Sediment Transport During Three Controlled-Flood Experiments on the Colorado River Downstream from Glen Canyon Dam, with Implications for Eddy-Sandbar Deposition in Grand Canyon National Park

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Cover: Nick Voichick (left), Greg Shellenbarger (center), and Steve Jones (right) in the sampling boat at the river-mile 61 study site on March 7, 2008, during high, steady discharge during the 2008 controlled-flood experiment (USGS photo by David J. Topping).

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
Length		
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Volume		
ounce, fluid (fl. oz)	0.02957	liter (L)
pint (pt)	0.4732	liter (L)
quart (qt)	0.9464	liter (L)
gallon (gal)	3.785	liter (L)
Flow rate		
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
Mass		
ounce, avoirdupois (oz)	28.35	gram (g)

SI to Inch/Pound

Multiply	By	To obtain
Length		
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
Volume		
liter (L)	33.82	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
Flow rate		
meter per second (m/s)	3.281	foot per second (ft/s)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
Mass		
gram (g)	0.03527	ounce, avoirdupois (oz)

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Notation

A_b	Fractional bed-sand area
$A_{b\text{-}ref}$	Reference fractional bed-sand area
C	Suspended-sediment concentration
C_{SAND}	Suspended-sand concentration
$C_{SILT\,\&\,CLAY}$	Suspended-silt-and-clay concentration
C_{ref}	Reference concentration of the suspended sand
D_{50}	Median grain size
D_b	Median grain size of the bed sand
$D_{b\text{-}ref}$	Reference median grain size of the bed sand
D_s	Median grain size of the suspended sand
$D_{s\text{-}ref}$	Reference median grain size of the suspended sand
J	Shear-velocity exponent in equation 1
K	Bed grain-size exponent in equation 1
L	Shear-velocity exponent in equation 6
M	Bed grain-size exponent in equation 6
n_{TRANS}	Number of transits taken by a depth-integrating suspended-sediment sampler at a vertical
n_{VERT}	Number of verticals (that is, sampling stations) in a cross-section
Q	Discharge of water
u_*	Shear velocity
β	Non-dimensional measure of the reach-averaged bed-surface grain size that interacts with the suspended sand in the flow

β_A Version of β corrected for differences in reach-averaged bed-sand area

δ Factor that needs to be applied to correct C_{SAND} for a change in the median grain size of suspended sand over time or space at constant reach-averaged boundary shear stress

ϕ Unit of grain size equal to $-\log_2 D$ where D is grain size in mm

ρ Density

τ_b Boundary shear stress

τ_{sf} Skin-friction component of the boundary shear stress

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Abstract

Three large-scale field experiments were conducted on the Colorado River downstream from Glen Canyon Dam in 1996, 2004, and 2008 to evaluate whether artificial (that is, controlled) floods released from the dam could be used in conjunction with the sand supplied by downstream tributaries to rebuild and sustainably maintain eddy sandbars in the river in Grand Canyon National Park. Higher suspended-sand concentrations during a controlled flood will lead to greater eddy-sandbar deposition rates. During each controlled flood experiment, sediment-transport and bed-sediment data were collected to evaluate sediment-supply effects on sandbar deposition. Data collection substantially increased in spatial and temporal density with each subsequent experiment. The suspended- and bed-sediment data collected during all three controlled-flood experiments are presented and analyzed in this report. Analysis of these data indicate that in designing the hydrograph of a controlled flood that is optimized for sandbar deposition in a given reach of the Colorado River, both the magnitude and the grain size of the sand supply must be considered. Because of the opposing physical effects of bed-sand area and bed-sand grain size in regulating suspended-sand concentration, larger amounts of coarser sand on the bed can lead to lower suspended-sand concentrations, and thus lower rates of sandbar deposition, during a controlled flood than can lesser amounts of finer sand on the bed. Although suspended-sand concentrations were higher at all study sites during the 2008 controlled-flood experiment (CFE) than during either the 1996 or 2004 CFEs, these higher concentrations were likely associated with more sand on the bed of the Colorado River in only lower Glen Canyon. More sand was likely present on the bed of the river in Grand Canyon during the 1996 CFE than during either the 2004 or 2008 CFEs. The question still remains as to whether sandbars can be sustained in the Colorado River in Grand Canyon National Park through use of controlled floods in conjunction with typical amounts and grain sizes of sand supplied by the tributaries that enter the Colorado River downstream from Glen Canyon Dam.

Introduction

The 1963 closure and subsequent operation of Glen Canyon Dam has resulted in substantial erosion of eddy-sandbar habitats in the Colorado River in Grand Canyon National Park (GCNP).

This has occurred as a result of (1) the dam cutting off approximately 94 percent of the natural sand supply at the upstream boundary of GCNP (Andrews, 1991; Topping and others, 2000a; Rubin and others, 2002; Wright and others, 2005), (2) dam releases generally exceeding lower seasonal pre-dam discharges where sand accumulation naturally occurred in the channel of the Colorado River in GCNP (Topping and others, 2000a, 2003; Rubin and others, 2002; White and others, 2005; Wright and others, 2008), and (3) the loss of natural flood flows to redeposit this accumulated sand in eddy sandbars (Dolan and others, 1974; Howard and Dolan, 1981; Rubin and others, 1990, 2002; Schmidt and Graf, 1990; Schmidt, 1990, 1999; Schmidt and Rubin, 1995; Schmidt and others, 2004). During the 12-year period from 1996 through 2008, three large-scale field experiments have been conducted utilizing controlled floods released from Glen Canyon Dam to test whether it were possible to sustainably rebuild and maintain eddy sandbars and associated habitat in the Colorado River in GCNP using only the available tributary-supplied sand. These three controlled-flood experiments occurred in March-April 1996, November 2004, and March 2008. The 1996 and 2004 experiments have been referred to in the scientific literature as "controlled floods" or "flood experiments" (Rubin and others, 1998; Webb and others, 1999; Hazel and others, 2006; Topping and others, 2000b, 2006a), whereas the 2008 experiment has been informally referred to as a "high flow." For consistency with the scientific literature and because the peak magnitudes of these artificial dam-released floods exceeded the natural pre-dam base flood magnitude of 18,500 ft^3/s defined in Topping and others (2003) based on flow-duration analyses, the term "controlled flood experiment" (CFE) is used herein to describe all three of these field experiments.

The hydrograph of the 1996 CFE was different from the hydrographs of the 2004 and 2008 CFEs. The peak discharge of the 1996 CFE (45,000 ft^3/s) was slightly higher than the peak discharges during the 2004 and 2008 CFEs (42,000 to 44,000 ft^3/s depending on reach). This difference in peak discharge primarily arose because of maintenance on Glen Canyon Dam during the 2004 and 2008 CFEs and to a lesser degree because of lower reservoir levels during the 2004 and 2008 CFEs. Greater tributary water input, mostly from the Little Colorado River, during the 2008 CFE helped to reduce the difference in peak discharge between the 1996 and 2008 CFEs in downstream reaches. This allowed direct comparison between suspended-sediment data collected during the 1996 and 2008 CFEs in downstream reaches (that is, below the mouth of the Little Colorado River) without needing to account for the influence of discharge differences on sediment transport. As released from Glen Canyon Dam, the duration of the high-, steady-discharge part of the flood hydrograph during the 1996 CFE was much longer (~7 days) than during the 2004 and 2008 CFEs (~60 hours). This difference in flood duration arose because, before the 1996 CFE, sand concentrations during the 1996 CFE were expected to be much lower than they actually were (E.D. Andrews, U.S. Geological Survey [USGS], oral commun., 1996). Before the 1996 CFE, the only available post-dam dataset of sediment-transport during floods consisted of data collected at various locations on the Colorado River in Grand Canyon during the 1980s (Garrett and others, 1993), when suspended-sand concentrations were anomalously low following the large degree of bed-sand coarsening during large dam-released floods in 1983-1986 (Topping and others, 2000b, 2005, 2007a, 2008). These anomalously low concentration data were the data used to design the duration of the 1996 CFE hydrograph (E.D. Andrews, USGS, oral commun., 1996). Finally, the rising limb of the flood hydrograph during the 1996 CFE was relatively short compared to the more gradual rising limbs of the flood hydrographs during the 2004 and 2008 CFEs, and the receding limb of the flood hydrograph of the 1996 CFE was longer than those of the 2004 and 2008 CFEs (fig. 1).

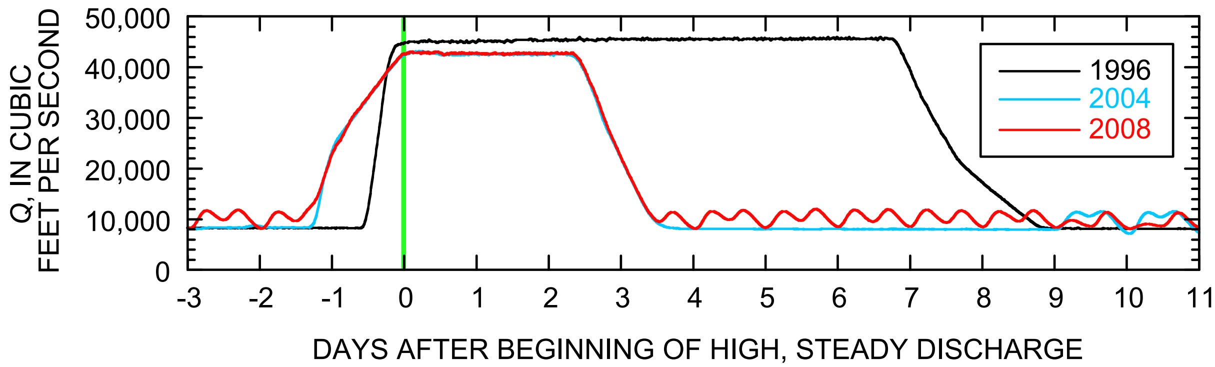

Figure 1. Comparison of the flood hydrographs of the 1996, 2004, and 2008 CFEs at the USGS gaging station on the Colorado River at Lees Ferry, Arizona (station number 09380000). These hydrographs were shifted in time such that zero time (indicated by vertical green line) is the beginning of high, steady discharge (*Q*) during each CFE. The Lees Ferry gaging station is located approximately 16 river miles downstream from Glen Canyon Dam (see fig. 3 below).

Although terminology in the nonscientific arena has varied over time in describing these events, the 1996, 2004, and 2008 CFEs are technically floods based on the flow-duration and flood-frequency analyses for the pre-dam Colorado River in Topping and others (2003). Flows of 42,000 to 45,000 ft^3/s were only equaled or exceeded 10.1 to 11.2 percent of the time in the natural pre-dam Colorado River at Lees Ferry, Arizona, near the upstream boundary of GCNP (computed from the data for fig. 22*A* in Topping and others, 2003). Before construction and operation of Glen Canyon Dam, floods with peak discharges of 42,000 to 45,000 ft^3/s had a recurrence interval of 1.1 to 1.2 years on the annual flood series and 0.9 years on the partial-duration flood series (fig. 2). Furthermore, the peak discharges of the 1996, 2004, and 2008 CFEs were substantially higher than the peak discharges of six[1] of the 42 annual snowmelt floods between 1921 and 1962, and only slightly lower in peak magnitude than two[2] more of these 42 floods. During the post-dam period of 1963-2000, the recurrence interval associated with floods with peak discharges of 42,000 to 45,000 ft^3/s increased dramatically to about 3 years in the partial-duration series (fig. 37 in Topping and others, 2003). This post-dam recurrence interval is somewhat misleading, however, because most of the post-dam floods in this discharge range occurred in April-June 1965 during the pulsed dam releases informally referred to as "channel-cleaning flows" by engineers (fig. 2*C* in Grams and others, 2007).

Given the different tributary sand supplies and dam releases antecedent to the 1996, 2004, and 2008 CFEs, these three experiments were probably conducted under very different sand-supply conditions, and these different sand-supply conditions likely controlled the resultant eddy-sandbar responses during these CFEs. Schmidt and others (1993) showed in flume experiments that the deposition rate in an eddy sandbar during a flood directly depends on suspended-sand concentration. However, as shown below, the relation between the antecedent upstream sand supply to a reach in a controlled flood and the concentration of suspended sand in a reach during a controlled flood is not straightforward, owing to the physics coupling bed-sand area and bed-sand

[1] These six floods were the annual snowmelt floods with peak discharges at Lees Ferry, Arizona, of 25,500 ft^3/s in 1934, 34,300 ft^3/s in 1954, 34,600 ft^3/s in 1931, 35,600 ft^3/s in 1955, 38,900 ft^3/s in 1959, and 40,200 ft^3/s in 1961.

[2] These two floods were the annual snowmelt floods with peak discharges at Lees Ferry, Arizona, of 46,800 ft^3/s in 1960 and 47,300 ft^3/s in 1940.

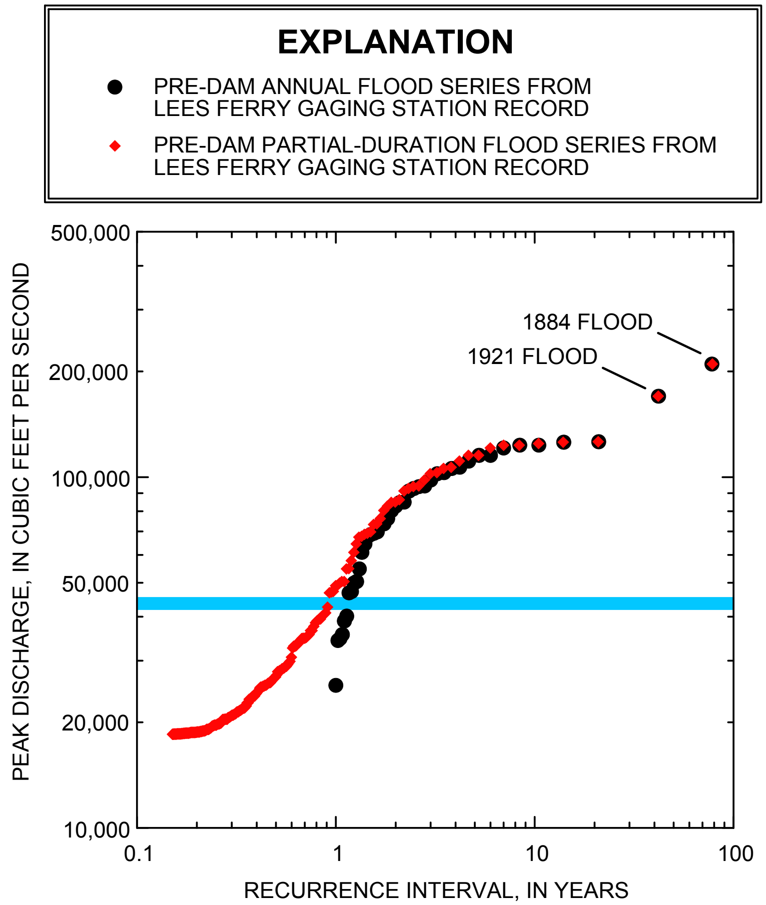

Figure 2. Pre-dam annual and partial-duration flood-frequency analysis for the Colorado River at Lees Ferry, Arizona gaging station. Blue band indicates the 42,000 to 45,000 ft^3/s range in the peak discharges of the 1996, 2004, and 2008 CFEs. See figure 3 for the location of the Lees Ferry gaging station. After figure 36 in Topping and others (2003).

grain size to suspended-sand concentration. Designing future controlled floods thus requires understanding how the different responses of eddy sandbars observed during these three CFEs were related to differences in the suspended-sand concentrations measured during these CFEs, which, in turn, were the product of the different sand supplies antecedent to these three CFEs.

To be a viable tool in rebuilding eddy sandbars in a sustainable manner, controlled floods must result in eddy sandbars increasing in overall size over large segments of the Colorado River in the study area. Eddy sandbars increase in overall size when the sand deposited in these sandbars is derived largely from upstream environments outside of eddies. Controlled floods conducted during relatively sand-depleted conditions, such as those that likely existed in upstream reaches during the 1996 CFE, result in the erosion of upstream eddy sandbars, with an increase in eddy-sandbar size only occurring in the most downstream reaches (Hazel and others, 1999; Schmidt, 1999). Repeated controlled floods conducted under such sand-depleted conditions would likely lead to the eventual erosion of much of the sand from the Colorado River in Grand Canyon, and this is therefore not a sustainable strategy for maintaining eddy sandbar size in GCNP (Topping and others, 2006a). Subsequent CFEs during 2004 and 2008 were thus conducted to test whether controlled floods conducted under greater levels of sand enrichment following large tributary floods and lower dam releases could result in greater, and potentially sustainable, eddy-sandbar deposition in the Colorado River in GCNP (Rubin and others, 2002; Topping and others, 2006a).

High-resolution sediment-transport and grain-size data are required to evaluate the reach-by-reach sand supplies before a CFE, the reach-by-reach sand supplies during a CFE, and the downstream patterns of erosion and deposition during a CFE. To meet this need, suspended- and bed-sediment data were collected at a number of fixed locations during the 1996, 2004, and 2008 CFEs, and suspended-sediment data were also collected using a Lagrangian reference frame during the 2004 and 2008 CFEs. The 1996 CFE resulted in major advances in the understanding of the role of supply limitation in regulating sand transport in the Colorado River in GCNP (Rubin and others, 1998, 2002; Topping and others, 1999, 2000a, 2000b, 2005, 2007a, 2008; Rubin and Topping, 2001, 2008; Schmidt and others, 2007). Therefore, as a result of this learning, suspended- and bed-sediment data were collected at much higher resolutions during the 2004 and 2008 CFEs than during the 1996 CFE.

Purpose and Scope

This study was conducted to collect and analyze sediment-transport data to help in the evaluation and future design of controlled floods as a possible tool in rebuilding and maintaining eddy sandbars in the Colorado River in Grand Canyon National Park. The purpose and scope of this report is to present the suspended- and bed-sediment data collected in the Colorado River during controlled-flood experiments conducted in 1996, 2004, and 2008 and to analyze those data.

Theoretical Background

Previous work has shown that the deposition rate in an eddy sandbar during a flood directly depends on suspended-sand concentration (Schmidt and others, 1993). To maximize eddy-sandbar deposition, a properly designed controlled flood would therefore maintain the highest suspended-sand concentrations for the longest time possible (at least through the duration of the flood). Conducting controlled floods when the sand supply in a river reach of interest is the largest, however, will not ensure that suspended-sand concentrations will be sufficiently high to optimize eddy-sandbar deposition. Because the boundary shear stress field, bed-sand grain size, bed-sand area, and the areal distribution of sand in a reach all interact to regulate suspended-sand transport, the highest suspended-sand concentration at a given discharge of water does not necessarily correspond to the largest sand supply in a reach. Based on equilibrium suspended-sediment theory developed for steady, uniform flow (reviewed by McLean, 1992) for beds entirely composed of sand with either narrow or wide lognormal grain-size distributions, and with or without dunes on the bed, Rubin and Topping (2001) found that

$$C_{SAND} \propto u_*^J D_b^K \,, \tag{1}$$

where C_{SAND} is the time- and spatially averaged suspended-sand concentration, u_* is the spatially averaged shear velocity, and D_b is the spatially averaged median grain size of the bed sand. Depending on the sorting of the bed-sand grain-size distribution and whether dunes were present on the bed, Rubin and Topping (2001) found that, for most cases, J equaled 3.5 and K ranged from -1.5 to -3.0. In the analyses in this report, J is set equal to 3.5 and K is set equal to -2.5. Using these values for J and K, and because

$$u_* = \sqrt{\tau_b/\rho} \,, \tag{2}$$

where τ_b is the spatially averaged boundary shear stress and $\rho \approx 1$ g/cm^3 is the density of the water/suspended-sediment mixture at typical water temperatures, equation 1 can be rewritten as

$$C_{SAND} \propto \tau_b^{1.8} D_b^{-2.5} . \quad (3)$$

For steady, uniform flow, and an approximately uniform areal distribution of sand on a gravel bed, the fractional area of the bed sand, A_b, ranges from 0 to 1 and exerts an approximately linear control on suspended-sand concentration (Topping, 1997; Grams, 2006; Grams and Wilcock, 2007), thus leading to the following form of equation 3:

$$C_{SAND} \propto A_b \tau_b^{1.8} D_b^{-2.5} . \quad (4)$$

For a flat bed composed entirely of sand (that is, a bed without form drag), the reach-averaged skin-friction component of the boundary shear stress, τ_{sf}, is equal to τ_b. As the area of sand on a gravel bed decreases, the spatially averaged form drag increases, resulting in a reduction of τ_{sf} relative to τ_b. In the absence of form-induced stresses (for example, Giménez-Curto and Lera, 1996; Nikora and others, 2001; McLean and Nikora, 2006) that may offset this reduction in τ_{sf}, the spatially averaged near-bed concentration of suspended sand should decrease quasi-linearly as a function of τ_{sf} (after Topping, 1997). To express this effect, equation 4 may be modified as

$$C_{SAND} \propto A_b \frac{\tau_{sf}}{\tau_b} \tau_b^{1.8} D_b^{-2.5} . \quad (5)$$

In gravel-bedded rivers where the bed-gravel grain size is very small relative to the flow depth (as in most of the Colorado River in the study area except in the riffles and rapids), the reach-averaged gravel form-drag component of τ_b must be much smaller than τ_b (Wiberg and Smith, 1991; Topping, 1997). As a gravel bed becomes buried in sand, dunes will develop on the sand patches (Topping, 1997; Rubin and others, 2001) resulting in an additional source of form drag, which may become larger than the form drag associated with the gravel (Smith and McLean, 1977; McLean, 1992, Topping, 1997, McLean and others, 1999; Maddux and others, 2003; Topping and others, 2007a). As a result of this effect, over these sand patches, the ratio τ_{sf}/τ_b in equation 5 may range from about 0.5 to 1. Because sand patches typically compose a minority of the bed of the Colorado River in the study area (Anima and others, 1998; Schmidt and others, 2007; R. Anima, USGS, 2008, unpublished 1998 and 1999 side-scan sonar data), however, the effect of dune form drag on the ratio τ_{sf}/τ_b in equation 5, when spatially averaged over large parts of the bed, is minimal. The ratio τ_{sf}/τ_b in equation 5 is thus likely equal to approximately 1 at the measurement cross-sections in this study and can be excluded from further consideration.

Using steady, uniform flow suspended-sediment theory, a proportionality similar to that in equation 4 can be derived relating the median grain size of the suspended sand to the median grain size of the bed sand. Unlike the proportionalities in equations 4 and 5, however, A_b does not enter into this new proportionality because it affects the flux of each size class of sediment between the bed and the suspended load equally (after Topping, 1997; Topping and others, 2007a). For sand beds with either narrow or wide lognormal grain-size distributions, and with or without dunes on the bed, Rubin and Topping (2001) found that

$$D_s \propto u_*^L D_b^M , \quad (6)$$

where D_s is the spatially averaged median grain size of the suspended sand. Depending on the sorting of the bed-sand grain-size distribution and whether dunes were present on the bed, Rubin and Topping (2001) found that L ranged from 0.15 to 0.4 and M ranged from 0.5 to 1.0. Based on these values and also on the integral constraints that $0.1J = L$, and that $M - 0.1K = 1$ (Rubin and

Topping (2001, 2008), L is set equal to 0.35 and M is set equal to 0.75 in the analyses in this report. Substituting equation 2 into equation 6, using these values for L and M, and rearranging yields:

$$D_s \propto \tau_b^{0.18} D_b^{0.75} . \quad (7)$$

Subsequent discussion of the theoretical background and physical assumptions used in the analyses in this report are thus based on equations 4 and 7.

Previous work has shown that suspended-sand transport in the Colorado River in the study area varies as a function of both the discharge of water and the upstream supply of sand (Topping and others, 2000a, 2000b) and that under typical dam releases, sand transport is regulated equally by the discharge of water (through τ_b) and by the grain-size distribution of the bed sand (Rubin and Topping, 2001, 2008). To a lesser degree than these two regulators of sand transport, the reach-averaged bed-sand area also regulates sand transport in the Colorado River (Topping and others, 2007a). Additionally, changes in how sand is distributed areally within a reach have been observed following large changes in discharge (Anima and others, 1998; Topping and others, 2000b; Schmidt and others, 2007), and these changes may also influence sand transport. Flow in the Colorado River in the study area is typically nonuniform as a result of complicated reach geometry (with lateral recirculation eddies, scour holes, and other bed undulations) and sand typically composes the minority of the bed (Howard and Dolan, 1981; Schmidt and Graf, 1990; Topping and others, 2005, 2008; Hazel and others, 2006). As in any river, the physical interaction between the flow and complicated bed topography controls the loci of sand deposition and erosion (for example, Nelson and Smith, 1989; Shimizu and others, 1990). Under typical sand-supply conditions and dam releases, sand is present mainly in eddy sandbars, along some of the banks, and as patches on a bed composed of fluvial gravel, colluvium, and bedrock (Anima and others, 1998; Schmidt and others, 2007; R. Anima, USGS, 2008, unpublished 1998 and 1999 side-scan sonar data). Sand patches will form in regions on the bed of the Colorado River where convergence occurs in τ_b, and these patches will continue to aggrade and enlarge until either convergence in τ_b disappears or the upstream supply of sand becomes insufficient at a given convergence in τ_b to maintain a depositional environment (Topping and others, 2000b). Sand patches will not form in regions on the bed where divergence in τ_b occurs, except in reaches downstream from tributaries following large tributary floods that can temporarily overwhelm the bed of the Colorado River with sand[3]. The regions on the bed where convergence or divergence in τ_b occurs change location with stage, resulting in different bed-sand areas and different areal distributions of sand within a reach at different water discharges (Topping and others, 2000b, 2007a). Large increases in sand-patch thickness will result in local increases in τ_b over these patches. Such large changes in sand-patch thickness have been observed between repeated bathymetric surveys, but have typically affected less than about 20 percent of the bed over the kilometer-long reach scale (USGS Grand Canyon Monitoring and Research Center, 2000-2005 unpublished data). Because it is unlikely that τ_b over these patches changes by more than 50 percent as these patches change thickness, typical changes in sand-patch thickness will likely result in less than a 10-percent change in the spatially averaged τ_b over the kilometer-long reach scale.

[3] The day after a large flood on the Paria River (located in fig. 3 below) on September 12, 1998 (described in Topping and others, 2000b), the downstream bed of the Colorado River was overwhelmed with sand. This resulted in a substantial decrease in flow depth across the entire channel. Associated with this change in channel geometry, Froude numbers were increased, and upstream-propagating breaking waves were observed over antidunes. In this transient situation, the reach-averaged τ_b was likely substantially increased by the large increase in reach-averaged bed-sand thickness and bed-sand area. By September 14, 1998, sand had been eroded from this reach, flow depths had increased, and the antidunes were gone.

Although equation 4 was developed for equilibrium suspended-sediment transport under steady, uniform flow, it can be applied to the supply-limited suspended-sand transport and nonuniform flow conditions that typify the Colorado River in the study area after some key physical assumptions. For typical flow conditions in the Colorado River in Marble and Grand Canyons, the spatial scale over which suspended sand may equilibrate with the bed ranges from about 600 m to well over 1 km (Topping and others, 2007a). Therefore, the following physical assumptions are utilized to use the physics described by equations 4 and 7 to allow analysis of the suspended-sediment data presented in this report. First, spatial averaging over the kilometer-long reach scale is used to relate a given C_{SAND} and D_s in a cross-section to the values of A_b, τ_b, and D_b averaged over the kilometer-long reach upstream from the measurement cross-section. Second, areal heterogeneities in A_b, τ_b, and D_b are assumed to occur over spatial scales much smaller than the kilometer-long reach scale. Third, and similar to arguments made in Rubin and Topping (2001) based in Einstein and Chien (1953), temporal changes in A_b and D_b caused by changes in the upstream sand supply are assumed to occur over longer time scales than changes in τ_b and sand transport. These three assumptions together allow use of suspended-sediment theory developed for equilibrium suspended-sediment transport under steady, uniform flow in the analysis of suspended-sediment data collected in a river. As a result of these three assumptions, measured values of C_{SAND} and D_s cannot be used to detect variations on A_b, τ_b, and D_b occurring over less than the kilometer-long reach scale. Finally, because changes in sand-patch thickness do not likely result in substantial changes in the reach-averaged value of τ_b, the reach-averaged τ_b is only allowed to vary as a function of changes in water discharge. The appropriateness of and alternatives to this final assumption will be evaluated in a subsequent section of this report.

For a given discharge of water, therefore, suspended-sand concentration depends strongly on the reach-averaged grain-size distribution of the sand on the bed, and to a lesser degree, the reach-averaged area of sand on the bed. By equation 4, the reach-averaged grain-size distribution of the bed sand exerts a nonlinear control on suspended-sand concentration (Rubin and Topping, 2001, 2008), whereas the reach-averaged area of sand on the bed exerts an approximately linear control on suspended-sand concentration (Grams, 2006; Grams and Wilcock, 2007). In the general case, where sand is uniformly distributed on the bed, a factor of 3 decrease in the reach-averaged median grain size of the bed will lead to an approximate factor of 10 increase in suspended-sand concentration (Topping and others, 2000b); a factor of 3 decrease in the reach-averaged area of sand on the bed will lead to an approximate factor of 3 decrease in suspended-sand concentration (Topping and others, 2007a). Changes in the reach-averaged bed-sand grain-size distribution will lead to changes both in suspended-sand concentration and in the grain-size distribution of the suspended sand, whereas changes in the reach-averaged area of sand on the bed will lead to changes in only suspended-sand concentration (Topping and others, 2007a). Because of these physical effects, a large increase in sand supply to a sand-starved reach under constant discharge will lead to an increase in suspended-sand concentration (through a large increase in reach-averaged bed-sand area and possibly a decrease in reach-averaged bed-sand median grain size depending on the differences between the antecedent bed-sand grain-size distribution and the grain-size distribution of the newly supplied sand), whereas a much smaller increase in a much finer sand supply to this same sand-starved reach under constant discharge will result in a much greater increase in suspended-sand concentration (through less of an increase in reach-averaged bed-sand area, but a much larger decrease in reach-averaged bed-sand median grain size). Because a greater amount of sand was supplied in the first of these two hypothetical scenarios, the supply-driven increase in suspended-sand concentration under the first scenario should be longer lived than the supply-driven larger increase in suspended-sand concentration under the second scenario. However, because the sand supply was coarser in the first of these two scenarios, the suspended-sand concentrations under this first scenario could be considerably lower than under the second scenario. Therefore, the "best sand supply" to maximize sandbar deposition for a given controlled flood is not the largest sand supply, but rather the sand supply composed of a sufficiently large volume of sand fine enough to maintain the highest suspended-sand concentrations for the duration of the controlled flood.

