response styles occurred to different extents in different parts of Marble and Grand Canyons (fig. 18*A*). Response Style 1 (increase in sand volume at all elevations) occurred most commonly in Grand Canyon, and Style 2 (increase in sand volume above reference stage and decrease below reference stage) was most prevalent in Marble Canyon (fig. 18*A*). Style 3 (net decrease in sand volume above and below reference stage) occurred at least once in every sediment-transport-flux reach, but less commonly in CGC and WGC than in UMC and LMC. The Style 4 response (decrease in sand volume above reference

A Areal and volumetric changes in eddy elevation



B Areal and volumetric changes in channel elevation

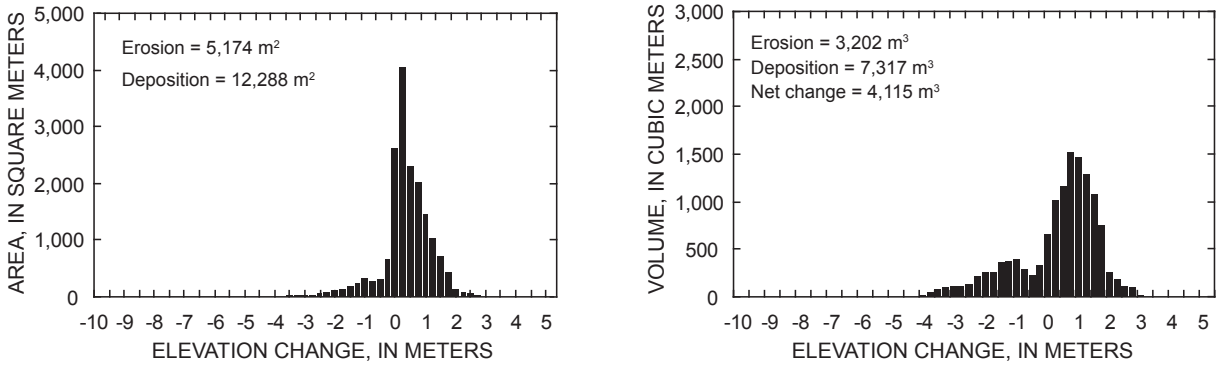


Figure 11. Areal and volumetric elevation-change distributions from the erosion-deposition map at site 44L shown in figure 9*C*. *A,* Total eddy. *B*, Main channel.

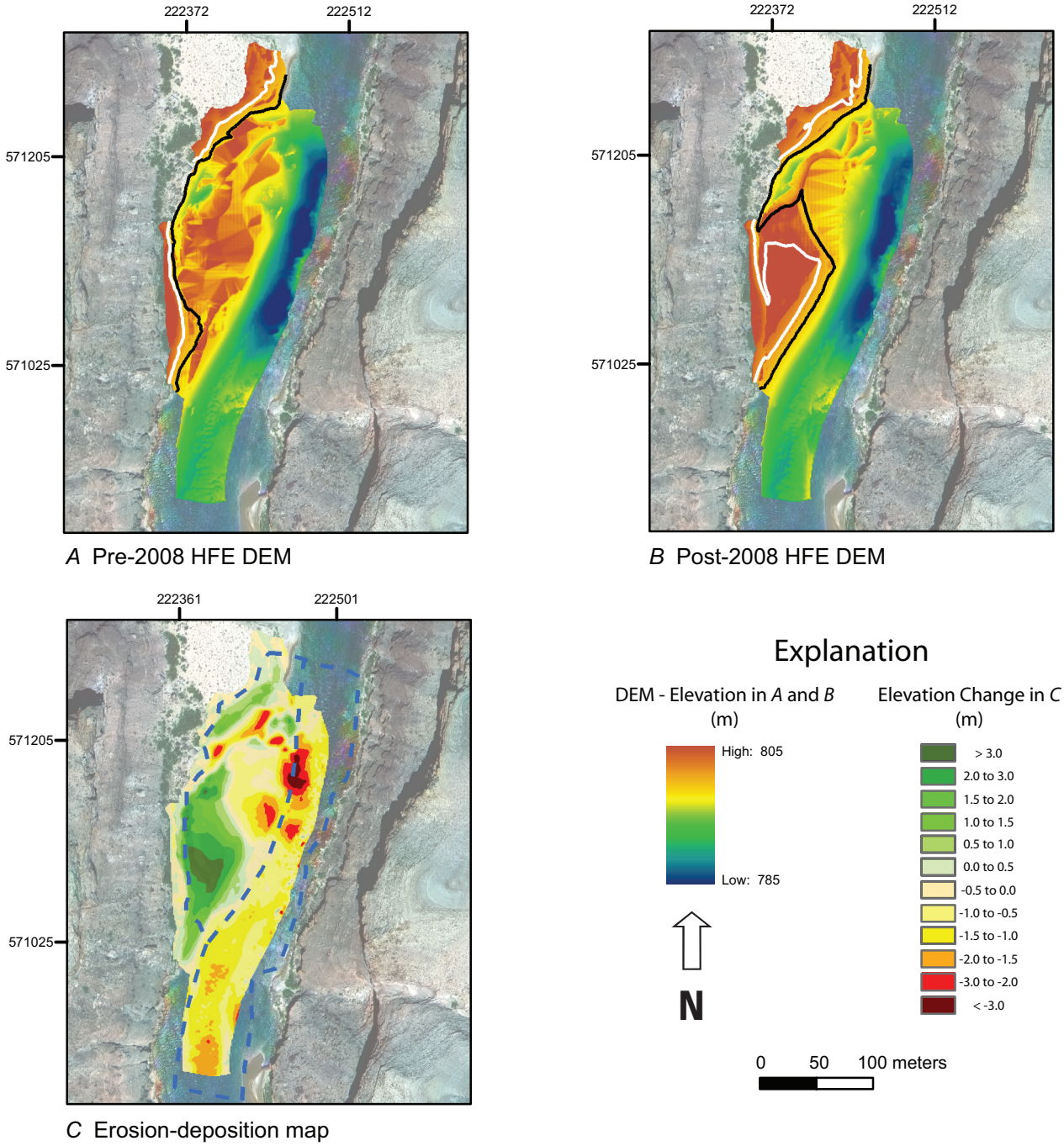


Figure 12. Comparison of repeat topographic and bathymetric surveys collected at 65R illustrating a variant of Style 2 response. Flow in the main channel is from top to bottom. The maps are inset on 2002 aerial photography. Northing and easting on the map projection is 1983 Arizona State Plane, central zone. *A*, Pre-2008 HFE digital elevation model (DEM). *B*, Post-2008 HFE DEM. *C*, The DEMs were differenced against each other to produce a map of spatially distributed elevation change. The solid black and white lines in *A* and *B* are the stage elevations reached by a flow of 227 m^3/s and 708 m^3/s, respectively. The dashed blue line in *C* is the computational boundary described in figure 2.

stage and increase below reference stage) occurred at only one site in EGC.

Despite downstream increase in the prevalence of Style 1, sandbars in the high-elevation zone throughout Marble and Grand Canyons increased in thickness to about the same degree. However, the styles of the eddy and total-site responses were more variable. The median increase in sandbar thickness above reference stage was similar in all reaches (fig. 18*B*). In general, the occurrence of Style 1 (widespread-deposition) increased longitudinally downstream, suggesting more sand was deposited than eroded. The variability between individual sites was greater in Marble Canyon and EGC; however, it is unclear whether that increased variability is the result of differences in behavior in those reaches or of greater study-site density. In contrast to the similarity between reaches of the median deposit response above the reference stage, the total-eddy median change in sandbar thickness increased from negative values in Marble Canyon to positive values downstream in Grand Canyon. However, the median change in total-eddy sandbar thickness in CGC was about half that in EGC and WGC. In contrast, the median change in total-site sand thickness progressively increased from 0.60 m of net erosion in upper Marble Canyon to 0.23 m of net deposition in western Grand Canyon (fig. 18*B*).

Longevity: Changes from April to October 2008

Sandbar erosion rates were greatest in the first 2 months following the 2008 HFE and declined thereafter, consistent with observations made following the 1996 HFE (Hazel and others, 1999). Between cessation of the high flow on March 10 and the post-2008 HFE measurements on April 15, 2008, dam releases consisted of fluctuating flows with daily peaks of 390 m^3/s or less (fig. 3). During this period most newly deposited sandbars were stable or eroded gradually (table 4). On April 15, 2008, release volumes increased and daily peak flows were between 425 and 462 m^3/s. The daily photographs show that the rate of bar erosion accelerated at 5 out of 32 sites monitored by remote camera (table 4; fig. 19). The bulk of this erosion occurred at laterally migrating cutbanks in the new deposits (figs. 10*D*, 13*C*, 16*D,* 19*C*-*E*). These observations are consistent with the sandbar surveys, which show substantial decreases in sandbar thickness above the reference stage in the 7 weeks between the post-2008 HFE surveys, conducted in late March and early April 2008, and the surveys conducted in May (fig. 20). During this 7-week period, the sandbar volume above reference stage eroded at a median rate of 5.3 m^3/day. From May to October 2008, the median erosion rate declined to 2.2 m^3/day. The greatest erosion rate was observed at site 65R, where the deposit above the reference stage eroded at a rate of 85 m^3/day between April 3 and May 24, 2008. A small cutbank at the site was 0.2 m high when measured on April 3 (fig. 13*A*). By the May 24 survey, the cutbank had migrated 10 to 15 m into the bar and was approximately 0.4 m high (fig. 13*B*). Between the May and the October 2008 survey, the

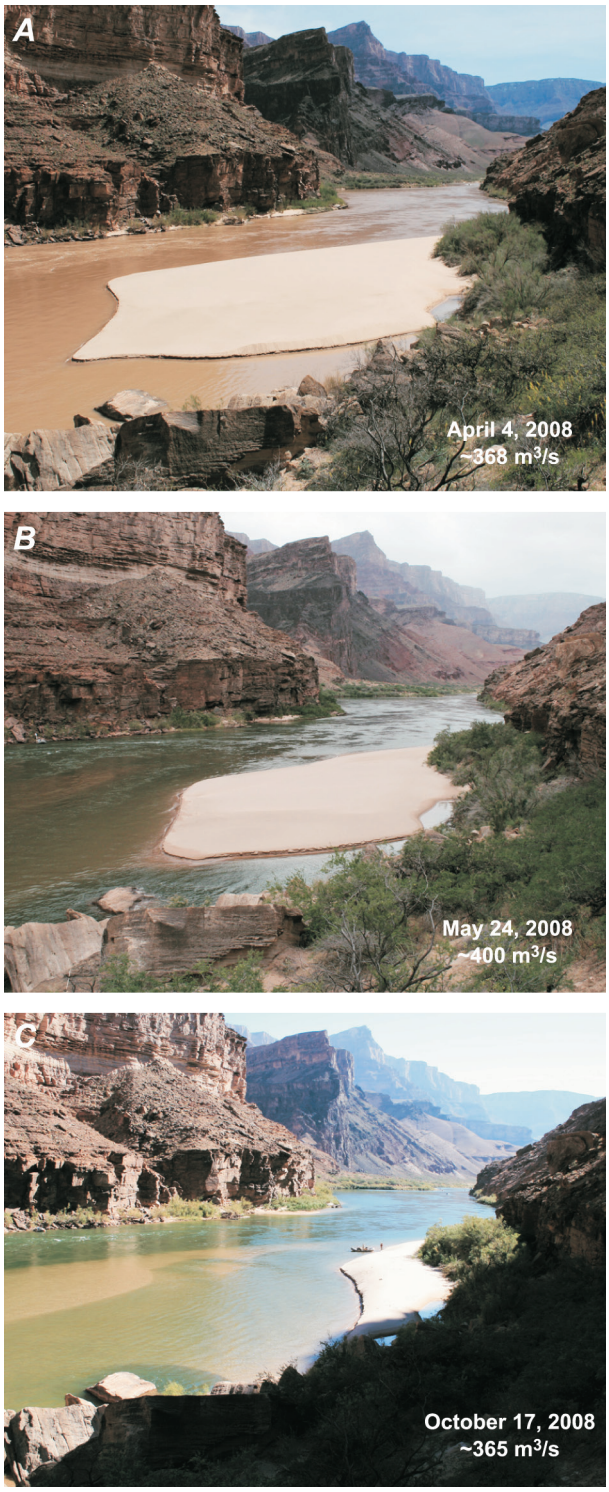


Figure 13. Selected daily photographs of the reattachment bar at site 65R. Flow in main channel is from bottom left to upper right. The indicated discharges are estimates based on travel time between USGS streamflow gaging stations on the Colorado River. *A,* The newly deposited reattachment bar. *B,* Onset of post-flood erosion. *C,* Extensive lateral cutbank retreat.

Table 4. Observations of erosion and deposition from repeat photography at sites along the Colorado River in Marble and Grand Canyons.

[These changes are our observations based on available images from the fixed-camera network taken between April and October 2008. S, bar was stable. GD, general deposition. GE, gradual erosion. RE, rapid erosion over a period ranging from 1 day to 2 weeks. -, no images were available because of camera failure or the system was tampered with. Site ID is river mile (RM) location based on the RM centerline (U.S. Geological Survey, 2006) downstream from Lees Ferry (river mile 0) in Grand Canyon National Park. The descriptors "L" and "R" denote the location of the emergent sandbar on left and right sides of the river, respectively, facing downstream.]

