Sedimentology (2005) **52,** 1133–1153 doi: 10.1111/j.1365-3091.2005.00738.x

Regulation of sand transport in the Colorado River by changes in the surface grain size of eddy sandbars over multi-year timescales

DAVID J. TOPPING*, DAVID M. RUBIN† and JOHN C. SCHMIDT‡
**U.S. Geological Survey, 2255 N. Gemini Dr., Flagstaff, AZ 86001, USA (E-mail: dtopping@usgs.gov)*
†U.S. Geological Survey, 400 Natural Bridges Dr., Santa Cruz, CA, 95060, USA
‡Department of Aquatic, Watershed, and Earth Resources, Utah State University, Logan, UT, 84322-5210, USA

ABSTRACT

In settings where the transport of sand is partially or fully supply limited, changes in the upstream supply of sand are coupled to changes in the grain size of sand on the bed. In this manner, the transport of sand under the supply-limited case is 'grain-size regulated'. Since the closure of Glen Canyon Dam in 1963, the downstream reach of the Colorado River in Marble and Grand Canyons has exhibited evidence of sand-supply limitation. Sand transport in the river is now approximately equally regulated by changes in the discharge of water and changes in the grain sizes of sand on the channel bed and eddy sandbars. Previous work has shown that changes in the grain size of sand on the bed of the channel (driven by changes in the upstream supply of sand owing to both tributary floods and high dam releases) are important in regulating sand transport over timescales of days to months. In this study, suspended-sand data are analysed in conjunction with bed grain-size data to determine whether changes in the grain size of sand on the bed of the channel or changes in the grain size of sand on the surface of eddy sandbars have been more important in regulating sand transport in the post-dam Colorado River over longer, multi-year timescales. The results of this study show that this combined theory- and field-based approach can be used to deduce which environments in a complicated setting are the most important environments for regulating sediment transport. In the case of the regulated Colorado River in Marble and Upper Grand Canyons, suspended-sand transport has been regulated mostly by changes in the surface grain size of eddy sandbars.

Keywords Colorado River, grain size, sand bars, sediment transport, suspended sediment.

INTRODUCTION

The transport of a given size of sediment is controlled by: (i) hydraulics (i.e. the boundary-shear-stress and velocity fields), and (ii) the upstream supply of that size class. In the case where the upstream supply of the given size class is sufficiently large, changes in hydraulics are the dominant controllers of transport. This case can be referred to as the 'equilibrium-upstream-supply case'. In the case where the upstream supply of the given size class is not sufficiently large to maintain transport in equilibrium with the hydraulics, changes in the upstream supply of that size class result in changes in the transport of that size class. This latter case is typically referred to as 'supply-limited transport'. In most situations, the transport of a given size of sediment is probably controlled by a combination of changes in the hydraulics and changes in the upstream supply. In the equilibrium-upstream-supply case, no substantial changes in the grain-size distribution of the bed sediment occur, whereas, in the supply-limited case, substantial changes in the grain-size distribution of the bed sediment accompany changes in the upstream supply of sediment (Topping *et al.*, 2000a,b). Sediment transport under the equilibrium-upstream-supply case is 'flow-regulated' and sediment transport under the supply-limited case is 'grain-size regulated' (Rubin & Topping, 2001).

Rubin & Topping (2001) developed a generalized analytical technique for determining the relative degrees to which sediment transport in a given setting is regulated by changes in bed-sediment grain size and changes in hydraulics. They determined that both processes are equally important in controlling sand transport in the Colorado River downstream from Glen Canyon Dam in Grand Canyon. In addition, they found that changes in bed-sand grain size can play important roles in regulating sand transport not only in bedrock-canyon rivers but also in alluvial rivers, e.g. the Mississippi River.

In this paper, the dam-regulated Colorado River is examined to determine the relative roles of different parts of the bed in regulating sand transport. Sand occurs in two key environments on the bed of this river. It occurs in the channel as patches on gravel, colluvium, and bedrock, and also in eddies as sandbars that may be more than several meters thick. Although the sand in eddies is typically thicker than on the bed of the channel, it probably covers less area because eddies comprise only about 20% of the area of the riverbed (Schmidt *et al.*, 2004; Hazel *et al.*, in press). As described in this paper, β-analyses of suspended-sand data suggest that the bed environment that is the dominant regulator of sand transport in the Colorado River has fined over the past several decades. To determine which riverbed environment, channel or eddy, is the dominant regulator of sand transport, β is calculated for discrete river-discharge intervals and all available surface grain-size data from the channel and eddy bed environments are analysed. These analyses show that the smallest part of the bed, i.e. the eddy sandbars, is the dominant regulator of sand transport in this river. This approach of using suspended-sediment data in conjunction with field observations of surface grain-size change in different bed environments should be of use in other settings to determine whether sediment transport is regulated by the sediment comprising large portions of the bed or by the sediment found in discrete environments that may comprise only a small part of the bed.

Goal of this study

Sand transport in the post-dam Colorado River is regulated by both changes in bed-sand grain size and changes in the discharge of water. Previous studies have concluded that changes in the grain size of the sand on the bed of the channel are the dominant regulator of sand transport in the Colorado River in Marble and Upper Grand Canyons over timescales of days to months. The goal of this study is to evaluate the relative roles of the sand on the bed of the channel and the sand on the surface of eddy sandbars in regulating sand transport in the Colorado River in Marble and Upper Grand Canyons over longer, multi-year timescales.

Study Area

The study area is the Colorado River in Marble and Upper Grand Canyons (Fig. 1). Discharge and sediment data from the following U.S. Geological Survey (USGS) gaging stations are analysed: Colorado River at Lees Ferry, Arizona, station

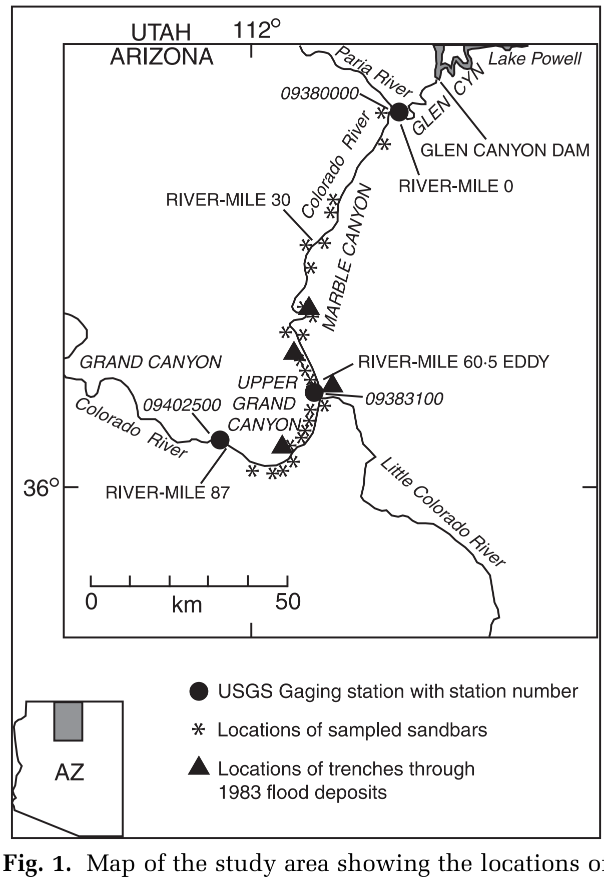

Fig. 1. Map of the study area showing the locations of selected USGS gaging stations, sampled eddy sandbars, and trenches excavated through 1983 flood deposits.

number 09380000 (herein referred to as 'the Lees Ferry gage'), Colorado River above Little Colorado River near Desert View, Arizona, station number 09383100 (herein referred to as 'the Lower Marble Canyon gage'), and Colorado River near Grand Canyon, Arizona, station number 09402500 (herein referred to as 'the Grand Canyon gage'). By convention, locations along the Colorado River are referred to by river mile, as measured downstream from the Lees Ferry gage (Stevens, 1983). Marble Canyon extends from the Lees Ferry gage 99 km to the mouth of the Little Colorado River at river-mile 61·5; Grand Canyon extends from the mouth of the Little Colorado River 346 km to the Grand Wash Cliffs at river-mile 276 (at the upstream end of Lake Mead reservoir). The upstream 42 km of Grand Canyon, from the mouth of the Little Colorado River to the Grand Canyon gage at river-mile 87·4, is herein referred to as Upper Grand Canyon. The study area begins 25·5 km downstream from Glen Canyon Dam, which impounds the Colorado River to form Lake Powell reservoir, and has regulated the discharge of water in the study area since its closure in March 1963 (Topping *et al.*, 2003). Closure of the dam has greatly reduced the supply of sand to the study area. The only substantial supplier of sand to the upstream end of the study area is now the Paria River, which supplies about 6% of the pre-dam sand load at this location (Topping *et al.*, 2000a).

The longitudinal profile of the Colorado River in Marble and Grand Canyons is characterized by long, gently sloping pools separated by short, steep drops in rapids (Leopold, 1969; Magirl *et al.*, 2005). The banks of the river are composed mostly of talus and bedrock, with lesser amounts of sand and finer material (Howard & Dolan, 1981). The rapids in which most of the elevation loss occurs are formed by debris fans composed of coarser sediment delivered to the Colorado River by debris flows and floods from relatively small tributaries (Cooley *et al.*, 1977; Webb *et al.*, 1989; Melis *et al.*, 1994). These debris fans give rise to the dominant geomorphic element in this reach, the fan-eddy complex (Schmidt & Rubin, 1995). The typical fan-eddy complex consists of a backwatered pool in the channel upstream from the debris fan, constricted flow through a rapid over the toe of the debris fan, and a large expansion in flow area downstream from the debris fan, where the downstream flow separates from the bank to form a lateral recirculation eddy along the bank (Fig. 2). Sandbars form in the eddy and are largely composed of sand deposited from suspension (Howard & Dolan, 1981; Rubin *et al.*, 1990, 1994; Schmidt, 1990; Schmidt & Graf, 1990). If the upstream supply of suspended sand is sufficient, sandbars may fill most of the eddy to a relatively high elevation (Wiele *et al.*, 1996).

Though only a small percentage of the river area is composed of eddies, the total area of sand in eddies is only about 33–50% less than the total area of sand on the bed of the channel. Analyses of historical aerial photography and recent surveys indicate that about 20% of the river in Marble Canyon is composed of lateral recirculation eddies (Schmidt *et al.*, 2004; Hazel *et al.*, in press). Side-scan-sonar data collected in the study area between 1994 and 2000 suggest that, on average, the channel bed is composed of by area 40% finer gravel (pebbles and cobbles of probable fluvial origin), 20–30% sand, 20–30% bedrock, and 10–20% large, immobile boulders that are either derived from tributaries or the hillslopes and cliffs adjacent to the river (Anima *et al.*, 1998; Wong *et al.*, 2003). These data also suggest that, on average, sandbars occupy at least 60% of the eddy area, with the remainder of the eddy area composed of finer gravel or boulders. Thus, the area of sand in eddies is equivalent to about 12% of the total river area and the area of sand in the channel is equivalent to about 16–24% of the total river area.

Although it begins 20 years after closure of Glen Canyon Dam, the study period 1983–2000 is the first multi-year post-dam period with suspended- and bed-sand data adequate for this study. The analyses presented in this paper require time-series of suspended-sand concentration and grain size (preferably from more than one location), and time-series of bed-sand grain size from multiple locations and environments. The study period includes both the largest post-dam flood (2750 m^3 sec^{-1} peak discharge) in 1983 and one of the longest post-dam periods of sustained low discharge in 2000 (Fig. 3). The period from 1983 through 1986 was characterized by higher than average dam releases because of full reservoir conditions in Lake Powell. The period from 1987 through July 1991 was characterized by large daily fluctuations in discharge for power generation. Beginning in August 1991, dam releases were constrained in an attempt to minimize the downstream effects of dam operations (National Research Council, 1996). In March–April 1996, an experimental 7-day controlled flood

Fig. 2. A typical eddy sandbar in Marble Canyon, the right-bank sandbar in the fan-eddy complex at river-mile 22. White arrows indicate direction of flow in the channel; the discharge of water is 227 $m^3 sec^{-1}$. This sandbar is completely inundated at a discharge of approximately 1,200 $m^3 sec^{-1}$.

with a peak discharge of 1270 $m^3 sec^{-1}$ (the 1996 controlled flood) was released from the dam (Webb *et al.*, 1999). In November 1997, a second experimental dam release was conducted consisting of a 2-day 890 $m^3 sec^{-1}$ powerplant-capacity dam release (Topping *et al.*, 2000b). In 2000, a third experimental dam release was conducted consisting of 3 months of constant 227 $m^3 sec^{-1}$ discharge between two 4-day powerplant-capacity flows.

