SEDIMENT RESOURCES HANDOUT
12/7/99 TWG MEETING — DAVE RUBIN

The GCMRC physical sciences program has been monitoring sediment input (Paria and Little Colorado) and export (mainstem); grain size of sediment in flood deposits, on the bed, and in suspension; volume of sediment in storage at selected sites; and surface area of sand deposits (geomorphic mapping and side-scan sonar mapping).

High mainstem flows have the potential of accomplishing two sediment-related goals: transferring sediment from low areas (under water) to high areas (on bars); this transfer of sediment may offer the additional benefit of reducing the loss of sediment downstream.

Monitoring data suggest that little—if any—of the sediment that is supplied by tributaries remains upstream of the Grand Canyon gage for more than a few months. High mainstem flows that are not timed to follow shortly after tributary floods may accomplish the first goal listed above (transferring sand to high areas on bars), but will not effectively accomplish the important goal of retaining tributary sediment.

To retain tributary sediment, artificial mainstem floods should be scheduled as soon as possible after tributary-input floods. This will provide more sediment than waiting many years for tributary sediment to accumulate.

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Colorado River sediment transport
2. Systematic bed-elevation and grain-size effects of sand supply limitation

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Abstract. The Colorado River in Marble and Grand Canyons displays evidence of annual supply limitation with respect to sand both prior to [*Topping et al.*, this issue] and after the closure of Glen Canyon Dam in 1963. Systematic changes in bed elevation and systematic coupled changes in suspended-sand concentration and grain size result from this supply limitation. During floods, sand supply limitation either causes or modifies a lag between the time of maximum discharge and the time of either maximum or minimum (depending on reach geometry) bed elevation. If, at a cross section where the bed aggrades with increasing flow, the maximum bed elevation is observed to lead the peak or the receding limb of a flood, then this observed response of the bed is due to sand supply limitation. Sand supply limitation also leads to the systematic evolution of sand grain size (both on the bed and in suspension) in the Colorado River. Sand input during a tributary flood travels down the Colorado River as an elongating sediment wave, with the finest sizes (because of their lower settling velocities) traveling the fastest. As the fine front of a sediment wave arrives at a given location, the bed fines and suspended-sand concentrations increase in response to the enhanced upstream supply of finer sand. Then, as the front of the sediment wave passes that location, the bed is winnowed and suspended-sand concentrations decrease in response to the depletion of the upstream supply of finer sand. The grain-size effects of depletion of the upstream sand supply are most obvious during periods of higher dam releases (e.g., the 1996 flood experiment and the 1997 test flow). Because of substantial changes in the grain-size distribution of the bed, stable relationships between the discharge of water and sand-transport rates (i.e., stable sand rating curves) are precluded. Sand budgets in a supply-limited river like the Colorado River can only be constructed through inclusion of the physical processes that couple changes in bed-sediment grain size to changes in sand-transport rates.

1. Introduction

In some rivers the upstream supply of sediment is in equilibrium with the upstream supply of water, whereas in others, the upstream supply of sediment is decoupled, either completely or partially, from the upstream supply of water. In the first type of river, changes in sediment transport are controlled by changes in the discharge of water, whereas in the second (and perhaps more common) type of river, changes in sediment transport are also coupled to changes in sediment grain size. In this paper we investigate the systematic changes in bed elevation, sediment transport, and sediment grain size that occur in response to changes in the upstream supply of sand in a river with an intermittent limited supply of sand, specifically the Colorado River in Marble and Grand Canyons (Figure 1). F1

To develop an intuitive understanding of the linkage between sediment grain size and the upstream supply of sediment in a river, it is informative to first examine sediment-transport flume experiments. As discussed by *Parker and Wilcock* [1993], these experiments typically fall into two categories: (1) those using sediment-recirculating flumes (in which the water and sediment are reintroduced at the upstream end of the flume at the same rate that they leave the downstream end) and (2) those using sediment-feed flumes (in which the sediment is supplied at the upstream end of the flume in a manner decoupled from the rate at which the sediment leaves the downstream end). In sediment-recirculating flumes the sediment supply at the upstream end of the flume equals the sediment export at the downstream end of the flume. Thus these flumes are like rivers in which the upstream supply of sediment is in equilibrium with the upstream supply of water. In these experiments, no substantial change occurs in the grain size of the sediment on the bed of the flume [e.g., *Guy et al.*, 1966]. In sediment-feed flumes, however, the upstream supply of sediment is decoupled from the upstream supply of water. In these experiments the grain-size distribution of the bed sediment and the sediment-transport rate are free to change substantially as a function of the interaction between the rates of sediment feed and downstream transport (as described by *Wilcock and McArdell* [1993]).

Prior to closure of Glen Canyon Dam in March 1963, the Colorado River in Marble Canyon and upper Grand Canyon (Figure 1) was annually supply-limited with respect to sand but

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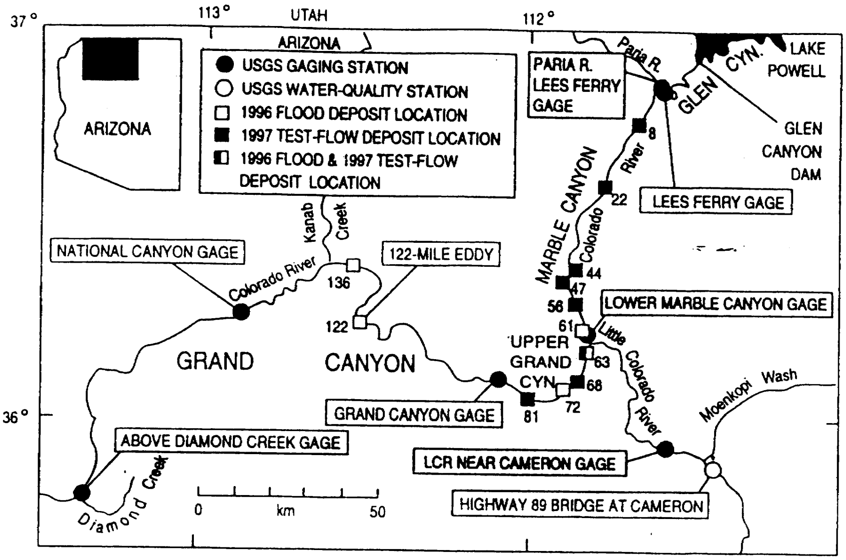


Figure 1. Map of Grand Canyon region showing measurement locations. Glen Canyon lies upstream of the mouth of the Paria River; Marble Canyon extends from the Paria River to the Little Colorado River; Grand Canyon lies downstream of the Little Colorado River; the portion of Grand Canyon between the mouth of the Little Colorado River and the Grand Canyon gage is herein referred to as upper Grand Canyon. The names and station numbers of the depicted U.S. Geological Survey (USGS) gaging and water-quality stations are Colorado River at Lees Ferry, station number 09380000 (herein referred to as the Lees Ferry gage); Paria River at Lees Ferry, station number 09382000 (herein referred to as the Paria River Lees Ferry gage); Colorado River above Little Colorado River near Desert View, station number 09383100 (herein referred to as the Lower Marble Canyon gage); Little Colorado River at Cameron, station number 09401200 (herein referred to as the Highway 89 bridge at Cameron); Little Colorado River near Cameron, station number 09402000 (herein referred to as the LCR near Cameron gage); Colorado River near Grand Canyon, station number 09402500 (herein referred to as the Grand Canyon gage), Colorado River above National Canyon near Supai, station number 09404120 (herein referred to as the National Canyon gage); and Colorado River above Diamond Creek near Peach Springs, station number 09404200 (herein referred to as the Above Diamond Creek gage). Numbers next to the locations of flood deposits indicate the river miles of these locations.

was not supply-limited during all seasons [*Topping et al.*, this issue]. In the predam river, sand would accumulate in Marble Canyon and upper Grand Canyon when flows were lower than about 200–300 m^3/s and would either be conveyed through or be eroded from this reach when flows were higher. Seasonal sediment budgets suggest that sand would accumulate in this reach for 9 months of the year (July–March), a period when flows were less than 250 m^3/s about 73% of the time. This stored sand would then be depleted from April through June during the annual snowmelt flood, a period when flows were greater than 250 m^3/s about 90% of the time [see *Topping et al.*, this issue, Figure 11]. Seasonal depletion of the upstream supply of sand during the annual snowmelt flood was associated with coarsening of the sand in the river (both on the bed and in suspension) and led to the production of inversely graded flood deposits [*Topping et al.*, this issue]. In the postdam river, *Rubin et al.* [1998] and *Topping et al.* [1999] have documented similar coarsening in response to the depletion of the upstream supply of sand.

In March 1963, the Colorado River was altered by the closure of Glen Canyon Dam, 24 km above the downstream terminus of Glen Canyon. Dam operation for power generation has flattened the shape of the annual hydrograph by not only removing the annual snowmelt flood but also by removing the low flows that were predominant during the predam season of sand accumulation and storage (July–March), such that flows of 250 m^3/s are now exceeded 74% of the time [*Topping et al.*, this issue]. Thus operation of the dam has eliminated most flows in the discharge range that caused sand to accumulate in predam Marble Canyon and upper Grand Canyon. Given that higher flows now dominate the entire year and that sand is supplied by the tributaries downstream from the dam primarily during 3 months of the year (July–September) [see *Topping et al.*, this issue, Figure 10b], the postdam Colorado River in Marble and Grand Canyons is essentially a large sediment-feed flume, with a feed device that functions only intermittently. Therefore the postdam river is the ideal natural laboratory for investigating the response of bed elevation and sediment grain size to changes in the upstream supply of sand. In this paper we present and analyze data collected in the Colorado River in Marble and Grand Canyons (1) during high main stem flows in 1996 and 1997 and (2) during and following large tributary floods in 1983, 1997, and 1998.

2. Systematic Changes in Bed Elevation, Sand Grain Size, and Suspended-Sand Concentration During the 1996 Flood Experiment

By virtue of conservation of mass, changes in bed topography are caused by divergence in the flux of sediment. During periods of changing discharge, divergence in the flux of sediment can be driven by two processes: (1) redistribution of the boundary shear stress field in a reach caused by a change in flow patterns (herein referred to reach-geometric effects) and (2) changes in the upstream supply of sediment. Changes in bed topography in Marble and Grand Canyons have been used extensively to deduce changes in the amount of sand storage in the river [*Graf et al.*, 1995, 1997; *Konieczki et al.*, 1997; *Hazel et al.*, 1999]. However, because substantial changes in bed topography can be caused by reach-geometric effects, relating bed-topographic changes to changes in sediment storage can be problematic.

During the 1996 Grand Canyon flood experiment (described by *Schmidt et al.* [1999]), a data set was collected that would allow separation of the two processes that control bed-topographic change. Daily topographic surveys of the reach at the Grand Canyon gage (at river mile 87.4) were conducted in conjunction with daily measurements of suspended-sediment concentration and grain size and bed-sediment grain size. To monitor changes in suspended-sediment concentration and grain size at other locations during the flood, data were also collected at the Lower Marble Canyon gage (at river mile 61, above the mouth of the Little Colorado River), in the eddy at the mouth of Hundred Twenty-Two Mile Creek (herein referred to as 122-mile eddy), and at the National Canyon gage (at river mile 166.1).

At the Grand Canyon gage the 1996 flood experiment consisted of 3 days of steady 238 m^3/s (8400 cfs) discharge, followed by 5.75 hours of increasing flow, followed by 7 days of steady 1290 m^3/s (45,400 cfs) discharge, followed by 3.2 days of decreasing flow back to a steady 238 m^3/s discharge. Throughout this paper the day prior to the arrival of the flood is referred to as "day −1," the 7 days of 1290 m^3/s discharge are referred to as "days 1–7," and the first day of the receding limb of the flood is referred to as "day +1."

2.1. Methods

During the 1996 flood experiment, bed topography in the reach at the Grand Canyon gage was measured daily by (1) sounding under the measurement cableway (herein referred to as the Grand Canyon cableway) and (2) surveying five cross sections located at 0, 46, 86, 118, and 158 m above the cableway
F2 (Figure 2). These cross sections were surveyed using the methodology developed by *Graf et al.* [1995]. U.S. Geological Survey (USGS) Arizona District personnel also surveyed these cross sections 3 weeks prior to and after the flood [*Konieczki et al.*, 1997]. To allow better topographic interpolation between the cross sections, daily longitudinal sections were also surveyed at locations 1/3 and 2/3 of the channel width.

Daily samples of bed sediment were collected at three to five locations under the Grand Canyon cableway (stations 140, 190, 240, 290, and 340) on days −1, 1–3, 5–7, and +1 (Figure 2). To monitor the suspended sediment during the 1996 flood experiment, we collected daily samples at the Grand Canyon cableway and in the 122-mile eddy. During the experiment, suspended-sediment samples were also collected by other investigators at the Lower Marble Canyon and National Canyon gages. The methods of collection and analyses of these samples are described by *Konieczki et al.* [1997] and *Topping et al.* [1999].

2.2. Results

At the Grand Canyon cableway, bed elevation, sand grain size (both on the bed and in suspension), and suspended-sand concentration all evolved during the 1996 flood experiment in a manner similar to that during the predam annual snowmelt

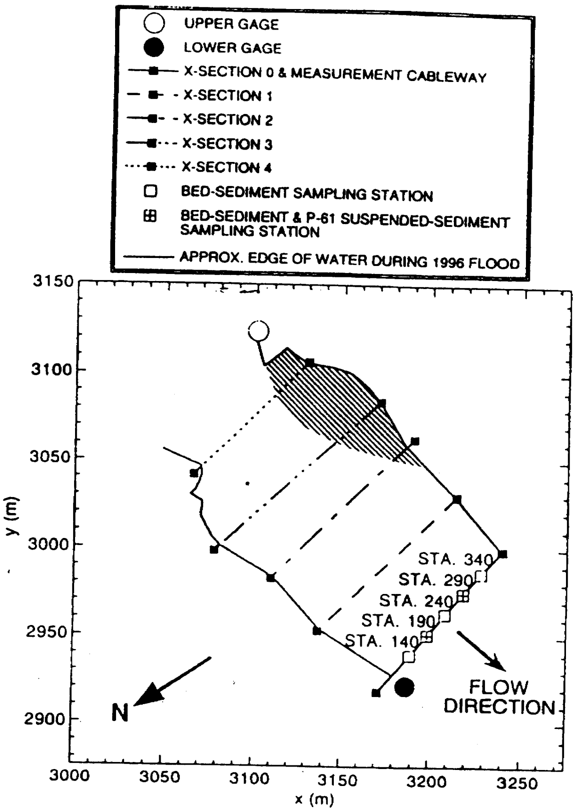


Figure 2. Map of the study area at the Grand Canyon gage showing the locations of the upper and lower gages, the measurement cableway, the locations of the bed-sediment and P-61 suspended-sediment sampling stations on the cableway, and the cross sections surveyed during the 1996 flood experiment. The cross-hatched area indicates the approximate location of a large lateral recirculation eddy on river left.

flood (Figures 3 and 4). In the average predam year the bed at F3 the Grand Canyon cableway aggraded as the water-surface stage increased during the snowmelt flood and then would begin to scour about 4 weeks prior to the peak of the flood (Figure 3a). This scour prior to the peak of the snowmelt flood was associated with coarsening of the bed and depletion of the upstream supply of sand [*Topping et al.*, this issue]. During the 1996 flood experiment, as during a predam snowmelt flood, the bed aggraded with the increase in water-surface stage, with maximum bed elevation being attained on days 4–5 of the 7-day flood. Then, also as during a predam snowmelt flood, the bed began to scour prior to the receding limb of the flood (Figure 3b). During the 1996 flood the bed initially fined as it aggraded (with the median size decreasing from 0.4 to about 0.3 mm between days −1 and 1). Then, after day 1 of the flood the bed began to coarsen (Figure 4a). This coarsening continued through at least the first day after the flood began to recede, and, importantly, this coarsening began while the bed was still aggrading.

