JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 111, F01025, doi:10.1029/2004JF000193, 2006

Influence of a dam on fine-sediment storage in a canyon river

Joseph E. Hazel Jr.,[1] David J. Topping,[2] John C. Schmidt,[3] and Matt Kaplinski[1]

Received 24 June 2004; revised 18 August 2005; accepted 14 November 2005; published 28 March 2006.

[1] Glen Canyon Dam has caused a fundamental change in the distribution of fine sediment storage in the 99-km reach of the Colorado River in Marble Canyon, Grand Canyon National Park, Arizona. The two major storage sites for fine sediment (i.e., sand and finer material) in this canyon river are lateral recirculation eddies and the main-channel bed. We use a combination of methods, including direct measurement of sediment storage change, measurements of sediment flux, and comparison of the grain size of sediment found in different storage sites relative to the supply and that in transport, in order to evaluate the change in both the volume and location of sediment storage. The analysis shows that the bed of the main channel was an important storage environment for fine sediment in the predam era. In years of large seasonal accumulation, approximately 50% of the fine sediment supplied to the reach from upstream sources was stored on the main-channel bed. In contrast, sediment budgets constructed for two short-duration, high experimental releases from Glen Canyon Dam indicate that approximately 90% of the sediment discharge from the reach during each release was derived from eddy storage, rather than from sandy deposits on the main-channel bed. These results indicate that the majority of the fine sediment in Marble Canyon is now stored in eddies, even though they occupy a small percentage (∼17%) of the total river area. Because of a 95% reduction in the supply of fine sediment to Marble Canyon, future high releases without significant input of tributary sediment will potentially erode sediment from long-term eddy storage, resulting in continued degradation in Marble Canyon.

Citation: Hazel, J. E., Jr., D. J. Topping, J. C. Schmidt, and M. Kaplinski (2006), Influence of a dam on fine-sediment storage in a canyon river, *J. Geophys. Res.*, *111*, F01025, doi:10.1029/2004JF000193.

1. Introduction

[2] In canyon rivers with debris fans, the flow field is divided between the area of downstream flow in the main channel and areas of lateral flow recirculation, or eddies, that occur in the lee of debris fans (Figure 1). Temporary and persistent storage of the sediment load occurs on the bed of the main channel, in eddies, and on the floodplain. Although the importance of debris fans as prominent landforms affecting channel planform, gradient, and hydraulics in canyon rivers is well documented [e.g., *Howard and Dolan*, 1981; *Kieffer*, 1985; *Webb et al.*, 1989; *Schmidt*, 1990; *Miller*, 1994; *Schmidt and Rubin*, 1995; *Grams and Schmidt*, 1999], the relative role of the main-channel bed, eddies, and the floodplain in short- and long-term storage of the sediment load is poorly known.

[3] Many dams in the western United States cause large reductions in the downstream supply of fine sediment, which can alter the volume and distribution of fine sediment stored in the river [*Petts*, 1979; *Galay*, 1983; *Williams and Wolman*, 1984; *Grant et al.*, 2003]. Understanding the spatial patterns of sediment distribution is a key part of understanding postdam channel evolution and in turn, the long-term impacts of flow regulation to other resources such as riverine ecology and recreation.

[4] This paper describes changes in predam and postdam patterns of sand, silt and clay (hereafter referred to as fine-sediment) distribution in the Colorado River in Grand Canyon National Park (GCNP), Arizona. The study area is the 99-km length of Marble Canyon, located between the Paria and Little Colorado Rivers, in eastern GCNP (Figure 2). The native Colorado River ecosystem developed in conjunction with a large seasonal flux of suspended fine sediment and seasonal accumulation of this sediment on the bed and banks. Fine sediment accounts for approximately 99% of the total sediment load of the Colorado River in the study area [*Rubin et al.*, 2001]. Completion of Glen Canyon Dam in 1963 caused a 95% reduction in the delivery of fine sediment to the modern river at the upstream boundary of GCNP [*Andrews*, 1990, 1991; *Topping et al.*, 2000a]. The result was erosion of fine sediment by winnowing of the bed and degradation of the bars that occur in eddies [*Schmidt et al.*, 2004]. The goal of modern river management in GCNP is to maintain eddy bars and floodplain deposits as large as possible under the prevailing dam-regulated conditions [*U.S. Department of the Interior*, 1996; *Schmidt et al.*, 1998; *National Research Council*, 1999].

[5] We examine sediment storage changes in Marble Canyon with aerial photographs and direct measurements

---

[1] Department of Geology, Northern Arizona University, Flagstaff, Arizona, USA.

[2] U.S. Geological Survey, Flagstaff, Arizona, USA.

[3] Department of Aquatic, Watershed, and Earth Resources, Utah State University, Logan, Utah, USA.

0148-0227/06/2004JF000193

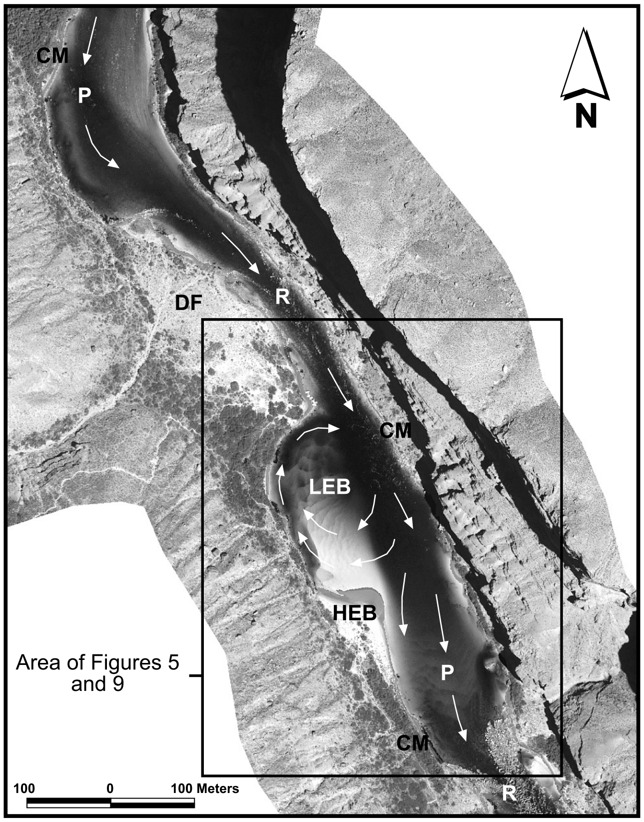

Figure 1. Panchromatic aerial photograph of Saddle Canyon, a typical fan-eddy complex of the Colorado River in Marble Canyon. The photograph was taken on 28 May 2002 at the base flow discharge of 227 m^3/s. The subaqueous zone is highlighted with an overlay of green-band, multispectral imagery from the same aerial overflight. DF, tributary debris fan; R, rapid or riffle; P, main-channel pool; HEB, high-elevation eddy bar; LEB, low-elevation eddy bar; CM, channel-margin deposits. Arrows indicate flow direction. Location is shown on Figure 2 as long-term study site 47. Photograph is by the Grand Canyon Monitoring and Research Center, U.S. Geological Survey.

of bed, eddy, and bar topography. We compare these changes and the grain size of sediment found in different storage sites to the sizes supplied to the reach and to those in transport. Our purpose is to evaluate the change in volume and distribution of active fine-sediment storage to flow regulation. We define active storage as the mass of fine sediment that is delivered by tributaries, temporarily stored on the bed or the floodplain, and transported downstream within a few months.

2. Background

[6] The geomorphology and ecology of the Colorado River in Grand Canyon was transformed by the closure and operation of Glen Canyon Dam [*Carothers and Brown*, 1991; *Webb et al.*, 1999], located 26 km upstream from the Paria River. The downstream riverine ecosystem is now the subject of a large-scale rehabilitation program called the Glen Canyon Dam Adaptive Management Program.

[7] Despite the best efforts to provide decision-makers with accurate estimates of fine-sediment flux and change in storage, scientists have only recently agreed on the severe sediment-deficit condition of the Colorado River in Marble Canyon. Although *Laursen et al.* [1976] predicted fine-sediment deficit, *Howard and Dolan* [1981], *Randle and Pemberton* [1987], *Andrews* [1991], and *Smillie et al.* [1993] predicted that there was a surplus of fine sediment in the postdam river because the capacity to transport sand had been reduced more than the supply. The predictions of each of these studies were based on application of a long-term average fine-sediment transport relation to estimate transport for periods when there were no measurements. We now understand that there is substantial hysteresis and systematic shifts in sand-transport relations, as described below, and use of average relations to estimate transport is inappropriate.

[8] The view that sediment-surplus conditions exist and that the Colorado River accumulates fine sediment over multiyear time periods was described in the Final Environmental Impact Statement (EIS) for Glen Canyon Dam Operations [*U.S. Department of the Interior*, 1995] and was the paradigm prior to the 1996 Controlled Flood [*Webb et al.*, 1999]. The EIS proposed that controlled floods, released as clear water from the dam, would entrain fine sediment delivered by tributaries during preceding years. Entrainment and transport during controlled floods would result in transfer of fine sediment from the main-channel bed to eddies and the floodplain, thereby achieving management objectives [*Schmidt et al.*, 1999].

2.1. Fine-Sediment Flux

[9] Sand-transport relations are not stationary and depend on the grain size and amount of sand on the bed that is available for transport [*Rubin et al.*, 1998; *Topping et al.*, 2000a]. The postdam variation in sand concentration is about 2 orders of magnitude at any given discharge [*Topping et al.*, 2000b]. When the Paria River, the predominant supply to Marble Canyon [*Andrews*, 1990, 1991; *Topping et al.*, 2000a], delivers sand, the bed fines and main stem transport increases. Following cessation of sand input, fines are winnowed, the bed coarsens, and transport rates decrease. These supply-driven changes in sand concentration and grain size occur over timescales of hours to days, precluding the development of stable or seasonally variable sand-transport relations. *Topping et al.* [2000b] and *Rubin et al.* [2002] showed that sand supplied from unregulated tributaries remains in storage for only a few months before most of it is transported downstream, unless flows are below approximately 250 m^3/s; longer-term sand accumulation does not occur. Thus the postdam river is actually in a condition of sand deficit rather than the sediment surplus predicted by previous studies.