In this report, the terms "sand supply" and "sand enrichment" are used to refer to the amount, mass or volume, of sand in a given reach of the Colorado River, which for a given discharge of water is always positively correlated with bed-sand area and, in most but not all instances, negatively correlated with bed-sand median grain size. In the Colorado River in Marble and Grand Canyons, negative correlation typically exists between the amount of sand in a reach and reach-averaged bed-sand median grain size (that is, more sand equates to a finer bed-sand grain-size distribution) because the median grain size of the sand supplied by tributaries is typically much finer than the median grain size of the sand on the bed of the river (Topping and others, 2000b). However, the exact sequence of inputs of new sand from tributaries and various dam releases on the Colorado River can negate this negative correlation. For example, Topping and others (2005, 2008) showed that, when substantial armoring of bed sand occurs, the surface grain size of the bed sand will be positively correlated with the amount of sand in a reach (that is, "more sand" is covered by a cap of coarser sand). Furthermore, over a longer period of time, a large input of sand from a tributary will be winnowed, such that the correlation between the amount of sand in the reach downstream from this tributary and reach-averaged bed-sand median grain size may be positively correlated over this longer time period. In other words, the following sequence of events is likely in the reach downstream from a large tributary over some period of time given the relative magnitudes of a sand input from this tributary and the dam releases in the Colorado River (an example of a scenario similar to this exists in figures 13 through 15 in Topping and others, 2000b):

(1) Initially, the sand in patches on the gravel bed of the Colorado River had an initial median grain size of 0.3 mm and composed about 20 percent of the bed.
(2) A large input of tributary sand occurs, causing the bed-sand area in the reach of the Colorado River downstream from this tributary to increase to almost 100 percent and the bed-sand median grain size to decrease to about 0.1 mm.
(3) At some time later, much of the finer fraction of this new input of tributary sand has been winnowed from the bed in this reach and transported downstream.
(4) At a later time, the sand in this reach has coarsened to about 0.4 mm and the reach-averaged bed-sand area has decreased to about 30 percent. Because of the nonlinearity between suspended-sand concentration and bed-sand median grain size and the linearity between suspended-sand concentration and bed-sand area, winnowing processes will likely increase the bed-sand median grain size faster than they will reduce the bed-sand area.[4]
(5) For the same discharge of water, the suspended-sand concentration over the final bed state would be about a factor of 1.8 lower than that over the initial bed state by only the effect of the coarser bed-sand median grain size, and would be about a factor of 1.5 greater than that by only the effect of the greater bed-sand area, thus resulting in a net 20 percent decrease in suspended-sand concentration between the initial bed state and the final bed state.

[4] As shown in Topping and others (2007a), bed-sand median grain size dominates over bed-sand area in regulating sand transport, and in certain cases the influence of changes in the bed-sand grain-size distribution can completely offset the influence of opposing changes in bed-sand area in regulating suspended-sand transport.

Thus, over the time period associated with the above scenario, lower suspended-sand concentrations are associated with a larger sand supply. In this case, sand supply is positively correlated with reach-averaged bed-sand area and bed-sand median grain size.

Future design of a controlled flood to maximize eddy-sandbar deposition requires knowing the sand-supply and grain-size conditions that gave rise to the suspended-sand concentrations observed during the 1996, 2004, and 2008 CFEs. Detailed "mass-balance" sand budgets constructed using high-resolution sand-flux data are available for various reaches of the Colorado River for the periods antecedent to and during the 2004 and 2008 CFEs, and similar sand budgets could be used to design future controlled floods. However, these sand budgets alone cannot be used to evaluate differences in the sand supplies between the different controlled floods for two key reasons. (1) Data to construct such sand budgets are unavailable for the period antecedent to and during the 1996 CFE. (2) Even when it is possible to construct such sand budgets, data collection for these budgets began in 2002 and thus do not include pre-2002 "background" sand storage in a reach; therefore, these sand budgets cannot compute the entire upstream sand supply in a reach. The differences in the sand supplies during the 1996, 2004, and 2008 CFEs can only be determined through careful physically based analyses of the suspended-sand data collected during these events. Analyses of differences in only suspended-sand concentration between two controlled floods of similar discharge will not allow determination of the differences in the upstream sand supply between these events. Ideally, analyses must be able to resolve the opposing influences of reach-averaged bed-sand grain size and area on suspended-sand concentration. To explain observed coupled changes in suspended-sand concentration and grain size, Rubin and Topping (2001, 2008) developed and tested such an analytical technique to back-calculate the required changes in bed-sand median grain size for a bed composed of 100 percent sand. Unfortunately, as published, this technique does not allow differences in bed-sand area to be evaluated. For reasons described above, bed-sand area is one of the most difficult parameters to measure, either directly or in a back-calculated sense from analyses of suspended-sediment data (Topping and others, 2007a), but it is the parameter that, at a given discharge of water, is always positively correlated with the upstream sand supply. In this report, suspended-sand data will be analyzed using a modified version of the Rubin and Topping (2001, 2008) technique to back-calculate the differences in reach-averaged bed-sand area between different reaches during the same controlled flood and between identical reaches during different controlled floods.

Even though reach-averaged bed-sand area and upstream sand supply are always positively correlated under constant discharge, they are not necessarily positively correlated during large increases in discharge nor are they necessarily positively correlated for some time after a large reduction in discharge, as a result of the transient effects of sand redistribution on the bed following large changes in the discharge of water. Because interactions between the flow field and local channel geometry may change with discharge, different regions of the bed can become aggradational or degradational as discharge varies (Topping and others, 2000b), resulting in different areal distributions of sand on the bed. In the Colorado River in Marble and Grand Canyons, the general equilibrium tendency is for sand to be more evenly distributed on the gravel bed at higher discharge than at lower discharge. Large increases in discharge tend to result in scour of sand from deeper pools and redistribution of this sand over larger parts of the gravel bed. Side-scan sonar data indicate that, in sand-starved reaches of the Colorado River, bed-sand area increases during floods as a result of this redistribution process (Anima and others, 1998; Schmidt and others, 2007). This process was observed in side-scan sonar data following the 1996 45,000 ft^3/s CFE and also following a 4-day 31,000 ft^3/s powerplant-capacity dam release in September

2000. At high discharge during the 1996 and 2004 CFEs, this sand redistribution process was detected to occur over time scales of one to several days through analyses of suspended-sand data conducted using a Rouse-mechanics-based model (Topping and others, 2007a). Even as the upstream supply of sand decreased during these CFEs, the reach-averaged area of bed sand was detected to increase by this transient redistribution process from about 25 percent on day 1 of high, steady discharge to about 37 percent on day 6 of high, steady discharge during the 1996 CFE, and from about 18 percent on day 1 of high, steady discharge to about 29 percent on day 3 of high, steady discharge during the 2004 CFE at the Colorado River near Grand Canyon, Arizona, gaging station (see fig. 3 below for the location of this gaging station). At lower discharge after recession of these artificial floods, it took longer for the sand to redistribute back to the regions of the bed it occupied before these events than it did to expand over larger regions of the bed at higher discharge. Before conducting analyses of reach-averaged bed-sand area, it is important to recognize the potential pitfalls arising from sand areal redistribution within a reach following large changes in discharge.

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Study Sites

During the three CFEs, suspended- and bed-sediment data were collected in cross-sections at as many as six study sites along the Colorado River in the study area in lower Glen, Marble, and Grand Canyons. These six study sites are:

(1) the Colorado River at Lees Ferry gaging station (USGS station number 09380000), located at the downstream end of Glen Canyon and above the mouth of the Paria River, herein referred to as the "River-mile 0" site;

(2) the River-mile 30 sediment station, located at the midpoint of Marble Canyon, herein referred to as the "River-mile 30" site;
(3) the former Colorado River above Little Colorado River near Desert View, Arizona, gaging station (09383100), located at the downstream end of Marble Canyon and above the mouth of the Little Colorado River, herein referred to as the “River-mile 61” site;
(4) the Colorado River near Grand Canyon, Arizona gaging station (09402500), herein referred to as the “River-mile 87” site;
(5) the former Colorado River above National Canyon near Supai, Arizona, gaging station (09404120), herein referred to as the “River-mile 166” site; and
(6) the Colorado River above Diamond Creek near Peach Springs, Arizona, gaging station (09404200), herein referred to as the “River-mile 225” site (fig. 3).

By standard convention on the Colorado River in the study area, river miles increase in the downstream direction from river mile 0 at the Lees Ferry gaging station. As used in this report, lower Glen Canyon extends from Glen Canyon Dam near river mile -16 to the Lees Ferry gaging station at river mile 0, Marble Canyon extends from river mile 0 to the mouth of the Little Colorado River near river mile 62, and Grand Canyon extends from river mile 62 to the Grand Wash Cliffs near river mile 277. The Colorado River in Glen Canyon is within Glen Canyon National Recreation Area, whereas the Colorado River in Marble and Grand Canyons is within GCNP. The Navajo Indian Reservation borders the Colorado River between river miles -13 and

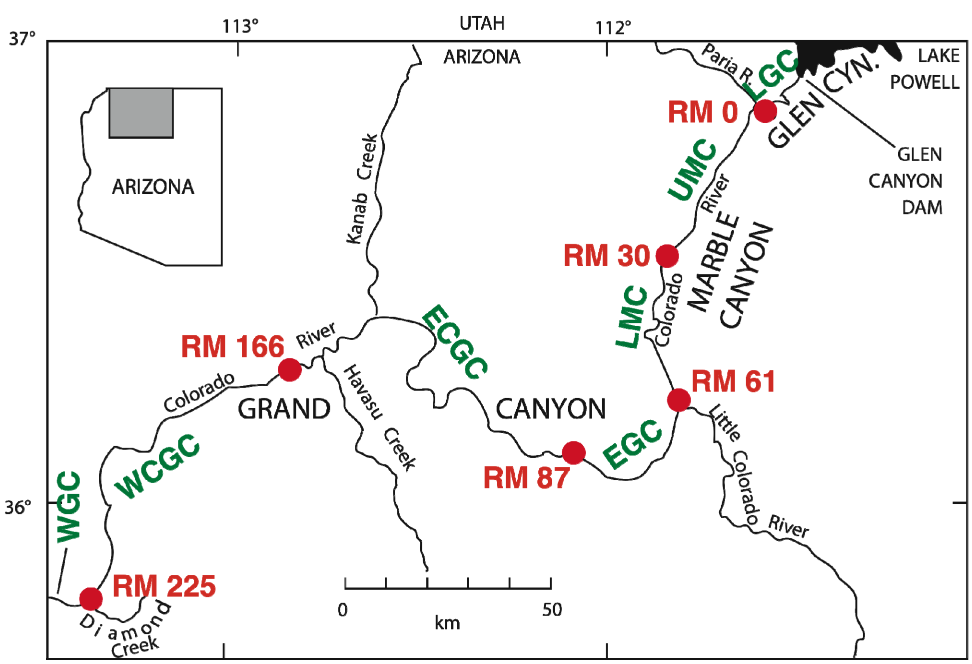

Figure 3. Map showing locations of study sites (red circles and labels) and reaches between the study sites (green labels); RM is abbreviation for river mile. RM 0 = Colorado River at Lees Ferry, Arizona, gaging station; RM 30 = River-mile 30 sediment station; RM 61 = former Colorado River above Little Colorado River near Desert View, Arizona, gaging station; RM 87 = Colorado River near Grand Canyon, Arizona, gaging station; RM 166 = former Colorado River above National Canyon near Supai, Arizona, gaging station; and RM 225 = Colorado River above Diamond Creek near Peach Springs, Arizona, gaging station. LGC = lower Glen Canyon; UMC = upper Marble Canyon; LMC = lower Marble Canyon; EGC = eastern Grand Canyon; ECGC = east-central Grand Canyon; WCGC = west-central Grand Canyon; and WGC = western Grand Canyon.

62, and the Hualapai Indian Reservation borders the Colorado River between river miles 165 and 273. The six study sites described above divide the Colorado River into seven study reaches:

(1) lower Glen Canyon (between Glen Canyon Dam and river mile 0),
(2) upper Marble Canyon (between river miles 0 and 30),
(3) lower Marble Canyon (between river miles 30 and 61),
(4) eastern Grand Canyon (between river miles 61 and 87),
(5) east-central Grand Canyon (between river miles 87 and 166),
(6) west-central Grand Canyon (between river miles 166 and 225), and
(7) western Grand Canyon (between river miles 225 and 277).

These study reaches were chosen for sediment-budgeting purposes; the study sites bounding these reaches were chosen on the basis of (1) locations of key sediment-supplying tributaries, (2) locations of existing or former USGS gaging stations, and (3) locations where substantial historical pre-dam and post-dam sediment-transport data have been collected by the USGS and provide context (Howard, 1947; Topping and others, 2000a).

The closure of Glen Canyon Dam in March 1963 cut off the upstream supply of sediment to the Colorado River (U.S. Department of the Interior, 1995; Topping and others, 2000a; Wright and others, 2005, 2008). The only suppliers of sand to lower Glen Canyon are now the small tributaries that enter the Colorado River below Glen Canyon Dam (Webb and others, 2000; 2001-2009 USGS Glen and Marble Canyons lesser tributary stage and sediment-transport data). The present suppliers of sand to the Colorado River in Marble and Grand Canyons are now, in decreasing order of importance, the Paria River (enters the Colorado River at river mile 1), the Little Colorado River (enters the Colorado River near river mile 62), Kanab Creek (enters the Colorado near river mile 143), Havasu Creek (enters the Colorado River near river mile 157), the small tributaries that enter the Colorado River between river miles 1 and 17, and finally all of the other small tributaries that enter the Colorado River between river miles 17 and 277 (Garrett and others, 1993; Melis and others, 1996; Rote and others, 1997; Topping, 1997; Topping and others, 2000a; Webb and others, 2000; 1963-1973 USGS sediment-transport data from the Kanab Creek near Fredonia, Arizona, gaging station (09403780); 2001-2009 USGS Glen and Marble Canyons lesser tributary stage and sediment-transport data). At the upstream boundary of Grand Canyon National Park (located at the mouth of the Paria River), the present sand supply to the Colorado River is almost entirely contributed by the Paria River and is only about 6 percent of the pre-dam supply (Topping and others, 2000a). By river mile 62, below the mouth of the Little Colorado River, the cumulative upstream supply of sand to the Colorado River is still only about 12 to 15 percent of the pre-dam supply (Topping and others, 2000a; Wright and others, 2005). Because of the relatively small sand contributions from the tributaries downstream from this point, the cumulative supply of sand to the Colorado River between Glen Canyon Dam and the head of Lake Mead reservoir is likely less than about 20 percent of the pre-dam supply. The Colorado River below river mile 236 is within the full-pool region of Lake Mead and is affected by the elevation of that reservoir (Smith and others, 1960).

Data

During the 1996 CFE, suspended-sediment data were collected at only four of the six study sites using only conventional depth- and point-integrating suspended-sediment samplers, and bed-sediment data were collected at only the River-mile 87 study site. During the 2004 CFE, the data-collection program vastly increased in scope and resolution, with suspended-sediment data collected at five of the six sites, using not only conventional samplers, but also at higher resolutions using ISCO pump samplers, Nortek acoustic-Doppler profilers, and Sequoia Scientific LISST laser-diffraction instruments (Melis and others, 2003; Topping and others, 2004, 2006a, 2006b, 2007b). Bed-sediment data were also collected at most of the study sites; no bed-sediment data were collected at the River-mile 0 study site because the bed at that site is almost entirely composed of cobbles and boulders. The data-collection program increased in scope again during the 2008 CFE, with suspended-sediment data collected at all six study sites and bed-sediment data collected at all but the River-mile 0 study site. During the 2004 CFE, a Lagrangian sampling program was conducted to sample suspended sediment in individual parcels of water between river miles 0 and 87 (Topping and others, 2006a). During the 2008 CFE, this effort was expanded and two Lagrangian sampling programs were conducted to sample suspended sediment in individual parcels of water between river miles 0 and 87 and between river miles 87 and 225. Suspended- and bed-sediment data collected during the 1996 CFE have been previously described and/or analyzed in Konieczki and others (1997), Rubin and others (1998), Rubin and Topping (2001, 2008), Smith (1999), Topping and others (1999, 2000a, 2000b, 2005, 2006a, 2007a, 2008, in press), and Hazel and others (2006). Suspended- and bed-sediment data collected during the 2004 CFE have been previously described and analyzed in Topping and others (2006a). An inventory of the suspended- and bed-sediment data collected during each CFE and analyzed in this report is provided in table 1.

At each study site, all suspended- and bed-sediment samples in this study were collected using standard USGS methods (described in Edwards and Glysson, 1999; Nolan and others, 2005). At most of the study sites, velocity-weighted suspended-sediment data were collected using either the Equal Depth Increment (EDI) or Equal Width Increment (EWI) methods. Point suspended-sediment samples were also collected at some of the study sites during the 1996 CFE. The suspended-sediment samplers used were: the P-61 and P-61-A1 point-integrating samplers (described in Edwards and Glysson, 1999; Federal Interagency Sedimentation Project, [n.d.]a), standard rigid-container D-77 depth-integrating samplers (described in Edwards and Glysson, 1999), D-77-bag-type depth-integrating samplers[5] (described in Szalona, 1982; Wilde and others, 1998), and D-96 and D-96-A1 depth-integrating samplers (described in Davis, 2001; Federal Interagency Sedimentation Project, 2003, [n.d.]b, [n.d.]c). Bed-sediment samplers used were: BM-54 bed-material samplers (described in Federal Interagency Sedimentation Project, 1958a; Edwards and Glysson, 1999) and pipe dredges. Description of the ISCO 6712 automatic pump samplers used in this study is provided in Topping and others (2006b). Data collected by the automatic pump samplers were calibrated using the suspended-sediment data collected in the EDI or EWI measurement cross-sections. These calibrations were performed for the following size classes of sediment: silt and clay, total sand, and each 1/4-ϕ size class of sand between 0.0625 mm and 0.25 mm to allow for computation of the median grain size of the suspended sand. Suspended sediment becomes more uniformly distributed between the pump intake and the middle of the channel as Rouse number decreases. To correct for this effect of increased cross-sectional mixing of the coarser sediment size classes in suspension with increased discharge, the calibrations for the data in the total sand and 1/4-ϕ size classes coarser than about 0.088 to 0.125 mm included discharge weighting. Methods for processing the acoustic-Doppler-profiler data for suspended-sand concentration, suspended-sand median grain size, and suspended-silt-and-clay concentration are described in Topping and others (2007b). More complete details on the methods for instrument

[5] The configuration of the D-77-bag-type depth-integrating suspended-sediment sampler varies slightly between its design in Szalona (1992) and its description in Wilde and others (1998). The configuration of this sampler used in this study during the 2004 and 2008 CFEs is that depicted in figure 2-1*D* in Wilde and others (1998) with the bottle-hole configuration depicted in figure 2-2*A* in Wilde and others (1998).

calibration, data processing, and error analysis for the automatic pump samplers and acoustic-Doppler profilers are to be published in a forthcoming USGS report.

Lagrangian sampling programs were conducted during the 2004 and 2008 CFEs to track the changes in suspended sediment in individual parcels of water as they traveled downstream through Marble and Grand Canyons. Thus, the Lagrangian reference frame used in these sampling programs traveled downstream at the mean velocity of the water. Analyses of the data collected during these sampling programs allowed determination of longitudinal patterns in:

(1) reach-scale sand erosion and deposition,
(2) reach-averaged suspended-sand median grain size,
(3) reach-scale silt and clay erosion and deposition,
(4) reach-averaged median grain size of the bed sand through use of Rubin and Topping's (2001, 2008) parameter β,
(5) reach-averaged area of the bed covered by sand through use of a modified form of Rubin and Topping's (2001, 2008) parameter β,
(6) reach-by-reach sand enrichment (by reach-averaged bed-sand median grain size and area) before each CFE, and
(7) reach-by-reach silt and clay enrichment before each CFE.

Identical sample-collection methods, but different suspended-sediment samplers, were used during the 2004 and 2008 Lagrangian sampling programs. During each sampling program, the suspended sediment in an individual parcel of water was sampled episodically by the collection of three sequential back-to-back, single-vertical, depth-integrated samples in the middle of the channel. Because rapids could not be run safely at night, breaks in the sampling program occurred resulting in different parcels of water being sampled on different days. These camping breaks resulted in backward steps in the Lagrangian reference frame between the different parcels of water. The average spacing between the sampling stations in the 2004 and 2008 Lagrangian sampling programs between river miles 0 and 87 was approximately 2.5 river miles; where possible, identical sampling stations were occupied during each of these programs. The average spacing between the sampling stations in the added second 2008 Lagrangian sampling program between river miles 87 and 225 was approximately 4 river miles. During the 2004 Lagrangian sampling program, data were collected using a P-61-A1 point-integrating suspended-sediment sampler operated in the upward depth-integrating mode. Because of the mechanical and electrical complexity of this sampler, it was difficult to keep the sampler operational during the 2004 sampling program; the first P-61-A1 sampler broke after sampling at river mile 24, and the backup P-61-A1 sampler broke after sampling at river mile 85. Thus, the simpler D-96-A1 depth-integrating suspended-sediment sampler was used to collect data during both 2008 Lagrangian sampling programs.

During the 2004 CFE, one Lagrangian sampling program was conducted between river miles 0 and 87. Travel times for the parcels of water through Marble and Grand Canyons were estimated based on the dye studies of Graf (1995, 1997) and Konieczki and others (1997), and the well-calibrated step-backwater model of Magirl and others (2008). On the first day of high, steady discharge during the 2004 CFE, this program sampled the suspended sediment in one parcel of water between river miles 0 and 52; and, on the second day of high, steady discharge, this program sampled the suspended sediment in a second parcel of water between river miles 52 and 85 (where the backup P-61-A1 suspended-sediment sampler ultimately broke). Owing to the differences in the velocity of discharge waves (that is, flood waves) and water based on physical laws (mostly conservation of mass), a flood wave travels much faster than the does the water in the Colorado River in Marble and Grand Canyons (Wiele, 1996; Wiele and Smith, 1996; Griffin and Wiele, 1996; Wiele and Griffin, 1998; Wiele and Torizzo, 2003). For example, during the 2008 CFE, the first 208 Lagrangian sampling program left the River-mile 0 study site just before the beginning of

Table 1. Inventory of suspended- and bed-sediment data collected during the three CFEs and analyzed in this report.

River-mile 0 study site (09380000, Colorado River at Lees Ferry, Arizona, gaging station)

Suspended-sediment data collected during the 1996 CFE

During March 26 through April 6, 1996, a total of 5 five-vertical Equal Discharge Increment (EDI) measurements were made from the cableway using a standard rigid-container D-77 depth-integrating sampler; of these 5 measurements, only 2 were made during the high, steady-discharge part of the CFE hydrograph.

Bed-sediment data collected during the 1996 CFE

None

Suspended-sediment data collected during the 2004 CFE

During November 19 through 28, 2004, a total of 28 five-vertical EDI measurements were made from the cableway using a D-96-A1 depth-integrating sampler. The sampling protocol was to make 4 EDI measurements per day from the start of the rising limb to the end of the receding limb of the CFE hydrograph. In addition, 4 EDI measurements were made during the two days before the rise of the CFE hydrograph, and 4 EDI measurements were made during the two days after the recession of the CFE.

Bed-sediment data collected during the 2004 CFE

None

Suspended-sediment data collected during the 2008 CFE

During March 4 through 10, 2008, a total of 24 five-vertical EDI measurements were made from the cableway using a D-96-A1 depth-integrating sampler. The sampling protocol was to make 4 EDI measurements per day from the start of the rising limb to the end of the receding limb of the CFE hydrograph. In addition, 2 EDI measurements were made during the day before the rise of the CFE hydrograph, and 2 EDI measurements were made during the day after the recession of the CFE.

Bed-sediment data collected during the 2008 CFE

None

River-mile 30 study site (River-mile 30 sediment station)

Suspended-sediment data collected during the 1996 CFE

None, study site not yet established

Bed-sediment data collected during the 1996 CFE

None, study site not yet established

Suspended-sediment data collected during the 2004 CFE

During November 18 through 30, 2004, a total of 38 five-vertical Equal Width Increment (EWI) measurements were made using a D-77-bag-type depth-integrating sampler deployed from a boat positioned under the tagline. The sampling protocol was to make 4 EWI measurements per day from the start of the rising limb to the end of the receding limb of the CFE hydrograph. In addition, 4 EWI measurements were made during the three days before the rise of the CFE hydrograph, and 14 EWI measurements were made during the five days after the recession of the CFE.

Table 1. Inventory of suspended- and bed-sediment data collected during the three CFEs and analyzed in this report.—Continued

During November 18 through 30, 2004, a total of 128 samples were collected using ISCO 6712 automatic pump samplers. From the start of the rising limb to the end of receding limb of the CFE hydrograph, these samples were collected every hour.

During November 18 through 30, 2004, a total of 1,162 suspended-sediment measurements were made using a Nortek 1MHz EasyQ sideways-looking acoustic-Doppler profiler. These measurements were made every 15 minutes, and processed for suspended-sand concentration and suspended-silt-and-clay concentration.

Bed-sediment data collected during the 2004 CFE

During November 19 through 30, 2004, a total of 17 bed-sediment measurements were made using a pipe dredge deployed from a boat positioned under the tagline. Each of these 17 measurements consisted of samples collected at the 3 middle of 5 equally spaced stations in the cross-section under the tagline (these 5 stations were the centroids of each EWI cell). Only 1 measurement during this period consisted of samples at 2 of these 3 stations. The leftmost and rightmost of the 5 stations were not sampled because of the presence of large boulders and colluvium on the bed on the sides of the cross-section. The sampling protocol was to make 2 of these measurements per day from the start of the rising limb through the end of the receding limb of the CFE hydrograph. In addition, 1 measurement was made per day during the two days before the rise of the CFE hydrograph, and 1 measurement was made per day during the five days after the recession of the CFE.

Suspended-sediment data collected during the 2008 CFE

During March 3 through 11, 2008, a total of 29 five-vertical EWI measurements were made using a D-96-A1 depth-integrating sampler and a total of 29 five-vertical EWI measurements were made using a D-77-bag-type depth-integrating sampler deployed from a boat positioned under the tagline. Measurements were made with these two samplers in a sequential back-to-back fashion. These back-to-back sample pairs were used with other back-to-back D-96-A1, D-77-bag-type sample pairs collected at this study site between February 22, 2007, and January 26, 2008, to develop bias-correction factors for suspended-sediment data collected previously at this study site with the non-isokinetic D-77-bag-type sampler (for example, the EWI measurements made at this study site during the 2004 CFE). The sampling protocol was to make 4 EWI measurements with each sampler per day from the start of the rising limb to the end of the receding limb of the CFE hydrograph. In addition, 3 EWI measurements were made with each sampler during the two days before the rise of the CFE hydrograph, and 5 EWI measurements were made with each sampler during the three days after the recession of the CFE.

During March 3 through 11, 2008, a total of 153 samples were collected using ISCO 6712 automatic pump samplers. From the start of the rising limb to the end of receding limb of the CFE hydrograph, these samples were collected every hour. From 1100 on March 5 through 0600 on March 10, the pump intake-tube mount was broken, and the intake tubes were loose in the current. This made the suspended-sand data collected by the pumps during 1100 on March 5 through 0600 on March 10 unusable; suspended-silt-and clay data collected by the pumps during this period were unaffected by this problem, however, and could still be used.

During March 3 through 11, 2008, a total of 940 suspended-sediment measurements were made using a Nortek 1MHz and 2MHz EasyQ sideways-looking acoustic-Doppler profiler (both of these instruments were used to make each of these 940 measurements). These measurements were made every 15 minutes, and processed for suspended-sand concentration, suspended-sand median grain size, and suspended-silt-and-clay concentration. During this period, an additional 20 measurements were made using either the 1MHz or 2MHz instrument, and were processed for only suspended-sand concentration, and suspended-silt-and-clay concentration. These additional one-instrument measurements were made while the other instrument was shut down for downloading.

Table 1. Inventory of suspended- and bed-sediment data collected during the three CFEs and analyzed in this report.—Continued

Bed-sediment data collected during the 2008 CFE

During March 3 through 11, 2008, a total of 15 bed-sediment measurements were made using a pipe dredge deployed from a boat positioned under the tagline. Each of these 15 measurements consisted of samples collected at the 3 middle of 5 equally spaced stations across the cross-section under the tagline (these 5 stations were the centroids of each EWI cell). The leftmost and rightmost of the 5 stations were not sampled because of the presence of large boulders and colluvium on the bed on the sides of the cross-section. The sampling protocol was to make 2 of these measurements per day from the start of the rising limb through the end of the receding limb of the CFE hydrograph. In addition, 3 measurements were made during the two days before the rise of the CFE hydrograph, and 1 measurement was made per day during the two days after the recession of the CFE.

River-mile 61 study site (09383100, former Colorado River above Little Colorado River near Desert View, Arizona, gaging station)

Suspended-sediment data collected during the 1996 CFE

During March 27 through April 2, 1996, a total of 3 five-vertical EDI measurements were made from the cableway using a standard rigid-container D-77 depth-integrating sampler; all 3 of these measurements were made during the high, steady-discharge part of the CFE hydrograph (data published in table 2 of Topping and others, 1999).

Bed-sediment data collected during the 1996 CFE

None

Suspended-sediment data collected during the 2004 CFE

During November 19 through December 4, 2004, a total of 52 five-vertical EWI measurements were made using a D-77-bag-type depth-integrating sampler deployed from a boat positioned under the tagline (at the former location of the measurement cableway from which data were collected during the 1996 CFE). The sampling protocol was to make 4 EWI measurements per day from the start of the rising limb to the end of the receding limb of the CFE hydrograph. In addition, 2 EWI measurements were made per day during the two days before the rise of the CFE hydrograph and the seven days after the recession of the CFE, and 1 final EWI measurement was made on the eighth day after the recession of the CFE.

During November 19 through December 4, 2004, a total of 191 samples were collected using ISCO 6712 automatic pump samplers. From the start of the rising limb to the end of receding limb of the CFE hydrograph, these samples were collected at least every hour.

During November 19 through December 4, 2004, a total of 1,486 suspended-sediment measurements were made using a Nortek 1MHz EasyQ sideways-looking acoustic-Doppler profiler. These measurements were made every 15 minutes, and processed for suspended-sand concentration and suspended-silt-and-clay concentration.