The upstream supply of sand was progressively depleted along at least 170 km of the river in Marble and Grand Canyons during the 1996 flood experiment. As the bed coarsened at the Grand Canyon cableway, the suspended sand coarsened (Figure 4a) and suspended-sand concentrations decreased (Figure 4b). This style of decrease in suspended-sand concentration coupled to coarsening was also observed at the three

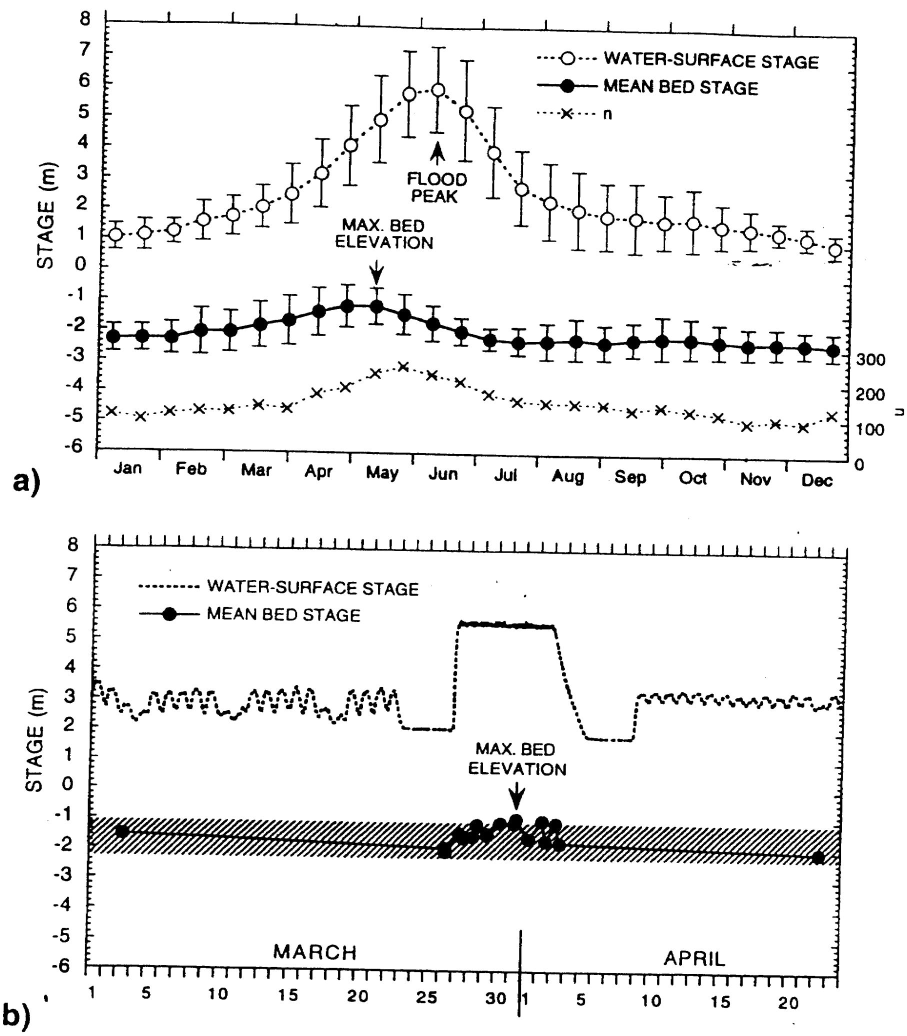


Figure 3. (a) Water-surface stage, mean bed stage, and minimum bed stage in 2-week bins during the average predam year. Values in Figure 3a were computed from the 3690 discharge measurements made from November 12, 1922, through December 31, 1962, by the USGS at the Grand Canyon cableway; stage shown is that at the lower gage in Figure 2. Here *n* is the number of data in each 2-week bin; error bars are 1 standard deviation. (b) Water-surface and mean bed stage measured at the Grand Canyon cableway during the 1996 flood experiment. Cross-hatched area indicates the range of values depicted in Figure 3a of the mean bed stage at the measurement cableway during the predam era. As during the average predam year, the bed at the cableway aggraded as the water-surface stage increased and began to scour prior to the receding limb of the flood.

other locations where suspended-sand concentration and grain size were measured during the flood (Figures 1 and 4b). Each day, the concentrations of suspended sand were similar along 127 km of the river, from the Grand Canyon gage to the National Canyon gage, with the concentrations of suspended sand being about a factor of 2 less at the Lower Marble Canyon gage (Figure 4b). Thus, during the 1996 flood, the upstream supply of sand at the Lower Marble Canyon gage was about half of that at the sites downstream in Grand Canyon. This relationship changed substantially by November 1997 as a result of a series of large floods on the Paria River that introduced large quantities of sand to Marble Canyon.

Over the 7 days of high discharge during the 1996 flood experiment, bed aggradation at the Grand Canyon cableway was offset by scour upstream, such that relatively little change in sand volume occurred in the 158-m-long reach immediately upstream from the cableway (Figures 5 and 6). Indeed, less sand was eroded from the reach during the 7 days of high discharge than during the 3 weeks prior to the flood (Figure 6b). The measured longitudinal pattern of scour and fill during the 1996 flood (Figure 5) supports the conceptual model of flood-induced rearrangement of sand in the Grand Canyon gage reach depicted in Figure 7 of *Howard and Dolan* [1981]. Because aggradation during floods at the Grand Canyon cableway is somewhat balanced by scour upstream, the dominant control on this rearrangement of sand in the reach is probably the redistribution of the boundary shear stress field as the stage increases (i.e., reach-geometric effects). F5&6

During the 1996 flood experiment the topographic respon of the bed to the measured depletion of the upstream supply of sand lagged about 3–4 days behind the measured coarsening of both the bed and the suspended sand (Figure 3a); this impor-

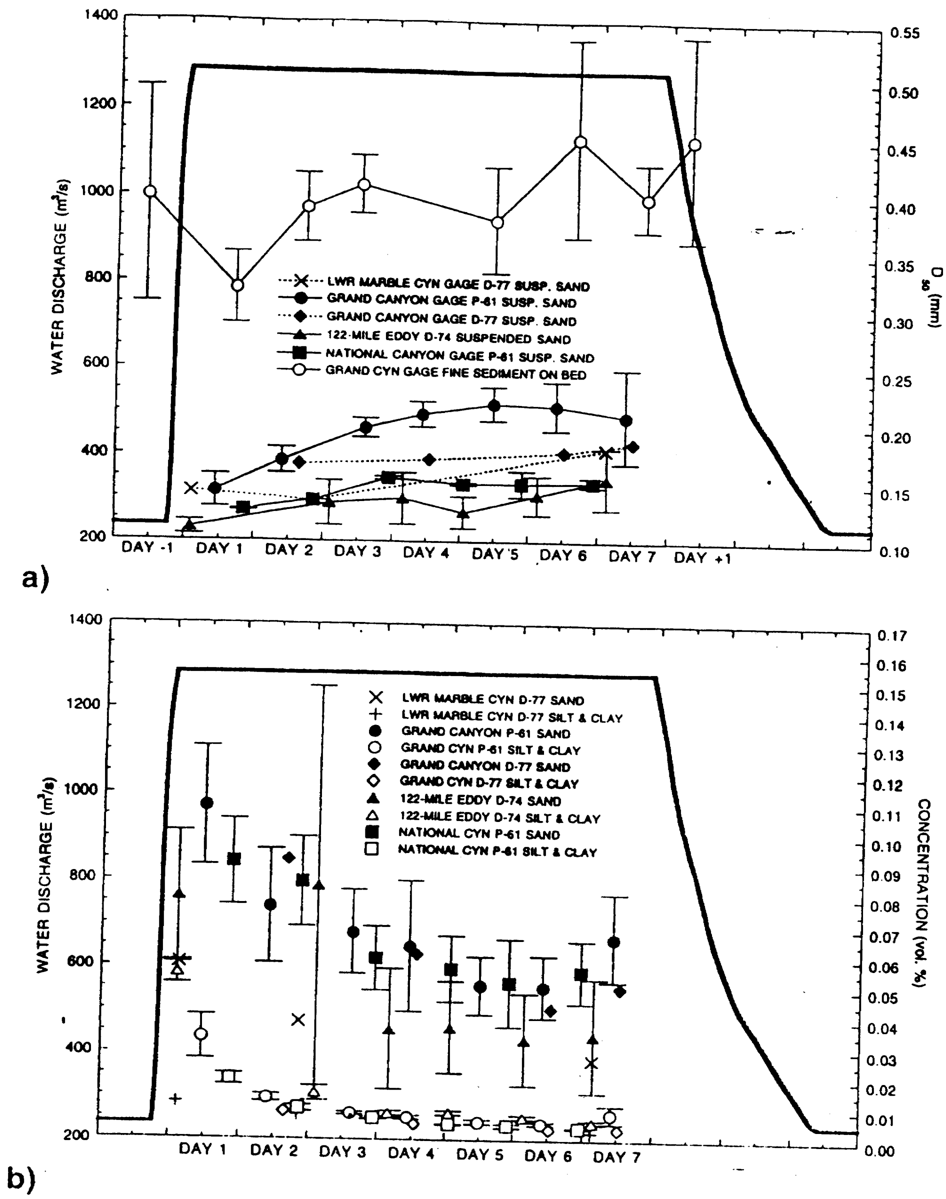


Figure 4. Sediment grain size and concentration during the 1996 flood experiment. At all locations where measurements were made during the flood, the fine sediment on the bed and suspended sand coarsened as the concentration of suspended sand decreased. (a) Hydrograph of the 1996 flood experiment (as measured at the Grand Canyon gage), spatially averaged median size of the fine sediment on the bed, and spatially averaged median size of suspended sand measured at four sites. Error bars are 1 standard deviation. The travel time of the flood wave between the various sites has been removed in Figure 4a such that the beginning of day 1 at each site corresponds to the time of the beginning of steady high discharge at each site. At the Grand Canyon gage the samples collected with the P-61 sampler were coarser than those collected with the D-77 sampler because (1) the P-61 was only deployed at two verticals in the central 2/3 of the channel (see Figure 2), whereas the D-77 was deployed at five verticals across the entire channel, and (2) a P-61 sampler samples much closer to the bed than a D-77 sampler. (b) Hydrograph of the 1996 flood experiment (as measured at the Grand Canyon gage) and spatially averaged concentrations of suspended sand and suspended silt and clay measured at four sites. Error bars are one standard deviation.

tant issue is revisited in section 6.1. The maximum volume of sediment in the reach was attained on day 4 (Figure 6b), correlating fairly well with the time of maximum bed elevation at the cableway on days 4–5 (Figure 3). After day 4 of the flood, erosion of sand from the reach dominated (Figure 6b) as the bed at the cableway began to scour (Figure 3b), possibly driven by the measured depletion of the upstream supply of sand (Figure 4b). The greatest amount of erosion in the reach occurred during the receding limb of the 1996 flood not during the 7 days of high discharge (Figure 6b). This erosion was due to the catastrophic failure of an eddy bar on river left in cross sections 3 and 4 beginning at 10:00 A.M. MST on April 3

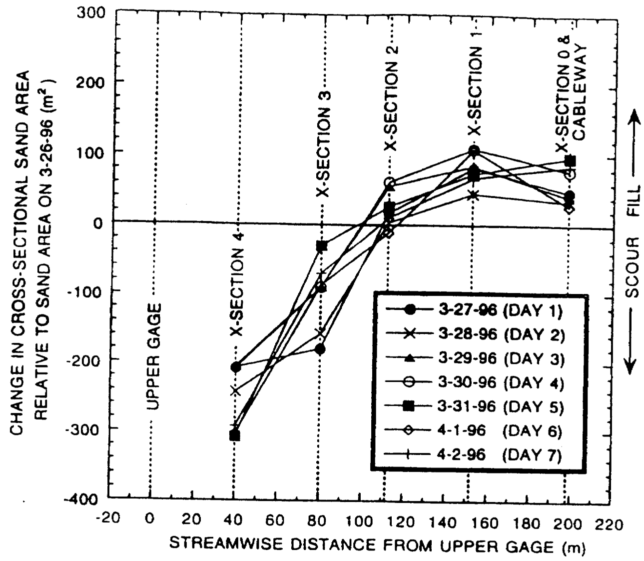


Figure 5. Measured changes in cross-sectional sand area on each of the 7 days of high discharge relative to the bed topography surveyed on the day before the 1996 flood experiment. During the 1996 flood experiment, aggradation (fill) of the bed in the downstream portion of the Grand Canyon gage reach occurred simultaneously with degradation (scour) of the bed in the upstream portion of the reach.

(Figure 6a). During the 3 weeks following the flood, this bar began to rebuild (as shown by the increase in sand area in cross sections 3 and 4), and the volume of sand in the reach recovered slightly (Figure 6b).

3. Observations During the 1997 Test Flow

3.1. Background

August through September 1997 was a period of substantial sediment transport in the Paria River. During these 2 months, approximately 2.0 ± 0.4 million t (t indicates metric ton) of sand and 2.4 ± 1.2 million t of silt and clay were delivered to the Colorado River by a series of large floods in the Paria River [after *Topping*, 1997]. Most of this sediment input occurred during four large floods: a 115-m^3/s flood on August 10, a 72-m^3/s flood on September 7, a flood with two peaks of 85 m^3/s and 110 m^3/s on September 15, and a 95-m^3/s flood on September 26; three of these floods were greater than the 90 m^3/s bank-full discharge [*Topping*, 1997] of the Paria River. Because of these floods, calendar year 1997 ranked among the top 20% in terms of sand input and among the top 12% in terms of silt and clay input during the 75 years of gage record on the Paria River. During the months of August and September the Little Colorado River also supplied sediment to the Colorado River but not in quantities nearly as large as the sediment inputs from the Paria River. In an attempt to prolong the residence time of this new sediment in Marble and Grand Canyons, a test flow on the Colorado River was designed by the Grand Canyon Monitoring and Research Center to transfer some of this sediment from the channel bottom to higher environments on the channel-margin sand bars. This test flow consisted of a steady 877-m^3/s (31,000 cfs) flow released from Glen Canyon Dam for 48 hours during November 3–5, 1997.

3.2. Methods

The USGS Arizona District conducted a program of suspended- and bed-sediment measurements at the four main stem gages depicted in Figure 1: the Lees Ferry gage, the Lower Marble Canyon gage, the Grand Canyon gage, and the Above Diamond Creek gage. At each of these gages, cross-sectionally averaged suspended-sediment samples were collected up to several times daily using D-77 bag samplers. Bed-sediment samples were collected using BM-54 samplers at the Lower Marble Canyon and Above Diamond Creek gages. On November 11, an additional sample of the bed was collected at the Lower Marble Canyon gage using a pipe dredge.

3.3. Results

At all four gages during the 2 days of steady high discharge, as during the 1996 flood experiment, suspended-sand and silt and clay concentrations decreased as the suspended sand coarsened (Figures 7a–7c). Though the degree of suspended- F7
sand coarsening was similar at all gages, the relative decrease in suspended-sand concentration was greater at the Lower Marble Canyon and Grand Canyon gages than it was at the Lees Ferry and Above Diamond Creek gages. Importantly, unlike during the 1996 flood experiment, during the 2 days of the 1997 test flow the sand concentrations measured at the Lower Marble Canyon gage equaled those measured at the Grand Canyon gage. This change occurred by a doubling of the sand-transport rates at the Lower Marble Canyon gage between April 1996 and November 1997, not by a decrease in the sand-transport rates at the Grand Canyon gage. Thus the large sand inputs from the Paria River in 1997 had the effect of doubling the sand export rate from Marble Canyon. This suggests that during August–October 1997 (given the upstream flow and sediment boundary conditions that existed), the available environments for storing sand in Marble Canyon were small relative to the magnitude of the sand supplied by the Paria River.

At both the Lower Marble Canyon and Above Diamond Creek gages, coarsening of the suspended sand was accompanied by winnowing of the finer sediment from the bed, though this winnowing occurred in different manners at the two gages (Figures 7d and 7e). In evaluating changes in the grain-size distribution of the bed, it is sometimes useful to track changes in both the median grain size of the fine sediment (i.e., sand and finer material) and also the fraction of the fine sediment on the bed composed of sand finer than 0.125 mm. The fraction of the fine sediment on the bed composed of 0.0625- to 0.125-mm sand is a useful indicator of the state of the sand supply because half of the sand input by the Paria and Little Colorado Rivers is between 0.0625 and 0.125 mm (D. J. Topping, unpublished data, 1997). At the Lower Marble Canyon gage, winnowing of the finer sediment from the bed caused an increase in the median size of the fine sediment on the bed (from 0.38 to 0.42 mm) and a decrease in the fraction of the fine sediment on the bed composed of 0.0625- to 0.125-mm sand (from 3.1 to 1.2%). The bed at this site continued to coarsen during the 5 days of moderately high flows (ranging from 447 m^3/s (15,800 cfs) to 631 m^3/s (22,300 cfs)) following the 2-day test flow. By November 11 the median size of the fine sediment on the bed had increased from 0.42 to 0.47 mm, and the fraction of the fine sediment on the bed composed of 0.0625- to 0.125-mm sand had decreased from 1.2 to 0.67%. At the farthest downstream gage, the Above Diamond Creek gage, the bed sediment was also winnowed during the test flow

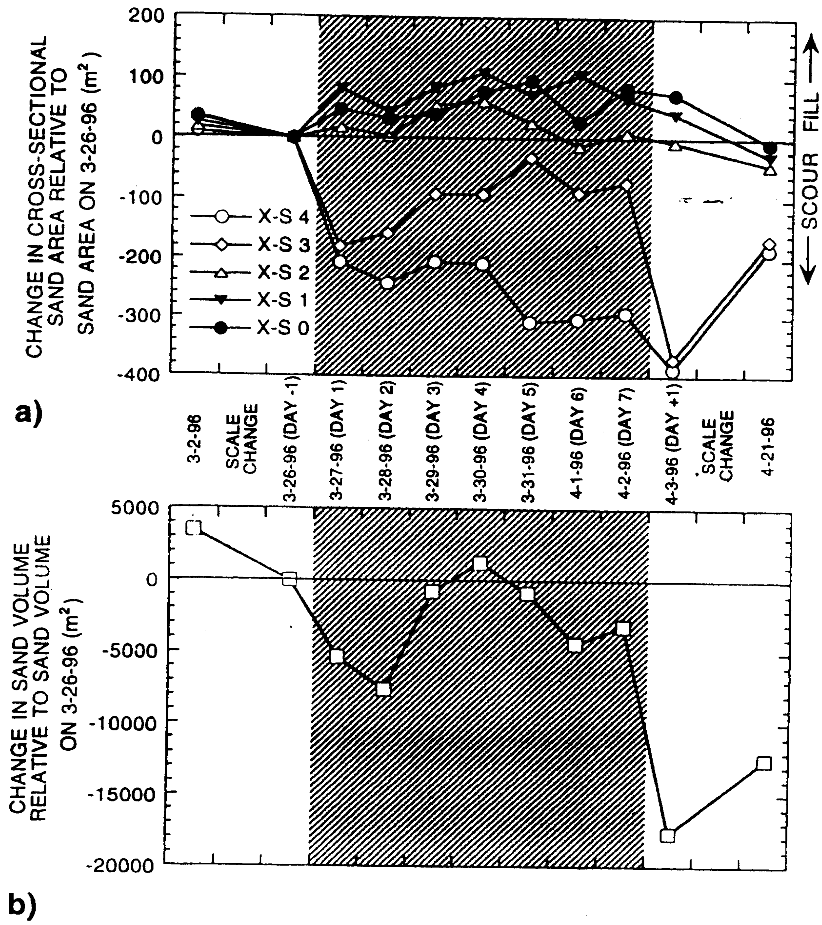


Figure 6. (a) Measured change in cross-sectional sand area over time relative to the bed topography surveyed on the day before the 1996 flood experiment. (b) Changes in sand volume in the 158-m-long reach upstream from the Grand Canyon cableway during the period encompassing the 1996 flood experiment. Volumes were computed using the data in Figure 6a. In Figures 6a and 6b, the cross-hatched region indicates the 7 days of steady high discharge; the scale of the x axis is compressed during the 3 weeks prior to and after the flood.

but in a different manner than at the Lower Marble Canyon gage. At this site the fraction of the fine sediment on the bed composed of 0.0625- to 0.125-mm sand decreased from 2.6 to 0.33%, while the median size of the fine sediment on the bed actually decreased from 0.41 to 0.35 mm.