2.2. Fine-Sediment Storage

[10] When a river is in fine-sediment deficit, erosion of long-term storage sites occurs and new supplies from tributaries do not persist. In the case of canyon rivers with

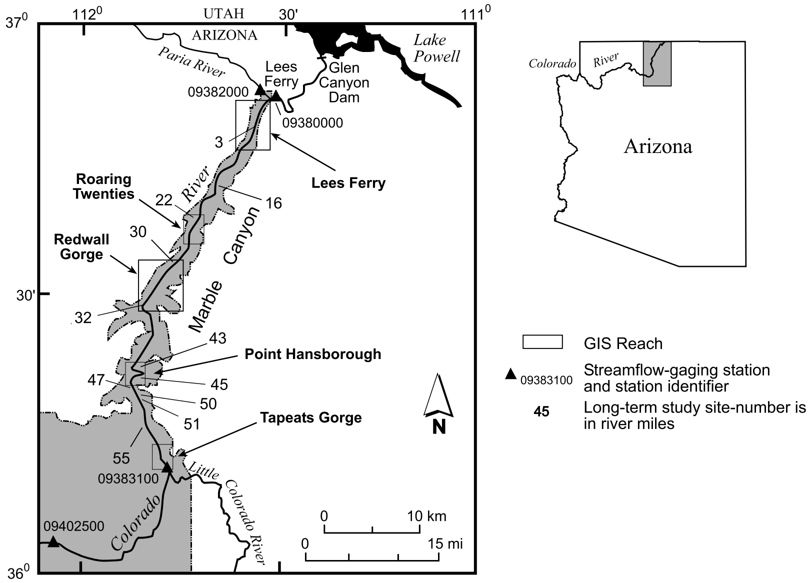

Figure 2. Colorado River in Marble Canyon, Arizona. The shaded area is Grand Canyon National Park. Shown are the locations of the U.S. Geological Survey streamflow-gauging stations, the 5 GIS-based reaches, and the 11 long-term study sites. The long-term study sites are referred to by distance in river miles downstream relative to Lees Ferry (river mile 0).

numerous eddies, predicting the locations from which persistent erosion occurs and the locations where newly supplied fine sediment is temporarily stored is important for interpreting the long-term effects of flow regulation. Understanding whether these locations are on the main-channel bed, in eddies, or on the floodplain should also improve the design of future controlled floods and ecological management of the river corridor.

[11] There is relatively little space for fine-sediment storage on the floodplain in Marble Canyon, because the valley is not much wider than the channel (Figure 3). The average width of the channel at base flow is 86 m [*Schmidt et al.*, 2004]. The average width of the valley, approximated by the average flow width at the predam mean annual flood, is only 54% greater [*Schmidt et al.*, 2004]. Thus there is relatively little room for alluvium to be stored on the floodplain, and most storage occurs on the main-channel bed or in eddies.

[12] Longitudinal variation in fine-sediment storage sites is determined by changes in river-level bedrock, which

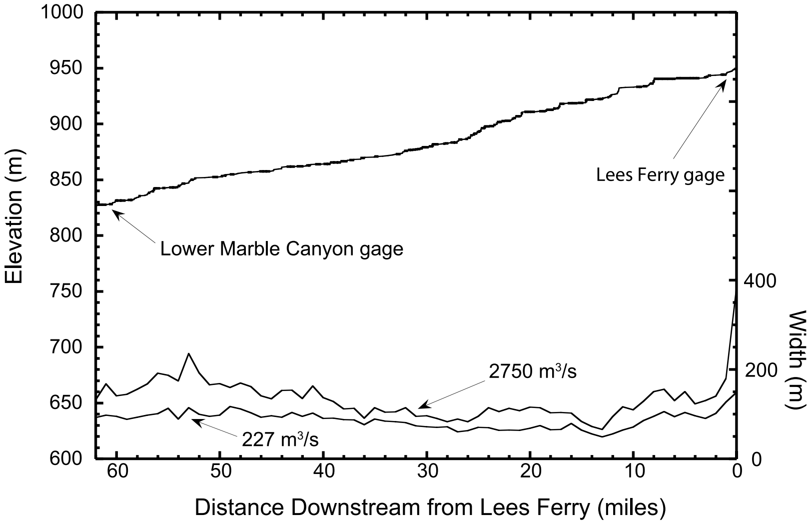

Figure 3. Longitudinal profile of the Colorado River in Marble Canyon, Arizona. Shown are channel and alluvial valley width. Channel and alluvial valley width are defined as the water surface width at flows of 227 m^3/s and 2750 m^3/s, respectively. The vertical exaggeration of the longitudinal profile is 123 (modified from *Schmidt et al.* [2004]).

controls valley width, and the location of tributaries, which determine the location of debris fans and the size and frequency of associated eddies [*Howard and Dolan*, 1981; *Schmidt et al.*, 2004]. The longitudinal profile of the bed includes shallow areas at rapids and riffles and deep pools that typically occur upstream and downstream from rapids (Figure 1). The bed of the postdam river is primarily composed of gravel, boulders, and bedrock. Overlying this coarse material are discontinuous patches of sand [*Wilson*, 1986; *Anima et al.*, 1998]. Many of these sand patches are thin in Marble Canyon, because gravel can be observed protruding through the troughs of dunes [*Rubin et al.*, 2001].

[13] Debris fans fix the locations of eddies that occur in the downstream channel expansion. Thus monitoring of the volume of eddy bars is not confounded by bar migration, because these bars do not migrate. Eddies larger than 1000 m^2 occur with a frequency of between 2 and 6 per kilometer [*Schmidt et al.*, 2004]. Large eddies may contain bars that are more than 10 m thick [*Rubin et al.*, 1994; *Barnhardt et al.*, 2001].

[14] Floodplain deposits are typically narrow, thin veneers of fine sediment along steeply sloping banks. These deposits are typically composed of predam deposits that are rarely or never inundated, and inset deposits formed by the postdam flow regime [*Schmidt and Rubin*, 1995; *Hereford et al.*, 1996]. We hereafter refer to these deposits as channel-margin deposits (Figure 1).

3. Sediment Storage in the Predam River

3.1. Seasonal Sediment Storage

[15] In the predam Colorado River in Marble Canyon, seasonal fluctuations in main stem discharge caused seasonal differences in the storage of the naturally large suspended load. Analyses of the daily sediment-transport data collected by the U.S. Geological Survey (USGS) between October 1947 and March 1963 at the two streamflow gauging stations bracketing the study area, the Colorado River at Lees Ferry, Arizona, station 09380000 (hereafter referred to as the Lees Ferry gauge) and the Colorado River near Grand Canyon, Arizona, station 09402500 (hereafter referred to as the Grand Canyon gauge) indicate that sediment accumulated and was temporarily stored in the study area when the discharge was typically less than 250 m^3/s. This typically occurred during the 9-month period between July and the subsequent March [*Topping et al.*, 2000a]. During the average predam year, the seasonal accumulation was 7 ± 6 million Mg and was greatest during the years with the largest tributary floods in late summer, fall, and winter. During the spring snowmelt flood between April and June, the amount of fine sediment exported past the Grand Canyon gauge was approximately equal to the amount transported past the Lees Ferry gauge plus the amount that accumulated between the two gauges since the previous July. Thus the total amount of fine sediment in storage was probably least immediately upon recession of the snowmelt flood.

3.2. Data Sources and Methods

[16] Although it is impossible to construct a partitioned sediment budget for the seasonal accumulation of fine sediment during each predam year for which there are sediment-transport data, the relative magnitude of storage on the main-channel bed and in eddies can be estimated by extrapolating from a database of channel and eddy bar area generated from aerial photographs taken in predam and postdam years [*Schmidt et al.*, 2004]. The data was measured in five reaches that range from 2.9 to 14 km in length, totaling approximately 44% of the study area (Figure 2).

[17] Channel maps, including fine-sediment deposits, were based on interpretation of between seven and nine aerial photograph series (mid-1930s, 1965, 1973, 1984, 1990, 1992, 1993, 1996, and 2000) overlain in a geographic information system (GIS). For each eddy bar, a polygon was established that enclosed the entire area with an eddy bar in any year (Figure 4). The number of aerial photographs mapped in each study reach varied on the basis of availability. This polygon, referred to as the eddy deposition zone (EDZ), is an objectively defined surrogate for the area of each eddy. Although this polygon is smaller than the eddy that exists in the flow field, the EDZ has the advantage of being defined without the necessity of field observations of flow, and indicates the area where substantial fine sediment storage has occurred at some time in the past.

3.3. Analysis of Sediment Storage in the Predam River

[18] There are 236 EDZs in the mapped reaches, of which 150 are larger than 1000 m^2 and for which we measured the area of fine sediment in each aerial photograph series. The average number of EDZs larger than 1000 m^2/km in the study area is approximately 3.5, which leads to an estimate that there are approximately 350 EDZs larger than 1000 m^2 in Marble Canyon (Table 1). The average EDZ size is about 7430 m^2, which leads to an estimate that there is approximately 2.6×10^6 m^2 of EDZ in Marble Canyon. The total area of main channel outside of eddies is approximately 8.5×10^6 m^2 at 227 m^3/s (Table 1).

[19] There is no way to determine the average thickness of predam annual scour and fill in EDZs. We estimated the maximum potential scour and fill in nine EDZs in or near the study area by integrating field surveys made since 1990. We determined the lowest measured elevation of the bed at 1-m-spaced grid nodes of the surveyed area. We refer to this artificial surface of lowest measured elevations as the "minimum surface" (Figure 5). Details of the field surveys are described in section 4.1.2.1. In each EDZ, the minimum surface was subtracted from a flat surface at the elevation of the water surface at 100 m^3/s, the lowest stage used in the calculation of the EDZs. The difference between these two surfaces is a conservative estimate of the maximum potential scour and fill, and thus of the active storage potential of fine sediment in eddies.

[20] The thickness of sediment between the two surfaces described above varies between 1.8 and 6.2 m, with a mean thickness of 3.2 m (Table 2). Multiplication of this thickness by the total estimated area of EDZs yields an estimate of 8.3×10^6 m^3 for the potential active storage volume of eddies in Marble Canyon. This volume would contain 13.1×10^6 Mg, which is about the same as the upper bound of the seasonal fine-sediment accumulation between the Lees Ferry and Grand Canyon gauges during the average year, estimated by *Topping et al.* [2000a].

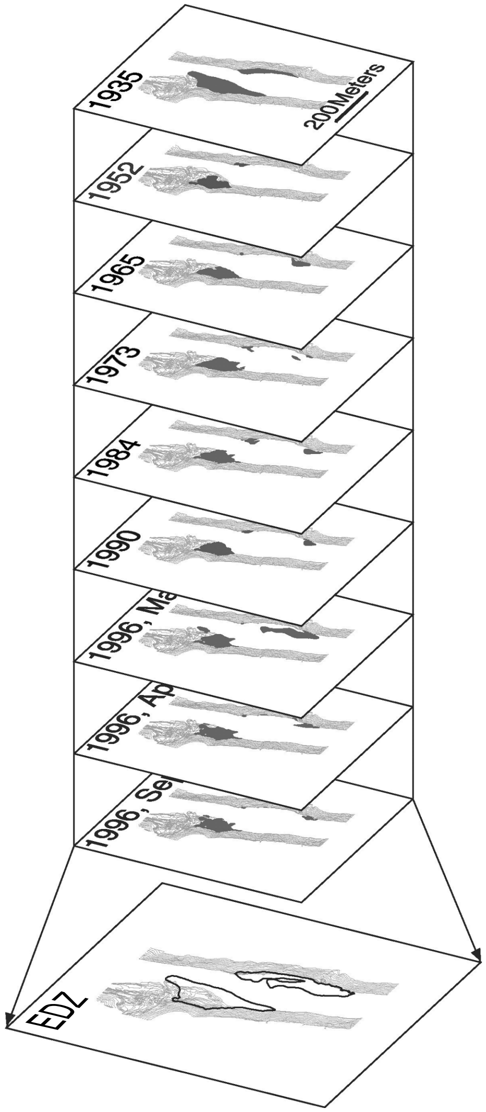

Figure 4. Diagram showing the method of calculation of eddy deposition zones (EDZs) from aerial photographs. The EDZ is shown at bottom of figure [from *Schmidt et al.*, 2004].