Previous Work

Beginning in the 1970s, concerns were raised about the effect of Glen Canyon Dam on the downstream ecosystem of the Colorado River in Marble and Grand Canyons (Dolan *et al.*, 1974). Sandbar erosion downstream from the dam led to the early sediment-transport and geomorphologic studies of Dolan *et al.* (1974); Howard (1975); Laursen *et al.* (1976), and Howard & Dolan (1981). Dolan *et al.* (1974) and Laursen *et al.* (1976) concluded that, under normal powerplant releases from Glen Canyon Dam, the transport capacity of the river exceeded the supply of sand, and that the eddy sandbars would gradually erode away. In contrast to the results of these earliest studies, Howard & Dolan (1981), Randle & Pemberton (1987), Andrews (1990, 1991), and U.S. Department of the Interior (1995) concluded that the tributary supply of sand downstream from the dam exceeded the transport capacity of the river under normal releases from the dam. These early sediment budgets relied on stable relationships between the discharge of water and sand transport. Following the experimental 1996 controlled flood, Topping *et al.* (2000b) showed that, because the grain size of the sand on the bed of the channel changes substantially over time in response to both tributary activity and dam releases, stable relationships between the discharge of water and sand transport do not exist. Rubin & Topping (2001) concluded that, under normal powerplant releases from the dam, sand transport in the Colorado River is equally regulated by changes in bed-sand grain size and changes in hydraulics. From their analysis

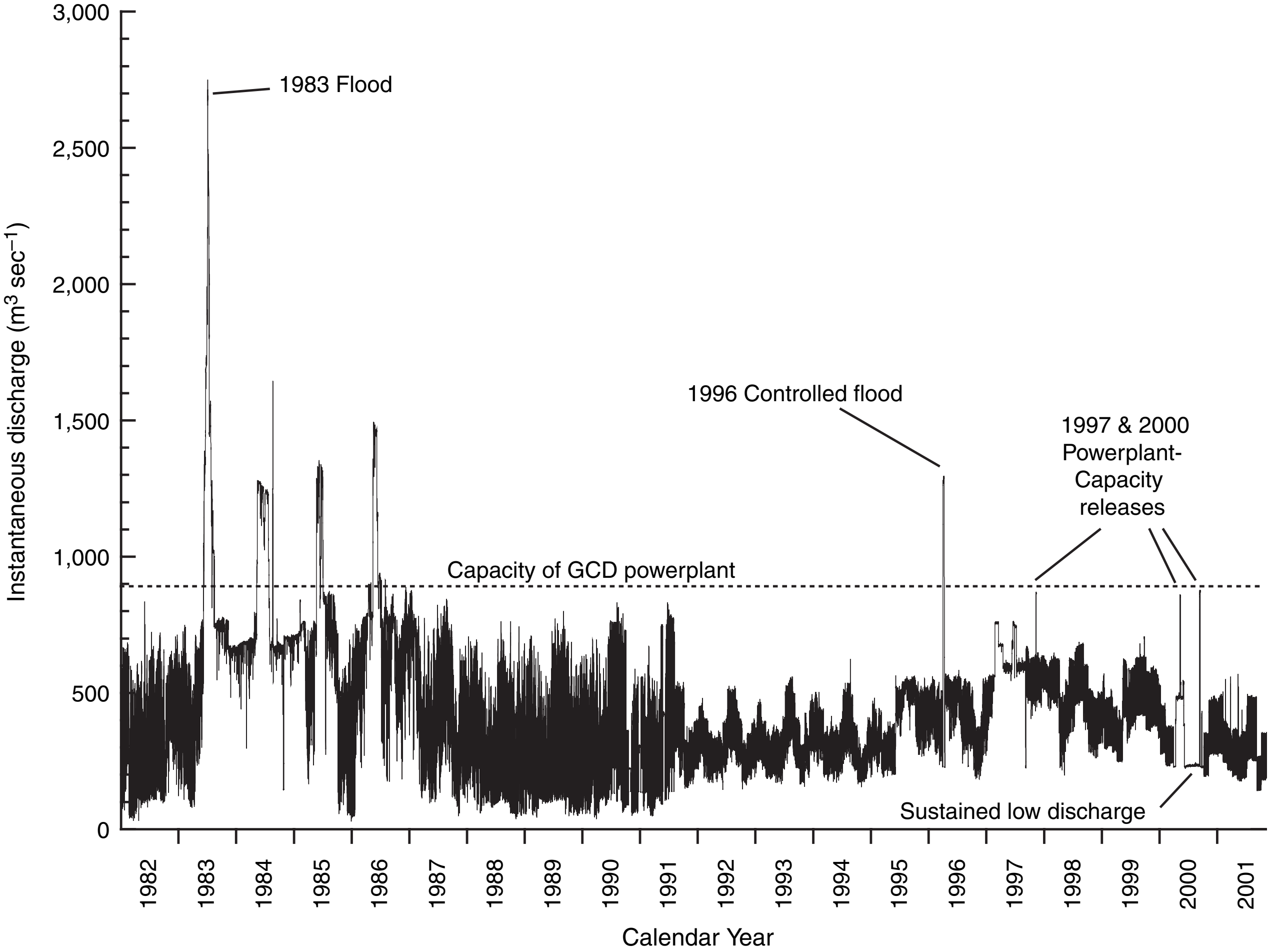

Fig. 3. Hydrograph of the Colorado River at the Lees Ferry gage between 1982 and 2001. Shown are the capacity of the Glen Canyon Dam (GCD) powerplant, the1983 flood (i.e. the post-dam flood of record), the 1996 controlled flood, the three 1997 and 2000 powerplant-capacity flows, and the three months of sustained low discharge during June–August 2000.

of only suspended-sand data, however, it is impossible to know which riverbed environment, channel or eddy, was most important in regulating sand transport.

Rubin *et al.* (2002) analysed recent sand-transport and geomorphic data, and determined that the sand budget for the study area was negative over the previous several years of normal powerplant releases from Glen Canyon Dam. Topping *et al.* (2000a) showed that, given the uncertainties in the sediment budget constructed using USGS historical daily sediment-transport data, one could not conclude that tributary-supplied sand was stored in the Colorado River in Marble and Upper Grand Canyons for more than a few months. Flynn & Hornewer (2003) showed that the amount of sediment decreased in 55 of 57 cross-sections surveyed repeatedly by the USGS between 1992 and 1999. Additionally, Schmidt *et al.* (2004) showed that, between the mid-1980s and 2000, the amount of sand in the channel and eddies in Marble and Upper Grand Canyons decreased by about 25%. More recently, Hazel *et al.* (in press), estimated that, by volume, between 51 and 94% of the sand in Marble Canyon is stored in eddies, and that, as suggested by Schmidt (1999), eddies are the primary source of sand deposited at higher elevations during high dam releases. Thus, under normal dam releases over multi-year timescales, the sand budget of the Colorado River in Marble and Upper Grand Canyons is negative and most of the sand in multi-year storage occurs in eddy sandbars that are getting smaller over time. This result suggests that, although the area of sand in eddies is about 50–67% of the area of sand in the channel, the sand stored in the eddy sandbars may play a dominant role in regulating sand transport in the post-dam Colorado River over longer, multi-year timescales.

Shorter-term coupled changes in sand-transport and bed-sand grain size in the channel

Recent work on the role that bed-sand grain size plays in regulating sand transport in the Colorado River has focused on the channel. Over shorter timescales, the grain size of the sand on the channel bed evolves quickly in response to large inputs of sand from the tributaries and in response to high releases from Glen Canyon Dam (Topping *et al.*, 2000b). Because the median size of the sand supplied by tributaries is about 1/4 to 1/2 of the median size of the sand typically comprising the channel bed, tributary-supplied sand is more mobile than the sand on the bed of the channel. Therefore, newly input sand travels downstream in the Colorado River as an elongating sediment wave, with a component in the suspended load, bedload, and bed sediment. As the front of a sediment wave propagates downstream, the bed of the channel fines, and suspended-sand concentrations increase in response to the enriched upstream supply of finer sand. Under normal powerplant releases from Glen Canyon Dam, these sediment waves propagate downstream quickly. Following the passage of a wave front, the sand on the bed is winnowed, and suspended-sand concentrations decrease in response to the depletion of the upstream supply of finer sand. Observations made by Topping *et al.* (2000b) in Marble Canyon during 1998 and 1999 suggest that the sand on the channel bed coarsens back to its pre-tributary-input antecedent condition within about 6 months during moderate dam releases.

High clear-water releases from Glen Canyon Dam cause the sand on bed of the channel to coarsen rapidly. During the 1270 m^3 sec^{-1} 1996 controlled flood, the sand on the channel bed and in suspension coarsened by about a factor of 1·5 as the suspended-sand concentrations decreased (Rubin *et al.*, 1998; Topping *et al.*, 1999, 2000b). Though the Grand Canyon gage was the only place where measurements of bed-sand grain size were made during this flood, the systematic progressive coarsening and depletion of the sand in suspension were observed everywhere where measurements were made (spanning a stream-wise distance of over 170 km). During the 2750 m^3 sec^{-1} flood released from Glen Canyon Dam in 1983, the sand on the bed of the channel at the Grand Canyon gage coarsened by about a factor of two (Fig. 4). As during the 1996 controlled flood, the Grand Canyon gage was the only location where bed-sand grain-size measurements were made during the peak part of the 1983 flood

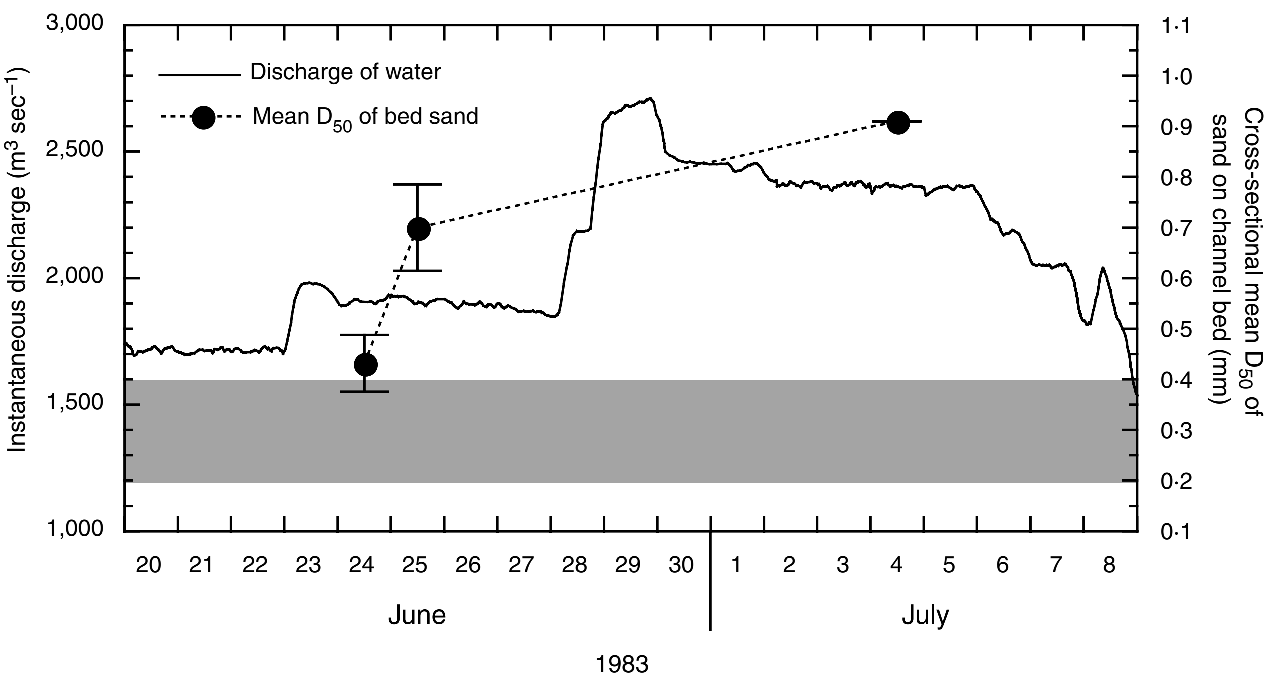

Fig. 4. Mean of the median size of the channel-bed sand over the central two-thirds of the cross-section at the Grand Canyon gage during the post-dam flood of record in June 1983. Gray-shaded region shows the full pre-dam range in the median size of the bed sand at the Grand Canyon gage. Error bars are one standard error. Data are from Garrett *et al.* (1993).