4. Vertical Trends in the Grain-Size Distribution of Colorado River Flood Deposits

4.1. Deposits of the 1996 Flood

Rubin et al. [1998] sampled the deposits of the 1996 flood experiment in trenches on five eddy bars between Lees Ferry and Diamond Creek (Figure 1). Just as the suspended and bed
F8 sediment coarsened during the 1996 flood (Figures 4 and 8), the sediment deposited during the flood also coarsened (Figure 8). Prior to *Rubin et al.* [1998], production of inversely graded deposits during floods had been documented by *Iseya* [1989] in Japanese rivers. Production of the inverse grading in the 1996 flood deposits occurred both by coarsening of the sand and a reduction in the content of silt and clay. As with the suspended sand, coarsening of the sand occurred not merely by the removal of fines but also by an increase in the modal size and an increase in size of the coarsest fraction [*Topping et al.*, 1999].

4.2. Deposits of the 1997 Test Flow

Deposits of the 1997 test flow were sampled in trenches on eight eddy bars between Lees Ferry and the Grand Canyon gage (Figure 1). At each site, samples were collected at multiple elevations between the base and top of the deposit. At several sites (i.e., upper Eminence Break and Tanner), vertical sample sets were also collected at different distances from the edge of the main channel. Where deposits were sampled in different lateral locations, they generally fined toward the bank. Just as the suspended and bed sediment coarsened during the test flow (Figures 7 and 9), the sediment deposited F9
during the 2-day test flow also coarsened (Figure 9). As with the 1996 flood deposits, this occurred by both coarsening of the sand and a reduction in the content of silt and clay. Also, as in 1996, coarsening of the sand occurred not merely by the removal of fines but also by an increase in the modal size and an increase in size of the coarsest fraction.

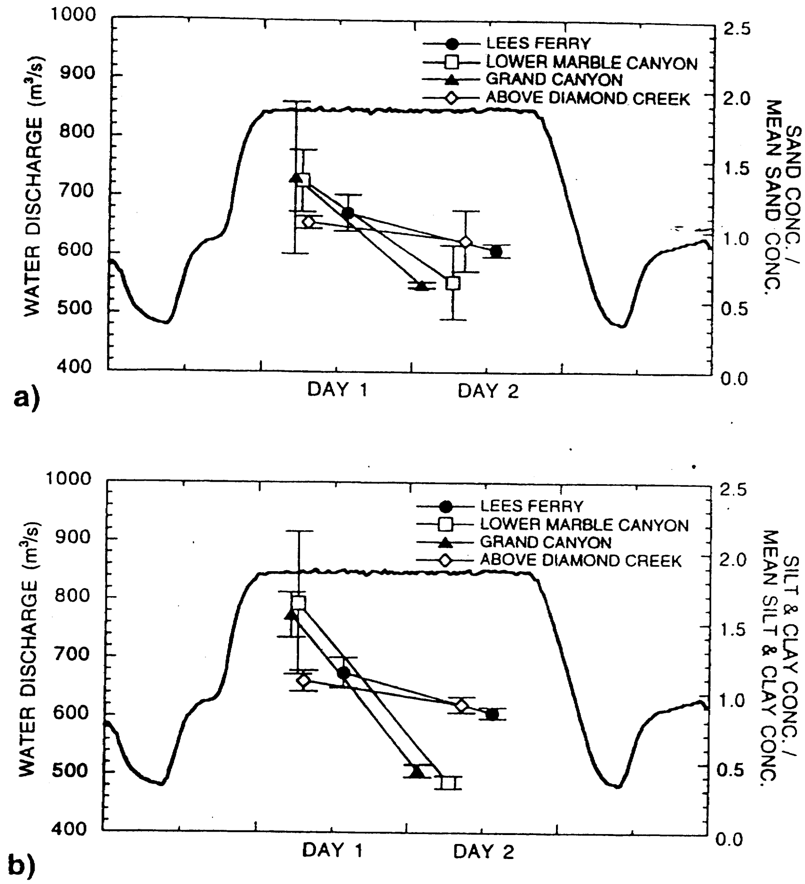


Figure 7. Hydrograph of the 1997 test flow (as measured at the Lees Ferry gage) and spatially averaged suspended-sediment and bed-sediment data collected at the four gages. The fine sediment on the bed was winnowed, and the suspended sand coarsened as the concentration of suspended sand decreased. The travel time of the flood between the four gages has been removed in Figure 7 such that the beginning of day 1 at each site corresponds to the time of the beginning of steady high discharge at each site. (a) Spatially averaged, mean-daily, nondimensional suspended-sand concentrations at the four gages. Mean-daily concentrations at each gage were nondimensionalized by dividing the mean concentration on each day by the mean concentration over both days; error bars are 1 standard deviation. At the Lees Ferry gage the mean suspended-sand concentration over both days was 0.0010%; at the Lower Marble Canyon gage the mean suspended-sand concentration over both days was 0.046%; at the Grand Canyon gage the mean suspended-sand concentration over both days was 0.042%; and at the Above Diamond Creek gage the mean suspended-sand concentration over both days was 0.050%. (b) Spatially averaged, mean-daily suspended-silt and clay concentrations nondimensionalized using the same approach as in Figure 7a. At the Lees Ferry gage the mean suspended-silt and clay concentration over both days was 0.0015%; at the Lower Marble Canyon gage the mean suspended-silt and clay concentration over both days was 0.021%; at the Grand Canyon gage the mean suspended-silt and clay concentration over both days was 0.024%; and at the Above Diamond Creek gage the mean suspended-silt and clay concentration over both days was 0.018%. (c) Spatially averaged, mean-daily median size of suspended sand; error bars are 1 standard deviation. (d) Spatially averaged, mean-daily median size of the fine sediment (i.e., sand and finer material) on the bed at the Lower Marble Canyon and Above Diamond Creek gages; error bars are 1 standard deviation. On the basis of observations made during the 1996 flood experiment at the Grand Canyon gage, a minimum of 50 g of sample is required at three positions across the channel for data collected by a BM-54 sampler to be representative of the bed. Therefore days with fewer than three bed-sediment samples in excess of 50 g were excluded from this analysis. (e) Spatially averaged fraction of the fine sediment on the bed composed of 0.0625- to 0.125-mm sand at the Lower Marble Canyon and Above Diamond Creek gages.

5. Coupled Changes in Suspended-Sand Concentration, Suspended-Sand Grain Size, and Bed Grain Size in the Colorado River Following Large Tributary Sand Inputs

During both the 1996 flood experiment and the 1997 test flow, sand on the bed and in suspension coarsened as the upstream supply of sand was depleted. Systematic coupl- ' changes in sand grain size and concentration should also o in the Colorado River during periods when the upstream s ply of sand is enhanced during large tributary floods. To determine the style of coupled sand-transport and grain-size changes in the Colorado River during and following large tributary floods, we analyzed: (1) suspended- and bed-

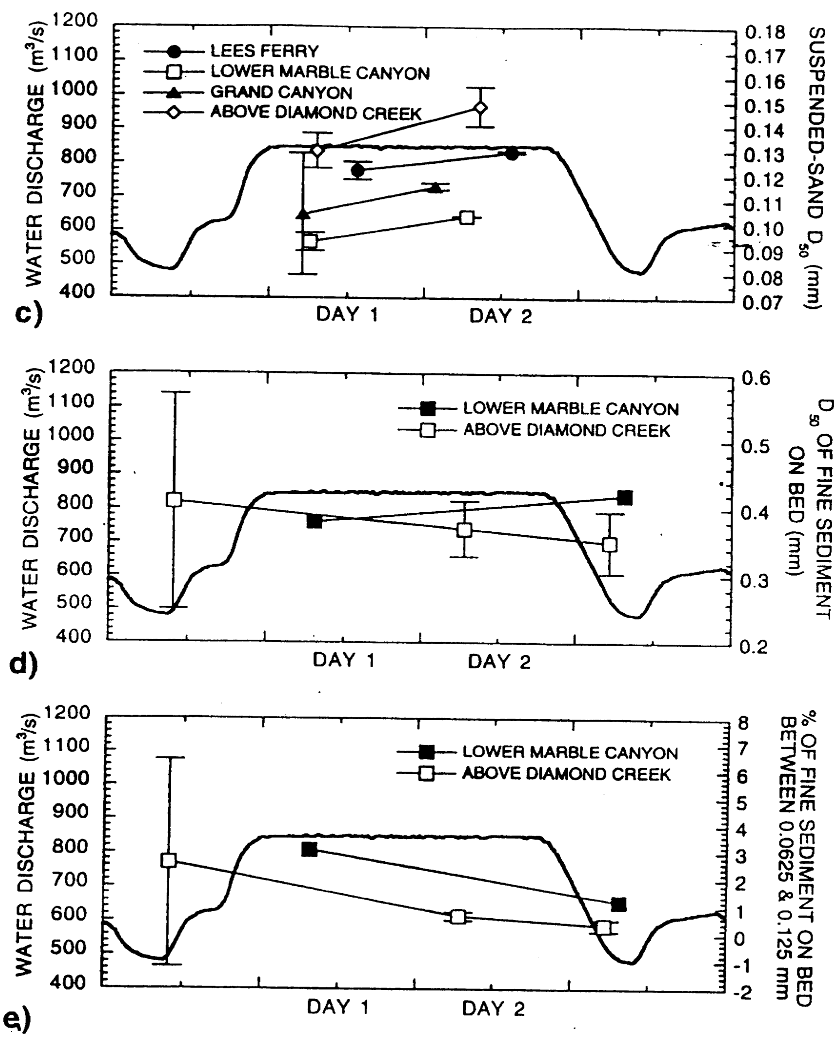


Figure 7. (continued)

sediment data collected at the Grand Canyon, National Canyon, and Above Diamond Creek gages during and after a large flood on the Little Colorado River in September–October 1983, (2) suspended- and bed-sediment data collected at the Lower Marble Canyon gage during a period of large Paria River and ungaged tributary floods in August–September 1997, (3) bed-sediment data collected along the 100-km length of Marble Canyon 6 months before, immediately after, and 9 months after two large Paria River floods in September 1998.

5.1. Methods: Collection and Processing of the 1983 Data

As part of the Bureau of Reclamation's "Glen Canyon Environmental Studies," the USGS Arizona District conducted an intensive sediment data collection program on the Colorado River and its major tributaries during July–December 1983 [*Garrett et al.*, 1993]. This 1983 data collection period included a 300-m^3/s (10,600 cfs) flood on the Little Colorado River; high flows on the Little Colorado River associated with this flood lasted from late September through early October (Figure
F10 10a). These high flows were measured to have transported approximately 1.0 ± 0.2 million t of sand into the Colorado River over 10 days. Following this event, no high flows occurred in the Little Colorado River, and thus no substantial inputs of sand to the Colorado River occurred through the end of the December sampling period. During mid-September through December, flows in the Colorado River were quasi-steady, with dam releases decreasing over this period from 770 to 670 m^3/s. The September–October high flows in the Little Colorado River had minimal impact on the flows in the Colorado River and increased the discharge of water at the Grand Canyon gage for several days by about 12%.

Prior to interpreting suspended-sediment data, it is important to check the data for possible bed-sediment contamination. Bed contamination of suspended-sediment samples (occurring when the nozzle of the sampler is dipped into the bed) is one of the largest sources of error in measuring suspended-sediment concentration [*Allen and Peterson*, 1981; D. J. Topping and R. S. Parker, unpublished data from the Colorado River near Cisco, Utah, 1995]. Contamination of suspended-sand samples with sand from the bed results in higher apparent suspended-sand concentrations and in a suspended-sand grain-size distribution that approaches that of the bed sand (D. J. Topping and R. S. Parker, unpublished data from the Colorado River near Cisco, Utah, 1995). Both suspended-sediment

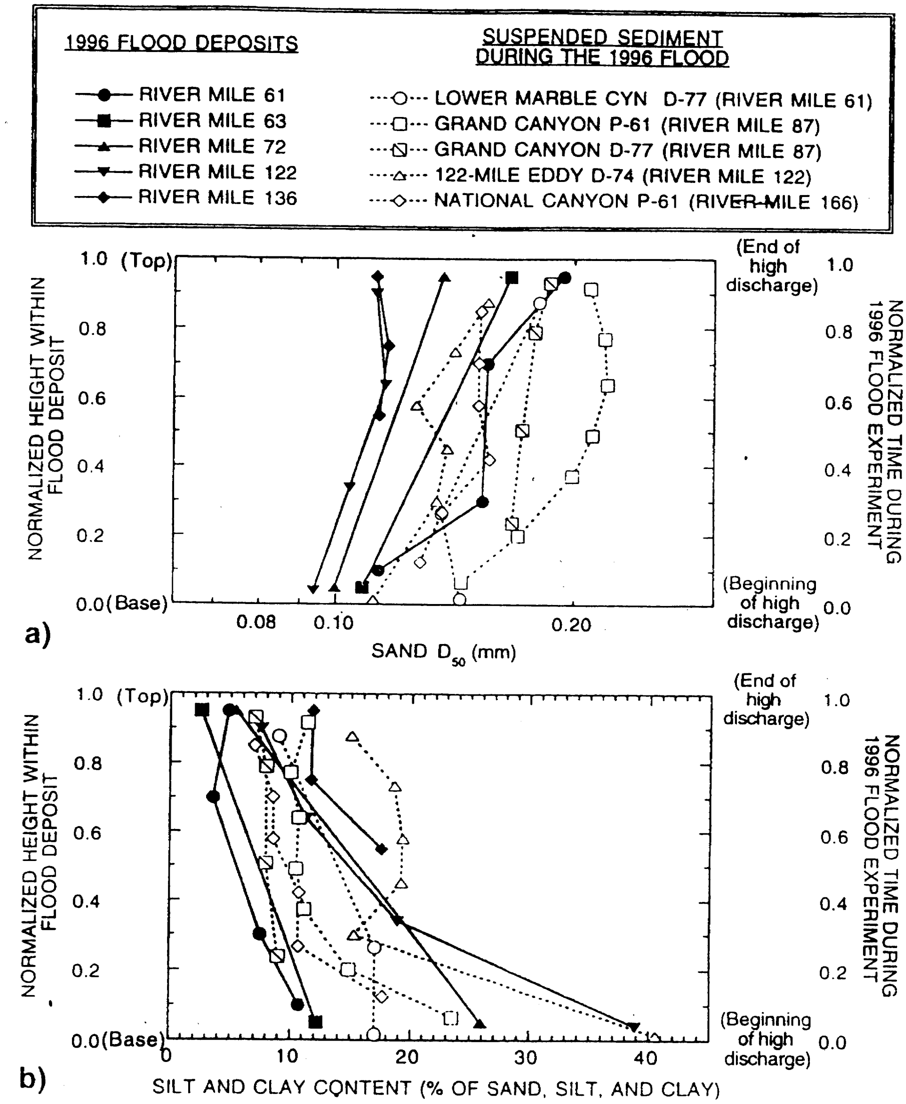


Figure 8. (a) Median grain size of sand as a function of normalized height within the deposits of the 1996 flood experiment and measured median grain size of sand in suspension as a function of normalized time during the 7 days of steady high discharge during the 1996 flood experiment. See Figure 1 for the locations of the five bars that were sampled. (b) Silt and clay content as a function of normalized height within the deposits of the 1996 flood experiment and measured silt and clay content in suspension as a function of normalized time during the 7 days of steady high discharge during the 1996 flood experiment.

theory and simultaneous field measurements of bed- and suspended-sand grain-size distributions (made during 1956–1970, the 1996 flood experiment, and the 1997 test flow) suggest that the median size of suspended sand in the Colorado River can be no more than about 60–65% of the median size of the sand on the bed.

Examination of the 1983 suspended-sand data of *Garrett et al.* [1993] indicates that many samples (especially those collected at the National Canyon gage) exceeded this threshold. This is understandable given that many of the people involved in collecting the 1983 data had little or no prior suspended-sediment sampling experience. Therefore a filter was applied to exclude all suspended-sand samples with a median grain size coarser than 75% of the median size of the bed sand present in the central 2/3 of the channel (i.e., the coarsest part of the bed). This filter was designed to be conservative in that it would allow possible retention of some bed-contaminated data but would not exclude any good data from the analysis. Application of this filter excluded 25% of the suspended-sediment samples collected at the Lower Marble Canyon gage, 34% suspended-sediment samples collected at the Grand Canyon gage, 60% of the suspended-sediment samples collected at the National Canyon gage, and 24% of the suspended-sediment samples collected at the Above Diamond Creek gage.

The bed-sediment and filtered suspended-sand data collected from mid-September through mid-December are shown in Figures 10b through 10f. Also shown in Figure 10b are the predictions of suspended-sand concentration at the Grand Canyon gage made by the stable sand rating curve approach of *Randle and Pemberton* [1987]. Integrated sand loads (with uncertainties) for this period are shown in Figure 11.