Site ID	Observation interval				Notes
	Feb. -2008 HFE	2008 HFE-April	April-May	May-Oct	
3L	S	S	S	GD	Minor erosion by late April. Deposition at low elevation upstream from the deposit.
8L	S	S	GE	S	
16L	S	S	GE	GE	Cutbank retreat. Surface modified by wind deflation on downstream end and aeolian dune development on upstream end.
22R	S	S	GE	GE	Gradual sustained erosion by cutbank retreat during all months.
30R	S	-	GE	RE	Mass failure of about half the bar platform on 6/3-6/4.
41R	S	-	GE	S	Cutbank retreat.
44L	S	GE	GE	GE	Cutbank retreat.
45L	S	GE	RE	RE	Rapid initial cutbank retreat with rates slowing by July.
47R	S	S	GE	GE	
50R	S	-	S	S	
51L	S	S	S	S	Very little new deposition to erode.
55R	S	-	S	S	
58R	S	GE	RE	S	Rapid erosion 4/15 – 4/16. Cutbank retreat.
66L	S	S	GE	GE	Cutbank development and evidence of wind deflation by April.
68R	-	RE	-	S	Rapid erosion starting 4/17 via large-scale cutbank retreat. New deposit on upstream end mostly eroded by 5/8.
70R	S	S	GE	GE	Cutbank retreat on the downstream end and formation of a large aeolian dune formation on the upstream end.
81L	S	S	GE	GE	Large cutbank on downstream end but gradual retreat.
87L	S	S	S	S	
91R	GE	GE	S	S	Gully formed on 2/23 followed by a small rapid erosion event on 2/28.
104R	S	S	GE	-	Minor cutbank development.

Table 4. Observations of erosion and deposition from repeat photography at sites along the Colorado River in Marble and Grand Canyons.—Continued

[These changes are our observations based on available images from the fixed-camera network taken between April and October 2008. S, bar was stable. GD, general deposition. GE, gradual erosion. RE, rapid erosion over a period ranging from 1 day to 2 weeks. -, no images were available because of camera failure or the system was tampered with. Site ID is river mile (RM) location based on the RM centerline (U.S. Geological Survey, 2006) downstream from Lees Ferry (river mile 0) in Grand Canyon National Park. The descriptors "L" and "R" denote the location of the emergent sandbar on left and right sides of the river, respectively, facing downstream.]

Site ID	Observation Interval				Notes
	Feb. -2008 HFE	2008 HFE-April	April-May	May-Oct	
119R	S	RE	GE	GE	Cutbank development on downstream end immediately after 2008 HFE. Rapid cutbank retreat 4/15 – 4/18; gradual cutbank retreat 5/27-7/2.
122R	S	GE	S	S	Cut bank retreat immediately after 2008 HFE.
123L	S	GE	GE	nc	Gradual cut bank retreat after 2008 HFE.
137L	S	GE	RE	NC	Gradual cutbank retreat in April followed by rapid cutbank retreat 4/15 – 4/18.
139R	S	S	-	-	
145L	S	-	S	-	2-m cutbank on downstream end formed immediately after 2008 HFE, but bar mostly stable.
172L	S	S	S	S	Bar stable with rapid regrowth of buried vegetation.
183R	-	-	GE, RE	-	Gradual cut bank retreat 4/11–4/15. Rapid cut bank retreat 4/15–4/20.
194R	-	S	S	S	
202R	S	S	GE, RE	S	Gradual cutbank retreat 4/11–5/5. Rapid cutbank retreat 5/5–5/6.
213L	-	S	S	S	
225R	S	S	S	-	Minor bank erosion.

cutbank had migrated laterally another 20 to 25 m and was 0.5 m high (fig. 13*C*).

Another important process that potentially contributed to decreases in sandbar volume was surface deflation by wind. However, volume changes by surface deflation can also be offset by the deposition of eolian dunes as sand is redistributed to different areas of the bar. Eolian dunes initially measured in May had increased in size and extent by October (Draut and others, 2009, figs. 16-17, 41-42). Despite wind modification of sandbar surfaces, we estimate that the dominant erosional process was that of lateral cutbank retreat at approximately 60 percent of the sites monitored with remote cameras (table 4). Other processes that result in bar erosion (that is, hillslope runoff and debris flows) were observed at one site (166L), where the eddy bar was incised by several distributary channels from September 2008 flooding in National Canyon, a tributary canyon to the Grand Canyon.

Campsite Area

Sand deposition associated with the 2008 HFE increased campsite area. At 31 out of the 37 sites where campsite area was measured, the total campsite area (combined mid- and high-elevation zones) increased between the pre- and post-2008 HFE measurements (appendix B; table 4). Increases in campsite area were as small as 3 m^2, and the greatest increase was more than 2,000 m^2 (fig. 21). The median campsite area increased from 263 to 437 m^2 (fig. 21). Campsite area increased in both mid- and high-elevation zones (fig. 22).

Of the six sites where campsite area decreased, the largest decrease was 260 m^2.

Post-2008 HFE sandbar erosion resulted in declines in campsite area, particularly in the midelevation zone. Between measurements made in April and the measurements repeated in October 2008, total campsite area decreased at 31 of the 37 sites. The median campsite area decreased from 437 to 319 m^2 (fig. 21). Midelevation campsite area in noncritical reaches was less than that measured in February. Despite the erosion measured between April and October, the total campsite area above the reference stage in October 2008 remained larger than the values measured in February 2008 (fig. 22).

To determine the effects of post-2008 HFE deposition and erosion on campsite area, the measured sandbar area and volume changes were compared to campsite area changes (fig. 23). Campsite area changes, including increases between February and April 2008 and decreases that occurred between April and October, were positively correlated with the magnitude of sandbar volume change (r^2=0.72, significant at the 95-percent confidence level). Correlation of changes in campsite area and sandbar area were not as strong (r^2=0.27). Sandbar volume has a better correlation with campsite area than with sandbar area because increases in volume frequently smooth irregular topography and temporarily bury vegetation; both of these processes can increase campsite area without affecting sandbar area.

The topographic changes described in the previous section show that sandbar deposition followed by cutbank retreat and resulting bar volume loss were the primary causes of the increases and then decreases in campsite area. As the result of the 2008 HFE, campsite area increased at all sites characterized by Style 1 and 2 responses. Deposition resulted in temporary burial of preexisting, vegetated portions of the sandbars (figs. 7*A*, 7*C*) and altered shorelines by covering rocks (figs. 10*A*, 10*C*). At several sites, campsite area increased dramatically where deposition in eddies created large, flat reattachment bars. For example, midelevation camp area at site 45L increased from 0 to 1,148 m^2

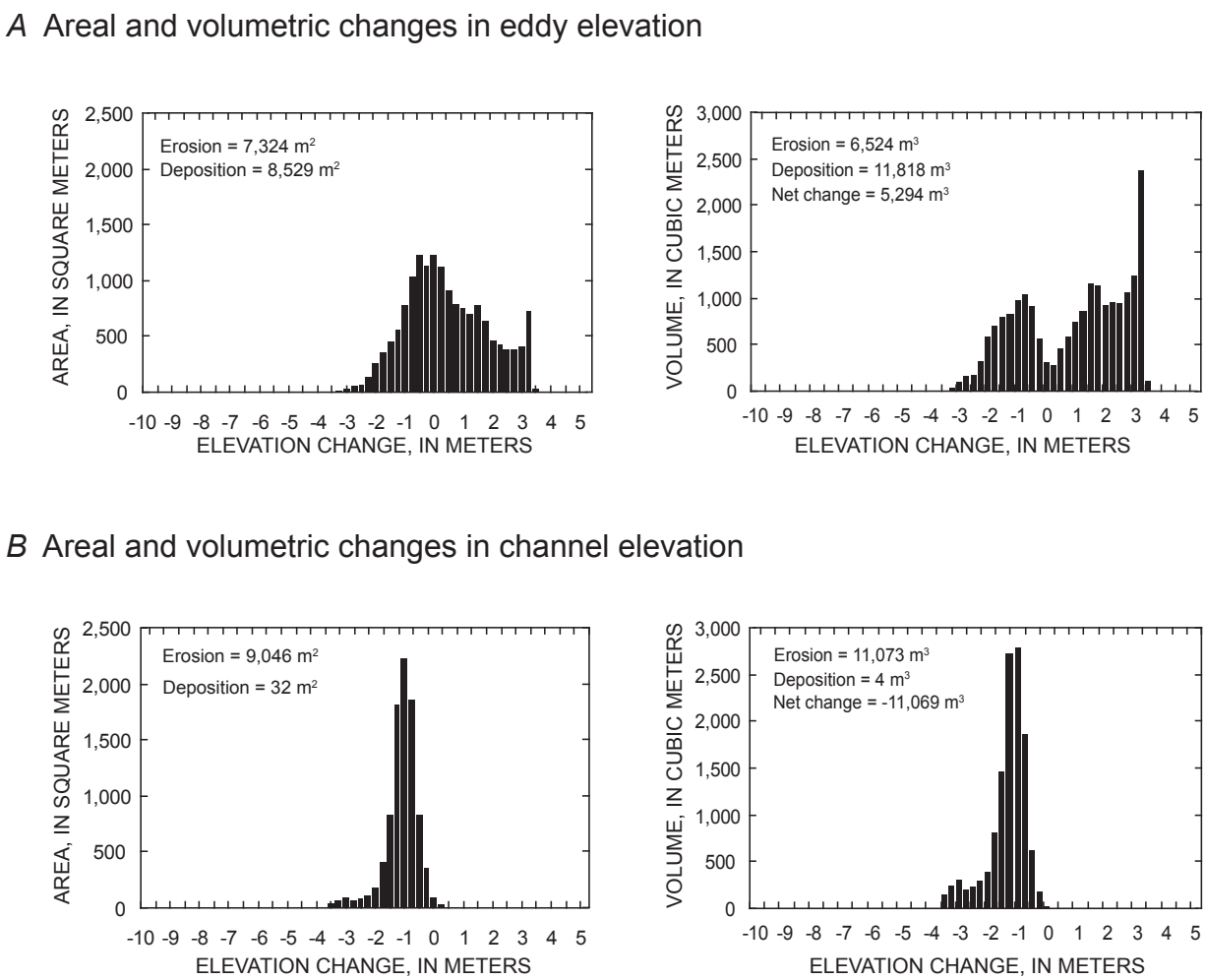


Figure 14. Areal and volumetric elevation-change distributions from the erosion-deposition map at site 65R shown in figure 12*C*. *A*, Total eddy. *B*, Main channel.

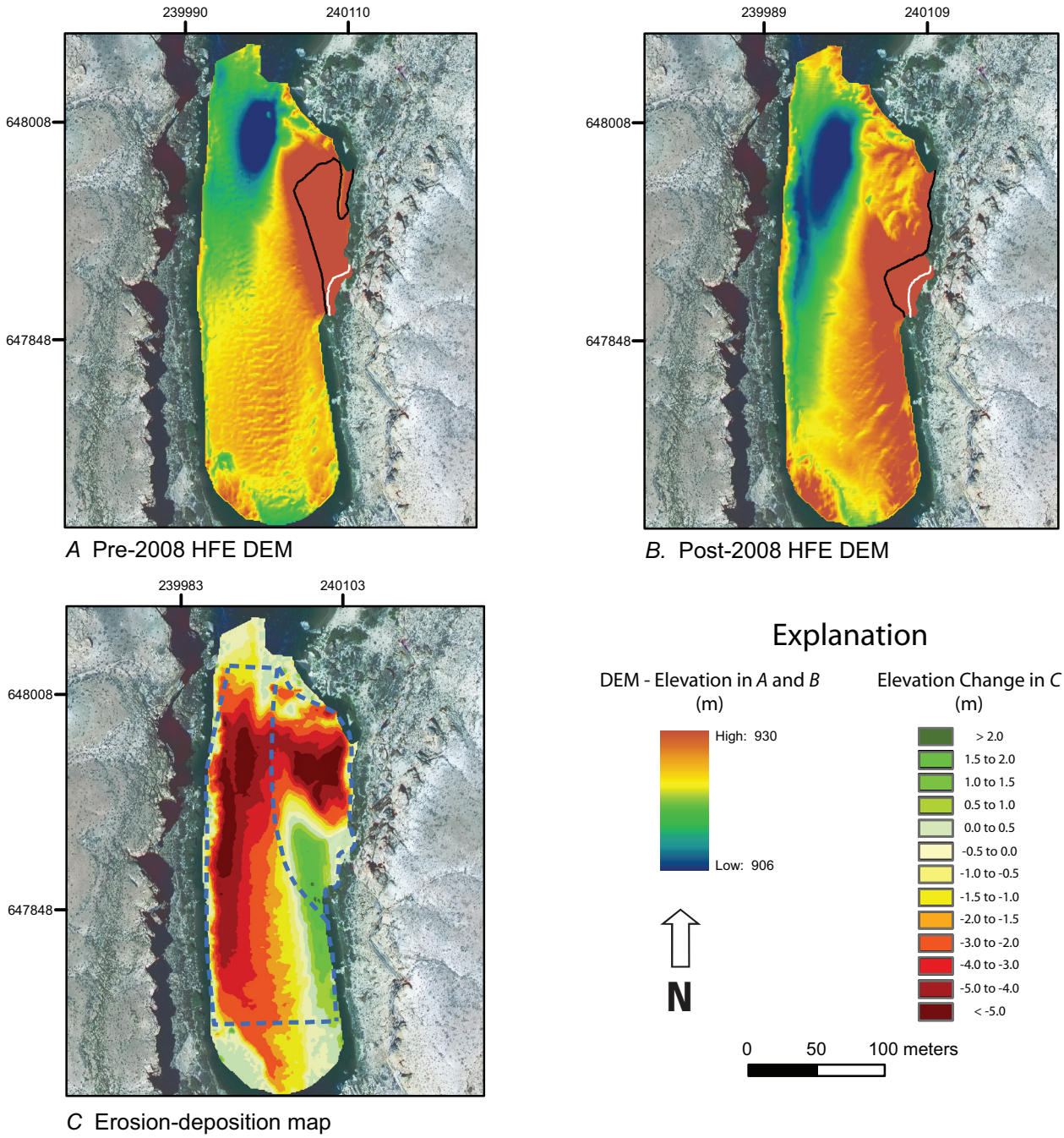


Figure 15. Comparison of repeat topographic and bathymetric surveys collected at site 3L. Flow in the main channel is from top to bottom. The maps are inset on 2002 aerial photography. Northing and easting on the map projection is 1983 Arizona State Plane, central zone. *A,* Pre-HFE digital elevation model (DEM). *B,* Post-HFE DEM. *C,* The DEMs were differenced against each other to produce a map of spatially distributed elevation change. The solid black and white lines in *A* and *B* are the stage elevations reached by a flow of 227 m^3/s and 708 m^3/s, respectively. The dashed blue line in *C* is the computational boundary described in figure 2.