(Garrett *et al.*, 1993). Unlike during the 1996 controlled flood, however, measurements of suspended sand concentration and grain size were not measured at any location until the receding limb of the 1983 flood.

CHANGES IN BED-SAND GRAIN SIZE INFERRED FROM β-ANALYSES OF SUSPENDED-SAND DATA

Between 1983 and 2000, there were many more measurements of suspended-sand concentration and grain size made at the Lower Marble Canyon and Grand Canyon gages than there were direct measurements of the grain size of the sand on the bed of the river. Thus, it is advantageous to use the suspended-sand data to infer temporal changes in bed-sand grain size. Furthermore, because suspension processes in the river effectively provide an average 'sample' of the sand on the upstream bed of the channel and the underwater portions of the eddy sandbars, an appropriate analysis of the suspended-sand data can yield information on changes in the grain size of the sand on the surface of the channel bed and eddy sandbars upstream from the suspended-sand measurement location. Rubin & Topping (2001) developed such a technique to analyse suspended-sediment data based on theory and tested this technique against data from flumes and rivers. Their parameter 'β' is a nondimensional measure of the average bed-surface grain-size that interacts with the suspended sand in the flow. β uses the concentration and grain size of the sand in suspension to compute the average upstream grain size of the sand on the bed of the channel and the underwater portions of the eddy sandbars. β is defined as

$$\beta = \frac{D_b}{D_{bm}} \quad (1),$$

where D_b is the median grain diameter of the bed sand at an instance in time and D_{bm} is the average of D_b over a specified time interval at the same location. For broad and narrow bed-sand grain-size distributions and cases with and without dunes on the bed, Rubin & Topping (2001) found that

$$\beta = \left(\frac{C}{C_m}\right)^{-0\cdot1} \left(\frac{D_s}{D_{sm}}\right)^{0\cdot2} \quad (2),$$

where C is the concentration of sand in suspension at an instance in time, C_m is the average of C over a specified time interval at the same location, D_s is the median grain diameter of sand in suspension at an instance in time, and D_{sm} is the average of D_s over a specified time interval at the same location. This result was computed using suspended-sediment theory reviewed by McLean (1992).

In the case where the sand on the channel bed and eddy sandbars is not armoured by coarser sediment, changes in β at a given location may correlate with changes in the volume of sand stored in the reach upstream. In this case, reductions in β indicate fining of the channel-bed and eddy-sandbar surfaces interacting with the flow upstream and suggest an increase in the amount of sand in storage upstream. Conversely, increases in β indicate winnowing of the inundated upstream sand deposits and suggest an overall decrease in the amount of sand in storage upstream. In the case where the sand on the channel bed or eddy sandbars may be armoured or inversely graded, however, changes in β may be inversely correlated with the overall sand budget. If the bed is armoured or inversely graded, erosion will expose finer sand underneath the surface and cause β to decrease even though the amount of sand in storage has also decreased.

To determine the relative changes in sand grain size on the bed of the river in Marble and Upper Grand Canyons, β was computed using the method of Rubin & Topping (2001) for all of the 1983–2000 suspended-sand data from the Lower Marble Canyon and Grand Canyon gages (Fig. 5). Analysis of variance indicates that the fining trends in β at the Lower Marble Canyon and Grand Canyon gages are significant at the $<1\cdot0 \times 10^{-16}$ level and $4\cdot9 \times 10^{-10}$ level, respectively. For this and subsequent statistical analyses, it is determined that trends or differences in means are significant when the computed level of significance is $<0\cdot05$. The fining trends in β at the two gaging stations are therefore significant. Segregation of the β time-series at the two gaging stations into two parts, 1983–1986 (i.e. the period following the 1983 flood) and 1991–2000, and analysis of these two parts using a Student's *t*-test comparing the means of two groups with unequal variance yield similar results. For this and subsequent *t*-tests, the Student's *t*-test comparing the means of two groups with equal variance is used when an *F*-test indicates that the variances of the two groups cannot be determined to be different at the 0·05 level, and the Student's *t*-test comparing the means of two groups with unequal

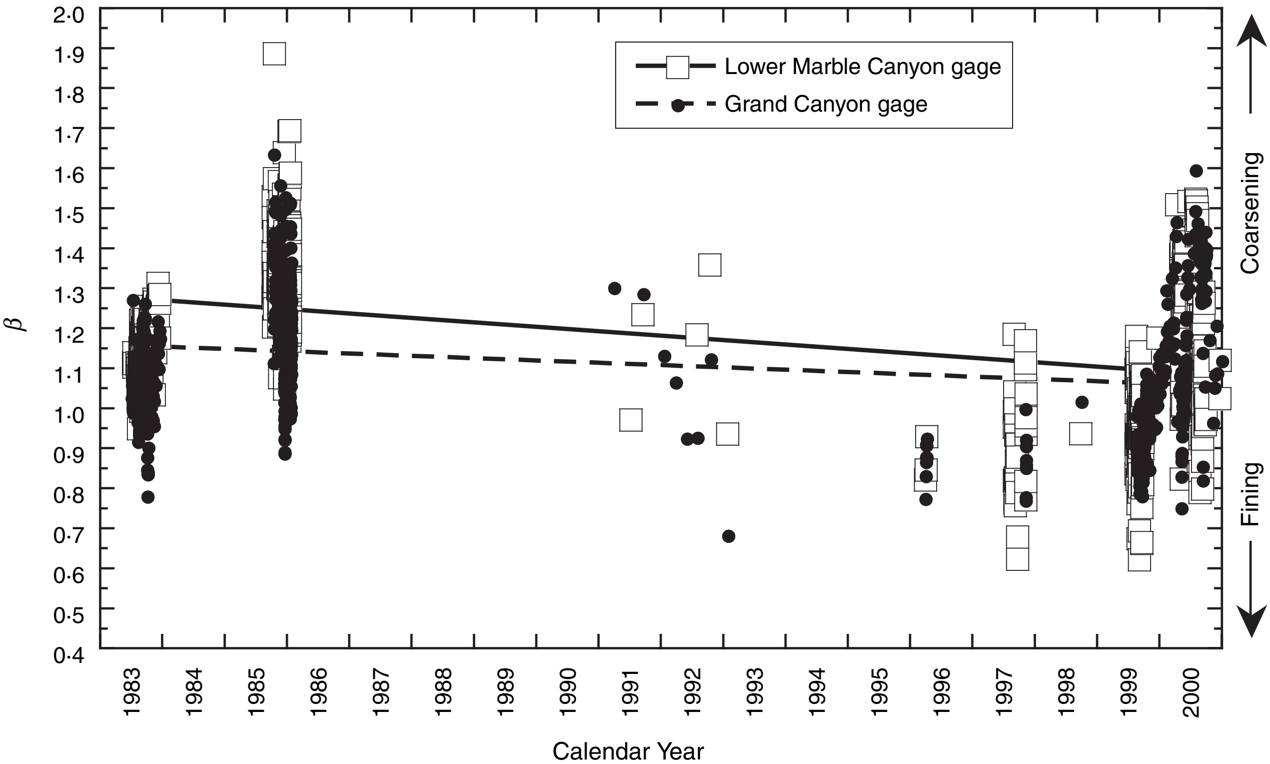

Fig. 5. β time-series computed from all 1983–2000 suspended-sand data collected at the Lower Marble Canyon and Grand Canyon gages. The solid line is the linear regression through β at the Lower Marble Canyon gage and the dashed line is the linear regression through β at the Grand Canyon gage. Both of these fining trends are significant.

variance is used when an *F*-test indicates that the variances of the two groups are different at the 0·05 level. The only difference between these two tests is in the degrees of freedom. The *t*-test comparing two groups with unequal variance has many fewer degrees of freedom than the *t*-test comparing two groups of equal variance. At the Lower Marble Canyon gage, the 1983–1986 β-computed bed sand was coarser than the 1991–2000 bed sand at the $<1{\cdot}0 \times 10^{-16}$ level of significance. At the Grand Canyon gage, the 1983–1986 β-computed bed sand was coarser than the 1991–2000 bed sand at the $4{\cdot}0 \times 10^{-15}$ level of significance. The next step in this study was to therefore determine which bed environment, the sand on the bed of the channel or the sand on the bed in the eddies, was most responsible for this fining trend in β.

METHODS

β-inferred changes in the grain size of bed sand as a function of elevation

To determine the relative changes in sand grain size on the bed of the channel and eddies in three elevation zones in Marble and Upper Grand Canyons, β was computed using the method of Rubin & Topping (2001) for all of the 1983–2000 suspended-sand data from the Lower Marble Canyon and Grand Canyon gages, and then segregated into three discharge intervals (Fig. 6). These discharge intervals were: (i) flows <250 m^3 sec^{-1}, (ii) flows from 250 to 700 m^3 sec^{-1}, and (iii) flows >700 m^3 sec^{-1}. These discharge intervals were chosen on the basis of river morphology and to ensure that sufficient suspended-sand data could be analysed over the entire study period in each interval. During the study period, flows in the lowest discharge interval (<250 m^3 sec^{-1}) occurred 6% of the time, flows in the middle discharge interval (250–700 m^3 sec^{-1}) occurred 65% of the time, and flows in the highest discharge interval (>700 m^3 sec^{-1}) occurred 29% of the time (though mostly during the early part of the study period). By using this approach, changes in β over time in the lowest discharge interval could be related to changes in the grain size of the sand on the bed of the channel and on the low-elevation parts of the eddy-sandbar surfaces. Changes in β in the middle discharge interval could be related to a combination of the changes in

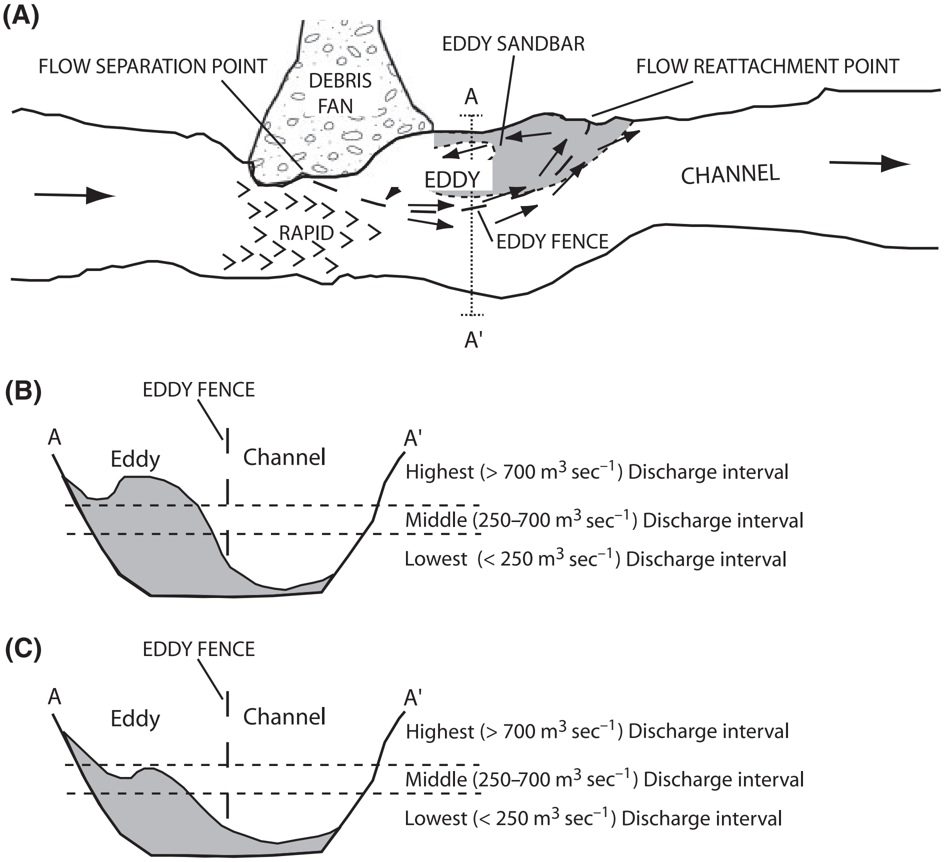

Fig. 6. (A) Cartoon showing a typical fan-eddy complex in Marble and Upper Grand Canyons indicating the relative positions of 'channel' and 'eddy' environments. Arrows indicate direction of flow. Modified after Schmidt (1990). (B) Cross-section through A-A′ in (A) showing the approximate elevations of the three discharge intervals used in the β-analysis immediately after a high dam release (e.g., the 1983 flood or 1996 controlled flood). (C) Cross-section through A-A′ in (A) showing the approximate elevations of the three discharge intervals used in the β-analysis after subsequent powerplant releases have partially eroded the sandbar.

the grain size of sand on the low-elevation parts of the bed, plus changes in the grain size of the sand on the surface of the eddy sandbars within the range of normal powerplant discharges. Similarly, changes in β in the highest discharge interval could be related to a combination of the changes in the grain size of sand on the low- and mid-elevation parts of the bed, plus changes in the grain size of the sand on the surface of the eddy sandbars that are inundated by only the highest powerplant releases and in discharges that exceed powerplant capacity (890 m^3 sec^{-1}) at Glen Canyon Dam.