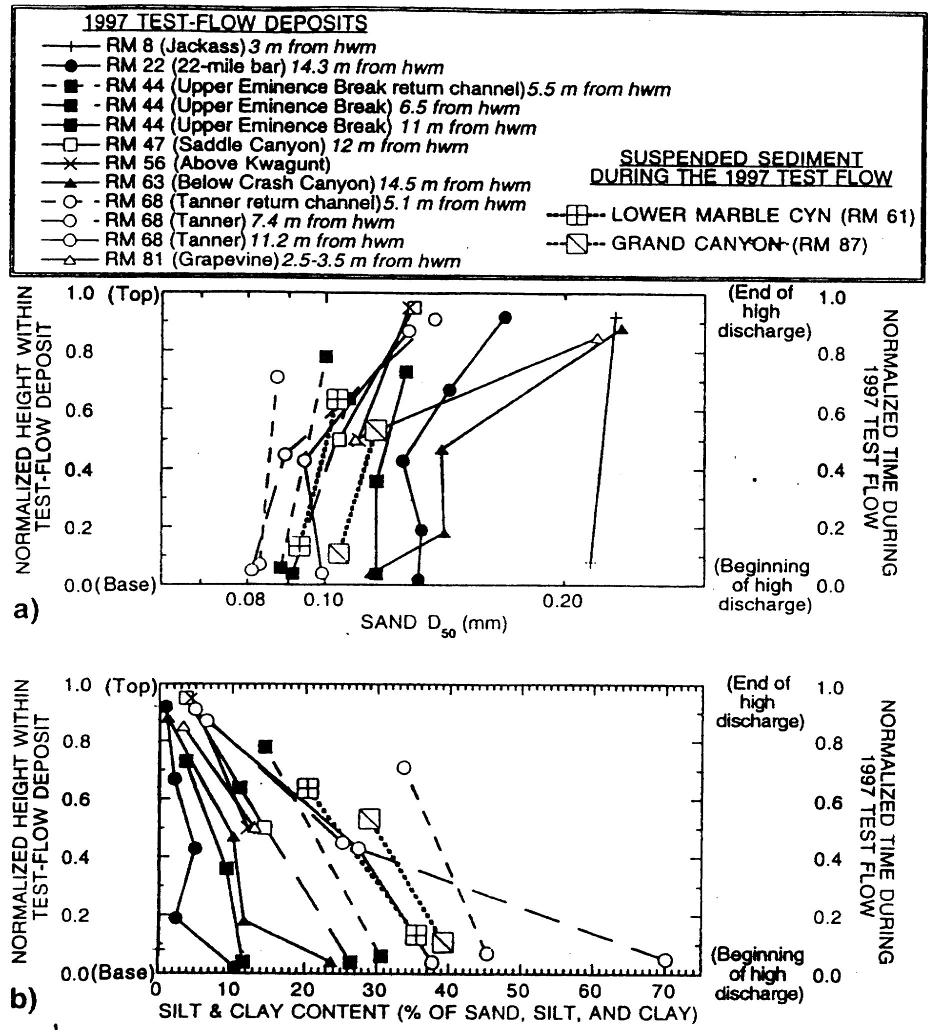


Figure 9. (a) Median grain size of sand as a function of normalized height within the deposits of the 1997 test flow and measured median grain size of sand in suspension as a function of normalized time during the 2 days of steady high discharge during the 1997 test flow. See Figure 1 for the locations of the eight bars that were sampled. The phrases in italics refer to the lateral distance of the sample site (in meters) from the test-flow high-water mark. (b) Silt and clay content as a function of normalized height within the deposits of the 1997 test flow and measured silt and clay content in suspension as a function of normalized time during the 2 days of steady high discharge during the 1997 test flow.

5.2. Results: 1983

During the 1983 Little Colorado River flood, suspended-sand concentrations increased at all three of the downstream gages on the Colorado River (Figure 10b). At the Grand Canyon gage (41 km downstream from the mouth of the Little Colorado River (LCR), suspended-sand concentrations were 0.002% the day before the beginning of the Little Colorado River flood. The peak discharge of the Little Colorado River flood passed the LCR near Cameron gage (located 73 km upstream from the confluence with the Colorado River) on September 30 (Figure 10a). Within 2 days, suspended-sand concentrations had increased to 0.11% at the Grand Canyon gage, a factor of 55 increase in concentration (Figure 10b). At the Grand Canyon gage this increase in concentration was associated with a fining of the suspended sand, with the median size decreasing from 0.20–0.25 mm to about 0.13 mm (Figure 10c). Because the Little Colorado River flood had only a small impact on the discharge of water at the Grand Canyon gage (<12% during the flood peak), this increase in suspended-sand concentration was most likely due to the enhancement of the upstream supply of sand in the Colorado River during the Little Colorado River flood. Moreover, if the increase in concentration were due to an increase in the discharge of water in the Colorado River, the grain size of sand in suspension should have coarsened and not fined. Because their approach does not allow for fining of the sand on the bed of the Colorado River during tributary floods, *Randle and Pemberton* [1987] greatly underestimate the concentrations of suspended sand at the Grand Canyon gage during this period (Figure 10b).

The short-term response of the suspended sand in the Colorado River to the Little Colorado River flood was not limited to only the upper portion of Grand Canyon. At the National Canyon gage (172 km downstream from the mouth of the Little Colorado River), suspended-sand concentrations increased from about 0.004 to 0.03% (a factor of 7.5 increase) in response to the Little Colorado River flood (Figure 10b). Like

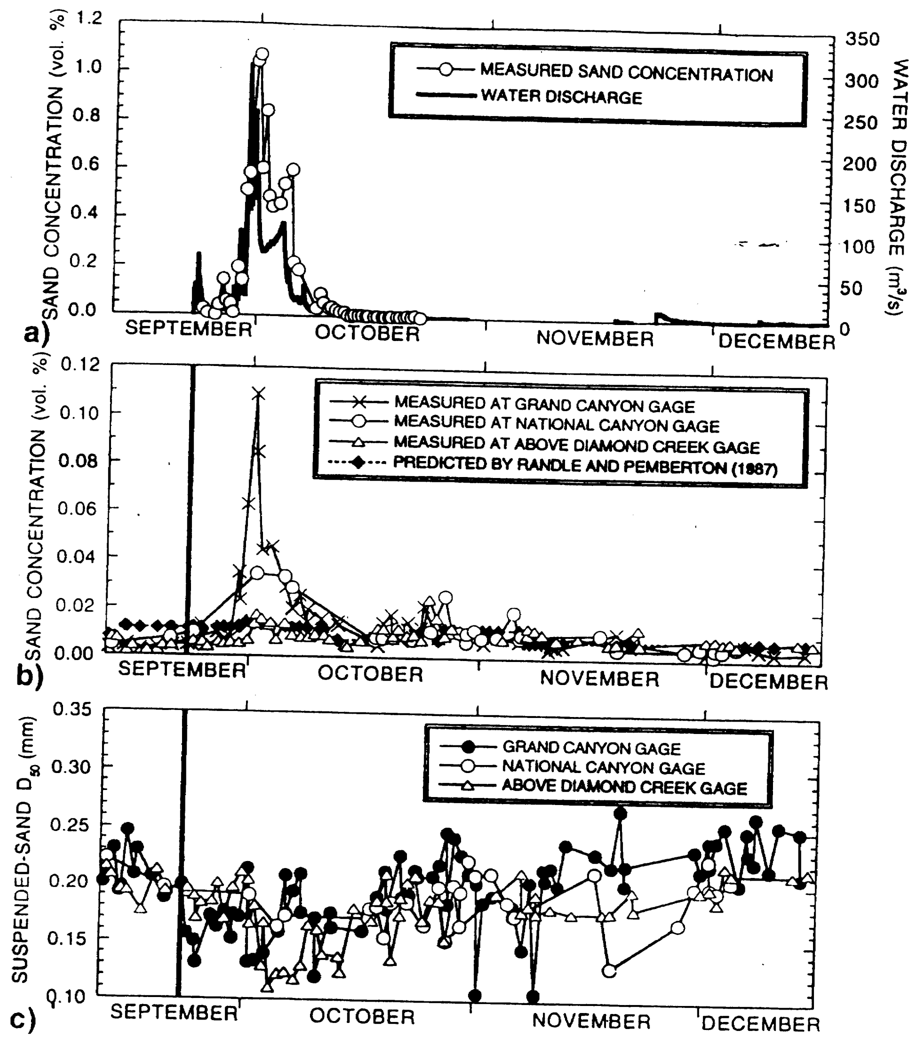


Figure 10. Coupled changes in suspended-sand concentration and grain size in the Colorado River associated with the 1983 Little Colorado River flood. (a) Suspended-sand concentration measured at the highway 89 bridge at Cameron during the September–October 1983 Little Colorado River flood and the computed instantaneous discharge of water at the LCR near Cameron gage from mid-September through mid-December 1983. (b) Measured suspended-sand concentration at the three gages downstream from the mouth of the Little Colorado River and the suspended-sand concentration predicted by *Randle and Pemberton* [1987] at the Grand Canyon gage. The measured concentration of suspended sand increased at all three downstream gages on the Colorado River immediately following the tributary flood peak. Because their approach was based on a fixed grain-size distribution of bed sediment, *Randle and Pemberton* [1987] do not predict this increase in concentration. (c) Measured median size of the suspended sand at the three gages downstream from the mouth of the Little Colorado River. Input of sand from the Little Colorado River caused the grain size to decrease. (d) Measured concentration of the finer (0.0625–0.125 mm) and coarser (0.25–2.0 mm) suspended-sand at the Above Diamond Creek gage. Figure 10d shows the segregation of grain sizes that occurred in the Colorado River following the tributary flood, with higher concentrations of finer sand occurring in early October and higher concentrations of coarser sand occurring after mid-November. (e) Spatially averaged median size of the fine sediment on the bed of the Colorado River at the three downstream gages. Only at the Grand Canyon gage did the median size of the fine sediment on the bed decrease in response to the Little Colorado River flood. Data appearing in Figures 10e and 10f were first filtered using the same approach as in Figure 7d. Also, because on some days more bed-sediment samples were collected near the banks than in the central portion of the channel, samples from the near-bank regions (i.e., the right and left 15% of the channel) were excluded from this analysis to avoid biasing the analysis toward the finer near-bank sediment. (f) Spatially averaged fraction of the fine sediment on the bed composed of 0.0625- to 0.125-mm sand. At all three downstream gages the amount of 0.0625- to 0.125-mm sand composing the fine sediment on the bed increased from trace amounts to about 5% after the beginning of the Little Colorado River flood. The bold vertical line in Figures 10b–10f indicates the time of the beginning of the Little Colorado River flood.

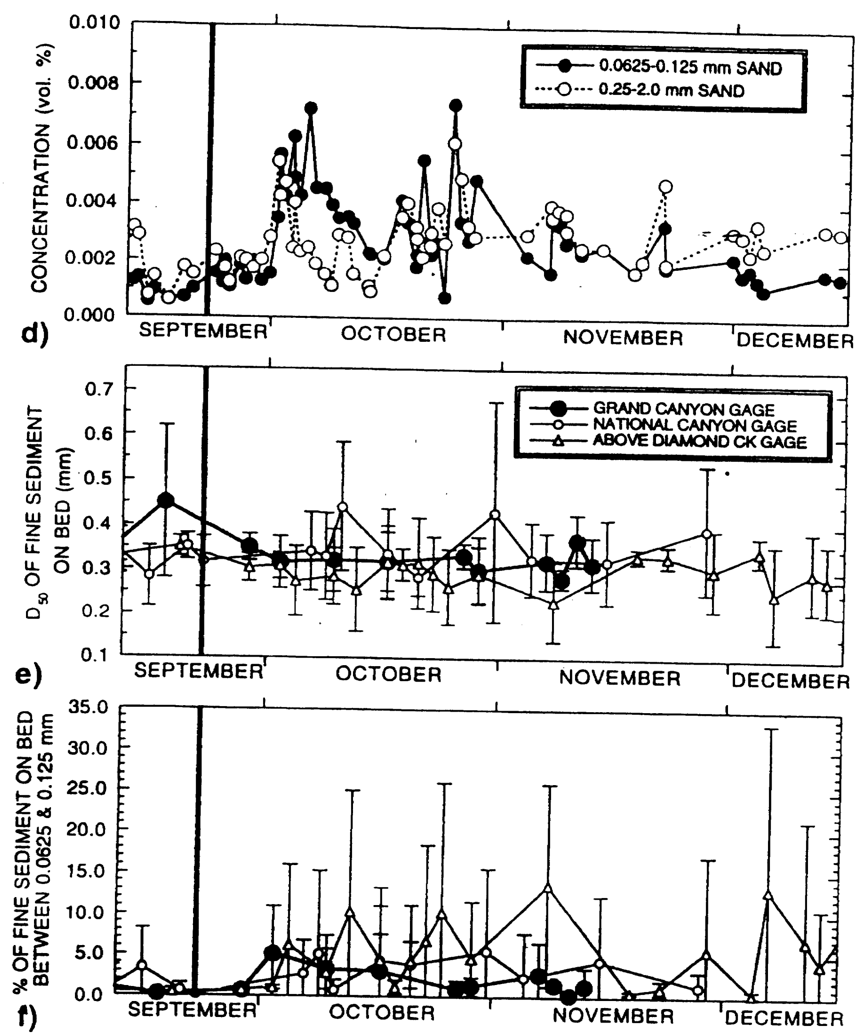
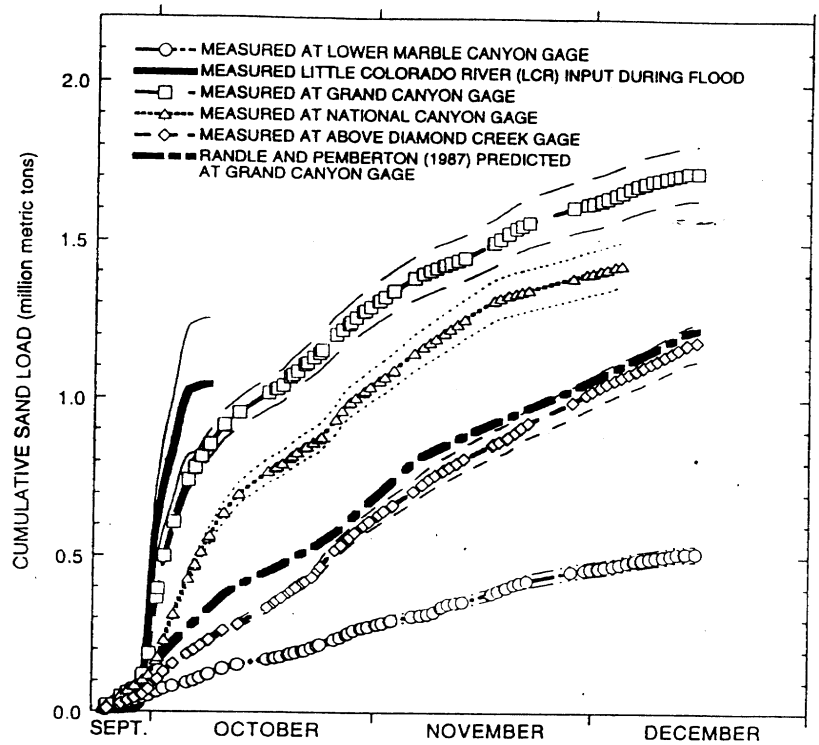


Figure 10. (continued)

the increase at the Grand Canyon gage, this increase in concentration was also associated with fining of the suspended sand, with the median size decreasing from about 0.22 to 0.16 mm at this site (Figure 10c). At the Above Diamond Creek gage (222 km downstream from the mouth of the Little Colorado River), suspended-sand concentration increased from about 0.003% to 0.02% (a factor of 6.7 increase) in response to the Little Colorado River flood (Figure 10b). This increase in concentration was also associated with fining of the suspended sand, with the median size decreasing from about 0.20 to 0.11 mm at this site (Figure 10c). The fact that the suspended-sand concentration increased along 138 km of the Colorado River within 2 days of the peak of the Little Colorado River flood passing the LCR near Cameron gage suggests that some portion of the sand input during a tributary flood travels downstream relatively quickly (at nearly the velocity of the water). In addition, the fact that the peak suspended-sand concentration decreased systematically in the downstream direction from about 0.11% at the Grand Canyon gage to 0.02% at the Above Diamond Creek gage indicates that some portion of this newly input sand was being deposited in the downstream direction.

Following the rapid increase at the three gages, suspended-sand concentrations decreased over 2 weeks as the Little Colorado River flood receded (Figures 10a and 10b). By the middle of October, suspended-sand concentration at all three gages had decreased to about 0.007%. This value was still higher, however, than the values measured before the beginning of the tributary flood. After recession of the Little Colorado River flood, suspended-sand concentrations continued to decrease more slowly from mid-October to mid-December (Figure 10b), and by the middle of December, suspended-sand concentrations were comparable to those measured in the Colorado River before the Little Colorado River flood. These decreases in suspended-sand concentrations were associated with coarsening of the suspended sand (Figure 10c). By the middle of December the median size of the suspended sand at each gage had increased back to a value comparable to that measured before the Little Colorado River flood.