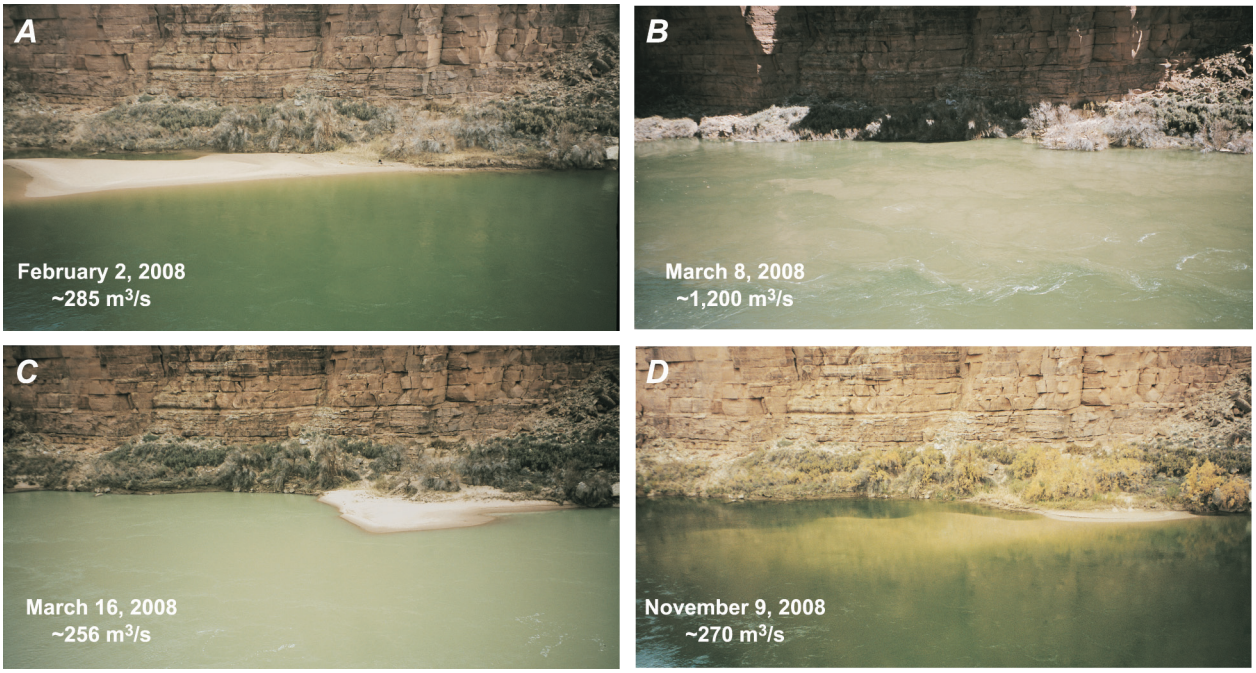


Figure 16. Selected daily photographs of the reattachment bar at site 3L. Flow in main channel is from left to right. The indicated discharges are estimates based on travel time between USGS stream-flow gaging stations on the Colorado River. *A,* A large, midelevation bar is present. *B,* The extent and height of site inundation by the 2008 HFE is shown. *C,* Upstream erosion and downstream deposition following the 2008 HFE. *D,* Erosion of the high-elevation bar between April and November 2008.

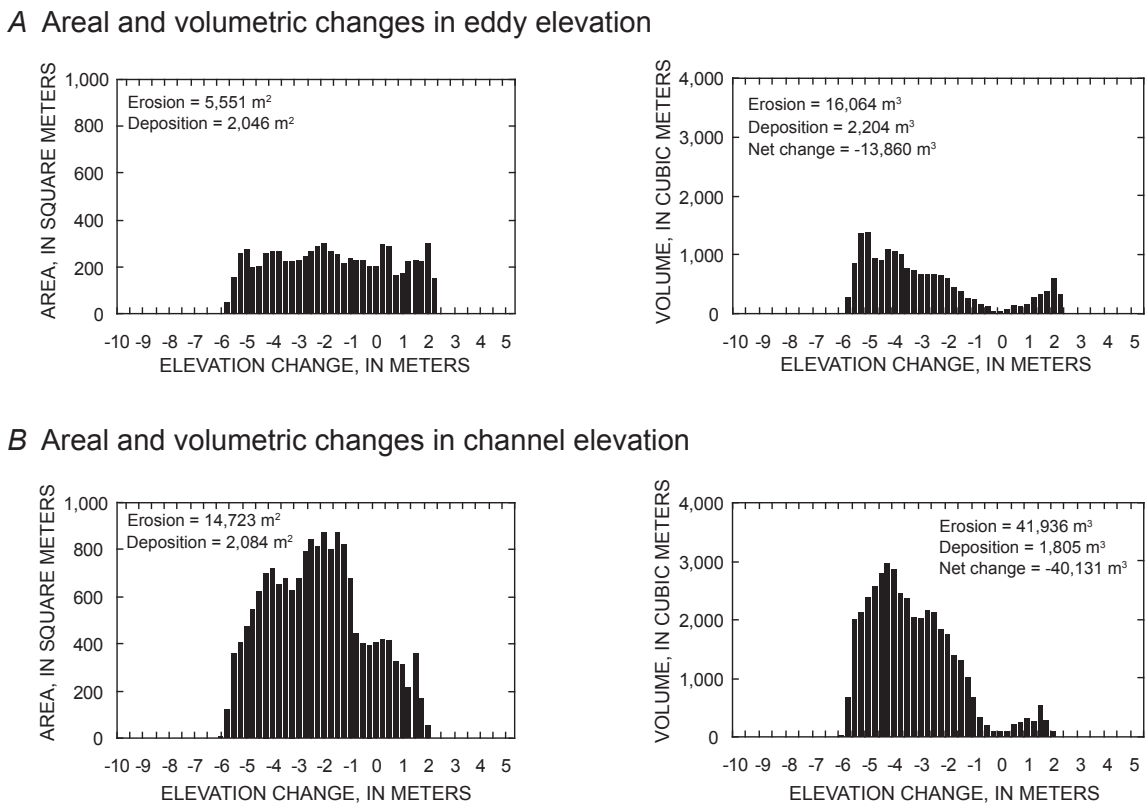


Figure 17. Areal and volumetric elevation-change distributions from the erosion-deposition map at site 3L shown in figure 15*C*. *A,* The total eddy. *B,* Main channel.

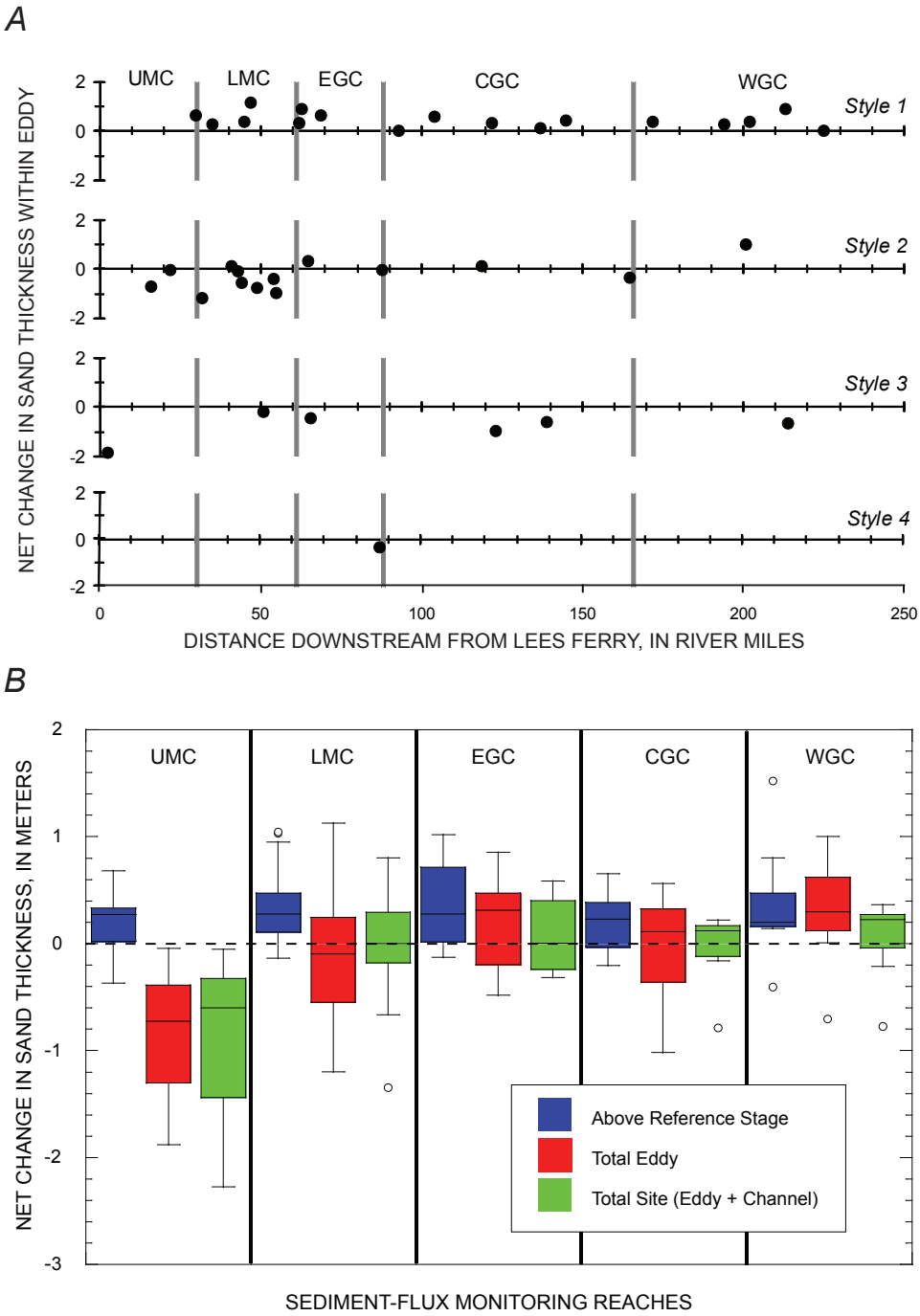


Figure 18. Downstream variations at study sites and sediment-transport-flux monitoring reaches in response to 2008 HFE. Upper Marble Canyon (UMC), lower Marble Canyon (LMC), eastern Grand Canyon (EGC), central Grand Canyon (CGC), and western Grand Canyon (WGC) reaches are shown. *A*, Graph showing the distribution of total-eddy net change in thickness of sand for each response style with distance downstream. *B*, Boxplots showing the distribution of change for above-reference-stage, total-eddy, and total-site thickness within the five sediment flux monitoring reaches. A boxplot summarizes the distribution of data by showing the interquartile range (25th percentile to 75th percentile) as the height of the box, the median value as the center line within the box, lines drawn to smallest and largest values within one step (equal to 1.5 times the interquartile range) beyond either end of the box, and outliers (values greater than two steps outside the box) as circles.

(appendix B; table 4). The large increase in midelevation-zone area and volume that occurred at 65R is another example of this response (fig. 13*A*). Decreases in campsite area resulted largely from lateral cutbank retreat. The large decreases in midelevation-zone area at 65R and 68R between April and October 2008 are good examples of this process (figs. 13, 19). The development of eolian dunes and the occurrence of surface runoff were also noted as causing campsite area decreases at several sites, but these surface modifications were less significant factors than the erosion associated with cutbank retreat (table 4).

Comparison of Three High-Flow Experiments: 1996, 2004, and 2008

Following the 2008 HFE, the volume of sand within the study sites was similar to or exceeded the volume of sand that existed following either the 1996 or 2004 HFEs. Cumulative probability distributions of total sand volume following each of the three high flows, expressed as the ratio of the volume measured following the high flow to the volume measured in February 1996, are depicted in figure 24. Although each sediment-transport-flux reach contains sites where the normalized sand volume was less than 1.0 (that is, less than the volume of sand measured in February 1996), the distribution curves for 2008 typically coincide with or are greater than the 1996 and 2004 curves, indicating total-site sand volume was similar or greater in 2008 than for the previous two HFEs. The total sand volume following the 2008 HFE was greater than following the 1996 HFE in all reaches and was similar to the storage condition following the 2004 HFE for the two reaches (UMC and LMC) where total-site sand volume was measured that year. The median values from these distributions are shown for each respective reach in figure 25*A*. In contrast to the previous high flows, the median post-2008 HFE normalized sand volume was approximately equal to or greater than 1.0 in all reaches.