Changes in the grain size of the sand on the bed of the channel and on the surface of eddy sandbars determined from direct observations

Changes in the grain size of the sand on the bed of the channel were evaluated using two independent datasets: cross-sectionally averaged datasets collected using USGS BM-54 samplers under the cableways at the Lower Marble Canyon and Grand Canyon gages between 1983 and 2000 (Fig. 1), and pipe-dredge datasets collected in the center of the channel at various locations in Marble and Upper Grand Canyons on river trips in September 1984, November 1997, March 1998, September 1998, May 1999, September 1999, and May 2000. Each BM-54 measurement consists of a cross-sectional average of the grain size of the bed sand sampled at two or more locations across the channel. These data provide a robust measure of how the grain size of the sand on the channel bed evolved over time at two locations, i.e., the cableways at the Lower Marble Canyon and Grand Canyon gages. The pipe-dredge data, though they contain fewer observations at fewer times than the BM-54 data, have the advantage of providing a more complete spatial measure of the changes in the grain size of the sand on the bed of the channel between the Lees Ferry and Grand Canyon gages.

Pipe-dredge samples collected during river trips in September 1984, September 1998, May 1999, September 1999, and May 2000 were used to evaluate changes in the grain size of the sand on the lowest-elevation part of the eddy sandbars. Pipe-dredge data were collected in the centers of the same 11 eddies in Marble Canyon in September 1998, May 1999, September 1999, and May 2000. During the September 1984 trip, only one eddy was sampled in the study area. The only eddy in which data were collected in each of the five trips between 1984 and 2000 was the eddy on the left side of the river at river-mile 60·5, herein referred to as the river-mile 60·5 eddy.

Changes in the surface grain size of the sand on the mid- and higher-elevation parts of the eddy sandbars between 1982 and 2000 were evaluated using grain-size data that we collected on river trips in 1996, 1997, and 2000, and using the eddy-sandbar surface grain-size data of Beus *et al.* (1983), Lojko *et al.* (1984), Lojko (1985, 1987), McKay (1991), and McCutcheon (1992). The dates, locations, and numbers of samples used from each dataset are shown in Table 1. To be sure that samples included in this analysis were from sandbar surfaces that had recently interacted with flow in the river, only those samples from these datasets that were collected at elevations that had been inundated by dam operations in the months preceding each sampling trip were used.

Samples collected from four trenches excavated through 1983 flood deposits were used to help evaluate the changes in the surface grain size of eddy sandbars during the course of the 1983 flood. The deposits from this flood comprise a bench that typically rises 1–2 m above the bench created by the more recent 1996 controlled flood.

RESULTS AND DISCUSSION

β-inferred changes in the surface grain size of bed sand as a function of elevation

Analyses of the discharge-binned β time-series indicate that the greatest universal fining of the bed sand between 1983 and 2000 occurred at mid- and high-elevations (Fig. 7). The average significant fining in β among the Lower Marble Canyon and Grand Canyon gages was 9% in the lowest discharge interval, 19% in the middle discharge interval, and 20% in the highest discharge interval. Therefore, the surfaces of the eddy sandbars probably fined to a greater degree than did the sand on the bed of the channel.

In the lowest discharge interval, β at the Lower Marble Canyon gage fined by about 18%, whereas β at the Grand Canyon gage remained constant between 1985 and 2000 (Fig. 7A). Analysis of variance indicates that the fining trend in

Table 1. Dates, locations, numbers of samples, and sources of data for sampled eddy-sandbar surfaces in Marble and Upper Grand Canyons.

Sampling date	River-mile locations of sampled sandbar surfaces	Source of data	Number of samples
7-24-1982 to 8-11-1982	8, 20, 22, 29·3, 43, 53, 68, 76	Beus *et al.* (1983)	8
7-29-1983 to 8-7-1983	8, 20, 29·3, 34·8, 43, 53, 59, 61·5, 65·5, 72·2, 75·5, 81·3	Lojko *et al.* (1984)	32
8-1-1984 to 8-11-1984	8, 20, 29·3, 34·7, 43, 53, 53·5, 61·8, 65·5, 72·2, 75·5, 81·3	Lojko (1985)	23
July–August 1985	8, 20, 29·3, 34·7, 53, 75·5	Lojko (1987)	7
July–August 1986	8, 20, 29·3, 34·7, 53, 75·5, 81·3	Lojko (1987)	8
July–August 1991	43	McKay (1991)	6
July–August 1992	8, 34·7, 53, 61·5, 75·5, 81·3	McCutcheon (1992)	10
April 1996	48, 63, 69·5	Rubin *et al.* (1998)	3
11-7-1997 to 11-14-1997	8, 22, 30·5, 43, 47, 55·5, 62·6, 68, 81·3	Topping *et al.* (2000b)	12
5-12-2000	8·8, 21·8, 30·5	Topping & Rubin at http://www.gcmrc.gov	3
8-19-2000 to 8-26-2000	1, 29·3, 29·9, 30·1, 43, 43·3, 43·4, 44·4, 59·9, 60·2, 63·3	Topping & Rubin at http://www.gcmrc.gov	13
9-8-2000 to 9-16-2000	1, 29·3, 43, 44, 60, 60·3, 62·5, 63, 65	Topping & Rubin at http://www.gcmrc.gov	17

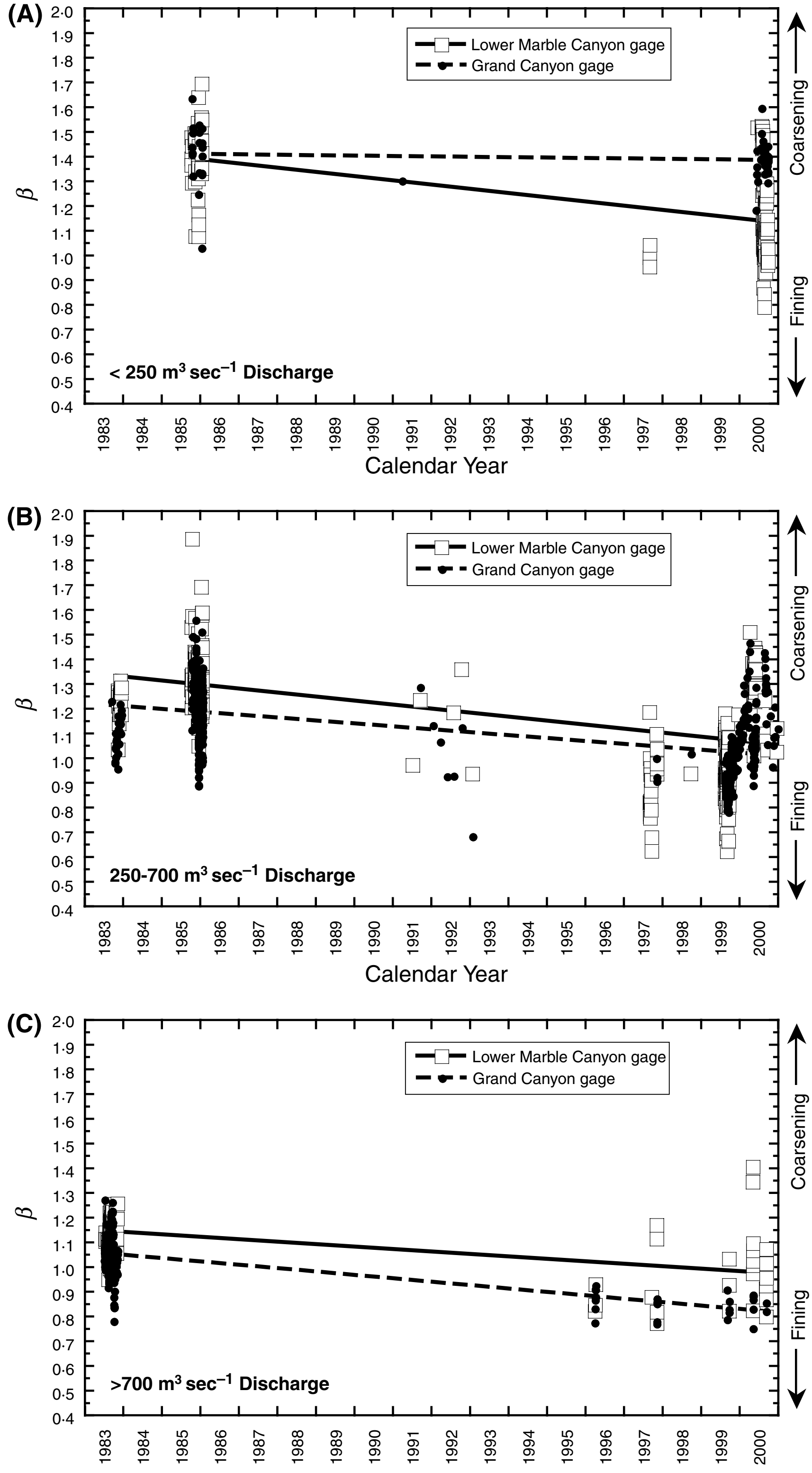

Fig. 7. 1983–2000 β time-series from Fig. 5 segregated into three discharge intervals. Solid lines are the linear regressions through β at the Lower Marble Canyon gage; dashed lines are the linear regressions through β at the Grand Canyon gage. (A) β time-series for the lowest discharge interval (<250 $m^3\ sec^{-1}$). The fining trend at the Lower Marble Canyon gage is significant. At the Grand Canyon gage, no significant trend exists in β at discharges less than 250 $m^3\ sec^{-1}$. (B) β time-series for the middle discharge interval (250–700 $m^3\ sec^{-1}$). The fining trends at both gaging stations are significant. (C) β time-series for the highest discharge interval (>700 $m^3\ sec^{-1}$). The fining trends at both gaging stations are significant.

low-discharge β at the Lower Marble Canyon gage is significant at the $7{\cdot}9 \times 10^{-12}$ level. Segregation of the β time-series at the Lower Marble Canyon gage into two parts, 1985–1986 and 1991–2000, and analysis of these two parts using a Student's *t*-test comparing the means of two groups with equal variance yields a similar result: low-discharge β was coarser in 1985–1986 than it was in 1991–2000 at the $1{\cdot}8 \times 10^{-12}$ level of significance. Analysis of variance indicates that the fining trend in low-discharge β at the Grand Canyon gage is significant at only the 0·36 level, and is therefore not significant. Segregation of the β time-series at the Grand Canyon gage into two parts, 1985–1986 and 1991–2000, and analysis of these two parts using a Student's *t*-test comparing the means of two groups with unequal variance yields the identical result: low-discharge β in 1985–1986 is different than low-discharge β in 1991–2000 at only the 0·36 level of significance. Because low-discharge β remained constant at the Grand Canyon gage, the average significant fining of the low-elevation bed sand among the two gaging stations was about 9%.