These observations of coupled changes in suspended-sand concentration and grain size suggest that sand supplied during a tributary flood travels down the Colorado River as an elongating sediment wave, with the finest sizes (because of their lower settling velocities) traveling the fastest. Because it is the farthest site downstream from the mouth of the Little Colorado River, this downstream segregation of grain sizes is shown best at the Above Diamond Creek gage. In Figure 10d a peak



a)

Figure 11. (a) Cumulative measured sand loads of the Colorado River at the Lower Marble Canyon gage and at the three gages downstream from the mouth of the Little Colorado River (LCR) and the cumulative measured sand load of the LCR at the highway 89 bridge at Cameron for the period after the beginning of the 1983 LCR flood. The lowest cumulative load was measured at the Lower Marble Canyon gage, because it is located on the Colorado River immediately upstream from the mouth of the LCR. The greatest cumulative sand load during early October was measured in the LCR. Downstream from the mouth of the LCR, progressively smaller loads were measured, since less of the LCR sand input passed each of these more distant sites during the sampling period. Uncertainties (thin dashed lines) of 5% were assigned to the measured sand loads of the Colorado River, and an uncertainty (thin solid lines) of 20% was assigned to the measured sand load of the LCR; see *Topping et al.* [this issue] for justification of these uncertainties. Also shown is the cumulative sand load predicted by *Randle and Pemberton* [1987] at the Grand Canyon gage. Because their approach was based on a fixed, coarsened grain-size distribution of bed sediment, *Randle and Pemberton* [1987] underpredict the sand load at the Grand Canyon gage during this period by about 30%. (b) Sand budget for the 1983 LCR flood constructed using the data in Figure 10a. Shown are (1) the cumulative measured sand load (with 20% uncertainties) during the LCR flood and (2) plus and minus 5% error envelopes for the adjusted cumulative measured and predicted sand loads at the gages on the Colorado River downstream from the mouth of the LCR. The cross-hatched region indicates the plus and minus 20% error envelope for the sand input during the LCR flood. The loads of the Colorado River downstream from the mouth of the LCR were adjusted by subtracting the measured load (with uncertainties) of the Colorado River at the Lower Marble Canyon gage. See text for further explanation.

in the concentration of all sizes of suspended sand is evident 2–3 days after the flood peak passed the LCR near Cameron gage. Following this peak, during the first half of October, the concentration of the finest (0.0625–0.125 mm) sand is higher than that of the coarser (0.25–2.0 mm) sand, whereas by December, the concentration of the coarser sand is much higher than that of the finest sand. This suggests that it takes longer for the bulk of the newly input coarser sand to travel the 222 km from the mouth of the Little Colorado River to the Above Diamond Creek gage than it does for the finest sand to travel this distance.

The response of the grain-size distribution of the bed of the Colorado River to the Little Colorado River flood was more complicated than the response of the grain size of the suspended sand (Figures 10e and 10f). The bed at the Grand Canyon gage shows perhaps the clearest behavior. During the Little Colorado River flood the median size of the fine sediment (i.e., sand and finer material) on the bed at this site decreased, and the amount of 0.0625- to 0.125-mm sand increased (from trace amounts to about 5% of the fine sediment on the bed). Following the Little Colorado River flood, as the suspended sand in the Colorado River coarsened, the finer sand was winnowed from the bed (with the fraction of fine sediment on the bed composed of 0.0625- to 0.125-mm s[illegible] decreasing from 5% to about 1%), with no substantial cha[illegible] in the median size of the fine sediment on the bed. This wa[illegible] similar to the observed response of the bed at the Above Diamond Creek gage during the 1997 test flow, where the finer sand was winnowed from the bed, but the median grain size of the fine sediment on the bed actually decreased slightly.

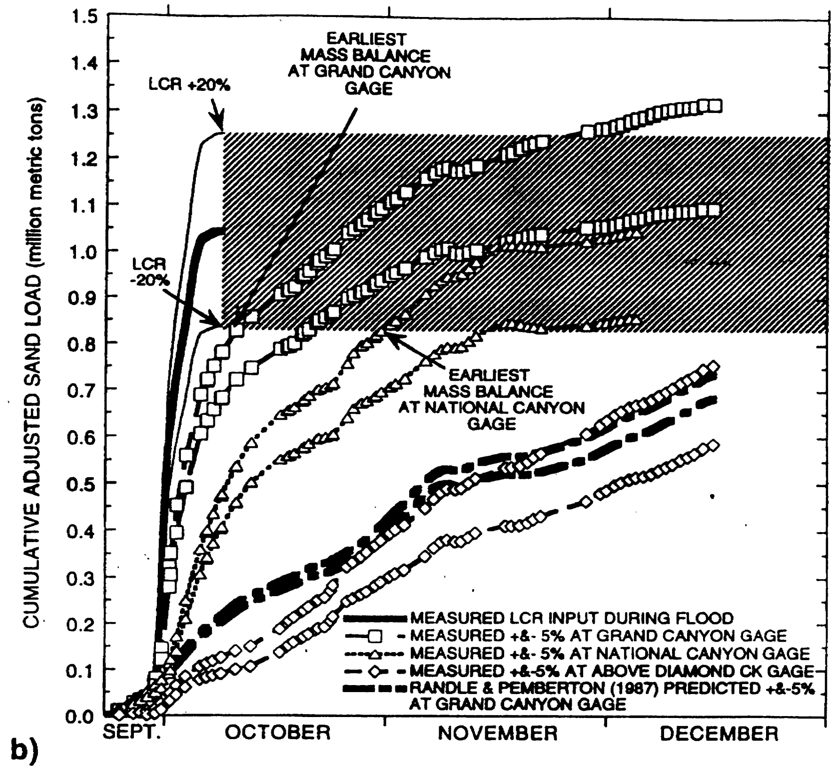


Figure 11. (continued)

As observed at the Grand Canyon gage, the amount of 0.0625- to 0.125-mm sand on the bed at the National Canyon and Above Diamond Creek gages also increased from trace amounts to about 5% of the fine sediment on the bed during the Little Colorado River flood. However, unlike at the Grand Canyon gage, this increase in finer sand occurred without any substantial decrease in the median size of the fine sediment on the bed. Also, unlike at the Grand Canyon gage, following this initial increase in the amount of finer sand, no measurable change in the grain size of the fine sediment on the bed occurred at these two downstream sites.

5.3. A Sand Budget for the 1983 Little Colorado River Flood

To evaluate the error associated with the assumption of a time-invariant grain-size distribution on the bed, a sand budget (with uncertainties) was constructed using the measured sand loads during and following the 1983 Little Colorado River flood. Cumulative sand loads, computed using the data in Figures 10a and 10b and the predictions of *Randle and Pemberton* [1987], for the period from the beginning of the Little Colorado River flood to the ends of the sampling periods are shown in Figure 11a. For the reasons discussed by *Topping et al.* [this issue], 5% uncertainties were assigned to the measured Colorado River sand loads, and 20% uncertainties were assigned to the measured Little Colorado River sand loads. As shown in Figure 11a, because their sand-transport algorithm was derived for a coarser bed grain-size distribution than existed at the Grand Canyon gage during the Little Colorado River flood, *Randle and Pemberton* [1987] underestimate the sand loads at the Grand Canyon gage (and therefore overestimate the upstream accumulation of sand) by about 30% (0.5 million t) during this 3-month period. Interestingly, the magnitude of this error is comparable to the predicted long-term accumulation rate between the Little Colorado River and the Grand Canyon gage given by *U.S. Department of the Interior* [1995].

The sand budget calculated using the information in Figure 11a suggests that the residence time in Grand Canyon of the sand supplied by the 1983 Little Colorado River flood was quite short (Figure 11b). The Colorado River downstream from the Little Colorado River receives sand from both the Little Colorado River and the Colorado River in Marble Canyon. Therefore, to construct a budget for only the sand supplied during the Little Colorado River flood, the cumulative measured and predicted loads at the sites downstream from the mouth of the Little Colorado River were adjusted by subtracting the cumulative supply of sand measured passing the Lower Marble Canyon gage. The uncertainties in the loads were propagated through this step to result in the error envelopes in Figure 11b. In Figure 11b the earliest mass balance (given the uncertainties) occurs at a given site when the upper bound of the error envelope intersects the lower bound of the error envelope associated with the sand supplied during the Little Colorado River flood (the cross-hatched region). Likewise, the latest mass balance occurs at a given site when the lower bound of the error envelope intersects the upper bound of the error envelope associated with the sand supplied during the Little Colorado River flood. Therefore the earliest an amount of sand equivalent to that supplied during the Little Colorado River flood could have passed (1) the Grand Canyon gage was on about October 10 (i.e., only 10 days after the flood peak passed the LCR near Cameron gage), (2) the National Canyon gage was on about October 30 (i.e., only 30 days after the flood peak passed the LCR near Cameron gage), and, by extrapolation, (3) the Above Diamond Creek gage was in about late December (i.e., only 3 months after the flood peak passed the LCR near Cameron gage). Because of the short period of record, it is not possible to determine the latest mass balance at any of the sites with any certainty. However, extrapolation of the curves in Figure 11b suggests that an amount of sand equivalent to that supplied during the Little Colorado River flood probably passed the Diamond Creek gage within 6 months to a year after the flood.

5.4. Methods: Collection and Processing of the 1997 Data

In anticipation of a large sediment input season from the Paria River and to monitor changes in sediment transport in Marble Canyon during August–September 1997, the USGS Arizona District conducted a daily bed and suspended-sediment measurement program at the Lower Marble Canyon gage from August 25 through September 18. During this sampling period, approximately 1.2 ± 0.2 million t of sand [after *Topping*, 1997] were input from the Paria River to the Colorado River, largely during the second and third of the four previously described 1997 Paria River floods. Floods on one or more of the ungaged tributaries between the Paria River and the Lower Marble Canyon gage also occurred on or around September 2 and possibly September 11–12. Though the amount of sand supplied during these floods is unknown, it was probably much smaller than that supplied by the Paria River during this period.

At the Lower Marble Canyon gage, bed samples were collected using a BM-54 sampler, and cross-sectionally averaged suspended-sediment samples were collected using a D-77 bag sampler. Prior to interpreting these suspended-sand data, the filter described in section 5.1 was applied to these data. Unlike in the 1983 case, however, because of the greater experience of the 1997 sampling personnel, this application resulted in exclusion of only one of the 23 suspended-sand samples (i.e., only 4% of the data).

The discharge of water in the Paria River and in the Colorado River at the Lees Ferry and Lower Marble Canyon gages and the bed and filtered suspended-sediment data from the Lower Marble Canyon gage during the August–September 1997 sampling period are shown in Figure 12. Also shown in Figure 12 are the predictions of suspended-sand concentration at the Lower Marble Canyon gage using the method of *Randle and Pemberton* [1987].

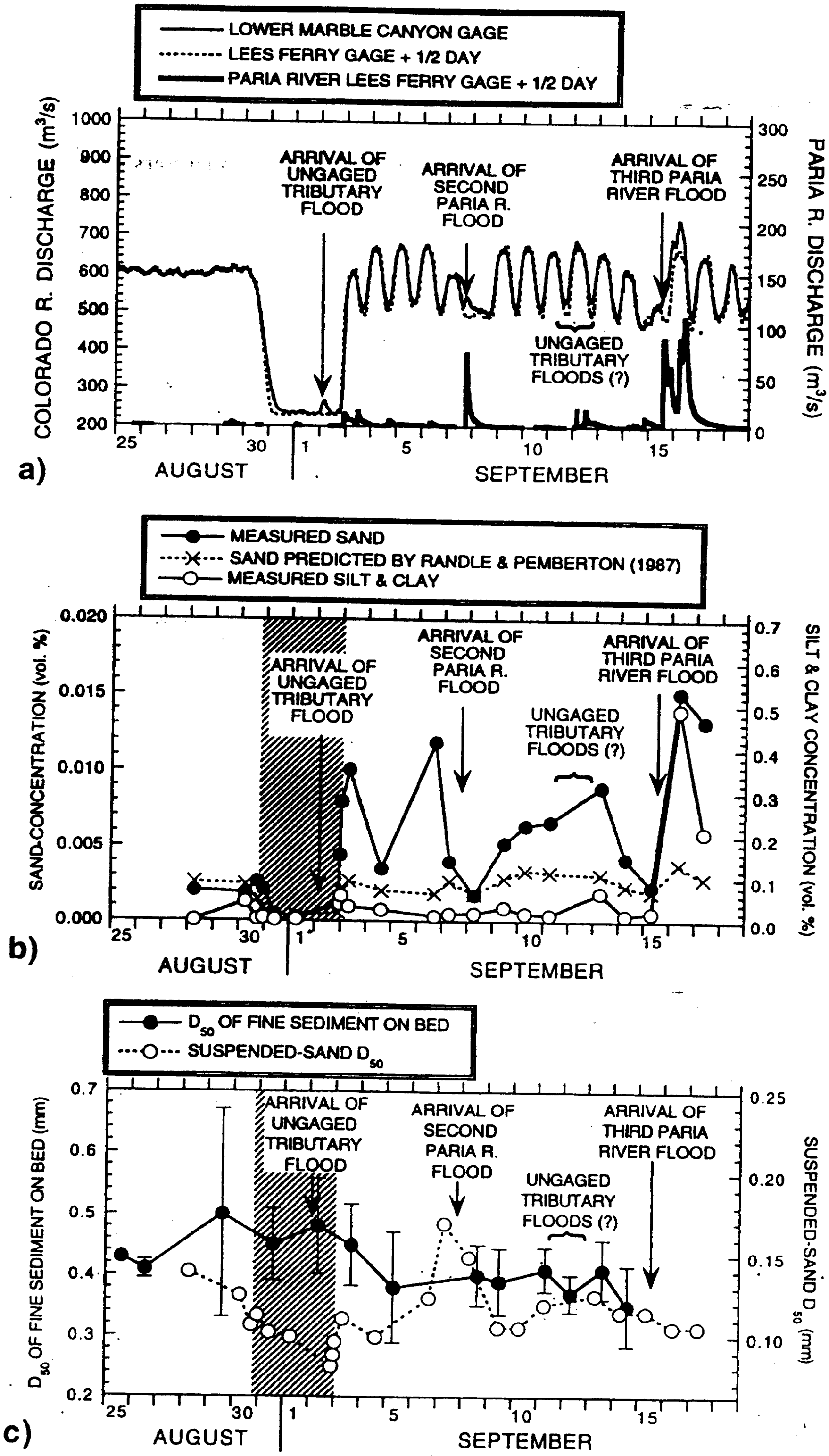
5.5. Results: 1997

Because of the short duration of the sampling program, the close spacing of multiple floods on the Paria River and ungaged tributaries, and 3 days of much lower dam releases (Figure 12a), the results from the August–September 1997 sampling program are not as clear as those from September–December 1983. However, coupled changes in grain size and suspended-sand concentration following tributary floods are still evident at the Lower Marble Canyon gage (Figures 12b and 12c). For analysis it is useful to divide the 1997 data into two portions, with one period from August 28 through 30 (prior to the decrease in flows) and one period from September 3 through 17 (after the return to higher flows). This effectively divides the data into a short period with no tributary activity and a period of increased tributary activity (Figure 12a). Because the mean discharge of water is comparable during these two periods (though the magnitudes of the daily fluctuations were greater after September 3), any substantial difference in suspended-sand concentration and grain size between these two periods is probably due to a difference i upstream supply of sand resulting from the tributary flo

During the period of increased tributary activity (September 3–17), suspended-sand concentration was, on average, higher than that measured prior to August 31 at the Lower Marble Canyon gage (Figure 12b). During September 3–17 the mean suspended-sand concentration was 0.007%, whereas during August 28–30 the mean suspended-sand concentration was 0.002%. Though not as dramatic as that following the 1983 Little Colorado River flood, slight fining of the suspended sand did occur with this increase in suspended-sand concentration (Figure 12c). From August 28 through September 17 the median size of the suspended sand decreased from about 0.13–0.14 to 0.10–0.11 mm. This factor of 3.5 increase in concentration and slight fining of the suspended sand was coupled to a decrease in the median grain size of the fine sediment on the bed. From August 29 through September 14 the median size of the fine sediment on the bed decreased from about 0.50 to 0.33 mm.

As during the period following the 1983 Little Colorado River flood, the concentrations of suspended sand predicted by *Randle and Pemberton* [1987] are in good agreement with those measured during the period of no tributary activity but are a factor of 2.3 low relative to those measured during the period of increased tributary activity (Figure 12b). This underprediction occurs because their approach treats bed-sediment grain size as a constant rather than as a variable; such an approach does not predict higher transport rates when the bed sediment fines as a result of enhancement of the upstream supp sand. Therefore, as in the 1983 example, the approac *Randle and Pemberton* [1987] seems to work reasonably w...

Figure 12. (opposite) Coupled changes in suspended-sand concentration and grain size in the Colorado River associated with the 1997 Paria River and ungaged tributary floods. (a) Computed discharge at the Lower Marble Canyon gage during the August–September 1997 sampling period. Also shown are the computed discharges at the Lees Ferry gage and the Paria River Lees Ferry gage. To allow direct comparison of the records from these upstream gages with those from the Lower Marble Canyon gage, the discharges at these two upstream gages were shifted by the 1/2-day travel time of the discharge waves through Marble Canyon. At the Lower Marble Canyon gage the indicated arrival times of water from the second and third of the four large 1997 Paria River floods (see text), a large ungaged tributary flood and a possible second ungaged tributary flood, were determined by this comparison. (b) Measured suspended-sand and suspended-silt and clay concentrations at the Lower Marble Canyon gage during the August–September 1997 sampling period. (c) Spatially averaged median size of the fine sediment on the bed and median size of the suspended sand at the Lower Marble Canyon gage during the August–September 1997 sampling period. The same filters used in Figures 7d and 10e were applied to these bed-sediment data. Also shown for comparison is the suspended-sand concentration at the time of each of the suspended-sediment measurements predicted by *Randle and Pemberton* [1987]. Th cross-hatched area in Figures 12b and 12c indicates the 3 of steady low flows in Figure 12a. Measured suspended-s concentration at the Lower Marble Canyon gage increased 1–2 days after each of the Paria River and ungaged tributary floods. Because a change in the upstream supply of sand and not a change in the discharge of water caused these increases, these increases were not predicted by *Randle and Pemberton* [1987].