The median sand volume above reference stage was similar to or exceeded the volumes following the previous

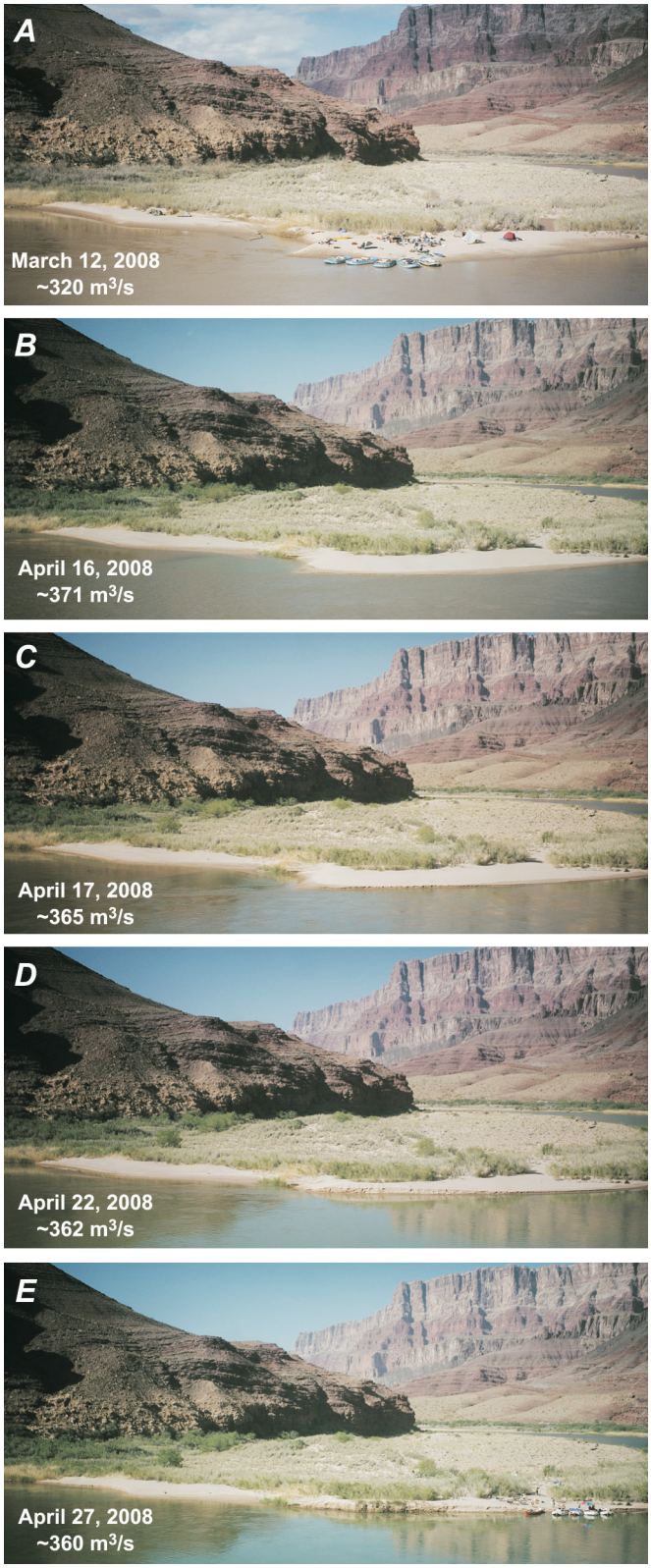


Figure 19. Photographic sequence at site 68R showing rapid erosion following the change in fluctuating flow regime at Glen Canyon Dam on April 15, 2008, when diurnal peak flows were increased to 425–462 m^3/s. Flow in main channel is from right to left. The indicated discharges are estimates based on travel time between USGS stream-flow gaging stations on the Colorado River. Flow rate at the time of each photograph is indicated. *A,* The new sandbar one day after recession of the 2008 HFE. *B,* Little change evident 35 days later at the onset of the new flow. *C,* A new cutbank appeared within 1 day of arrival of the higher peak flows. *D,* Within 5 days a 1-2 m cutbank was eroding the thicker portion of the deposit. E, Within 10 days a large portion of the new deposit and associated camping area had eroded.

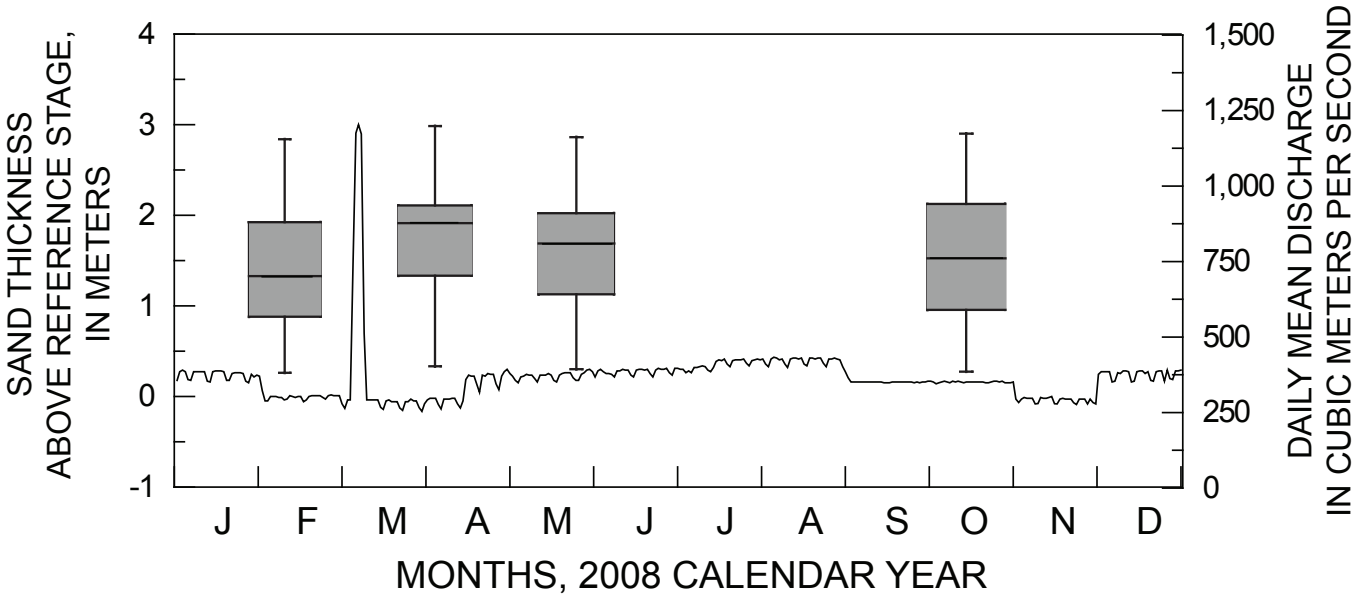


Figure 20. Boxplot showing temporal sequence of deposit thickness above the reference stage compared to daily mean discharge following the 2008 HFE. A boxplot summarizes the distribution of data by showing the interquartile range (25th percentile to 75th percentile) as the height of the box, the median value as the center line within the box, lines drawn to smallest and largest values within one step (equal to 1.5 times the interquartile range) beyond either end of the box, and outliers (values greater than two steps outside the box) as circles.

high flows in four out of the five sediment-flux monitoring reaches. Cumulative probability distributions for sand volumes above the reference stage are shown in figure 26. These plots indicate that the volume of sand above the 227-m^3/s stage was slightly less than 1996 and 2004 in UMC and similar or greater in LMC, EGC, CGC, and WGC. This pattern is also shown in figure 25*B,* where the median values are plotted for each reach. All median values, including that for upper Marble Canyon, are larger than 1.0, indicating that the volume of sand in sandbars above the reference stage was greater following the 2008 HFE than the volume measured before the 1996 HFE.

Discussion and Conclusions

The 2008 HFE, which followed a period of greatly increased sand supply by the Paria River, resulted in a net increase in the size and volume of sandbars throughout Marble and Grand Canyons. One of the objectives of this third controlled-flood experiment was to evaluate whether a high flow conducted under sediment-enriched conditions could result in sandbar building throughout the system. These sandbar monitoring results show that there was (1) widespread high-elevation deposition and (2) less sand depletion at low elevation within eddies and the main channel than occurred during the two previous HFEs in 1996 and 2004. The net aggradational response also resulted in proportional increases in campsite area in both critical and noncritical reaches.

The increases in eddy deposit thickness above reference stage was similar in all sediment-transport flux reaches, while total-eddy response, strongly influenced by site-specific topographic changes below reference stage, was more variable. The response Style 1, in which all elevations increased in sand volume, occurred more commonly further downstream; upstream reaches had a response typically characterized by high-elevation deposition and low-elevation erosion (Style 2). The median change in total-site deposit thickness increased from negative values at sites located in Marble Canyon to positive values at sites located further downstream in Grand Canyon. Not every eddy aggraded in the same proportion, and there was at least one site in each sediment-transport-flux reach that experienced net erosion (for example, 3L, 55R, 65R, 123L, 214R). Despite widespread deposition of high-elevation sandbars, this pattern was still accompanied by net erosion in some eddies, which also occurred during previous high flows (Andrews and others, 1999; Hazel and others, 1999; Topping and others, 2006a). Because sandbars above reference stage typically occupy a small percentage of total eddy area, large-scale low-elevation erosion, where it occurred, typically resulted in a net loss of sand from eddies and the adjacent

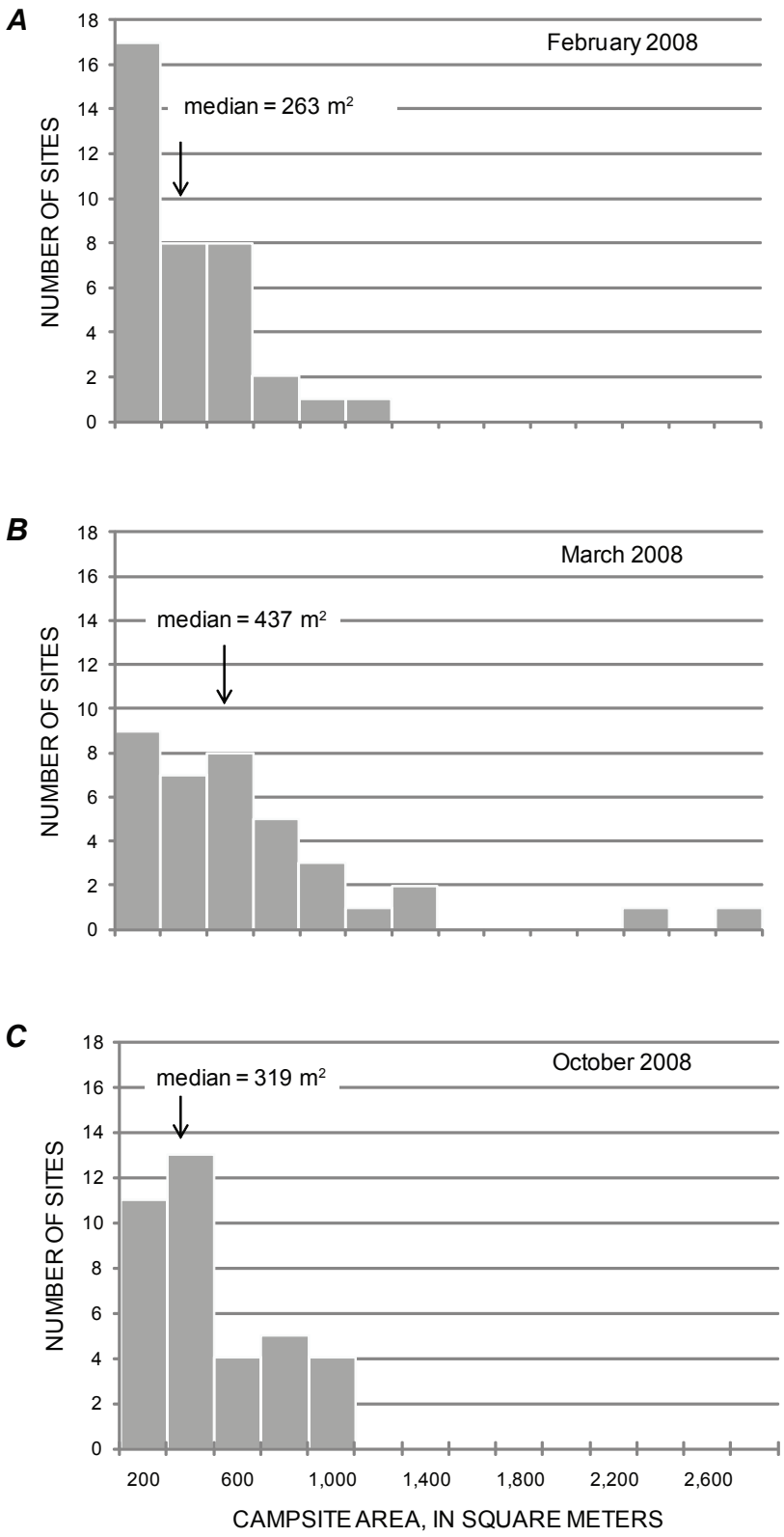


Figure 21. Histograms showing the distribution of campsite area above the reference stage (combined mid- and high-elevation zones shown on figure 2*C*). *A*, February 2008. *B*, April 2008. *C*, Six months after the 2008 HFE.