In the middle discharge interval, β at the Lower Marble Canyon gage fined by about 21%, and β at the Grand Canyon gage fined by about 17% between 1983 and 2000 (Fig. 7B). Analysis of variance indicates that the fining trends in mid-discharge β at the Lower Marble Canyon and Grand Canyon gages are both significant at the $<1 \times 10^{-16}$ level. Segregation of the β time-series at the two gaging stations into two parts, 1983–1986 and 1991–2000, and analysis of these two parts using a Student's *t*-test yield identical results. Based on the results of *F*-tests, a *t*-test comparing the means of two groups with unequal variance was used on the Lower Marble Canyon gage data; and a *t*-test comparing the means of two groups with equal variance was used on the Grand Canyon gage data. At both the Lower Marble Canyon and Grand Canyon gages, mid-discharge β was coarser in 1983–1986 than it was in 1991–2000 at the $<1 \times 10^{-16}$ level of significance. The average significant fining of the combined low- and mid-elevation bed sand was therefore about 19%, based on the changes in mid-discharge β at the two gaging stations.

In the highest discharge interval, β at the Lower Marble Canyon gage fined by about 16%, and β at the Grand Canyon gage fined by about 23% between 1983 and 2000 (Fig. 7C). Analysis of variance indicates that the fining trend in high-discharge β at the Lower Marble Canyon gage is significant at the $3{\cdot}8 \times 10^{-12}$ level, and the fining trend in high-discharge β at the Grand Canyon gage is significant at the $<1 \times 10^{-16}$ level. Segregation of the β time-series at the two gaging stations into two parts, 1983 and 1996–2000, and analysis of these two parts using a Student's *t*-test comparing the means of two groups with unequal variance yield similar results. At the Lower Marble Canyon gage, high-discharge β was coarser in 1983 than it was in 1996–2000 at the $6{\cdot}2 \times 10^{-6}$ level of significance; at the Grand Canyon gage, high-discharge β was coarser in 1983 than it was in 1996–2000 at the $<1 \times 10^{-16}$ level of significance. The average significant fining in the combined low-, mid-, and high-elevation bed sand was therefore about 20%, based on the changes in high-discharge β at the two gaging stations.

In addition to the fining in β during the late 1980s and early 1990s, β fines with increasing discharge at any given time (Fig. 8). This occurs because, as the discharge in the river increases, more finer sand on the bed at higher elevations is inundated by the flow and is therefore available to go into suspension. Rubin & Topping (2001) reported this type of behaviour for the Colorado River (pre- and post-dam) and two alluvial rivers (the Paria and Mississippi Rivers). Also evident in Fig. 8 is the result that, although β fined at low discharges at the Lower Marble Canyon gage, it remained constant at low discharges at the Grand Canyon gage between 1986 and 1991.

Changes in the grain size of the sand on the bed of the channel

Despite the short-term large changes in the grain size of sand on the bed of the channel described in the introduction, the grain size of the sand on the channel bed has either not changed or has coarsened by about 10–20% during the 17 years following the 1983 flood. Although this result is in agreement with the result from the low-discharge β-analysis at the Grand Canyon gage (that showed no significant change in the grain size of the low-elevation bed sand), it is in disagreement with the fining observed in the low-discharge β-analysis at the Lower Marble Canyon gage. Thus, the average 9% fining between 1983 and 2000 observed in the low-discharge β-analyses between the two gaging stations was probably not due to fining of the sand on the channel bed.

Analyses of variance of the cross-sectionally averaged BM-54 datasets from the Lower Marble Canyon and Grand Canyon gages indicate that the sand on the channel bed at both of these locations coarsened slightly (by 10–20%) from 1983 through 2000 (Fig. 9). The large variability in channel-bed grain size at each gaging station within each year results from the short-term changes in channel-bed grain size described in the Introduction, with fining of the bed during periods of upstream tributary resupply of finer sand and winnowing of the bed either after

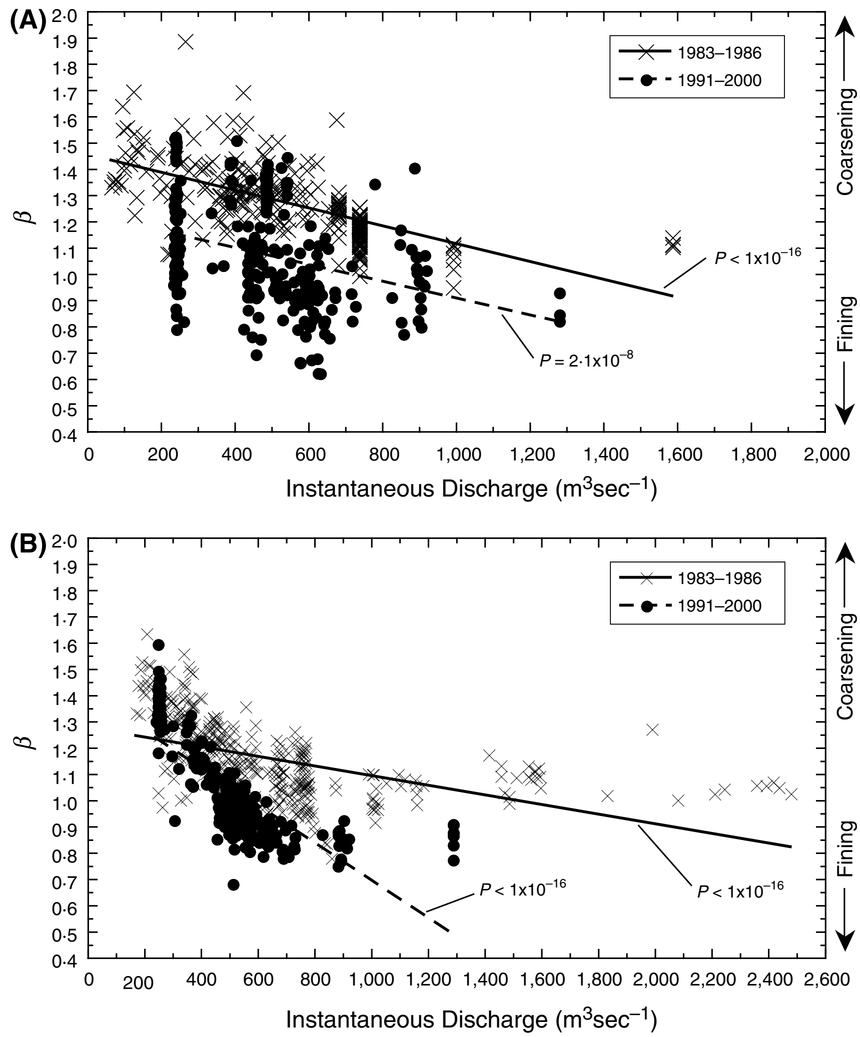

Fig. 8. β as a function of the discharge of water at (A) the Lower Marble Canyon gage, and (B) the Grand Canyon gage. Solid lines are the linear regressions through the 1983–1986 data; dashed lines are the linear regressions through the 1991–2000 data. Levels of significance (*p*) of the trends in β as a function of discharge are indicated.

cessation of upstream tributary activity or during periods of high dam releases. During 1983–2000, the cross-sectional mean of the median size of the sand on the channel bed at the Lower Marble Canyon gage coarsened from about 0·36 mm to 0·40 mm and the cross-sectional mean of the median size of the sand on the channel bed at the Grand Canyon gage coarsened from about 0·37 mm to 0·43 mm. Owing to the large number of observations, these slight coarsening trends are significant at the 0·0073 and $2{\cdot}4 \times 10^{-7}$ levels, respectively. Segregation of the time-series at the two gaging stations into two parts, 1983–1986 and 1996–2000, and analysis of these two parts using a Student's *t*-test comparing the means of two groups with unequal variance yield similar results. The sand on the channel bed at the Marble Canyon gage was coarser in 1996–2000 than it was during 1983–1986 at the 0·00011 level of significance, and the sand on the channel bed at the Grand Canyon gage was coarser in 1996–2000 than it was during 1983–1986 at the 0·00043 level of significance. Furthermore, although comparable with the coarsest pre-dam value (0·4 mm), the cross-sectional mean of median size of the channel-bed sand at the Grand Canyon gage during 1983–2000 was 90% coarser than the finest pre-dam value (0·2 mm) and 27% coarser than the mean pre-dam value (Fig. 9).

Analyses of the seven pipe-dredge datasets shows that, despite substantial short-term fining of the channel-bed sand in uppermost Marble Canyon following floods on the Paria River, there is no significant difference between the grain size of the sand on the channel bed measured on each of the river trips from September 1984 through May 2000 (Fig. 10). Analysis of variance of the data in Fig. 10A indicates that, at the 0·11 level of significance, variance is minimized when the 1984–2000 pipe-dredge data are treated as a single dataset rather than seven different datasets. In other words, at the 0·11 level of significance,

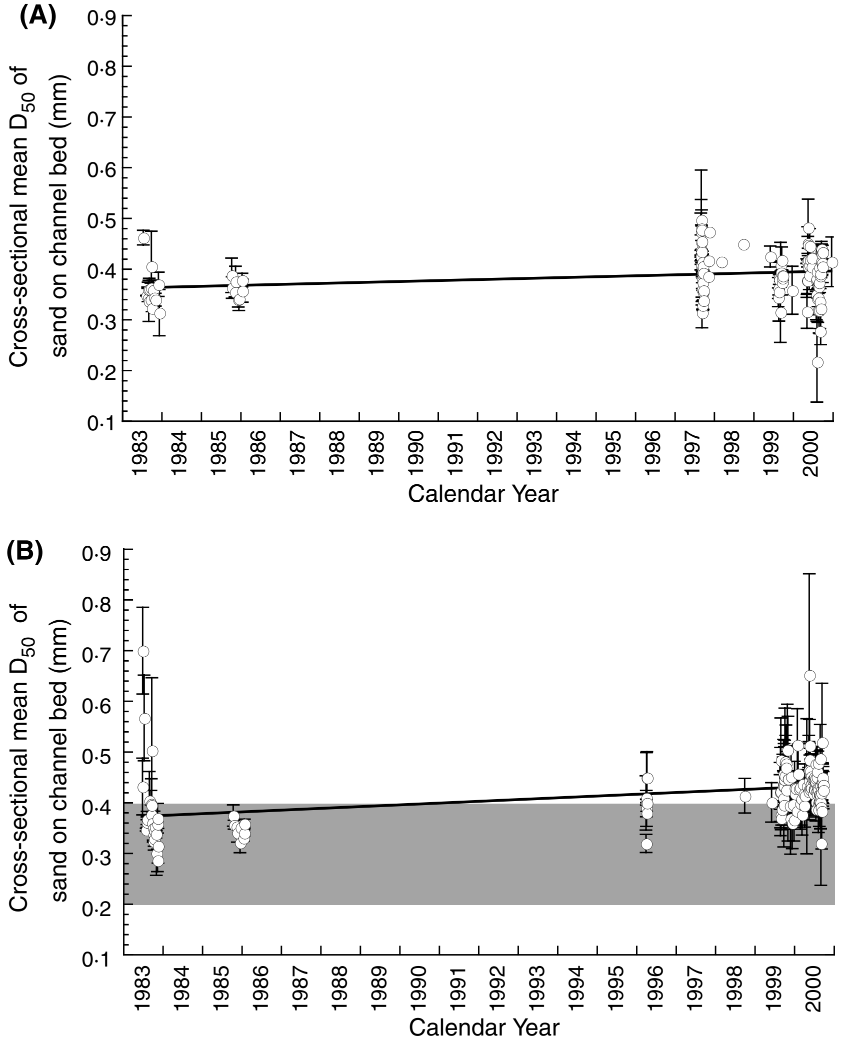

Fig. 9. Temporal variation in sand grain size on the channel bed at the Lower Marble Canyon and Grand Canyon gages from 1983 through 2000. The cross-sectional mean of the median sizes is computed by averaging the median grain sizes of the sand from two or more samples collected across the central two-thirds of the cross-section. Error bars are one standard error. (A) Cross-sectional mean of the median sizes of the sand on the bed at the Lower Marble Canyon gage. Solid line is the linear regression through these data. (B) Cross-sectional mean of the median sizes of the sand on the bed at the Grand Canyon gage. Gray-shaded region shows the full pre-dam range in the median size of the bed sand at this location. Solid line is the linear regression through these data. All data in (A) and (B) were collected using a BM-54 sampler except for the data in September 1998 and May 1999, which were collected using a pipe dredge. Data are from Garrett *et al.* (1993) and http://www.gcmrc.gov.

the variance about a single linear regression fit to all of the 1984–2000 data is less than the variance about different linear regressions fit to the data from each of the seven trips. Therefore, because this level of significance is >0·05, it cannot be concluded that the 1984–2000 data in Fig. 10A are seven different datasets. Although the longitudinal mean of the median sizes of the channel-bed sand was slightly finer in the late 1990s than it was in September 1984, analysis of variance indicates that the slight fining trends in the longitudinal mean of the median grain sizes of the channel-bed sand in Marble and Upper Grand Canyons are not significant (Fig. 10B).