LOWER MARBLE CANYON GAGE
LEES FERRY GAGE + 1/2 DAY
PARIA RIVER LEES FERRY GAGE + 1/2 DAY
COLORADO R. DISCHARGE (m^3/s)
PARIA R. DISCHARGE (m^3/s)
ARRIVAL OF UNGAGED TRIBUTARY FLOOD
ARRIVAL OF SECOND PARIA R. FLOOD
ARRIVAL OF THIRD PARIA RIVER FLOOD
UNGAGED TRIBUTARY FLOODS (?)
AUGUST
SEPTEMBER
a)
MEASURED SAND
SAND PREDICTED BY RANDLE & PEMBERTON (1987)
MEASURED SILT & CLAY
SAND-CONCENTRATION (vol. %)
SILT & CLAY CONCENTRATION (vol. %)
ARRIVAL OF UNGAGED TRIBUTARY FLOOD
ARRIVAL OF SECOND PARIA R. FLOOD
ARRIVAL OF THIRD PARIA RIVER FLOOD
UNGAGED TRIBUTARY FLOODS (?)
AUGUST
SEPTEMBER
b)
D_{50} OF FINE SEDIMENT ON BED
SUSPENDED-SAND D_{50}
D_{50} OF FINE SEDIMENT ON BED (mm)
SUSPENDED-SAND D_{50} (mm)
ARRIVAL OF UNGAGED TRIBUTARY FLOOD
ARRIVAL OF SECOND PARIA R. FLOOD
ARRIVAL OF THIRD PARIA RIVER FLOOD
UNGAGED TRIBUTARY FLOODS (?)
AUGUST
SEPTEMBER
c)

during periods of little or no tributary activity but greatly underestimates sand transport when the bed is enriched in fines. Therefore the magnitudes of sand accumulation in the Colorado River predicted by a stable rating curve calibrated to depleted bed conditions (as done by *U.S. Department of the Interior* [1995]) are probably too high.

In addition to the average increase in suspended-sand concentration after the increase in tributary activity on about September 2, shorter-term changes in suspended-sand concentration coupled to changes in suspended-sand grain size are evident after some of the tributary floods. After each tributary flood, peaks in the measured concentration of suspended sand occur at the Lower Marble Canyon gage (Figure 12b). The greatest measured increase in suspended-sand concentration was between September 15 and 16, when the concentration of suspended sand increased by a factor of 6.3. This occurred in response to a large increase in the discharge of the Paria River the day before (Figure 12a). Because the mouth of the Paria River is located 97 km upstream from the Lower Marble Canyon gage (Figure 1), this suggests that, like in the 1983 example, some portion of the sand input during a tributary flood travels downstream relatively quickly (at nearly the mean velocity of the water). Substantial changes in suspended-sand grain size were also measured at the Lower Marble Canyon gage after two of the four tributary floods (Figure 12c). Following the rapid increase in suspended-sand concentration after the arrival of water from an ungaged tributary flood on September 2, the median size of the suspended sand increased from about 0.10–0.11 to 0.15–0.17 mm as the concentrations started to decrease. Also, after the September 7 Paria River flood, the median size of the suspended sand at the Lower Marble Canyon gage decreased from about 0.15–0.17 to 0.10–0.12 mm as the concentrations increased.

5.6. Methods: Collection and Processing of the 1998 Data

To monitor seasonal changes in the grain size of the bed throughout Marble Canyon following large inputs of sand from the Paria River during the summer thunderstorm season (mid-July through early-October), bed samples were collected in March 1998, September 1998, and May 1999. Bed samples were collected with a pipe dredge in the center of the channel throughout the 99-km length of Marble Canyon (Figures 13
F14a&b and 14). Luckily, the Paria River cooperated with this sampling program, and on September 5, 1998, a flood with a peak discharge of approximately 200 m^3/s, the largest flood in 18 years, occurred on the Paria River. During this flood and a second flood (with a peak discharge of about 110 m^3/s) on September 12 a total of 1.2 ± 0.2 million t of sand and 1.5 ± 0.8 million t of silt and clay [after *Topping*, 1997] were transported from the Paria River into Colorado River. This second flood occurred 3 days prior to the day on which the September 1998 sampling trip was launched.

5.7. Results: 1998

The bed of the upper 80% of Marble Canyon fined both considerably and quickly as a result of the Paria River floods on September 5 and 12, 1998, as indicated by comparison of the grain-size data collected in March and September 1998
F15 (Figures 13, 14, and 15). This newly input sediment was observed on the bed as far downstream as river mile 50. This sediment was observed to be in the form of a sediment wave, with an upstream portion that blanketed the preexisting coarser bed and a downstream portion that occurred as a secondary mode mixed with the preexisting coarser bed.

The upstream portion of the sediment wave blanketed the preexisting coarser bed sediment, such that from the mouth of the Paria River to river mile 6.8, the bed was unimodal and very fine. This portion of the sediment wave fined in the downstream direction. From the mouth of the Paria River to river mile 6.8 the median size of the fine sediment on the bed decreased from 0.30 to 0.11 mm (Figure 13a), the fraction of the fine sediment on the bed composed of 0.0625- to 0.125-mm sand increased from 0.97 to 88% (Figure 13b), and the fraction of the fine sediment on the bed composed of silt and clay increased from 0.094 to 2.2% (Figure 13c). As a result of the 1998 Paria River floods, the amount of fine sediment on the bed composed of the finer sand sizes increased by about a factor of 1000–1500, and the amount of fine sediment on the bed composed of silt and clay increased by a factor of 71 at river mile 6.8 (Figures 15a). At both river miles 5.7 and 6.8 the median size of the fine sediment measured on the bed of the Colorado River was 0.11 mm (Figure 13a and 14), roughly equal to the 0.11- to 0.15-mm median size of the suspended sand measured in the Paria River during floods [*Topping*, 1997]. The front of this upstream portion of the sediment wave occurred between river miles 6.8 and 7.2. Presumably, the coarser upstream tail of this portion of the wave (from the mouth of the Paria River to river mile 6.8) resulted from winnowing of the finer grain sizes from the bed after cessation of the upstream supply of sediment from the Paria River.

The downstream portion of the sediment wave (from about river miles 7.2 through 50.1) occurred as a secondary mode mixed with the preexisting coarser bed sediment (Figure 14). Throughout this portion of Marble Canyon the primary mode was composed of the coarser grain-size distribution measured in March 1998. The secondary mode was composed of the newly input finer sediment. Though no substantial decrease in the median size of the fine sediment was observed from river mile 7.2 through 50.1 (Figure 13a), fining of the bed due to the growth of this secondary mode resulted in an increase in the silt and clay and an increase in the 0.0625- to 0.125-mm sand relative to the amounts composing the fine sediment on the bed in March 1998 (Figure 15a).

The secondary mode decreased in magnitude from about river miles 7.2 through 50.1 and decreased in grain size from about 0.1 mm at river mile 7.2 to about 0.07 mm at river mile 50.1 (Figure 14). Also, immediately downstream from the front of the upstream unimodal portion of the sediment wave (i.e., from river miles 6.8 through 7.2), enrichment of the fine sediment on the bed decreased faster with increasing grain size (Figure 15a). Between river miles 6.8 and 7.2 the September 1998 to March 1998 ratio of the amount of silt and clay composing the fine sediment on the bed decreased by only a factor of 4.4. Over this same section of the river the comparable ratios for the 0.0625- to 0.077-mm sand, 0.077- to 0.088-mm sand, 0.088- to 0.105-mm sand, and 0.105- to 0.125-mm sand decreased by factors of 6.8, 6.9, 13.9, and 69, respectively (Figure 15a). These observations suggest that (as previously suggested by the suspended-sand data in Figure 12d) following a tributary flood, finer grain sizes travel downstream faster than coarser sizes.

Between September 1998 and May 1999 the grain size of the fine sediment on the bed in Marble Canyon evolved substantially, and the bimodality observed in September 1998 disappeared. Depletion of the finer sand on the bed during this

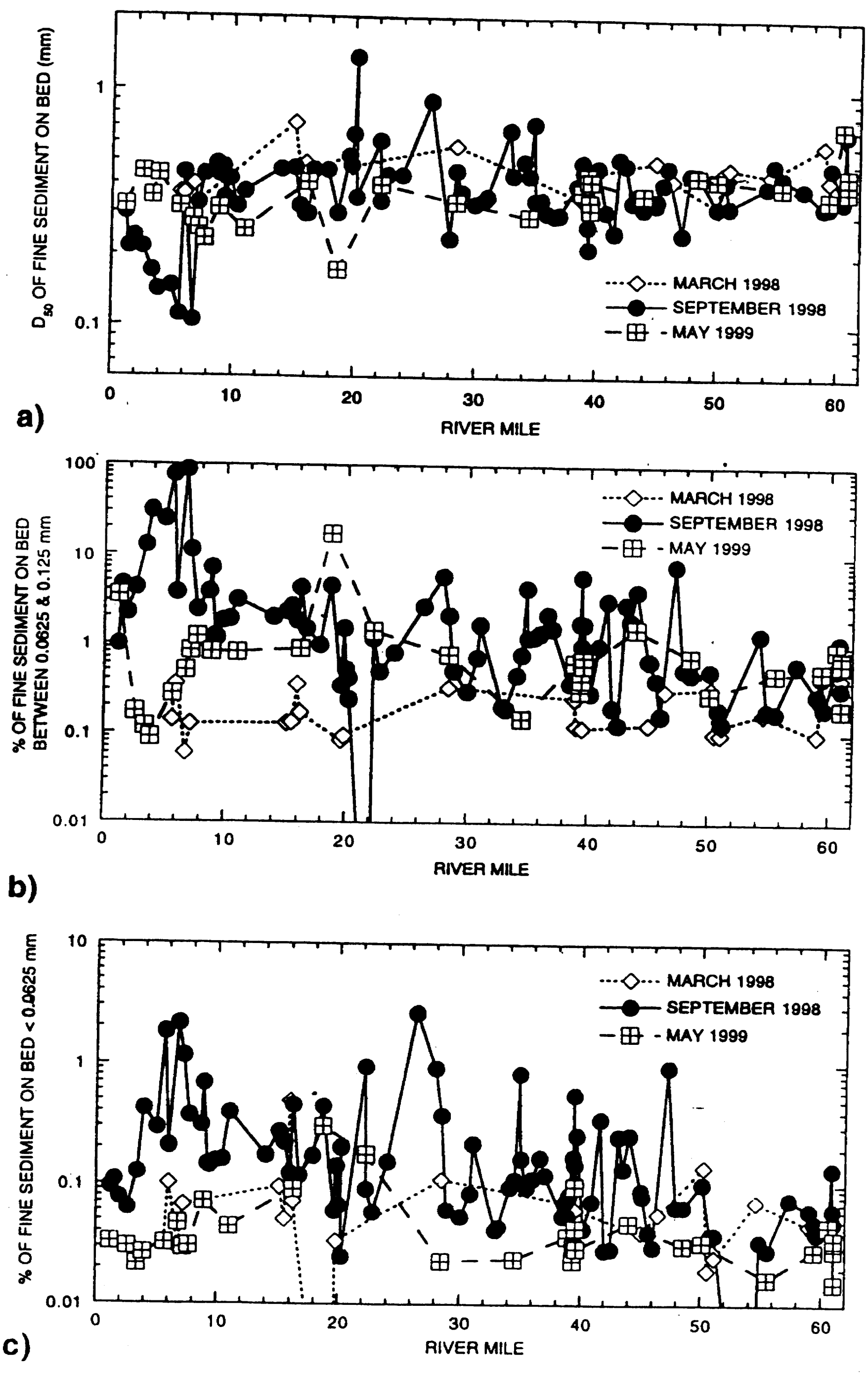


Figure 13. (a) Median size of the fine sediment on the bed of the Colorado River in Marble Canyon measured on March 1-5, 1998, on September 15–21, 1998 (immediately following the two large Paria River floods), and on May 27–29, 1999. (b) Measured fraction of the fine sediment on the bed of the Colorado River in Marble Canyon composed of 0.0625- to 0.125-mm sand. (c) Measured fraction of the fine sediment on the bed of the Colorado River in Marble Canyon composed of silt and clay.

period was inversely correlated with grain size (Figures 15b). Throughout Marble Canyon a substantial decrease in the amount of the 0.0625- to 0.077-mm sand occurred between September 1998 and May 1999 (Figure 15b), but, on average, a factor of 1.7 more of this size class was present in May 1999 than in March 1998 (Figure 15c). Progressively smaller decreases occurred with increasing grain size, such that almost no change in the amount of 0.105- to 0.125-mm sand occurred downstream from river mile 7 between September 1998 and May 1999 (Figures 15b). On average, a factor of 5.0 more of this size class was present in Marble Canyon in May 1999 than in March 1998 (Figure 15c). Thus the bed grain-size data suggest that some unknown fraction of the sand supplied by the Paria River in September 1998 was retained in storage 8.5

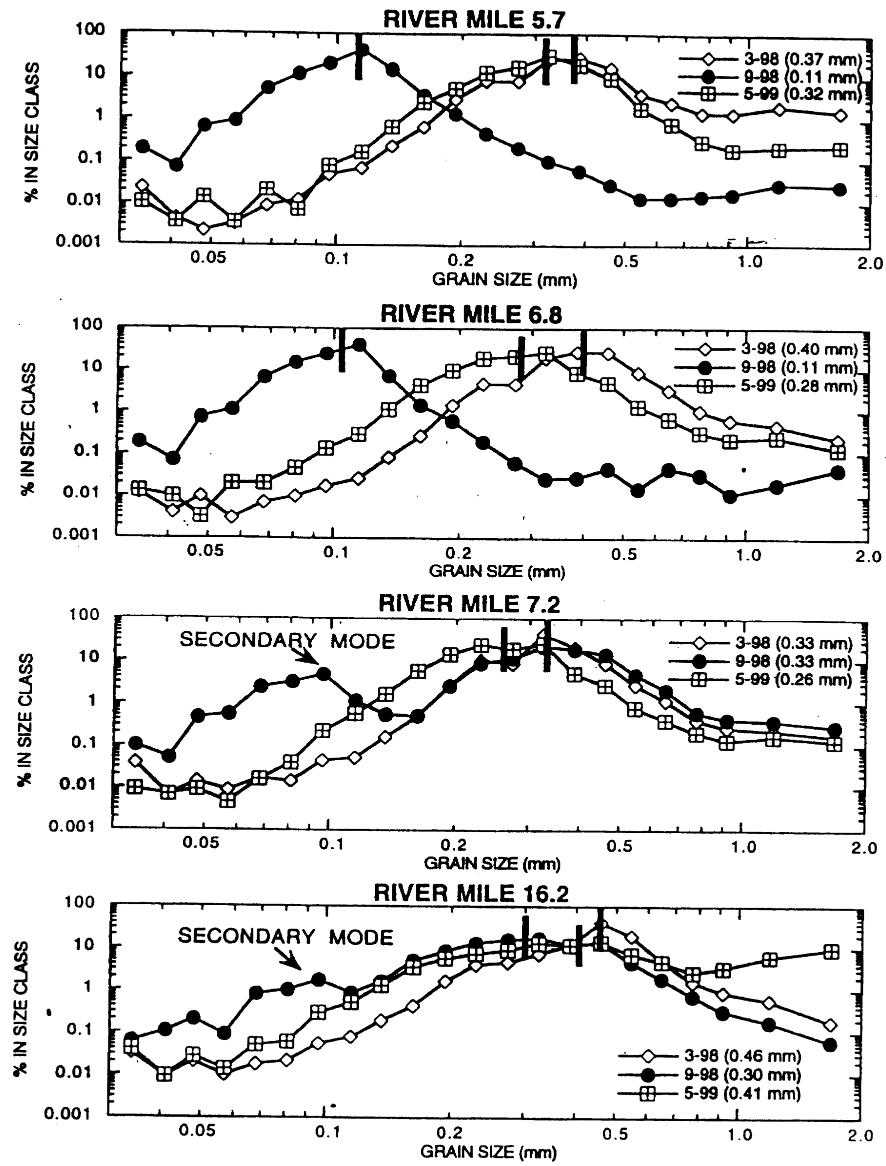


Figure 14. Measured grain-size distributions of the fine sediment on the bed of the Colorado River in Marble Canyon at selected locations in March 1998, September 1998 (immediately following the two large 1998 Paria River floods), and May 1999. Sediment introduced by these floods caused a substantial fining of bed sediment downstream to river mile 6.8 and produced a weaker but detectable secondary mode as far downstream as river mile 50.1. Bold vertical lines indicate the median grain sizes; values of the median grain sizes are listed in parentheses.

months later. Preliminary analyses of topographic surveys, however, suggest that no substantial change in the volume of sand stored in Marble Canyon occurred between April 1998 and May 1999 (J. E. Hazel Jr., personal communication, 1999). One hypothesis can account for these apparently contradictory observations of sediment grain size and sediment volume: If the total volume of sand in stored in Marble Canyon were small, then small volumes of newly input sand may cause substantial changes in grain size without causing detectable changes in sand storage.