[21] We estimated the magnitude of average scour and fill of the main-channel bed and eddies under: (1) different amounts of seasonal fine-sediment accumulation, (2) different proportions of this accumulation occurring on the main-channel bed and in eddies, and (3) different proportions of the main-channel bed where large amounts of fine sediment could be stored. We compared these estimates of scour and fill with historical observations. We made these estimates for three scenarios, including the upper bound of the seasonal fine-sediment accumulation for the average predam year ($\sim 13 \times 10^6$ Mg).

[22] In a year when 7×10^6 Mg of fine sediment accumulated between July and the next March and where half of the fine sediment accumulated in eddies and half in the main channel, the average elevation change in eddies would have been about 0.6 m and the average change in the main-channel bed elevation would have been 0.5 m, assuming that all main-channel bed storage occurred in 30% of the channel area (Table 3). The estimate for average main-channel bed scour and fill is less than the range of annual scour and fill measured at the Lees Ferry and Grand Canyon gauges. The bed scoured and filled between 3 and 6 m and between 1 and 3 m, respectively, in the pools at the two gauges in the predam era [*Topping et al.*, 2000a]. We suspect that the magnitude of the scour and fill measured in these pools occurred only in the pools immediately above or below the rapids formed by the debris fans and not on the majority of the channel bed, because these larger magnitudes of bed change could not have occurred over large parts of the channel under any scenario of seasonal sediment accumulation and a reasonable proportion of eddy storage [*Schmidt et al.*, 2004].

[23] Scenarios where a larger proportion was stored in either the main-channel bed or in eddies yield unrealistically small values of scour and fill in the other storage environment. If one assumes that more than 50% of fine sediment was stored on the main-channel bed and less was stored in eddies, then the estimated average range of change in active eddy storage is unrealistically low and less than that indicated by the repeat photography of *Webb* [1996]. For example, if eddies were the repository of only 10% of the total accumulation, then average bed-elevation changes in eddies would have been about 0.1 m, an unreasonably small value. Although there is no way to confirm our estimates,

Table 1. Summary of Sediment Storage Environments in Marble Canyon

	GIS Reaches					
Sediment Budget Components	Lees Ferry	Roaring Twenties	Redwall Gorge	Point Hansborough	Tapeats Gorge	Marble Canyon Average
Reach length,[a] km	14.0	7.5	10.0	10.8	2.9	99.0
Number of eddies larger than 1000 m^2/km[a]	2.2	4.4	3.3	3.8	5.7	3.5
Average eddy area,[a] m^2	9230	4980	4760	10660	7000	7430
Average eddy area inundated by the 1996 controlled flood,[a] m^2	6210	3230	3750	6240	5160	4830
Average new channel-margin deposit area in 1996,[a] m^2/km	520	780	770	3930	1440	1760
Average new channel-margin deposit area in 2000, [a] m^2/km	NA[b]	NA[b]	NA[b]	1110	NA[b]	460
Channel area excluding eddies at 227 m^3/s, [a] m^2/km	132,840	58,460	70,200	86,330	73,740	84,850
Percentage of channel composed of rapids and riffles[c]	6	10	16	9	10	10
Percentage of postdam channel composed of gravel, boulders, and bedrock[d]	93	NA[b]	88	85	NA[b]	88

[a]From *Schmidt et al.* [2004].
[b]No data available.
[c]From *Magirl al.* [2005] using a water surface slope of 0.002 or greater to delineate rapid/riffle length.
[d]Estimated by S. Goeking, Utah State University (written communication, 2003) using the data of *Wong et al.* [2003].

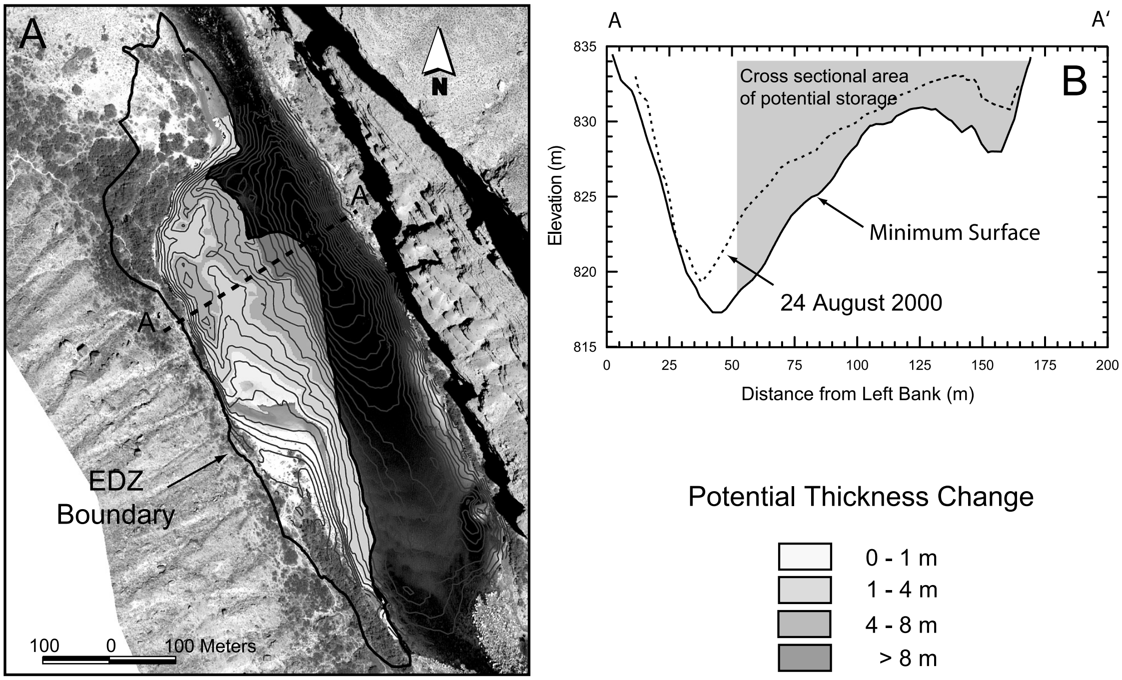

Figure 5. Maximum predam potential scour and fill in EDZs determined from the minimum surface at long-term study site 47 (location shown on Figure 1). (a) Thickness change based on subtracting the minimum surface from the 100 m^3/s stage elevation within the area of EDZ overlap. Minimum surface contour interval is 1 m. (b) Cross section A-A′ constructed from the minimum surface. For comparison, the 24 August 2000 profile is shown. The gray shaded area illustrates the overlap of the EDZ and the minimum surface up to the 100 m^3/s stage elevation.

the greatest agreement with the sparse historical data is the scenario where half of the fine sediment was stored in a relatively small proportion of the total bed area and half the fine sediment was stored in eddies (Table 3).

4. Sediment Storage in the Postdam River

4.1. Data Sources and Methods

[24] Our strategy to examine fine-sediment storage during postdam conditions was to first quantify the total volume of active storage within the two main storage environments, eddies and the main channel; and second, develop sediment budgets for two periods when dam releases were high and when influx and efflux of sediment were measured. These two periods were the 1996 Controlled Flood, between 26 March and 2 April 1996, and the September 2000 Powerplant Capacity Flow between 5 and 8 September 2000 (Figure 6). The 1996 Controlled Flood consisted of a 7-day steady discharge of 1274 m^3/s, and the September 2000 Powerplant Capacity Flow consisted of a 4-day steady discharge of 878 m^3/s.

[25] We used two different techniques to estimate changes in fine-sediment storage during the 1996 Controlled Flood and September 2000 Powerplant Capacity Flow. The first estimate was derived from direct measurements of topographic change and the GIS database described in

Table 2. Estimates of the Potential Fine-Sediment Storage Volume in Nine EDZs

EDZ Name	EDZ Area,[a] m^2	Minimum Surface Area,[b] m^2	EDZ and Minimum Surface Overlap, %	Area of Comparison, m^2	Void Volume,[c] m^3	Void Volume Thickness, m
Cathedral	11,658	8392	72	7124	25,122	3.53
Fence Fault	11,479	9448	82	4954	8949	1.81
South Canyon	10,837	9536	88	4316	11,877	2.75
Anasazi Bridge	25,348	11,318	45	4545	12,412	2.73
Eminence Break	80,259	30,377	38	12,884	34,776	2.70
Saddle Canyon	44,977	29,935	67	21,831	92,797	4.25
Crash Canyon	20,103	17,816	89	14,878	92,787	6.24
Carbon	20,253	18,123	89	10,971	24,451	2.23
Tanner	11,476	9422	82	4269	11,822	2.77

[a] From *Schmidt et al.* [2004].

[b] Computed from all topographic surveys conducted at each site 1990–2000.

[c] Represents the potential storage volume of fine sediment in the EDZ between the minimum surface and the stage associated with a discharge of 100 m^3/s.

Table 3. Estimates of the Average Predam Change in Fine-Sediment Thickness in Marble and Upper Grand Canyons[a]

		Equivalent Thickness,[c] m					
Seasonal Sediment Accumulation, Mg	Equivalent Volume,[b] m^3	Eddies 0.1	Channel [0.9] (0.3) 0.9	Eddies **0.5**	Channel [0.9] (0.3) **0.5**	Eddies 0.9	Channel [0.9] (0.3) 0.1
1,000000	640,000	0.02	[0.04] (0.13)	**0.08**	[0.02] **(0.07)**	0.15	[0.00] (0.01)
7,000,000	4,460,000	0.11	[0.30] (0.91)	**0.57**	[0.17] **(0.51)**	1.03	[0.03] (0.10)
13,000,000	8,280,000	0.21	[0.56] (1.69)	**1.06**	[0.31] **(0.94)**	1.91	[0.06] (0.19)

[a]Under various scenarios of seasonal sediment accumulation, relative proportion of accumulation stored in eddies and the main channel, and proportion of the main channel where storage occurs. The two assumptions about the proportion of the channel that can store fine sediment are shown in brackets and parentheses as 90% and 30%, respectively. Boldface indicates the most likely scenario for predam seasonal storage of fine sediment.

[b]Assumes bulk specific weight of deposited fine sediment is 1570 kg/m^3.

[c]Assumes area of eddies is 3.9×10^6 m^2, and area of channel is 14.7×10^6 m^2.

section 3.1. The second estimate of change in storage was derived by partitioning the sediment export from Marble Canyon into main channel- and eddy-derived components, on the basis of the characteristic grain sizes of each storage environment.

4.1.1. Sediment Transport

[26] Fine-sediment influx and efflux was computed using streamflow and sediment-transport measurements at the Lees Ferry gauge and one at the downstream end of Marble Canyon (Colorado River near Desert View, Arizona, hereafter called the lower Marble Canyon gauge) (Figure 2). Influx was set equal to zero during both the 1996 Controlled Flood and the September 2000 powerplant flow, because both dam releases had zero sediment content, and sediment supply from the Paria River during both releases was negligible (Figure 7). Measurements of suspended-sediment concentration at the Lees Ferry gauge indicate that the reach between Glen Canyon Dam and the Paria River supplied little sediment to the study reach. The contributions of sediment from the smaller, ungauged tributaries in Marble Canyon were also ignored; the annual magnitude of the fine-sediment supply from these tributaries is only 5–20% of that from the Paria River [*Webb et al.*, 2000].