Segregation of the data in Fig. 10B into two parts, 1984 and combined 1997–2000, and analysis of these two parts from Marble and Upper Grand Canyons using a Student's *t*-test yields a slightly different result. In Marble Canyon, analysis using a *t*-test comparing the means of two groups with equal variance indicates that the longitudinal mean of the median grain size of the channel-bed sand in the combined 1997–2000 data set is slightly finer than it was during the 1984 river trip, at the 0·046 level. Because this level of significance is essentially identical to the 0·05 level set as the threshold for significance in the analyses, this difference may or may not be significant. In any case, the slight difference between the 1984 and combined 1997–2000 Marble Canyon data is the result of the short-term fining of the channel bed in September 1999 following large Paria River floods. In Upper Grand Canyon, analysis using a *t*-test comparing the means of two groups with unequal variance indicates that the longitudinal mean of the median grain size of the channel-bed sand in the combined 1997–2000 data set is slightly finer than it was during the 1984 river trip, but at only the 0·71 level (a difference that is not significant).

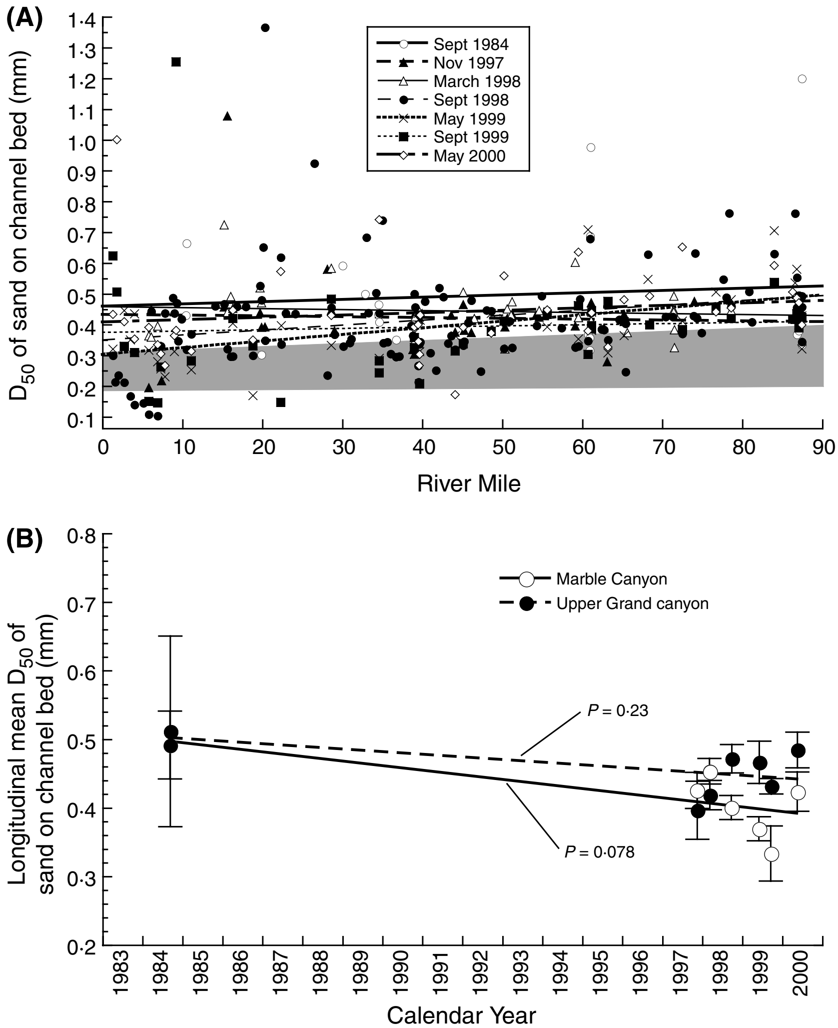

Fig. 10. Longitudinal and temporal variation in sand grain size on the channel bed between the Lees Ferry and Grand Canyon gages from 1984 through 2000 determined from pipe-dredge data. (A) Longitudinal variation in the median size of the channel-bed sand between the Lees Ferry and Grand Canyon gages during seven river trips between 1984 and 2000. Solid and dashed lines are the linear regressions through the data from each of the river trips. Analysis of variance indicates that the data from the seven trips are not significantly different and that variance is minimized when the 1984–2000 pipe-dredge data are treated as a single data set. Gray-shaded region shows the pre-dam range in the median size of channel-bed sand interpolated between the measurements at the Lees Ferry and Grand Canyon gages. (B) Temporal variation in the longitudinal mean of the median grain sizes in (A) for Marble and Upper Grand Canyons. Error bars are one standard error. Solid line is the linear regression through the longitudinal mean of the median grain sizes of the channel-bed sand in Marble Canyon and the dashed line is the linear regression through the longitudinal mean of the median grain sizes of the channel-bed sand in Upper Grand Canyon. Levels of significance (p) of the slight fining trends are indicated. At the 0·05 level, no significant trend exists in the longitudinal mean of the median grain sizes of the channel-bed sand between 1984 and 2000.

Changes in the surface grain size of sand on the lowest-elevation parts of eddy sandbars

Pre-1997 data from the lowest-elevation parts of eddy sandbars are extremely sparse, and it is impossible to know whether any major change in the grain size of sand on the lowest-elevation parts of eddy sandbars occurred between 1984 and 2000 (Fig. 11). Analysis of the data from the one eddy sampled throughout the study period (i.e. the river-mile 60·5 eddy) indicates that the grain size of sand on the lowest-elevation part of this eddy sandbar was relatively coarse and of similar size during the September 1984, September 1998, and September 1999 river trips, and was relatively fine and of similar size during the May 1999 and May 2000 river trips (Fig. 11B). Finally, despite the observation in Fig. 11A that sand

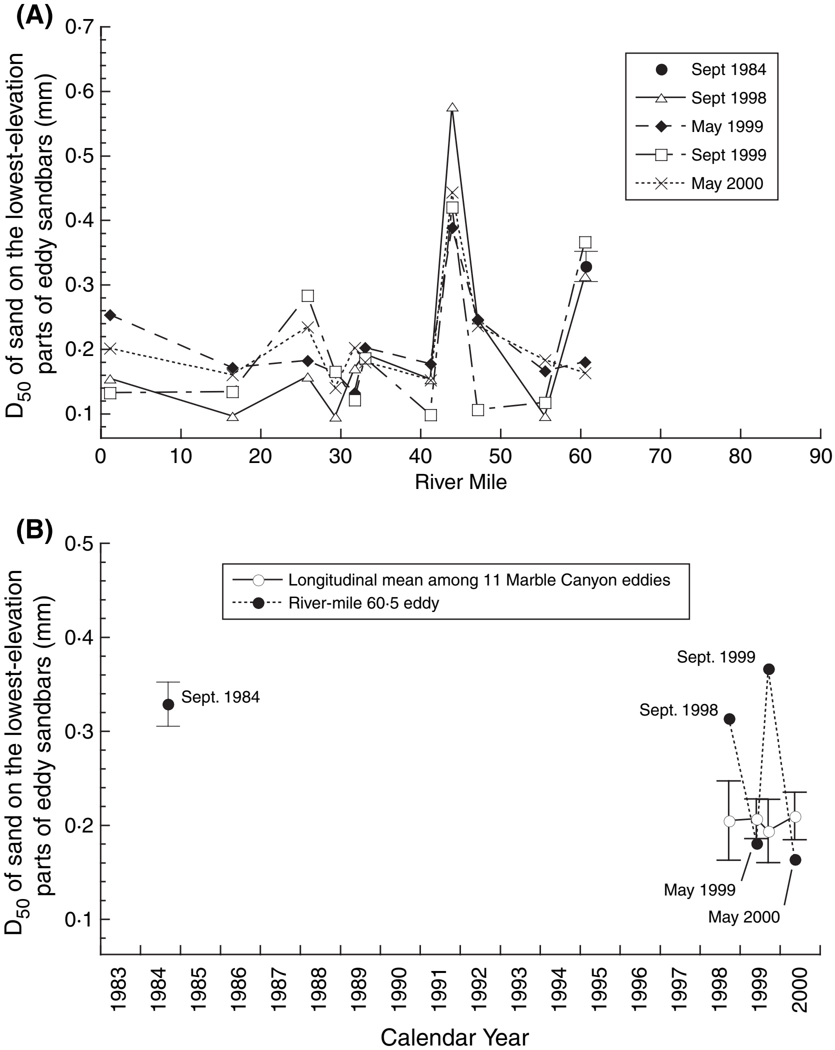

Fig. 11. Longitudinal and temporal variation in sand grain size on the lowest-elevation parts of eddy sandbars in Marble Canyon determined from pipe-dredge data. Error bars are one standard error. (A) Longitudinal variation in the median size of the sand on the lowest-elevation parts of the 11 eddy sandbars sampled between 1984 and 2000. Two samples were collected in September 1984 from the sandbar in the river-mile 60·5 eddy. (B) Temporal variation in the longitudinal mean of the median grain sizes in (A), and the median grain size of the sand on the lowest-elevation part of the sandbar in the only eddy sampled in 1984 and in 1998–2000, the river-mile 60·5 eddy.

sampled on the lowest-elevation parts of eddy sandbars in uppermost Marble Canyon tended to be finer in September after new inputs of sand from the Paria River (as was the case on the channel bed in the previous section), there is no statistically significant difference in the longitudinal mean of the median grain sizes on the lowest-elevation parts of the eddy sandbars among the 11 eddies sampled in Marble Canyon between September 1998 and May 2000 (Fig. 11B).

Changes in the surface grain size of sand on the mid- and higher-elevation parts of eddy sandbars

Substantial changes in the mean median grain size of the eddy-sandbar surfaces at mid- and high-elevations occurred in Marble and Upper Grand Canyons between August 1982 and September 2000 (Fig. 12A). The eddy sandbar surfaces coarsened during the 1983 flood, remained coarse through 1986, fined between 1986 and 1991, and then remained relatively fine through 2000. The mid- and high-elevation parts of the eddy sandbars are therefore the only riverbed environment that tracks with the fining observed in β between 1983 and 2000. In addition, the discharge-binned β-analyses presented above indicate that the greatest amount of fining over time in the bed sand 'sampled' by the suspended sand occurred at the highest elevations. The grain size of the eddy-sandbar surfaces was thus the most important regulator of sand transport during the study period.