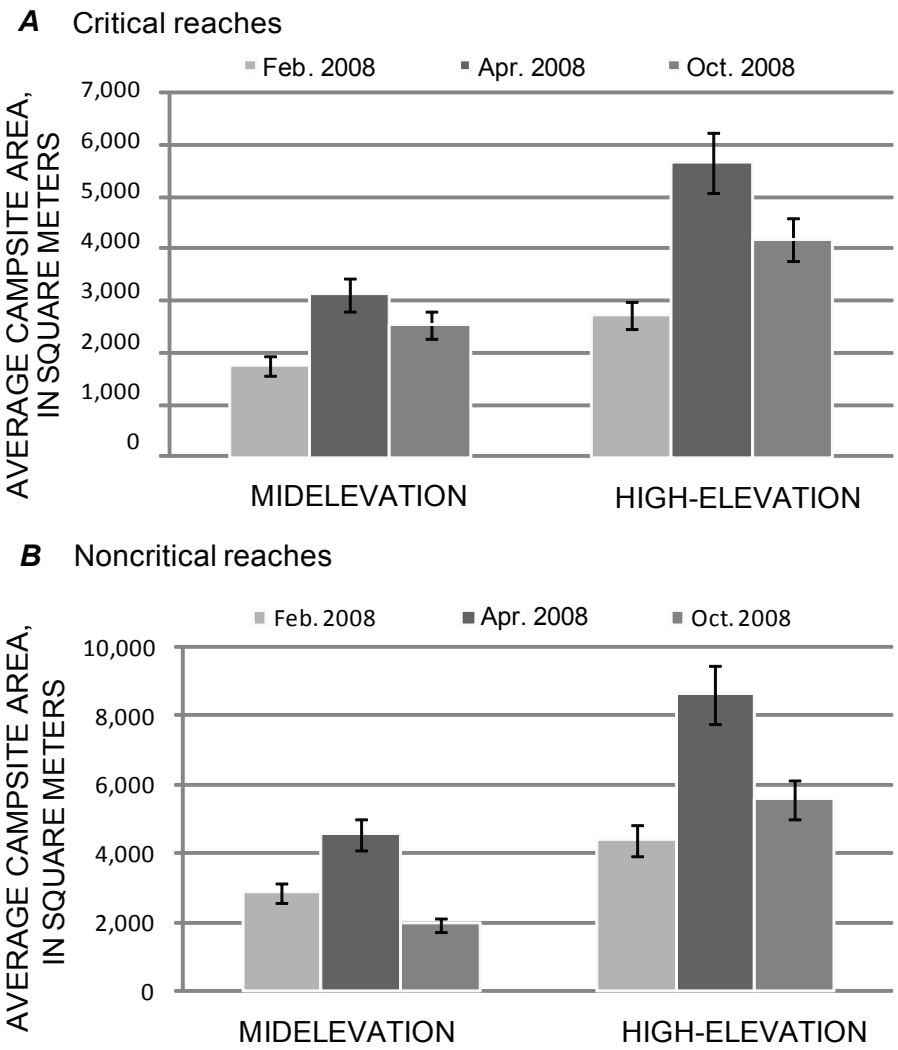


Figure 22. Average campsite area above the reference stage before, after, and about 6 months after the 2008 HFE. Error bars show plus and minus 10 percent of total. *A*, Critical reaches. *B*, Noncritical reaches.

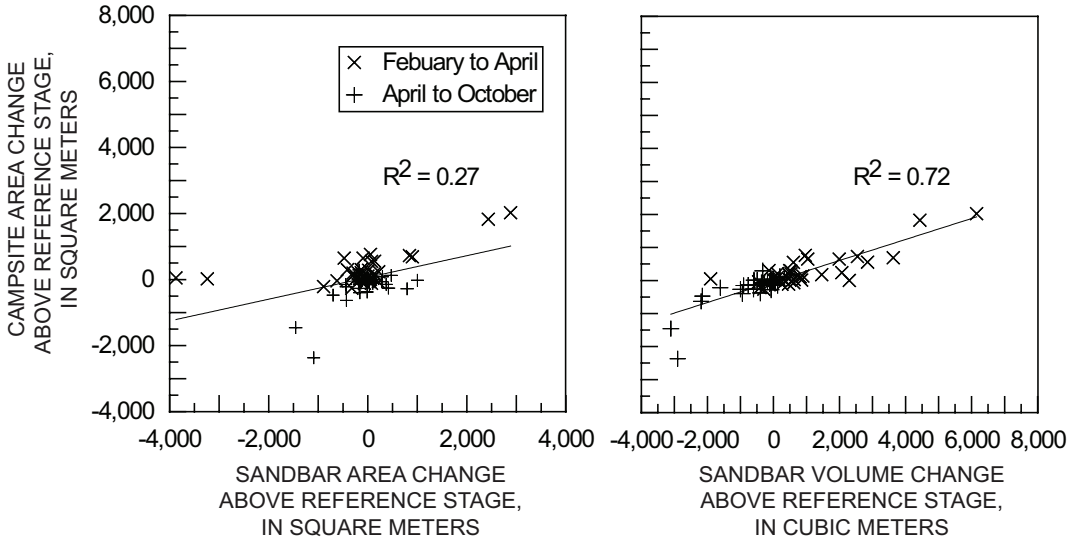


Figure 23. The relation of change in campsite area to change in sandbar area and volume for two time intervals in 2008, pre- to postflood (February-April) and the following 6 months (April-October). A linear regression fit for both time intervals combined is shown.

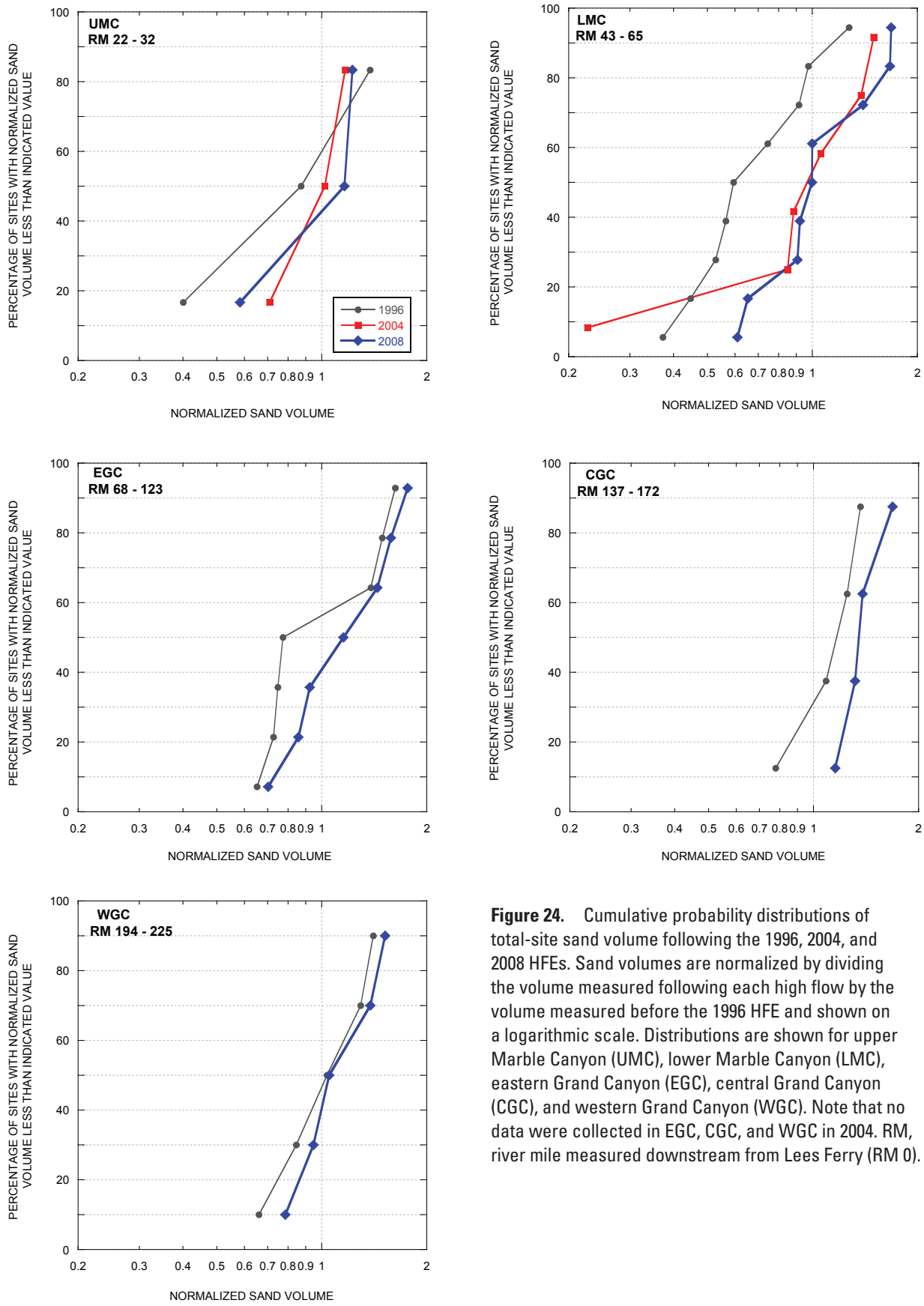


Figure 24. Cumulative probability distributions of total-site sand volume following the 1996, 2004, and 2008 HFEs. Sand volumes are normalized by dividing the volume measured following each high flow by the volume measured before the 1996 HFE and shown on a logarithmic scale. Distributions are shown for upper Marble Canyon (UMC), lower Marble Canyon (LMC), eastern Grand Canyon (EGC), central Grand Canyon (CGC), and western Grand Canyon (WGC). Note that no data were collected in EGC, CGC, and WGC in 2004. RM, river mile measured downstream from Lees Ferry (RM 0).

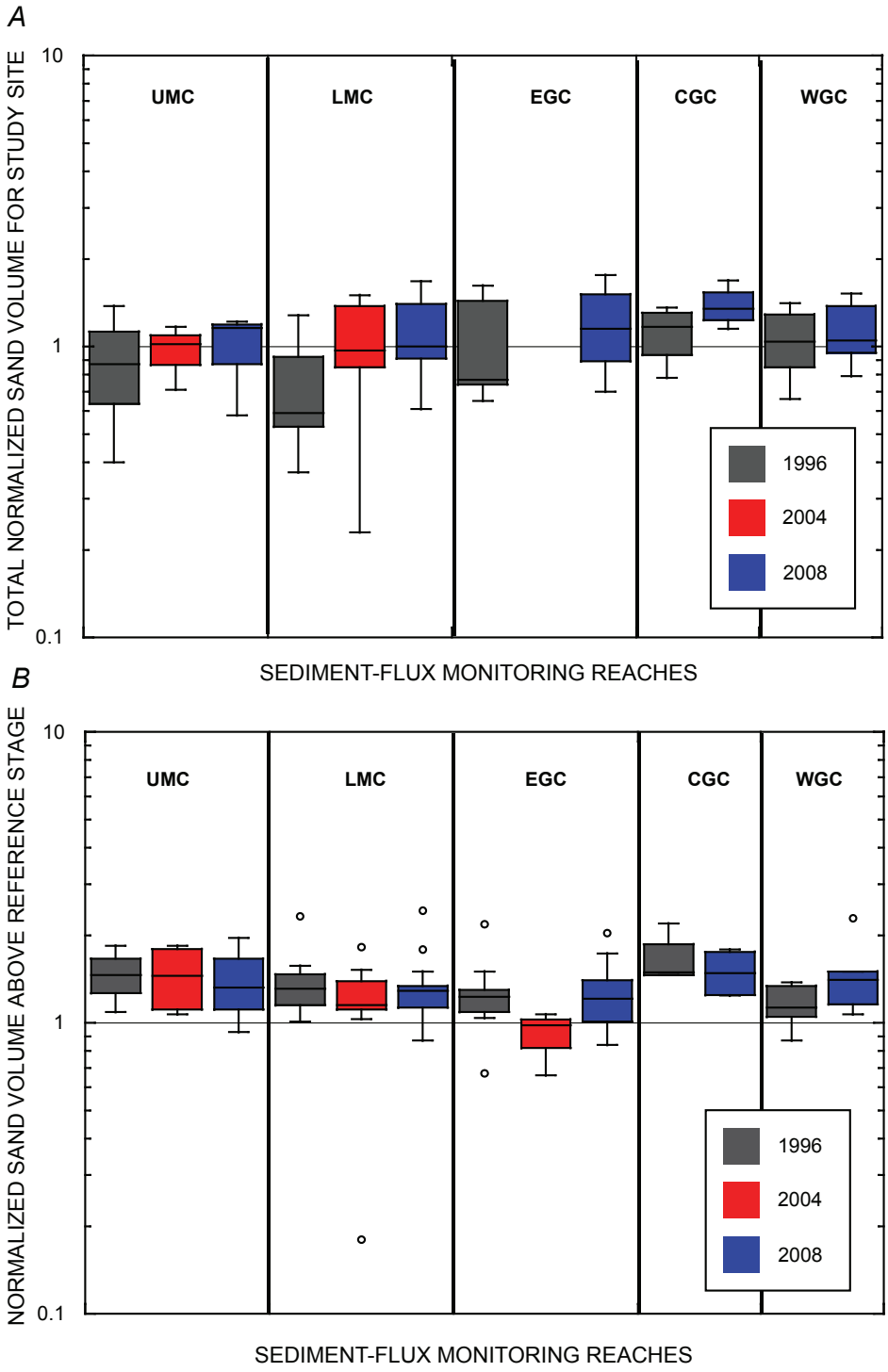


Figure 25. Boxplots showing normalized sand volumes of all sites within each sediment-transport-flux monitoring reach. Sand volumes are normalized by dividing the volume measured following each high flow by the volume measured before the 1996 HFE and shown on a logarithmic scale. Upper Marble Canyon (UMC), lower Marble Canyon (LMC), eastern Grand Canyon (EGC), central Grand Canyon (CGC), and western Grand Canyon (WGC) reaches are shown. *A,* Total-site volume. *B,* Above-reference-stage volume. A boxplot summarizes the distribution of data by showing the interquartile range (25th percentile to 75th percentile) as the height of the box, the median value as the center line within the box, lines drawn to smallest and largest values within one step (equal to 1.5 times the interquartile range) beyond either end of the box, and outliers (values greater than two steps outside the box) as circles.