Table 1. Inventory of suspended- and bed-sediment data collected during the three CFEs and analyzed in this report.—Continued

Bed-sediment data collected during the 2004 CFE
During November 19 through December 4, 2004, a total of 21 bed-sediment measurements were made using a pipe dredge deployed from a boat positioned under the tagline. Each of these 21 measurements consisted of samples collected at 5 equally spaced stations in the cross-section under the tagline (these 5 stations were the centroids of each EWI cell). At least 3 samples had to be collected among the 5 stations to constitute a measurement. The sampling protocol was to make 2 of these measurements per day from two days before the start of the rising limb through the end of the receding limb of the CFE hydrograph. In addition, 1 measurement was made per day during the three days after the recession of the CFE, and during December 3 and 4. It became easier to sample the sand and finer sediment on the bed after the start of the CFE, and samples at all 5 stations were collected beginning on November 22. Because of the predominance of gravel on the bed at the tagline cross-section before the CFE, samples were only collected at 3 or 4 of the 5 stations during November 19-21.
Suspended-sediment data collected during the 2008 CFE
During March 3 through 12, 2008, a total of 31 five-vertical EWI measurements were made using a D-96-A1 depth-integrating sampler and a total of 31 five-vertical EWI measurements were made using a D-77-bag-type depth-integrating sampler deployed from a boat positioned under the tagline. Measurements were made with these two samplers in a sequential back-to-back fashion. These back-to-back sample pairs were used with other back-to-back D-96-A1, D-77-bag-type sample pairs collected at this study site between January 12, 2003, and January 28, 2008, to develop bias-correction factors for suspended-sediment data collected previously at this study site with the non-isokinetic D-77-bag-type sampler (for example, the EWI measurements made at this study site during the 2004 CFE). The sampling protocol was to make 4 EWI measurements with each sampler per day from the start of the rising limb to the end of the receding limb of the CFE hydrograph. In addition, 3 EWI measurements were made with each sampler during the two days before the rise of the CFE hydrograph, and 8 EWI measurements were made with each sampler during the three days after the recession of the CFE.
During March 3 through 6, 2008, and during March 10 through 12, 2008, a total of 108 samples were collected using ISCO 6712 automatic pump samplers. During the rising limb and during the day after recession of the CFE hydrograph, these samples were collected every hour. From 1800 on March 6 through 1100 on March 10, the pump intake-tube mount was broken, and the intake tubes were pinched against a large rock. This made all data collected by the pumps during 1800 on March 6 through 1100 on March 10 unusable.
During March 3 through 12, 2008, a total of 855 suspended-sediment measurements were made using a Nortek 1MHz EasyQ and an OTT 2MHz SLD sideways-looking acoustic-Doppler profiler (both of these instruments were used to make each of these 855 measurements). These measurements were made every 15 minutes, and processed for suspended-sand concentration, suspended-sand median grain size, and suspended-silt-and-clay concentration. During this period, an additional 100 measurements were made using either the 1MHz or 2MHz instrument, and were processed for only suspended-sand concentration and suspended-silt-and-clay concentration. Some of these additional one-instrument measurements were made while the other instrument was shut down for downloading. Others were made while the mount for the OTT 2MHz SLD was shut down for repairs. The mount for the OTT 2MHz SLD broke at 1800 on March 6 when the pump intake-tube mount was broken, and the 2MHz OTT SLD became lodged on a large rock. Data from the OTT 2MHz SLD could still be used, however, until 1045 on March 9, when the water receded below the elevation of the instrument lodged on the rock. The mount for the 2MHz OTT SLD was repaired and the instrument was placed back in service at 1045 on March 10. Subsequent modifications to this instrument mount should increase its strength during any future CFE.

Table 1. Inventory of suspended- and bed-sediment data collected during the three CFEs and analyzed in this report.—Continued

Bed-sediment data collected during the 2008 CFE

During March 3 through 11, 2008, a total of 13 bed-sediment measurements were made using a pipe dredge deployed from a boat positioned under the tagline. Each of these 13 measurements consisted of samples collected at 5 equally spaced stations in the cross-section under the tagline (these 5 stations were the centroids of each EWI cell). At least 3 samples had to be collected among the 5 stations to constitute a measurement. The sampling protocol was to make 2 of these measurements per day from two days before the start of the rising limb through the end of the receding limb of the CFE hydrograph. In addition, 1 measurement was made per day during the two days before the rising limb of the CFE, during the first day of the rising limb of the CFE, and during the two days after the recession of the CFE. As during the 2004 CFE, it became easier to sample the sand and finer sediment on the bed after the start of the CFE, and samples at all 5 stations were collected beginning on March 6. As during the 2004 CFE, because of the predominance of gravel on the bed at the tagline cross-section before the 2008 CFE, samples were only collected at 3 of the 5 stations during March 3 and at 4 of the 5 stations on March 5. Samples were collected at all 5 stations, however, on March 4.

River-mile 87 study site (09402500, Colorado River near Grand Canyon, Arizona, gaging station)

Suspended-sediment data collected during the 1996 CFE

During March 30 through April 2, 1996, a total of 4 five-vertical EDI measurements were made from the cableway using a standard rigid-container D-77 depth-integrating sampler; all 4 of these measurements were made during the high, steady-discharge part of the CFE hydrograph (data published in table 2 of Topping and others, 1999).

During March 27 through April 3, 1996, a total of 8 two-vertical EDI measurements were made from the cableway using a P-61 point-integrating suspended-sediment sampler deployed in the upward depth-integrating mode (verticals were located at stations at 190 and 290 feet on the cableway); the first 7 of these 8 measurements were made one per day during the high, steady-discharge part of the CFE hydrograph (inventory of data published in table 3 of Konieczki and others, 1997; data published in table 2 of Topping and others, 1999; data collected during the individual transits at each vertical in these EDI measurements published in Topping and others, in press; positions of the stations at 190 and 290 feet on the cableway indicated in figure 5 of Topping and others, 2007a, and figure 2B of Topping and others, in press).

On March 28, 30, and April 2, 1996, 3 point samples were collected at each of 6 elevations in the flow at two stations in the cross-section (at 190 and 290 feet on the cableway) using a P-61 point-integrating suspended-sediment sampler deployed from the cableway (inventory of data published in table 3 of Konieczki and others, 1997; data collected at each elevation in the verticals at the two stations published in Topping and others, in press).

Table 1. Inventory of suspended- and bed-sediment data collected during the three CFEs and analyzed in this report.—Continued

Bed-sediment data collected during the 1996 CFE
During March 26 through April 3, 1996, a total of 8 bed-sediment measurements were made using a BM-54 sampler deployed from the cableway (data published in table 1 of Topping and others, 1999). Each of these 8 measurements consisted of samples collected at 5 equally spaced stations in the cross-section under the cableway (at least 3 samples had to be collected among the 5 stations to constitute a measurement). Sampling proved difficult during the 1996 CFE, and only three of the 8 measurements consisted of samples collected at all 5 stations. The sampling protocol was to make 1 of these measurements per day from the day before the rising limb through the first day of the receding limb of the CFE hydrograph. Insufficient samples to constitute a full measurement were collected on March 30 (that is, only two samples were collected among the 5 stations on this day). The BM-54 sampler broke after the collection of samples at the leftmost and rightmost of the 5 stations on March 31; a third station in the middle of the cross-section was sampled on this day using a pipe dredge. The BM-54 sampler was fixed prior to sampling on April 1.
Suspended-sediment data collected during the 2004 CFE
During November 20 through 30, 2004, a total of 31 five-vertical EDI measurements were made from the cableway using either a D-96 or a D-96-A1 depth-integrating sampler. The sampling protocol was to make 4 EDI measurements per day from the start of the rising limb to the end of the receding limb of the CFE hydrograph (only 3 EDI measurements were actually made during the first day of high, steady discharge, however). In addition, 4 EDI measurements were made during the two days before the rise of the CFE hydrograph, and 2 EDI measurements were made per day during the four days after the recession of the CFE.
During November 20 through 30, 2004, a total of 163 samples were collected using an ISCO 6712 automatic pump sampler. From the day before the start of the rising limb through the day after the end of receding limb of the CFE hydrograph, these samples were collected every hour.
During November 20 through 30, 2004, a total of 713 suspended-sediment measurements were made using Nortek 600kHz Aquadopp, 1MHz EasyQ, and 2MHz EasyQ sideways-looking acoustic-Doppler profilers (all three instruments were used to make each of these 713 measurements. These measurements were made every 15 minutes, and processed for suspended-sand concentration, suspended-sand median grain size, and suspended-silt-and-clay concentration. During this period, an additional 217 measurements were made using only two of the instruments, and were also processed for suspended-sand concentration, suspended-sand median grain size, and suspended-silt-and-clay concentration. During this period, an additional 113 measurements were made with only one of the instruments, and were processed for only suspended-sand concentration and suspended-silt-and-clay concentration. The measurements made with less than all 3 instruments arose because each instrument was episodically shut down for downloading.
Bed-sediment data collected during the 2004 CFE
During November 20 through 30, 2004, a total of 20 bed-sediment measurements were made using a BM-54 sampler deployed from the cableway. Each of these 20 measurements consisted of samples collected at 5 equally spaced stations in the cross-section under the cableway (at least 3 samples had to be collected among the 5 stations to constitute a measurement). Only three of these measurements consisted of samples collected at less than all 5 stations. The sampling protocol was to make 2 of these measurements per day from the start of the rising limb through the end of the receding limb of the CFE hydrograph. In addition, 1 measurement was made per day during the two days before the rise of the CFE hydrograph, and 2 measurements were made per day during the four days after the recession of the CFE.

Table 1. Inventory of suspended- and bed-sediment data collected during the three CFEs and analyzed in this report.—Continued

Suspended-sediment data collected during the 2008 CFE

During March 4 through 12, 2008, a total of 28 five-vertical and 1 four-vertical EDI measurements were made from the cableway using either a D-96 or a D-96-A1 depth-integrating sampler. The sampling protocol was to make 4 EDI measurements per day from the start of the rising limb to the end of the receding limb of the CFE hydrograph. In addition, 2 EDI measurements were made during the day before the rise of the CFE hydrograph (one of these was the four-vertical measurement), and 3 EDI measurements were made during the two days after the recession of the CFE.

During March 4 through 12, 2008, a total of 166 samples were collected using an ISCO 6712 automatic pump sampler. From the day before the start of the rising limb through the day after the end of receding limb of the CFE hydrograph, these samples were collected every hour.

During March 4 through 12, 2008, a total of 862 suspended-sediment measurements were made using Nortek 600kHz Aquadopp, 1MHz EasyQ, and 2MHz EasyQ sideways-looking acoustic-Doppler profilers (all three instruments were used to make each of these 862 measurements). These measurements were made every 15 minutes, and processed for suspended-sand concentration, suspended-sand median grain size, and suspended-silt-and-clay concentration. During this period, only an additional 2 measurements were made with only one of the instruments, and were processed for only suspended-sand concentration and suspended-silt-and-clay concentration. The 2 measurements made with less than all 3 instruments arose because each instrument was episodically shut down for downloading (the instruments were downloaded much less frequently at this study site than during the 2004 CFE).

Bed-sediment data collected during the 2008 CFE

During March 4 through 12, 2008, a total of 15 bed-sediment measurements were made using a BM-54 sampler deployed from the cableway. Each of these 15 measurements consisted of samples collected at 5 equally spaced stations in the cross-section under the cableway (at least 3 samples had to be collected among the 5 stations to constitute a measurement). Only one of these measurements consisted of samples collected at less than all 5 stations. The sampling protocol was to make 2 of these measurements per day from the start of the rising limb through the end of the receding limb of the CFE hydrograph (only 1 measurement was actually made during the last day of the recession). In addition, 1 measurement was made the day before the rise of the CFE hydrograph, and 1 measurement was made per day during the two days after the recession of the CFE.

River-mile 166 study site (09404120, former Colorado River above National Canyon near Supai, Arizona, gaging station)

Suspended-sediment data collected during the 1996 CFE

On March 28 and 29, 1996, point samples were collected at 7 elevations in the flow at 10 stations in the cross-section using a P-61 point-integrating suspended-sediment sampler deployed from the cableway (at stations at 175, 195, 210, 230, 245, 260, 275, 290, 310, and 325 feet on the cableway). On March 29, 1996, an additional depth-integrated sample was collected using a P-61 sampler at the station at 160 feet on the cableway. On each day during March 30 through April 2, 1996, point samples were collected at 7 elevations in the flow at 11 stations in the cross-section (at stations at 160, 175, 195, 210, 230, 245, 260, 275, 290, 310, and 325 feet on the cableway) using a P-61 point-integrating suspended-sediment sampler deployed from the cableway. On these 4 days, additional depth-integrated samples were collected using a P-61 sampler at the stations at 145 and 340 feet on the cableway. All samples were analyzed for suspended-sand concentration and suspended-silt-and-clay concentration (data published in table 5 of Konieczki and others, 1997); grain-size distributions of the suspended sand were analyzed for only those samples collected at stations 245 and 325 feet (cross-section averages of these data published in table 2 of Topping and others, 1999).

Table 1. Inventory of suspended- and bed-sediment data collected during the three CFEs and analyzed in this report.—Continued

Bed-sediment data collected during the 1996 CFE

None

Suspended-sediment data collected during the 2004 CFE

None

Bed-sediment data collected during the 2004 CFE

None

Suspended-sediment data collected during the 2008 CFE

During March 5 through 13, 2008, a total of 29 five-vertical EWI measurements were made using a D-96-A1 depth-integrating sampler deployed from a boat positioned under the tagline (at the former location of the measurement cableway from which data were collected during the 1996 CFE). The sampling protocol was to make 4 EWI measurements per day from the start of the rising limb to the end of the receding limb of the CFE hydrograph. In addition, 3 EWI measurements were made during the two days before the rise of the CFE hydrograph, and 6 EWI measurements were made during the three days after the recession of the CFE.

During March 6 through 11, 2008, a total of 105 samples were collected using an ISCO 6712 automatic pump sampler. From the day before the start of the rising limb through the day after the end of receding limb of the CFE hydrograph, these samples were collected every hour (except from 1200 on March 9 through 1200 on March 10, when the pump sampler was inadvertently not launched).

During March 5 through 13, 2008, a total of 943 suspended-sediment measurements were made using a Nortek 1MHz EasyQ and an OTT 2MHz SLD sideways-looking acoustic-Doppler profiler (both of these instruments were used to make each of these 943 measurements). These measurements were made every 15 minutes, and processed for suspended-sand concentration, suspended-sand median grain size, and suspended-silt-and-clay concentration. During this period, an additional 16 measurements were made using either the 1MHz or 2MHz instrument, and were processed for only suspended-sand concentration and suspended-silt-and-clay concentration. These additional one-instrument measurements were made while the other instrument was either shut down for downloading or for repairs to its mount. Both of the instruments rotated on their mounts during the CFE, and the data had to be adjusted to compensate for this rotation. Both mounts were repaired on March 13. Subsequent modifications to these instrument mounts should prevent this rotation in any future CFE.

Bed-sediment data collected during the 2008 CFE

During March 5 through 13, 2008, a total of 10 bed-sediment measurements were made using a pipe dredge deployed from a boat positioned under the tagline. Each of these 10 measurements consisted of samples collected at the 3 middle of 5 equally spaced stations across the cross-section under the tagline (these 5 stations were the centroids of each EWI cell). The leftmost and rightmost of the 5 stations were not sampled because of the presence of large boulders and colluvium on the bed on the sides of the cross-section. The sampling protocol was to make 2 of these measurements per day during the first two days of high, steady discharge during the CFE hydrograph. Only 1 measurement per day was made per day during March 5, 6, 9-11, and 13. Despite repeated efforts to sample all 3 stations, a sample could only be collected at the station in the middle of the river on March 5 because the bed at the tagline cross-section was composed mostly of gravel before the rising limb of the CFE. Despite the predominance of gravel on the bed, samples at all 3 stations were collected during 7 of the 10 measurements, and samples at 2 of the 3 stations were collected during 2 of the 10 measurements.

Table 1. Inventory of suspended- and bed-sediment data collected during the three CFEs and analyzed in this report.—Continued

River-mile 225 study site (09404200, Colorado River above Diamond Creek near Peach Springs, Arizona, gaging station)

Suspended-sediment data collected during the 1996 CFE

None

Bed-sediment data collected during the 1996 CFE

None

Suspended-sediment data collected during the 2004 CFE

During November 21 through 30, 2004, a total of 28 five-vertical EDI measurements were made from the cableway using either a D-96 or a D-96-A1 depth-integrating sampler. The sampling protocol was to make 4 EDI measurements per day from the second day of the rising limb to the end of the receding limb of the CFE hydrograph. In addition, 3 EDI measurements were made during the two days before the rise of the CFE hydrograph, and 7 EDI measurements were made during the four days after the recession of the CFE.

During November 21 through 30, 2004, a total of 154 samples were collected using an ISCO 6712 automatic pump sampler. From the day of the start of the rising limb through the day after the end of receding limb of the CFE hydrograph, these samples were collected every hour.

During November 21 through 30, 2004, a total of 1,056 suspended-sediment measurements were made using a Nortek 1MHz sideways-looking acoustic-Doppler profiler. These measurements were made every 15 minutes, and processed for suspended-sand concentration and suspended-silt-and-clay concentration.

Bed-sediment data collected during the 2004 CFE

During November 21 through December 1, 2004, a total of 18 bed-sediment measurements were made using a BM-54 sampler deployed from the cableway. Each of these 18 measurements consisted of samples collected at 10 equally spaced stations in the cross-section under the cableway (at least 3 samples had to be collected among the 10 stations to constitute a measurement). Typically, samples could be collected at only 5 of the 10 stations. The sampling protocol was to make 2 of these measurements per day from the start of the rising limb through the end of the receding limb of the CFE hydrograph. In addition, 1 measurement was made per day during the two days before the rise of the CFE hydrograph, and 7 measurements were made during the four days after the recession of the CFE.

Suspended-sediment data collected during the 2008 CFE

During March 5 through 13, 2008, a total of 28 five-vertical EDI measurements were made from the cableway using a D-96 depth-integrating sampler. The sampling protocol was to make 4 EDI measurements per day from the second day of the rising limb to the end of the receding limb of the CFE hydrograph. In addition, 2 EDI measurements were made during the day before the rise of the CFE hydrograph, 2 EDI measurements were made during the first day of the rising limb of the CFE hydrograph, and 2 EDI measurements were made during the two days after the recession of the CFE.

Table 1. Inventory of suspended- and bed-sediment data collected during the three CFEs and analyzed in this report.—Continued

During March 5 through 13, 2008, a total of 163 samples were collected using an ISCO 6712 automatic pump sampler. From the day before the start of the rising limb through the day after the end of receding limb of the CFE hydrograph, these samples were collected every hour.
During March 5 through 13, 2008, a total of 864 suspended-sediment measurements were made using a Nortek 1MHz and 2MHz EasyQ sideways-looking acoustic-Doppler profiler (both of these instruments were used to make each of these 864 measurements). These measurements were made every 15 minutes, and processed for suspended-sand concentration, suspended-sand median grain size, and suspended-silt-and-clay concentration.
Bed-sediment data collected during the 2008 CFE
During March 5 through 13, 2008, a total of 15 bed-sediment measurements were made using a BM-54 sampler deployed from the cableway. Each of these 15 measurements consisted of samples collected at 5 equally spaced stations in the cross-section under the cableway (at least 3 samples had to be collected among the 5 stations to constitute a measurement). Of these 15 measurements, 11 consisted of samples collected at all 5 stations; the remaining 4 of these 15 measurements consisted of samples collected at 4 of the 5 stations. The sampling protocol was to make 2 of these measurements per day from the start of the rising limb through the end of the receding limb of the CFE hydrograph. In addition, 1 measurement was made per during the one day before the rise of the CFE hydrograph, and during the two days after the recession of the CFE.
2004 Lagrangian sampling program
During November 22 and 23, 2004, 3 replicate single-vertical depth-integrated samples were collected at a total of 31 sampling stations in the middle of the channel between river miles 0 and 85 by one field crew. These samples were collected using a P-61-A1 point-integrating sampler operated in the upward depth-integrating mode deployed from a boat. Two parcels of water were sampled in a Lagrangian reference frame in this sampling program.
2008 Lagrangian sampling programs
During March 6 through 9, 2008, 3 replicate single-vertical depth-integrated samples were collected at a total of 67 sampling stations in the middle of the channel between river miles 0 and 225 by two field crews (one sampling between river miles 0 and 87 on March 6 and 7; one sampling between river miles 87 and 225 on March 7 through 9). These samples were collected using D-96-A1 depth-integrating samplers deployed from two boats. Five parcels of water were sampled in a Lagrangian reference frame in these sampling programs.

high, steady discharge and passed the River-mile 30 study site approximately 3 hours after the high, steady discharge reached that location. On the second day of sampling, after taking an 11-hour break in camp at river mile 52, this sampling program passed the River-mile 61 study site approximately 19.3 hours after the high, steady discharge arrived at that location and concluded at the River-mile 87 study site approximately 22.2 hours after the high, steady discharge arrived at that location.

All suspended-sediment data collected in this study were processed for suspended-sediment concentration using standard USGS methods, with sand-sized material being separated from silt and clay-sized material by wet sieving using a 0.0625-mm stainless steel sieve (Guy, 1969; Knott and others, 1992, 1993). For the 1996 data, grain-size distributions of the material retained on this sieve were either measured at 1/4-ϕ increments through use of a visual accumulation tube (Federal Interagency Sedimentation Project, 1957, 1958b) or measured at 1-ϕ increments by wet sieving[6]. The visual accumulation tube was calibrated to give results identical to those obtained by dry sieving. For the 2004 and 2008 data, grain-size distributions of the material retained on the 0.0625-mm sieve were measured at 1/4-ϕ increments through use of a Beckman Coulter LS-100Q Laser Diffraction Particle Size Analyzer calibrated using dry sieving. Wet sieving results in some silt and clay adhering to the sand retained on the 0.0625 mm sieve. This effect has been observed using electron microscopy (Gordon and others, 2001) and has been observed in our laboratory through comparison of results from wet and dry sieving. In this study, the amount of silt and clay retained with the sand during wet sieving was measured using either the visual accumulation tube or the LS-100Q Laser Diffraction Particle Size Analyzer. Silt and clay concentrations were then computed by adding the amount of silt and clay retained on the 0.0625-mm sieve during the wet-sieving process to the weight of the sediment passing through this sieve. Sand concentrations were computed by subtracting the amount of the silt and clay retained on the 0.0625-mm sieve from the weight of the material retained on this sieve. This approach removes the negative bias in silt and clay concentration and the positive bias in sand concentration observed by Gordon and others (2001). The grain-size distributions of the 1996 bed-sediment data were measured through use of dry sieving at 1/2-ϕ increments; the grain-size distributions of the 2004 and 2008 bed-sediment data were measured through use of dry sieving at 1/4- ϕ increments. All dry sieving was conducted using standard 8-inch sieves in a Tyler RO-TAP sieve shaker.

Removal of Bias in Data Collected by D-77-Bag-Type Samplers

Recent measurements at multiple locations along the Colorado River in Grand Canyon indicate that, on average, the D-77-bag-type sampler oversamples suspended silt and clay by about 5 percent and oversamples suspended sand by about 20 percent relative to the D-96-A1 sampler. Among the various sand size classes, the oversampling is positively correlated with grain size. This oversampling arises because, although both the D-77-bag-type sampler and D-96-type samplers have been shown to sample isokinetically in flumes (Szalona, 1982; Davis, 2001), the D-77-bag-type sampler samples nonisokinetically, at a rate lower than the instantaneous flow velocity, when deployed in a river[7] (Sabol and others, 2010). This behavior likely arises from backpressure created by the bag unfolding too slowly within the sampler cavity (Pickering, 1983). To make suspended-sediment data collected by D-77-bag-type and D-96-A1 samplers equivalent, bias-correction

[6] Only the EDI measurements made during the 1996 CFE using a D-77-bag-type depth-integrating sampler were processed for sand grain size using wet sieving.

[7] See Federal Interagency Sedimentation Project (1941) for analyses of the effect of nonisokinetic sampling on measurements of suspended-sediment concentration for various size classes of sediment.

factors were therefore empirically determined for data collected using a D-77-bag-type sampler. These bias-correction factors were determined using sequential back-to-back samples collected with D-96-A1 and D-77-bag-type samplers at the River-mile 30, 61, 87, and 225 study sites from 2003 through 2008. The details of these sampler comparisons with the computed D-77 bias-correction factors for each of these study sites are to be published in a forthcoming USGS report. At each study site, the bias-correction factor for each size class was used to convert the suspended-sediment concentration measured by a D-77-bag-type sampler in that size class to be equivalent to that measured by a D-96-A1 sampler. For the purposes of this study, the bias in the median grain size of the suspended sand measured by a D-77-bag-type sampler was removed by first applying the appropriate bias-correction factor to the D-77-measured concentration of sand in each 1/4-ϕ size class and then computing the median grain size of the suspended sand. Because the bias in the data collected with a D-77-bag-type sampler is caused by the behavior of the bag, this sampling bias is not present in the data collected during the 1996 CFE with a standard rigid-container D-77 depth-integrating sampler.

Errors

In this study, errors have only been assigned to suspended-sediment data collected using standard depth- or point-integrating suspended-sediment samplers when deployed using the EDI, EWI, or point-sampling methods (samplers and methods described in Edwards and Glysson, 1999). Evaluation of the errors associated with the calibrated pump measurements and acoustic measurements of suspended-sediment concentration and grain size is the subject of ongoing research and is to be published in a forthcoming USGS report. The analyses to date suggest that the errors associated with these two approaches are only slightly larger than those associated with the standard EDI, EWI, or point-sample measurements (Topping and others, 2006b), but because these analyses are not yet finalized, no error from these approaches is assigned in this study.

Errors associated with the standard EDI, EWI, or point-sample measurements are divided into field and laboratory components, which are combined in quadrature. The field components of these errors consist of both time-averaging and spatial-averaging errors and are computed on the basis of Topping and others (in press). From Topping and others (in press), the 95-percent-confidence-interval field error in the EDI- or EWI-measured velocity-weighted suspended-sand concentration in a cross-section, in units of percent, is:

$$\pm 1.96\sqrt{\left(\frac{12.0}{n_{VERT}^{\;0.7}}\right)^2 + \left(\frac{15.4}{\sqrt{n_{TRANS}n_{VERT}}}\right)^2}\,\%, \tag{8}$$

the 95-percent-confidence-interval field error in the EDI- or EWI-measured velocity-weighted suspended-sand median grain size in a cross-section, in units of percent, is:

$$\pm 1.96\sqrt{\left(\frac{12.0}{n_{VERT}^{\;0.7}}\right)^2 + \left(\frac{2.5}{\sqrt{n_{TRANS}n_{VERT}}}\right)^2}\,\%, \tag{9}$$

and, the 95-percent-confidence-interval field error in the EDI- or EWI-measured velocity-weighted suspended-silt-and-clay concentration in a cross-section, in units of percent, is:

$$\pm 1.96\sqrt{\left(\frac{0}{{n_{VERT}}^{0.7}}\right)^2+\left(\frac{8.6}{\sqrt{n_{TRANS}n_{VERT}}}\right)^2}\,\%\,, \tag{10}$$

In equations 8 through 10, n_{VERT} is the number of verticals (that is, sampling stations in a cross-section) and n_{TRANS} is the number of transits at each vertical. In this usage, “one transit” is defined as the path a depth-integrating suspended-sediment sampler takes either from the water surface to the bed or from the bed to the water surface. Therefore, standard deployment of a depth-integrating sampler at a vertical, where the nozzle is open as the sampler is lowered to the bed and subsequently raised to the surface, consists of two transits. Because collection of point suspended-sediment samples involves greater time averaging than the collection of depth-integrated suspended-sediment samples, the 95-percent-confidence-interval field errors in point-sample-measured suspended-sand concentration, suspended-sand median grain size, and suspended-silt-and-clay concentration in a cross-section consist of only the first of the two terms in equations 8 through 10.

The laboratory components of these errors were computed on the basis of the performance of different USGS sediment laboratories and the performance of the USGS sediment laboratory at the USGS Grand Canyon Monitoring and Research Center in the USGS Branch of Quality Systems Sediment Laboratory Quality-Assurance Project (Gordon and Newland, 2000; Gordon and others, 2000). Most of the samples in this study were processed at the USGS sediment laboratory at the USGS Grand Canyon Monitoring and Research Center. Computations of the laboratory components of the errors were based on the 2008-2009 performance of nine different USGS laboratories in their analysis of 151 samples for sand concentration and silt and clay concentration. These computed errors were found to be consistent with those computed for only the USGS Grand Canyon Monitoring and Research Center sediment laboratory over the 2002-2009 span of its existence. For both sand concentration and silt and clay concentration, the laboratory processing errors decreased with increasing concentration. The 95-percent-confidence-interval laboratory-processing error in C_{SAND} used in this report, in units of percent, is:

$$\pm 69 C_{SAND}^{-0.5}\,\%\,, \tag{11}$$

and the 95-percent-confidence-interval laboratory processing error in silt and clay concentration ($C_{SILT\&CLAY}$) used in this report, in units of percent, is:

$$\pm 3.9 C_{SILT\&CLAY}^{-0.06}\,\%\,. \tag{12}$$

Units of concentration used for C_{SAND} and $C_{SILT\&CLAY}$ in equations 11 and 12 are in mg/L. In comparisons between dry sieving and laser-diffraction measurements, the 95-percent-confidence-interval laboratory processing error in sand median grain size was found to be approximately ±6 percent.

Antecedent Conditions for Each Controlled-Flood Experiment (CFE)

Brief Description of Sand-Budgeting Approach

Construction of meaningful sand budgets for reaches of the Colorado River downstream from Glen Canyon Dam requires an intensive data-collection effort. Large discharge-independent changes in suspended-sand concentration occur over short time scales, of less than one hour, in the Colorado River in Marble and Grand Canyons; these changes in concentration are coupled to changes in suspended-sand grain size and are driven by upstream changes in the sand supply associated with changes in bed-sand grain size (Topping and others, 2000a, 2000b, 2007a; Rubin and Topping, 2001, 2008). Because of these discharge-independent changes in suspended-sand concentration, suspended-sediment data have to be collected at a relatively high resolution (that is, at increments of less than an hour) to accurately compute sand loads in Colorado River (Topping and others, 2004, 2006b, 2007b). Such accurate loads are needed to compute meaningful sand budgets for reaches of the Colorado River downstream from Glen Canyon Dam. To collect suspended-sediment data at a sufficiently high resolution, ISCO automatic pump samplers, Sequoia Scientific LISST laser-diffraction instruments, and Nortek EasyQ acoustic-Doppler sideways looking profilers were installed at the River-mile 30, 61, 87, and 225 study sites in August 2002 (Melis and others, 2003; Topping and others, 2004, 2006b, 2007b). To provide information on the state of the sand budget in central Grand Canyon, this network was expanded to include the River-mile 166 study site through the installation of the first of two acoustic-Doppler sideways looking profilers in March 2007; an automatic pump sampler was also temporarily installed at this study site during the 2008 CFE. Sand loads and silt and clay loads were computed for the applicable study sites on the Colorado River for the periods leading up to and including each CFE using the highest resolution data available (typically 15-minute resolution for the 2004 and 2008 CFEs) and the standard USGS methods described in Porterfield (1972). Sand loads were increased by 5 percent at each study site to include bedload (after Rubin and others, 2001) and the load in the "unsampled zone" near the bed that is not sampled by depth-integrating samplers (fig. 1 in Edwards and Glysson, 1999) as estimated based on Topping and others (2007a).