6. Discussion

6.1. Bed-Elevation Changes

To correctly interpret changes in the bed elevation of a river during a flood, it is important to distinguish changes in bed elevation driven by local reach-geometric effects from changes in bed elevation driven by temporal changes in the upstream sediment supply. The bed at a cross section in a nonuniform reach typically either aggrades (fills) or degrades (scours) with a change in water-surface stage. During a flood, bed-elevation change at a cross section is usually driven by reach geometry [*Colby*, 1964; *Andrews*, 1979; *Howard and Dolan*, 1981] but can also be driven by changes in the upstream supply of sediment [*Leopold and Maddock*, 1953; *Brooks*, 1958; *Howard and Dolan*, 1981]. Temporal changes in bed elevation are coupled to both temporal changes in the volume of sediment in suspension and spatial changes in the flux of sediment:

$$\frac{\partial \eta}{\partial t} = -\frac{1}{c_b}\left(\frac{\partial V_s}{\partial t} + \nabla \cdot \mathbf{Q}_s\right), \qquad (1)$$

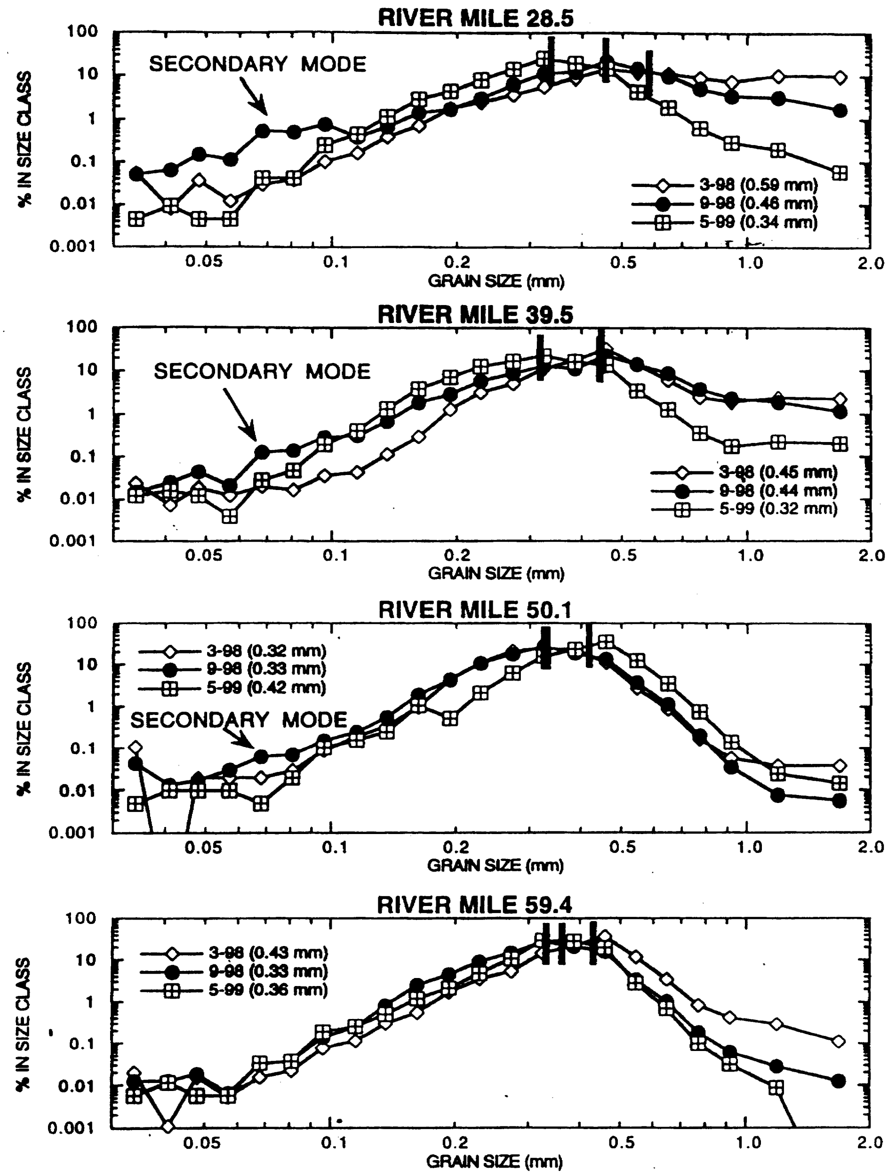


Figure 14. (continued)

where η is the elevation of the bed, c_b is the concentration of sediment in the bed, V_s is the volume of sediment in suspension, and $\mathbf{Q}_s$ is the flux of sediment.

Changes in the volume of sediment in suspension with respect to time ($\partial V_s/\partial t$) are driven primarily by changes in the boundary shear stress at a given location over time. *Colby* [1964] demonstrated that in a typical sand-bedded river, the magnitude of bed scour and fill related to temporal changes in the volume of suspended sediment during a flood (i.e., $\partial V_s/\partial t$) is small. As noted by *Rubin and Hunter* [1982], the volume of sediment available for deposition in response to $\partial V_s/\partial t$ is limited to the volume of sediment in transport over the depositional site on the bed. In contrast, when the volume of sediment in transport decreases in the downstream direction, the volume of sediment available for deposition includes all of the upstream sediment in transport. Thus, in most situations, the portion of scour and fill driven by $\nabla \cdot \mathbf{Q}_s$ dominates over the portion of scour and fill driven by $\partial V_s/\partial t$. Indeed, in the case of the 1996 Grand Canyon flood experiment, only 1 cm of bed scour at the Grand Canyon cableway would be needed to equal the measured increase in the unit volume of sediment in suspension during the rising limb of the flood. However, while this maximum of 1 cm of bed scour could have occurred in response to $\partial V_s/\partial t$ during the rising limb of the flood, the bed at the Grand Canyon cableway aggraded by 0.5 m in response to $\nabla \cdot \mathbf{Q}_s$.

Divergence in the flux of sediment ($\nabla \cdot \mathbf{Q}_s$) can be driven by either reach-geometric effects, changes in the magnitude of the upstream sediment supply, or both. For example, given a constant upstream supply of sediment, streamwise divergence in the flux of sediment at a cross section can be caused purely by reach-geometric effects if, given a change in water-surface stage, the sediment-transport rate at that cross section increases faster than the sediment-transport rate at the cross section upstream. Conversely, a decrease in the upstream supply of sediment will also result in streamwise divergence in the

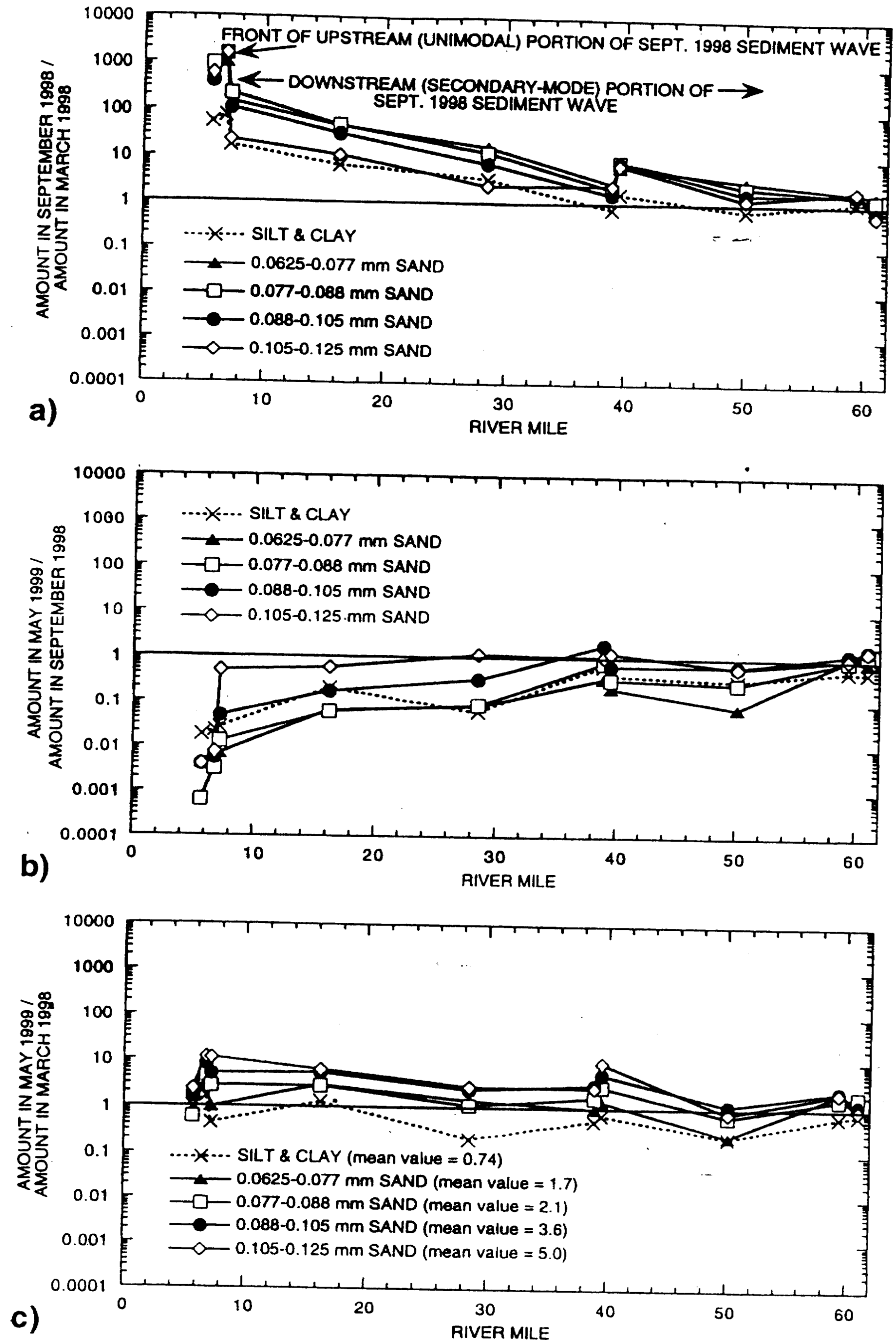


Figure 15. Changes in the amount of silt and clay and four size classes of finer sand on the bed of the Colorado River in Marble Canyon associated with the September 1998 Paria River floods. These changes are shown only for the locations that were sampled on all three trips (in March 1998, September 1998, and May 1999). (a) Ratio of the amount of each size class composing the fine sediment on the bed following the Paria River floods in September 1998 to the amount of each size class that composed the fine sediment on the bed in March 1998. Impact of the tributary-flood sediment on local grain-size decreases downstream is shown. This effect is most pronounced for intermediate grain sizes, since finest sediments (silt and clay) tended to bypass this reach and coarser sizes (>0.105 mm) had not yet greatly arrived by the time of the September 1998 sampling trip. (b) Ratio of the amount of each size class composing the fine sediment on the bed in May 1999 (8.5 months after the Paria River floods) to the amount of each size class that composed the fine sediment on the bed in September 1998 (immediately following the Paria River floods). (c) Ratio of the amount of each size class composing the fine sediment on the bed in May 1999 (8.5 months after the Paria River floods) to the amount of each size class that composed the fine sediment on the bed in March 1998 (6 months before the Paria River floods). The mean values of the ratios for each size class are shown in parentheses.

flux of sediment. In this case, as the upstream supply of sediment is decreased, the sediment-transport rate at a cross section will be higher than the sediment-transport rate at the cross section upstream, causing streamwise divergence in the sediment flux. Thus, in both situations, the bed at a cross section will stop degrading only when the sediment transport rates equilibrate between that cross section and the cross section upstream.

Cross sections surveyed in the Grand Canyon gage reach the day before the 1996 flood experiment provide a good example of the control of reach geometry on bed aggradation and scour
F16 (Figure 16). In the Grand Canyon gage reach, as the water-surface stage increases, the cross-sectional area of downstream flow at the cableway increases faster than at the upstream end of the reach. In this usage, cross-sectional area of downstream flow excludes that portion of the channel occuppied by lateral recirculation eddies. Because the water-surface stage ranged from 2.1 m to 3.4 m during the 2 weeks prior to the survey, the bed topography was probably in equilibrium with a water-surface stage in this range. Indeed, because the cross-sectional areas of downstream flow at the two cross sections were approximately equal at a water-surface stage of about 3.4 m, the bed topography the day before the 1996 flood experiment was probably in equilibrium with a water-surface stage of about 3.4 m. At higher water-surface stages the cross-sectional area of downstream flow would increase faster at the downstream (cableway) cross section than at the upstream cross section (as observed during the 1996 flood experiment). Thus, by conservation of mass, the mean velocity at the downstream cross section would increase more slowly than at the upstream cross section. Because suspended-sediment transport scales as roughly the second to third power of the boundary shear stress [e.g., *Engelund and Hansen*, 1967] and the boundary shear stress scales approximately as the square of the mean velocity, this effect produces substantial convergence in the flux of sediment, driving deposition at the cableway cross section. This deposition would continue, given an adequate upstream supply of sediment and enough time, until the area of the cableway cross section decreased enough to remove the streamwise convergence in the boundary shear stress field, resulting in a new equilibrium bed topography. By the same process, subsequent decreases in water-surface stage would cause erosion at the cableway cross section.

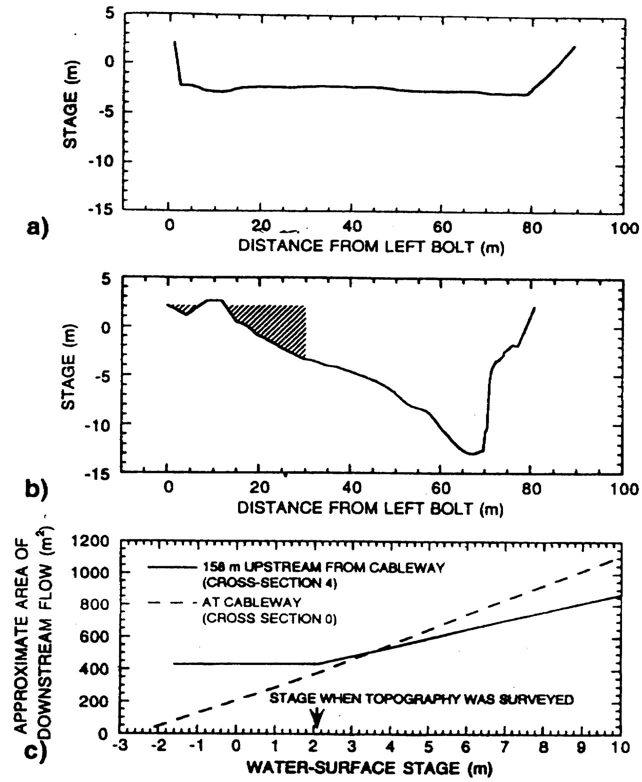


Figure 16. (a) Cross section 0 (at the Grand Canyon cableway) surveyed on March 26, 1996. Except for in narrow zones near the banks, downstream flow occurs over most of this cross section. (b) Cross section 4 surveyed on March 26, 1996. The cross-hatched regions indicate the approximate areas of a lateral recirculation eddy (see Figure 2 for the planform view of this eddy), in which downstream flow is balanced by upstream flow. (c) Approximate area of downstream flow as a function of water-surface stage at both cross sections based on the topography surveyed on March 26, 1996. The faster increase in the cross-sectional area of downstream flow with increasing water-surface stage drives deposition at the cableway during floods (see text for discussion).

To extend these results to cross sections with geometries different from that at the Grand Canyon cableway and to further illustrate the influences of both local reach geometry and upstream sediment supply on bed elevation during a flood, we constructed and applied a simple one-dimensional model using (1). This model was applied to two different types of cross sections (both with sandy beds), first for the case in which the upstream sediment supply is in equilibrium with the sediment-transport capacity throughout a flood and then for the case in which the upstream sediment supply decreases (resulting in an additional streamwise increase in sediment flux through the cross section) during a flood. In the first type of cross section (with a geometry similar to that at the Grand Canyon cableway), convergence occurs in the boundary shear stress field as the water-surface stage increases during a flood, causing deposition at this cross section. In the second type of cross section, divergence occurs in the boundary shear stress field as the water-surface stage increases during a flood, causing erosion at this cross section.

To make these calculations simple, the model was first run using a critical assumption. This assumption is that the timescale of bed-topographic adjustment is much shorter than the timescale of the rising limb of a flood. Thus, in this first round of calculations, given a stable upstream supply of sediment, the bed topography is always in equilibrium with the flow. To make the physical linkage between changes in the upstream sediment supply and the topographic response of the bed clear, the results of this simple model (Figure 17) are discussed first. F1' Then, to make these calculations general, the results of the simple model are extended to situations where this assumption does not apply, that is, when the timescale of bed-topographic adjustment is substantial with respect to the timescale of the rising limb of a flood.

As shown in Figure 17, given an equilibrium upstream supply of sediment during a flood, the time of maximum or minimum bed elevation (in both types of cross sections) should occur simultaneously with the peak water-surface stage. In this case the bed at the cross section may aggrade or scour, depending on the local reach geometry. In contrast, if the upstream supply of sediment decreases during a flood, a lag will occur between the time of the flood peak and the time of either maximum or minimum bed elevation at a cross section. In the

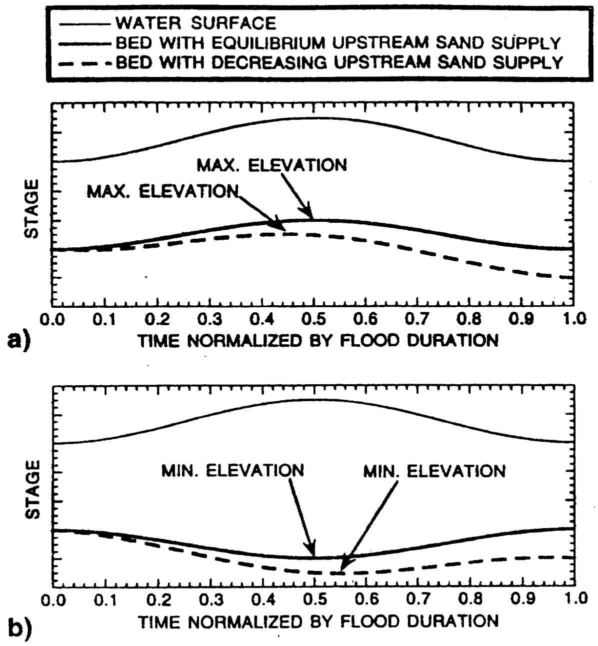


Figure 17. Results of calculations based on equation (1) for cases where the upstream supply of sediment does not change with time and decreases linearly with time during the course of a flood for cross sections where (a) geometrically driven convergence in the sediment flux occurs with increasing flow depth and (b) geometrically driven divergence in the sediment flux occurs with increasing flow depth.

case of a decreasing upstream supply of sediment, (1) maximum bed elevation will lead the flood peak at a cross section where the bed aggrades with increasing water-surface stage (Figure 17a), and (2) the time of minimum bed elevation will lag the flood peak at a cross section where the bed scours with increasing water-surface stage (Figure 17b).

If the assumption used in Figure 17 does not apply and the timescale of bed-topographic adjustment is substantial with respect to the timescale of the rising limb of a flood, the effect is to delay the time of either maximum or minimum bed elevation. Therefore, in the first type of cross section (Figure 17a), the time of maximum bed elevation does not have to occur prior to, but could occur either with or after, the time of a flood peak. In the second type of cross section (Figures 17b) the time of minimum bed elevation will still occur after the time of a flood peak, and the bed may still aggrade during the receding limb. Thus, in this case the effect of a slower response of the bed topography to changing flow conditions produces a result that cannot be distinguished from the effect of sand supply limitation.