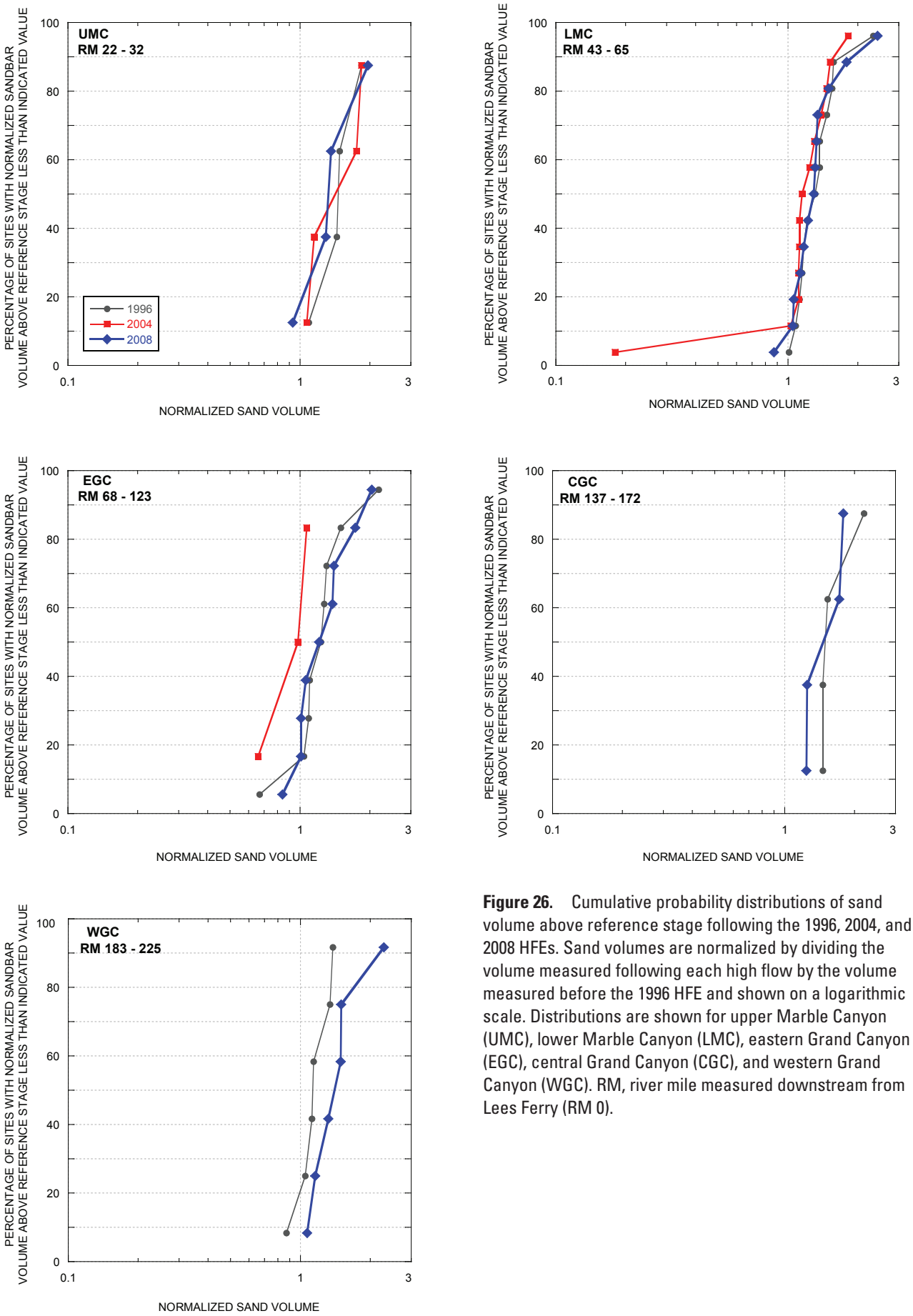


Figure 26. Cumulative probability distributions of sand volume above reference stage following the 1996, 2004, and 2008 HFEs. Sand volumes are normalized by dividing the volume measured following each high flow by the volume measured before the 1996 HFE and shown on a logarithmic scale. Distributions are shown for upper Marble Canyon (UMC), lower Marble Canyon (LMC), eastern Grand Canyon (EGC), central Grand Canyon (CGC), and western Grand Canyon (WGC). RM, river mile measured downstream from Lees Ferry (RM 0).

channel (fig. 18). These results are similar to those observed in association with the 1996 HFE, where the source of sand deposited at the sites differed between sites located in Marble and Grand Canyons (Schmidt, 1999).

Direct comparison of the topographic response of sandbars with those observed during two previous high-flow experiments conducted in 1996 and 2004 indicate that the total-site sand volume was similar or greater following the 2008 HFE in all sediment-transport-flux monitoring reaches. These results suggest that the antecedent condition prior to controlled flooding is an important factor in the resulting sandbar response. During the 2004 high flow, increases in sand volume above reference stage were much greater in UMC than in LMC and sand volume above reference stage in EGC decreased to a magnitude similar to that measured before the 1996 high flow. In contrast, sand volume above the reference stage following the 2008 HFE was similar to or larger than sand volume for the same sites following the 1996 HFE in all reaches. The greater consistency among the sediment-transport-flux monitoring reaches observed following the 2008 HFE is consistent with the observation that accumulated sand was more evenly distributed throughout all geomorphic reaches preceding the 2008 HFE than it was before the 2004 HFE.

In the 6-month period following the 2008 HFE, readjustment of the newly aggraded eddy bars to regular dam operations led to rapid, but declining rates of erosion. Post-2008 HFE sandbar erosion also resulted in concomitant decreases in campsite area. Although newly deposited sandbars may differ in susceptibility to erosion during normal, diurnal fluctuating-flow dam operations associated with the modified low fluctuating flow operation, previous work has shown that elevated fluctuating flows following past sandbar-building experiments result in rapid, systemwide erosion of sandbars of all types (Schmidt and Graf, 1990; Hazel and others, 1999; Rubin and others, 2002). Observations by remote camera indicate that sandbars were stable or gradually eroding between the 2008 HFE and the April 2008 sandbar measurements. Erosion rates were highest between April and May and lower between May and October 2008. The transition in dam operations from spring fluctuating flows to early summer fluctuating flows occurred immediately after the April sandbar measurements, and the remote camera observations show high rates of cutbank retreat at several sites from April to May 2008. These observations suggest that the transition from the spring flows to the higher volume early summer flows caused accelerated sandbar erosion, although the rate of erosion that would have occurred under a different flow regime is not known. Similarly, repeat daily photos of one of the study sites (30R) immediately following the 2004 HFE also demonstrated stability of a rebuilt sandbar until higher and more widely ranging flow fluctuations began in January 2005.

The marked decrease in erosion rates between the early summer flows and the higher, late summer flows is likely owing to the fact that many of the sandbars had substantially eroded by the time the late summer flows started (fig. 20). Previous studies have shown that erosion rates decrease as the availability of erodible sediment decreases (Schmidt and others, 1995; Hazel and others, 1999) or as a stable slope is reached (Budhu and Gobin, 1994). Thus, much of the redistribution of sand had already occurred by the time that the late summer fluctuations occurred, thereby limiting the potential of lower, steady flows released from the dam in September and October 2008 to enhance stability of the 2008 HEF sandbar deposits.

Monitoring and prediction of sandbar response to experimental controlled floods at Glen Canyon Dam are complicated by variations in channel and debris-fan geometry (Schmidt and Graf, 1990), the cumulative downstream nature of the limited sand supply, and the physics that governs sediment transport (Topping and others, 2000; Rubin and Topping, 2001; Topping and others, 2007; Rubin and Topping, 2008), as well as because of the spatial and temporal variability of study sites utilized for monitoring (Schmidt and others, 2004). It is still unclear whether controlled floods will provide a sustainable strategy for longer term habitat restoration and maintenance using only sand supplied by the remaining tributary sources of sand below the dam. This will require integration of the results described in this report with results from other studies and continued experimentation, monitoring, and evaluation.

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Appendixes A–B

Appendix A. Summary of study sites and types of data collected, Colorado River in Marble and Grand Canyons

[Site ID is river mile (RM) location based on the RM centerline (U.S. Geological Survey, 2006) downstream from Lees Ferry (river mile 0) in Grand Canyon National Park. The descriptors "L" and "R" denote the location of the emergent sandbar on left and right sides of the river, respectively, facing downstream. Date of study is that of topographic survey (month/day/year). Discharges were estimated from the water surface during topographic surveys using the stage-discharge relations of Hazel and others (2006b). √, data were collected. -, no data were collected or data were not recoverable.]

Site ID	Date	Discharge (m^3/s)	Topographic survey	Bathymetric survey	Campsite survey	Time-lapse photography	Scour chains
1R	02/02/08	285	√	-	-	-	-
	03/28/08	278	√	√	-	-	-
	05/17/08	232	√	-	-	-	-
	10/11/08	355	√	-	-	-	-
3L	02/02/08	322	√	√	-	√	-
	03/28/08	352	√	√	-	√	-
	05/17/08	318	√	-	-	√	-
	10/11/08	394	√	-	-	√	-
8L	02/02/08	253	√	-	√	-	-
	03/28/08	313	√	-	√	√	-
	10/11/08	360	√	-	√	√	-
9L	02/03/08	252	√	-	-	-	-
	03/29/08	300	√	√	-	-	-
	05/17/08	369	√	-	-	-	-
	10/12/08	358	√	-	-	-	-
16L	02/03/08	282	√	√	√	-	-
	03/29/08	279	√	√	√	√	-
	10/12/08	384	√	-	√	?	-
22R	02/03/08	284	√	√	√	√	-
	03/29/08	267	√	√	√	√	-
	05/17/08	265	√	-	-	√	-
	10/12/08	366	√	-	√	√	-
24L	02/04/08	255	√	-	√	-	-
	03/29/08	257	√	-	√	-	-
	10/12/08	368	√	-	√	-	-
29L	02/04/08	287	√	-	√	-	-
	03/30/08	246	√	-	√	-	-
	09/22/08	309	√	-	√	-	-
30R	02/04/08	266	√	√	√	√	√
	03/30/08	257	√	√	√	√	-
	05/19/08	336	√	-	-	√	-
	10/13/08	365	√	-	√	√	-
32R	02/05/08	265	√	√	√	-	-
	03/30/08	235	√	√	√	-	-
	10/13/08	379	√	-	-	-	-
33L	02/05/08	264	√	-	-	-	-
	03/30/08	220	√	√	-	-	-
	10/13/08	347	√	-	-	-	-
35L	02/05/08	272	√	√	√	-	-
	03/30/08	212	√	√	√	-	-
	10/13/08	348	√	√	√	-	-

Appendix A. Summary of study sites and types of data collected, Colorado River in Marble and Grand Canyons. —Continued

[Site ID is river mile (RM) location based on the RM centerline (U.S. Geological Survey, 2006) downstream from Lees Ferry (river mile 0) in Grand Canyon National Park. The descriptors "L" and "R" denote the location of the emergent sandbar on left and right sides of the river, respectively, facing downstream. Date of study is that of topographic survey (month/day/year). Discharges were estimated from the water surface during topographic surveys using the stage-discharge relations of Hazel and others (2006b). √, data were collected. -, no data were collected or data were not recoverable.]

Site ID	Date	Discharge (m^3/s)	Topographic survey	Bathymetric survey	Campsite survey	Time-lapse photography	Scour chains
41R	02/05/08	303	√	√	√	√	-
	03/31/08	316	√	√	√	-	-
	05/19/08	294	√	-	-	√	-
	10/14/08	357	√	-	√	√	-
43L	02/06/08	282	√	√	√	-	-
	03/31/08	273	√	√	√	-	-
	05/19/08	301	√	-	-	-	-
	10/14/08	368	√	-	√	-	-
44L	02/06/08	270	√	√	√	√	√
	03/31/08	237	√	√	√	√	-
	05/19/08	-	-	-	-	√	-
	10/14/08	345	√	-	√		-
45L	02/07/08	320	√	√	√	√	-
	03/31/08	227	√	√	√	√	-
	05/20/08	385	√	-	-	√	-
	10/15/08	358	√	-	√	√	-
47R	02/07/08	339	√	-	√	√	-
	03/31/08	307	√	-	√	√	-
	05/20/08	343	√	√	-	√	-
	10/15/08	361	√	√	√	√	-
49R	02/07/08	253	√	√	-	-	-
	03/31/08	282	√	√	-	-	-
	05/20/08	394	√	-	-	-	-
	09/24/08	346	√	-	-	-	-
49L	02/07/08	253	√	√	-	-	-
	04/01/08	256	√	√	-	-	-
	05/20/08	343	√	-	-	-	-
	09/24/08	358	√	-	-	-	-
50R	04/01/08	292	√	√	√	√	-
	05/20/08	309	√	-	-	√	-
	10/15/08	360	√	-	√	√	-
51L	02/08/08	335	√	√	√	-	-
	04/02/08	328	√	√	√	-	-
	05/21/08	414	√	-	-	-	-
	10/15/08	358	√	-	√	-	-
54R	02/08/08	334	√	√	-	-	√
	04/02/08	319	√	√	-	-	-
	10/16/08	358	√	-	-	-	-

Appendix A. Summary of study sites and types of data collected, Colorado River in Marble and Grand Canyons. —Continued

[Site ID is river mile (RM) location based on the RM centerline (U.S. Geological Survey, 2006) downstream from Lees Ferry (river mile 0) in Grand Canyon National Park. The descriptors "L" and "R" denote the location of the emergent sandbar on left and right sides of the river, respectively, facing downstream. Date of study is that of topographic survey (month/day/year). Discharges were estimated from the water surface during topographic surveys using the stage-discharge relations of Hazel and others (2006b). √, data were collected. -, no data were collected or data were not recoverable.]

