COMPARISON OF SEDIMENT-TRANSPORT AND BAR-RESPONSE RESULTS FROM THE 1996 AND 2004 CONTROLLED-FLOOD EXPERIMENTS ON THE COLORADO RIVER IN GRAND CANYON

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INTRODUCTION

Sandbars and other sandy deposits in and along the Colorado River in Grand Canyon National Park (Fig. 1) were an integral part of the natural riverscape, and are important for riparian habitat, fish habitat, protection of archeological sites, and recreation (Rubin et al., 2002). Recent work has shown that these sandbars in lateral recirculation eddies contain the bulk of the sand, silt, and clay in storage (Hazel et al., in press), and the surface grain size of these sandbars is the dominant regulator of sand transport over multi-year timescales (Topping et al., 2005). These deposits have eroded substantially following the 1963 closure of Glen Canyon Dam that reduced the supply of sand at the upstream boundary of Grand Canyon National Park by about 94% (Topping et al., 2000a). In response to this reduction in sand supply and the alteration of the natural hydrograph by dam operations (Topping et al., 2003), sandbars in Marble Canyon and the upstream part of Grand Canyon have substantially decreased in size since closure of the dam (Schmidt et al., 2004) and are still in decline under normal powerplant operations at the dam (Wright et al., 2005).

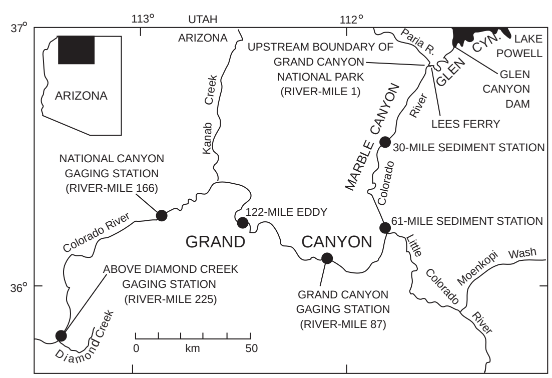

Figure 1 Map of the study area showing the locations where sediment-transport measurements were made during either the 1996 or 2004 controlled-flood experiments (solid circles). Formal names and station numbers of the Grand Canyon, National Canyon, and above Diamond Creek gaging stations are in Webb et al. (1999). By convention, locations along the Colorado River in Marble and Grand Canyons are referred to by river mile. Marble Canyon extends from Lees Ferry to the mouth of the Little Colorado River; Grand Canyon begins at the mouth of the Little Colorado River.

Prior to the 7-day 1,270 m^3/s 1996 controlled-flood experiment (Webb et al., 1999), the sediment-transport paradigm for the regulated Colorado River in Marble and Grand Canyons was that, under normal powerplant releases from Glen Canyon Dam, tributary-supplied sand would accumulate in the channel over multi-year timescales and that this accumulated sand could be transferred from the channel bed to eddies during controlled floods, increasing both the total area and volume of eddy sandbars. As summarized in Rubin et al. (2002), work conducted during and subsequent to the 1996 controlled flood indicated that this paradigm was based on assumptions that were either false or only partially true. First, sand did not accumulate in the channel of the river over multi-year time scales. Second, during the 1996 flood, sand deposited at higher elevations in eddy sandbars was eroded mostly from the lower parts of upstream sandbars (not from the channel bed) causing a net decrease in total sandbar area and volume (although sandbars did gain sand at higher elevations). Tributary inputs of new sand were relatively low in the year preceding the 1996 flood and dam releases were moderate to high. Thus, the 1996 flood experiment was conducting during a period when the Colorado River in Marble and Grand Canyons was relatively depleted with respect to sand.

