Sand Deposition in the Colorado River Ecosystem from Flooding of the Paria River and the Effects of the November 1997, Glen Canyon Dam Test Flow

Final Report

Joseph E. Hazel, Matt Kaplinski, Roderic Parnell, and Mark Manone

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May 24, 2000

Proposal Title:	**Monitoring Changes in Fine-grained Sediment Deposits Throughout the Colorado River Ecosystem in Glen, Marble, and Grand Canyons during Fiscal Years 1998 and 1999**
Cooperative Agreement:	**CA 1425-98-FC-40-22630**
Principal Investigator:	**Dr. Roderic Parnell**

Department of Geology

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May 24, 2000

Ted Melis, Phys. Science Program Manager
Grand Canyon Monitoring and Research Center
2255 N. Gemini Dr., MS-5000
Flagstaff, Arizona 86001

Dear Ted,

Enclosed is the final report for Contingecy Plan II: Measuring changes to Colorado River Sand Bars in Response to a "Habitat Maintenance Flow", Fall 1997, entitled "Sand Deposition in the Colorado River Ecosystem from Flooding of the Paria River and the Effects of the November 1997, Glen Canyon Dam Test Flow". This report completes our (NAU) contractual obligation for the modification to our existing contract in 1997 for the November 1997 river trip and the repeated surveys during the test at the Cathedral Wash eddy.

Sincerely,

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ABSTRACT

Flooding from the Paria River in August-September 1997, delivered an estimated 770,000 m^3 (2.0 $\pm$ 0.4 million Mg) of sand to the Colorado River ecosystem below Glen Canyon Dam. The Glen Canyon Dam adaptive management program implemented a 48 hr high flow of 878 m^3/s on November 3, 1997, termed the 1997 Test Flow, to test the hypothesis that a short-duration, peak power plant discharge could redistribute tributary-derived sand from the bed to the banks of the Colorado River. A combination of field measurements and modeling were used to determine the volume and distribution of sand supplied by the Paria River, the rates of downstream redistribution of that sand, and the effectiveness of the 1997 Test Flow at sand redistribution. Repeat surveys of the 3-km reach at the head of Marble Canyon, immediately downstream from the Paria River, indicate that about 24 to 36% of the Paria River sand inputs were immediately deposited in this reach. Approximately 50% of the flood deposition in the 3-km reach was eroded within 37 days of flood cessation. Large increases in suspended-sediment transport at the lower end of Marble Canyon were measured within 1-2 days of these Paria River floods, suggesting that a measurable fraction of the supplied sand was transported through Marble Canyon within days of input. Less than 10% of the sand delivered to the Colorado River in August-September 1997, remained in the 3-km reach at the end of the 1997 Test Flow. The estimated sand export from Marble Canyon during the 2-day flow was 70,000 m^3 (0.19 $\pm$ 0.04 million Mg), about 9% of the total Paria River sand input.

Despite the sand delivery to the Colorado River by the Paria River, the 1997 Test Flow did not significantly aggrade sand bars at high-elevation. We conclude that stage elevations reached by the 1997 Test Flow were not sufficient to distribute sand to open depositional locations. In order to redistribute sand to higher elevations, future controlled floods need to be of greater discharge than the 1997 Test Flow. Future high releases also need to be closely timed with tributary inputs, on the order of weeks or months, to optimize sand storage and prolong the residence time of new sand supplied to the Colorado River ecosystem.

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ACKNOWLEDGMENTS

This work was funded by the Grand Canyon Monitoring and Research Center (GCMRC) with the cooperation of Grand Canyon National Park. This report integrates data sets collected by researchers at Northern Arizona University (NAU), the U.S. Geological Survey (USGS) and the GCMRC survey staff. As a result of this data integration, other researchers that participated in the data collection may or may not concur with the interpretations in this report, which are solely the responsibility of the authors. A key contribution was the hydrographic data collected by Mark Gonzales, GCMRC survey staff, that enabled us to track the Paria River sediment inputs in August and September 1997. Bill Vernieu provided discharge data. David Topping provided 1997 gaging station data collected by USGS Arizona District personnel and model estimates of Paria River sand inputs. David Topping, Jack Schmidt, Steve Wiele, Ted Melis, and Jenn Martin sampled the deposits of the 1997 Test Flow. David Topping provided grain size analyses of the samples. We greatly appreciate the enthusiasm and effort of all the Namdors, particularly Greg Spoonenburgh and Eric Kellerup, in namming the field sites. We thank the many professional river guides that assisted in this study, particularly Steve Bledsoe, Brian Dierker, Billy Ellwanger, Lars Neimi, Kelly Smith, and Peter Weiss. We also thank Jim Bennet, David Topping, Jack Schmidt, Ted Melis and one anonymous reviewer for their extremely helpful and constructive comments.

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INTRODUCTION

After 1963, deposition of fine-grained sediment in the Colorado River ecosystem below Glen Canyon Dam (Glen, Marble and Grand Canyons) depended on annual operations combined with limited sediments supplied by tributaries (U.S. Department of Interior, 1995). The dam eliminated upper basin sediment supply, making downstream tributaries the only source for replenishing sand deposits on the bed and banks of the Colorado River. Channel margin sand deposits are important environmental resources, providing substrate for some habitats of endangered and native fish species (Valdez and Ryel, 1995), riparian vegetation, marsh and wetlands (Stevens et al., 1995), and are also used as recreational campsites (Kearsley et al., 1994). However, sand delivery from tributaries is highly variable and the dam has dramatically reduced the frequency and magnitude of both low and high flows. This flattening of the annual hydrograph has also reduced the net storage potential of sand at higher shoreline elevations. Additionally, operations have elevated seasonal minimal flows to the point that most dam releases now have considerable sediment-transport capacity. In the pre-dam era, prolonged low flows (less than 200 to 250 m^3/s) allowed fine sediment to accumulate in the channel during summer through winter seasons (Topping et al., 2000a).

The first opportunity to study physical processes during controlled flooding of the Colorado River ecosystem occurred in spring 1996, with the release of a seven day, controlled flood of 1,274 m^3/s (45,000 ft^3/s) from Glen Canyon Dam (Collier et al., 1997; Webb et al., 1999). A major objective of the 1996 Controlled Flood was to determine if high releases from Glen Canyon Dam could effectively redistribute sand from the river bed to the channel margins (Schmidt et al., 1999a). Results from investigations conducted during the experiment indicate that this objective was achieved (Andrews et al., 1999; Hazel et al., 1999; Schmidt, 1999; Wiele et al., 1999). Rates of sand bar deposition were more rapid than expected and the majority of sand bar deposition occurred within the first two days (Andrews et al., 1999; Rubin et al., 1998; Schmidt, 1999). Suspended-sediment progressively coarsened over time (Topping et al., 1999; 2000b) and the grain size of post-flood deposits vertically-coarsened (Rubin et al., 1998; Topping et al., 1999; 2000b), presumably because of rapid depletion of the supply of fine-grained sediment. Modeling of depositional processes indicates that rates of bar deposition were proportional to the supply of sediment (Wiele et al., 1999). These physical process studies demonstrated that controlled flooding could be used in river management but that the design of future high releases need take into account the effect of decreasing main-channel sand concentrations on transport and deposition of sediment (Rubin et al., 1998; Schmidt, 1999).

The possibility that a shorter duration and lower magnitude release than the 1996 Controlled Flood (i.e., a non-spill release) could achieve some level of sediment conservation was of interest to the Glen Canyon Dam adaptive management program. Discharge beyond the 940 m^3/s (33,200 ft^3/s) power plant capacity requires use of the river outlet works (U.S. Department of Interior, 1995). Water and power interests in the adaptive management program were concerned about the loss of power revenues and water storage, which increased the overall cost of the 1996 experiment (Harpman, 1999). If similar results could be achieved without bypassing the power plant, the cost would be considerably lowered and increased flexibility in implementing sediment-conserving dam operations would be realized.

The sediment supply is particularly limited in Marble Canyon (Topping et al., 2000a), the 98-km reach between the Paria and Little Colorado Rivers, because of intermittent sediment delivery from the Paria River and proximity to Glen Canyon Dam (Fig. 1). Flooding on the Paria River in August and September 1997, significantly replenished sand in the Colorado River downstream from the confluence. Shortly after the sediment input, the adaptive management program recommended that a short-duration, power plant capacity test flow be released from Glen Canyon Dam. Termed the 1997 Test Flow, the release occurred beginning November 3, 1997, and consisted of a constant flow of 878 m^3/s (31,000 ft^3/s) for 48 hours.

In this report, we evaluate the accumulation and transport of Paria River-supplied sand in the Colorado River ecosystem and the effectiveness of the 1997 Test Flow at redistributing sand to the channel margins. The focus of the report is the reach of Marble Canyon below the Paria River, a portion of the ecosystem between river miles 1-61 (km 2-100). We used a combination of repeat topographic and hydrographic surveys, suspended sediment and grain size measurements, and model estimates of sediment inputs. Determining the distribution of sand added to the Colorado River ecosystem and understanding the rates of downstream redistribution of that sand are important for planning the timing, magnitude, and duration of dam releases intended for bar restoration purposes.

PREVIOUS STUDIES

The Colorado River in Marble and Grand Canyons flows through a deeply incised channel confined by bedrock and talus. Channel width is controlled by the erodibility of the bedrock exposed at river level (Howard and Dolan, 1981; Schmidt and Graf, 1990; Melis, 1997). Transport and deposition of fine-grained sediment in the channel is associated with a repeating pattern of long, low