The 1983 flood deposited coarsening-upward flood deposits, causing the surface grain size of the eddy sandbars to coarsen substantially and significantly. Subsequent surface grain-size data collected by Lojko (1985, 1987), McKay (1991), and McCutcheon (1992) indicate that the regularly inundated surfaces on the eddy sandbars remained coarse through at least August 1986,

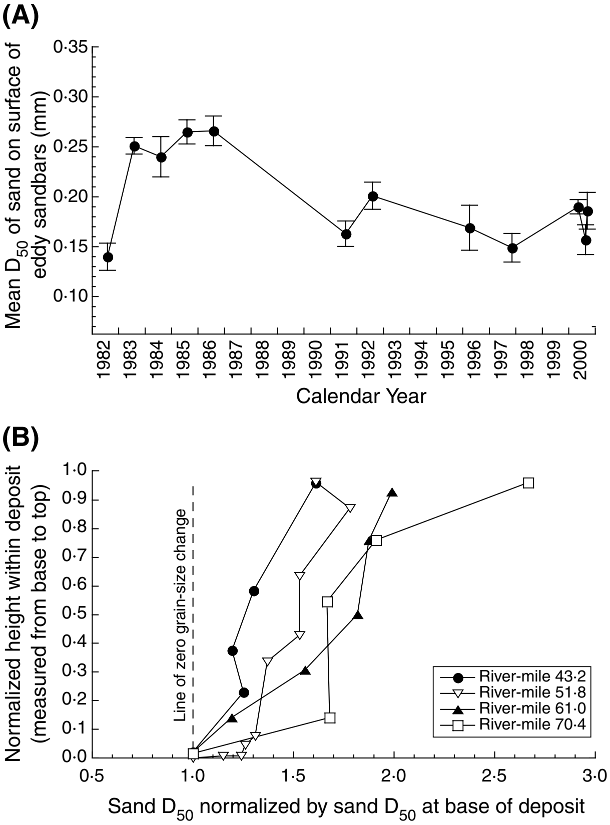

Fig. 12. (A) Mean median size of the sand on the surface of eddy sandbars in Marble and Upper Grand Canyons from 1982 through 2000. Error bars are one standard error. (B) Normalized median grain size of sand measured vertically through four 1983 flood deposits in Marble and Upper Grand Canyons. Median grain sizes at each elevation were normalized by dividing by the median grain size at the base of the deposit. These four deposits coarsened upward by a mean factor of 1·8, in agreement with the observed factor of 1·8 coarsening of the eddy sandbar surfaces between 1982 and 1983 in (A).

and began fining in the late 1980s and early 1990s. In August 1982, the mean median grain size of the sand on the surface of the eddy sandbars was 0·14 mm (Beus *et al.*, 1983). This value is within the 0·12–0·19 mm range of median grain sizes of the sand on the surfaces of eddy sandbars in the mid-1970s reported by Howard & Dolan (1981). Following the 1983 flood, the mean median grain-size of sand on the eddy sandbars in Marble and Upper Grand Canyons coarsened by a factor of 1·8 to a value of 0·25 mm (Beus *et al.*, 1983; Lojko *et al.*, 1984). Analysis of the 1982 and 1983 data using a Student's *t*-test comparing the means of two groups with equal variance indicates that the coarsening of the eddy sandbar surfaces during the 1983 flood was significant at the $3{\cdot}3 \times 10^{-7}$ level. An identical degree of average coarsening was observed in four trenches excavated through 1983 flood deposits in Marble and Upper Grand Canyons (Fig. 12B).

The similarity of the magnitude and direction of the changes in the grain size of the eddy-sandbar surfaces with the observed factor of two coarsening of the channel-bed sand at the Grand Canyon gage during the 1983 flood (Fig. 4) suggests that the sand supplied to the eddy sandbars during the 1983 flood coarsened through time as the bed of the channel was winnowed. Thus, it is likely that the coarsening of the eddy sandbar surfaces during the 1983 flood was due to the same processes observed by Rubin *et al.* (1998) and Topping *et al.* (1999) during the 1996 controlled flood and Topping *et al.* (2000b) during the 2-day 890 m^3 sec^{-1} powerplant-capacity release in November 1997. Coarsening-upward eddy deposits were also produced during two 4-day powerplant-capacity releases in 2000 (data available from http://www.gcmrc.gov). During all of these high-discharge releases from the dam, the upstream supply of sand decreased, causing the bed to winnow. This coarsening of the channel bed, in turn, caused the sand available to be deposited in eddies to coarsen, resulting in coarsening-upward flood deposits and a general coarsening of the eddy-sandbar surfaces.

Grain-size data collected from eddy-sandbar surfaces during the late 1990s indicate that, after the eddy-sandbar surfaces fined between 1986 and the early 1990s, these surfaces remained relatively fine through 2000. Analysis of the combined 1983–1986 and combined 1991–2000 data using a Student's *t*-test comparing the means of two groups with unequal variance indicates that the fining of the bar surfaces between 1986 and 1991 was significant at the $2{\cdot}6 \times 10^{-11}$ level. The fining of the bar surfaces in the late 1980s was probably due to three different processes: (i) lateral erosion through the coarsening upward 1983 flood deposits, (ii) reworking or addition of a thin layer of finer sand supplied from upstream eddy sandbars and tributaries, and (iii) less depletion of the upstream supply of finer sand during the 1996 controlled flood, and 1997 and 2000 powerplant-capacity releases relative to during the much larger 1983 flood.

The area of eddy sandbars decreased by gradual lateral erosion from the mid-1980s to just prior to the 1996 controlled flood (Schmidt *et al.*, 2004). Rubin *et al.* (1994) and Barnhardt *et al.* (2001) showed that the basal contact of the 1983 flood deposit generally slopes offshore at a gentle angle

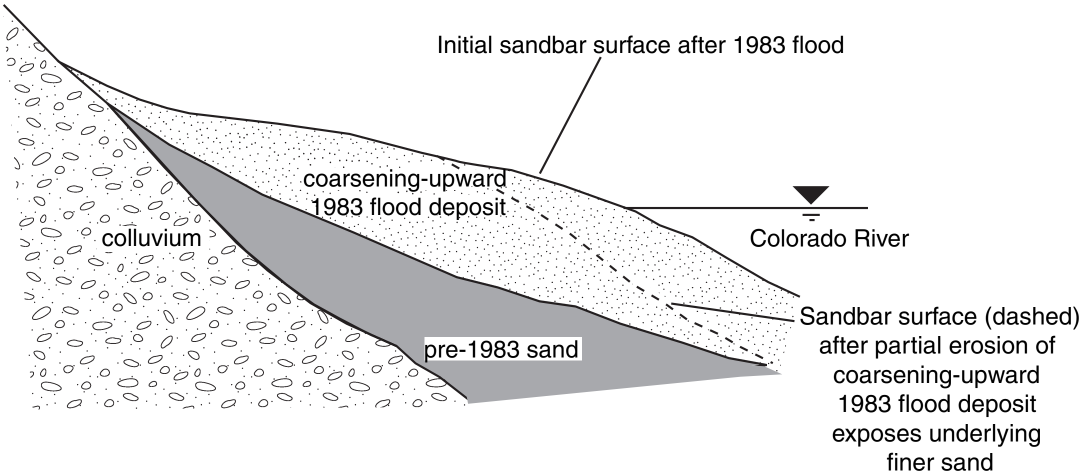

Fig. 13. Cartoon cross-section idealized from Rubin *et al.* (1994) and Barnhardt *et al.* (2001) showing an eroding eddy sandbar capped by a coarsening-upward 1983 flood deposit. The initial sandbar surface after the 1983 flood is relatively coarse. Subsequent lateral erosion of the sandbar exposes the finer sand at progressively greater depths within the 1983 flood deposit.

in the eddy sandbars, and that the 1983–1986 high-flow deposits overlay older pre-1983 deposits. Therefore, as lateral erosion progressed during the late 1980s and early 1990s, the coarser surfaces of the 1983–1986 eddy sandbars were gradually removed exposing the finer sand at progressively greater depths and lateral distances within the 1983 flood deposits (Fig. 13). This newly exposed finer sand was then available for downstream transport and could be added to downstream eddy sandbars. Similarly, new finer sand supplied from upstream tributaries and deposited on the eroding 1983–1986 eddy-sandbar surfaces caused additional fining of the sandbar surfaces (e.g. the deposits from the 1993 Little Colorado River floods described by Rubin *et al.*, 1994).

Available USGS bed grain-size data collected during the 1996 controlled flood, and during the 1997 and 2000 powerplant-capacity releases indicate that the sand on the bed of the channel never coarsened during these smaller floods to the degree that it did during the 1983 flood. Likewise, available USGS suspended-sand data indicate that, throughout the 1996 controlled flood, suspended-sand concentrations were higher and suspended-sand grain sizes were finer than during the larger 1983 flood. Similarly, USGS suspended-sand data indicate that, throughout the peaks of the much lower 1997 and 2000 powerplant-capacity releases, suspended-sand concentrations were comparable with those measured during the peak of the 1983 flood, and suspended-sand grain sizes were finer than during the peak of the 1983 flood. Thus, although the upstream sand supply decreased during all five high clear-water dam releases, the upstream supply of sand became more depleted during the 1983 flood than during the 1996 controlled flood or the 1997 and 2000 powerplant-capacity releases. Therefore, the sand available to be transported from the channel into eddies at the peak of the 1983 flood was much coarser than that available to be transported into eddies during the 1996, 1997, and 2000 high-discharge releases.

CONCLUSIONS

This study shows that β-analyses of suspended-sediment data can be used in conjunction with analyses of surface grain-size data to deduce which environments in a complicated setting are the most important environments for regulating sediment transport, regardless of whether these environments comprise a relatively large or small part of the total environment. In the case of the sand-supply-limited Colorado River in Marble and Upper Grand Canyons, the bed environment that is the dominant regulator of sand transport in the river over multi-year timescales, the eddy environment, comprises only a small percentage of the total area of the river.

In Marble and Upper Grand Canyons, grain-size data indicate that the only environment in which the grain size of the bed sand substantially changed over multi-year timescales was the surface of the eddy sandbars. As the upstream supply of sand became depleted during the 1983 flood, the sand in suspension and on the bed of the channel coarsened. This led to the production of coarsening-upward flood deposits in eddies. As a result of this process, the eddy-sandbar surfaces coarsened by about a factor of 1·8 during the 1983 flood and remained relatively coarse through the high flows of 1984, 1985, and 1986. Then, as the eddy sandbars eroded, exposing underlying finer sand (and mixing in finer sand supplied from upstream), the eddy-sandbar surfaces fined such that the sandbar surfaces in 1991–2000 were not substantially coarser than they were in either 1982 or the mid-1970s.

β-analyses at both the Lower Marble Canyon and Grand Canyon gages suggest that the dominant signal in the suspended-sand data collected since 1983 has been the fining of the eddy-sandbar surfaces as the bars eroded between the mid-1980s and the early 1990s. This finding has major implications for sand transport in Marble and Upper Grand Canyons. Between 1986 and the early 1990s, the median size of the sand on the bar surfaces decreased by about 30–40%. Topping *et al.* (2000b, fig. 18) showed that, for a narrow grain-size distribution in deeper water, this magnitude of change in bed grain size corresponds to about a factor of two increase in the concentration of sand in suspension over this surface. For the more general case in shallower water, Rubin & Topping (2001) showed that this effect would be only slightly smaller. Thus, as the eddy-sandbar surfaces became finer, substantially more sand could be carried in suspension over the eddy sandbars. This increase in flux over the eddy-sandbar surfaces as the bar surfaces fined can lead to greater deposition and erosion rates in the eddies depending on the details of the flow fields in the eddies (Schmidt *et al.*, 1993; Nelson *et al.*, 1994, 2003; Nelson & McDonald, 1995; Rubin *et al.*, 1998; Wiele *et al.*, 1999). Analysis of aerial photographs (Schmidt *et al.*, 2004) and side-scan-sonar data (Anima *et al.*, 1998; Wong *et al.*, 2003) indicate that eddy sandbars comprise only about 12% of the riverbed area (sandbars comprise somewhat greater than 60% of the eddies by area, which comprise about 20% of the river by area). Despite covering a small percentage of the riverbed area, the eddy sandbars in Marble and Upper Grand Canyons are the dominant storage environment for finer sand in the regulated post-dam river (Hazel *et al.*, in press). Furthermore, the grain size of the surfaces of these eddy sandbars is the dominant multi-year regulator of suspended-sand transport under normal powerplant releases from Glen Canyon Dam.

ACKNOWLEDGEMENTS

Funding for this study was provided by the Bureau of Reclamation through the USGS Grand Canyon Monitoring and Research Center. This study was motivated by conversations with Randy Peterson (Bureau of Reclamation). Richard Wilson and Julie Graf (USGS) collected the September 1984 pipe-dredge data used in this study. Sara Goeking (Utah State University) provided her analyses of side-scan sonar data collected in 2000 by Roberto Anima (USGS). Ted Melis and Steve Wiele provided valuable input and help during the 1997–2000 fieldwork. Logistical support for fieldwork on the Colorado River in Grand Canyon was provided by Humphrey Summit Support. We would like to thank Amy Draut, Ted Melis, Jon Nelson, and Ned Andrews for helpful reviews of earlier versions of this manuscript.

REFERENCES

Andrews, E.D. (1990) The Colorado River; A perspective from Lees Ferry, Arizona. In: Wolman, M.G., Church, M., Newbury, R., Lapointe, M., Frenette, M., Andrews, E.D., Lisle, T.E., Buchanan, J.P., Schumm, S.A., and Winkley, B.R., The riverscape. In: *Surface Water Hydrology* (Eds M.G. Wolman and H.C. Riggs), *The Geology of North America*, **O-1**, 281–328. Geological Society of America, Boulder, Colorado.