The 2004 controlled-flood experiment was designed to, first, keep dam releases relatively low (<280 m^3/s) during September-November 2004 to allow the accumulation and retention of new tributary sand inputs in the channel, and, second, if more than 800,000 metric tons of new sand were retained in Marble Canyon, follow this period of lower dam releases by a 60-hour controlled-flood release of 1,160 m^3/s in November 2004 to redistribute this new sand from the channel bed into the eddies. Between July 1, 2004, and the November 2004 controlled flood, 760,000-1,200,000 (range in values results from uncertainties in calculations) metric tons of new tributary-supplied sand and 190,000-380,000 metric tons of new tributary-supplied silt and clay were retained in the Colorado River in Marble Canyon upstream from river-mile 30[1]. Virtually all of this retention of new tributary-supplied sediment occurred after dam releases were decreased to $\leq$280 m^3/s on September 1. No appreciable transport of sand was measured at river-mile 30 after this date, in spite of the fact that the Paria River supplied about 920,000$\pm$180,000 metric tons of sand between September 1, 2004, and the November 2004 controlled flood.

SEDIMENT TRANSPORT DURING THE TWO FLOODS

Substantially more sand, silt, and clay was present in suspension in the 99-km-long reach of the Colorado River in Marble Canyon during the 2004 controlled flood than during the 1996 controlled flood, with the enrichment in sand, silt, and clay during the 2004 controlled flood being greatest in the upstream half of Marble Canyon. Likewise, substantially more silt and clay was present in suspension in the 300-km-long reach of the Colorado River in Grand Canyon during the 2004 controlled flood than during the 1996 controlled flood. During the 2004 controlled flood, however, less sand was present in suspension in this downstream reach than during the 1996 controlled flood.

Suspended silt and clay concentrations measured at all sites during the 2004 controlled flood were substantially higher than those measured during the 1996 controlled flood (Fig. 2). Suspended-sand concentrations measured in Marble Canyon during the 2004 flood were 160-240% higher than those estimated at river-mile 30 during the 1996 flood, and 60-90% higher than those measured at river-mile 61 during the 1996 flood (Fig. 2). This resulted from the lower dam releases between September 1, 2004, and the November 2004 flood retaining much of the silt and clay and almost all of the sand supplied from the Paria River and other tributaries after September 1.

Suspended-sediment data were collected during the early part of the first day of the 2004 flood in a Lagrangian scheme designed to sample the same "parcel" of water as it moved downstream. These data indicate that suspended-sand concentrations increased rapidly from river-mile 0 to 7, and then increased more slowly to river-mile 23 (Fig. 3). This rapid increase in sand concentration indicates that the highest erosion rate occurred in the first 6 river miles below the mouth of the Paria River (at river-mile 1). Thus, at the beginning of the 2004 flood, most of the newly supplied sand from the Paria River was located, not only upstream from river-mile 30, but upstream from river-mile 7. In fact, analysis of multi-beam bathymetric surveys conducted before and after the flood indicates that a large part of this new sand was retained on the bed of the channel upstream from river-mile 3. Downstream from this erosional reach, sand concentrations decreased from river-mile 23 to about river-mile 43, indicating deposition of sand in this reach, presumably in eddies. From river-mile 43 through the downstream end of Marble Canyon at river-mile 62, sand concentrations increased again. Erosion in this second reach of increasing sand concentration likely occurred by erosion of sand stored in eddies because: (1) sediment-transport data collected prior to the flood indicate that little accumulation of new tributary-supplied sand occurred in this reach, and (2) recent work by Hazel et al. (in press) has shown that most of the "background" storage of sand in Marble Canyon occurs in the

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[1] River-mile 30 is the location of one of four sediment stations using conventional, pump, laser-diffraction, and acoustic methods to measure sediment transport at a resolution of 15 minutes. Laser-acoustic instrumentation at the 30-mile sediment station, 61-mile sediment station, and above Diamond Creek gaging station are similar to those at Grand Canyon gaging station described in Topping et al. (this volume).