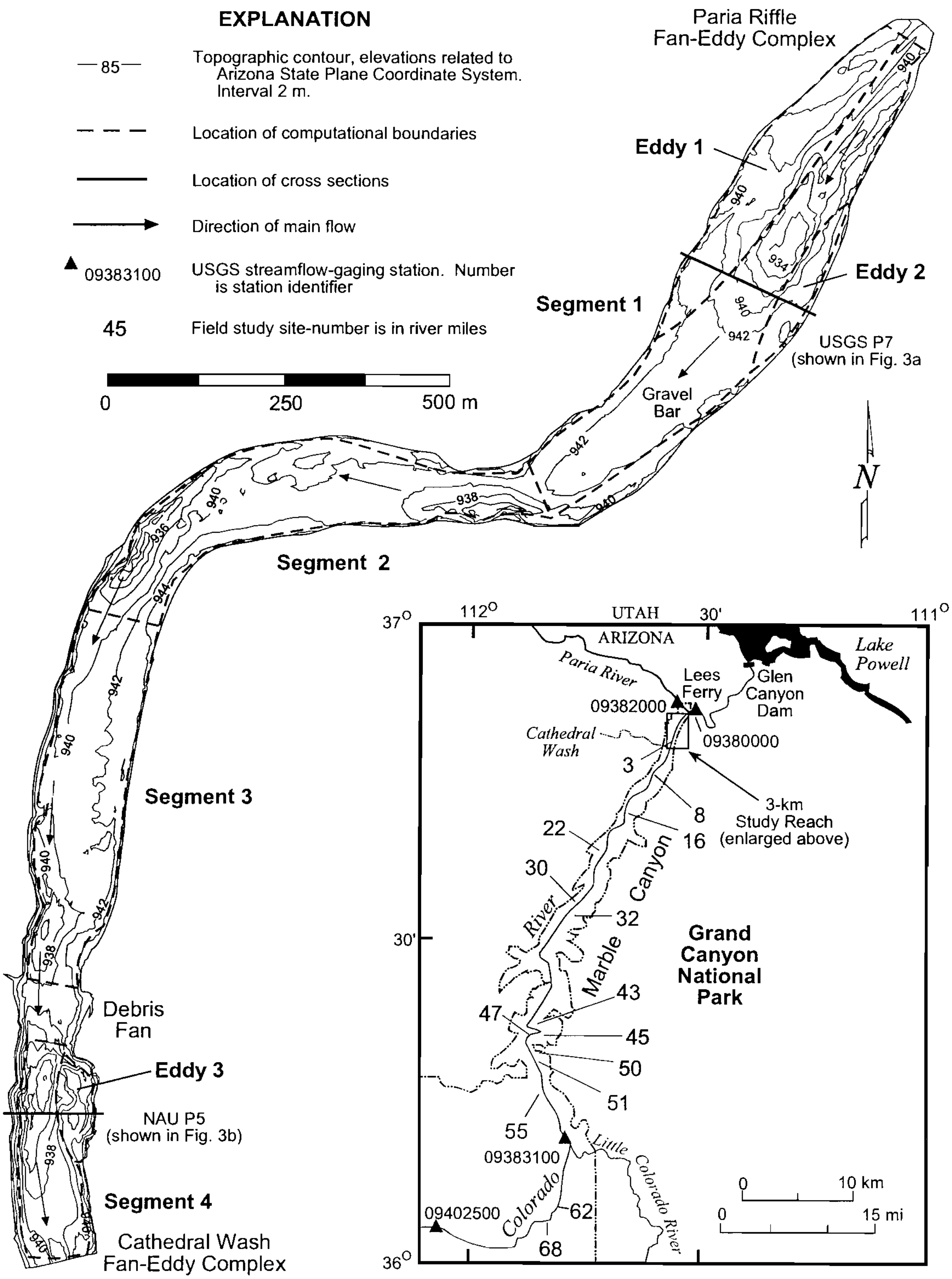

Figure 1. Map of the Marble Canyon portion of the Colorado River ecosystem and location of the 3-km study reach. The topographic channel map was surveyed on August 10, 1997. Flow in main channel is from top to bottom. The locations of USGS streamflow-gaging stations discussed in the text are shown. Study site reference numbers use river mile location. The location of selected USGS and NAU cross-sections and volume computational boundaries are shown.

velocity pools caused by drops that occur at rapids or riffles (Leopold, 1969). Rapids and riffles are associated with river constricting debris fans formed by debris flows and floods from steep, side canyon tributaries (Howard and Dolan, 1981; Webb et al., 1989; Melis et al., 1994). Pool length is determined by the spacing between debris fans, whose locations are controlled by local jointing, faulting and bedrock structure (Dolan et al., 1978). Schmidt and Rubin (1995) termed this basic, repeating channel unit as the "fan-eddy complex", which is composed of the channel constricting debris fan, an upstream pool created by the backwater effect of the constriction, a channel expansion and plunge pool immediately downstream from the fan, and a gravel bar further downstream. The accelerated flow through the rapids results in downstream scour holes in the main channel bed and flow separation leading to the formation of eddies in the channel expansion. Scour holes can be as much as nine times deeper than the depth in the upstream rapid (Schmidt and Graf, 1990) and potentially have the capacity to accumulate significant amounts of sand during tributary flooding (Wiele et al., 1996). The low velocities in eddies promote deposition from the suspended load (Leopold, 1969).

Sand deposits in eddies have been described and classified by Schmidt (1990) as separation bars, which form near the upstream part of the eddy; and reattachment bars, which form where flow reattaches to the bank. Eddy sand bars in some reaches contain up to 75 percent of the total sand stored along the banks of the Colorado River (Schmidt and Rubin, 1995). Eddies have the potential to completely fill with sediment (Schmidt et al., 1999b) and contain bars more than 10-m thick (Rubin et al., 1994). In contrast, the extent of sand distribution in the main channel varies from complete coverage of dune fields 1 to 2 m thick to patchy coverage over an immobile bed of bedrock and gravel (Howard and Dolan, 1981; Wilson, 1986; Anima et al., 1998). A greater percentage of the bed in narrow reaches is composed of bedrock and gravel because the channel is generally deeper and has a steeper water slope (Wilson, 1986; Schmidt and Graf, 1990).

Sand supplied to the river by tributary floods is temporarily stored in pools and in eddies; however, the relative proportion of sand stored in these two environments has not been determined (Schmidt, 1999). An important finding now in question, in the 1996 Record of Decision (ROD) for the Glen Canyon Dam Final Environmental Impact Statement, is that sand accumulates on the bed in Marble Canyon at most dam releases because of tributary inputs from the Paria River and smaller, ungaged tributaries (U.S. Department of Interior, 1995). Sand mass balance models using stable sediment rating curves were developed that predicted aggradation of sand between the Paria and Little Colorado Rivers if peak discharges were less than power plant capacity, tributary inflows were at least average, and wide daily fluctuations in discharge were restricted (Randle and Pemberton, 1987; Randle et al., 1993; Smillie et al., 1993). However, transport rates are highest when the bed has a large proportion of fines and sediment rating curves shift over time as a function of the sand grain sizes present on the bed (Topping et al., 2000a; 2000b). Therefore, previous studies of sand mass balance underestimate sediment transport through the system immediately following tributary inputs and over predict accumulation on the bed during the intervening periods. The rate of sediment transport in Marble Canyon is a critical resource issue because it may not be possible to store large amounts of tributary supplied fine sediment on the bed for periods longer than a few months (Topping et al., 2000b) under current ROD dam operating criteria (U.S. Department of Interior, 1995).

THE 1997 PARIA RIVER FLOODS

The Paria River is an arid region stream that drains 3,600 km^2 in southern Utah and northern Arizona, and is subject to infrequent floods of short duration. Historically, large floods on the Paria River are generated by runoff in the uppermost 14% of the drainage basin by eastern Pacific Ocean tropical storms and intense but more isolated rainfall associated with the southwestern monsoon (Topping, 1997; Topping et al., 1998). Most of the sediment carried by the Paria River is derived from areas of lower basin elevation that are underlain by sedimentary rocks of Mesozoic and younger ages. Between 1923 and 1996, the mean annual sediment load delivered to the Colorado River by the Paria River was 9.1×10^5 m^3 (2.4 ± 1.2 million Mg) of sand, silt, and clay, of which about 50% was sand (Topping, 1997). However, annual inputs from the Paria River to the Colorado River ecosystem are not only variable but were mostly below average from 1980 through 1996. Variability in sand delivery from the Paria River has been attributed to long-term climate variations (Graf et al., 1991; Hereford and Webb, 1992) and land-use changes (Topping, 1997).

Heavy precipitation in the drainage basin produced four large floods in late summer 1997 (Fig. 2a). The flood peaks were 115 m^3/s (4,061 ft^3/s) on August 10, 72 m^3/s (2,542 ft^3/s) on September 7, a double-peaked flood with peaks of 85 m^3/s (3,001 ft^3/s) and 110 m^3/s (3,884 ft^3/s) on September 15, and 95 m^3/s (3,354 ft^3/s) on September 26. Three of the floods exceeded the 90 m^3/s bank-full discharge of the Paria River estimated by Topping (1997). These storms were associated with a series of dissipating tropical storms combined with a strong monsoon season that resulted in high antecedent moisture conditions. Approximately 7.7×10^5 m^3 (2.0 ± 0.4 million Mg) of sand and 9.2×10^5 m^3 (2.4 ± 1.2 million Mg) of silt and clay were delivered to the Colorado River (Topping et al., 2000b), nearly twice the Paria River mean-annual sediment input. The sand inputs from the Paria River in

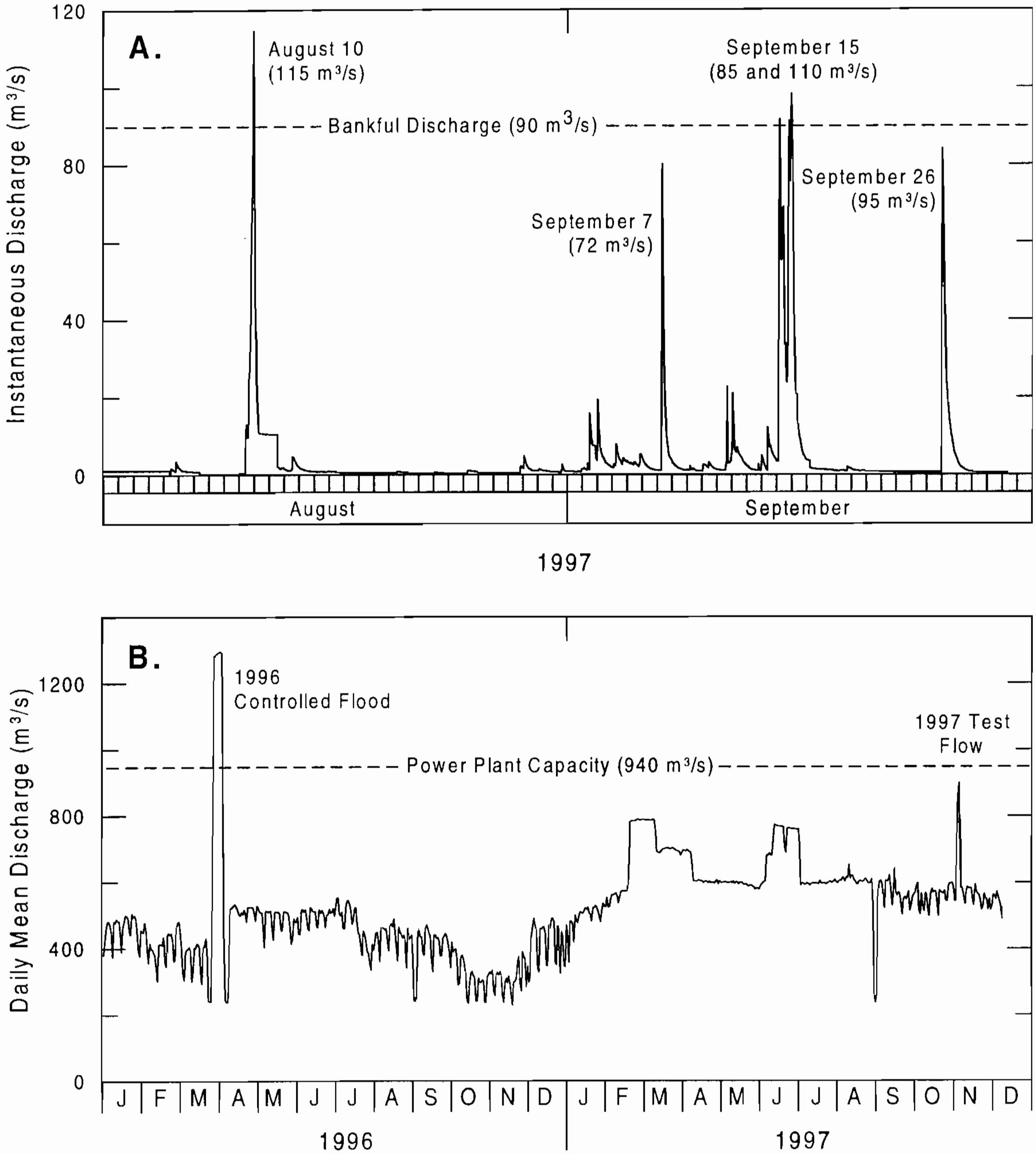

Figure 2. Discharge hydrographs. A, Instantaneous discharge at USGS streamflow gaging station Paria River at Lees Ferry, Arizona, August and September 1997. B, Daily mean discharge at the USGS streamflow-gaging station, Colorado River above Little Colorado River near Desert View (lower Marble Canyon gage), Arizona, January 1996 to December 1997.