Site ID	Date	Discharge (m^3/s)	Topographic survey	Bathymetric survey	Campsite survey	Time-lapse photography	Scour chains
55R	02/08/08	318	√	√	-	√	-
	04/02/08	275	√	√	√	√	-
	05/21/08	328	√	-	-	√	-
	10/16/08	348	√	-	-	√	-
56R	04/02/08	252	√	-	-	-	-
	05/21/08	303	√	-	-	-	-
	10/16/08	372	√	-	-	-	-
58L	02/08/08	307	√	-	-	√	-
	04/03/08	337	√	-	-	√	-
	05/23/08	-	√	-	-	√	-
	10/16/08	368	√	-	-	√	-
62R	02/09/08	352	√	√	√	-	-
	04/03/08	380	√	√	√	-	-
	10/17/08	356	√	-	√	-	-
63L	02/09/08	337	√	√	-	-	-
	04/03/08	340	√	√	-	-	-
	05/24/08	397	√	-	-	-	-
	10/17/08	340	√	-	-	-	-
65R	02/09/08	372	√	√	-	-	-
	04/03/08	332	√	√	-	-	-
	05/24/08	410	√	-	-	-	-
	10/17/08	387	√	-	-	-	-
65L	02/09/08	375	√	√	-	√	-
	04/04/08	347	√	√	-	√	-
	05/24/08	424	√	-	-	√	-
	10/17/08	368	√	-	-	√	-
66L	02/10/08	265	√	-	-	√	-
	04/04/08	315	√	-	-	√	-
	05/24/08	353	√	-	-	√	-
	10/18/08	363	√	-	-	√	-
68R	02/10/08	279	√	√	-	√	-
	04/05/08	341	√	√	-	√	-
	05/25/08	420	√	-	-	√	-
	10/18/08	344	√	-	-	√	-
70R	02/10/08	345	√	-	-	√	-
	04/05/08	372	√	-	-	-	-
	10/18/08	370	√	-	-	√	-
81L	02/11/08	303	√	-	√	√	-
	04/06/08	293	√	-	√	√	-
	05/25/08	405	√	-	-	√	-
	09/26/08	362	√	-	√		

Appendix A. Summary of study sites and types of data collected, Colorado River in Marble and Grand Canyons. —Continued

[Site ID is river mile (RM) location based on the RM centerline (U.S. Geological Survey, 2006) downstream from Lees Ferry (river mile 0) in Grand Canyon National Park. The descriptors "L" and "R" denote the location of the emergent sandbar on left and right sides of the river, respectively, facing downstream. Date of study is that of topographic survey (month/day/year). Discharges were estimated from the water surface during topographic surveys using the stage-discharge relations of Hazel and others (2006b). √, data were collected. -, no data were collected or data were not recoverable.]

Site ID	Date	Discharge (m^3/s)	Topographic survey	Bathymetric survey	Campsite survey	Time-lapse photography	Scour chains
84R	02/11/08	309	√	-	√	-	-
	04/06/08	279	√	-	√	-	-
	09/27/08	353	√	-	-	-	-
87L	02/11/08	334	√	√	√	√	-
	04/06/08	329	√	√	√	√	-
	10/19/08	368	√	-	-	√	-
88R	02/11/08	327	√	√	-	-	-
	04/06/08	300	√	√	-	-	-
	10/19/08	337	√	-	-	-	-
91R	02/12/08	346	√	-	-	√	-
	04/07/08	280	√	-	-	√	-
	10/19/08	372	√	-	-	√	-
93L	02/12/08	322	√	√	√	-	-
	04/07/08	276	√	√	√	-	-
	10/20/08	360	√	-	√	-	-
104R	02/12/08	323	√	√	√	√	-
	04/07/08	303	√	√	√	√	-
	10/20/08	360	√	-	√	√	-
119.4r	02/12/08	319	√	√	√	√	√
	04/08/08	299	√	√	√	√	-
	10/21/08	372	√	-	√	√	-
119.8r	02/12/08	317	√	√	-	-	-
	04/08/08	318	√	√	-	-	-
	05/27/08	386	√	-	-	-	-
	10/21/08	368	√	-	-	-	-
122R	02/12/08	343	√	√	√	√	√
	04/08/08	337	√	√	√	√	-
	05/27/08	411	√	-	-	√	-
	10/21/08	363	√	-	√	√	-
123L	02/13/08	358	√	√	√	√	-
	04/08/08	286	√	√	√	√	-
	05/28/08	360	√	-	-	√	-
	10/21/08	376	√	-	√	√	-
137L	02/13/08	336	√	√	√	√	-
	04/09/08	284	√	√	√	√	-
	10/22/08	362	√	-	√	√	-

Appendix A. Summary of study sites and types of data collected, Colorado River in Marble and Grand Canyons. —Continued

[Site ID is river mile (RM) location based on the RM centerline (U.S. Geological Survey, 2006) downstream from Lees Ferry (river mile 0) in Grand Canyon National Park. The descriptors "L" and "R" denote the location of the emergent sandbar on left and right sides of the river, respectively, facing downstream. Date of study is that of topographic survey (month/day/year). Discharges were estimated from the water surface during topographic surveys using the stage-discharge relations of Hazel and others (2006b). √, data were collected. -, no data were collected or data were not recoverable.]

Site ID	Date	Discharge (m^3/s)	Topographic survey	Bathymetric survey	Campsite survey	Time-lapse photography	Scour chains
139R	02/13/08	346	√	√	√	√	-
	04/09/08	299	√	√	√	√	-
	10/22/08	380	√	-	√	√	-
145L	02/13/08	346	√	√	√	√	-
	04/09/08	327	√	√	√	√	-
	05/29/08	327	√	-	-	√	-
	10/22/08	365	√	-	√	√	-
165R	02/14/08	351	√	√	-	-	-
	04/10/08	325	√	√	-	-	-
	05/29/08	329	√	-	-	-	-
	09/30/08	367	√	-	-	-	-
166L	02/14/08	336	√	-	√	-	√
	04/10/08	286	√	-	√	-	-
	05/29/08	343	√	-	-	-	-
	10/23/08	340	√	-	√	-	-
172L	02/14/08	344	√	√	-	√	√
	04/10/08	297	√	√	-	√	-
	05/30/08	362	√	-	-	√	-
	10/23/08	346	√	-	-	-	-
183R	02/15/08	386	√	-	√	√	-
	04/11/08	363	√	√	√	-	-
	05/31/08	417	√	-	-	√	-
	10/24/08	369	√	-	√	-	-
194L	02/15/08	376	√	√	√	√	-
	04/11/08	349	√	√	√	√	-
	05/31/08	377	√	-	-	√	-
	10/24/08	363	√	-	√	√	-

Appendix A. Summary of study sites and types of data collected, Colorado River in Marble and Grand Canyons. —Continued

[Site ID is river mile (RM) location based on the RM centerline (U.S. Geological Survey, 2006) downstream from Lees Ferry (river mile 0) in Grand Canyon National Park. The descriptors "L" and "R" denote the location of the emergent sandbar on left and right sides of the river, respectively, facing downstream. Date of study is that of topographic survey (month/day/year). Discharges were estimated from the water surface during topographic surveys using the stage-discharge relations of Hazel and others (2006b). √, data were collected. -, no data were collected or data were not recoverable.]

Site ID	Date	Discharge (m^3/s)	Topographic survey	Bathymetric survey	Campsite survey	Time-lapse photography	Scour chains
201R	02/16/08	371	√	√	-	-	-
	04/11/08	366	√	√	-	-	-
	06/01/08	405	√	-	-	-	-
	10/25/08	369	√	-	-	-	-
202R	02/16/08	381	√	√	√	√	-
	04/11/08	322	√	√	√	√	-
	06/01/08	418	√	-	-	√	-
	10/25/08	366	√	-	√	√	-
213L	02/17/08	344	√	√	√	√	-
	04/12/08	338	√	√	√	√	-
	06/02/08	433	√	-	-	-	-
	10/26/08	362	√	-	√	√	-
214R	02/17/08	363	√	√	-	-	-
	04/12/08	343	√	√	-	-	-
	06/02/08	453	√	-	-	-	-
	10/26/08	374	√	-	-	-	-
220R	02/17/08	449	√	√	√	-	-
	04/12/08	415	√	√	√	-	-
	10/26/08	438	√	-	√	-	-
225R	02/18/08	372	√	√	-	√	-
	04/13/08	328	√	√	-	√	-
	06/03/08	391	√	-	-	-	-
	10/26/08	364	√	-	-	√	-

Appendix B. Basic Data Tables for Studied Sites on Colorado River, Marble and Grand Canyons

Table B1. High-elevation-zone area and volume at four measurement times in 2008 at each study site.

[Site ID is river mile (RM) location based on the RM centerline (U.S. Geological Survey, 2006) downstream from Lees Ferry (river mile 0) in Grand Canyon National Park. The descriptors "L" and "R" denote the location of the emergent sandbar on left and right sides of the river, respectively, facing downstream. -, indicates no data were collected or data were not recoverable.]

Site ID	Area (m^2)				Volume (m^3)			
	February	April	May	October	February	April	May	October
1R	901	960	961	999	817	845	842	843
3L	161	170	165	163	103	107	108	109
8L	781	841	-	802	420	432	-	395
9L	430	1,267	1,121	807	183	798	669	508
16L	88	170	-	153	32	42	-	60
22R	724	848	845	821	900	1,241	1,203	1,205
24L	117	152	-	149	17	26	-	24
29L	416	691	-	538	369	472	-	381
30R	598	1,131	1,095	808	641	1,077	1,041	794
32R	725	773	-	745	656	623	-	598
33L	3,291	3,364	-	3,299	9,876	9,964	-	9,791
35L	838	918	-	895	1,047	1,085	-	1,079
41R	3,886	6,083	-	5,833	3,600	4,964	-	5,515
43L	2,520	2,583	2,567	2,645	2,818	2,882	2,865	2,984
44L	3,192	4,239	4,239	3,914	3,775	4,721	4,721	4,460
45L	1,937	3,455	3,455	2,878	2,871	3,778	3,778	3,593
47R	1,022	2,130	2,010	1,623	707	1,222	1,220	1,090
49R	909	2,279	1,955	1,524	926	2,037	1,942	1,656
49L	1,394	1,674	1,660	1,656	1,343	1,863	1,835	1,875
50R	1,935	2,066	2,066	1,979	3,285	3,270	3,270	3,346
51L	6,002	6,194	6,182	6,189	5,585	6,070	6,038	6,056
54R	760	1,328	-	1,270	424	655	-	781
55R	6,004	6,659	6,608	6,558	3,879	4,424	4,555	4,276
56R	1,565	2,148	2,073	2,068	1,175	1,240	1,247	1,288
58L	3,141	3,608	3,621	3,635	4,198	5,007	4,945	5,049
62R	350	382	-	397	203	315	-	299
63L	256	714	714	736	121	295	295	316
65R	797	4,085	4,085	1,263	625	2,897	2,897	714
65L	324	1,589	1,630	1,651	105	717	899	735
66L	114	3,174	2,468	682	33	488	313	58
68R	2,347	3,294	2,912	2,856	1,276	1,733	1,776	1,834
70R	746	1,502	-	1,126	519	1,502	-	951
81L	1,103	1,558	1,491	1,445	867	1,341	1,239	1,162
84R	252	301	-	286	363	448	-	432
87L	344	369	-	362	309	390	-	376
88R	212	365	-	302	138	266	-	218

Table B1. High-elevation-zone area and volume at four measurement times in 2008 at each study site.—Continued

[Site ID is river mile (RM) location based on the RM centerline (U.S. Geological Survey, 2006) downstream from Lees Ferry (river mile 0) in Grand Canyon National Park. The descriptors "L" and "R" denote the location of the emergent sandbar on left and right sides of the river, respectively, facing downstream. -, indicates no data were collected or data were not recoverable.]