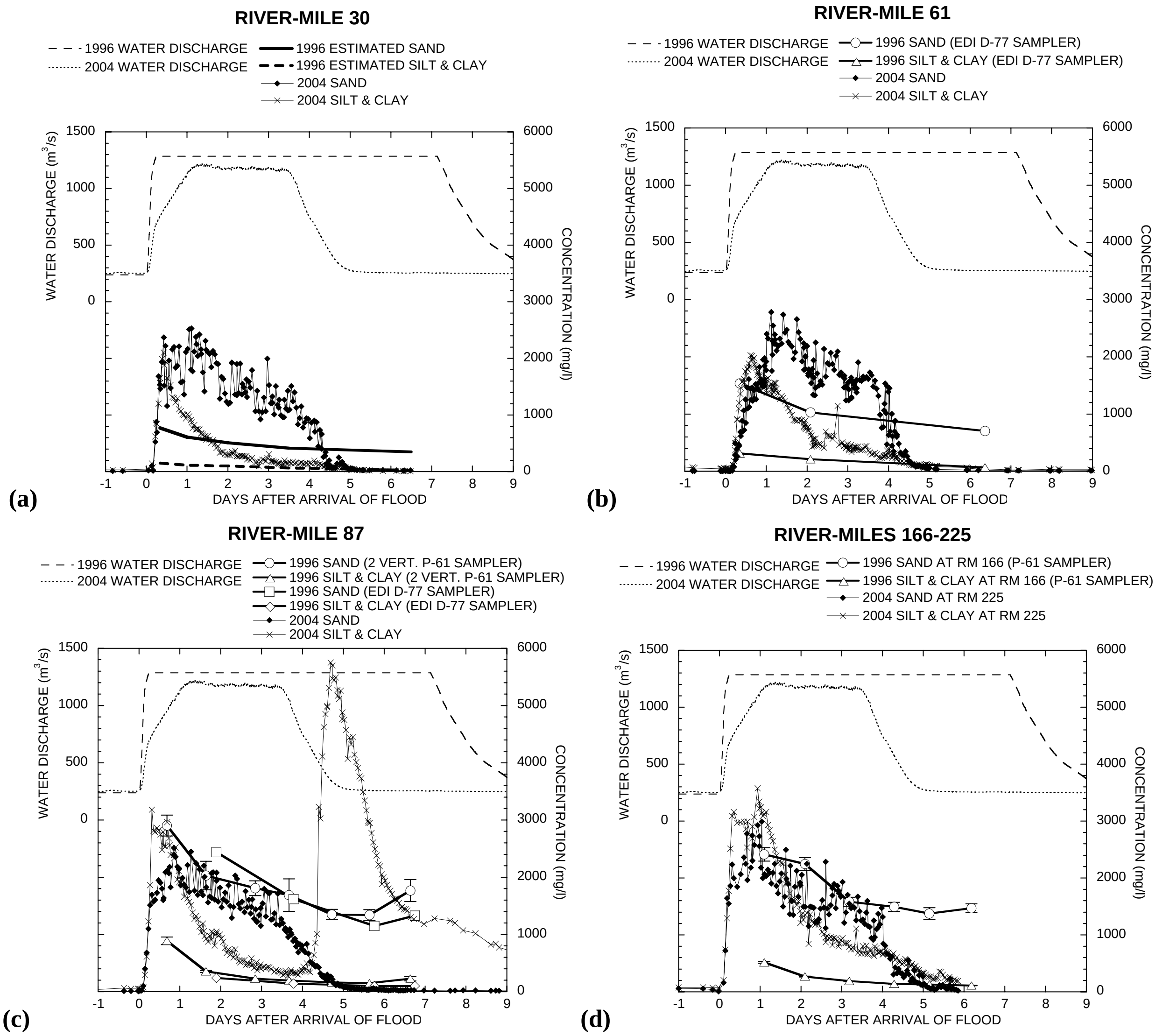


Figure 2 Hydrographs and suspended-sediment concentrations during the 1996 and 2004 controlled-flood experiments at **(a)** river-mile 30, **(b)** river-mile 61 at the lower end of Marble Canyon, **(c)** the Grand Canyon gaging station at river-mile 87 (second peak in silt and clay concentration in 2004 due to Little Colorado River flood during recession of 2004 controlled flood), and **(d)** the National Canyon gaging station (now decommissioned) at river-mile 166 in 1996 and the above Diamond Creek gaging station at river-mile 225 in 2004. Suspended-silt and clay, and suspended-sand concentrations estimated for river-mile 30 in 1996 based on sampling trip conducted in spring 2000 under sediment-depleted conditions similar to those that existed during the 1996 controlled-flood experiment. Under such conditions, silt and clay, and sand concentrations increase approximately linearly in a downstream direction from river-mile 1 to river-mile 61. Thus, 1996 silt and clay, and 1996 sand concentrations at river-mile 30 were estimated to be half of those measured at river-mile 61. Error bars for 1996 P-61 measurements are one standard error.

lower-elevation parts of eddy sandbars. Sand concentrations increased rapidly again downstream from the Little Colorado River presumably by erosion of the ~50,000 metric tons of sand supplied by this tributary between September 1, 2004, and the November 2004 controlled flood. Finally, sand concentrations decreased from river-mile 72 to the Grand Canyon gaging station at river-mile 87, where the Lagrangian sampling effort ended.