1997 ranked among the top 20% during the 75 years of gage record on the Paria River (Topping et al., 2000b). This new sediment was the first significant input from the Paria River since the winter of 1995, and the largest since 1980. It is important to note that Paria River floods generally do not have a significant effect on mainstem river stage because the water volumes are small relative to those in the mainstem and the duration of peak discharge is short, on the order of hours.

THE 1997 TEST FLOW

The 1997 Test Flow was the first attempt by the adaptive management program to implement a flow release strategy for sediment redistribution following a tributary flood. The hydrograph of the test flow, beginning on November 3, consisted of a rapid increase in discharge from 479 m^3/s (16,909 ft^3/s) to a steady flow of 878 m^3/s (31,000 ft^3/s) for 48 hours, followed by a slow decrease to 480 m^3/s on November 6 (Fig. 2b). The maximum rate of upramp was 68 m^3/s (2,400 ft^3/s) per hour and the maximum downramp rate was 39 m^3/s (1,377 ft^3/s) per hour. Similar to the hydrograph for the 1996 Controlled Flood, the slower rate of downramp was designed to reduce erosion caused by dewatering of bank stored water in sand bars and to avoid stranding of trout in the tailwaters fishery upstream from Lees Ferry. The release was approximately 93% of maximum power plant capacity.

STUDY AREAS AND METHODS

Modeling Tributary Sand Inputs

A flow and sediment transport model for the Paria River was previously developed by Topping (1997). The outputs from this model are the wetted reach-averaged cross-section geometry, the discharge of water, the sand transport rate (in 10 size classes), and the silt and clay transport rate. The model provides excellent agreement with the historical record for discharges, suspended-sediment concentrations and hydraulic geometries for previous floods. In the future, model estimates may provide cost-effective, real-time predictive capabilities for suspended-sediment yields to the Colorado River.

To examine the rate at which sand inputs from the Paria River were transported downstream, we compared model predicted sand loads (0.0625-2.0 mm) to measured bed changes below the mouth of the Paria River (described below). Model loads were compared to deposit volume changes by assuming a porosity of 35% for sand-sized sediment on the bed and 20% uncertainties associated with the suspended-sand measurements [see Appendix B in Topping et al. (2000a)].

Field Measurements of Bed and Suspended Sediment

Bed and suspended sediment samples were collected during the 1996 Controlled Flood, in August-September 1997, and during the 1997 Test Flow by the USGS at streamflow gaging stations on both the Colorado and Paria Rivers. We discuss only the data pertaining to Marble Canyon and upper Grand Canyon in this report (Fig. 1). Konieczki et al. (1997) and Topping et al. (1999) report the grain-size analyses of samples collected in 1996. The sites on the Colorado River are located at Lees Ferry (streamflow gaging station #09380000), 100 km downstream from Lees Ferry just above the confluence with the Little Colorado River (streamflow gaging station #09383100), and 42 km downstream from the Little Colorado River confluence (streamflow gaging station #09402500). Following the usage of Topping et al. (2000a, 2000b) we informally refer to these gages as the Lees Ferry gage, the lower Marble Canyon gage, and the upper Grand Canyon gage, respectively. Streamflow gaging on the Paria River is located just upstream from the confluence with the Colorado River at Lees Ferry (streamflow gaging station #09382000) and is herein referred to as the Paria gage. Cross-sectionally averaged suspended-sediment samples were collected from the USGS cableways once to several times daily using D-77 bag samplers and the equal-discharge increment methodology described by Edwards and Glysson (1988). Bed sediment was sampled across the channel at one or more locations using a BM-54 sampler. Concentrations of suspended sediment were determined using standard USGS techniques (Guy, 1969). Use and estimates of error in sampling Colorado River sediment are described in Konieczki et al. (1997) and Topping et al. (2000a).

Field Studies in the 3-km Reach Downstream from the Paria River

We examined the volume and distribution of sand initially deposited in the Colorado River in a 3-km long reach below the confluence with the Paria River (Fig. 1). The study reach is 1.5 km downstream from Lees Ferry and 0.25 km downstream from the mouth of the Paria River. Bedrock at river level is the Permian Kaibab limestone. The 3-km reach has a gradient of 0.000625 at a discharge of 227 m^3/s (8,000 ft^3/s) (H. Shiek, written comm., 1999), and extends from the downstream half of the Paria Riffle fan-eddy complex to the upstream part of the Cathedral Wash riffle fan-eddy complex. We divided this reach into four segments, each less than 1-km long, and each bounded upstream and downstream by debris fans, rock falls, or river bends (Fig. 1). The segments are informally numbered in the downstream sequence in which they occur. The eddy along the right bank of Segment 1 is one of the largest in the Colorado River ecosystem. We refer to this eddy as Eddy 1. We surveyed 37,600 m^2 of Eddy 1 that were inundated during the study period. Segment 1 also contains an eddy on river left that we refer to as Eddy 2. We surveyed 9,500 m^2 of this eddy. Segments 2 and 3 are bordered by small eddies and channel-margin deposits on the inside of bends. The downstream end of Segment 3 is a small riffle formed by a low debris fan and rock fall. Segment 4 includes an eddy along the left bank that we refer to as Eddy 3. We surveyed 6,100 m^2 of Eddy 3. This eddy was first surveyed in 1985 (Schmidt and Graf, 1990), and the eddy and adjacent channel have been surveyed one or more times a year since 1991 (Hazel et al., 1999, site #3). Sand has been subaerially exposed at some time in Eddies 1, 2, and 3 between 1935, and the present (H. Sheik, pers. comm., 1999).

Hydrographic surveys of the entire reach were collected before and after the first, and after the last of the Paria River floods in 1997, and daily hydrographic and topographic surveys were conducted in Segments 3 and 4 for 4 days before, during, and after the 1997 Test Flow (Table 1). During the 1997 Test Flow, Segment 3 was surveyed once a day and Segment 4 was surveyed twice a day. With the exception of Eddy 3 where survey coverage extends to the area inundated by flows of 1,274 m^3/s (45,000 ft^3/s), subaerial bank and bar deposits higher than the elevation reached by flows of 566 m^3/s (20,000 ft^3/s) or in areas that extend beyond our survey limits were not examined in the 3-km reach. Ground and hydrographic points were combined and topographic surface models created using the triangulated irregular network method of contouring with surface modeling software. To compare the relative proportion of sand stored in pools and in eddies, area and volume calculations were differentiated for the two environments by utilizing a boundary that estimates the position of the eddy fence, the streamline dividing downstream flow and the eddy, and by assuming this zone extends vertically to the bed (Fig. 1). It is important to note that eddies change in length with changes in flow (Schmidt, 1990). In our analysis, eddy fence location was determined by aerial photographs and by surveying the positions of separation and reattachment points in the field at different discharges. This general approximation of eddy-fence location best represents the eddy dimensions at most flows within 1,274 m^3/s (45,000 ft^3/s). Accuracy and precision of these techniques are discussed in Beus et al. (1992), Andrews et al. (1999), and Hazel et al. (1999). Area and volume calculations were rounded to reflect the accuracy of ground and hydrographic points. Conversions of sand volumes to mass were made assuming a porosity of 35% and a bulk density of 2.65 Kg/m^3 for sand-sized sediment.

Field Studies at Sites in Marble Canyon

Annual and more frequent surveys of thirty-one to thirty-five long-term study sites located in the Colorado River ecosystem are reported for data collected between 1991 and 1998, by Kaplinski et al. (1995; 1998) and Hazel et al. (1999). Sand bar and subaqueous channel bed change were measured

Table 1. Summary of sand volume changes in the 3-km study reach.

Survey Date	Segment 1 Main Channel	Segment 1 Eddy 1	Segment 1 Eddy 2	Segment 2	Segment 3	Segment 4 Main Channel	Segment 4 Eddy 3
August 10 Paria River Flood							
970815	24,340	23,140	7,950	26,300	8,870	2,510	-350
September 7, 15, and 26 Paria River Floods							
970927	84,090	38,620	13,030	65,040	31,280	66,850	10,850
Net Deposition from 1997 Paria River Floods							
	108,430	61,760	20,980	91,340	40,150	69,360	8,940
Pre 1997 Test Flow							
971103	---	---	---	---	-18,870	-31,050	-6,270
Day 1							
971104 a.m.	---	---	---	---	-14,760	2,000	-3,860
971104 p.m.	---	---	---	---	---	740	560
Day 2							
971105 a.m.	---	---	---	---	280	-12,790	-1,800
971105 p.m.	---	---	---	---	---	1,140	1230
Post 1997 Test Flow							
971106	---	---	---	---	-1,760	-130	1,300
Net Pre- to Post 1997 Test Flow Erosion							
	---	---	---	---	-16,240	-9,040	-2,570

Values are in units of cubic meters

using the methods described above for the study reach downstream from the Paria River. Each study site is located at a fan-eddy complex. To reduce the influence of the Little Colorado River, only 12 of the 35 sites were included in the present analysis [study site locations, descriptions, and patterns of erosion and deposition between 1991 and 1997, at all 35 sites is provided by Kaplinski et al. (1995; 1998) and Hazel et al. (1999)]. Volume data from three environments in the fan-eddy complex (main channel, eddy, and high-elevation sand bar) were converted to average thickness, respectively, to provide an unambiguous means of reporting change between surveys. We define the high elevation sand bar as bedforms deposited in eddies occurring above the 566 m^3/s (20,000 ft^3/s) stage elevation. Distances along the Colorado River in Grand Canyon are traditionally measured in river miles, with river mile 0 beginning at Lees Ferry, Arizona. Accordingly, study site reference numbers use river mile location (Fig. 1).

An analysis averaged from single sites may be too small a sample set to accurately represent reach-scale or canyon-wide patterns of change. Eddies can have high site-to-site variability in sand storage because low-elevation sand bars are dynamic over short time-scales (Cluer, 1995; Grams and Schmidt, 1999). However, Schmidt et al. (1999b) showed that individual eddy response during the 1996 Controlled Flood at several sites in this study was similar to the average reach scale behavior determined from photographic analysis. In addition, observations of channel-bed sediment distributions using side-scanning sonar indicated that the monitored pools were representative of observed reach-scale patterns of sand coverage in Marble Canyon in September 1998 (R. Anima, USGS, personal commun., 1998).