In addition to accurate high-resolution sediment-transport data on the Colorado River, sand budgets for reaches of the Colorado River downstream from Glen Canyon Dam must also include accurate measurements and/or model estimates of the sand supplied to each reach by tributaries. Data collection in these tributaries is difficult because of (1) their remote, ephemeral, and flashy nature and (2) the potential of extremely high suspended-sand concentrations during floods; for example, one tributary, the Paria River, has some of the highest suspended-sand concentrations in the world when it is in flood (Beverage and Culbertson, 1964; Topping, 1997). Most of the uncertainty in the reach-scale sand budgets for the Colorado River currently arises from errors in computed tributary sand loads during floods. Fortunately, the two most important sand-supplying tributaries to the Colorado in Marble and Grand Canyons have a long history of sediment-transport data collection by the USGS. These tributaries are the Paria River, where sediment-transport data were first collected in October 1947, and the Little Colorado River, where sediment-transport data were first collected in July 1931. Substantial gaps in the sediment-transport data collected in these tributaries occurred in the 1970s through early 1990s. In response to the need for increased information on the sand delivery to the Colorado River from these tributaries to assess management strategies for Glen Canyon Dam, the USGS focused more-intensive data-collection activities on these two tributaries beginning in the late 1990s. The other sand-supplying tributary with substantial historical sediment-transport data is Kanab Creek, where sediment-transport data were first collected in December 1963.

To improve the real-time estimates of sand transport in the Paria River, Topping (1997) developed and tested a physically based sediment-transport model coupled to average geomorphic and sedimentologic conditions in the channel and floodplains of the Paria River. Support for this average modeling approach was provided in Rubin and Topping (2001), who showed that sand transport in the largely alluvial Paria River is essentially "flow regulated" with no systematic hysteresis in suspended-sand concentration caused by changes in the grain size of the bed sand during floods. Tests of this model using extensive data from 1947 through 1983 and from a period of four large floods in 1997 indicated that this model predicted sand loads within 20 percent of the measurements during most floods, and well within 20 percent during the 1997 floods. However, in subsequent tests against data collected during large floods in 2003 and 2004, it became clear that the differences in the model predictions and measurements of sand loads during individual floods could be substantial and biased. Therefore, an approach analogous to the "shifting-control method" used to compute discharge in rivers (described in Rantz and others, 1982) was developed to apply smoothed time-varying shifts to the model predictions of sand transport to increase the agreement between the model-predicted and measured sand transport. This is the approach used in this study to compute sand loads in the Paria River.

A slightly different approach is used to compute sand loads in the more complicated Little Colorado River. Most of the sand-transport data in the Little Colorado River is collected at a location within the nonalluvial bedrock gorge of this river. Unlike sand transport in the Paria River, sand transport in this nonalluvial river is controlled to a measurable degree by changes in the upstream supply of sand. Modeling efforts by the USGS to develop more accurate methods for computing real-time sand loads in the Little Colorado River are ongoing. Because these models are still incomplete, a shifting sand rating curve[8] approach was used in this study that weights the "elevation" of the sand rating curve within the "cloud" of sand-concentration data in discharge-concentration space by the number of measurements within that part of the cloud. Because the contributions of sand to the Colorado River from both Kanab and Havasu Creeks are much smaller than the sand contributions of the Paria and Little Colorado Rivers, estimates of the sand supplied by these other two large tributaries are included with the estimates of the sand supplied by the other small tributaries described in the next paragraph.

The other smaller tributaries, hereafter referred to as the "lesser tributaries," have only very limited sediment-transport data and are the most difficult parts of the sand budgeting to constrain. The first comprehensive sediment budget for the lesser tributaries to lower Glen and Marble Canyons was completed by the Bureau of Reclamation in the late 1950s as part of its planning activities for the construction of Marble Canyon Dam (unpublished memoranda from the Denver Technical Center files of the Bureau of Reclamation). During the late 1990s, a second sediment budget for these tributaries was completed by Webb and others (2000), albeit with large uncertainties owing to the small size of the available sediment-transport dataset. To rectify the large uncertainties associated with sand loads in the lesser tributaries, downward-looking Campbell Scientific SR-50 stage gages and sediment-sampling equipment were installed in 2001 on one key lesser tributary in lower Glen Canyon[9] and in 2000 (Schmidt and others, 2007; Griffiths and others, 2010) and 2001, at six locations on five lesser tributaries in Marble Canyon. Data collected in these tributaries suggest that the lesser tributaries in Marble Canyon between river miles 0 and 17 cumulatively supply, on average, about 10 percent of the sand supplied by the Paria River in a given year[10]. This small percentage arises, not because the concentrations of suspended sand are low, but because the durations of floods are much shorter and the peak discharges of floods in these tributaries are much smaller in these tributaries than for floods of comparable recurrence interval in the Paria River. These data also suggest that the amount of sand supplied by the tributaries

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[8] A sand rating curve relates the concentration of suspended sand to the discharge of water.

[9] This monitored tributary, Water Holes Canyon, makes up about 23 percent of the total lesser-tributary drainage area in this reach.

[10] The monitored lesser tributaries between river-miles 0 and 17 cumulatively make up 77 percent of the total drainage area of the lesser tributaries in this part of Marble Canyon.

downstream from about river mile 17 is nonzero, but very small[11]. From suspended-sediment samples collected between 2001 and 2009, the ratio of suspended sand to suspended silt and clay in floods in the lesser tributaries downstream from river mile 17 is about 1/5. Therefore, in this study:

(1) the sand loads in the lesser tributaries in lower Glen Canyon are estimated relative to the flood activity in the one tributary monitored in that reach,

(2) the sand loads in the lesser tributaries in upper Marble Canyon are estimated as 10 percent of the Paria sand load,

(3) the cumulative sand loads of the lesser tributaries in lower Marble Canyon are estimated to be approximately 20 percent of the measured increase in the silt and clay loads between the River-mile 30 and 61 study sites over time scales of years (this assumption is consistent with the integral constraint that changes in the silt and clay budget in long reaches must equal zero over longer time scales in the Colorado River),

(4) the timing of the sand inputs from the lesser tributaries in lower Marble Canyon is set equal to the timing of the largest increases in silt and clay load between the River-mile 30 and 61 study sites, and

(5) the sand loads of the lesser tributaries between each of the River-miles 61 and 87, 87 and 166, and 166 and 225 study sites are estimated by the same approach outlined in the two previous steps.

In the sand-budget computations in this study, uncertainties were applied that represent the largest potential persistent bias in the computed sand loads at each site on the Colorado, Paria, and Little Colorado Rivers. These uncertainties include the greatest likely persistent bias in both the discharge of water and the concentration of suspended sand. For example, at a given site, if the discharge of water were, on average, measured to be 3 percent high because of either instrumentation bias or cross-section effects, and the suspended-sand concentration were, on average, measured to be 2 percent high, this would result in the computed sand loads being, on average, 5 percent high. At some study sites, the uncertainties in the discharge of water and suspended-sand concentration are likely positively correlated, whereas, at other sites, these uncertainties are likely negatively correlated. Unfortunately, there is no way to know the real magnitudes or signs of the biases giving rise to these uncertainties because there is no independent measure of either the discharge of water or the concentration of suspended sand. Recent field measurements on the Colorado have indicated that EWI measurements at adjacent cross-section can systematically disagree by several percent or more over periods of years. Because no net aggradation or degradation on this scale can be occurring between these adjacent cross-sections, this difference cannot be real and must be included in an estimate of uncertainty. The uncertainty in the discharge of water in the Colorado River over months is likely at most several percent, as indicated by water balances conducted between the various study sites. The uncertainties associated with the sand loads in the tributaries are more poorly constrained than those associated with the sand loads in the Colorado River (Topping and others, 2000a). The best way to treat the uncertainties in the sand loads is therefore to (1) realize that they cannot be zero, (2) make every effort to reduce detected biases in the field, and (3) assign values to the uncertainties that are reasonable. The uncertainties chosen for the sand budgets in this study are, therefore, 5 percent for the sand loads at the study sites on the Colorado River[12], 10 percent for the sand loads in the Paria and Little Colorado Rivers[13], and 50 percent for the sand loads in the lesser tributaries[14], Kanab Creek, and Havasu Creek.

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[11] The monitored lesser tributaries between river-miles 17 and 61 cumulatively make up 39 percent of the total drainage area of the lesser tributaries in this part of Marble Canyon.

[12] This value is identical to the uncertainty used for the Colorado River data in Topping and others (2000a).

[13] This value is half of the uncertainty used for the Paria and Little Colorado River data in Topping and others (2000a).

Sand Enrichment in Each Reach Before the 2004 and 2008 CFEs

Because the 2004 and 2008 CFEs were very different, the sand-budget "accounting periods" antecedent to these two experiments were of different durations. In this usage, "accounting period" is defined as the period from the zero time at which sand budgeting begins until the beginning of the rising limb of a controlled flood. As described in Topping and others (2006a), the 2004 CFE was designed to test the hypothesis that a sufficiently large single-season input of sand from the Paria River could be retained in the channel of the Colorado River through reduced dam releases and then redistributed into sandbars during a relatively short-duration artificial flood released from Glen Canyon Dam. In essence, this experiment was a test of experimental option two suggested by Rubin and others (2002). Therefore, the accounting period antecedent to the 2004 CFE began at the beginning of the sediment-input season on July 1, 2004, (see definition of "sediment year" in Topping and others, 2000a) and extended until the start of the rising limb of the November 2004 controlled-flood release. The design of the 2008 CFE was different from the design of the 2004 CFE. Hence the accounting period antecedent to the 2008 CFE began upon recession of the 2004 CFE and extended until the start of the rising limb of the March 2008 controlled-flood release. Planning for the 2008 CFE started in response to the extremely large quantity of sand supplied by the Paria River in October 2006. During October 2006, a flood with a peak discharge of 5,200 ft^3/s on the Paria River was followed one week later by a flood with a peak discharge of 5,300 ft^3/s. A flood with a peak discharge in this range has a recurrence interval of about 7 years on the 1923-1996 Paria River annual-maximum or partial-duration flood series (Topping, 1997). Thus, two 7-year flood events occurred on the Paria River within about a week. These events together supplied about 1.3 million metric tons of sand to the Colorado River. Because other large sand inputs occurred from both the Paria and Little Colorado Rivers, and dam releases were relatively low between October 2006 and the controlled flood in March 2008, the 2008 CFE became a test of the degree of sandbar building that could occur in Marble and Grand Canyons given a much higher than average level of sand enrichment in the system. Because the antecedent conditions for the 2008 CFE are relatively rare, results from the 2008 CFE cannot provide guidance on the degree of sandbar building that could occur if controlled floods were conducted relatively frequently with more typical sand-enrichment conditions, as suggested in the conclusions of Topping and others (2006a). Because the first acoustic-Doppler profiler was not deployed at the River-mile 166 study site until March 2007, part way through the accounting period, the level of sand enrichment during the accounting period antecedent to the 2008 CFE could only be computed for the two reaches between the River-mile 87 and 225 study sites, the east-central and west-central Grand Canyon reaches, combined into a single reach.

The sand supply from the various sources and the sand export past the various study sites during the accounting periods antecedent to the 2004 and 2008 CFEs are provided in table 2. Sand enrichment in each reach during the accounting periods antecedent to the 2004 and 2008 CFEs is provided in table 3. No sand enrichment or depletion can be demonstrated in a reach when the propagated uncertainties are larger than the absolute value of the change in sand storage. Finally, it is important to note that the "sand enrichment" computed by this sand-budgeting approach does not include the "background" sand that was stored in each reach before the antecedent accounting periods. The same level of sand enrichment computed by this sand-budgeting approach may result

[14] Because of the almost infinitely greater resolution of the data available upon the completion of this report than was available in 2000, this value is considerably less than the factor of 3 uncertainty used for sand transport in the lesser tributaries in Topping and others (2000a).

Table 2. Sand supply and sand export during the accounting periods antecedent to the 2004 and 2008 CFEs.

Sand inputs from the following sources during the accounting periods	Antecedent 2004 CFE sand input with uncertainty during the accounting period (million metric tons)	Antecedent 2008 CFE sand input with uncertainty during the accounting period (million metric tons)
lower Glen Canyon tributaries	*Tributaries less active than before 2008 CFE, thus equating to less sand enrichment than before 2008 CFE*	*Tributaries more active than before 2004 CFE, thus equating to more sand enrichment than before 2004 CFE*
Paria River	0.617±0.062	3.350±0.335
upper Marble Canyon lesser tributaries	0.062±0.031*	0.335±0.168*
lower Marble Canyon lesser tributaries	0.044+0.022*	0.096±0.048*
Little Colorado River	0.180±0.018	3.021±0.302
eastern Grand Canyon lesser tributaries	0.037±0.019*	0.081±0.041*
combined east- and west-central Grand Canyon tributaries	0.102±0.051*	0.372±0.186*
Sand export past the following study sites during the accounting periods	**Antecedent 2004 CFE sand export with uncertainty during the accounting period (million metric tons)**	**Antecedent 2008 CFE sand export with uncertainty during the accounting period (million metric tons)**
River-mile 30	0.296±0.015	2.490±0.125
River-mile 61	0.226±0.011	2.051±0.103
River-mile 87	0.481±0.024	4.317±0.216
River-mile 225	0.427±0.021	3.586±0.179

*These values agree within the large error bars of the predictions of Webb and others (2000).

Table 3. Sand enrichment in each reach during the accounting periods antecedent to the 2004 and 2008 CFEs.

[Reaches without demonstrable change in sand storage (that is, propagated uncertainty is much greater than the absolute value of net change in sand storage) indicated by red type.]

Reach	Antecedent 2004 CFE sand enrichment in reach with propagated uncertainty during the accounting period (million metric tons)	Antecedent 2008 CFE sand enrichment in reach with propagated uncertainty during the accounting period (million metric tons)
lower Glen Canyon	Less than before 2008 CFE	More than before 2004 CFE
upper Marble Canyon	+0.383±0.108	+1.195±0.628
lower Marble Canyon	+0.114±0.048	+0.535±0.276
eastern Grand Canyon	-0.014±0.048	+0.836±0.662
combined east-central and west-central Grand Canyon	+0.156±0.096	+0.917±0.395

in very different suspended-sand concentrations and grain sizes during a controlled flood depending on both the grain size of the "enriching sand" and if the amount of sand in background storage is relatively small or large compared to the level of sand enrichment.

Estimation of the Relative Levels of Sand Enrichment Antecedent to the 1996, 2004, and 2008 CFEs

Unfortunately, during the period antecedent to the 1996 CFE, no sediment-transport monitoring program on the Colorado River existed, the sediment-transport monitoring program on the two major tributaries (that is, the Paria and Little Colorado Rivers) was less robust, and extremely few data existed on sediment-transport in the lesser tributaries. Therefore, a method alternative to that presented in the previous section must be used to compare the levels of tributary sand enrichment in the Colorado River antecedent to the 1996 CFE relative to those antecedent to the 2004 and 2008 CFEs. This simple alternative method uses (1) the same method as above for computing the sand supply from the Paria and Little Colorado Rivers during the year leading up to each CFE and (2) the sand-transport results from Topping and others (2000a) to evaluate whether it is likely that the dam releases during the year leading up to each CFE were likely to retain or export tributary-supplied sand in the Colorado River in Marble and Grand Canyons past the River-mile 87 study site. As shown in table 4, the year antecedent to the 1996 CFE had the conditions least likely to result in the accumulation of tributary-supplied sand in the Colorado River between the River-mile 0 and 87 study sites. This year was characterized by both the highest discharges and the lowest sand inputs from the two major tributaries. On the basis of sand-supply information alone, the year leading up to the 2008 CFE was the year most likely to result in the accumulation of tributary-supplied sand in the Colorado River in Marble Canyon and eastern Grand Canyon. On the basis of discharge alone, the year leading up to the 2004 CFE was only slightly more likely than the year leading up to the 2008 CFE to result in the accumulation of tributary-supplied sand in the Colorado River in Marble Canyon and eastern Grand Canyon. Therefore, these results, combined with the detailed sand-budgeting results in the previous section, suggest that (1) the 1996 CFE was likely the least tributary-sand-enriched of any of the three CFEs, (2) the 2008 CFE was by far the most tributary-sand-enriched of any of the three CFEs, and (3) the 2004 CFE was in the middle of

Table 4. Comparison of discharge and sand supply during the years leading up to each CFE.

[Conditions most likely to be conducive to sand accumulation in the Colorado River upstream from the River-mile 87 study site are shown in green, conditions least likely to be conducive to sand accumulation are shown in red.]

CFE	Median dam release during year leading up to controlled flood	Sand supply during year leading up to controlled flood	
		Paria River	Little Colorado River
1996	15,400 ft^3/s*	~0.38 million metric tons	~0.04 million metric tons
2004	10,500 ft^3/s**	~0.63 million metric tons	~0.19 million metric tons
2008	11,300 ft^3/s	~0.92 million metric tons	~1.12 million metric tons

* This discharge would result in either no accumulation of the tributary-supplied sand or net scour of sand already stored in the Colorado River during the year prior to the CFE (after Topping and others, 2000a).

** This discharge is low enough to be within the range in Topping and others (2000a) under which net sand accumulation is most likely to occur.

the three CFEs with respect to sand enrichment from tributaries, with the most tributary-sand-enriched reach being upper Marble Canyon. Note that the analysis in table 4 has no bearing on possible changes in background sand storage in the Colorado River occurring over the multi-year periods between the CFEs (for example, decreases in sand storage arising from possible long-term scour of sand from the Colorado River in Marble Canyon and eastern Grand Canyon).

Analysis

Data Collected at Each Study Site During Each CFE

Flood hydrographs, and the suspended-sediment and bed-sand data collected at each study site during each CFE are presented in figure 4. As first observed by Rubin and others (1998) during the 1996 CFE, and subsequently observed during the 2004 and 2008 CFEs, the general tendencies at all study sites during the high, steady discharge part of a CFE are:

(1) the suspended-silt-and-clay concentration decreases over time, indicating depletion of the upstream supply of silt and clay,
(2) the suspended-sand concentration decreases over time, indicating depletion of the upstream supply of sand,
(3) the grain-size distribution of the suspended sand coarsens over time as the upstream supply of sand becomes depleted,
(4) the grain-size distribution of the bed sand coarsens over time as the upstream supply of sand becomes depleted, and
(5) the fraction of the bed sand finer than about 0.125 mm[15] decreases over time as the upstream supply becomes depleted.

More analyses focused on comparing the behaviors of the suspended and bed sediment at each study site during all three CFEs, and at all study sites during each CFE are provided below.

Data collection increased substantially, both temporally and spatially, between the 1996 and 2004 CFEs, with further improvement in data resolution and quality between the 2004 and 2008 CFEs (fig. 4). During each subsequent CFE, substantial effort was made to increase data resolution and reduce error. For example, during the 1996 CFE, only 3 EDI measurements and no bed-sediment measurements were made at the River-mile 61 study site, whereas during the 2004 CFE, 52 EWI measurements, 191 pump samples, 1,486 single-frequency acoustic suspended-sediment measurements, and 21 five-station bed-sediment measurements were made at this study site. Because of the relatively large degree of sandbar scour in Marble Canyon during the 1996 CFE (Schmidt, 1999), the River-mile 30 study site was added before the 2004 CFE to improve spatial data resolution within Marble Canyon. To improve data resolution in the western part of Grand Canyon, the River-mile 225 study site was also added before the 2004 CFE, although the River-mile 166 study site was dropped, leading to a decrease in data resolution in the central part of Grand Canyon. The biggest single improvement between the 1996 and 2004 CFEs was the introduction of the use of single-frequency acoustics to collect 15-minute-resolution suspended-sediment data at the River-miles 30, 61, and 225 study sites and the use of three-frequency acoustics to collect 15-minute-resolution suspended-sediment data at the River-mile 87 study site.

During the 2008 CFE, data were collected at all study sites where data were collected during either the 1996 or 2004 CFEs, including the River-mile 166 study site. On the basis of the analysis of the errors associated with the use of depth-integrating samplers in Topping and others (in press), errors in the EDI and EWI measurements made during the 2008 CFE were reduced by

[15] This is roughly the fraction of sand finer than the 0.105-0.125 median size of the sand supplied by most tributaries

increasing the number of transits at each vertical. The other major improvement between the 2004 and 2008 CFEs was the addition of two-frequency acoustics at the River-mile 30, 61, 166, and 225 study sites. This improvement allowed 15-minute-resolution measurements of suspended-sand median grain size to be made at the River-mile 30, 61, 87, 166, and 225 study sites; this increase in data resolution allowed much better evaluation of the changes in the sand supply at each study site during the 2008 CFE than was previously possible. Furthermore, improvements in the deployments, both in the mounting of the instruments and through the addition of more measurement cells, and improvements in instrument maintenance resulted in a decrease in the noise in the acoustic data between the 2004 and 2008 CFEs. One new problem that occurred during the 2008 CFE and resulted in a decrease in data resolution during the 2008 CFE was the breakage of the mounts for the pump intake tubes at the River-mile 30 and 61 study sites. This was a result of an oversight in maintenance at these sites before the 2008 CFE.

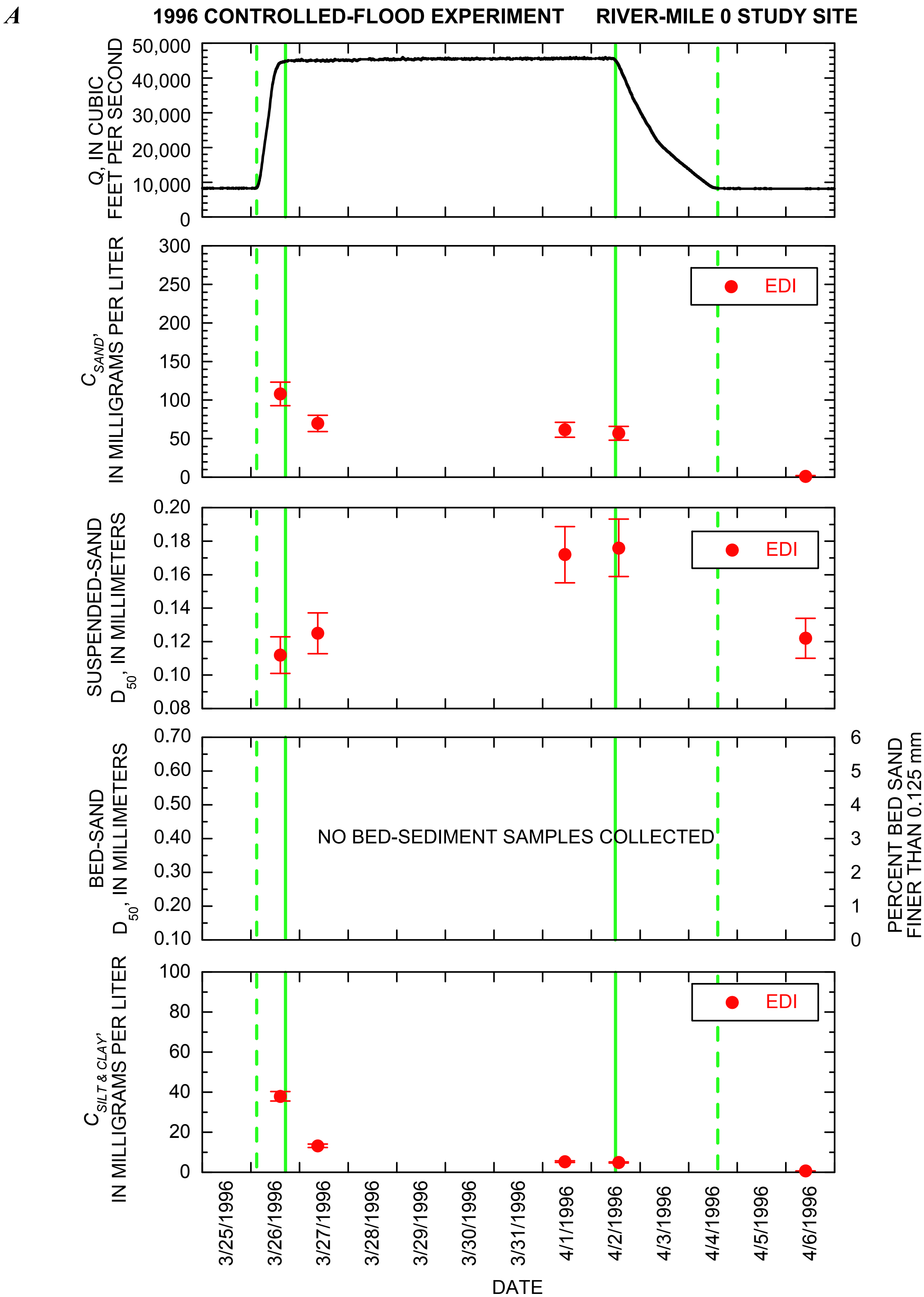
The high-resolution acoustic suspended-sediment data are normally used in combination with the other suspended-sediment data to compute suspended-silt-and-clay concentration and load, suspended-sand concentration and load, and suspended-sand median grain size when the acoustic data are in general agreement with the EDI or EWI measurements. However, during both the 2004 and 2008 CFEs, there are periods when the acoustic data are systematically biased as a result of grain-size effects; the acoustic data from these periods are not used. These grain-size related biases in concentration are evident in (1) the acoustic measurements of suspended-silt-and-clay concentration during most of the 2004 and 2008 CFE hydrographs at all study sites and (2) the acoustic measurements of suspended-sand concentration and median grain size during the rising limb of the 2004 and 2008 CFEs at the River-mile 30 and 61 study sites (fig. 4).

Laser-diffraction analyses in the laboratory indicate that suspended silt and clay in the Colorado River in Marble and Grand Canyons during periods of normal dam operations (that is, not during controlled floods) is dominated by clay-sized particles. These analyses indicate, however, that the suspended silt and clay during controlled floods is dominated by silt-sized particles that, as shown below, are winnowed from the bed. The data used at all study sites to calibrate measurements of acoustic attenuation to the concentrations of suspended silt and clay in the EDI or EWI-measurement cross-sections (method described in Topping and others, 2007b) are the clay-dominated silt-and-clay-concentration data that are more typical of most conditions in the Colorado River in Marble and Grand Canyons. By virtue of this approach, the agreement between acoustic and physical measurements of suspended-silt-and-clay concentration in the Colorado River during normal dam operations tends to be excellent. However, because the relation between silt and clay concentration and acoustic attenuation is sensitive to particle size (Urick, 1948; Flammer, 1962), and the particle size of the silt and clay during controlled floods is very different from that during normal dam operations, the acoustic measurements of silt and clay concentration during controlled floods can be less accurate, especially during the rising limbs. Thus, at all study sites, the acoustic measurements of suspended silt and clay concentration were excluded from further analyses and sediment budgeting during periods of substantial disagreement between these measurements and physical measurements (EDI, EWI, or calibrated pump samples) of suspended-silt-and-clay concentration. "Substantial disagreement" is defined to be when the acoustic measurements of suspended-silt-and-clay concentration lie significantly outside the 95-percent confidence intervals associated with the EDI or EWI measurements of suspended-silt-and-clay concentration.
Although typically excellent, the agreement between the acoustic measurements and physical measurements of suspended-sand concentration and median grain size can also be quite poor during periods of highly anomalous grain size. Such periods typically lasted less than 12 hours and

occurred during parts of the rising limbs of 2004 and 2008 CFEs only at the River-mile 30 and 61 study sites (figs. 4*D-E*, *G-H*). No such periods of substantial disagreement were observed anywhere downstream from these sites during either CFE. Owing to the effects of particle attenuation and backscatter on acoustic data of different frequencies (for example, Flammer, 1962; Thorne and Campbell, 1992; Thorne and others, 1993; Thorne and Hanes, 2002), high concentrations of suspended sand with an anomalously fine grain size may result in acoustic measurements of suspended-sand concentration that are too high or too low, depending on the frequency at which the acoustic measurements are made. During the 2004 CFE, acoustic measurements of suspended-sand concentration were only made at the River-mile 30 and 61 study sites with 1 MHz acoustic-Doppler profilers. Upon fining of the suspended sand during the initial part of the rising limb at these study sites, the acoustic measurements of suspended-sand concentration began to underpredict the physical measurements of suspended-sand concentration. This problem reoccurred at these two study sites, but in an opposing sense, during the 2008 CFE. During the 2008 CFE, acoustic measurements of suspended-sand concentration were made at these study sites using a two-frequency approach employing both 1 MHz and 2 MHz acoustic-Doppler profilers. Upon much greater fining of the suspended sand during the initial part of the rising limb of the 2008 CFE due to extreme fining of the bed sand[16] at these study sites, the two-frequency acoustic measurements of suspended-sand concentration began to overpredict the physical measurements of suspended-sand concentration. Associated with this overprediction of suspended-sand concentration was an underprediction of the median grain size of the suspended sand. Therefore, the acoustic measurements of suspended-sand concentration and grain size were excluded from the further analyses and sediment budgeting presented in this report during the periods of substantial

Figure 4 (next pages). Hydrographs, suspended-sediment data, and bed-sand data collected at each study site during each CFE. Solid green vertical lines indicate the beginning and end of the high, steady discharge part of a controlled flood at a given site; dashed green vertical lines indicate the beginning of the rising limb and end of receding limb of a controlled flood at a given site. Error bars for the EDI, EWI, or point suspended-sediment concentration and grain-size data indicate the 95-percent confidence interval associated with these measurements (incorporating the field and laboratory errors described above). Error bars for the bed-sediment data are one standard error, indicating the 67-percent confidence interval associated with the mean value of the median grain size or < 0.125-mm sand fraction among the stations sampled across the cross-section in each bed-sediment measurement. Q is water discharge, C_{SAND} is the velocity-weighted concentration of suspended sand in the cross-section, $C_{SILT\&CLAY}$ is the velocity-weighted concentration of suspended silt and clay in the cross-section, and D_{50} is either the median grain-size of the bed sand or the velocity-weighted median grain size of the suspended sand in the cross-section. Hydrograph and data collected at (*A*) the River-mile 0 study site during the 1996 CFE; (*B*) the River-mile 0 study site during the 2004 CFE; (*C*) the River-mile 0 study site during the 2008 CFE; (*D*) the River-mile 30 study site during the 2004 CFE; (*E*) the River-mile 30 study site during the 2008 CFE; (*F*) the River-mile 61 study site during the 1996 CFE; (*G*) the River-mile 61 study site during the 2004 CFE; (*H*) the River-mile 61 study site during the 2008 CFE; (*I*) the River-mile 87 study site during the 1996 CFE; (*J*) the River-mile 87 study site during the 2004 CFE; (*K*) the River-mile 87 study site during the 2008 CFE; (*L*) the River-mile 166 study site during the 1996 CFE; (*M*) the River-mile 166 study site during the 2004 CFE; (*N*) the River-mile 225 study site during the 2004 CFE; and (*O*) the River-mile 225 study site during the 2008 CFE.