[27] Sediment transport at the lower Marble Canyon gauge was calculated using suspended-sediment samples collected on 27 and 29 March and 2 April 1996 (days 1, 3, and 7 of the 1996 Controlled Flood), and daily during the September 2000 Powerplant Capacity Flow (Figure 8). Uncertainties associated with calculating sediment loads from measured sediment concentrations for the Colorado River are at least 5% [*Topping et al.*, 2000b]. In this paper, a more conservative uncertainty of 10% was assigned to the measured sediment loads of the Colorado River for both high flows. Given that discharge remained constant and there was no tributary flooding during the budget computation periods, the error associated with estimating sediment load over each flood is primarily that associated with estimating the suspended sediment concentrations. The

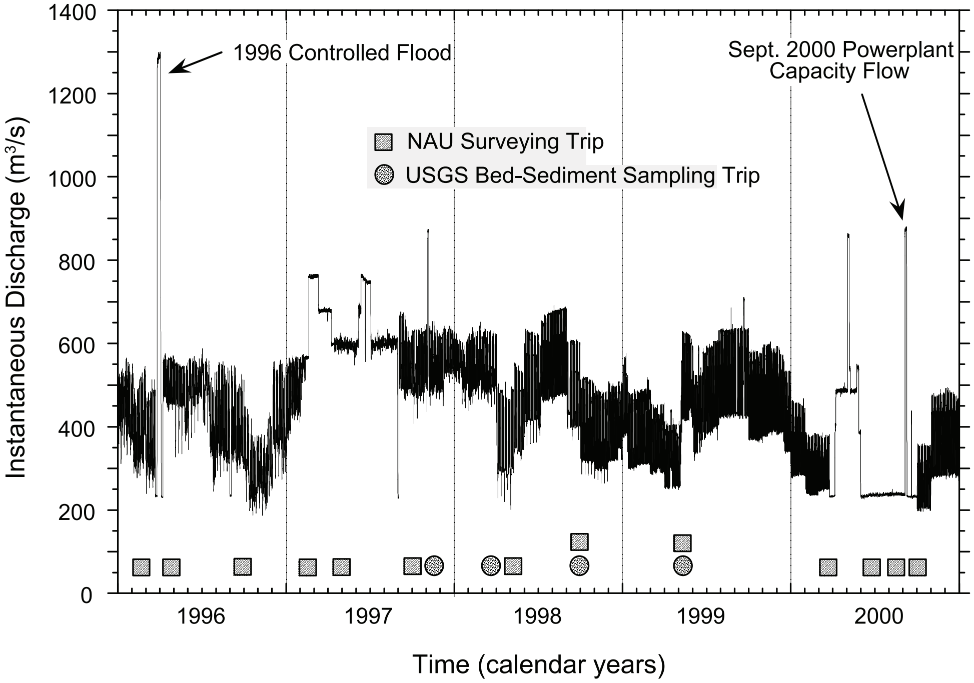

Figure 6. Instantaneous discharge of the Colorado River at the Lees Ferry gauge 1995–2000. Shown are the 1996 Controlled Flood and the September 2000 Powerplant Capacity Flow, the times of the Northern Arizona University (NAU) surveying trips, and the times of the USGS bed-sediment sampling trips.

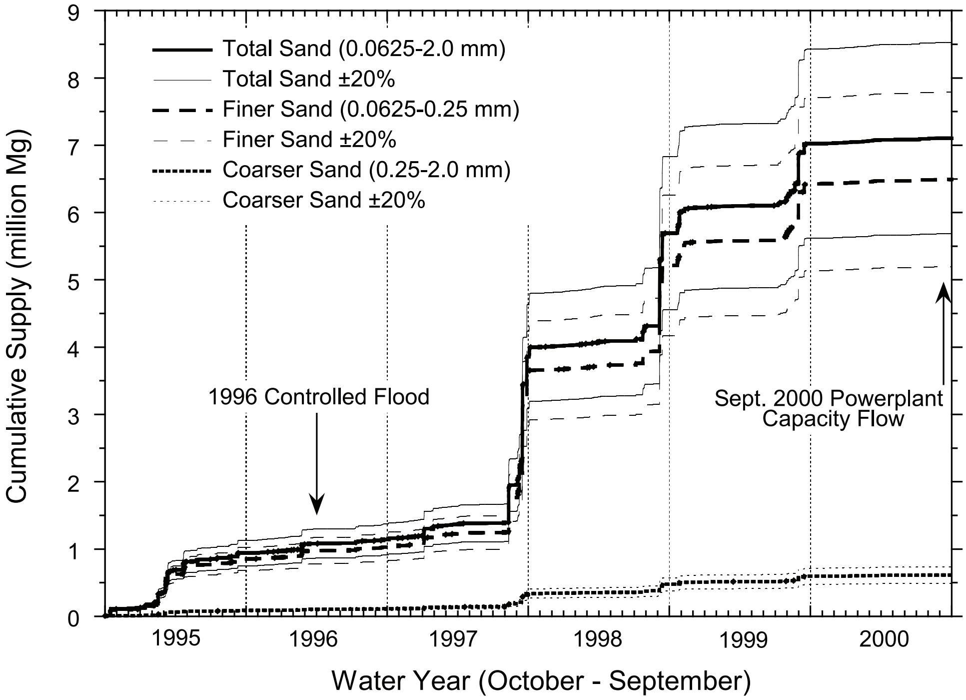

Figure 7. Estimated sediment supplied by the Paria River between October 1994 and September 2000. The amount and grain sizes of sediment were calculated using the predictive flow and sediment-transport model of *Topping* [1997]. The cumulative mass of total sand (0.0625–2.0 mm), fine sand (0.0625–0.25 mm) and coarse sand (0.25–2.0 mm) with 20% uncertainties is shown. Also shown are the times of the 1996 Controlled Flood and the September 2000 Powerplant Capacity Flow. The mean annual sand supply for this 6-year period, 1.2 ± 0.3 million Mg, was average compared to the entire period of gauge record estimated by *Topping* [1997]. Nearly two thirds of this sediment supply occurred during floods in 1997 and 1998. In addition, the median size (D_{50}) of the sand inflow was about the same as the estimated D_{50} of 0.13 mm for the period of record.

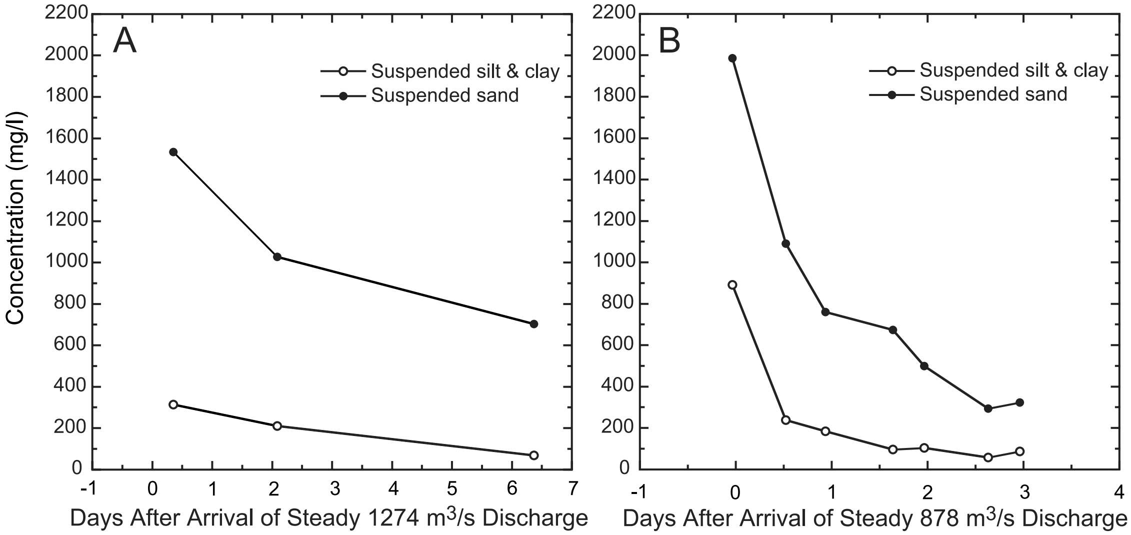

Figure 8. Measured suspended-sediment concentrations at the Lower Marble Canyon gauge. (a) The 1996 Controlled Flood. (b) The September 2000 Powerplant Capacity Flow. Note that the peak suspended-sand concentration measured during the September 2000 Powerplant Capacity Flow is greater than that during the 1996 Controlled Flood. This is probably not a result of a greater sediment supply but simply a result of the measurements being made more closely in time to the arrival of the peak discharge in 2000. Travel time of each high dam release has been removed, so that zero corresponds to the arrival time of the released flood peak.

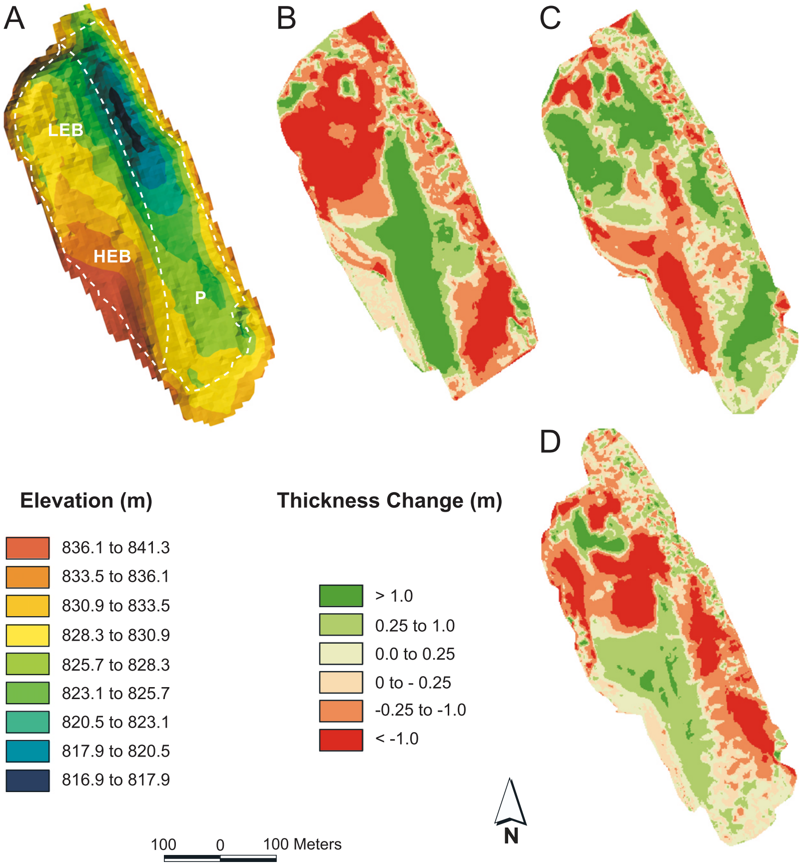

Figure 9. (a) Triangulated irregular network (TIN) model fit to the combined topographic and hydrographic data collected on 24 August 2000 at long-term study site 47. The thickness of erosion and deposition (b) following the 1996 Controlled Flood, (c) between the 1996 Controlled Flood and the September 2000 Powerplant Capacity Flow, and (d) following the September 2000 Powerplant Capacity Flow. The dashed white line in Figure 9a is the location of the boundary used for volumetric changes in eddy and main-channel environments. P, main-channel pool; HEB, high-elevation eddy bar; LEB, low-elevation eddy bar. The sequence shows a pattern of deposition at high elevations in the eddy and erosion at low elevations in the eddy and main channel during high flows, and the opposite pattern of high elevation erosion and low elevation deposition during the intervening low flows.