To examine bar deposition as a result of the 1997 Test Flow, the sites were surveyed immediately following cessation of the test. However, hydrographic mapping was not conducted downstream of the study reach because the test flow occurred during Grand Canyon National Park's annual non-motor season (September 15 to December 15). Hydrographic surveys require the use of motorized craft and were therefore excluded from the post-test flow survey plans. Thus, our analysis of post-1997 Test Flow change was limited to high-elevation bar change downstream of the 3-km reach. In addition to topographic changes, sediment deposited at each site by the 1997 Test Flow was examined in trenches and sampled vertically between deposit base and top for grain size changes. The sand was then dry sieved a ¼ phi intervals to determine grain size using the methods of Folk (1974). Grain-size analyses of the 1997 samples are also reported by Topping et al. (2000b).

THE 1997 PARIA RIVER FLOODS: DEPOSITION AND DOWNSTREAM TRANSPORT

Deposition in the 3-km Reach Downstream from the Paria River

A significant proportion of the sand delivered to the Colorado River by the August-September 1997, Paria River floods was temporarily stored in the 3-km reach (Table 1). The total volume of sand deposited in the study reach during the August 10 flood was 92,800 m^3 (0.16 million Mg), or about 24 to 36% of the estimated sand load of the Paria River (0.56 ± 0.11 million Mg) for the 10-day period between field surveys. The total volume of sand deposited in the reach between August 15 and September 27, was sand from the September 7, 15, and 26 Paria River floods; the volume deposited was 310,000 m^3 (0.53 million Mg). As after the August 10 Paria River flood, the total volume of sand deposited in the study reach between August 15 and September 27 was about 24 to 36% of the estimated Paria River sand load (1.85 ±0.37 million Mg) during this period. Thus, between 64 and 76% of the sand delivered by these tributary floods was quickly transported through the reach and downstream in Marble Canyon. Based on the observations of Topping et al. (2000b) following Paria River floods in September 1998, the large fraction of the sand that bypassed this reach was probably the finer 64-76% (because of their lower settling velocities) of the sand supplied during the August-September 1997, floods.

Both the rate and volume of sand deposition after the August 10 flood was greatest in Segment 1, but new sand deposited from the September floods was more evenly distributed amongst the 4 segments (Table 1). About 60% of the total deposition resulting from the August 10 flood occurred in Segment 1, where channel width and eddies are largest. There was little deposition in Segment 4. Though large amounts of sand were still deposited in Segment 1 in September, a greater percentage of the deposition occurred further downstream following the September Paria River floods.

The proportion of new deposition that occurred in the main channel and in eddies varied between August and September. In August, slightly more than half of the deposition in Segment 1 was in eddies where as much as 2 m of sediment was deposited. Although eddy bars aggraded in September, large amounts of sand were deposited on the channel bed, where there was as much as 5 m of aggradation in Segment 1 (Fig. 3a) and 6 m of aggradation in Segment 4 (Fig. 3b).

The high bed elevations and flattened channel geometry in the 3-km study reach suggest that the main channel and eddy environments had filled to near capacity during the two month period of tributary flooding. Continued sediment input after pool filling, during the same flood or during the next, was delivered to the next pool downstream or transported completely through the reach. This process was well documented by Wiele et al. (1996) following a flood from the Little Colorado River in January 1993. They found that both the rate and the volume of sand deposited in the channel was correlated to pool morphology. Segment 1 has the widest channel expansion in the 3-km reach with large eddies along both banks (Eddies 1 and 2). As a result, Segment 1 trapped about half of the sand deposited in the reach. Segment 4 trapped the greatest thickness of sand because this pool has the deepest scour hole (16 m before the flood inputs at a discharge of 566 m^3/s). The large increase in flow depth at scour holes causes vertical expansion of flow and divergence of the boundary shear stress leading to rapid deposition when sand concentrations in the mainstem are high (Wiele et al., 1996).

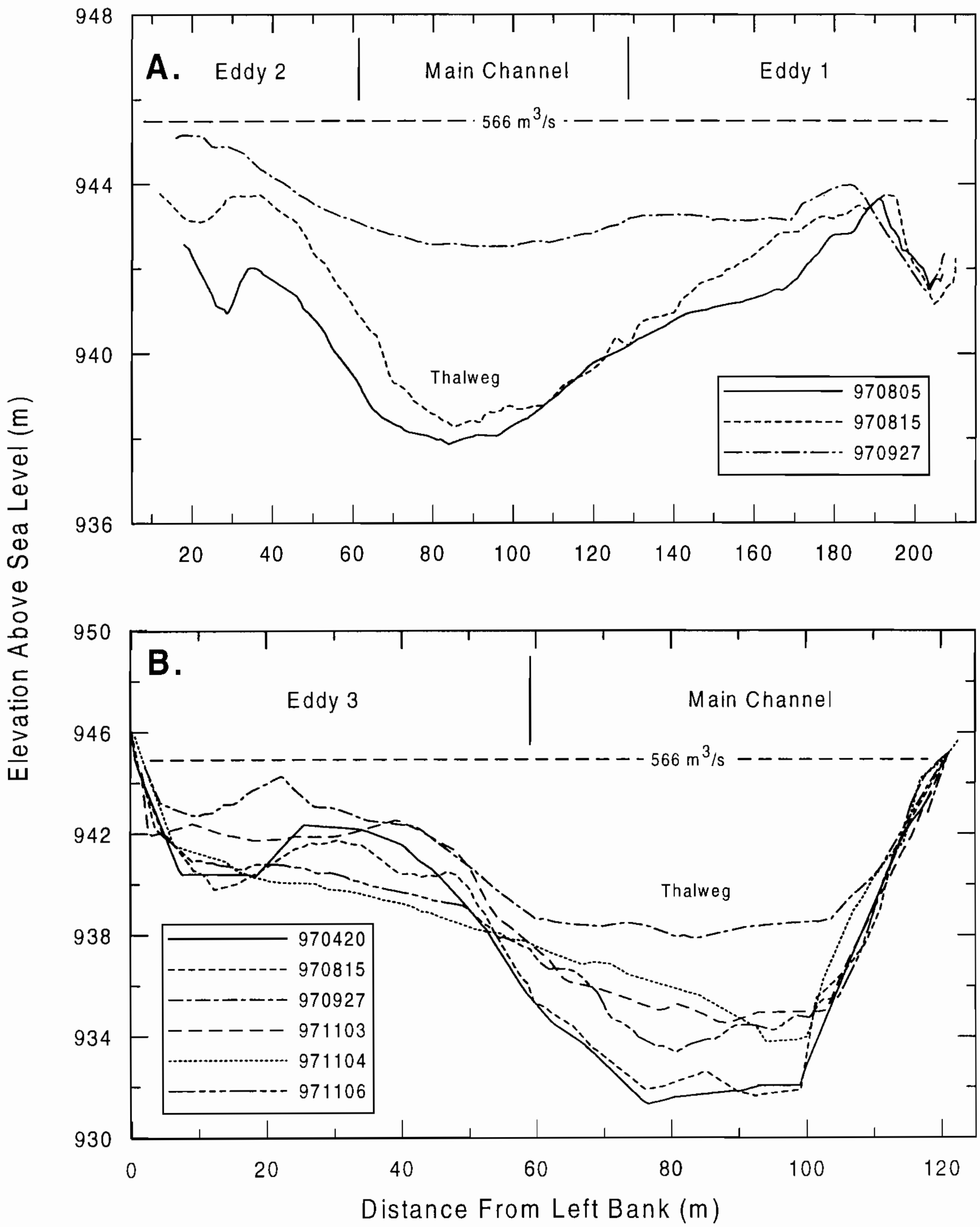

Figure 3. USGS cross-section p7 in A and NAU cross-section p5 in B. Stage elevation for a discharge of 566 m^3/s is shown. Location is shown on Fig. 1.

Transport of Flood-Derived Sand From the 3-km Reach

Less than 20% of the sand delivered to the Colorado River in August-September 1997, remained in the 3-km reach by early November when the 1997 Test Flow occurred. The amount of flood-derived sand in the reach just prior to the 1997 Test Flow was estimated by comparing bed topography in Segments 3 and 4 on September 27 and November 3 (Table 1). Segments 1 and 2 were not surveyed in November. Assuming that the decrease in storage was as great as in Segments 3 and 4, the total volume of August-September Paria River-derived sand remaining in the study reach at the onset of the 1997 Test Flow was 205,000 m^3 (0.35 million Mg). Thus, 36 days after the last 1997, Paria River flood, the estimated volume of sand remaining in the reach was approximately 12 to 18% of the preceding cumulative sand input (2.41 $\pm$ 0.48 million Mg) in August-September. In other words, nearly half of the volume of sand supplied by the Paria River during August-September 1997 had been eroded prior to the start of the 1997 Test Flow.

These results show that sand initially deposited immediately downstream from the mouth of the Paria River is rapidly transported further downstream within weeks to months. The rapid erosion of accumulated sediment in the 3-km reach in fall 1997, was similar to the response of the bed at selected cross sections in the reach to a large influx of Paria River sediment in August 1992, when sand deposited by this tributary flood was mostly eroded within 4 months (see Figs. 12-20 on pp. 29-34 in Graf et al., 1995).

Changes in Suspended Sediment Concentrations and Grain Size

Results from the USGS suspended-sediment and bed material sampling program at the lower Marble Canyon gage from August 28 to September 18, 1997, have important implications for the rates at which Paria River sediment inputs were being transported downstream. Suspended sand concentrations increased at the gage after each tributary flood (Fig. 4). The greatest measured increase was observed following the September 15 flood, which had the longest flood duration (~ 9 hours above 50 m^3/s) of the four 1997, Paria River floods (Fig. 2a). The arrival of Paria-derived streamflow on September 16 coincides with a total sediment concentration increase of nearly a factor of twenty-four (the sample was taken about 3 hours after the peak had reached the gage), from an average concentration of 0.022% by volume on September 15 to a value of 0.506% on September 16. Silt and clay concentrations increased by a factor of twenty-seven (from 0.019% to 0.491% by volume) and sand concentrations increased by a factor of six (from 0.002% to 0.015% by volume). During this and other events during the sampling period, rapid increases in suspended-sand concentration were