[16] The bed sand fined by a factor of two, from a median size of about 0.3 mm to an extremely fine value of 0.15 mm, during the initial part of the rising limb of the 2008 CFE. This degree of fining has never before been observed during the rising limb of any flood in the Colorado River in Marble or Grand Canyons. The only time this degree of bed fining has been observed was in uppermost Marble Canyon in September 1998 immediately following two large floods on the Paria River (Topping and others, 2000b).


A
1996 CONTROLLED-FLOOD EXPERIMENT
RIVER-MILE 0 STUDY SITE
Q, IN CUBIC FEET PER SECOND
50,000
40,000
30,000
20,000
10,000
0
C_SAND, IN MILLIGRAMS PER LITER
300
250
200
150
100
50
0
EDI
SUSPENDED-SAND D50, IN MILLIMETERS
0.20
0.18
0.16
0.14
0.12
0.10
0.08
EDI
BED-SAND D50, IN MILLIMETERS
0.70
0.60
0.50
0.40
0.30
0.20
0.10
NO BED-SEDIMENT SAMPLES COLLECTED
PERCENT BED SAND FINER THAN 0.125 mm
6
5
4
3
2
1
0
C_SILT & CLAY, IN MILLIGRAMS PER LITER
100
80
60
40
20
0
EDI
3/25/1996
3/26/1996
3/27/1996
3/28/1996
3/29/1996
3/30/1996
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4/6/1996
DATE

B

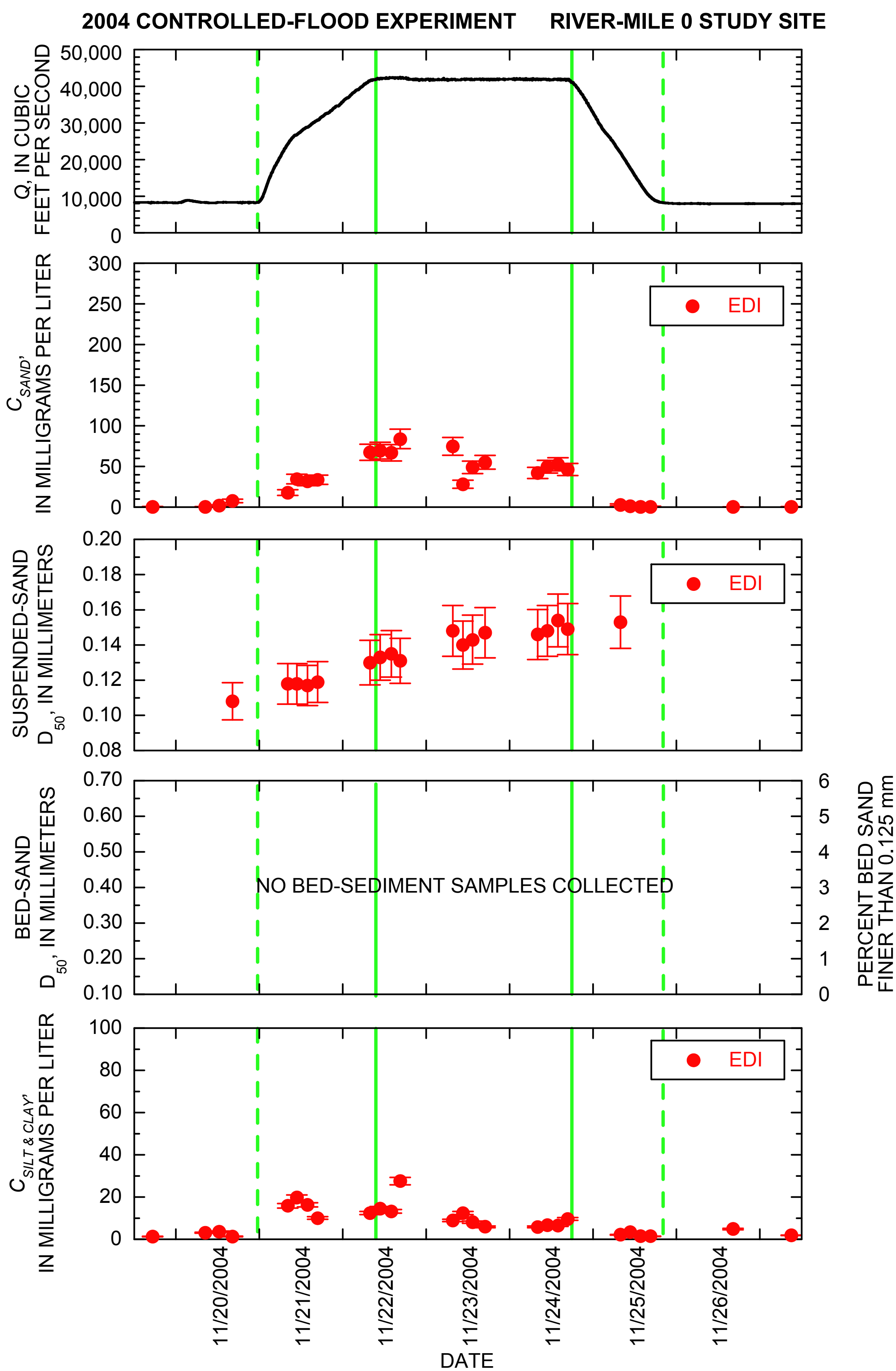


Figure 4. — Continued.

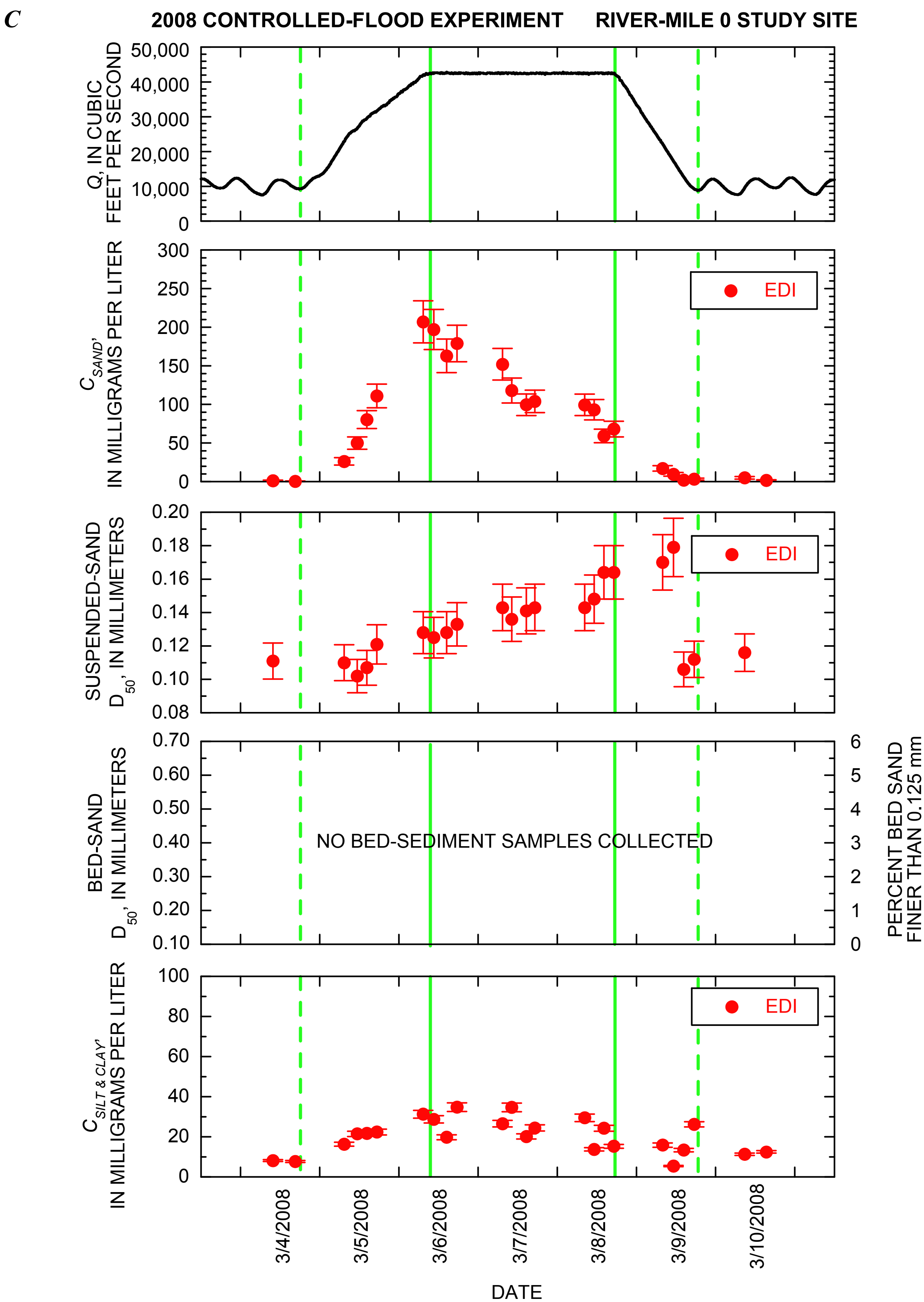
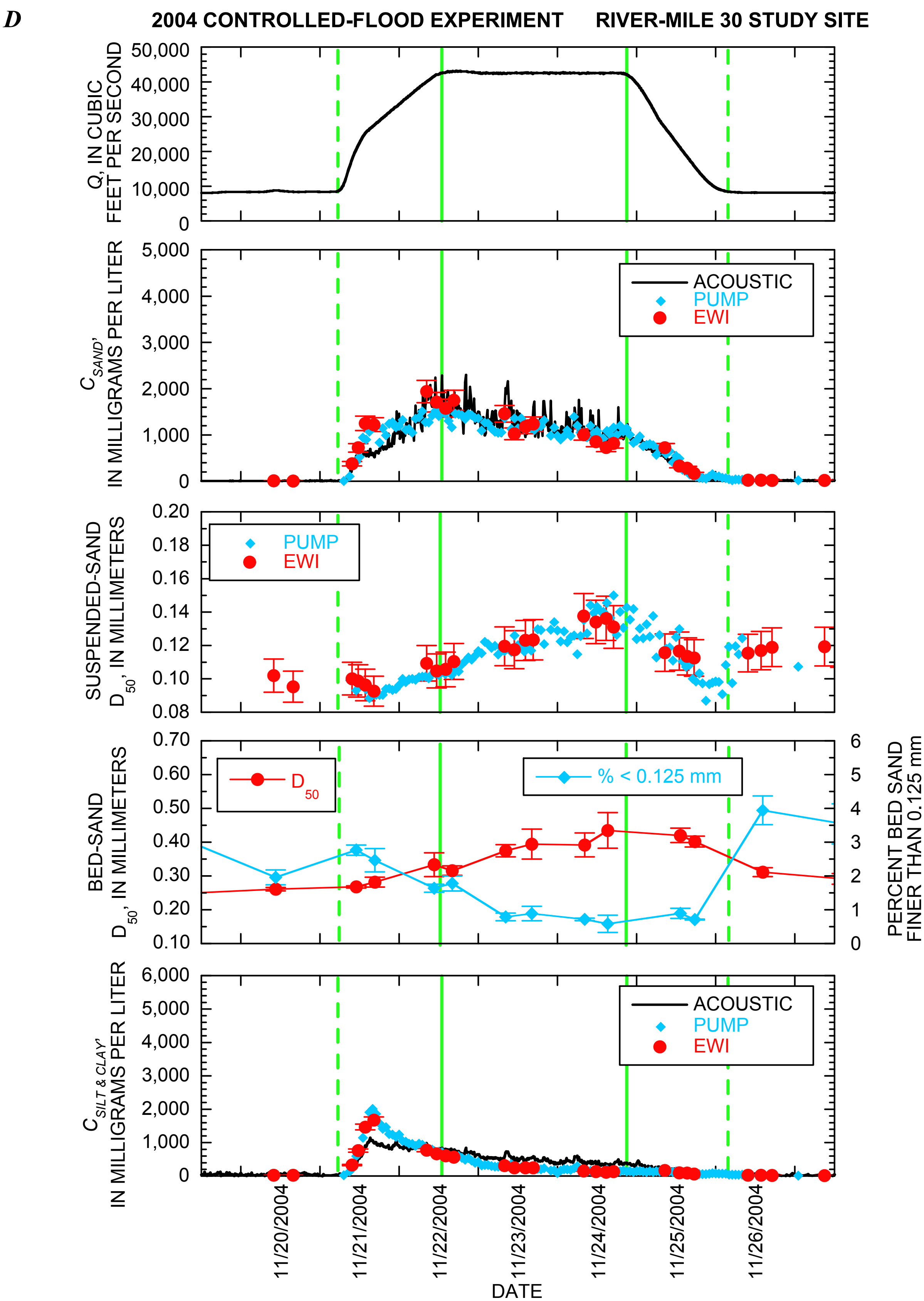


Figure 4. — Continued.

D



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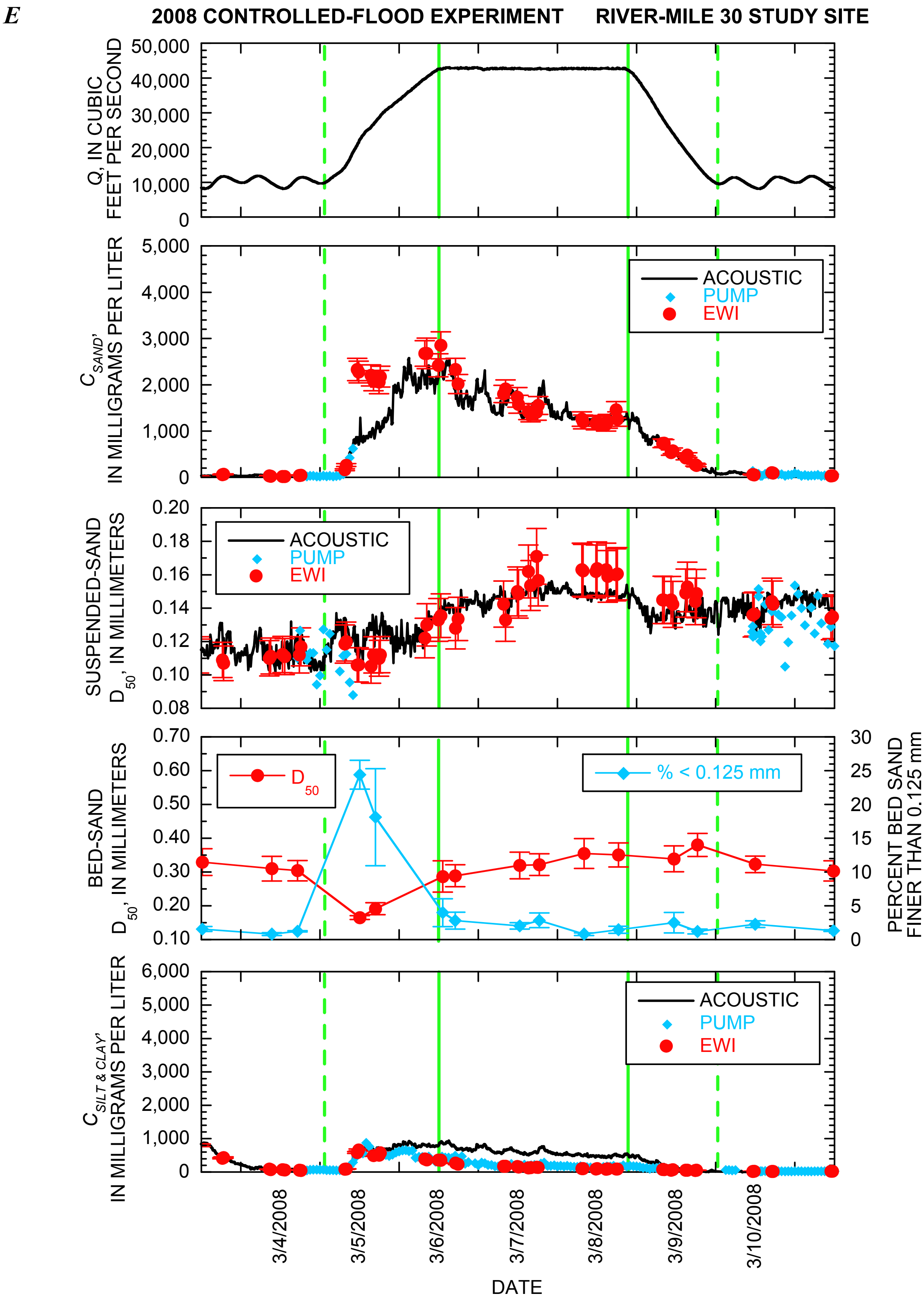


Figure 4. — Continued.

F

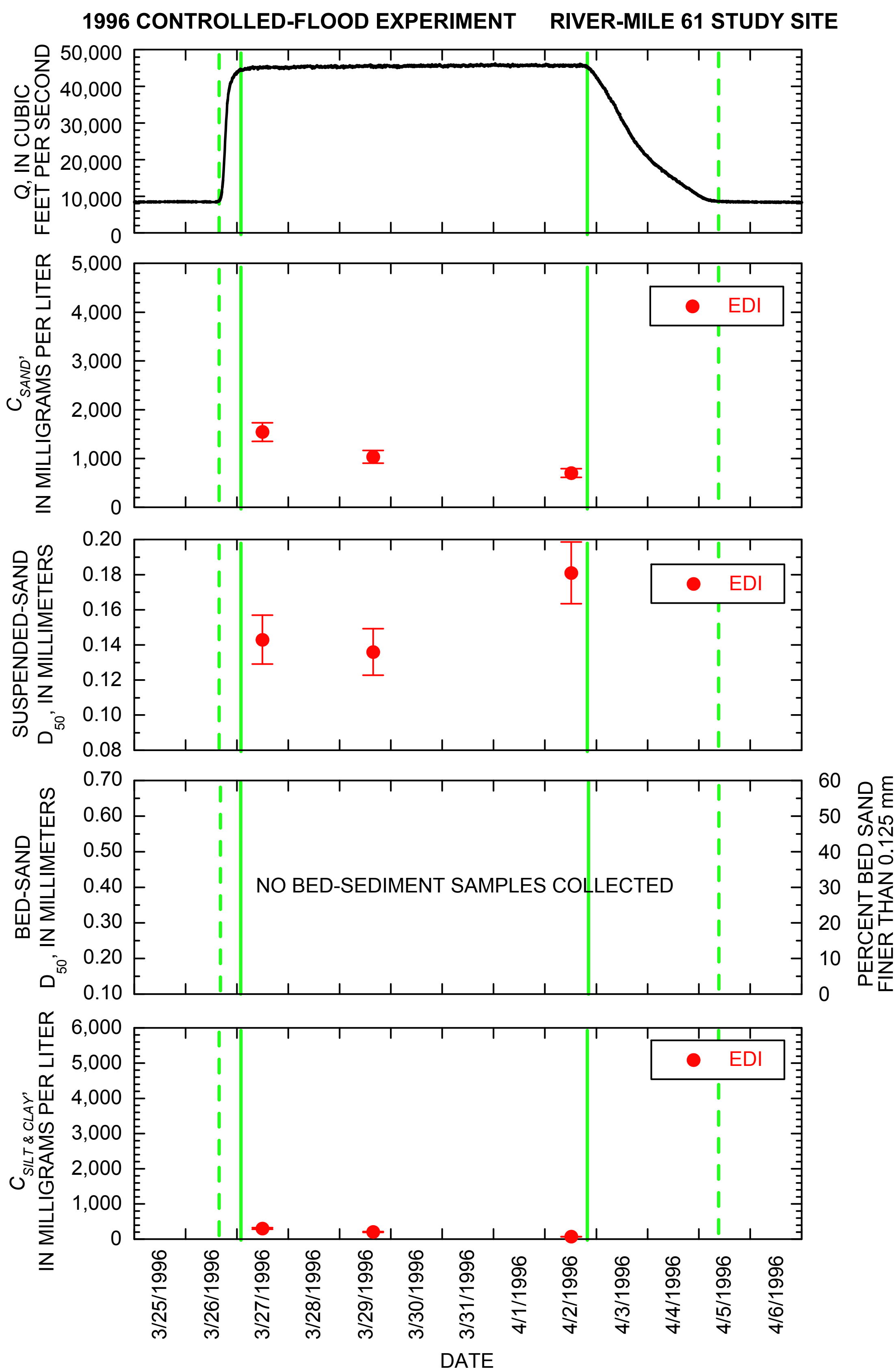
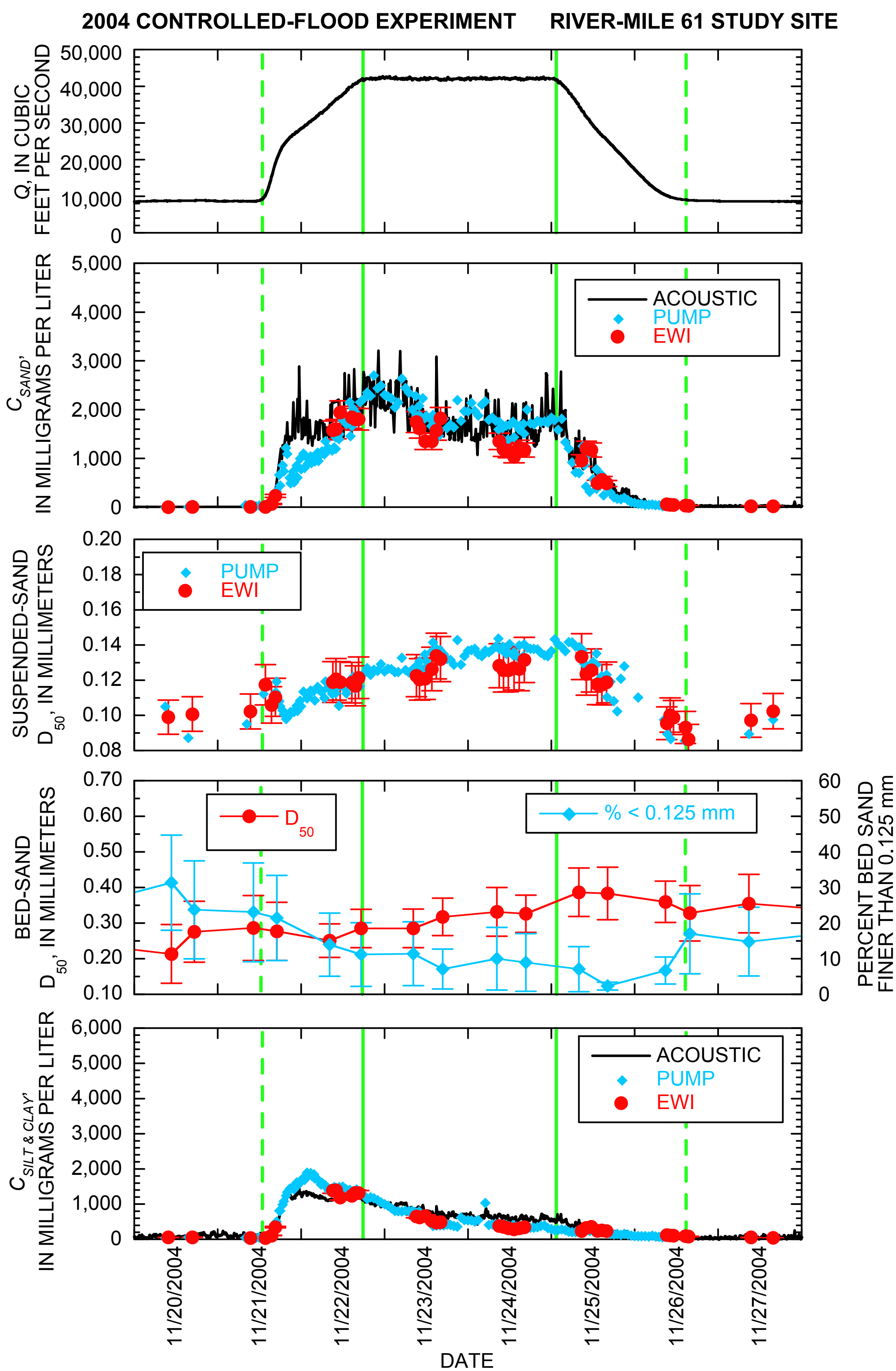


Figure 4. — Continued.

G



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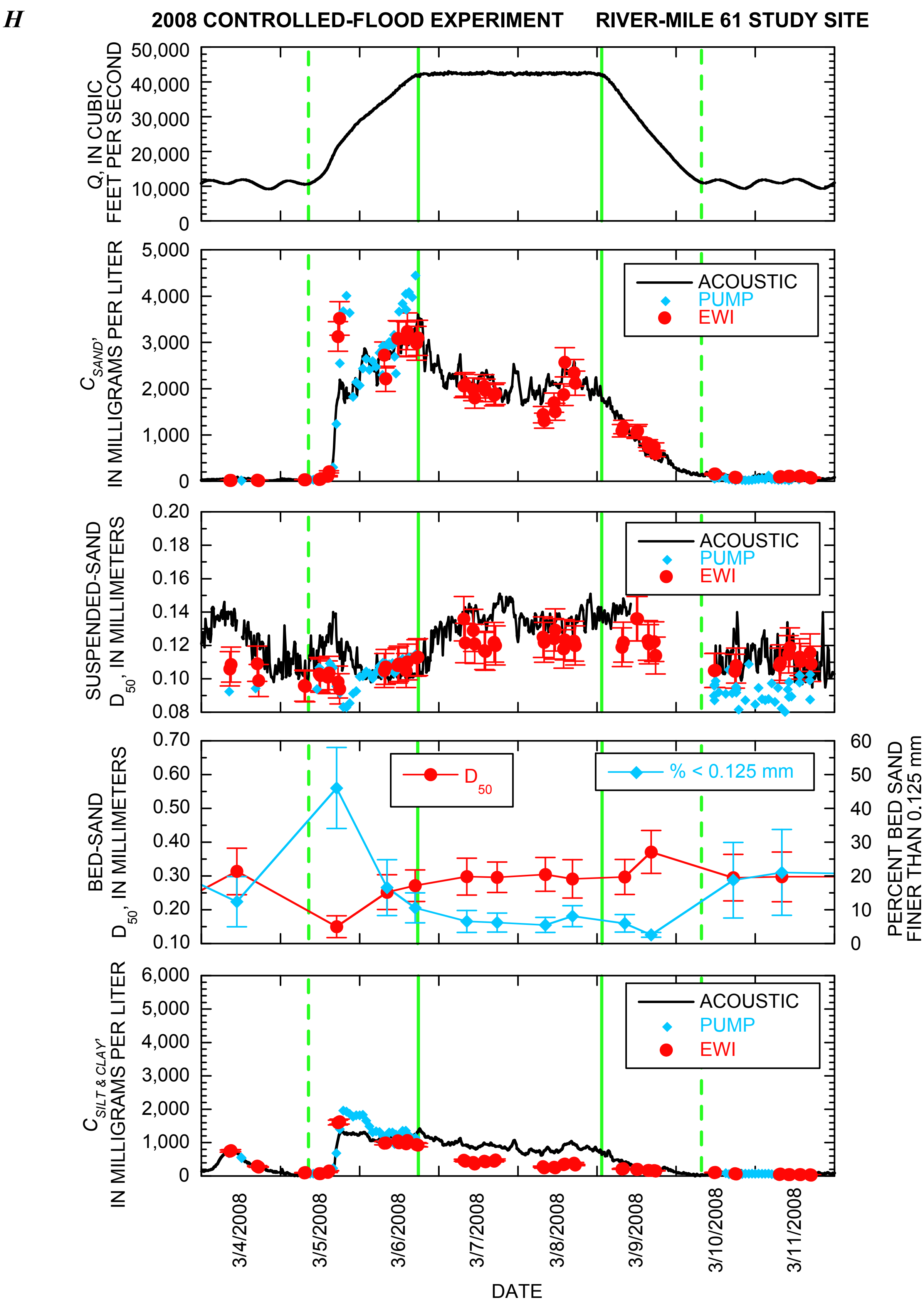

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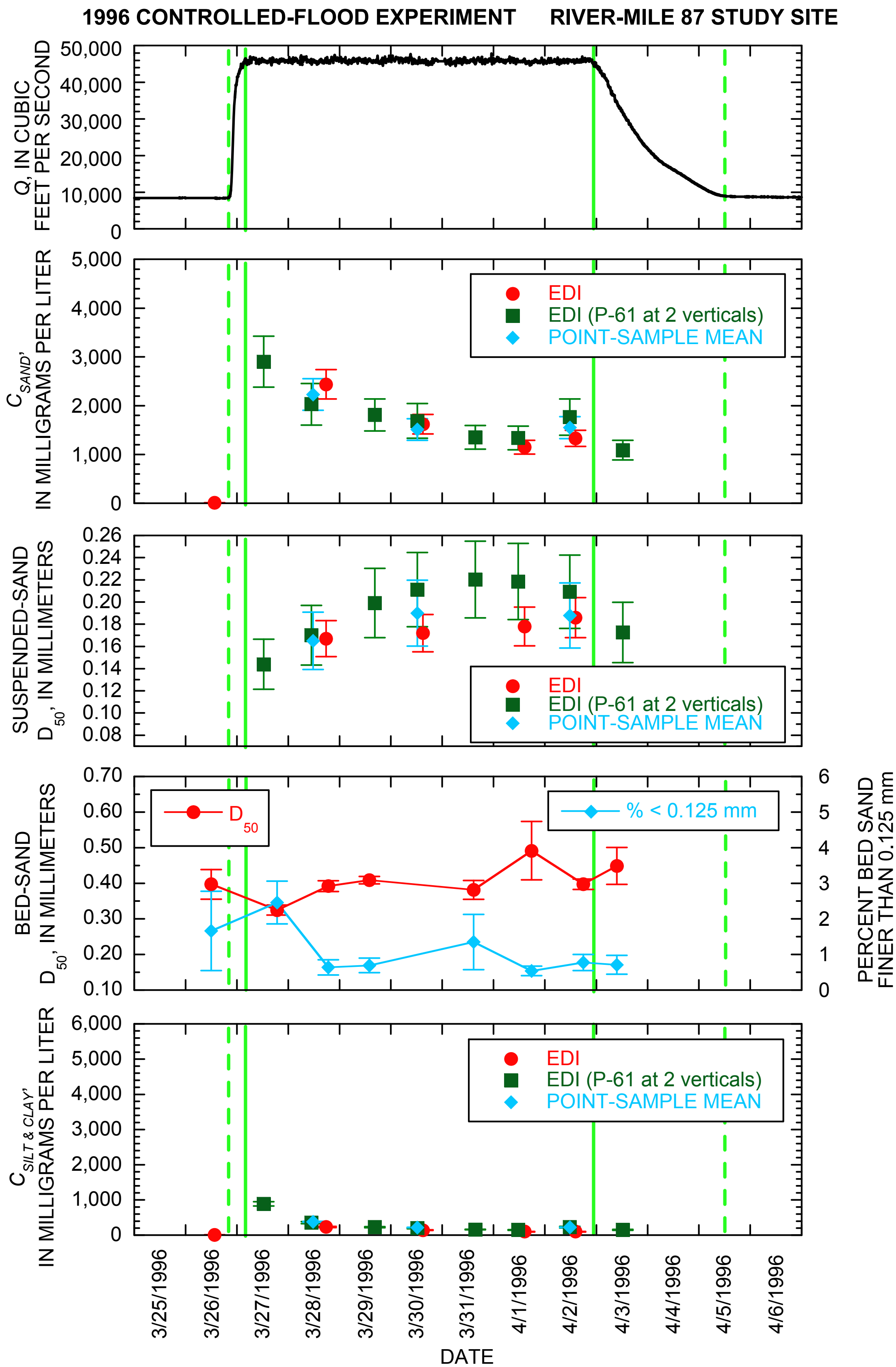
I