Construction of a "mass-balance" sediment budget using sediment-transport data from the tributaries, 30-mile sediment station, 61-mile sediment station, Grand Canyon gaging station (river-mile 87), and above Diamond Creek

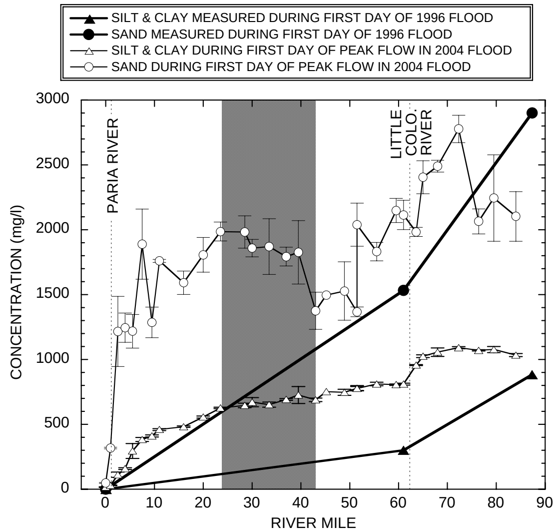


Figure 3 Cross-sectionally averaged suspended-silt and clay, and sand concentrations measured during the Lagrangian sampling program in the 2004 flood compared to cross-sectionally averaged suspended-silt and clay, and sand concentrations measured on the first day of the 1996 flood. Linear interpolation between the sparse 1996 measurements is justified in Fig. 2. Error bars are one standard error. Gray shaded region indicates reach in Marble Canyon that was net depositional with respect to sand early on the first day of the 2004 flood.

gaging station (river-mile 225) indicate that, of the 760,000-1,200,000 metric tons of the new tributary-supplied sand retained in uppermost Marble Canyon prior to the 2004 controlled flood, at least 130,000 metric tons were deposited above river-mile 30 during the 2004 flood (probably in eddy sandbars). In contrast, these data suggest that the change in the mass balance of sand during the 2004 flood was either zero or slightly negative in the downstream half of Marble Canyon and all of Grand Canyon, depending on the level of uncertainty included in the analysis. Therefore, either no change in the amount of sand in background storage or slight erosion of sand from background storage occurred downstream from river-mile 30. The total amount of sand eroded between river-miles 30 and 225 during the 2004 flood, however, was much less than the amount of new tributary-supplied sand deposited upstream from river-mile 30 during the 2004 flood. Thus, the sand budget for the period from July 1, 2004, through the end of the November 2004 flood was positive throughout the entire length of Marble and Grand Canyons.

Suspended-sand concentrations at the Grand Canyon gaging station and above Diamond Creek gaging station were approximately equal throughout the 2004 controlled flood, but about 20-45% lower than measured in this reach at the Grand Canyon gaging station, 122-mile eddy, and the National Canyon gaging station during the 1996 controlled flood (Fig. 2). This difference can be explained only in part by the fact that the peak discharge during the 2004 flood was slightly less than that during the 1996 flood. Thus, unlike the sand-enriched conditions in Marble Canyon, the sand supply in Grand Canyon was less during the 2004 flood than during the 1996 flood. This indicates that more sand was eroded from Grand Canyon between the 1996 and 2004 floods than could be replenished by the 760,000-1,200,000 metric tons of new tributary-supplied sand that were retained in uppermost Marble Canyon between July 1, 2004, and the beginning of the November 2004 controlled flood.