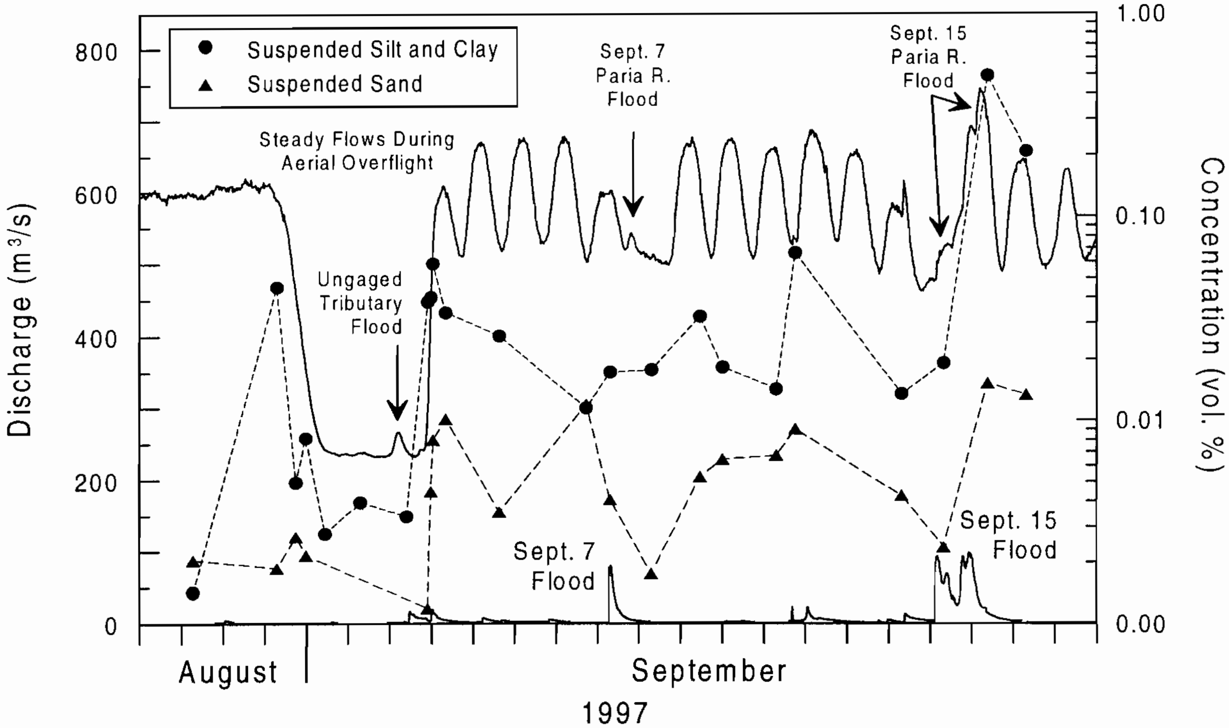

Figure 4. Suspended sediment concentrations and instantaneous discharge at the lower Marble Canyon gage from August 28 through September 18, 1997. Also shown is the instantaneous discharge at the Paria River gage for the period.

simultaneous with, or followed by, fining of both the sand in suspension and on the bed (Topping et al., 2000b). These data suggest that a substantial portion of the Paria River-supplied sand was passing the lower Marble Canyon gage within days. Approximately 56,000 m^3 (0.15 $\pm$ 0.03 million Mg) of sand or about 7% of the flood-supplied sand was exported from Marble Canyon during the 25 days of sampling.

GEOMORPHIC EFFECTS OF THE 1997 TEST FLOW

Daily Changes in the 3-km Reach Downstream from the Paria River

Daily and hourly rates of bed and eddy bar adjustment were examined in Segments 3 and 4 of the 3-km study reach during the 1997 Test Flow. The increase in flow resulted in a stage elevation increase of nearly 1 m. Additional sediment was eroded from Segments 3 and 4; 16,240 m^3 (0.028 million Mg) of sand was eroded from Segment 3 and 11,610 m^3 (0.02 million Mg) of sand was eroded from Segment 4 (Table 1). The erosion of the bed in Segment 3 mostly occurred during the first 15 hours of peak flow. In Segment 4, 3,860 m^3 of sand were eroded from Eddy 3 during the first 15 hours, and this sand probably was deposited in the adjacent plunge pool. This conclusion is based on the morphology of the area of eddy erosion (Fig. 5), which resembled the shapes of the scars left by the mass failures described by Cluer (1995) and Andrews et al. (1999). A semi-circular depression more than 3 m deep was formed in the reattachment bar at the downstream end of eddy (Fig. 5b). Failure of the eddy bar was entirely subaqueous and the high-elevation bar was not affected. Approximately half of this mass failure was deposited on the slope of the bed between Eddy 3 and the main channel in Segment 4 (Fig. 3b). On day 2, 12,790 m^3 of sand were eroded from the main channel in Segment 4, and an additional 1,800 m^3 of sand was eroded from Eddy 3. The proportion of these changes that occurred in Eddy 3 and in the adjacent pool varied over time. Despite deposition in Eddy 3 towards the end of the test flow, the net change was erosion of 2,570 m^3 of sand. The net effect of the 2-day test flow in segments 3 and 4 was erosion (Table 1). The estimated amount of remaining Paria-supplied sand in the 3-km reach at the end of the 1997 Test Flow was 115,000 m^3 (0.20 million Mg), about 7 to 10% of the 1997, August-September sand inputs.

Changes in Suspended Sediment Concentrations and Grain Size

Suspended-sediment concentrations in the main-channel at the lower Marble Canyon gage decreased during the two days of the 1997 Test Flow (Fig. 6a). There was a decrease by a factor of five in silt and clay concentration (from 0.04% to 0.008% by volume) and a decrease by more than a factor of three in sand concentration (from 0.07% to 0.02% by volume). In contrast to the sampling 2 months earlier during tributary flooding, sand was the dominant portion of the suspended load during the test flow, increasing from 62% on the first day to 82% on the second and last day. These results are remarkably similar to measurements during the 1996 Controlled Flood when the total sediment concentration decreased the most during the first two days of the flood and sand varied from 73% to 88% of the total suspended sediment (Rubin et al., 1998; Topping et al., 1999).

The decrease in suspended-sediment concentration in the main-channel during the 1997 Test Flow was coincident with an increase in suspended grain-size and bed-material grain-size. The median grain size of the suspended sediment increased from 0.09 to 0.105 mm and the bed particles increased from 0.27 to 0.3 mm, mostly during the first day (Fig. 6b). This same pattern was observed during the 1996 Controlled Flood and is thought to result from depletion of fine-grained sediment from the channel bed, either by deposition at higher elevations along the channel margin or transport through the canyon (Rubin et al., 1998; Topping et al., 1999). The main difference between the suspended-sediment grain-size evolution during the two flood experiments is that at the start of the 1997 Test Flow both the suspended sediment and the bed material at the lower Marble Canyon gage was finer. At the end of

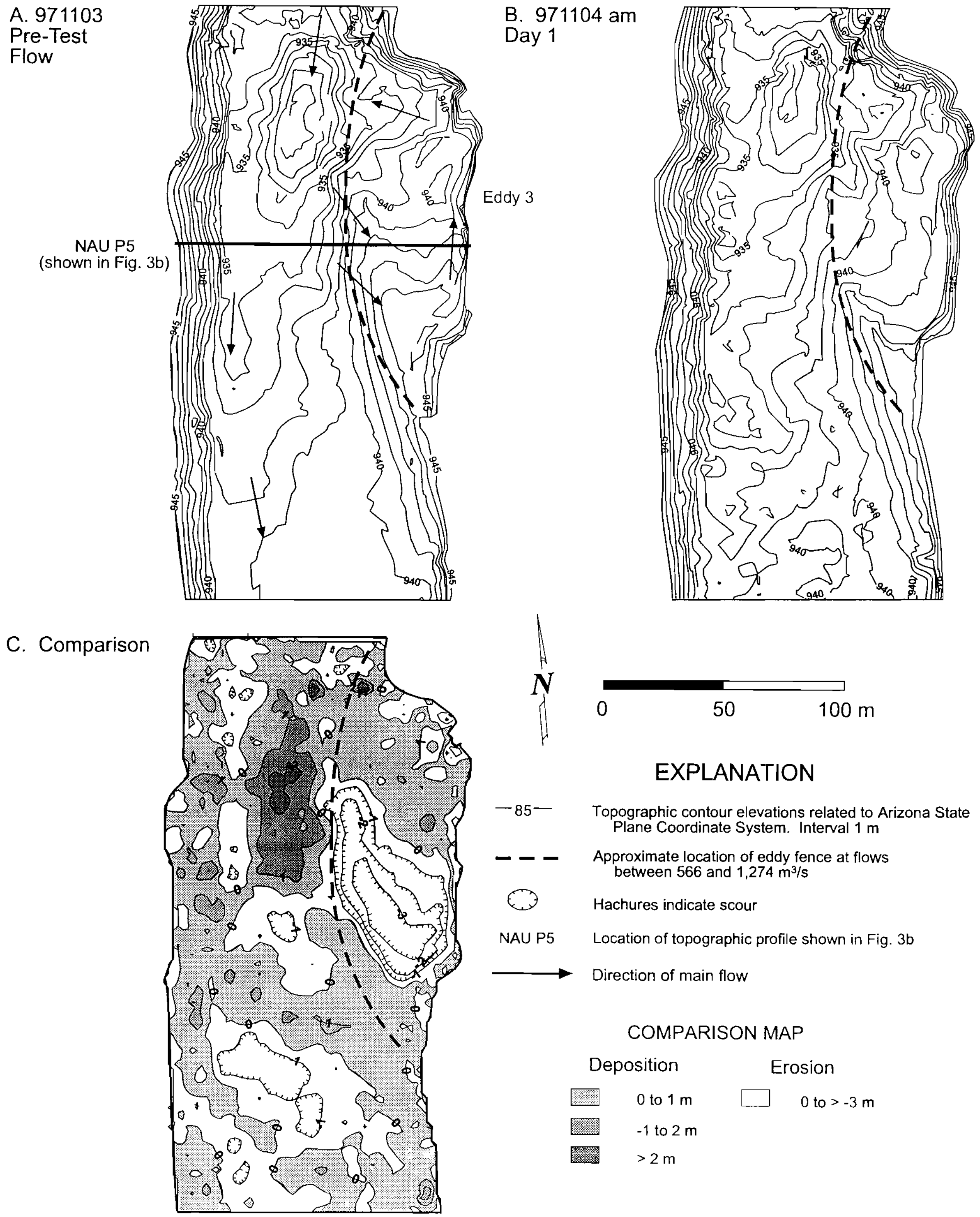

Figure 5. Maps of the main channel and Eddy 3 in Segment 4. A, November 3, 1997. B, November 4, 1997. C, Comparison map showing areas of erosion and deposition between the surveys in A and B. Flow in channel is from top to bottom.