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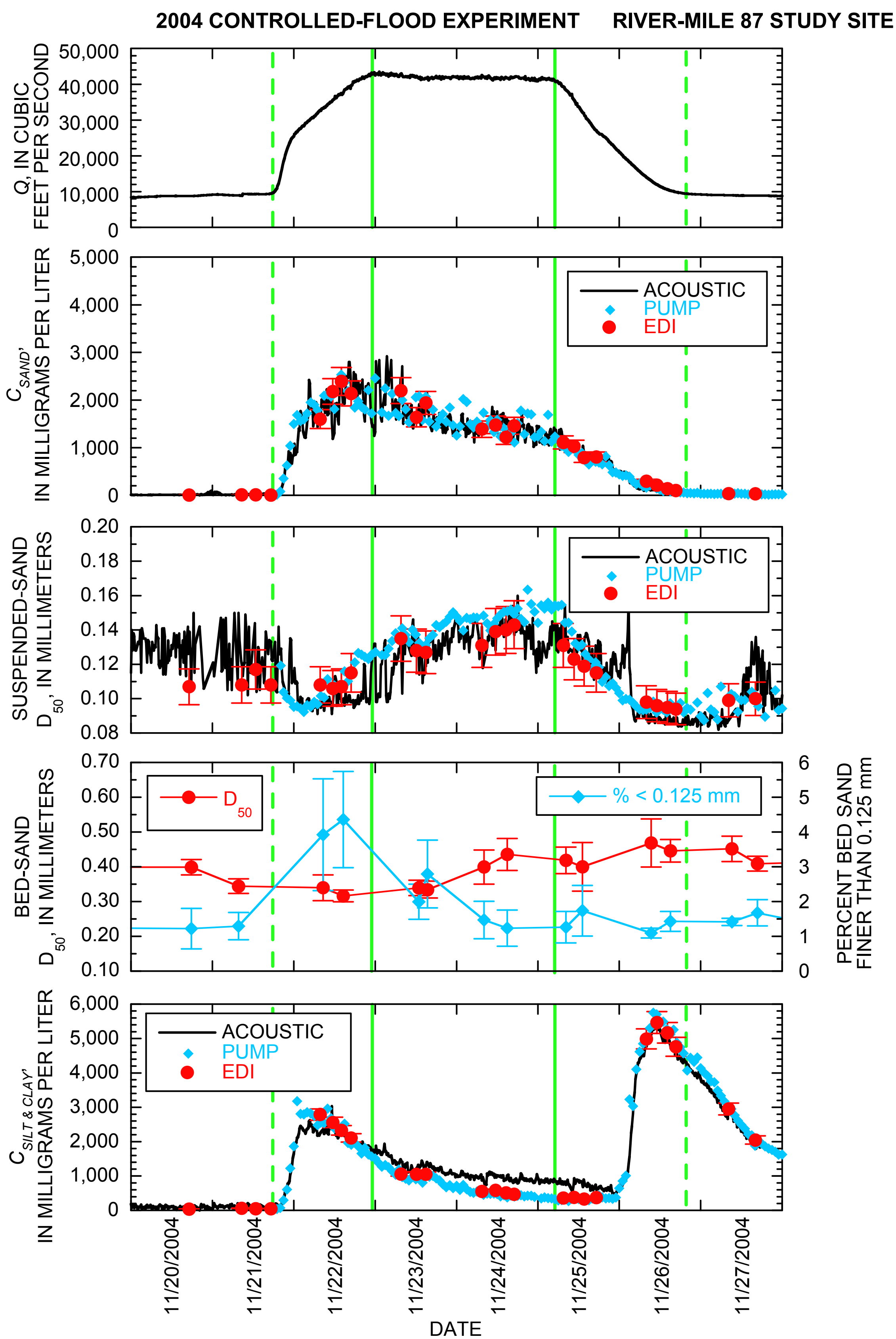

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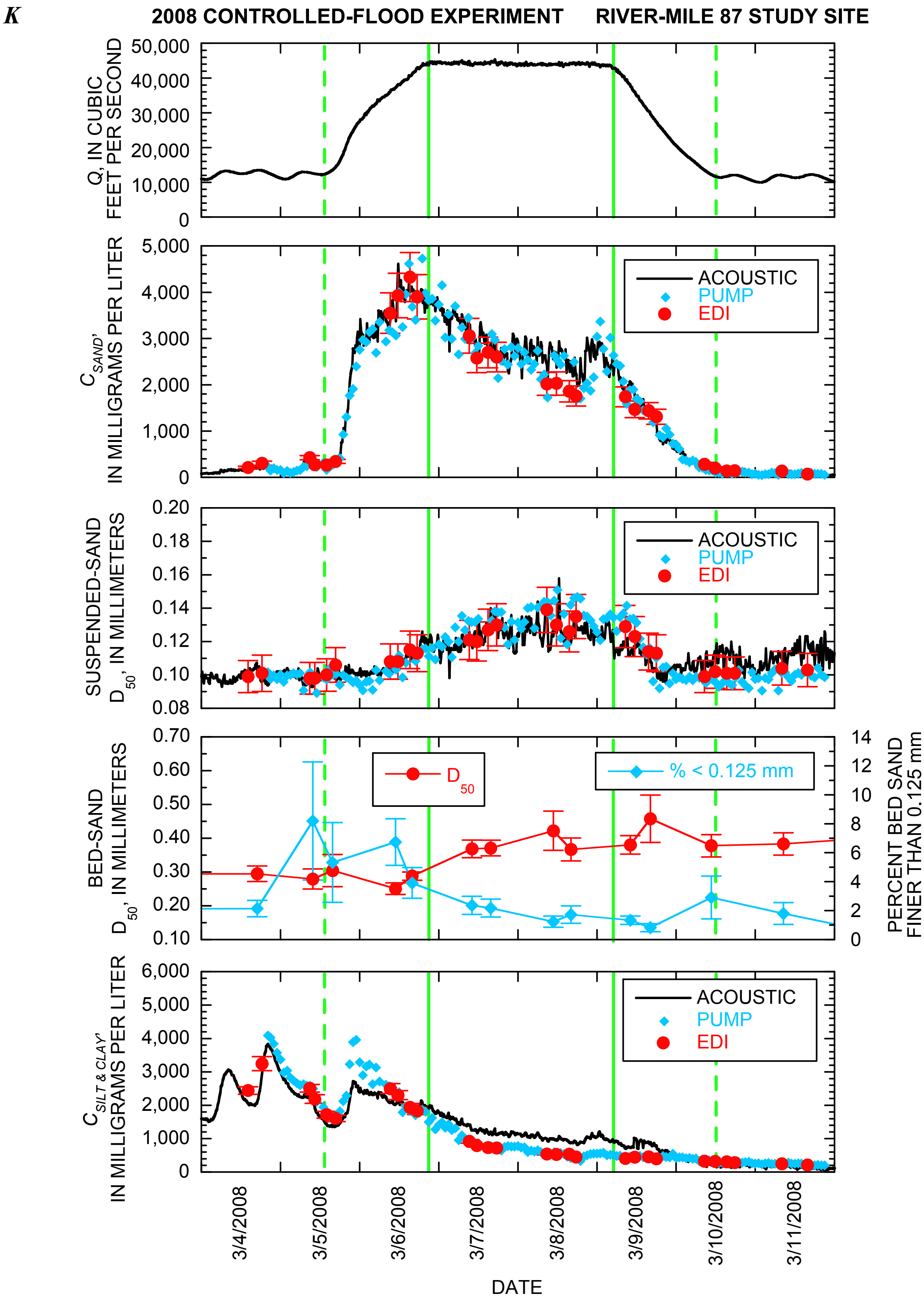

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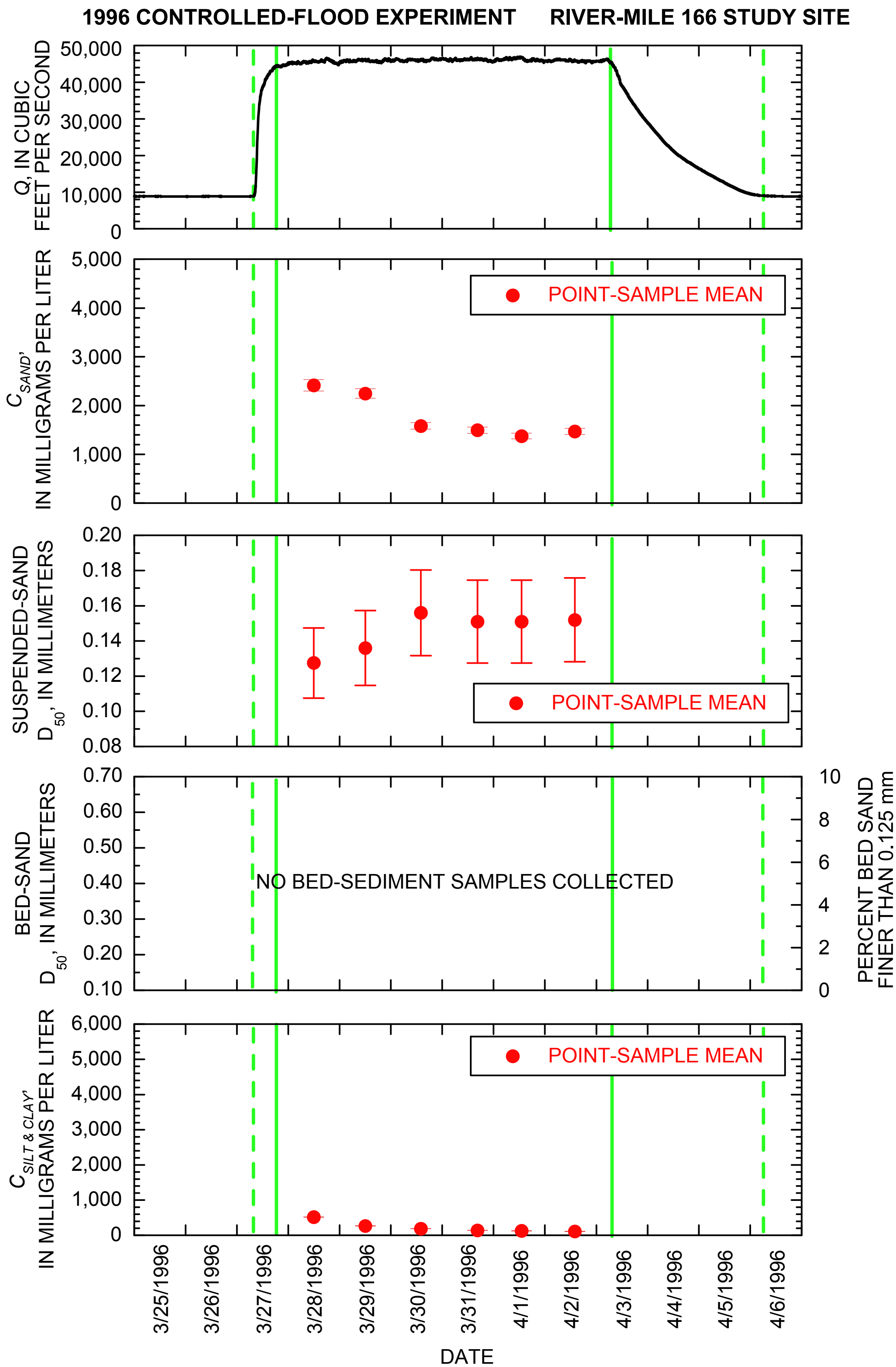
L



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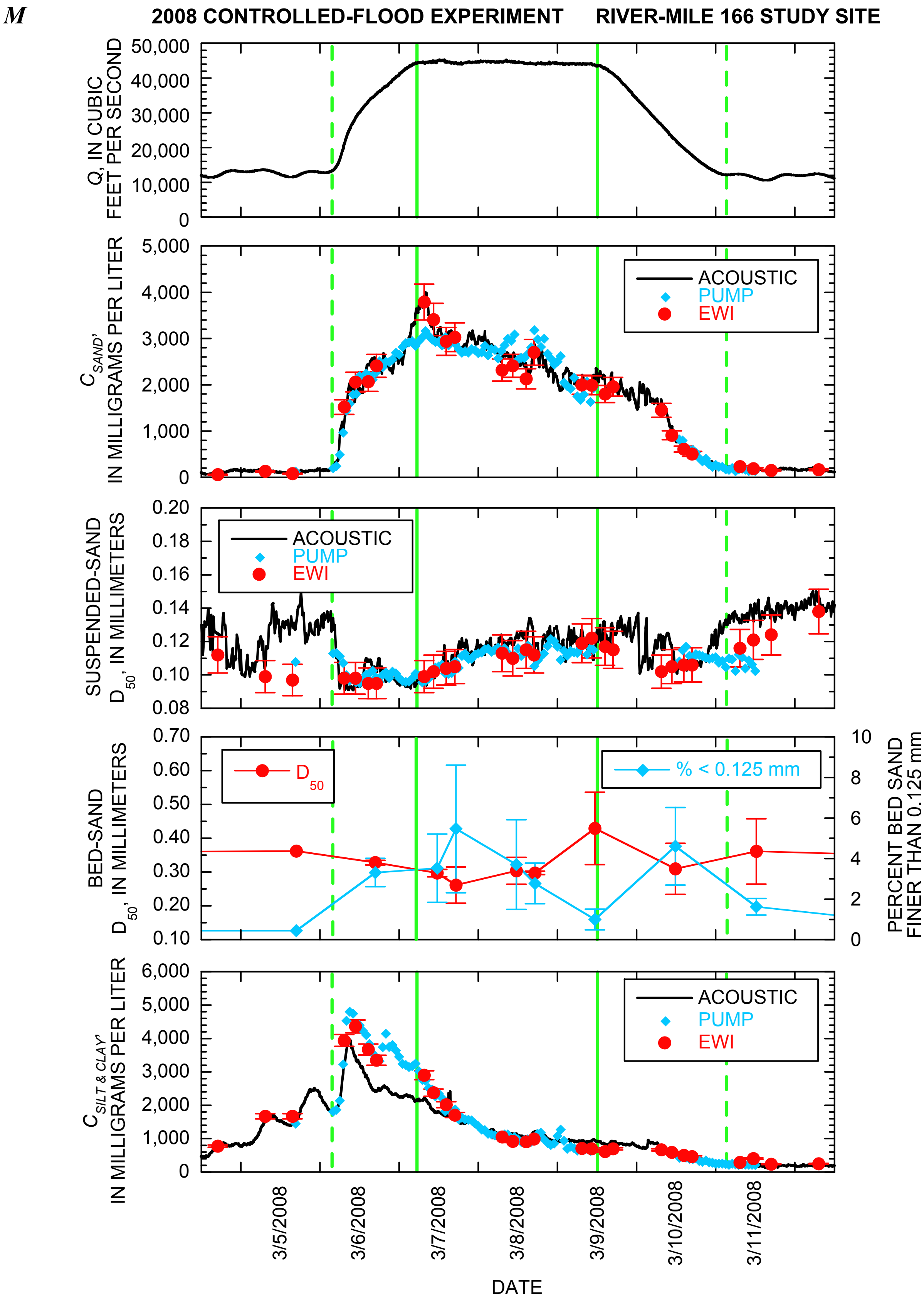

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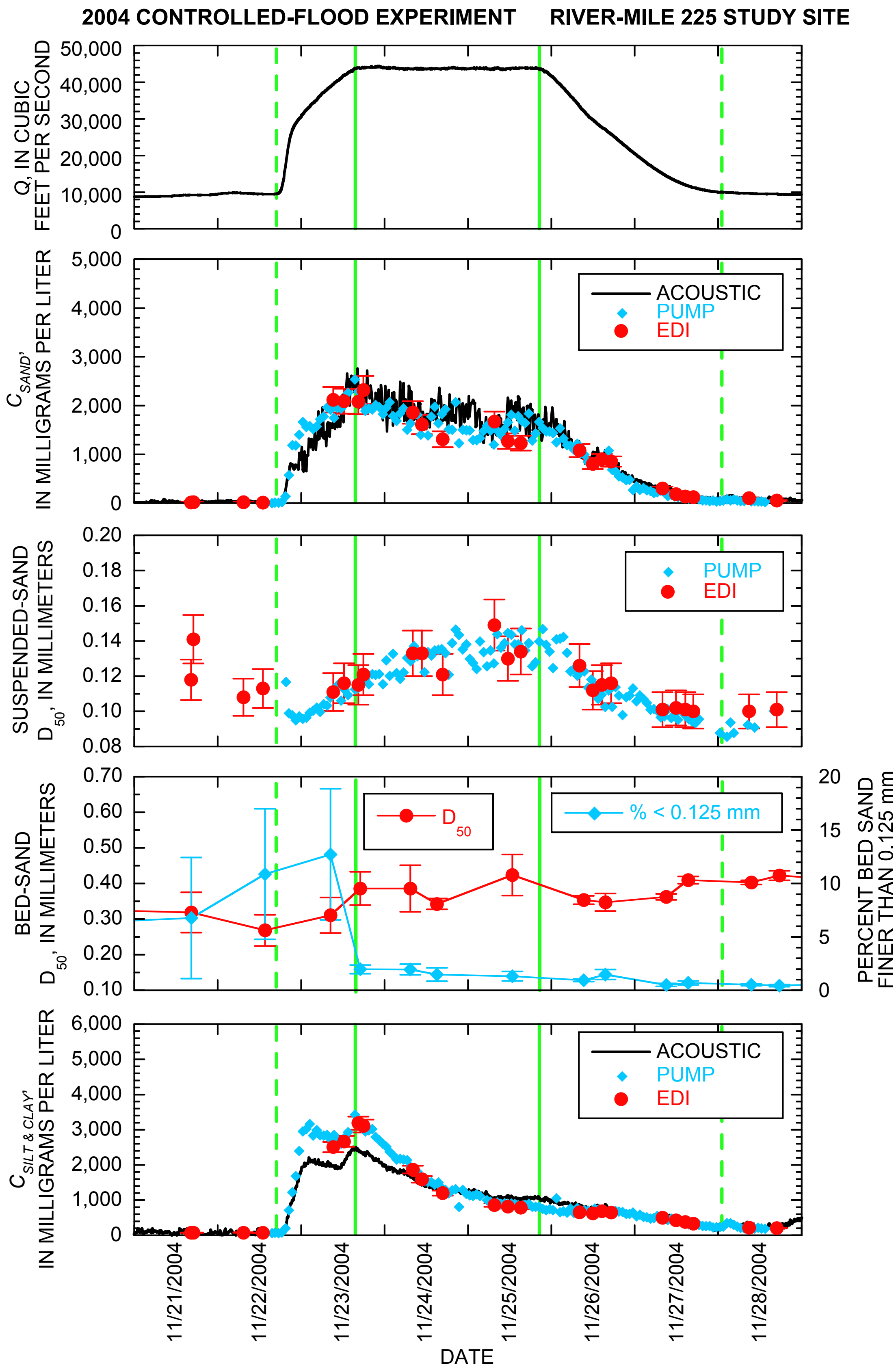

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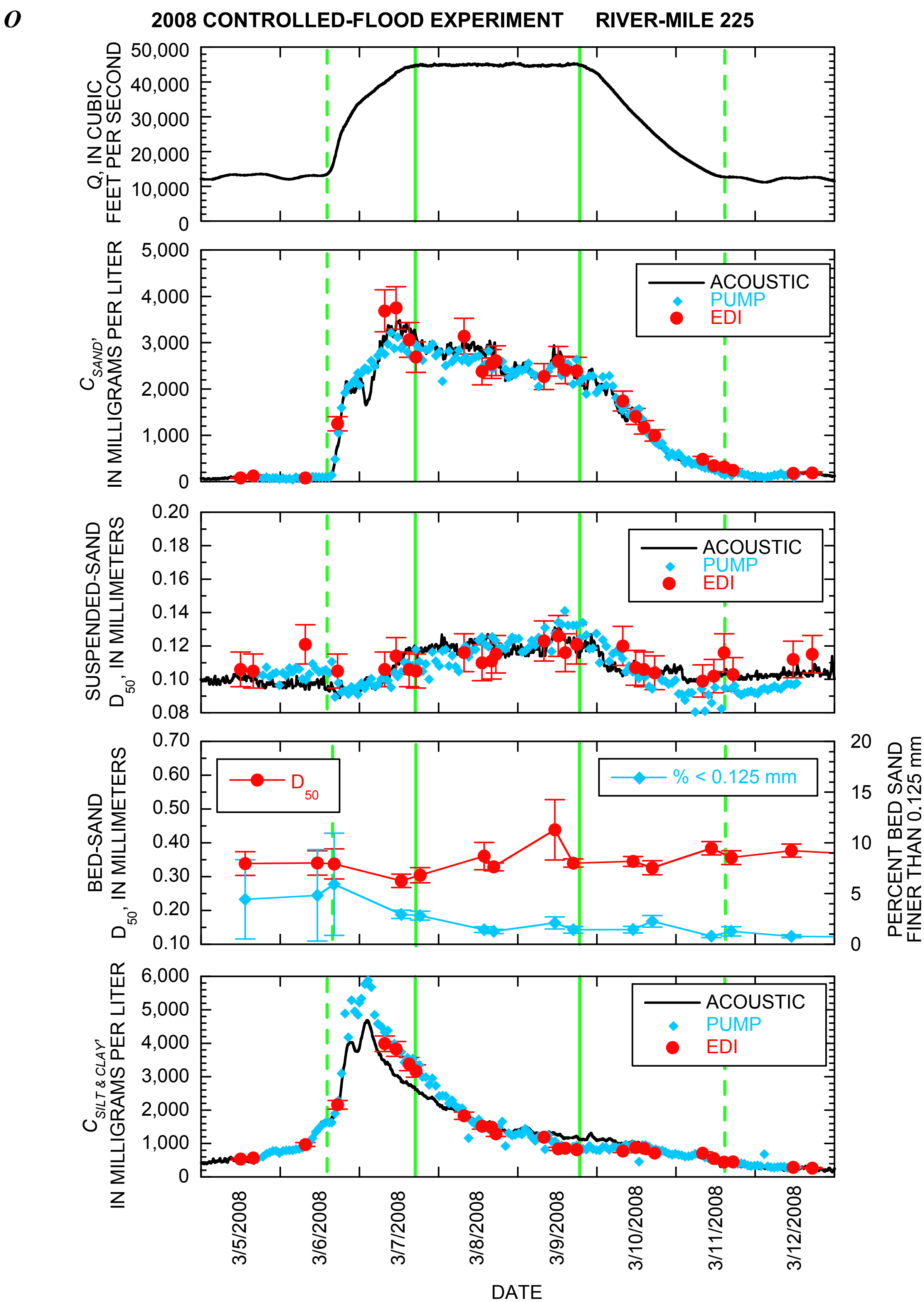


Figure 4. — Continued.

disagreement between these measurements and physical measurements of suspended-sand concentration and grain size at only the River-mile 30 and 61 study sites during the rising limbs of the 2004 and 2008 CFEs (figs. 4*D-E*, *G-H*). Again, "substantial disagreement" is defined to be when the acoustic measurements of suspended-sand concentration and median grain size lie significantly outside the 95-percent confidence intervals associated with the EDI or EWI measurements of suspended-sand concentration and median grain size.

Data Collected at Each Study Site During All CFEs

Comparisons of the data collected at each study site during all three CFEs are provided in figures 5 and 6. Although differences in the upstream sediment supplies at the study sites during each CFE resulted in very different concentrations and grain sizes, similar processes were observed during each CFE at the study sites where data collection was at a sufficiently high temporal resolution. The following processes were observed in the suspended sediment during the rising limb of the 2004 and 2008 CFEs at the sites with 15-minute data resolution. Although these processes likely also occurred at all study sites during the 1996 CFE and at the River-mile 0 study site during all CFEs, limited data resolution prevented making such inferences.

(1) At each study site during the 2004 and 2008 CFE, suspended-sand concentration increased with the initial increase in the discharge of water during the rising limb. Associated with this increase in suspended-sand sand concentration is a decrease in the median grain size of the suspended sand.

(2) In Marble Canyon at the River-mile 30 and 61 study sites during the 2004 and 2008 CFEs, two peaks in suspended-sand concentration occurred during the rising limb. The first of these peaks coincided with the minimum median grain size of the suspended sand. This occurred at a water discharge of approximately 20,000 ft^3/s (a dam release slightly higher than any discharge during the antecedent accounting periods for each CFE). During both the 2004 and 2008 CFEs, this initial peak in suspended-sand concentration was more pronounced at the River-mile 61 study site than at the River-mile 30 study site. Following this initial peak in concentration coupled to the minimum median grain size, the median grain size of the suspended sand increased as the discharge continued to increase. During this second part of the rising limb, suspended-sand concentration first decreased and then increased, all while the median grain size of the suspended sand increased.

(3) No initial peak in suspended sand concentration is evident in the data collected at the River-mile 87, 166, and 225 study sites in Grand Canyon during either the 2004 or 2008 CFE. However, after the initial increase in suspended-sand concentration associated with the decrease in suspended-sand median grain size, suspended-sand concentration and median grain size both increased through the remainder of the rising limb as discharge increased from about 20,000 ft^3/s to 42,000 ft^3/s.

(4) Peak suspended-sand concentration generally occurred at all study sites either at or just before the attainment of peak discharge. At the River-mile 30 and 61 study sites, this was the second peak in suspended-sand concentration.

(5) At each study site during the 2004 and 2008 CFE, suspended-silt-and-clay concentration increased with the initial increase in the discharge of water during the rising limb. Peak silt and clay concentration generally coincided with the above-described minimum in suspended-sand median grain size (and at a discharge of about 20,000 ft^3/s). Following this peak in concentration, suspended-silt-and-clay concentration decreased during the remainder of the rising limb.

The following processes were typically, but not always, observed in the bed sediment during the rising limb of each CFEs at each study site.

(1) The median grain size of the bed sand decreased, sometimes associated with a substantial increase in the fraction of the bed sand composed of sand finer than 0.125 mm.

(2) Silt and clay was winnowed from the bed. This winnowed silt and clay was likely the source of the peak in suspended-silt-and-clay concentration during the initial part of the rising limb.

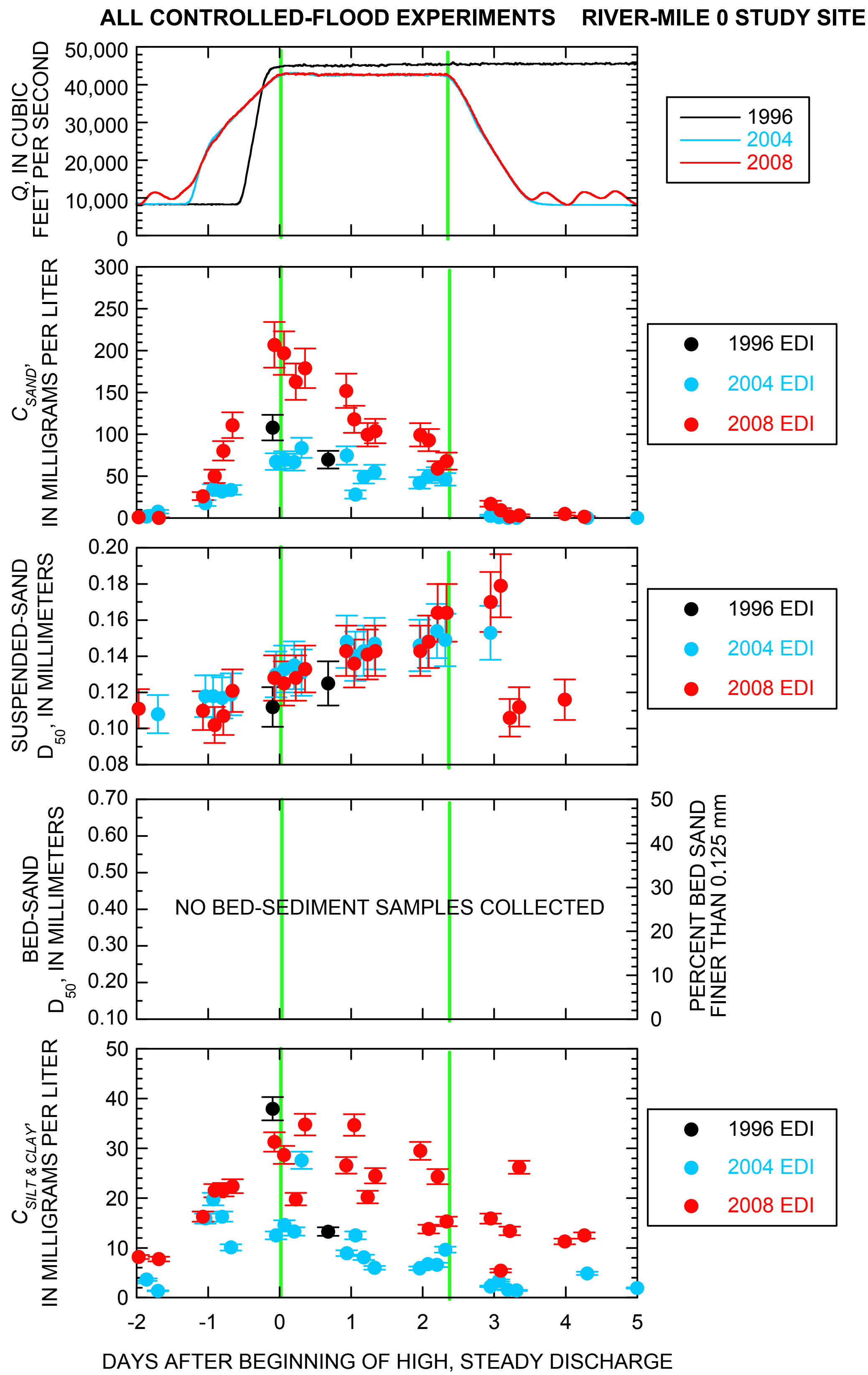
The following processes were observed in the suspended- and bed-sediment at all study sites during the high, steady discharge part of all CFEs. These processes have been previously described in Rubin and others (1998), Topping and others (1999, 2000a, 2000b, 2005, 2006a, 2007a, 2008), Rubin and Topping (2001, 2008), Schmidt and others (2007).