GRAIN-SIZE EVOLUTION ON THE BED AND IN SUSPENSION DURING THE TWO FLOODS

As observed during the 1996 controlled flood, the grain size of the sand on the bed and in suspension coarsened as the upstream supply of sand became depleted during the 60-hours of peak flow during the 2004 controlled flood (Fig. 4). In addition, during both floods, the concentration of silt and clay decreased rapidly over time (Fig. 2). Because the concentration of silt and clay decreased more rapidly than the concentration of sand, the silt and clay content of the total suspended load available to be deposited in eddies decreased over time during both floods. The median grain size of the bed sand at the Grand Canyon gaging station (the only place where bed-sand grain size was measured in 1996) was slightly finer during the 2004 flood than during the 1996 flood, despite the fact that less sand was present in suspension during the 2004 flood at this site. Regardless of whether more or less sand was present in

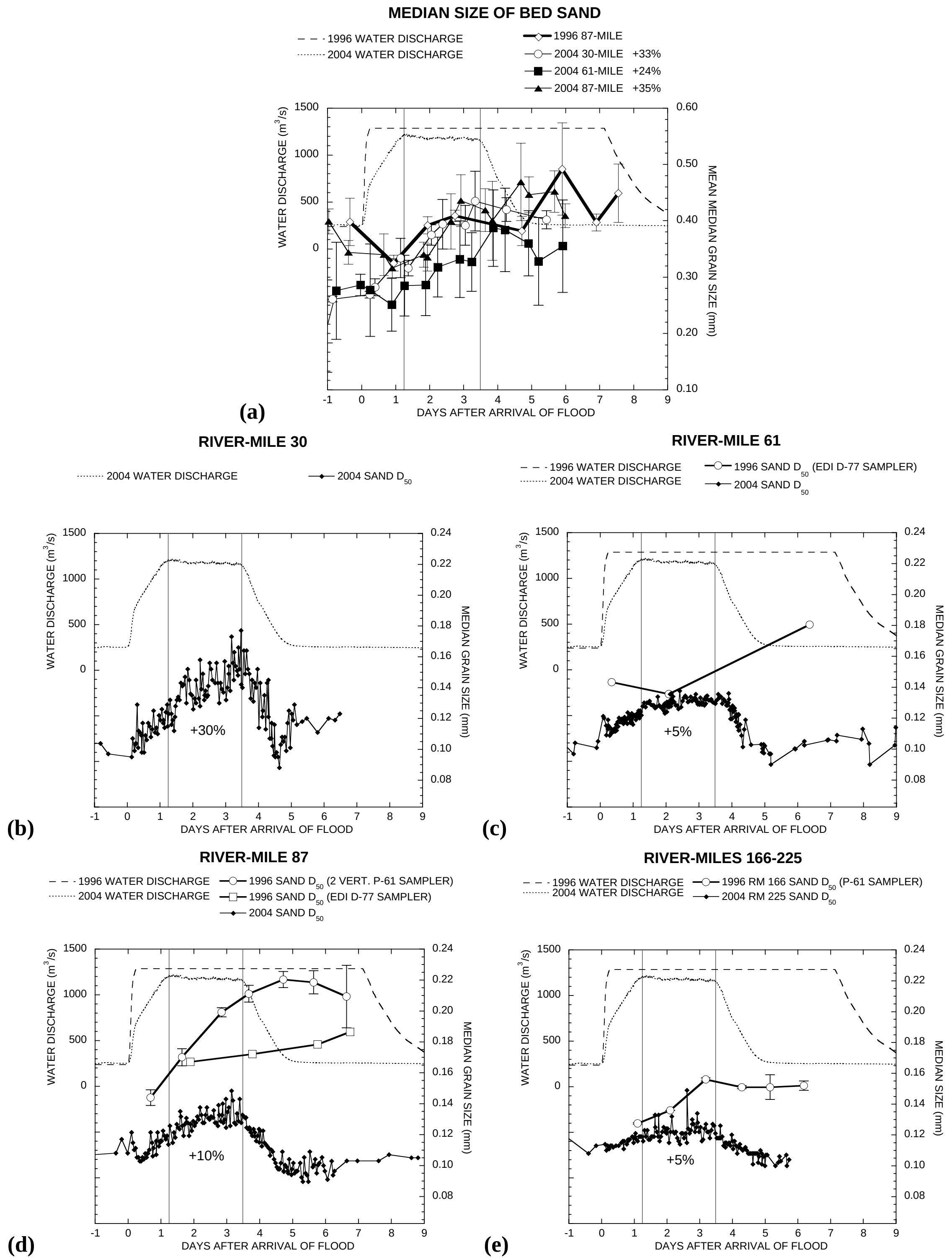


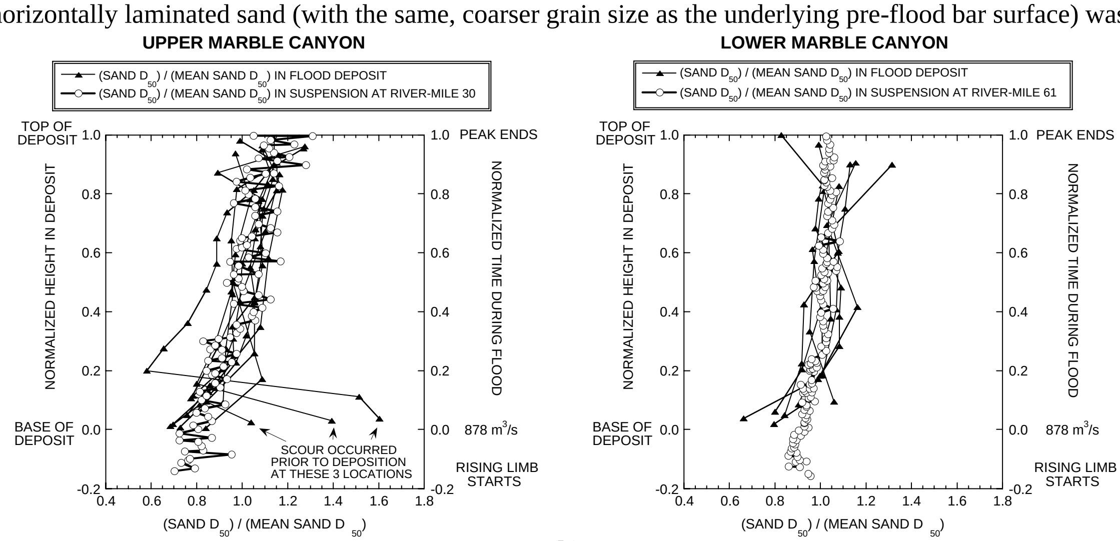
Figure 4 Hydrographs and median grain size (D_{50}) of sand during the 1996 and 2004 floods. Two vertical lines denote duration of peak-flow part of 2004 flood; degree of coarsening during peak-flow part of 2004 flood is indicated for each site in percent. Error bars are one standard error. **(a)** On the bed. **(b)** In suspension at river-mile 30. **(c)** In suspension at river-mile 61. **(d)** In suspension at the Grand Canyon gaging station at river-mile 87. **(e)** In suspension at either the National Canyon gaging station at river-mile 166 (in 1996 flood) or at the above Diamond Creek gaging station at river-mile 225 (in 2004 flood).

suspension, however, the median grain size of the suspended sand (like the bed sand) was finer at all sites where measurements were made during the 2004 flood. At the Grand Canyon and above Diamond Creek gaging stations, this difference (like the lower sand concentrations during the 2004 flood) can be explained only in part by the fact that the peak discharge during the 2004 flood was slightly lower than it was during the 1996 flood. Thus, not only was the supply of sand during the 2004 flood slightly less below about river-mile 75 (Figs. 2 & 3), the supply of sand available to be transported in suspension also was slightly finer than it was during the 1996 flood (Fig. 4).