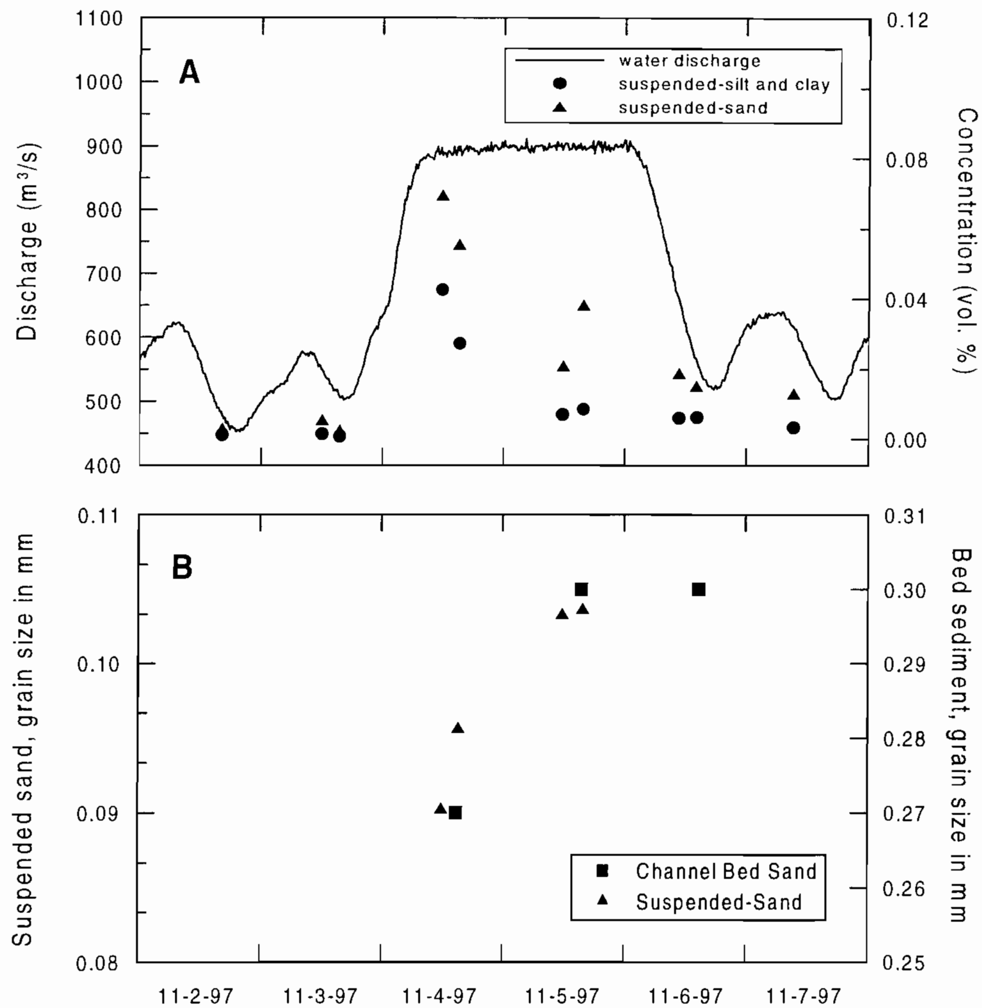

Figure 6. Suspended sediment concentrations and instantaneous discharge at the lower Marble Canyon gage during the 1997 test flow in A. Suspended sediment grain size and bed sediment grain size in B.

the 1997 Test Flow the median grain size of suspended sediment was still finer than that observed at the start of the 1996 Controlled Flood but the bed material grain size had nearly equaled the size measured towards the end of the 1996 Controlled Flood (Topping et al., 2000b).

There was one important difference that existed in sand transport characteristics at the Lower Marble Canyon gage between the controlled high releases in 1996 and 1997. During the 1996 Controlled Flood, the suspended-sand concentrations at the Lower Marble Canyon gage were approximately half those measured at the Grand Canyon gage, located 42 km further downstream (Topping et al., 2000b). However, during the 2 days of the lesser magnitude 1997 Test Flow, the sand concentrations measured at the Lower Marble Canyon gage equaled those measured at the Grand

Canyon gage (Topping et al., 2000b). This change occurred because the November 1997, sand-transport rates at the Lower Marble Canyon gage were twice that observed during the 1996 Controlled Flood. Thus, the large sand inputs from the Paria River in 1997 resulted in a doubling of the sand export rate from Marble Canyon during the 1997 Test Flow. The estimated sand transport was 70,000 m^3 (0.19 ± 0.04 million Mg), or about 9% of the 1997 Paria River sand inputs. In addition, net sand deposition above the 566 m^3/s (20,000 ft^3/s) stage elevation was significantly less than that achieved throughout Marble Canyon by the 1996 Controlled Flood (discussed in detail below).

High-Elevation Sand Bar Changes

Sand bars downstream from Glen Canyon Dam attain elevations and volumes directly related to flow magnitude and adjust vertically according to changes in dam operation. To examine temporal changes in high-elevation sand bar thickness we integrated the results of this study with measured changes since 1996, for Marble Canyon (Fig. 7a). Because the gradient and channel width of the Colorado River changes greatly near river mile 38 (Schmidt and Graf, 1990; Melis, 1997), we divided the sample sites into two populations: those in upper Marble Canyon (6 bars) and those in lower Marble Canyon (8 bars).

The time series demonstrate that sand was successfully redistributed to high-elevation by the 1996 Controlled Flood (Fig. 7a). The average thickness increase was 0.5 m in upper Marble Canyon and 0.7 m in lower Marble Canyon. During the interval between the 1996 Controlled Flood and the 1997 Test Flow, readjustment of the newly aggraded bars to lower, sustained high flows led to rapid but declining rates of erosion (also see Kaplinski et al., 1998). As a result, nearly all of the flood-related deposition in upper Marble Canyon was eroded, whereas in lower Marble Canyon, the magnitude of erosion was substantially less and one-third of the sites measured eroded.

The 1997 Test Flow did not result in aggradation great enough to compensate for the erosion that had occurred between April 1996 and November 1997 (Fig. 7a). Net high-elevation bar thickness did not increase at the sites because deposition of sand on the inundated part of the bar was offset by erosion of high-elevation parts of the preexisting deposits (Fig. 8). In general, as much as 1 m of deposition was located at the downstream parts of eddies where recirculating flow reattaches to the bank. Erosion occurred as the result of cutbanks that retreated horizontally as much as 5 m. The base of the cutbanks developed at the stage elevation reached by the 878 m^3/s flow. The high-elevation erosional trend evident in the time series in 1996 and 1997, suggests that potential depositional area was open, especially in upper Marble Canyon (Fig. 7a). The lack of net deposition, despite high sand

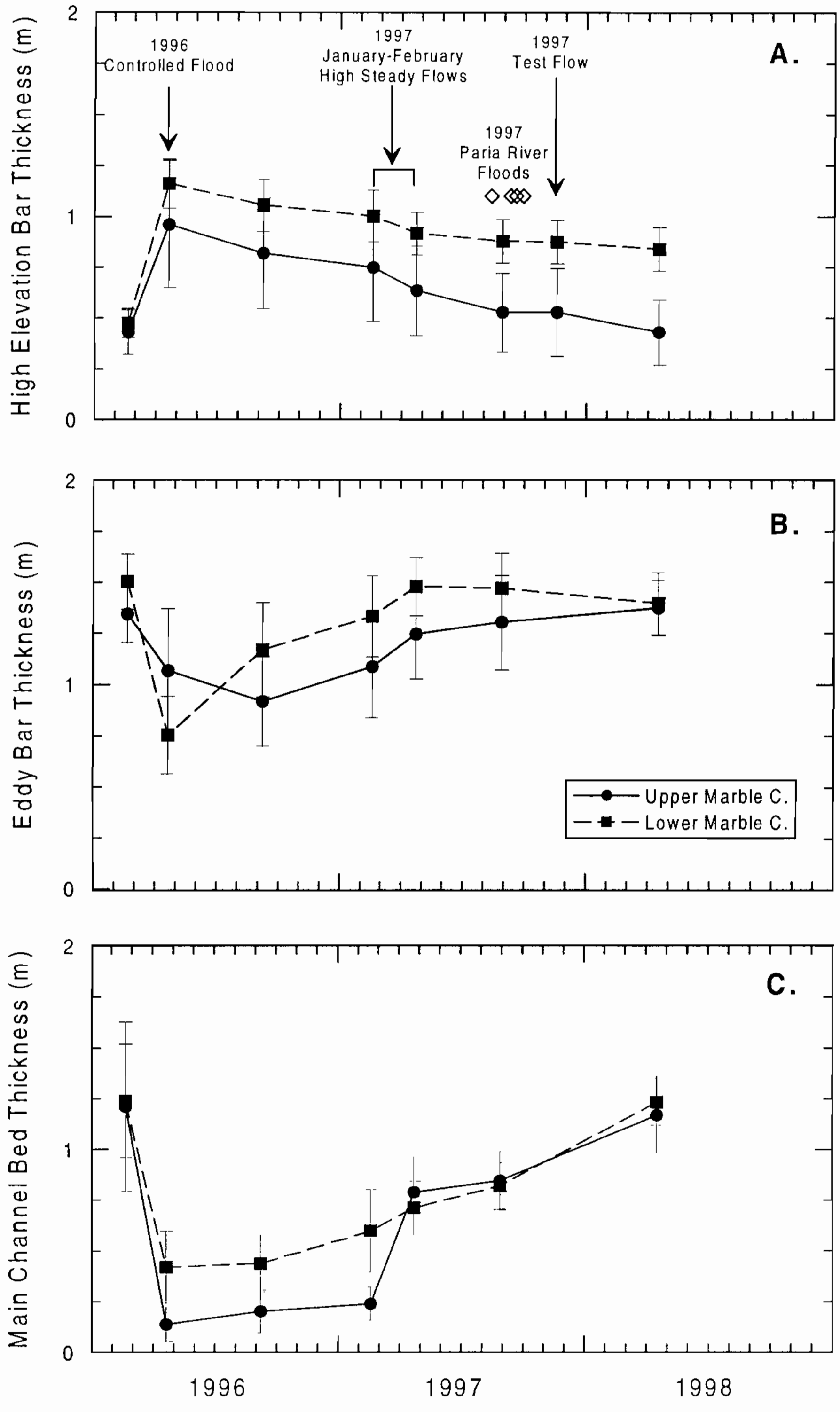

Figure 7. Average sand thickness changes in Marble Canyon versus time. High elevation bar thickness in A, total eddy bar thickness in B, and main channel bed thickness in C. Error bars are standard error about the mean.

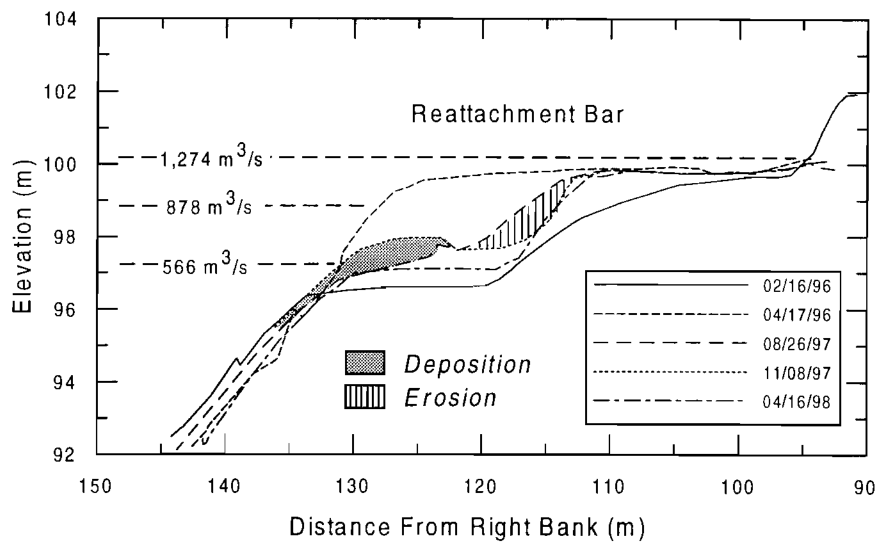

Figure 8. Selected cross section of the high-elevation part of the sand bar at site #30 in upper Marble Canyon. Elevation datum is arbitrary. Flow stage elevations for high-elevation (566 m^3/s), the 1997 Test Flow (878 m^3/s), and the 1996 Controlled Flood (1,274 m^3/s) are shown. Erosion and deposition as a result of the 1996 Controlled Flood and the 1997 Test Flow are depicted. Location is shown in Fig. 1.

concentrations in the main channel at the lower Marble Canyon gage (discussed earlier), suggests that the stage change during the 1997 Test Flow was not high enough to redistribute sand to areas where depositional sites were open. Hazel et al. (1999) show that the stage elevations reached during the 1996 Controlled Flood inundated areas where space was available for deposition, termed "accommodation space," and differences in depositional thickness were directly correlated with the magnitude of stage change in Marble Canyon. The stage change during the 1997 Test Flow was roughly half that of the 1996 Controlled Flood in Marble Canyon (Fig. 9).