1996 samples and techniques for determining suspended sediment concentration are reported by *Konieczki et al.* [1997], grain-size analyses of the 1996 samples are reported by *Topping et al.* [1999], and similar analyses of the 2000 samples are available electronically from http://www.gcmrc.gov/.

4.1.2. Sediment Storage and Characteristic Grain Sizes

[28] Changes in fine-sediment storage were estimated from field measurements of topographic change, estimates of sediment storage area from aerial photographs and side-scan sonar surveys, and measurements of sediment grain size. For the purposes of this study, sediment stored above the elevation reached by the 1996 Controlled Flood were not considered active storage and were excluded from the sediment budget.

4.1.2.1. Topographic Data

[29] Detailed field measurements were made at 11 long-term study sites that had been surveyed annually or more frequently between 1990 and 2002 [*Beus et al.*, 1992; *Kaplinski et al.*, 1995; *Hazel et al.*, 1999] (Figure 2). The sites comprise approximately 4% and 5% of the eddy and main-channel area, respectively, in the study area. Each site includes an eddy and adjacent main-channel bed (Figure 9). Surveys were conducted immediately before and after each high release to define changes in storage over the same periods during which sediment transport was measured (Figure 6). We combined bathymetric surveys of submerged areas with ground surveys of emergent areas and produced a triangulated irregular network (TIN) model using Delaunay triangulation [see *McCullagh*, 1988, 1998]. Topographic change caused by erosion or deposition of fine sediment was determined by direct TIN comparison.

[30] We estimated the volume of sediment stored in each eddy at specific times as the difference between each TIN and the same minimum surface used to calculate the predam active storage volume (Figure 5). We separated the main-channel bed from each eddy by establishing a fixed boundary at the base of the eddy bars because this topographic feature remained relatively stable throughout the 1990s (Figure 9). Although the area of the eddy defined in this way is somewhat different than the area of the associated EDZ (Figure 5), it does not affect the interpretation of our

results. We also distinguished between the high-elevation and low-elevation part of each eddy bar as the area above or below the stage of 227 m^3/s, respectively.

[31] Channel-margin deposits were not directly surveyed before or after the 1996 Controlled Flood, and sediment-thickness changes were based on observations of excavated trenches (D. Rubin, USGS, and J. C. Schmidt, Utah State University, unpublished data, 1999). During the September 2000 Powerplant Capacity Flow, channel-margin deposits were surveyed at 6 cross-sections previously established by *Graf et al.* [1995] and at 18 cross sections established in March 2000 by *Cain et al.* [2001].

4.1.2.2. Area Measurement of Sediment-Storage Environments

[32] Results from the five GIS reaches were used to determine the aerial proportion of eddy, channel-margin deposit, and main-channel storage in Marble Canyon (Table 1). We multiplied these areas by the average change in deposit thickness in order to estimate the total volume change in each storage environment. We assumed that all bed change in the storage environments involved fine sediment. The total area of the main channel (8.5×10^6 m^2) was scaled by the percentage of bed in the main channel composed of gravel, boulders, and bedrock (where fine sediment does not occur) and rapid/riffle area (Table 1), which leads to an aerial extent of fine sediment on the main-channel bed as approximately 0.94×10^6 m^2 (or 11% of the total channel area excluding eddies). The percentage of bed in the main channel composed of gravel, boulders, and bedrock was extrapolated from GIS analysis (S. Goeking, Utah State, unpublished data, 2003) of side-scan sonar surveys conducted before and after the September 2000 Powerplant Capacity Flow by *Wong et al.* [2003]. Although sand in interstices of gravel is a potentially important component of the sediment budget in some rivers [*Lisle*, 1995], changes in the storage of this component were ignored in this analysis, because (1) interstitial sand comprises a much smaller volume than either the volume of sand in patches on the channel bed or in the eddy bars, and (2) video images of interstitial sand indicate that this sand is typically very coarse.

4.1.3. Sediment Grain Size

[33] The uncertainties in extrapolating the detailed measurements to the entire study area led us to develop an alternative technique with which to partition sediment storage changes. There is strong evidence that fine-sediment sizes are segregated among depositional environments. Generally, fine sediment on the main-channel bed is medium and coarse sand with little or no silt or clay [*Wilson*, 1986; *Schmidt and Graf*, 1990; *Topping et al.*, 2000b]. In contrast, the sizes of sediment in eddy bars and channel-margin deposits are finer [*Howard and Dolan*, 1981; *Schmidt and Graf*, 1990; *Budhu and Gobin*, 1994; *Rubin et al.*, 1998; *Topping et al.*, 1999; *Topping et al.*, 2000b].

[34] The fine-sediment grain size in each of the storage environments was determined from pipe-dredge samples. Sand patches on the main-channel bed were sampled in the center of downstream flow, and eddies were sampled in their center. These samples were collected throughout the study area in November 1997, March 1998, September 1998, and May 1999 (Figure 6). Field methods and grain-size analyses for the 1997 and 1998 samples were previously reported by *Topping et al.* [2000b]. Channel-margin deposits were not systematically sampled in this study because the average grain-size was found by *Schmidt and Graf* [1990] to be similar to that of eddy bars. Because the average differences between the 1997, 1998, and 1999 data were relatively small, we assumed that the mean 1997–1999 grain-size distributions for the main-channel and eddy storage environments were good approximations for the grain-size distributions in these storage environments in other years.

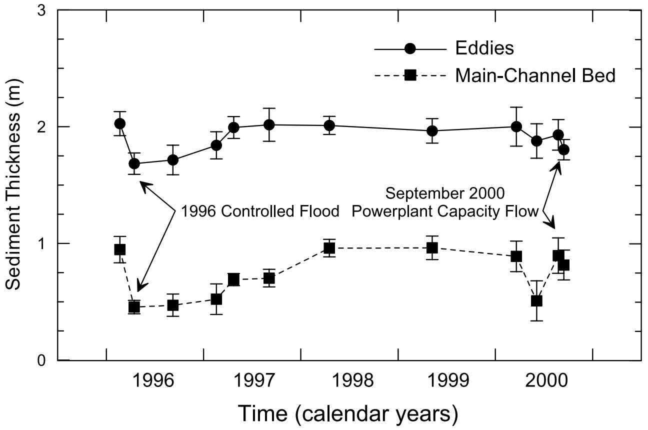

Figure 10. Temporal sequence of average eddy and main-channel bed sediment thickness changes at the 11 long-term monitoring sites 1996–2000. Error bars are standard error.

4.2. Results

4.2.1. Analysis of Fine-Sediment Storage in the Postdam River

[35] The mean thickness of sediment stored in eddies at the detailed study sites was 2.02 ± 0.10 m in March 1996 (Figure 10). The total eddy area below the stage of the 1996 Controlled Flood is approximately 1.7×10^6 m^2, which leads to an estimate of the volume of fine sediment in active storage in Marble Canyon eddies as about 3.4×10^6 m^3, or 5.9 million Mg. The average thickness of sediment stored in the main channel at the detailed study sites was 0.92 ± 0.11 m in March 1996 (Figure 10), which leads to an estimate of the volume of fine sediment stored on the main channel bed as about 0.8×10^6 m^3 (or 1.4 million Mg). These results are probably accurate to within a factor of 2 and, given this uncertainty, 51–94% of the sediment in Marble Canyon is stored in eddies; despite the fact that eddies only comprise ~17% of the total surface area of the flow field.

4.2.2. Variation in the Size of Fine Sediment in Storage and in Transport

[36] The mean grain-size of sediment in eddies was much finer than that on the bed of the main channel during 4 years of measurements, despite short-term local fining of the channel bed following Paria River floods (Figure 11). Between 1997 and 1999, the average D_{50} of fine sediment on the main-channel bed was about 0.40 mm, and the average D_{50} of eddy sediment was about 0.18 mm. On average, 70% of the fine sediment in the eddies during the study period was finer than 0.25 mm, and 2.4% was finer than sand, whereas only 17% of the fine sediment in the channel was finer than 0.25 mm, and 0.16% was finer than

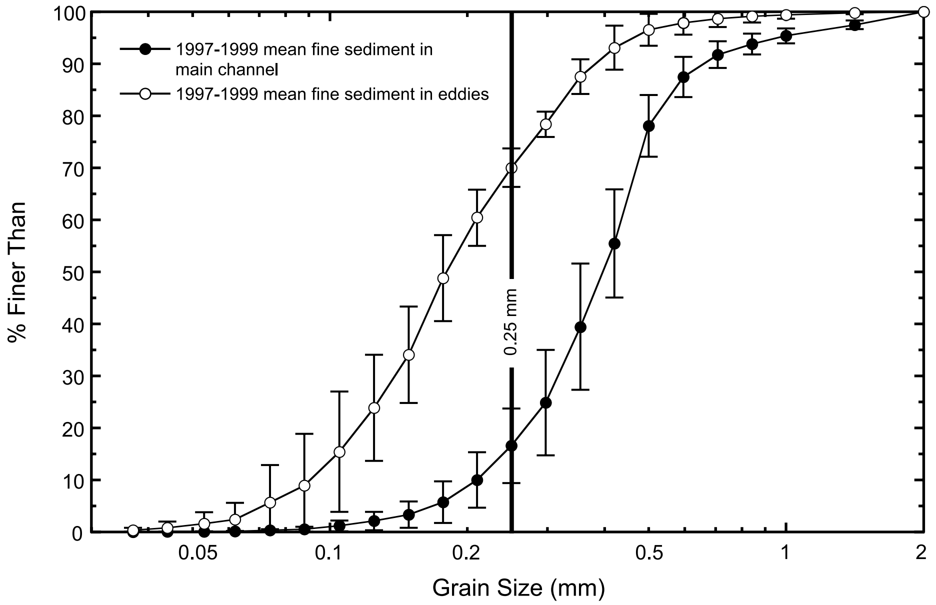

Figure 11. Average cumulative grain-size distributions for the sand on the main-channel bed and in eddies in the Colorado River in Marble Canyon. Error bars are 1 standard deviation. The patches of sand on the bed of the channel are predominantly composed of sand coarser than 0.25 mm; eddies are composed of sand predominantly finer than 0.25 mm.

sand. This distinct difference in grain-size distribution between eddy and main-channel storage environments proves crucial in computing a fine-sediment budget based on grain size, because about 92% of the influx of sand from the Paria River is finer than 0.25 mm (Figure 7).