Although Marble Canyon was enriched with respect to sand during the 2004 flood relative to during the 1996 flood, this enrichment was not sufficient to prevent the occurrence during the 2004 flood of the grain-size-evolution effects of sand-supply limitation observed during the 1996 flood (Rubin et al., 1998; Topping et al., 1999; Topping et al., 2000b). In both floods, the bed winnowed, suspended sand coarsened, and suspended-sand concentration decreased. The greatest amounts of suspended-sand coarsening occurred in the reaches most enriched with respect to finer sand prior to the 2004 flood, i.e., the reaches downstream from the two key sand-supplying tributaries, the Paria River (which enters the Colorado River at river-mile 1) and the Little Colorado River (which enters the Colorado River at river-mile 62). During the peak-flow part of the 2004 flood, the median grain size of the suspended sand coarsened by 30% at river-mile 30 (downstream from the reach most highly enriched in finer sand prior to the flood) and 10% at river-mile 87. The least amount of coarsening of the suspended sand occurred at river-miles 61 and 225, where the median grain size coarsened by only 5% during the peak-flow part of the 2004 flood. These two measurement locations were the farthest downstream from the sand-enriched reaches below the Paria and Little Colorado Rivers.

SEDIMENTOLOGIC AND TOPOGRAPHIC RESPONSE OF EDDY SANDBARS

As during the 1996 flood (Rubin et al., 1998; Topping et al., 2000b, Fig. 8), the eddy deposits produced during the 2004 flood coarsened upward by both a coarsening of the sand (Fig. 5) and a decrease in the silt and clay content. Unlike during the 1996 flood, however, in areas where scour preceded deposition during the 2004 flood, 2-10 cm of clean, horizontally laminated sand (with the same, coarser grain size as the underlying pre-flood bar surface) was



(a) **(b)**

Figure 5 Median grain size of the sand in a deposit (normalized by the mean median grain size of the sand in each deposit) as a function of normalized height within a deposit, and the median grain size of the sand in suspension (normalized by the mean median grain size of the sand in suspension during the flood) as a function of normalized time (0 = time at which the flood rises above 878 m^3/s and bars are mostly inundated, 1 = time of end of peak flow): **(a)** in deposits between river-miles 21 and 31 and in suspension at river-mile 30, **(b)** in deposits between river-miles 43 and 60 and in suspension at river-mile 61.

sometimes deposited prior to the coarsening-upward part of the deposit. The deposits produced during both floods tracked the coarsening of the suspended sediment through time (Topping et al., 2000b, Fig. 8; Fig. 5). In the ten deposits sampled between river-miles 21 and 31, after the first arrival of the silt and clay, the median grain size of the sand coarsened upward on average by 46%, and the silt and clay content decreased on average by about 93%. At river-mile 30, the median grain size of the suspended sand coarsened by 50% and the silt and clay content of the suspended load decreased by 85% during the rising-limb and peak-flow part of the flood. In the eight deposits sampled between river-miles 43 and 60, the median grain size of the sand coarsened upward on average by 20%, and the silt and clay content decreased on average by about 87%. At river-mile 61, the median grain size of the suspended sand coarsened by 18% and the silt and clay content of the suspended load decreased by 79% during the rising-limb and peak-flow part of the flood. Because more silt and clay was present in suspension during the 2004 flood, more silt and clay was present in the 2004 deposits (16%) than in the 1996 deposits (~5%) in Marble Canyon.

In the upstream half of Marble Canyon (the reach with the greatest degree of sand enrichment relative to the 1996 flood), sandbars produced during the 2004 flood were much larger in total area and volume than those produced during the 1996 flood. The topographic response of eddy sandbars in this reach during the 2004 flood correlates well with: (1) the observed spatial pattern in suspended-sand concentration during the Lagrangian sampling trip showing net deposition of sand between river-miles 23 and 43, and (2) the sediment budget showing post-flood retention of at least 130,000 metric tons of the new tributary-supplied sand upstream from river-mile 30. Half of the sandbars surveyed in this reach were substantially larger in both area and volume above the stage associated with 227 m^3/s (i.e., base flow for daytime dam operations) than they were immediately following the 1996 flood. In addition, analysis of combined multi-beam bathymetric, ground-based, and airborne LiDAR surveys indicates that, during the 2004 flood, the eddy sandbars between river-miles 21 and 32 increased in total area and volume. In contrast, during the 1996 flood, eddy sandbars increased in area and volume only at higher elevations, with larger amounts of erosion of the lower-elevation parts of the bars (Hazel et al., 1999; Schmidt, 1999). Thus, eddy sandbars in Marble Canyon decreased in total area and volume during the 1996 flood.