Sediment deposited during the 1997 Test Flow was sampled vertically in trenches at 11 of the study sites (Fig. 10). The new deposits were less than 1 m thick above the 566 m^3/s stage elevation and were typically composed of fine-grained climbing ripple stratification. The deposits lacked the coarser-grained cross bedding that characterized the top portion of the 1996 Controlled Flood deposits described by Rubin et al. (1998). However, the same upward-coarsening trend described by Rubin et al. (1998) was observed (Topping et al., 2000b). With the exception of one out of 11 sites, the mean grain size increased upward by the same factor of two, from 0.015-0.15 mm at the base to 0.065-0.24 mm at the top of the deposits.

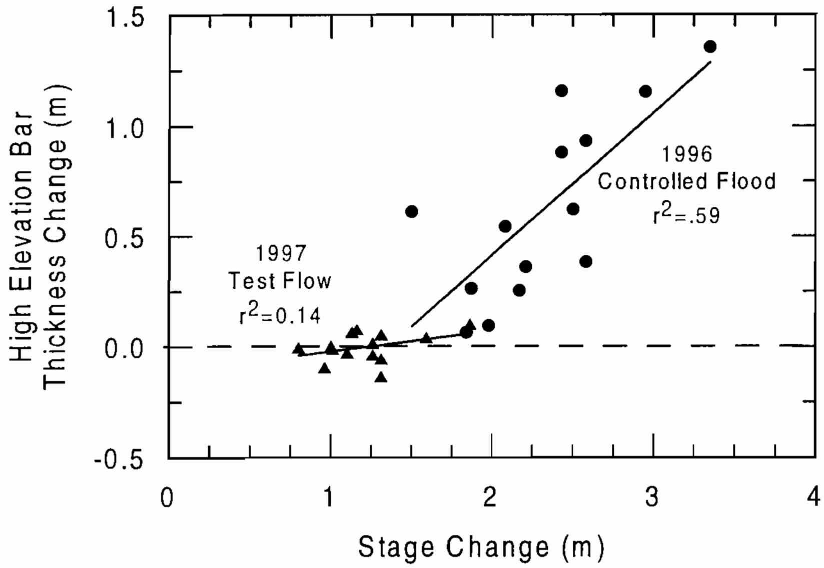

Figure 9. The relation between stage change and high-elevation thickness change in Marble Canyon. The stage change is based on the elevation difference from 566 to 878 m^3/s (1997 Test Flow) and from 566 to 1,274 m^3/s (1996 Controlled Flood) at each study site. Note that thickness change was positively correlated to the magnitude of stage change (r^2=0.59, significant at the 95% confidence level) during the 1996 Controlled Flood, whereas there was no significant correlation as a result of the 1997 Test Flow.

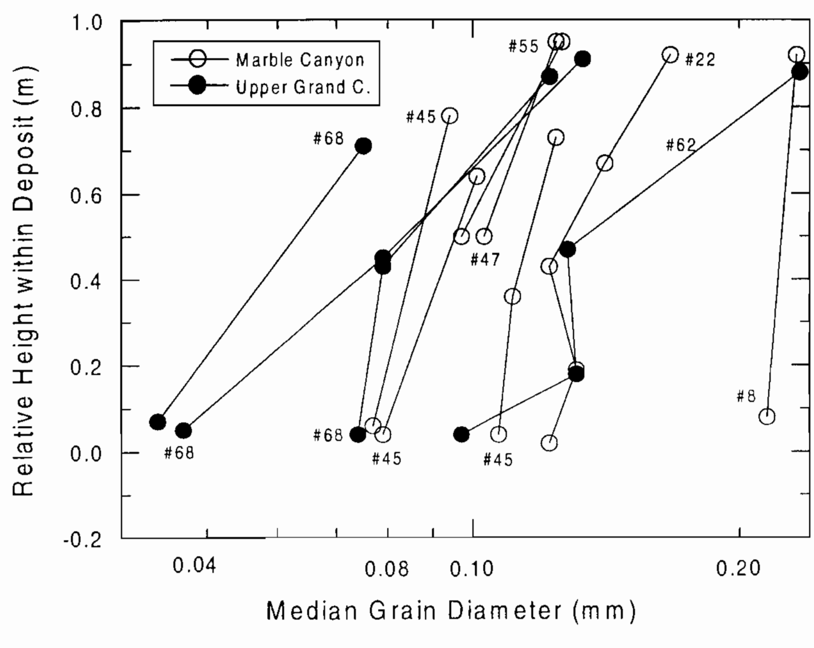

Figure 10. Graph of median grain size as function of relative height within deposits caused by the 1997 Test Flow. The locations of the sampled sites are shown on Fig. 1. Seven sites are located in Marble Canyon and 2 in a segment of upper Grand Canyon below the Little Colorado River.

CHANNEL AND EDDY STORED SEDIMENT IN MARBLE CANYON

Sand transported during the 1997 Test Flow must have come from locations on the channel bed, low elevation parts of eddies, or other areas along the inundated channel margin. Unfortunately, hydrographic surveys were not conducted downstream of the 3-km study reach in November 1997, and an examination of subaqueous change at the downstream study sites was not possible owing to restrictions on use of motorized craft during the fall season. Nonetheless, estimates of bed thickness and total sand mass at the study sites in Marble Canyon for other time periods provide valuable information on the spatial and temporal extent of sediment storage in the Colorado River ecosystem.

The average eddy and channel sand thickness through time are illustrated in Figure 7b and c for 1996-1998. Similar to the high-elevation bar thickness changes described above, we separated the sample into sites located in upper and lower Marble Canyon. The time-series shows scour of low elevation areas, the channel and eddies, following high flows greater than power plant capacity (e.g., the 1996 Controlled Flood). A period of aggradation of channel and eddy sand occurs as sand from eroding bars is then redistributed back to low elevation environments. Recovery from scour is faster in eddies because they are more effective traps for sand than the main channel when suspended sediment concentrations in the mainstem are low (Hazel et al., 1999; Wiele et al., 1996).

These data suggest that sand eroded from high-elevation was redistributed to lower elevations, or advected into eddies from upstream sources, resulting in fill of low-elevation areas scoured by the 1996 Controlled Flood. In contrast, the main channel bed at the sites did not begin to aggrade until a year later (Fig. 7c). This recovery occurred during February and March 1997, when reservoir drawdown priorities resulted in steady discharges of about 765 m^3/s (27,000 ft^3/s) for 21 days, and 680 m^3/s (24,000 ft^3/s) for 30 days (Fig. 2b). We believe that these high flows were of great enough stage and duration to erode other areas of temporary bank storage besides eddy bars, such as channel margin deposits and terraces. Although high elevation bar erosion continued during this two-month period of sustained high flow, little change in total eddy thickness suggests that eddies were relatively full because of low elevation aggradation (Fig. 7b).

Subaqueous sand storage changes at the sites were measured in April 1998, about 7 months after the previous survey (late August, 1997) and 5 months after the 1997 Test Flow, respectively. Because these data were not collected following the 3 Paria River floods in September 1997, or during the 1997 Test Flow (except in the 3-km reach), we were not able to examine the volume and distributions of sand supplied by the Paria River at the downstream sites or isolate the effects of the 1997 Test Flow. For example, whether the 1997 Test Flow produced low elevation scour similar to the response of the study sites to the 1996 Controlled Flood. In addition, the data indicate no response at the sites following the August 10, Paria River flood. During the August 1997-April 1998 period, the average main channel bed thickness increased 0.33 m and 0.42 m in upper and lower Marble Canyon, respectively (Fig. 7c). However, average eddy thickness remained relatively unchanged, suggesting that eddies remained at a relatively full condition as compared to August 1997. Dam releases during this period were moderately high [average daily mean of 538 m^3/s (19,000 ft^3/s)]. The channel bed thickness increase is possibly the result of the coarsest size fractions of the Paria River supplied sand moving slowly downstream (compared to the finer sizes). In contrast, there is no indication that deposition of Paria-supplied sediment in eddies occurred during this period.

The total mass of sand stored at the study sites is illustrated in Fig. 11 for 1996-1998. During this two-year period, the Paria River sand input was below normal in 1996 and above normal in 1997 (D. Topping, written comm., 1999). On the basis of this mass sum, we conclude that within two years of the 1996 Controlled Flood, sand storage at the sites had returned to levels comparable to those measured before the flood. These data suggest that the low elevation areas recover from scour following high flows, such as the 1996 Controlled Flood, over a period of several years. Recovery results from a combination of intracanyon recycling (erosion and transfer of high-elevation sand back to low elevation storage) and from tributary sand inputs. However, most of the recovery at the sites occurred prior to sand inputs by the 1997 Paria River floods. This may indicate, as suggested by Topping et al. (2000b), that the total volume of sand in low elevation eddy and channel storage in Marble Canyon is small, compared to the amount of sediment supplied to it by the Paria River.

In order to prolong the residence time of tributary-supplied sediment in the system, a greater stage increase is required to access high elevation areas available for deposition. Floods on the Paria River do not raise mainstem discharge high enough and for sufficient duration to result in channel margin deposition above stage levels reached by normal dam releases. Timing higher flows to be coincident with or shortly following the summer and fall sediment input season improves the likelihood that finer sediments will be effectively conserved, especially within upstream reaches closest to the dam.