[37] Depletion of the upstream supply of fine sediment resulted in rapid decrease in the total sediment concentration during the first day of both the 1996 Controlled Flood and the September 2000 Powerplant Capacity Flow (Figure 8). The sediment exported from the study area during each high flow was eroded from the sediment stored in Marble Canyon because there was negligible fine-sediment influx from either the Paria River or the Colorado River upstream from the Lees Ferry gauge during these two releases. The sediment export at the lower Marble Canyon gauge during the 1996 Controlled Flood was approximately 0.67 million Mg of sand and 0.12 million Mg of silt and clay. Of the sand-sized sediment, about 41% was very fine sand (0.0625–0.125 mm), about 38% was fine sand (0.125–0.25 mm), about 19% was medium sand (0.25–0.5 mm), and only about 2% was coarser than 0.5 mm [*Topping et al.*, 1999]. During the September 2000 Powerplant Capacity Flow, approximately 0.22 million Mg of sand and 0.065 million Mg of silt and clay were exported past the lower Marble Canyon gauge. Of the sand-sized sediment, about 62% was very fine sand (0.0625–0.125 mm), about 32% was fine sand (0.125–0.25 mm), about 5% was medium sand (0.25–0.5 mm), and only about 1% was coarser than 0.5 mm.

4.2.3. Sediment Budgets for the 1996 Controlled Flood and the September 2000 Powerplant Capacity Flow

[38] The two different techniques used to estimate changes in fine-sediment storage during the 1996 Controlled Flood and September 2000 Powerplant Capacity Flow each have their own respective strengths and provide independent checks on the other. Measurement of topographic change at selected sites provides a direct accounting of the depositional and erosional environments, but relies on substantial extrapolation. The grain-size technique provides a more global accounting of the source environments of the sediment eroded from Marble Canyon but involves no actual measurements of topographic change.

4.2.3.1. Sediment Budgets Developed From Topographic Measurements

[39] Measurements during both high flows indicate that high-elevation deposition in eddies and as channel-margin deposits was accompanied by scour of the low-elevation parts of eddy bars and those parts of the main-channel bed where fine sediment was stored (Figure 9) [also see *Andrews et al.*, 1999; *Hazel et al.*, 1999; *Schmidt*, 1999]. In both high flow events, the average increase in fine sediment thickness at high elevation was greatly exceeded by losses in fine-sediment thickness at low elevation (Table 4). The topographic-based sediment budget for Marble Canyon was determined as

$$\Delta S = A_{eddies}T_{eddies} + A_{cm\,deposits}T_{cm\,deposits} + A_{channel}T_{channel}, \qquad (1)$$

where ΔS is the total sediment-storage change in Marble Canyon, A is the storage area in Marble Canyon for eddies, channel-margin deposits, and the main-channel bed (Table 1), and T is the average thickness change of eddy, channel margin deposits, and the main-channel bed (Table 4). The accuracy of the sediment budget was evaluated by comparing ΔS to the difference in sediment flux at the upstream and downstream ends of the study area,

$$\Delta S = S_{supply} - S_{export}, \qquad (2)$$

Table 4. Summary of Average Sediment-Thickness Changes Derived from Topographic Data

Topographic Storage Components	1996 Controlled Flood,[a] m	September 2000 Powerplant Capacity Flow,[a] m
High-Elevation Eddy	0.18 ± 0.05	0.03 ± 0.02
Low-Elevation Eddy	−0.56 ± 0.18	−0.15 ± 0.08
Channel Margin	0.30 ± 0.10	0.15 ± 0.07
Main-Channel Bed	−0.49 ± 0.13	−0.08 ± 0.07

[a]Uncertainties are 1 standard error.

where S_{supply} is the sediment supply from the Paria River (set equal to zero) and S_{export} is the sediment export past the Lower Marble Canyon gauge.

[40] The difference between ΔS and S_{export} during the two high releases represents an imbalance in the budgets (Table 5). The difference is approximately 0.94×10^6 Mg and 0.17×10^6 Mg for the 1996 Controlled Flood and September 2000 Powerplant Capacity Flow, respectively. The budget imbalance reflects errors in our extrapolation methods and indicates that one or more of the storage environments was not accurately characterized. Although the error could be a result of an inaccurate estimate of S_{export}, we attribute the inaccuracy to the fact that the estimates of ΔS in the main-channel bed are based on measurements made in pools immediately upstream or downstream from rapids. Thus, as in the case of the predam observations of scour and fill in the pools at the Lees Ferry and Grand Canyon gauges, the magnitudes of scour and fill measured in pools probably overestimates the average magnitude of scour and fill elsewhere in the main channel. Also, as observed at the Grand Canyon gauge [*Topping et al.*, 2000b] and elsewhere in selected reaches during the 1996 Controlled Flood [*Anima et al.*, 1998], scour of sediment from main-channel pools during high flows is partially balanced by deposition of sediment outside of the deeper pools. Another and perhaps more likely possibility is that the overestimation is a result of coarser material mobilized in areas of high sheer stress produced by the high flows [*Wiele et al.*, 1999]. Thus bed thickness changes may not be solely due to changes in fine sediment.

4.2.3.2. Sediment Budgets Developed From Measurements of the Grain-Size Distribution of Exported Sediment

[41] The grain-size budgeting technique was developed to independently evaluate the errors in the topographic budget described above. The grain-size budgeting technique involved using the measured size distribution of sand, silt, and clay exported past the lower Marble Canyon gauge in conjunction with (1) the 1997–1999 mean grain-size distributions of the fine sediment stored in the eddy and main-channel environments (Figure 11) and (2) the computation that between 51 and 94% of the sand, silt, and clay in Marble Canyon is stored in eddies. The change in the mass of fine sediment was approximated by

$$\Delta S = \sum_{i=1}^{N} \left(\frac{a_{eddies} b_{eddies_i}}{a_{eddies} b_{eddies_i} + a_{channel} b_{channel_i}} \Delta S_i + \frac{a_{channel} b_{channel_i}}{a_{eddies} b_{eddies_i} + a_{channel} b_{channel_i}} \Delta S_i \right), \qquad (3)$$

where N is the total number of size classes of sand, silt, and clay, a_{eddies} is the proportion of sand, silt, and clay stored in the eddies in Marble Canyon (given the uncertainty in this estimate, this value ranges from 0.51 to 0.94), $a_{channel}$ is the fraction of sand, silt, and clay stored in the main channel (given the uncertainty in this estimate, this value ranges from 0.06 to 0.49), b_{eddies_i} is the fraction of each sediment size class i stored in eddies (computed from the data in Figure 9), $a_{channel_i}$ is the fraction of each sediment size class i stored in the main channel (computed from the data in Figure 11), and ΔS_i is the change in the mass of each sediment size class i in Marble Canyon (as measured at the lower Marble Canyon gauge). Thus the change in the mass of the sand, silt, and clay in the eddies in Marble Canyon is

$$\Delta S_{eddies} = \sum_{i=1}^{N} \left(\frac{a_{eddies} b_{eddies_i}}{a_{eddies} b_{eddies_i} + a_{channel} b_{channel_i}} \Delta S_i \right), \qquad (4)$$

and the change in the mass of the sand, silt, and clay in the main channel in Marble Canyon is

$$\Delta S_{channel} = \sum_{i=1}^{N} \left(\frac{a_{channel} b_{channel_i}}{a_{eddies} b_{eddies_i} + a_{channel} b_{channel_i}} \Delta S_i \right). \qquad (5)$$

The mass of eddy- and main-channel-derived sediment exported from Marble Canyon is shown in Figure 12 for each grain-size class. Given the uncertainties in the methods described above, these results indicate that nearly all of the silt and clay and the majority of the very fine to fine sand (0.0625–0.25 mm) exported during the 1996 Controlled Flood and the September 2000 Powerplant Capacity Flow were eroded from eddies, whereas the medium to coarse

Table 5. Topographic-Based Sediment Budget for the Colorado River in Marble Canyon[a]

Budget Components	1996 Controlled Flood, 10^6 Mg	September 2000 Powerplant Capacity Flow, 10^6 Mg
Supply from the Paria River (S_{supply})	Negligible	Negligible
High-elevation sediment in eddies, >227 m^3/s	0.54 ± 0.14	0.09 ± 0.06
Low-elevation sediment in eddies, <227 m^3/s	−1.63 ± 0.52	−0.44 ± 0.23
Channel-margin deposits, >227 m^3/s	0.09 ± 0.02	0.01 ± 0.01
Main-channel bed sediment, <227 m^3/s	−0.73 ± 0.20	−0.12 ± 0.11
Total sediment storage change, ΔS	−1.73 ± 0.57	−0.46 ± 0.28
Export past Lower Marble Canyon gauge, S_{export}	0.79 ± 0.08	0.29 ± 0.03

[a]Uncertainties in storage components are based on the standard error of the mean sediment-thickness change and do not include errors associated with the GIS maps and extrapolation of component area to the reach scale. Uncertainty in the export component is based on the 10% uncertainties associated with the suspended-sediment measurements.

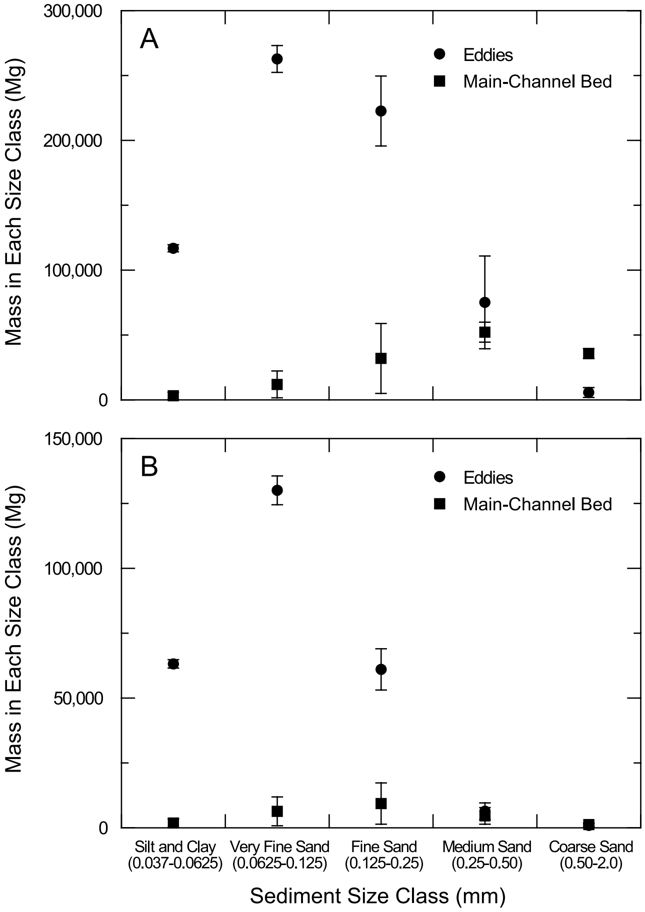

Figure 12. The proportions of eddy- and channel-derived sediment eroded from Marble Canyon. (a) The 1996 Controlled Flood. (b) The September 2000 Powerplant Capacity Flow. Error estimates incorporate uncertainties associated with the suspended-sediment and grain-size measurements and the estimate that 51 to 94% of the fine sediment in Marble Canyon is stored in eddies (see section 4.2.1).

sand (0.25–2.0 mm) was eroded from both eddies and the main channel. About 0.68 ± 0.08 million Mg (~86%) of the sediment mobilized and transported downstream, during the 1996 Controlled Flood, was eroded from eddies, whereas during the September 2000 Powerplant Capacity Flow, about 0.26 ± 0.02 million Mg (~92%) of the sediment in transport was eroded from eddies. The magnitudes of eddy and channel-derived sand in each size class were relatively similar between the two experimental releases. Very fine and fine sand was the dominant portion of the sediment eroded from eddies varying from 71% during the 1996 Controlled Flood, to 73% during the September 2000 Powerplant Capacity Flow. Of the sediment eroded from the main channel, fine to medium sand was the dominant portion, varying from 79% during the 1996 Controlled Flood, to 60% during the September 2000 Powerplant Capacity Flow.