Andrews, E.D. (1991) Sediment transport in the Colorado River basin. In: *Colorado River Ecology and Dam Management* (Committee to Review the Glen Canyon Environmental Studies, Water Science and Technology Board, Commission on Geosciences, Environment, and Resources), pp. 54–74. National Academy Press, Washington, D.C.

Anima, R.J., Marlow, M.S., Rubin, D.M. and **Hogg, D.J.** (1998) Comparison of Sand Distribution Between April 1994 and June 1996 Along Six Reaches of the Colorado River in Grand Canyon, Arizona. *U.S. Geological Survey Open-File Report 98–141*, 33 pp.

Barnhardt, W., Kayen, R., Rubin, D. and **Minasian, D.** (2001) The Internal Structure of Sand Bars on the Colorado River, Grand Canyon, as Determined by Ground-Penetrating Radar. *U.S. Geological Survey Open-File Report 01–425*.

Beus, SS., Biddle, J.W., Glass, M., Iaquinto, P., Lojko, F.B. and **McAfee, B.** (1983) Beach sand grain size on the Colorado River from Glen Canyon to Diamond Creek. In: *Colorado River Investigations I, July–August 1982* (by Students and Staff of Biology 571-Geology 538, instructors S.S. Beus and S.W. Carothers), report submitted to Grand Canyon National Park, pp. 20–27. Available at the USGS Grand Canyon Monitoring and Research Center, Flagstaff, AZ, USA.

Cooley, M.E., Aldridge, B.N. and **Euler, R.C.** (1977) Effects of the Catastrophic Flood of December, 1966, North Rim Area, Eastern Grand Canyon, Arizona. *U.S. Geological Survey Professional Paper 980*, 43 pp.

Dolan, R., Howard, A. and **Gallenson, A.** (1974) Man's impact on the Colorado River in the Grand Canyon. *Amer. Sci.*, **62,** 392–401.

Flynn, M.E. and **Hornewer, N.J.** (2003) Variations in Sand Storage Measured at Monumented Cross Sections in the Colorado River Between Glen Canyon Dam and Lava Falls Rapid, Northern Arizona, 1992–1999. *U.S. Geological Survey Open-File Report 03–4104*, 39 pp.

Garrett, W.B., Van De Vanter, E.K. and **Graf, J.B.** (1993) Streamflow and Sediment-Transport Data, Colorado River and Three Tributaries in Grand Canyon, Arizona, 1983 and 1985–86. *U.S. Geological Survey Open-File Report 93–174*, 624 pp.

Hazel J., Jr. Topping, D.J., Schmidt, J.C. and **Kaplinski, M.** (in press) Influence of a dam on fine-sediment storage in a canyon river. *J. Geophys. Res. – Earth Surface*.

Howard, A.D. (1975) *Establishment of Benchmark Study Sites Along the Colorado River in Grand Canyon National Park for Monitoring of Beach Erosion Caused by Natural Forces and Human Impact*. University of Virginia Grand Canyon Study Technical Report No. 1, 182 pp. Available at the USGS Grand Canyon Monitoring and Research Center, Flagstaff, AZ, USA.

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

Laursen, E.M., Ince, S. and **Pollack, J.** (1976) On sediment transport through Grand Canyon. *Proceedings of the Third Federal Interagency Sedimentation Conference*, 4.76–4.87.

Leopold, L.B. (1969) The rapids and the pools – Grand Canyon. In: *The Colorado River Region and John Wesley Powell. U.S. Geological Survey Professional Paper 669*, 131–145 pp.

Lojko, F.B. (1985) Beach sand grain size on the Colorado River in Grand Canyon. In: *Colorado River Investigations III, July–August 1984* (by Students and Staff of Geology 538–626 Northern Arizona University, under the supervision of S.S. Beus and S.W. Carothers, Ed. D.A. House), report submitted to Grand Canyon National Park, 85–93 pp. Available at the USGS Grand Canyon Monitoring and Research Center, Flagstaff, AZ, USA.

Lojko, F.B. (1987) Five year comprehensive study on beach sand grain size of the Colorado River in the Grand Canyon. In: *Colorado River Investigations V, July–August 1986* (by Students and Staff of Geology 538–626 Northern Arizona University, under the supervision of S.S. Beus and S.W. Carothers, Ed. G.C. Weiss), report submitted to Grand Canyon National Park, 34–52 pp. Available at the USGS Grand Canyon Monitoring and Research Center, Flagstaff, AZ, USA.

Lojko, F.B., Burmaster, B., Spears, G., Nelson, W., Dancis, D. and **Byars, B.** (1984) Beach sand grain size on the Colorado River in Grand Canyon. In: *Colorado River Investigations II, July–August 1983* (by Students and Staff of Geology 538–626 Eds S.S. Beus and S.W. Carothers), report submitted to Grand Canyon National Park, 49–57 pp. Available at the USGS Grand Canyon Monitoring and Research Center, Flagstaff, AZ, USA.

Magirl, C.S., Webb, R.H. and **Griffiths, P.G.** (2005) Changes in the water surface profile of the Colorado River in Grand Canyon, Arizona, between 1923 and 2000. *Water Resour. Res.*, **41,** W05021, 10 pp.

McCutcheon, D.J. (1992) Size, shape, and composition of beach sand from selected sites in the Grand Canyon. In: *Colorado River Investigations XI, July–August 1992* (by Students and Staff of Geology 601-Biology 680 Northern Arizona University, directed S.S. Beus, J.N. David, F.B. Lojko and L.E. Stevens), report submitted to Grand Canyon National Park, 139–155. Available at the USGS Grand Canyon Monitoring and Research Center, Flagstaff, AZ, USA.

McKay, S. (1991) Beach grain sizes on two selected beaches in the Grand Canyon. In: *Colorado River Investigations #10, July–August 1991* (by Students and Staff of Geology 601, Biology 680 Northern Arizona University, under the supervision of, S.S. Beus, L.E. Stevens and F.B. Lojko), report submitted to Grand Canyon National Park, 56–65 pp. Available at the USGS Grand Canyon Monitoring and Research Center, Flagstaff, AZ, USA.

McLean, S.R. (1992) On the calculation of suspended load for noncohesive sediments. *J. Geophys. Res.*, **97,** 5759–5770.

Melis, T.S., Webb, R.H., Griffiths, P.G. and **Wise, T.J.** (1994) Magnitude and Frequency Data for Historic Debris Flows in Grand Canyon National Park and Vicinity, Arizona. *U.S. Geological Survey Water Resources Investigations Report 94–4214*, 285 pp.

National Research Council (1996) *River Resource Management in the Grand Canyon*. National Academy Press, Washington, D.C., 226 pp.

Nelson, J.M. and **McDonald, R.R.** (1995) *Mechanics and Modeling of Flow and Bed Evolution in Lateral Separation Eddies*. USGS Director's Approved report submitted to the USGS Grand Canyon Monitoring and Research Center, Flagstaff, Arizona, 39 pp. 14 figs.

Nelson, J.M., McDonald, R.R. and **Rubin, D.M.** (1994) Computational prediction of flow and sediment transport patterns in lateral separation eddies. *EOS, Transactions, American Geophysical Union*, **75,** 268.

Nelson, J.M., Bennett, J.P. and **Wiele, S.M.** (2003) Flow and sediment-transport modeling. In: *Tools in Fluvial Geomorphology* (Eds G.M. Kondolf and H. Piegay), pp. 539–576. John Wiley & Sons, Ltd., Chichester, West Sussex, England.

Randle, T.J. and **Pemberton, E.L.** (1987) *Results and Analysis of STARS Modeling Efforts of the Colorado River in Grand Canyon*. U.S. Bureau of Reclamation Glen Canyon Environmental Studies Report, 41 pp. Available at the USGS Grand Canyon Monitoring and Research Center, Flagstaff, AZ, USA.

Rubin, D.M. and **Topping, D.J.** (2001) Quantifying the relative importance of flow regulation and grain-size regulation of suspended-sediment transport (α), and tracking changes in bed-sediment grain size (β). *Water Resour. Res.*, **37,** 133–146.

Rubin, D.M., Schmidt, J.C. and **Moore, J.N.** (1990) Origin, structure, and evolution of a reattachment bar, Colorado River, Grand Canyon, Arizona. *J. Sediment. Petrol.*, **60,** 982–991.

Rubin, D.M., Schmidt, J.C., Anima, R.A., Brown, K.M., Hunter, R.E., Ikeda, H., Jaffe, B.E., McDonald, R., Nelson, J.M., Reiss, T.E., Sanders, R. and **Stanley, R.G.** (1994) Internal structure of bars in Grand Canyon and evaluation of proposed flow alternatives for Glen Canyon Dam. *U.S. Geological Survey Open-File Report 94–594*, 56 pp.

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

Rubin, D.M., Topping, D.J., Schmidt, J.C., Hazel, J., Kaplinski, K. and **Melis, T.S.** (2002) Recent sediment studies refute Glen Canyon Dam hypothesis. *EOS, Transactions, American Geophysical Union*, **83,** 273 & 277–278.

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 geomorphoric studies conducted during the 1996 controlled flood in Grand Canyon. In: *The 1996 Controlled Flood in Grand Canyon* (Eds R.H. Webb, J.C. Schmidt, G.R. Marzolf and R.A. Valdez), *Geophys. Monogr.* American Geophysical Union, Washington, D.C., **110,** 329–342.

Schmidt, J.C. and **Graf, J.B.** (1990) Aggradation and Degradation of Alluvial Sand Deposits, 1965 to 1986, Colorado River, Grand Canyon National Park, Arizona. *U.S. Geological Survey Professional Paper 1493*, 74 pp.

Schmidt, J.C. and **Rubin, D.M.** (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* (Eds J.E. Costa, A.J. Miller, K.W. Potter and P.R. Wilcock), *Geophys. Monogr.*, **89,** 177–195. American Geophysical Union, Washington, D.C.

Schmidt, J.C., Rubin, D.M. and **Ikeda, H.** (1993) Flume simulations of recirculating flow and sedimentation. *Water Resour. Res.*, **29,** 2925–2939.

Schmidt, J.C., Topping, D.J., Grams, P.E. and **Hazel, J.E.** (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 to the USGS Grand Canyon Monitoring and Research Center, Flagstaff, Arizona, 107 pp.

Stevens, L. (1983) *The Colorado River in Grand Canyon*. Red Lake Books, Flagstaff, Arizona, 115 pp.

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

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

Topping, D.J., Schmidt, J.C. and **Vierra, L.E., Jr.** (2003) Computation and Analysis of the Instantaneous-Discharge Record for the Colorado River at Lees Ferry, Arizona – May 8, 1921, Through September 30, 2000. *U.S. Geological Survey Professional Paper 1677*, 118 pp.

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

Webb, R.H., Pringle, P.T. and **Rink, G.R.** (1989) Debris Flows from Tributaries of the Colorado River, Grand Canyon National Park, Arizona. *U.S. Geological Survey Professional Paper 1492*, 39 pp.

Webb, R.H., Schmidt, J.C., Marzolf, G.R. and **Valdez, R.A.** (Eds) (1999) *The 1996 Controlled Flood in Grand Canyon, Geophysical Monograph 110*. American Geophysical Union, Washington, D.C., 367 pp.

Wiele, S.M, Graf, J.B. and **Smith, J.D.** (1996) Sand deposition in the Colorado River in the Grand Canyon from flooding of the Little Colorado River. *Water Resour. Res.*, **32,** 3579–3596.

Wiele, S.M., Andrews, E.D. and **Griffin, E.R.** (1999) The effect of sand concentration on depositional rate, magnitude, and location in the Colorado River below the Little Colorado River. In: *The 1996 Controlled Flood in Grand Canyon* (Eds R.H. Webb, J.C. Schmidt, G.R. Marzolf and R.A. Valdez), *Geophys. Monogr.*, **110,** 131–145. American Geophysical Union, Washington, D.C.

Wong, F.L., Anima, R.J., Galanis, P., Codianne, J., Xia, Y., Bucciarelli, R. and **Hamer, M.** (2003) Grand Canyon Riverbed Sediment Changes, Experimental Release of September 2000; A Sample Data Set. *U.S. Geological Survey Open-File Report 03-0265*.

Manuscript received 17 June 2004; revision accepted 24 May 2005.