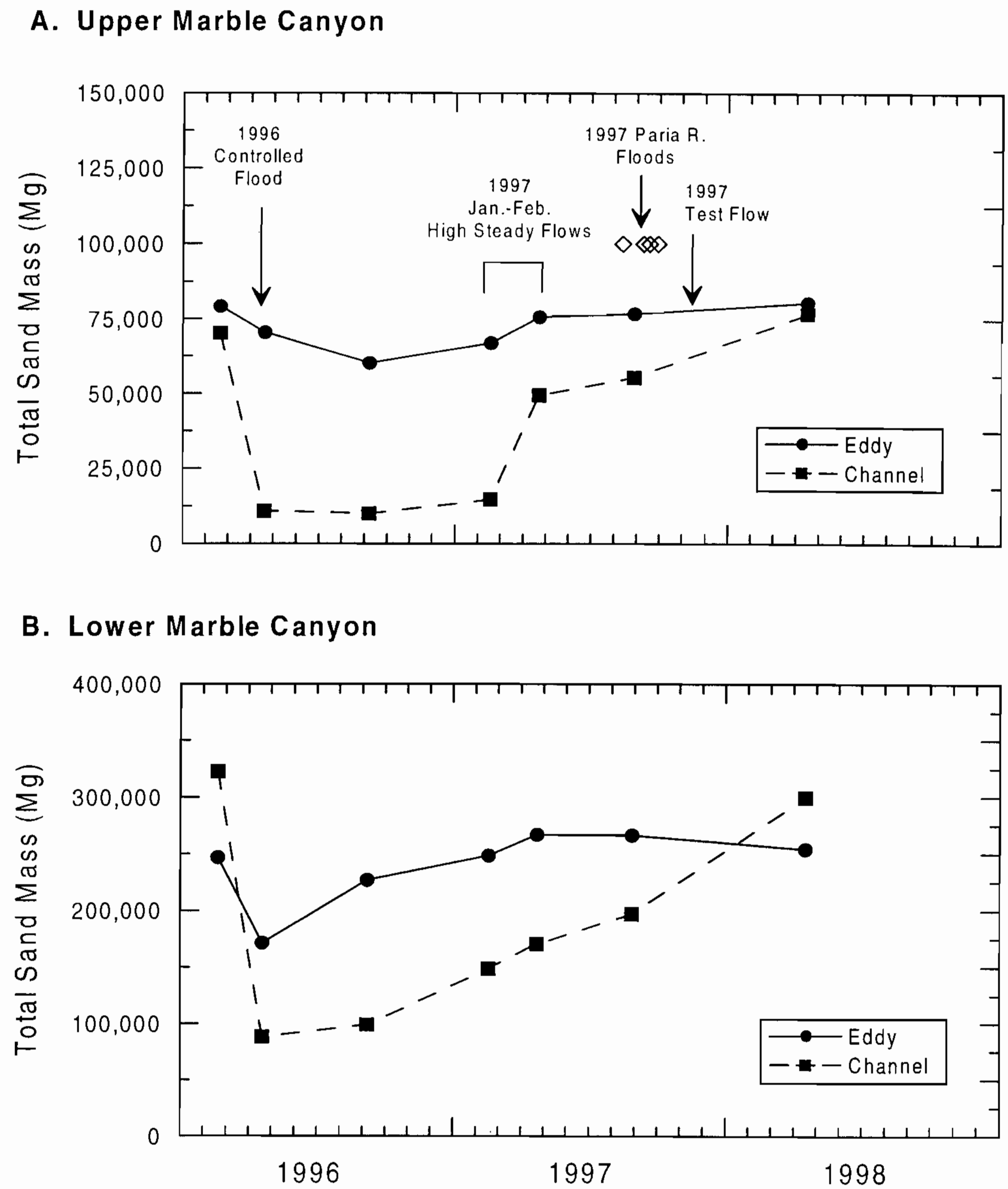

Figure 11. The total mass of sand stored at the study sites in Marble Canyon between 1996-1998. A, Upper Marble Canyon (river miles 1-38). B, Lower Marble Canyon (river miles 38-61). The storage is differentiated for eddy and main channel environments. Eddy mass is the total low and high elevation storage. See text for explanation of sand volume conversion to metric tons (Mg).

DISCUSSION AND CONCLUSIONS

In this report we document the initial distribution of sand added to the 98-km long Marble Canyon reach of the Colorado River ecosystem during a two-month period. During August-September 1997, the Paria River contributed nearly twice the mean-annual Paria River sand input. We also examine the downstream redistribution of those sand inputs and evaluate the effects of the 1997 Test Flow at redistributing sand to higher elevation locations in eddies. We compare field surveys of long-term storage sites to modeled estimates of the Paria River sand inputs and measurements of sediment export. The comparison of sediment storage changes using different methods is possible because the measurement error associated with topographic surveys is very small relative to the volumetric changes, and is considerably less than the errors associated with the other methods: sediment transport calculations and suspended-sediment measurements [i.e., uncertainties of 5-20% of the mean (Appendix A in Topping et al., 2000a)].

The series of short duration, large floods on the Paria River in late summer 1997, supplied the Colorado River ecosystem with approximately 770,000 m^3 (2.0 $\pm$ 0.4 million Mg) of sand. Detailed channel surveys of the 3-km reach at the head of Marble Canyon, immediately downstream from the Paria River, show that approximately 24 to 36% of the sand input from these floods was immediately deposited in this 3-km reach. Large increases in suspended-sediment transport at the lower end of Marble Canyon were measured within 1-2 days of these Paria River floods, suggesting that a measurable fraction of the supplied sediment was never deposited on the bed and was carried in suspension through Marble Canyon at or near the speed of the daily discharge release. The finer grain sizes travel downstream faster than the coarser sizes following tributary input (Topping et al., 2000b). Approximately 56,000 m^3 (0.15 $\pm$ 0.03 million Mg) of sand were exported from Marble Canyon during the 25-day sampling period in August-September, an amount equivalent to about 7% of the sand supplied by the Paria River. Following the last Paria River flood on September 26, approximately 50% of the flood deposition in the 3-km reach was eroded during the 37 days prior to release of the 1997 Test Flow.

Because there were no measurements of suspended sediment transport at the lower Marble Canyon gage during the interval of time between the August-September USGS sampling program and the 1997 Test Flow, we could not determine the amount of Paria River sand inputs that were still retained in Marble Canyon prior to the test flow or how much of the Paria River input still remained upstream from the lower Marble Canyon gage following the test flow. However, the sand-transport rates at the lower Marble Canyon gage during the 1997 Test Flow were twice that observed during the 1996

Controlled Flood. The estimated sand export from Marble Canyon during the 2-day test flow was 70,000 m^3 (0.19 ± 0.04 million Mg), approximately 9% of the total Paria River sand inputs in August-September, 1997. This suggests that a substantial portion of the 1997 Paria River sand input was still retained in Marble Canyon when the 1997 Test Flow was released. Much of this sediment, however, may have accumulated in lower Marble Canyon as the sand inputs moved downstream. This interpretation is supported by the fact that the net effect of the 1997 Test Flow within the first 3-km reach of Marble Canyon was erosion. Less than 10% of the 1997 August-September sand inputs remained in that reach after implementation of the 2-day test. More accurate estimates of sand transport rates following tributary inputs require longer intervals of suspended sediment sampling at the gages. In addition, we could not determine if eddies were a source of low elevation sand (similar to the 1996 Controlled Flood response) during the 1997 Test Flow because the required hydrographic data could not be collected.

Despite occurring within 2 months of the Paria River sand inputs, the 1997 Test Flow was not effective at long-term conservation of the tributary supplied sediment at elevations above the 566 m^3/s (20,000 ft^3/s) stage. The topographic measurements at the study sites in Marble Canyon show that the 1997 Test Flow did not result in significant and persistent high elevation deposition. The new deposits were completely eroded by April 1998. Aggradation of at high elevation was limited, even though sites for potential deposition (accommodation space) were available and suspended sand concentrations were high. We conclude that the geomorphic effects of the 1997 Test Flow were largely stage-limited rather than controlled by fine-sediment supply limitations in Marble Canyon. Although the magnitude and duration of the test did not result in widespread deposition of high-elevation bars, it did duplicate processes at lower elevations which were observed during the 1996 Controlled Flood: high suspended sediment concentrations that decreased with time, suspended and bed material grain size increases, inversely graded deposits, and at least one bar failure.

The results of this study should provide some guidance for those developing physically based models of the transport and deposition of tributary sand inputs through the Colorado River ecosystem. For example, a one-dimensional sand transport model, coupled with an unsteady flow model that incorporates reach-averaged hydraulic geometry (Wiele and Smith, 1996), is being developed to predict the rate at which different grain size fractions are transported downstream under a range of dam operations (Wiele and Franseen, 1999). Continued monitoring and research of the physical processes that control sediment transport and deposition in eddies and main channel pools are needed for the formulation and application of models so that fluvial processes are accurately represented.

MANAGEMENT IMPLICATIONS

As controlled flooding becomes a tool for regulated river resource management, predicting the outcome of floods under a range of antecedent conditions is important. Greater understanding is needed of the basic physical processes that control sediment transport following tributary sand inputs because limitations in sediment supply during flooding control main-channel concentrations (Rubin et al., 1998; Topping et al., 1999) and eddy bar deposition rates (Wiele et al., 1999). In addition to sediment availability and discharge, the volume of sand occupying the depositional site prior to flooding (antecedent storage) is an important factor in determining the magnitude and persistence of flood-related deposition (Hazel et al., 1999; Wiele et al., 1999). Prediction of change is further complicated by variability in channel and debris fan geometry (Webb et al., 1989; Schmidt and Graf, 1990; Melis, 1997), the cumulative downstream nature of the limited sand supply (Topping et al., 2000a, 2000b), and in the spatial and temporal variability of study sites utilized for monitoring (Schmidt et al., 1999b; Grams and Schmidt, 1999).

The 1997 Test Flow was the first attempt by the Glen Canyon Dam adaptive management group to implement a release closely timed with tributary floods on the Paria River. The potential benefit of floods timed closely with tributary inputs is that in the presence of finer sediment, sand concentrations will be higher resulting in higher rates of deposition in eddies (Topping et al., 1999). As a result, planned floods can be shorter in duration and lessen the economic cost associated with loss of hydropower generation and altered water-release patterns (Harpman, 1999). Because of these associated costs it was important for river managers to know if a peak power plant discharge, the 1997 Test Flow, could prolong the residence time of sediment supplied by the Paria River. Our data suggests that this management goal was not achieved, and we conclude that the discharge of future planned floods designed to redistribute sediment to high elevation will need to be at least similar to the magnitude of the 1996 Controlled Flood, if not greater. Controlled floods designed to prolong the residence time of newly input sand in Marble Canyon need to take into account where storage environments are available, especially at higher elevations, as well as the antecedent conditions of sand storage on the bed with respect to volume, grain size, and spatial distribution.

Timing future floods to coincide with years or months of above average sediment delivery by the Paria River is a critical resource issue (Schmidt, 1999). Large floods on the Paria River typically occur during the late summer or early fall (Topping, 1997). Coordination of high releases at this time of year is difficult because flows in excess of power plant capacity can only be released to avert hydrologic emergencies, a situation that is most likely to occur in late spring or early summer when inflow to Lake

Powell is above average and reservoir storage is high. Although efforts as part of adaptive management of the resources of the Colorado River are underway to reevaluate current flood release policies, all policy recommendations must take into account other resource concerns such as habitat destruction, impacts to endangered species, loss of archeological sites, recreation and power-production economics, and engineering constraints such as use of the spillways (Schmidt et al., 1998; 1999a; Marzolf et al., 1999). In addition, physical scientists charged with evaluating the effects of floods that occur between September 15 and December 15 (non-motor season in Grand Canyon National Park) must cope with imposed limitations on monitoring fieldwork.

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