4.2.3.3. Reconciliation Between the Topographic- and Grain-Size-Based Sediment Budgets

[42] Although there is potential for large error in a sediment budget constructed from a variety of data sources, the estimates of ΔS in eddies by the two independent methods provides an estimate of the accuracy of the extrapolation of the topographic data to the reach scale. Subtracting the sediment transferred to high-elevation eddy bars and channel-margin deposits from that eroded from lower elevations in eddies, yields the total sediment efflux from Marble Canyon supplied by eddies (Table 5). This estimate of eddy-derived sediment during the 1996 Controlled Flood (1.0 ± 0.36 million Mg) agrees, within estimated error, with the grain-size based estimate in Figure 12 (0.68 ± 0.08 million Mg). These findings support the conclusion of *Schmidt* [1999] that eddies were the primary source of most of the sediment in transport during the 1996 Controlled Flood. Similar to the results for the 1996 Controlled Flood, the topographic-based estimate of the export of eddy-derived sediment during the September 2000 Powerplant Capacity Flow (0.34 ± 0.17 million Mg) agrees, within error, with the grain-size based estimate in Figure 12 (0.26 ± 0.02 million Mg). These results suggest that the main-channel storage environment in the topographic-based budget was overestimated and accounts for the budget imbalance in Table 5.

[43] The topographic-based estimate of eddy-derived sediment and the grain-size estimate of channel-derived sediment can be reconciled into a complete sediment budget that is balanced between ΔS and S_{export} during the two high dam releases. During the 1996 Controlled Flood, about 1.74 ± 0.6 million Mg of sediment was eroded from eddies and the main channel bed. About 94% of this amount was eroded from the lowest parts of eddy bars. Of this eroded mass, 36% was deposited as high-elevation bank deposits above the stage of 227 m^3/s. Of the sediment deposited at high elevation, about 86% was deposited in eddies and the remainder as channel-margin deposits. Using the same reasoning as for the 1996 Controlled Flood, the sediment budget constructed for the September 2000 Powerplant Capacity Flow indicates that about 0.46 ± 0.25 million Mg of sediment was eroded from eddies and the main channel. About 95% of this amount was eroded from low-elevation eddy bars, and 21% of this amount was deposited at high elevation. About 91% of the sediment redistributed to high elevation was deposited in eddies. Although the pattern of storage change was similar to the budget for the 1996 Controlled Flood, 6 times less sediment was deposited as high-elevation eddy bars and channel-margin deposits, during the lower-discharge September 2000 Powerplant Capacity Flow, and a greater percentage of sediment was exported from Marble Canyon.

5. Discussion

[44] Glen Canyon Dam releases clear water into a river channel formerly adjusted to extremely large suspended sediment loads, resulting in long-term changes in sediment storage. Whereas fine sediment was stored in both the main channel and in eddies in the predam environment, eddies are now the dominant temporary storage site. Thus eddies are the primary sink and source term in the postdam sediment budget; a result suggested by previous studies but never quantified [*Rubin et al.*, 1994; *Schmidt and Rubin*, 1995]. A fine-sediment deficit exists in Marble Canyon and downstream response of the channel includes degradation of eddy

storage and textural segregation of fine sediment into distinct grain-size distributions.

[45] Calculations of average bed-elevation change suggest that about half of the fine sediment stored in Marble Canyon in the predam era was stored on the main-channel bed (Table 3). Parts of the main-channel bed that once scoured during the three months of the annual snowmelt flood and refilled during the nine months of the fine-sediment accumulation season are now permanently devoid of fine sediment [*Schmidt et al.*, 2004]. The magnitude and proportion of fine sediment evacuated from storage during the two experimental dam releases in this study indicates that about 90% of the fine sediment in the riverine ecosystem is now stored in eddies (Table 5).

[46] During the short periods when the Paria River is in flood, eddies and the main channel are blanketed with fine sediment and neither environment predominates as a sink for new inputs. However, when tributary flooding ceases and suspended-sand concentrations begin to decrease this material is rapidly eroded from the bed under normal dam operations. The bed coarsens, especially in the main channel [*Topping et al.*, 2000b]. Within months, active storage of fine sediment is almost exclusively in eddies, and only small amounts of the finer sand sizes (<0.25 mm) are stored in sandy patches on the main-channel bed, where the median size is much coarser (Figure 11). This downstream response to the transport capacity of the river and the available sediment supply results in a marked similarity of bed-material grain sizes between the sediment stored in eddies and that supplied by the Paria River (Figure 7).

[47] The results presented here are of more than scientific interest. The long-term fate of sandbars depends on the ability of dam managers to utilize special dam releases for redistribution of the relatively limited amount of sand supplied by the Paria River [*Rubin et al.*, 2002]. Dam managers want to know how much sand is delivered from the Paria River, how long that sand remains in Marble Canyon, where that sand resides before it is transported downstream, and how much will be mobilized during these special dam releases. Because they are infrequently inundated, higher-elevation flood deposits have a longer response time to normal dam operations than subaqueous deposits in low-elevation eddies or on the main-channel bed. These higher-elevation deposits erode or adjust over a period of years to decades [*Schmidt et al.*, 2004]. Unfortunately, high dam releases that occur when the channel bed is not temporarily enriched in fine sediment scour the sediment in active eddy storage. During the 1996 Controlled Flood, the percentage of sand redistributed to higher elevations was small (∼36%), relative to that transferred out of eddies, and this ratio was even smaller during the September 2000 Powerplant Capacity Flow (∼26%).

[48] *Rubin et al.* [1994] made generalized predictions of the long-term fate of bars at different distances downstream from Glen Canyon Dam. The model that presented the greatest difficulties in managing the scarce sand resources in GCNP turns out to be the case that actually exists: Most sand is stored in eddies. Prolonged periods without significant input of sand from the Paria River will result in continued erosion of sandbars in Marble Canyon. The area of high-elevation eddy deposits in 2003 was smaller than the area of these deposits in 1984 or 1990 [*Schmidt et al.*, 2004]. The dilemma for the future is that in sediment-deficient reaches near Glen Canyon Dam, and for some undetermined distance downstream, controlled floods will export sediment from the same eddies where bar building is desired.

6. Conclusions

[49] The combination of a greatly reduced sediment supply and the operations of Glen Canyon Dam have changed the pattern of sediment transport and storage in Marble Canyon. The predominant proportion of fine sediment in this canyon river is now stored in eddies, rather than stored in both eddies and the main-channel bed. Because eddies comprise only ∼17% of the total channel area in Marble Canyon, the supply available for entrainment by high releases is limited. In addition, the spatial distribution of sizes of sediment is different between eddy and main-channel deposits, with the grain-size distribution in eddies being far more similar to the median size of the long-term supply of sand from the Paria River. Both the sediment budgets and field data indicate that floods scheduled in seasons other than the short period of time when sediment is shown to accumulate in this system (during periods of tributary flooding) will erode sediment from long-term eddy storage, resulting in continued degradation of the fine-sediment deposits in Marble Canyon.

[50] **Acknowledgments.** This study was funded by the U.S. Bureau of Reclamation through the Glen Canyon Environmental Studies and later through the USGS Grand Canyon Monitoring and Research Center. The authors thank Mark Gonzales, Keith Kohl, and Mark Manone for assistance in the field and Sara Goeking, Mike Breedlove, and Jairo Hernandez for GIS support. Thanks also go to Paul Grams, Ted Melis, Rod Parnell, and Steve Wiele for helpful and constructive comments on the initial version of this manuscript. A subsequent version was reviewed by Peter Ashmore, Yvonne Martin, and Robert Jacobson. We thank Peter Wilcock, John Pitlick, and an anonymous reviewer for suggestions on improving the final version of the manuscript.

References

Andrews, E. D. (1990), Effects of stream flow and sediment on channel stability of the Colorado River: A perspective from Lees Ferry, Arizona, in *The Geology of North America*, vol. 0–1, *Surface Water Hydrology*, edited by M. G. Wolman and H. C. Riggs, pp. 303–310, Geol. Soc. of Am., Boulder Colo.

Andrews, E. D. (1991), Sediment transport in the Colorado River basin, in *Colorado River Ecology and Dam Management*, edited by G. R. Marzolf, pp. 54–74, Natl. Acad. Press, Washington, D. C.

Andrews, E. D., C. E. Johnston, J. C. Schmidt, and M. Gonzales (1999), Topographic evolution of sand bars, in *The Controlled Flood in Grand Canyon*, *Geophys. Monogr. Ser.*, vol. 110, edited by R. H. Webb et al., pp. 117–130, AGU, Washington, D. C.

Anima, R. J., M. S. Marlow, D. M. Rubin, and D. J. Hogg (1998), Comparison of sand distribution between April 1994 and June 1996 along six reaches of the Colorado River in Grand Canyon, Arizona, *U.S. Geol. Surv. Open File Rep., 98-141*, 33 pp.

Barnhardt, W., R. Kayen, D. Rubin, and D. Minasian (2001), The internal structure of sand bars on the Colorado River, Grand Canyon, as determined by ground-penetrating radar, *U.S. Geol. Surv. Open File Rep., 01-425*, 8 pp.

Beus, S. S., C. C. Avery, L. E. Stevens, M. A. Kaplinski, and B. L. Cluer (1992), The influence of variable discharge regimes on Colorado River sandbars below Glen Canyon Dam, in *The Influence of Variable Discharge Regimes on Colorado River Sandbars Below Glen Canyon Dam*, edited by S. S. Beus and C. C. Avery, final report to Glen Canyon Environmental Studies, Natl. Park Service, Flagstaff, Ariz.

Budhu, M., and R. Gobin (1994), Instability of sandbars in Grand Canyon, *J. Hydraul. Eng.*, *120*, 919–933.

Cain, J., IV, M. Kaplinski, J. E. Hazel Jr., M. Manone, R. Parnell, and J. Souter (2001), Monitoring channel margin fine-grained sediment deposits in the Colorado River ecosystem downstream from Glen Canyon Dam, final report to Grand Canyon Monitoring Research Center, 19 pp., N. Ariz. Univ., Flagstaff, Ariz.

Carothers, S. W., and B. T. Brown (1991), *The Colorado River through Grand Canyon: Natural History and Human Change*, Univ. Ariz. Press, Tucson.

Galay, V. J. (1983), Causes of riverbed degradation, *Water Resour. Res.*, *19*, 1057–1090.

Graf, J. B., J. E. Marlow, G. G. Fisk, and S. M. D. Jansen (1995), Sand storage changes in the Colorado downstream from the Paria and Little Colorado Rivers, June 1992 to February 1994, *U. S. Geol. Surv. Open File Rep., 95-446*, 61 pp.

Grams, P. E., and J. C. Schmidt (1999), Geomorphology of the Green River in the eastern Uinta Mountains, Dinosaur National Monument, in *Varieties of Fluvial Form*, edited by A. J. Miller and A. Gupta, pp. 81–111, John Wiley, Hoboken, N. J.