In summary, at a cross section that aggrades with increasing water-surface stage, the observation that the time of maximum bed elevation occurs prior to either the peak or the receding limb of a flood indicates a decrease in the upstream supply of sand during a flood (i.e., sand supply limitation). However, at a cross section that scours with increasing water-surface stage, the observation that the time of minimum bed elevation occurs after the peak of a flood does not necessarily indicate the presence of sand supply limitation. Therefore, because of the strong control of reach geometry on bed topography and the possibly delayed response of bed topography to changing flow conditions, the best type of cross section to use in deducing the presence of sand supply limitation is one that aggrades with increasing water-surface stage (e.g., the Grand Canyon cableway cross section).

Observations made during the 1996 flood experiment suggest that changes in bed elevation during floods in the Colorado River in Grand Canyon are primarily driven by reach geometry and only secondarily by depletion of the upstream sand supply. Depletion of the upstream supply of sand does not necessarily prevent bed aggradation when a strong streamwise convergence exists in the boundary shear stress field. Measurements of suspended-sand concentration and bed grain size at the Grand Canyon cableway during the 1996 flood indicate that the upstream supply of sand was being depleted as early as day 1 of the flood, 4 days before the bed stopped aggrading. Depletion of the upstream sand supply therefore only has the effect of creating or modifying a lag between the time of a flood peak and the time of either maximum or minimum bed elevation. At a cross section where convergence occurs in the boundary shear stress field with increasing flow, the time of maximum bed elevation in a supply-limited case will occur prior to that in a non–supply-limited case; and, at a cross section where divergence occurs in the boundary shear stress field with increasing flow, the time of minimum bed elevation in a supply-limited case will occur after that in a non–supply-limited case.

6.2. Sediment Grain-Size Evolution

The concentration and grain size of sediment in suspension is tightly coupled to the grain-size distribution of the bed. For steady, uniform flow, and an upstream supply of sediment that is in equilibrium with the flow conditions, the concentration of each size class of sediment in suspension depends mainly (1) the proportion of the fine sediment on the bed composed of that size class, (2) the settling velocity of that size class, and (3) the median size of the fine sediment on the bed. In this framework the grain-size distribution of the bed is treated as an independent variable. However, in rivers in which the upstream supply of sediment is not in equilibrium with the flow conditions, the grain-size distribution of the bed is a dependent variable (as in either sediment-feed flumes or the Colorado River) and evolves over time as a function of changes in the sediment supply. Before adding this degree of complexity to the problem, it is useful to review the coupling between the suspended and bed sediment in the Colorado River through solution of the following equations for suspended-sediment concentration derived for multiple size classes in steady, uniform flow and an upstream supply of sediment that is in equilibrium with the flow conditions.

In steady, uniform flow, when the effects of bedforms and density stratification are excluded,

$$\left(\frac{c_m}{1-c_s}\right)_z = \left(\frac{c_m}{1-c_s}\right)_a \left[\left(\frac{a}{z}\right)\left(\frac{h-z}{h-a}\right)\right]^p \qquad z \le 0.2h \qquad (2a)$$

$$\left(\frac{c_m}{1-c_s}\right)_z = \left(\frac{c_m}{1-c_s}\right)_a \left[\left(\frac{a}{0.2h}\right)\left(\frac{0.8h}{h-a}\right)\right]^p \cdot \exp\left[-p\,\frac{\beta}{h}(z-0.2h)\right] \qquad z > 0.2h. \qquad (2b)$$

These equations were derived using the two-part eddy viscosity of *Rattray and Mitsuda* [1974]; see *McLean* [1992] for the basis of the derivation. In 2, c_m is the volumetric concentration of sediment in size class m, c_s is the total concentration of sediment in all size classes, z is the vertical dimension, h is the flow depth, a is the level (determined by the method of *Wiberg and Rubin* [1989]) at which the reference concentration is calculated, p is the Rouse number, and $\beta = 6.25$ is a constant set by the matching height of $0.2h$. The Rouse number,

$$p = w_m/ku_*, \tag{3}$$

where w_m is the settling velocity of sediment in size class m and u_* (the shear velocity) is set equal to $\sqrt{\tau_b/\rho}$ for a planar bed. On the basis of the work of *Smith and McLean* [1977] the lower boundary condition for suspended sediment is

$$(c_m)_a = A_s i_m c_b \gamma\left(\frac{\tau_b - \tau_{cr}}{\tau_{cr}}\right), \tag{4}$$

where $(c_m)_a$ is the near-bed, time-averaged concentration of suspended sediment in size class m, A_s is the fractional area of the patches of fine sediment (i.e., sand and finer material) on the bed, i_m is the volumetric fraction of sediment size-class m in the patches of fine sediment on the bed, $c_b = 0.65$ is the volumetric concentration of fine sediment in that portion of the bed covered by fine sediment, γ is a constant set equal to 0.0045 (P. Wiberg, personal communication, 1989) when a is determined by the method of *Wiberg and Rubin* [1989], and τ_{cr} is the critical shear stress of the median size of the fine sediment on the bed calculated by the method of *Wiberg and Smith* [1987]. To preclude the occurrence of physically unrealistic high concentrations of suspended sediment, in the cases where $(c_s)_a$ is predicted to be greater than 0.5 by (4), $(c_m)_a = 0.5A_s i_m$. *Topping* [1997] showed that (4), used in combination with the full suspended-sediment theory (i.e., including the effects of both bed forms and density stratification) of *Smith and McLean* [1977] and *McLean* [1992], is a good predictor of both the measured depth-integrated concentration and grain-size distribution of suspended sediment in the flume experiments of *Kennedy* [1961] and *Guy et al.* [1966] and is also a good predictor of both the measured near-bed concentration and grain-size distribution of suspended sediment in the Rio Puerco data of *Nordin* [1963].

As illustrated by *McLean* [1992], inclusion of the effects of bed forms and density stratification decreases the suspended-sediment concentration and grain size relative to those predicted by the approach outlined above. By reducing the stress on the bed, but maintaining a high degree of vertical mixing in the interior of the flow, inclusion of the effect of bed forms can decrease the concentration of suspended sediment by as much as an order of magnitude and can decrease the depth-averaged median size of the suspended sediment by as much as 20%. By partially damping the turbulence and reducing the vertical mixing in the flow, inclusion of the effect of density stratification can decrease both the depth-averaged concentration and median size of the suspended sediment by about 20%. Thus the combined impact of these two effects on the predicted magnitudes of the depth-averaged suspended-sediment concentration and grain size can be quite large. However, the predicted change in suspended-sediment concentration and grain size as a function of a change in bed-sediment grain size is similar (within 20%) regardless of whether or not these effects are included. Therefore these two effects are excluded for the sake of keeping the discussion below simple.

Solution of (2), (3), and (4) suggests that the grain-size distribution of the fine sediment on the bed exerts a greater control on the concentration of suspended sediment than does the surface area of the patches of fine sediment on the bed. The coupling between the grain-size distribution of the fine sediment on the bed and the concentration of suspended sediment is strongly nonlinear, whereas the coupling between the area of the patches of fine sediment on the bed is approximately linear (depending on how the patches are distributed on the bed). Regardless of whether the fine sediment on the bed is relatively fine or coarse, coarsening of the fine sediment on the bed by a factor of two will produce a decrease in suspended-sediment concentration of about an order of magnitude (Figure 18a). In contrast, solution of (2), (3), and (4) F18 suggests that a factor of 2 decrease in the area of the patches of fine sediment on the bed will produce a factor of 2 decrease in suspended-sediment concentration.

A situation in which a change in the area of the patches of fine sediment on the bed may be predicted to have a nonlinear influence on the concentration of suspended sediment is when the area of the patches gets small enough that the drag due to protrusion of gravel through the fine sediment results in a substantial reduction in the boundary shear stress (by the mechanism proposed by *Wiberg and Smith* [1991] and *Nelson et al.* [1991]). When the diameter of the gravel on the bed is small relative to the flow depth (i.e., the median grain diameter is less than 10% of the flow depth), this effect may be important only when the patches of fine sediment cover less than 5% of the bed [*Topping*, 1997]. However, other mechanisms, for example, enhanced near-bed turbulence because of the protrusion of gravel particles into the flow [*Schmeeckle*, 1998], may offset the effect of the gravel reducing the boundary shear stress. In any case, because the median size of the gravel in the pools of the Colorado River is less than several percent of the flow depth and a 5% patch area is less than that observed in pools by *Anima et al.* [1998], this effect is probably not important in the Colorado River in Marble and Grand Canyons.

In a given flow the grain-size distribution of the suspended sediment is tightly coupled to the grain-size distribution of the fine sediment on the bed (Figure 18b) and is unaffected by changes in only the area of the patches of fine sediment on the bed. Changes in the area of the patches of fine sediment on the bed, though probably accompanying the changes in the grain size of the fine sediment on the bed, are neither necessary nor sufficient to explain the observations made in the Colorado River. During the 1996 flood experiment, the 1997 test flow, following the 1983 Little Colorado River flood, and following the 1997 Paria River and ungaged tributary floods, changes in suspended-sand concentration were inversely related to changes in the grain size of the suspended sand and the fine sediment on the bed. In contrast, the area of the patches of fine sediment on the bed did not change substantially from before to after the 1996 flood experiment [*Anima et al.*, 1998].

By virtue of the physics in (2), (3), and (4), finer grain sizes are more mobile than coarser grain sizes. This results in systematic coupled changes in sand grain size and transport in a river with an intermittent and limited supply of sand [e.g., *Bennett and Nordin*, 1977]. Because of their lower settling velocities, the finer grain sizes of sand will be suspended higher in the flow than the coarser sizes. Thus the finer grain sizes will travel downstream at progressively higher velocities than the coarser grain sizes. Therefore the finite quantity of sand that is supplied to the Colorado River during a tributary flood will travel downstream as an elongating sediment wave, with the finest sizes (because of their lower settling velocities) traveling the fastest (as observed in September 1998). Because the grain size of this newly input sand ($D_{50} \sim 0.11$–0.15 mm) is typ-

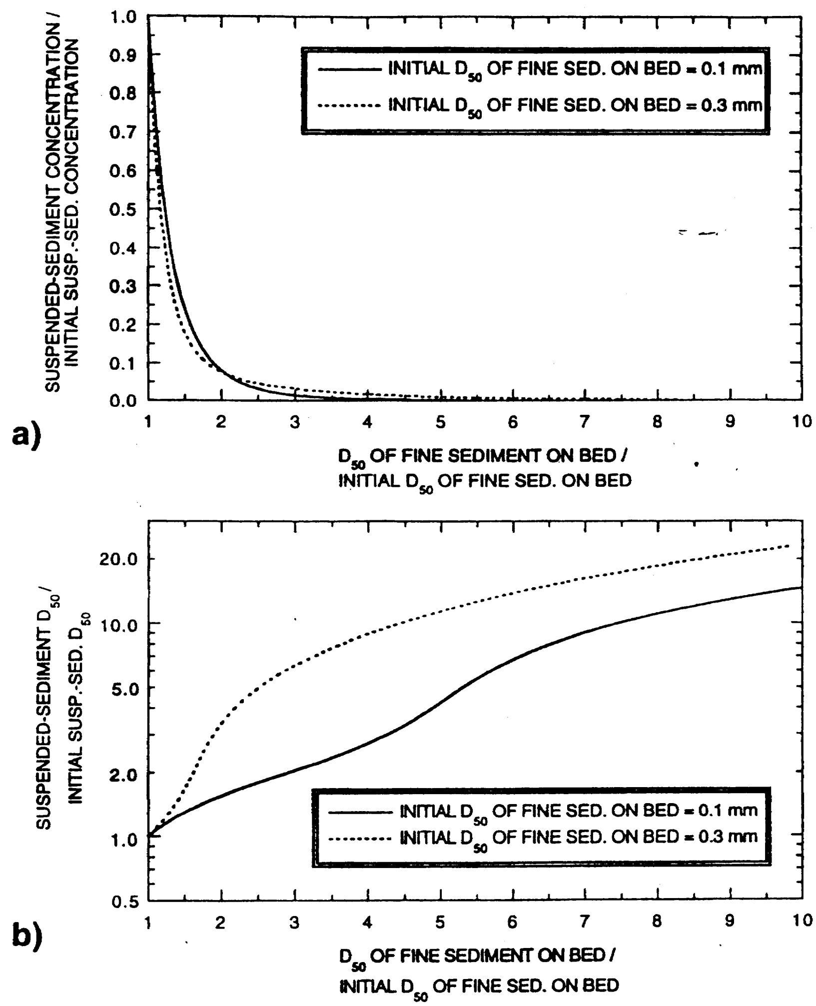


Figure 18. Model-predicted changes in suspended-sediment concentration and grain size as a function of coarsening the grain-size distribution of the fine sediment on the bed. For these calculations, equations (2), (3), and (4) were solved for flow over a planar bed; the depth was held constant at 5 m, and the shear velocity was held constant at 5 cm/s (typical values based on measurements made at the Grand Canyon gage); the sorting of the fine sediment on the bed was held constant at $\sigma_\phi = 0.55$ (a typical value for the fine sediment on the bed of the Colorado River); the grain-size distribution of the fine sediment on the bed was divided into 97 1/16-ϕ size classes; the settling velocity of each size class was determined by the method of *Dietrich* [1982] for sediment with a Powers index of 3.0 and a Corey shape factor of 0.7 (typical values for Colorado River sand); the water temperature was set at 15°C. (a) Depth-averaged suspended-sediment concentration as a function of the median size of the fine sediment on the bed for two cases: a finer-bed case with an initial bed $D_{50} = 0.1$ mm and a coarser-bed case with an initial bed $D_{50} = 0.3$ mm. Values in Figures 18a and 18b are nondimensionalized by the initial values. For either the finer- or coarser-bed case, as the fine sediment on the bed coarsens, the suspended-sediment concentrations decrease nonlinearly and substantially. (b) Depth-averaged median size of the suspended sediment as a function of the median size of the fine sediment on the bed for the same cases as in Figure 18a. For either case, as the fine sediment on the bed coarsens, the median size of the suspended sediment coarsens.

ically much finer than that on the bed of the Colorado River ($D_{50} \sim 0.3$–0.7 mm), substantial changes in the grain size of the bed occur as a sediment wave migrates downstream. As the fine front of a sediment wave reaches a given location and the upstream supply of sediment becomes enhanced, the concentration of the finer grain sizes in suspension will be higher than that which can be supported by the grain-size distribution of the bed downstream. This produces a mass transfer of the finest sizes from the suspended sediment to the bed, resulting in fining of the bed. This was observed at all measurement locations following the 1983 Little Colorado River flood, at the Lower Marble Canyon gage following the 1997 Paria River and ungaged tributary floods, and on the bed in the upper 80 km of Marble Canyon following the 1998 Paria River floods. As the front of a sediment wave passes a given location and the stream supply of sediment becomes depleted, the concention of the finer grain sizes in suspension will decrease to be lower than that which can be supported by the now finer grain-size distribution of the bed. This produces a mass transfer of the finest sizes from the bed back to the suspended sediment (i.e., the fines will be winnowed from the bed), resulting in coarsening of the bed. This was observed at the Grand Canyon gage following the 1983 Little Colorado River flood, at all measurement locations during the 1996 flood experiment, at all measurement locations during the 1997 test flow, and on the bed of Marble Canyon between September 1998 and May 1999. A stratigraphic record of this winnowing process is preserved in the inversely graded flood deposits that were produced during predam snowmelt floods [*Rubin et al.*, 1998; *Topping et al.*, this issue], the 1996 flood experiment, and the 1997 test flow.

7. Conclusions

Systematic changes in bed elevation at a cross section during a flood can be used to make inferences about depletion of the upstream sediment supply in rivers. At a cross section that aggrades with increasing water-surface stage (e.g., the Grand Canyon cableway cross section), the observation that the time of maximum bed elevation occurs prior to either the peak or the receding limb of a flood indicates the presence of sediment supply limitation. However, at a cross section that scours with increasing water-surface stage, the effects of depletion of the upstream sediment supply cannot be separated from the effects of a delayed response of the bed topography to changing flow conditions.

The grain-size distribution of sediment in rivers evolves systematically as a function of changes in the upstream sediment supply. In the Colorado River, grain size evolves in response to both tributary activity and dam operation, resulting in significant changes in sediment-transport rates over time. Sand-transport rates in the Colorado River have been observed to change by as much as a factor of 55 in response to these changes in grain size. After sediment is added to the Colorado River during tributary floods, it travels downstream as a sediment wave that elongates as finest sizes are preferentially transported downstream (as observed on the bed of Marble Canyon in September 1998). As the fine front of a sediment wave reaches a given site, both the bed and suspended sediment will first fine, and sediment-transport rates will increase. On the "receding limb" of a sediment wave both the bed and suspended sediment will coarsen as the upstream supply of the finer grain sizes decreases. In response to the decreased upstream supply of the finer sizes, fines will be winnowed from the bed, and sediment-transport rates will decrease. During mainstem floods this process results in coarsening of the sediment supplied to eddies and produces inversely graded deposits.

Because sand-transport rates change substantially in response to grain-size changes following tributary sediment inputs, sediment budgets cannot be constructed for reaches of a bedrock, supply-limited river like the Colorado River by assuming stable relationships between the discharge of water and sand-transport rates. Such an approach [*U.S. Department of the Interior*, 1995] calibrated to a relatively depleted state preferentially underestimates sand-transport rates following tributary floods and results in the prediction of substantial sand accumulation in the Colorado River over time. The key to understanding sand transport and therefore sand budgets in the Colorado River, is an understanding of the processes that control the short-term fining of sand in the river following large tributary floods and the subsequent coarsening of sand in the river as the fines are winnowed from the bed and either deposited in eddies or transported downstream.

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