In contrast to the results in the upstream half of Marble Canyon, only 18% of the sandbars surveyed in the downstream half of Marble Canyon and the upstream part of Grand Canyon (above river-mile 87) were larger in both area and volume above the stage associated with 227 m^3/s immediately following the 2004 flood than they were immediately following the 1996 flood. Furthermore, analysis of combined multi-beam bathymetric, ground-based, and airborne LiDAR surveys indicates that the total area and volume of eddy sandbars downstream from river mile 42 generally decreased during the 2004 flood. The topographic response of the eddy sandbars during the 2004 flood in this reach also correlates well with: (1) the observed spatial pattern in suspended-sand concentration during the Lagrangian sampling trip showing general erosion of sand downstream from river-mile 43, and (2) the sediment budgets showing no change or slightly negative change in the reaches downstream from river-mile 30.

CONCLUSIONS

Results from the 2004 controlled-flood experiment indicate that substantial increases in total eddy-sandbar area and volume in the Colorado River in Marble and Grand Canyons are possible only during controlled floods conducted under the sediment-enriched conditions that follow large tributary floods. Results from the 1996 controlled-flood experiment indicate that, during sediment-depleted conditions, sand deposited at higher elevations in downstream eddy sandbars is derived from the lower-elevation parts of upstream sandbars. Thus, controlled floods conducted under these conditions result in decreases in total eddy-sandbar area and volume (especially in Marble Canyon). Analysis of surveys conducted one to four times per year during the 1990s indicates that sandbars in Marble Canyon and the upstream part of Grand Canyon contained ~25% less sand at lower elevations in 2000 than in 1991, and that the lower-elevation parts of these sandbars and the adjacent channel bed never fully recovered in sand volume after scouring during the 1996 flood (Schmidt et al., 2004). Thus, controlled floods conducted under sediment-depleted conditions, such as those that existed in 1996, cannot be used to sustain sandbar area and volume. Under the lower dam releases that preceded the 2004 flood, most of the new tributary-supplied sand was retained in the uppermost part of Marble Canyon. During the 2004 flood, this sand was eroded from the channel bed and transported downstream, with a fraction transferred into eddies. This resulted in a net increase in the total area and volume of eddy sandbars in the upstream half of Marble Canyon. In addition, about half of the sandbars surveyed in this reach following the 2004 flood were substantially larger at higher elevations than they were following the 1996 flood. Downstream reaches were not as enriched with new tributary-supplied sand, however. During the 2004 flood, sand concentrations in Grand Canyon were lower than they were during the 1996 flood. The total area and volume of eddy sandbars downstream from about river-mile 42 generally decreased during the 2004 flood. Only 18% of the sandbars surveyed following the 2004 flood between river-miles 42 and 87 were larger at higher elevations than they were following the 1996 flood. Therefore, the amount of new sand in retention prior to the 2004 controlled flood was sufficient to result in substantial increases in sandbar area and volume in only the first 50 km of the 400-km long reach of the Colorado River in Marble and Grand Canyons. Only a relatively small amount of the new tributary-supplied sand in retention prior to the flood was deposited in the upstream half of Marble Canyon during the 2004 flood, resulting in the observed increases in total eddy-sandbar area and volume in this reach. Lengthening the hydrograph of a future controlled flood with a similar amount of sand as the 2004 flood, thus, would likely drive the sediment budget in the upstream half of Marble Canyon negative, resulting in either no change or a decrease in total eddy-sandbar area and volume. Therefore, in future controlled floods, more sand is required to achieve increases in the total area and volume of eddy sandbars throughout all of Marble and Grand Canyons. Annual tributary inputs of sand much larger than one million metric tons occur, but are relatively rare. Therefore, "more sand" could be achieved directly by augmentation from sand trapped in the reservoir impounded by Glen Canyon Dam or perhaps indirectly by following each large tributary input of sand with short-duration controlled floods. Frequent short-duration controlled floods under sand-enriched conditions could result in the downstream propagation (into the downstream half of Marble Canyon and into Grand Canyon) of the gains in total eddy-sandbar area and volume observed in the upstream half of Marble Canyon during the 2004 controlled-flood experiment.

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