Site ID	Area (m^2)				Volume (m^3)			
	February	April	May	October	February	April	May	October
91R	550	589	-	583	1,006	1,057	-	1,048
93L	1,088	1,490	-	1,381	659	1,212	-	1,105
104R	246	312	-	265	232	330	-	284
119R	1,091	1,748	1,623	1,363	1,474	2,115	2,044	1,926
120R	817	1,096	1,085	1,062	867	1,401	1,399	1,381
122R	1,324	2,164	2,086	2,093	1,187	1,769	1,779	1,783
123L	1,114	1,313	1,240	1,195	2,038	2,330	2,312	2,320
137L	684	1,006	-	726	659	736	-	647
139R	432	477	-	476	274	382	-	378
145L	448	692	650	575	533	709	656	584
165R	280	1,165	1,123	1,081	100	700	684	677
166L	2,386	2,938	2,820	2,513	2,792	3,235	3,201	3,368
172L	1,593	2,825	2,763	2,759	1,364	2,388	2,322	2,266
183L	1,210	1,413	1,313	1,278	2,380	2,690	2,646	2,620
194R	5,633	6,140	6,157	6,029	5,755	7,165	7,170	7,008
201R	208	2,134	1,838	987	70	1,149	1,116	799
202R	1,007	1,508	1,308	1,205	673	1,116	1,115	1,064
213L	665	1,212	1,071	968	638	1,476	1,436	1,330
214R	232	198	196	187	161	144	143	134
220R	1,338	1,408	-	1,346	1,100	1,332	-	1,287
225R	1,443	1,891	-	1,819	1,076	1,608	-	1,585

Table B2. Midelevation zone area and volume at four measurement times in 2008 at each study site.

[Site ID is river mile (RM) location based on the RM centerline (U.S. Geological Survey, 2006) downstream from Lees Ferry (river mile 0) in Grand Canyon National Park. The descriptors "L" and "R" denote the location of the emergent sandbar on left and right sides of the river, respectively, facing downstream. -, indicates no data were collected or data were not recoverable.]

Site ID	Area (m^2)				Volume (m^3)			
	February	April	May	October	February	April	May	October
1R	7,361	12,164	11,744	10,468	7,507	7,752	9,608	8,576
3L	2,297	754	588	598	2,143	978	838	765
8L	1,361	1,515	-	1,377	2,278	2,883	-	2,594
9L	3,417	2,383	2,429	2,045	4,841	6,838	6,150	4,537
16L	1,351	970	-	1,088	1,099	1,546	-	1,410
22R	1,962	1,701	1,677	1,283	5,148	5,698	5,321	4,831
24L	2,007	2,048	-	2,197	3,266	3,862	-	3,877
29L	1,208	1,774	-	1,758	2,529	4,970	-	4,296
30R	1,750	2,116	2,470	2,007	3,448	6,638	6,312	4,732
32R	2,748	2,471	-	2,317	3,014	3,504	-	3,198
33L	656	924	-	552	9,360	9,811	-	9,265
35L	1,450	1,220	-	1,047	7,922	9,096	-	7,930
41R	12,118	10,040	-	8,586	20,326	26,560	-	23,536
43L	1,401	1,206	1,218	1,175	7,910	7,966	7,989	7,989
44L	6,225	5,970	-	6,562	12,068	14,522	-	12,820
45L	2,214	3,316	2,483	2,842	5,888	11,778	10,002	8,760
47R	2,581	3,906	3,241	3,323	4,841	8,762	7,443	5,993
49R	2,248	1,147	558	1,211	2,746	4,891	3,831	3,347
49L	2,472	1,053	1,006	1,817	3,797	3,781	3,687	3,903
50R	2,141	1,711	2,026	1,446	6,439	6,532	6,386	5,894
51L	6,237	2,173	1,968	2,462	18,483	16,097	15,975	16,096
54R	3,312	1,323	-	3,109	3,821	3,770	-	4,826
55R	8,269	4,374	4,497	5,476	14,877	14,385	14,251	14,455
56R	2,507	1,433	1,700	2,095	3,582	4,830	4,700	4,765
58L	2,401	2,179	3,015	2,394	8,817	10,409	10,619	10,021
62R	716	687	-	692	1,407	1,428	-	1,443
63L	4,978	5,856	4,290	4,697	5,215	10,000	8,105	7,102
65R	6,705	4,271	3,160	3,759	4,525	12,425	8,365	4,239
65L	5,901	2,335	2,745	3,363	5,346	4,636	4,800	5,242
66L	5,134	4,389	4,067	4,121	1,873	7,990	6,637	3,927
68R	2,280	2,657	1,702	1,657	5,135	7,069	5,672	5,433
70R	607	1,602	-	1,764	1,955	1,602	-	2,953
81L	951	550	609	650	3,564	4,054	3,935	3,835
84R	830	636	-	743	1,462	1,390	-	1,340
87L	493	333	-	366	1,605	1,390	-	1,450
88R	1,455	1,174	-	1,252	1,660	1,841	-	1,689
91R	872	511	-	407	2,261	1,920	-	1,818
93L	1,221	624	-	601	3,220	3,197	-	2,943
104R	201	236	-	277	844	1,028	-	893
119R	2,280	1,762	1,588	1,447	4,989	7,200	6,245	5,235
120R	2,086	1,219	1,341	1,306	4,038	4,175	4,063	3,770
122R	2,739	1,804	2,614	2,246	6,492	7,899	8,054	7,613

Table B2. Midelevation zone area and volume at four measurement times in 2008 at each study site.—Continued

[Site ID is river mile (RM) location based on the RM centerline (U.S. Geological Survey, 2006) downstream from Lees Ferry (river mile 0) in Grand Canyon National Park. The descriptors "L" and "R" denote the location of the emergent sandbar on left and right sides of the river, respectively, facing downstream. -, indicates no data were collected or data were not recoverable.]

Site ID	Area (m^2)				Volume (m^3)			
	February	April	May	October	February	April	May	October
123L	1,755	664	713	1,256	4,343	3,646	3,403	3,850
137L	2,845	2,045	-	2,742	4,710	5,671	-	5,156
139R	1,506	839	-	1,136	2,884	2,327	-	2,665
145L	492	265	-	358	1,916	2,268	-	2,029
165R	3,695	1,510	1,576	2,669	7,318	7,018	6,920	7,728
166L	1,877	1,296	1,429	1,715	6,612	7,021	6,787	6,556
172L	2,643	1,457	1,767	1,559	6,492	7,756	7,662	7,330
183L	1,333	718	860	1,647	4,206	4,391	4,036	4,390
194R	2,865	2,408	2,305	2,661	15,081	15,967	15,706	15,631
201R	3,315	2,888	2,846	3,300	2,677	9,258	6,612	4,000
202R	1,687	882	961	1,024	3,965	4,330	3,718	3,439
213L	1,356	1,029	674	835	5,005	6,237	5,227	4,772
214R	1,757	505	1,413	2,548	1,781	696	1,112	1,777
220R	423	428	-	453	2,796	2,820	-	2,791
225R	1,123	649	-	878	4,516	4,742	-	4,608

Table B3. Low-elevation-zone eddy area and volume, and main-channel volume at four measurement times in 2008 at each study site.

[Site ID is river mile (RM) location based on the RM centerline (U.S. Geological Survey, 2006) downstream from Lees Ferry (river mile 0) in Grand Canyon National Park. The descriptors "L" and "R" denote the location of the emergent sandbar on left and right sides of the river, respectively, facing downstream. -, indicates no data were collected or data were not recoverable.]

Site ID	Low-elevation eddy zone Area (m^2)		Low-elevation eddy zone Volume (m^3)		Main-channel Volume (m^3)	
	February	April	February	April	February	April
1R	-	27,750	-	48,246	-	-
3L	5,148	6,683	25,818	12,665	67,587	26,320
8L	-	-	-	-	-	-
9L	-	8,618	-	3,158	-	-
16L	6,715	7,013	16,209	9,842	12,172	8,907
22R	4,462	4,599	17,590	16,389	5,245	4,854
24L	-	-	-	-	-	-
29L	-	-	-	-	-	-
30R	6,175	5,276	10,890	12,359	7,893	8,390
32R	8,152	8,381	26,762	12,398	13,216	7,014
33L	-	-	-	-	-	-
35L	19,088	19,233	33,324	39,397	35,196	47,696
41R	26,046	25,913	27,687	24,685	7,443	7,714
43L	4,538	4,670	8,141	7,199	58,758	56,612
44L	17,147	16,351	53,466	34,263	24,379	28,442
45L	18,399	15,779	16,762	17,886	4,564	7,170
47R	24,835	22,402	23,350	51,026	25,630	31,591
49R	4,483	4,215	22,398	19,793	-	-
49L	10,604	11,743	52,857	35,025	41,368	49,553
50R	-	-	-	-	-	-
51L	19,463	23,335	46,263	40,975	38,652	38,648
54R	8,295	9,715	15,197	9,874	22,450	27,946
55R	10,072	13,314	60,244	35,847	63,334	54,769
56R	-	-	-	-	-	-
58L	-	-	-	-	-	-
62R	14,758	14,869	30,241	35,184	15,413	10,691
63L	22,610	21,294	62,432	81,323	22,941	31,147
65R	9,654	8,779	46,807	41,986	43,702	26,494
65L	6,069	8,371	26,564	20,761	9,367	9,350
66L	-	-	-	-	-	-
68R	10,500	9,176	22,300	29,374	21,605	29,095
70R	-	-	-	-	-	-
81L	-	-	-	-	-	-
84R	-	-	-	-	-	-
87L	316	451	625	367	9,209	12,300
88R	1401	1511	1430	966	31,008	23,296
91R	-	-	-	-	-	-
93L	1,285	1,479	4,303	3,838	9,339	12,265
104R	575	474	290	586	1,368	1,649
119R	5,558	5,419	11,788	9,929	6,805	6,315
120R	-	-	-	-	-	-

Table B3. Low-elevation-zone eddy area and volume, and main-channel volume at four measurement times in 2008 at each study site.—Continued

[Site ID is river mile (RM) location based on the RM centerline (U.S. Geological Survey, 2006) downstream from Lees Ferry (river mile 0) in Grand Canyon National Park. The descriptors "L" and "R" denote the location of the emergent sandbar on left and right sides of the river, respectively, facing downstream. -, indicates no data were collected or data were not recoverable.]

Site ID	Low-elevation eddy zone Area (m^2)		Low-elevation eddy zone Volume (m^3)		Main-channel Volume (m^3)	
	February	April	February	April	February	April
122R	4,178	4,273	7,521	8,222	4,798	5,363
123L	5,179	6,072	13,080	5,306	17,662	10,801
137L	1,609	2,088	1,556	1,090	1,214	1,939
139R	5,249	5,870	12,072	7,844	6,199	8,329
145L	380	363	435	426	2,441	2,901
165R	1,180	2,479	10,857	8,704	4,345	4,679
166L	-	-	-	-	-	-
172L	5,165	5,119	12,875	14,147	12,493	14,110
183L	-	-	-	-	-	-
194R	5,638	5,590	9,880	10,980	24,944	28,775
201R	8,533	7,035	3,432	7,890	30,702	798
202R	12,919	13,227	21,018	25,795	8,811	10,904
213L	1,973	1,753	2,407	3,783	7,734	7,967
214R	3,256	4,545	4,637	2,058	11,301	12,229
220R	688	612	580	841	-	-
225	3,070	3,096	9,062	8,346	31,625	34,591

Table B4. Midelevation zone and high-elevation-zone campsite area measured at four measurement times in 2008 at each study site.

[Site ID is river mile (RM) location based on the RM centerline (U.S. Geological Survey, 2006) downstream from Lees Ferry (river mile 0) in Grand Canyon National Park. The descriptors "L" and "R" denote the location of the emergent sandbar on left and right sides of the river, respectively, facing downstream. -, indicates no data were collected or data were not recoverable. Recreational reaches as defined by Kearsley and Warren (1993); C, critical reach. NC, noncritical reach.]

Site	Recreation Reach	February		March		October	
		Midelevation (m^2)	High-elevation (m^2)	Midelevation (m^2)	High-Elevation (m^2)	Midelevation (m^2)	High-Elevation (m^2)
8L	NC	231	300	107	357	387	370
16L	C	216	269	363	318	299	273
22R	C	255	130	148	373	102	268
24L	C	163	16	699	30	637	35
29L	C	102	96	637	288	578	210
30R	C	71	189	397	552	52	267
32R	C	0	372	0	418	0	347
35L	C	0	481	79	430	30	490
41R	NC	104	229	96	341	36	145
43L	NC	0	184	3	392	0	251
44L	NC	257	576	249	762	175	571
45L	NC	0	263	1,148	1,140	64	766
47R	NC	717	384	1,837	1,092	232	330
50R	NC	124	593	0	611	45	560
51L	NC	0	110	0	161	0	98
55R	NC	0	0	0	20	0	0
62R	NC	0	31	0	135	40	132
81L	C	77	391	60	1,170	0	853
84R	C	109	82	97	98	65	64
87L	C	0	0	0	302	9	206
91R	C	256	218	0	214	2	197
93L	C	88	45	8	325	4	231
104R	C	0	70	6	107	0	76
119R	NC	36	137	391	339	132	125
122R	NC	208	98	299	657	92	719
123L	NC	187	174	0	150	189	89
137L	C	380	183	633	581	670	286
139R	C	21	77	0	59	81	63
145L	C	9	103	0	394	7	317
166L	NC	70	88	43	128	169	42
172l	NC	0	0	214	176	0	0
183L	NC	0	0	17	37	0	6
183R	NC	107	21	97	330	4	145
194R	NC	85	493	0	581	270	317
202R	NC	498	146	158	598	85	273
213L	NC	238	76	106	444	11	323
220R	NC	0	461	0	347	0	302
sum		4,609	7,086	7,892	14,457	4,467	9,747
median		85	137	79	341	45	251
s.d.		157	171	375	293	181	213

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