(1) Suspended-sand concentration decreased over time.
(2) Suspended-sand median grain size increased over time.
(3) Suspended-silt-and-clay concentration continued to decrease over time.
(4) The median grain size of the bed sand increased. This was typically associated with a substantial decrease in the fraction of the bed sand composed of sand finer than 0.125 mm.
(5) The amount of silt and clay in the bed either continued to decrease or remained constant at extremely low levels.

Although similar suspended- and bed-sediment processes were observed at the various study sites during the three CFEs, suspended-sand concentrations and grain sizes were very different among the different study sites during the three CFEs, owing to very different upstream supplies of sand. For a given discharge of water, the dominant nonlinear controller of suspended-sand concentration is the reach-averaged grain size of the sand on the bed, and the secondary linear controller of suspended-sand concentration is the reach-averaged area of the sand on the bed (summarized in Topping and others, 2007a). Owing to this boundary condition, the same concentration of sand in suspension can be supported by coarser bed sand covering a large fraction of the bed in a reach or by finer bed sand covering a small fraction of the bed in a reach. By this logic, it is evident that increasing levels of sand enrichment could be associated with decreasing concentrations of suspended sand if the "enriching sand" covers more of the bed in a reach as its grain size progressively coarsens (however unlikely this scenario might be). In addition, when one also incorporates the complexities in relating reach-averaged bed-sand area and grain size to the upstream sand supply reviewed in the "Theoretical Background" section of this report, it becomes

Figure 5 (next pages). Hydrographs, suspended-sediment data, and bed-sand data collected at each study site during all three CFEs. Hydrographs and sediment data were shifted in time such that zero time (indicated by the leftmost vertical green line) is the beginning of high, steady discharge (*Q*) during each CFE. Right vertical green line indicates the end of the high, steady discharge part of the 2004 and 2008 controlled floods at a given site; note that data collected during the 1996 CFE to the right of the right green line cannot be compared to data collected during the 2004 and 2008 CFEs because of the much greater duration of high, steady discharge during the 1996 CFE. Data collected after day 5 of high, steady discharge during the 1996 CFE not shown. Error bars for the EDI, EWI, or mean point suspended-sediment concentration and grain-size data indicate the 95-percent confidence interval associated with these measurements (incorporating the field and laboratory errors described in the text). Error bars for the bed-sediment data are one standard error, indicating the 67-percent confidence interval associated with the mean value of the median grain size or < 0.125-mm sand fraction among the stations sampled across the cross-section in each bed-sediment measurement. *Q* is water discharge, C_{SAND} is the velocity-weighted concentration of suspended sand in the cross-section, $C_{SILT\&CLAY}$ is the velocity-weighted concentration of suspended silt and clay in the cross-section, and D_{50} is the median grain size of the bed sand or the velocity-weighted median grain size of the suspended sand in the cross-section. Hydrograph and data collected at (*A*) the River-mile 0 study site during the 1996, 2004, and 2008 CFEs; (*B*) the River-mile 30 study site during the 2004 and 2008 CFEs; (*C*) the River-mile 61 study site during the 1996, 2004, and 2008 CFEs; (*D*) the River-mile 87 study site during the 1996, 2004, and 2008 CFEs; (*E*) the River-mile 166 study site during the 1996 and 2008 CFEs; and (*F*) the River-mile 225 study site during the 2004 and 2008 CFEs.

A



ALL CONTROLLED-FLOOD EXPERIMENTS RIVER-MILE 0 STUDY SITE
Q, IN CUBIC FEET PER SECOND
50,000
40,000
30,000
20,000
10,000
0
1996
2004
2008
C_SAND, IN MILLIGRAMS PER LITER
300
250
200
150
100
50
0
1996 EDI
2004 EDI
2008 EDI
SUSPENDED-SAND D50, IN MILLIMETERS
0.20
0.18
0.16
0.14
0.12
0.10
0.08
BED-SAND D50, IN MILLIMETERS
0.70
0.60
0.50
0.40
0.30
0.20
0.10
NO BED-SEDIMENT SAMPLES COLLECTED
PERCENT BED SAND FINER THAN 0.125 mm
50
40
30
20
10
0
C_SILT & CLAY, IN MILLIGRAMS PER LITER
-2
-1
0
1
2
3
4
5
DAYS AFTER BEGINNING OF HIGH, STEADY DISCHARGE

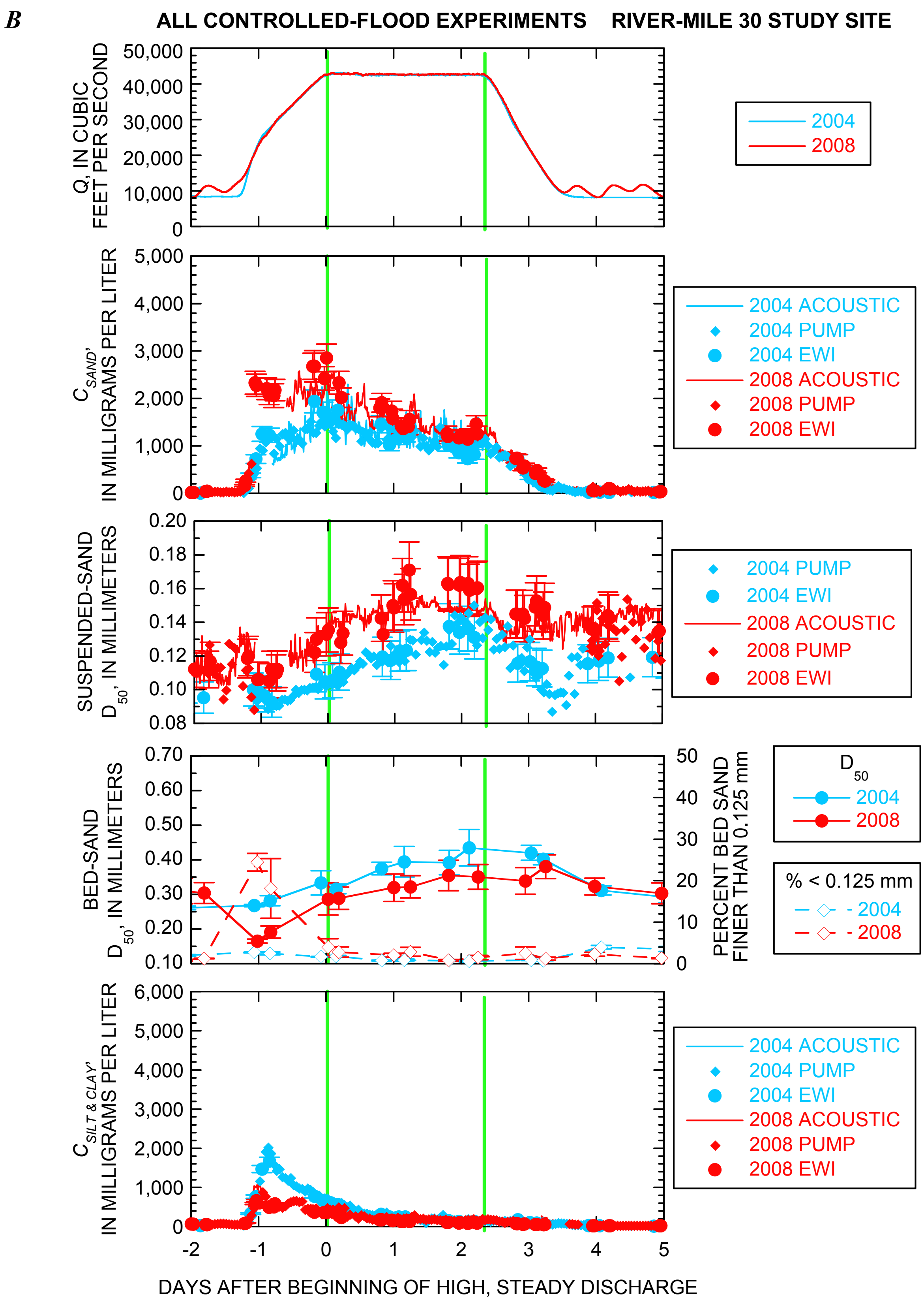
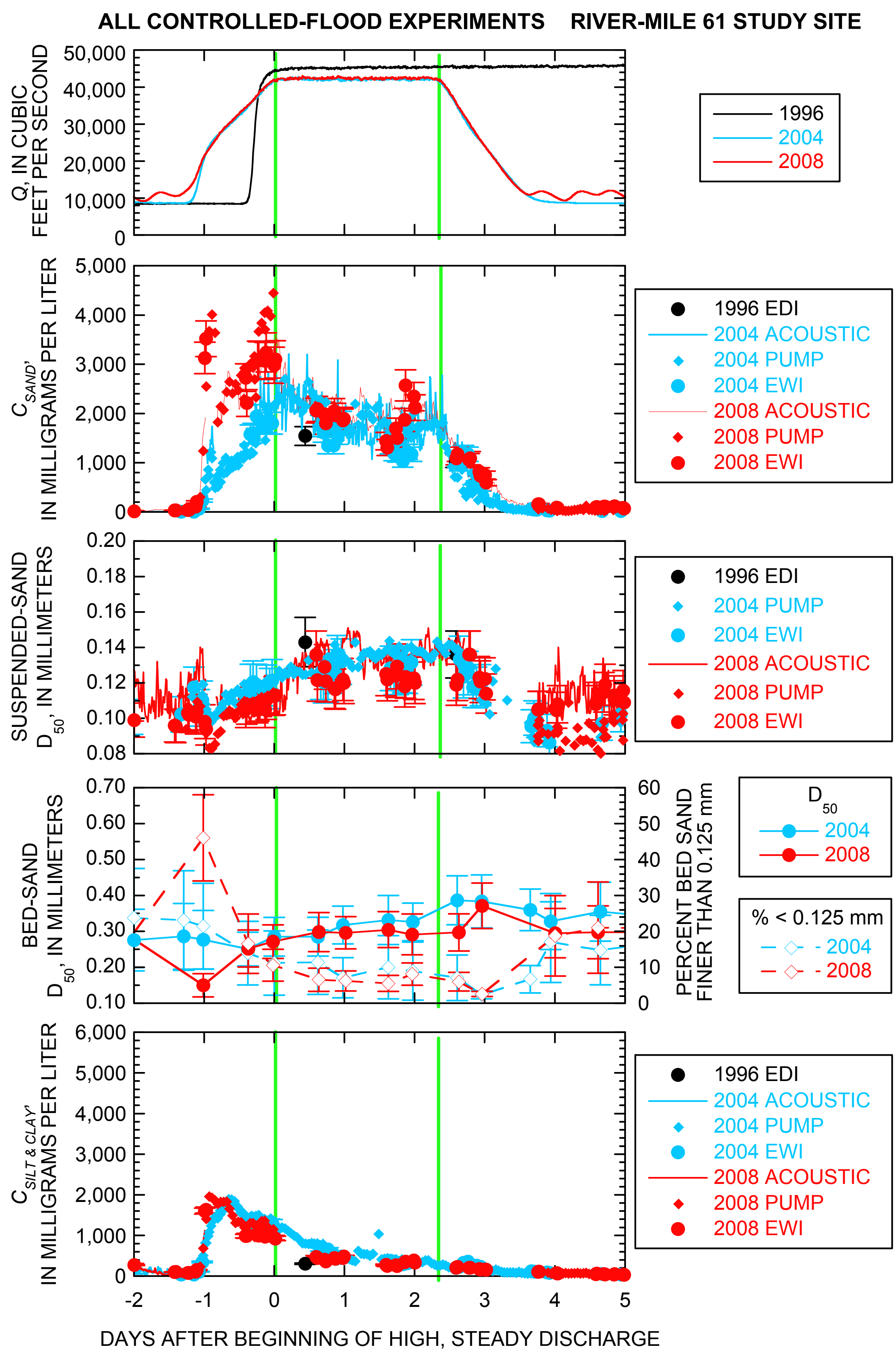


Figure 5. — Continued.

C



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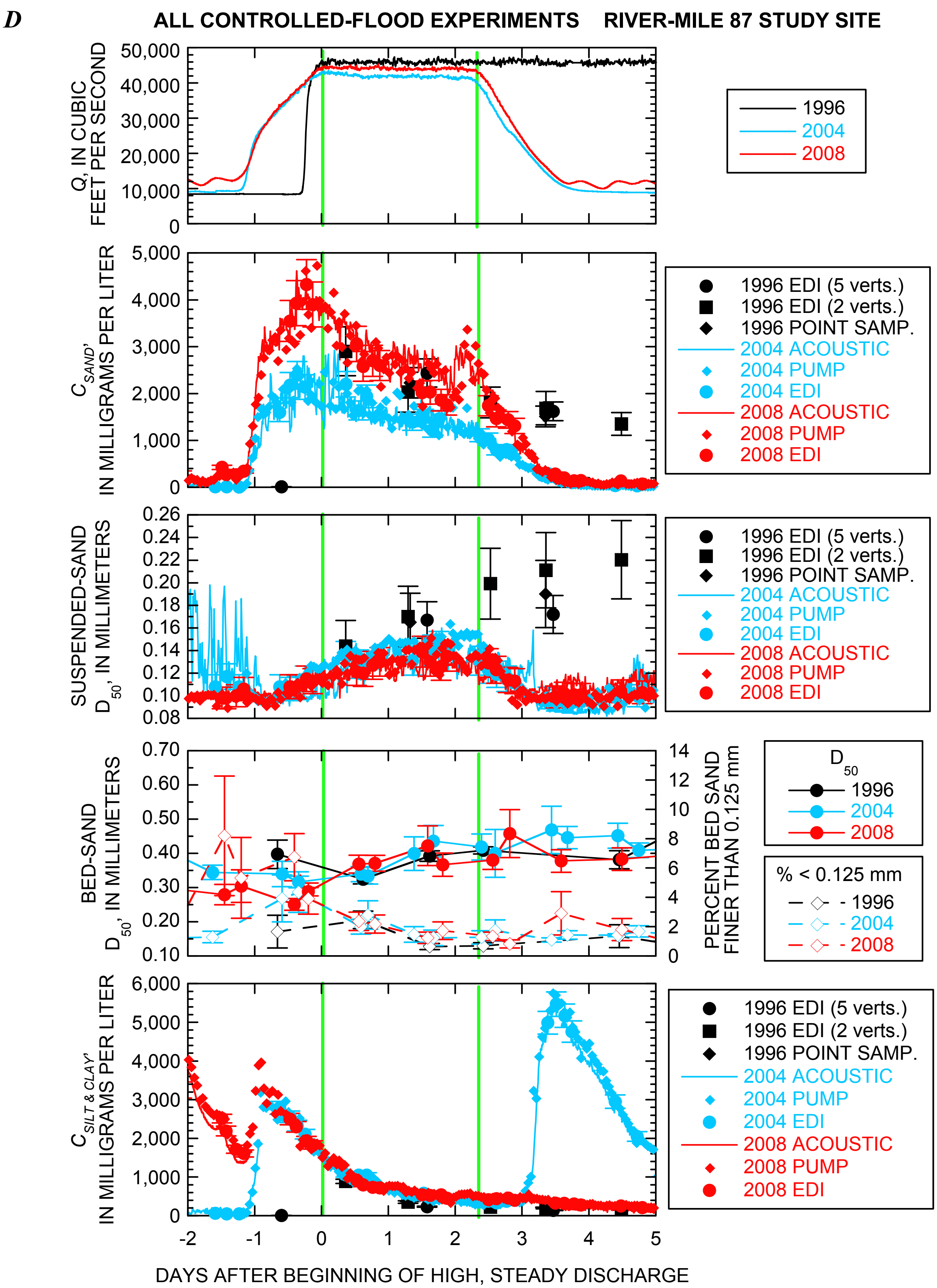

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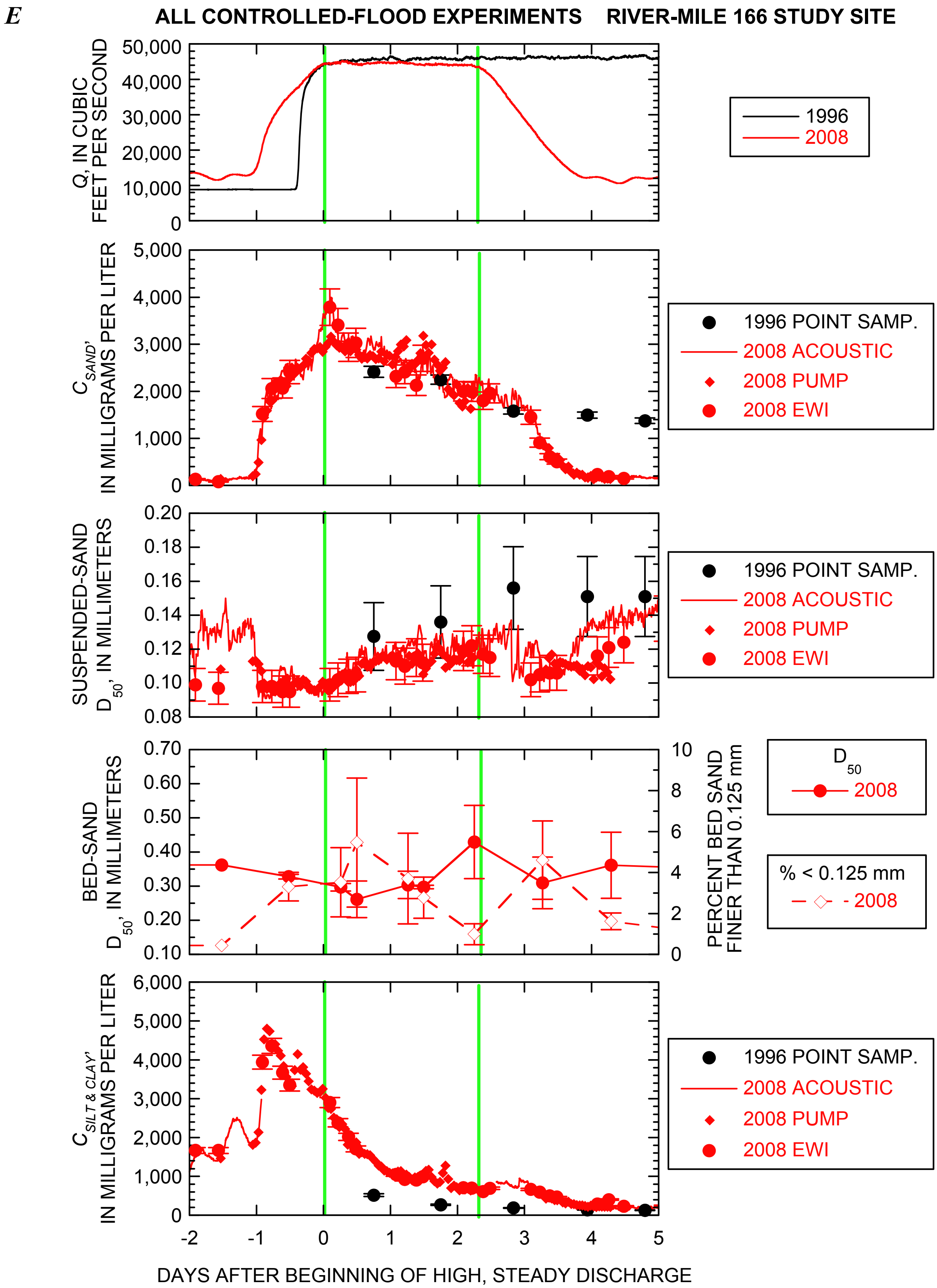

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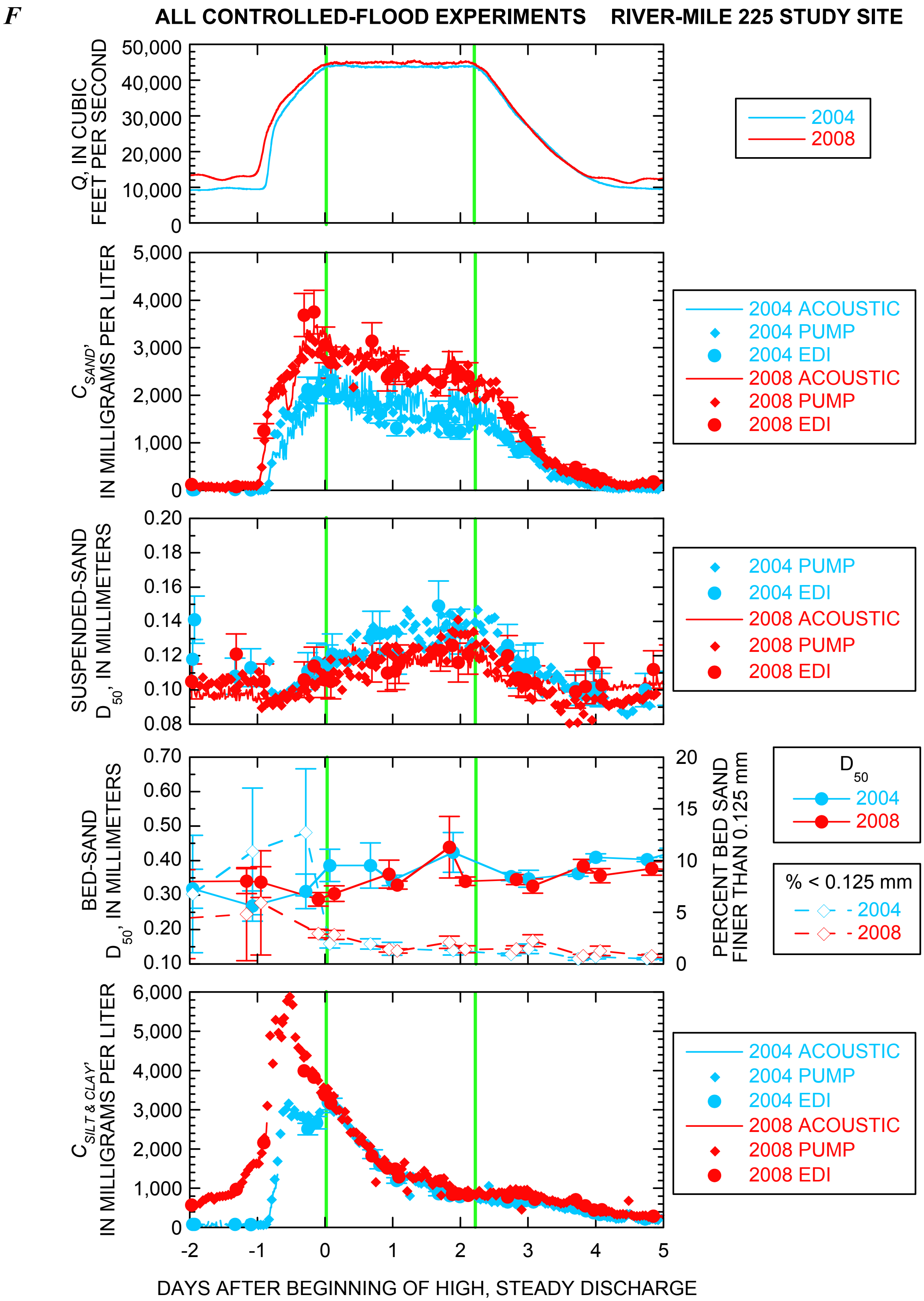


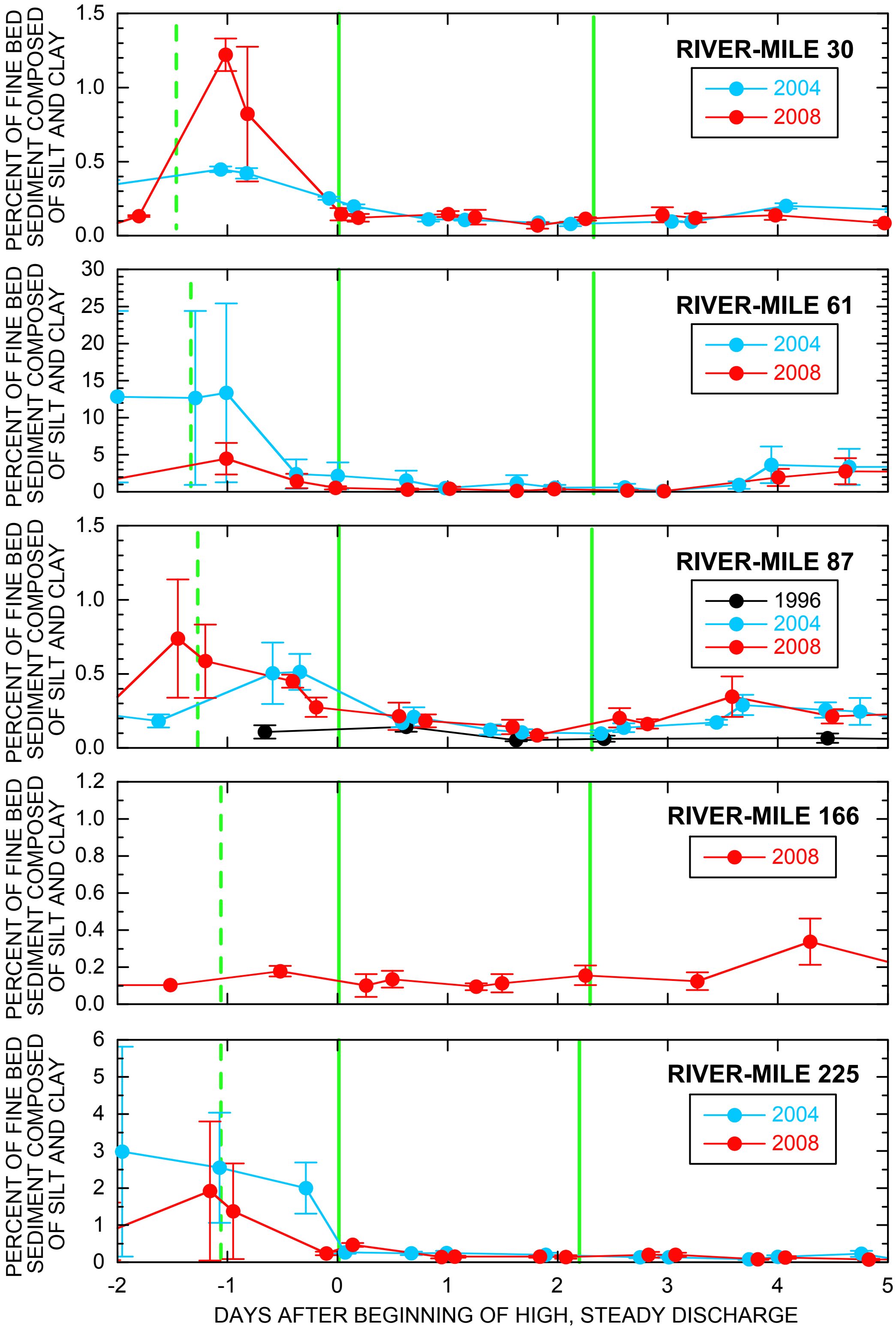
Figure 5. — Continued.

apparent that estimating differences in the upstream sand supply from suspended- or bed-sediment data is a nontrivial exercise that requires coupled analyses of sediment load, concentration, and grain size, with consideration of whether differences in the upstream sand supply could be causing differences in the reach-averaged τ_b. These more complicated analyses are pursued later in this report.

Before conducting these more complicated analyses, it is informative to first evaluate the differences in upstream sediment supply between the three CFEs through ranking of the data collected at each study site in figures 5 and 6 in terms of concentration and grain size. When ranking these data, it is important to realize that, by definition, the suspended-sediment data are more representative of the bed-sediment conditions in the reach upstream from a measurement cross-section than are bed-sediment data collected only at that measurement cross-section. At a given discharge of water, that is, reach-averaged τ_b, differences in the grain-size distribution of the sand in suspension can only be explained by changes in the grain-size distribution of the sand on the bed upstream, with the reach-averaged grain size of the sand on the bed and in suspension being proportional (equation 7). The spatial scale over which suspended sand equilibrates with the bed sand ranges from about 600 m to well over 1 km under typical flow conditions in the Colorado River in the study area (Topping and others, 2007a). Therefore, a proper analysis of the grain-size distribution of the suspended sand will provide a more representative sample of the grain-size distribution of the bed sand in the reach upstream from a measurement cross-section than does only bed-sediment measurements made only at the measurement cross-section (Rubin and Topping, 2001, 2008). For example, the apparent inconsistency at the River-mile 30 study site between the coarser suspended sand during the 2008 CFE than during the 2004 CFE and finer bed sand during the 2008 CFE than during the 2004 CFE can be explained by the bed-sand data at the measurement cross-section being less representative of the bed-sand grain-size distribution in the reach upstream from this study site than are the suspended-sand data.

An alternative explanation to this inconsistency could be that, because more sand was present on the bed upstream from the River-mile 30 study site (table 3), thus resulting in thicker sand patches over much of the bed, the reach-averaged τ_b upstream from the River-mile 30 study site could have been higher during the 2008 CFE than during the 2004 CFE. This difference in reach-averaged τ_b would result in coarser suspended sand during the 2008 CFE than during the 2004 CFE, with bed sand that was finer during the 2008 CFE than during the 2004 CFE. This alternative explanation can be illustrated by moving along a path from the origin up and slightly left of the "D_b = constant" line in figure 3*B* in Rubin and Topping (2001), with the origin representing conditions during the 2004 CFE. Moving along such a path results in an increase in reach-averaged τ_b, a decrease in reach-averaged median grain size of the bed sand, an increase in suspended-sand concentration, and an increase in the median grain size of the suspended sand

Figure 6 (next page). Bed silt and clay data collected at each study site during all three CFEs. Data were shifted in time such that zero time (indicated by the leftmost vertical solid green line) is the beginning of high, steady discharge during each CFE. Right vertical green line indicates the end of the high, steady discharge part of the 2004 and 2008 controlled floods at a given site. As in figure 5, data collected after day 5 of high, steady discharge during the 1996 CFE not shown. Vertical dashed green line indicates beginning of rising limb of 2008 CFE at each study site. Silt and clay were winnowed from the bed at most study sites during the rising limbs of the CFEs. Error bars for the bed-sediment data are one standard error, indicating the 67-percent confidence interval associated with the mean value of the silt and clay fraction among the stations sampled across the cross-section in each bed-sediment measurement.