Grant, G. E., J. C. Schmidt, and S. L. Lewis (2003), A geological framework for interpreting downstream effects of dams on rivers, in *A Peculiar River: Geology, Geomorphology, and Hydrology of the Deschutes River, Oregon*, *Water Sci. Appl.*, vol. 7, edited by J. E. O'Connor and G. E. Grant, pp. 203–219, AGU, Washington, D. C.

Hazel, J. E., Jr., M. Kaplinski, R. Parnell, M. Manone, and A. Dale (1999), Topographic and bathymetric changes at thirty-three long-term study sites, in *The Controlled Flood in Grand Canyon*, *Geophys. Monogr. Ser.*, vol. 110, edited by R. H. Webb et al., pp. 161–184, AGU, Washington, D. C.

Hereford, R., K. S. Thompson, K. J. Burke, and H. C. Fairly (1996), Tributary debris fans and the late Holocene alluvial chronology of the Colorado River, eastern Grand Canyon, Arizona, *Geol. Soc. Am. Bull.*, *108*(1), 3–19.

Howard, A. D., and R. Dolan (1981), Geomorphology of the Colorado River, *J. Geol.*, *89*, 269–298.

Kaplinski, M., J. E. Hazel Jr., and S. S. Beus (1995), Monitoring the effects of Interim Flows from Glen Canyon Dam on sand bars in the Colorado River Corridor, Grand Canyon National Park, Arizona, final report to Glen Canyon Environmental Studies, 62 pp., N. Ariz. Univ., Flagstaff, Ariz.

Kieffer, S. W. (1985), The 1983 hydraulic jump in Crystal Rapid: Implications for river running and geomorphic evolution in the Grand Canyon, *J. Geol.*, *93*, 385–406.

Konieczki, A. D., J. B. Graf, and M. C. Carpenter (1997), Streamflow and sediment data collected to determine the effects of a controlled flood in March and April 1996 on the Colorado River between Lees Ferry and Diamond Creek, Arizona, *Geol. Surv. Open File Rep., OF97-224*, 55 pp.

Laursen, E. M., S. Ince, and J. Pollack (1976), On sediment transport through Grand Canyon, paper presented at Third Federal Interagency Sedimentation Conference, Water Resour. Counc., Denver, Colo.

Lisle, T. E. (1995), Particle size variations between bed load and bed material in natural gravel bed channels, *Water Resour. Res.*, *31*, 1107–1118.

Magirl, C. S., R. H. Webb, and P. G. Griffiths (2005), Changes in the water surface profile of the Colorado River in Grand Canyon, Arizona, between 1923 and 2000, *Water Resour. Res.*, *41*, W05021, doi:10.1029/2003WR002519.

McCullagh, M. J. (1988), Terrain and surface modeling systems: Theory and practice, *Photogramm. Rec.*, *12*, 747–779.

McCullagh, M. J. (1998), Quality, use and visualization in terrain modeling, in *Landform Monitoring, Modeling and Analysis*, edited by S. N. Lane, K. S. Richards, and J. H. Chandler, pp. 95–117, John Wiley, Hoboken, N. J.

Miller, A. J. (1994), Debris-fan constrictions and flood hydraulics in river canyons: Some implications from two-dimensional flow modeling, *Earth Surf. Processes Landforms*, *19*, 681–697.

National Research Council (1999), *Downstream: Adaptive Management of Glen Canyon Dam and the Colorado River Ecosystem*, 230 pp., Natl. Acad. Press, Washington, D. C.

Petts, G. E. (1979), Complex response of river channel morphology subsequent to reservoir construction, *Prog. Phys. Geogr.*, *3*(3), 329–362.

Randle, T. J., and E. L. Pemberton (1987), Results and analysis of STARS modeling efforts of the Colorado River in Grand Canyon, *Tech. Rep. NTIS PB88-183421*, 41 pp., Bur. of Reclam., Glen Canyon Environ. Stud., Salt Lake City, Utah.

Rubin, D. M., R. A. Anima, and R. Sanders (1994), Measurements of sand thickness in Grand Canyon, Arizona, and a conceptual model for characterizing changes in sand bar volume through time and space, *U.S. Geol. Surv. Open File Rep., OF94-597*, 9 pp.

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

Rubin, D. M., G. B. Tate, D. J. Topping, and R. A. Anima (2001), Use of a rotating side-scan sonar to measure bedload, paper presented at Seventh Federal Interagency Sedimentation Conference, Subcomm. on Sed. Interagency Advis. Comm., Reno, Nev.

Rubin, D. M., D. J. Topping, J. C. Schmidt, J. Hazel, M. Kaplinski, and T. S. Melis (2002), Recent sediment studies refute Glen Canyon Dam hypothesis, *Eos Trans. AGU*, *83*(25), 277–278, 273.

Schmidt, J. C. (1990), Recirculating flow and sedimentation in the Colorado River in Grand Canyon, Arizona, *J. Geol.*, *98*, 709–724.

Schmidt, J. C. (1999), Summary and synthesis of geomorphic studies conducted during the 1996 controlled flood in Grand Canyon, in *The Controlled Flood in Grand Canyon*, *Geophys. Monogr. Ser.*, vol. 110, edited by R. H. Webb et al., pp. 329–342, AGU, Washington, D. C.

Schmidt, J. C., and J. B. Graf (1990), Aggradation and degradation of alluvial sand deposits, 1965 to 1986, Colorado River, Grand Canyon National Park, Arizona, *U. S. Geol. Surv. Prof. Pap., 1493*, 74 pp.

Schmidt, J. C., and D. M. Rubin (1995), Regulated streamflow, fine-grained deposits, and effective discharge in canyons with abundant debris fans, in *Natural and Anthropogenic Influences in Fluvial Geomorphology: The Wolman Volume*, *Geophys. Monogr. Ser.*, vol. 89, edited by J. E. Costa et al., pp. 177–195, AGU, Washington, D. C.

Schmidt, J. C., R. H. Webb, R. A. Valdez, G. M. Marzolf, and L. E. Stevens (1998), Science and values in river restoration in the Grand Canyon, *Bioscience*, *48*(9), 735–747.

Schmidt, J. C., E. D. Andrews, D. L. Wegner, D. T. Patton, G. R. Marzolf, and T. O. Moody (1999), Origins of the 1996 controlled flood in Grand Canyon, in *The Controlled Flood in Grand Canyon*, *Geophys. Monogr. Ser.*, vol. 110, edited by R. H. Webb et al., pp. 23–36, AGU, Washington, D. C.

Schmidt, J. C., D. J. Topping, P. E. Grams, and J. E. Hazel Jr. (2004), System-wide changes in the distribution of fine sediment in the Colorado River corridor between Glen Canyon Dam and Bright Angel Creek, Arizona, final report, 107 pp., U.S. Geol. Serv. Grand Canyon Monit. and Res. cent., Flagstaff, Ariz.

Smillie, G. M., W. L. Jackson, and D. Tucker (1993), Colorado River sand budget: Lees Ferry to Little Colorado River, *Tech Rep. NPS/NRWRD/NRTR-92/12*, Natl. Park Serv., Washington, D. C.

Topping, D. J. (1997), Physics of flow, sediment transport, hydraulic geometry, and channel geomorphic adjustment during flash floods in an ephemeral river, the Paria River, Utah and Arizona, Ph.D. dissertation, 406 pp., Univ. of Wash., Seattle.

Topping, D. J., D. M. Rubin, J. M. Nelson, P. J. Kinzel III, and J. P. Bennett (1999), Linkage between grain-size evolution and sediment depletion during Colorado River floods, in *The Controlled Flood in Grand Canyon*, *Geophys. Monogr. Ser.*, vol. 110, edited by R. H. Webb et al., pp. 71–98, AGU, Washington, D. C.

Topping, D. J., D. M. Rubin, and L. E. Vierra Jr. (2000a), Colorado River sediment transport: 1. Natural sediment supply limitation and the influence of Glen Canyon Dam, *Water Resour. Res.*, *36*, 515–542.

Topping, D. J., D. M. Rubin, J. M. Nelson, P. J. Kinzel III, and I. C. Corson (2000b), Colorado River sediment transport: 2. Systematic bed-elevation and grain-size effects of sand supply limitation, *Water Resour. Res.*, *36*, 543–570.

U. S. Department of the Interior (1995), Operation of Glen Canyon Dam—Final environmental impact statement, report, 337 pp., Bur. of Reclamation, Upper Colo. Region, Salt Lake City, Utah.

U. S. Department of the Interior (1996), Record of decision, operation of Glen Canyon Dam—Final environmental impact statement, report, 13 pp., Bur. of Reclamation, Upper Colo. Region, Salt Lake City, Utah.

Webb, R. H. (1996), *Grand Canyon—A Century of Change: Rephotography of the 1889–1890 Stanton Expedition*, 290 pp., Univ. of Ariz. Press, Tucson.

Webb, R. H., P. T. Pringle, and G. R. Rink (1989), Debris flows from tributaries of the Colorado River, Grand Canyon National Park, Arizona, *U. S. Geol. Surv. Prof. Pap., 1492*, 39 pp.

Webb, R. H., J. C. Schmidt, G. R. Marzolf, and R. A. Valdez (Eds.) (1999), *The controlled flood in Grand Canyon*, *Geophys. Monogr. Ser.*, vol. 110, AGU, Washington, D. C.

Webb, R. H., P. G. Griffiths, T. S. Melis, and D. R. Hartley (2000), Sediment delivery by ungaged tributaries of the Colorado River in Grand Canyon, *Water Resour. Invest. Rep. 00-4055*, 67 pp., U. S. Geol. Surv., Boulder, Colo.

Wiele, S. M., E. D. Andrews, and E. R. Griffin (1999), The effects of sand concentration on depositional rate, magnitude, and location in the Color-

ado River below the Little Colorado River, in *The Controlled Flood in Grand Canyon*, *Geophys. Monogr. Ser.*, vol. 110, edited by R. H. Webb et al., pp. 161–184, AGU, Washington, D. C.
Williams, G. P., and M. G. Wolman (1984), Downstream effects of dams on alluvial rivers, *U.S. Geol. Surv. Prof. Pap.*, *1286*, 83 pp.
Wilson, R. P. (1986), Sonar patterns of the Colorado riverbed, Grand Canyon, paper presented at Fourth Federal Interagency Sedimentation Conference, Subcomm. on Sed. of the Interagency Advis. Comm. on Water Data, Las Vegas, Nev.
Wong, F. L., R. J. Anima, P. Galanis, J. Codianne, Y. Xia, R. Bucciarelli, and M. Hamer (2003), Grand Canyon riverbed sediment changes: Experimental release of September 2000—A sample data set, *U.S. Geol. Surv. Open File Rep., 03-0265*, 7 pp.

J. E. Hazel Jr. and M. Kaplinski, Department of Geology, Northern Arizona University, P.O. Box 4099, Flagstaff, AZ 86011-4099, USA. (joe.hazel@nau.edu; matt.kaplinski@nau.edu)

J. C. Schmidt, Department of Aquatic, Watershed, and Earth Resources, Utah State University, Logan, UT 84322-5210, USA. (jschmidt@cc.usu.edu)

D. J. Topping, U.S. Geological Survey, 2255 North Gemini Drive, Flagstaff, AZ 86001, USA. (dtopping@usgs.gov)