PERCENT OF FINE BED SEDIMENT COMPOSED OF SILT AND CLAY
RIVER-MILE 30
2004
2008
RIVER-MILE 61
2004
2008
RIVER-MILE 87
1996
2004
2008
RIVER-MILE 166
2008
RIVER-MILE 225
2004
2008
DAYS AFTER BEGINNING OF HIGH, STEADY DISCHARGE

between the 2004 and 2008 CFEs. Whether such a path is physically realistic for this River-mile 30 study-site example can be evaluated by:

(1) setting constant coefficients of proportionality for equations 4 and 7 at the River-mile 30 measurement cross-section between the 2004 and 2008 CFEs,
(2) converting the proportionalities in equations 4 and 7 to equations relating the ratios of *C*, A_b, τ_b, D_b, and D_s at this cross-section between the 2004 and 2008 CFEs,
(3) substituting the values of *C*, D_b, and D_s measured at the measurement cross-section during the first day of steady, high discharge during the 2004 and 2008 CFEs,
(4) solving for values of reach-averaged τ_b and A_b, and
(5) determining whether these values of reach-averaged τ_b and A_b are realistic.

When using conditions during the 2004 CFE as the reference conditions, equation 4 can be rewritten in terms of ratios as:

$$\frac{(C_{SAND})_{2008}}{(C_{SAND})_{2004}} = \left(\frac{(A_b)_{2008}}{(A_b)_{2004}}\right)\left(\frac{(\tau_b)_{2008}}{(\tau_b)_{2004}}\right)^{1.8}\left(\frac{(D_b)_{2008}}{(D_b)_{2004}}\right)^{-2.5}, \qquad (13)$$

where the subscripts "2008" refer to conditions during the 2008 CFE and the subscripts "2004" refer to conditions during the 2004 CFE. Similarly, equation 7 can be rewritten in terms of ratios as:

$$\frac{(D_s)_{2008}}{(D_s)_{2004}} = \left(\frac{(\tau_b)_{2008}}{(\tau_b)_{2004}}\right)^{0.18}\left(\frac{(D_b)_{2008}}{(D_b)_{2004}}\right)^{0.75}. \qquad (14)$$

Using EWI and bed-sediment measurements made on the first day of steady, high discharge at the River-mile 30 study site during both CFEs, the following values of the ratios are obtained: $\frac{(C_{SAND})_{2008}}{(C_{SAND})_{2004}} = 1.4$, $\frac{(D_s)_{2008}}{(D_s)_{2004}} = 1.2$, and $\frac{(D_b)_{2008}}{(D_b)_{2004}} = 0.86$. Inserting these values into equations 13 and 14 and rearranging yields: $\left(\frac{(\tau_b)_{2008}}{(\tau_b)_{2004}}\right) = 5.2$, and $\left(\frac{(A_b)_{2008}}{(A_b)_{2004}}\right) = 0.049$.

These ratios of reach-averaged τ_b and A_b are physically unrealistic, given that the maximum likely 2008 to 2004 ratio in reach-averaged τ_b associated with changes in sand thickness on the bed should be about 1.1 based on the "Theoretical Background" section of this report, and a more likely 2008 to 2004 ratio in reach-averaged A_b should be greater than 1 based on the much greater sand enrichment in upper Marble Canyon antecedent to the 2008 CFE than antecedent to the 2004 CFE (table 3). Support for an approximate 10-percent increase in reach-averaged τ_b and constant water discharge between the 2004 and 2008 CFEs is provided by acoustic-Doppler-current-profiler velocity measurements made at 5 stations across the measurement cross-section at the River-mile 30 study site during both CFEs. These measurements indicate that the mean velocity through the measurement cross-section was on average 6 percent greater at steady, high discharge during the 2008 CFE than it was during the 2004 CFE. This increase in mean velocity was, in fact, associated with a decrease in cross-sectional area at the measurement cross-section arising from greater sand thickness on the bed. Because mean velocity is proportional to τ_b^2, this suggests that the 2008 to 2004 ratio in reach-averaged τ_b associated with the increase in sand thickness on the bed should, in fact, be about 1.1. Inserting this value and the measured $\frac{(D_s)_{2008}}{(D_s)_{2004}} = 1.2$ into equation 14 and rearranging to solve for a more plausible reach-averaged value of $\frac{(D_b)_{2008}}{(D_b)_{2004}}$ yields $\frac{(D_b)_{2008}}{(D_b)_{2004}} = 1.2$, not the above value of $\frac{(D_b)_{2008}}{(D_b)_{2004}} = 0.86$ that is based on bed-sediment measurements made at only the one cross-section where suspended-sediment measurements were made. Furthermore, inserting values of $\frac{(C_{SAND})_{2008}}{(C_{SAND})_{2004}} = 1.4$, $\frac{(D_b)_{2008}}{(D_b)_{2004}} = 1.2$, and $\frac{(\tau_b)_{2008}}{(\tau_b)_{2004}} = 1.1$ into equation 13 and rearranging to solve for a more likely 2008 to 2004 ratio in reach-averaged A_b yields $\left(\frac{(A_b)_{2008}}{(A_b)_{2004}}\right) = 1.9$. For comparison, inserting values of $\frac{(C_{SAND})_{2008}}{(C_{SAND})_{2004}} = 1.4$, $\frac{(D_b)_{2008}}{(D_b)_{2004}} = 1.2$, and $\frac{(\tau_b)_{2008}}{(\tau_b)_{2004}} = 1$ into equation 13 and rearranging to solve for a 2008 to 2004 ratio in reach-averaged A_b that is computed by excluding the effects of changes in bed-sand thickness on reach-averaged τ_b (as done in the analyses later in this report) yields $\left(\frac{(A_b)_{2008}}{(A_b)_{2004}}\right) = 2.2$. Therefore (1) as suggested above, the apparent suspended- and bed-sand grain-size inconsistency at the River-mile 30 study site between the 2004 and 2008 CFEs can best be explained by the bed-sand data at the measurement cross-section being less representative of the bed-sand grain-size distribution in the reach upstream from this study site than are the suspended-sand data, and (2) changes in reach-averaged τ_b arising from reach-averaged changes in bed-sand thickness may play an important role in regulating suspended-sand concentration and median grain size: however, exclusion of this role will likely result in only an approximate 16-percent error in reach-averaged bed-sand area estimated from suspended-sediment data.

With the notable exception of the suspended- and bed-sand grain-size inconsistency at only the River-mile 30 study site, the general results from the simple comparative analyses in figures 5 and 6 are:

(1) Average suspended-sand concentrations at each study site during the 2008 CFE were as high as or higher than during all other CFEs.

(2) Except at the River-mile 87 study site, average suspended-sand concentrations at each study site during the 1996 CFE were as low as or lower than during all other CFEs.

(3) Average suspended-sand median grain size at and and downstream from the River-mile 61 study site during the 2008 CFE was as fine as or finer than during all other CFEs. At the River-mile 0 study site, average suspended-sand median grain size was finest during the 1996 CFE, and at the River-mile 30 study site, average suspended-sand median grain size was finest during the 2004 CFE.

(4) Though not necessarily representative of the grain size of the bed sand in the reaches upstream from these cross-sections, the bed sand at the measurement cross-sections during the 2008 CFE was as fine as or finer than that during the 2004 CFE. Most of the difference in the bed-sand grain-size distribution between these two CFEs was during the rising limb, when the bed during the 2008 CFE was considerably finer than during the 2004 CFE.

(5) At the one measurement cross-section where bed-sediment data were collected during all three CFEs, at the River-mile 87 study site, the bed sand during the 2008 CFE was

slightly finer than that during both the 1996 and 2004 CFEs. Bed-sand median grain size was similar at this study site during the 1996 and 2004 CFEs.

(6) Except at the River-mile 30 study site, where suspended-silt-and-clay concentrations were higher during the 2004 CFE than during the 2008 CFE, average suspended-silt-and-clay concentrations during the 2008 CFE were as high as or higher than during all other CFEs.

(7) There was typically more silt and clay present in the bed sediment before the 2008 CFE than there was before the 2004 CFE or 1996 CFE.

Data Collected During Each CFE at All Study Sites

Comparison of the suspended-sand data collected during each CFE at all study sites is provided in figure 7.

Averaged over the 1996 CFE, suspended-sand concentration increased between the River-mile 0 and 87 study sites and then remained constant between the River-mile 87 and 166 study sites. As the concentration of suspended sand increased between the River-mile 0 and 87 study sites, suspended-sand median grain size coarsened. Suspended-sand median grain size then fined between the River-mile 87 and 166 study sites while suspended-sand concentration remained constant.

Averaged over the 2004 CFE, suspended-sand concentration increased the most between the River-mile 0 and 30 study sites. Between the River-mile 30 and 61 study sites, suspended-sand concentration again increased, but to a lesser degree, and then remained approximately constant between the River-mile 61 and 225 study sites. However, suspended-sand concentration during the rising limb at the River-mile 87 study site was greater than at either the River-mile 61 or 225 study sites. Suspended-sand median grain size was coarsest at the River-mile 0 study site and finest at the River-mile 30 study site. Between the River-mile 30 and 87 study sites, suspended-sand median grain size coarsened; between the River-mile 87 and 225 study sites, suspended-sand median grain size fined to be approximately equal to that at the River-mile 61 study site. Suspended-sand median grain size was anomalously coarse during the rising limb at the River-mile 61 study site, nearly as coarse as at the River-mile 0 study site.

Averaged over the 2008 CFE, suspended-sand concentration increased the most between the River-mile 0 and 30 study sites, as it did during the 2004 CFE. Similarly, during the 2008 CFE, suspended-sand concentration increased between the River-mile 30 and 61 study sites, as it did during the 2004 CFE. In contrast to the 2004 CFE, however, suspended-sand concentrations continued to increase between the River-mile 61 and 87 study sites over the entire flood hydrograph, not just during the rising limb. Downstream from the River-mile 87 study site, suspended-sand concentration decreased between the River-mile 87 and 166 study sites, mostly during the rising limb; suspended-sand concentration then remained approximately constant between the River-mile 166 and 225 study sites, although at a level greater than at the River-mile 61 study site. Suspended-sand median grain size was coarsest at the River-mile 30 study site and finest at the River-mile 166 study site; in contrast, during the 2004 CFE, suspended-sand median grain size was finest at the River-mile 30 study site. Suspended-sand median grain size coarsened between the River-mile 0 and 30 study sites and then fined between the River-mile 30 and 166 study sites. Suspended-sand median grain size then coarsened, but only slightly between the River-mile 166 and 225 study sites.

These observations encompass almost every possible coupled change in suspended-sand concentration and grain size through a reach (table 5). The following coupled changes in suspended-sand concentration and grain size have been observed during a CFE through the long

A

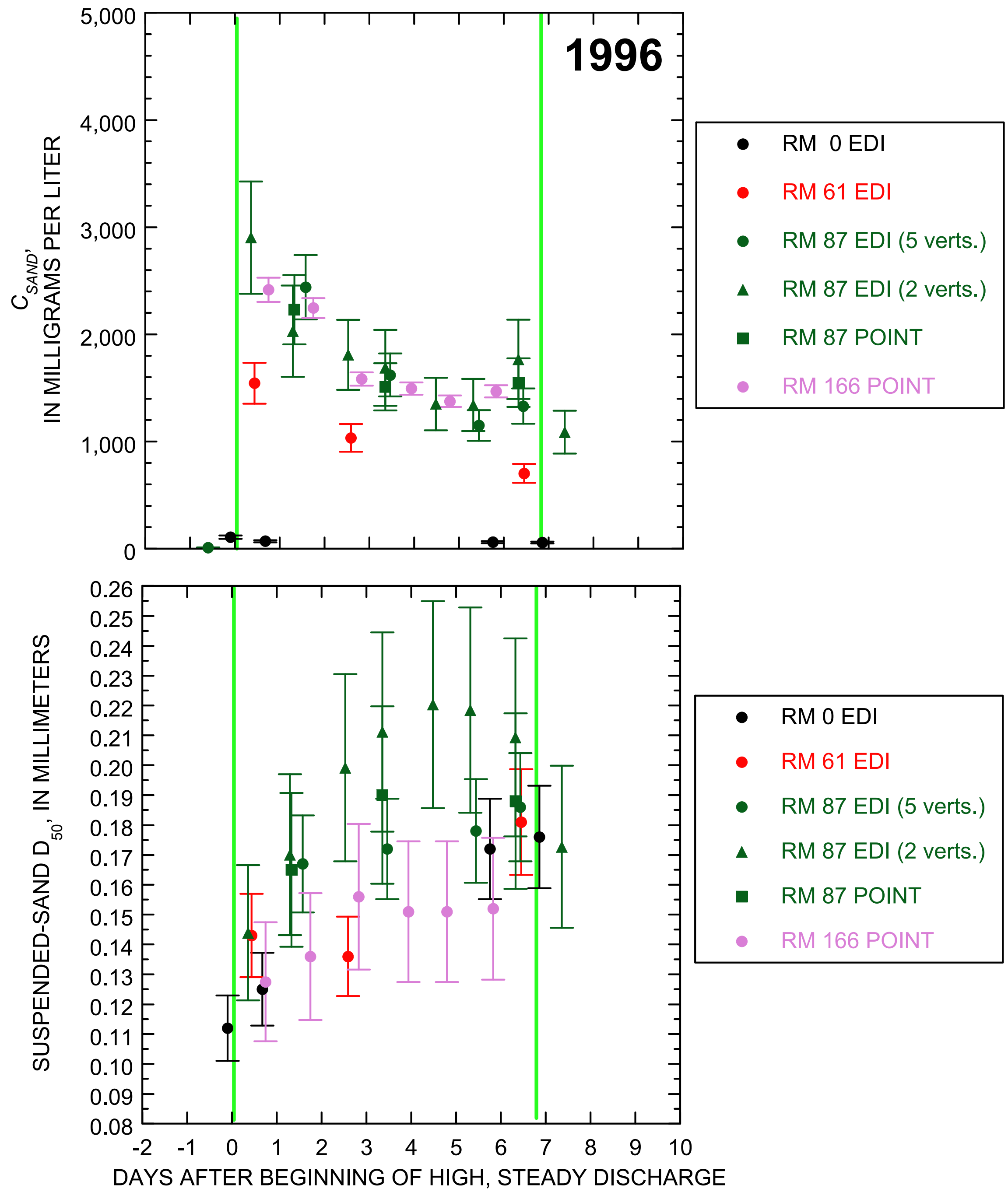


Figure 7. Suspended-sand data collected during each CFE at all study sites. Upper graphs, suspended-sand concentration; lower graphs, suspended-sand median grain size. Data were shifted in time such that zero time (indicated by the leftmost vertical solid green line) is the beginning of high, steady discharge during each CFE. Right vertical green line indicates the end of the high, steady discharge part of the 1996, 2004, and 2008 controlled floods at a given site. Error bars for the EDI, EWI, or mean point suspended-sediment concentration and grain-size data indicate the 95-percent confidence interval associated with these measurements (incorporating the field and laboratory errors described above). *A*, 1996 CFE. *B*, 2004 CFE. *C*, 2008 CFE.

B

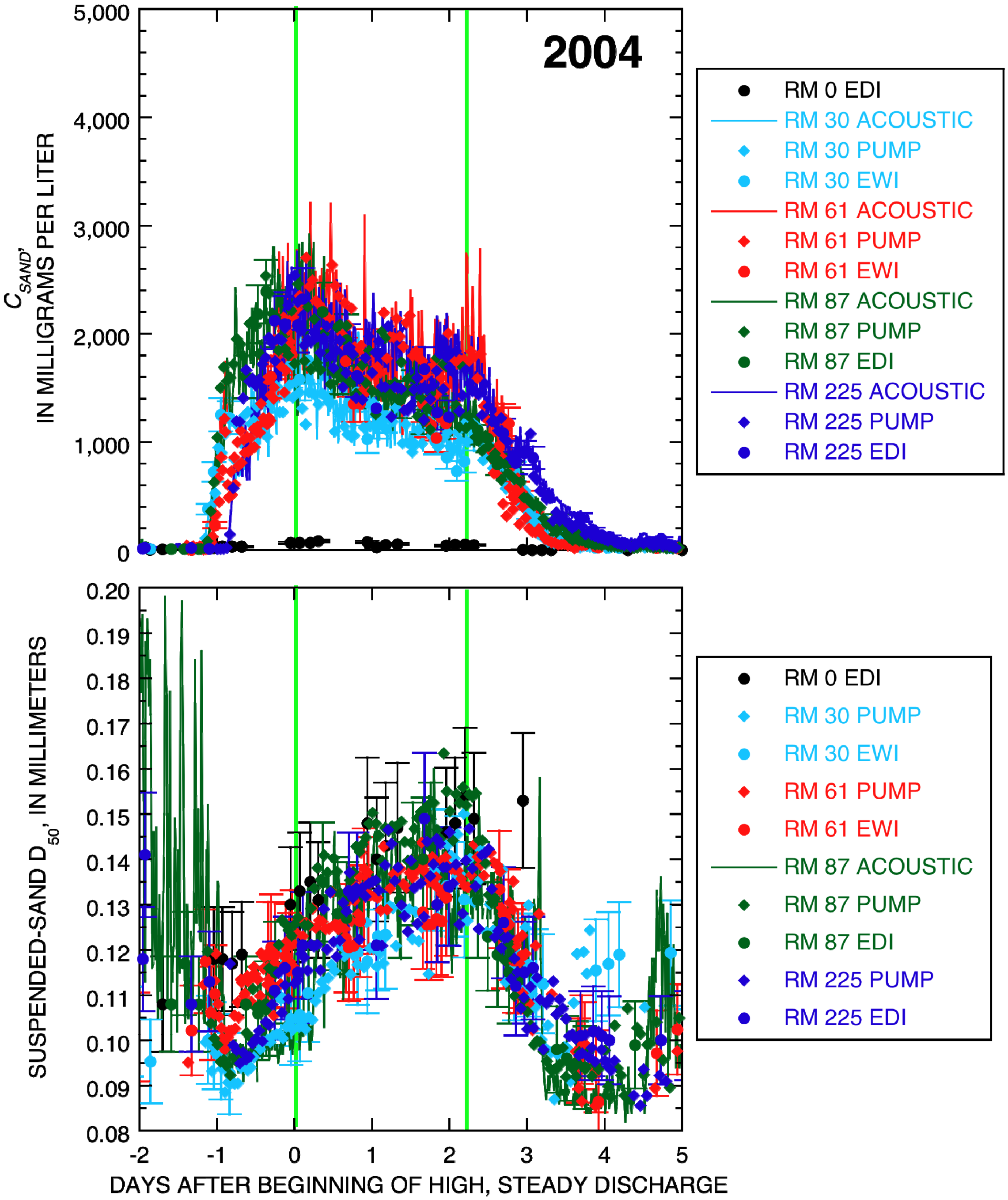


Figure 7. — Continued.

C

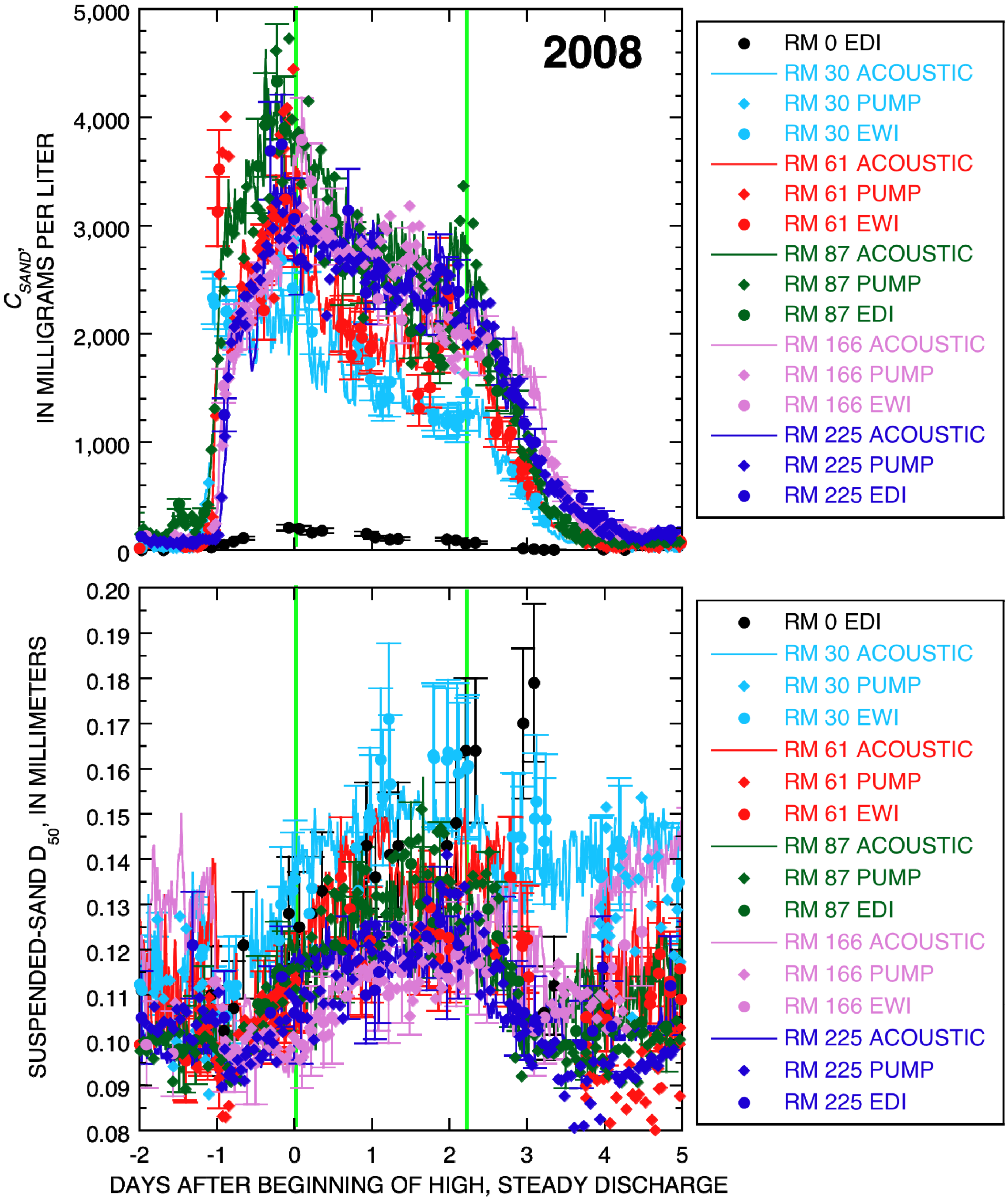


Figure 7. — Continued.

reaches between the study sites:

(1) concentration increase with coarsening,
(2) concentration increase with no change in grain size,
(3) concentration increase with fining,
(4) concentration decrease with fining,
(5) no change in concentration with fining, and
(6) no change in concentration with coarsening.

Of these six different coupled changes in concentration and median grain size, numbers 1, 2, and 6 require a longitudinal increase in bed-sand area in the downstream direction through a reach (at assumed constant reach-averaged τ_b), numbers 4 and 5 require a longitudinal decrease in bed-sand area in the downstream direction through a reach, and only number 3 requires a longitudinal decrease in bed-sand median grain size in the downstream direction through a reach. Interestingly, only the following two coupled changes in suspended-sand concentration and median grain size have not yet been observed during a CFE through the long reaches between the study sites: (1) concentration decrease with coarsening and (2) concentration decrease with no change in median grain size. As shown below, however, these last two coupled changes in concentration and median grain size have been observed over shorter reaches than those between the study sites in the suspended-sand data collected during the 2004 and 2008 Lagrangian sampling programs. Therefore, any possible coupled change in suspended-sand concentration and median grain size is possible in the downstream direction through a reach of the Colorado River during a CFE, depending on the details of the longitudinal distribution of the upstream sand supply (for example, downstream changes in reach-averaged bed-sand area and median grain size) and the details of the longitudinal distribution of the reach-averaged τ_b antecedent to the CFE.

Table 5. Observed coupled changes in suspended-sand concentration and median grain size through each reach during each CFE.

<table>
<tr><th>Reach</th><th>1996 CFE</th><th>2004 CFE</th><th>2008 CFE</th></tr>
<tr><td>upper Marble Canyon</td><td rowspan="2">Concentration increase with slight coarsening</td><td>Concentration increase with fining</td><td>Concentration increase with coarsening</td></tr>
<tr><td>lower Marble Canyon</td><td>Concentration increase with coarsening</td><td>Concentration increase with fining</td></tr>
<tr><td>eastern Grand Canyon</td><td>Concentration increase with coarsening</td><td>Slight rising limb concentration increase then no concentration change with coarsening</td><td>Concentration increase with no change in median grain size</td></tr>
<tr><td>east-central Grand Canyon</td><td>No change in concentration with fining</td><td rowspan="2">No net change in concentration with fining (opposing concentration changes on rising and receding limbs)</td><td>Slight concentration decrease with fining</td></tr>
<tr><td>west-central Grand Canyon</td><td>No data</td><td>No change in concentration with coarsening</td></tr>
</table>

Sediment Export Past the Study Sites During the 1996, 2004, and 2008 CFEs

Using the same approach used to compute sand export in table 2, sand export and silt and clay export past the various study sites during the 1996, 2004, and 2008 CFEs are provided in table 6. As in table 2, uncertainties are 5 percent for the sand loads at the study sites on the Colorado River. Uncertainties used for the silt and clay loads are 2 percent. Loads during each CFE are computed from the beginning of the rising limb through the recession. At each study site, sand loads during the 1996 CFE are typically as large as or larger than those during the 2004 and 2008 CFEs because of the much greater duration of high, steady discharge during the 1996 CFE.

Table 6. Sand export and silt and clay export past the study sites on the Colorado River during the 1996, 2004, and 2008 CFEs.

Study site	Sand export with uncertainty during the 1996 CFE (million metric tons)	Sand export with uncertainty during the 2004 CFE (million metric tons)	Sand export with uncertainty during the 2008 CFE (million metric tons)
River-mile 0	0.06±0.003	0.020±0.001	0.048±0.002
River-mile 30	no data	0.476±0.024	0.651±0.033
River-mile 61	0.84±0.04	0.657±0.033	0.879±0.044
River-mile 87	1.52±0.08	0.622±0.031	1.197±0.060
River-mile 166	1.54+0.08	no data	1.076±0.054
River-mile 225	no data	0.689±0.034	1.055±0.053
Study site	Silt and clay export with uncertainty during the 1996 CFE (million metric tons)	Silt and clay export with uncertainty during the 2004 CFE (million metric tons)	Silt and clay export with uncertainty during the 2008 CFE (million metric tons)
River-mile 0	0.01±0.0002	0.004±0.0001	0.010±0.0002
River-mile 30	no data	0.177±0.004	0.109±0.002
River-mile 61	0.14±0.002	0.278±0.006	0.236±0.005
River-mile 87	0.24±0.005	0.489±0.010	0.464±0.009
River-mile 166	0.22±0.004	no data	0.715±0.014
River-mile 225	no data	0.646±0.013	0.866±0.017

Sand Budgeting During the 2004 and 2008 CFEs

Employing the same approach used to compute the mass-balance sand budgets during the accounting periods antecedent to the 2004 and 2008 CFEs in table 3, sand budgets for the periods from the beginning of the accounting periods antecedent to each CFE through the recession of each of the 2004 and 2008 CFEs are provided in table 7. For simplicity, this extended sand-budgeting period is herein referred to as the CFE sand-budgeting period. These sand budgets were computed using the data in tables 3 and 6, with propagated uncertainty. As in table 3, no sand enrichment or depletion can be demonstrated in a reach when the propagated uncertainties are much larger than the absolute value of the change in sand storage during the CFE sand-budgeting period; in table 7 this threshold uncertainty value is arbitrarily set equal to a factor of 1.5 times the absolute value of

Table 7. Sand budgets for each reach during the 2004 and 2008 CFE sand-budgeting periods.

[Reaches without demonstrable change in sand storage (that is, propagated uncertainty is much greater than the absolute value of net change in sand storage) indicated by red type. Reaches with likely but not necessarily positive net change in sand storage (that is, propagated uncertainty is only slightly greater than positive value of net change in sand storage) shown in black type. Reaches with demonstrable positive change in sand storage (that is, propagated uncertainty is less than positive value of net change in sand storage) indicated by green type. No reaches can be demonstrated to have negative net change in sand storage during the sand-budgeting periods for either CFE.]

Reach	Net change in sand storage during 2004 CFE sand-budgeting period with propagated uncertainty (million metric tons)	Net change in sand storage during 2008 CFE sand-budgeting period with propagated uncertainty (million metric tons)
upper Marble Canyon	-0.073±0.133	+0.592±0.663
lower Marble Canyon	-0.067±0.105	+0.307±0.353
eastern Grand Canyon	+0.021±0.112	+0.518±0.766
combined east-central and west-central Grand Canyon	+0.089±0.161	+1.059±0.508

the change in sand storage. As one measure of the sustainability of a given controlled-flood design in building sandbars, the sand budget for the accounting period antecedent to a controlled flood through the recession of that controlled flood should not be negative. In other words, a controlled flood should not be demonstrated to have exported more sand from a reach than was supplied to that reach during the period leading up to the controlled flood. If a controlled flood can be shown to have exported more sand from a reach than was supplied to it during the period leading up to that controlled flood, then that particular controlled-flood design scoured sand from “background storage” in that reach and cannot be used to sustainably rebuild sandbars; this scenario is likely what happened during the 1996 CFE in Marble Canyon, based on Schmidt (1999). As shown in table 7, in all reaches where sand budgets could be computed for the 2004 CFE, no demonstrable change in sand storage occurred in any reach during the 2004 CFE sand-budgeting period because the uncertainties were much larger than absolute values of change in sand storage. In contrast, during the much more sand-enriched 2008 CFE, the sand budgets in the upstream three reaches (upper Marble, lower Marble, and Grand Canyons) were likely but not necessarily positive during the 2008 CFE sand-budgeting period. The sand budgets in these three reaches were likely but not necessarily positive because the changes in sand storage were all positive, but the uncertainties were slightly larger than the changes in sand storage. Only in one reach and only during the 2008 CFE was a sand budget demonstrably positive, in the combined east- and west-central Grand Canyon reach located between the River-mile 87 and 225 study sites.

Lagrangian Sampling-Program data

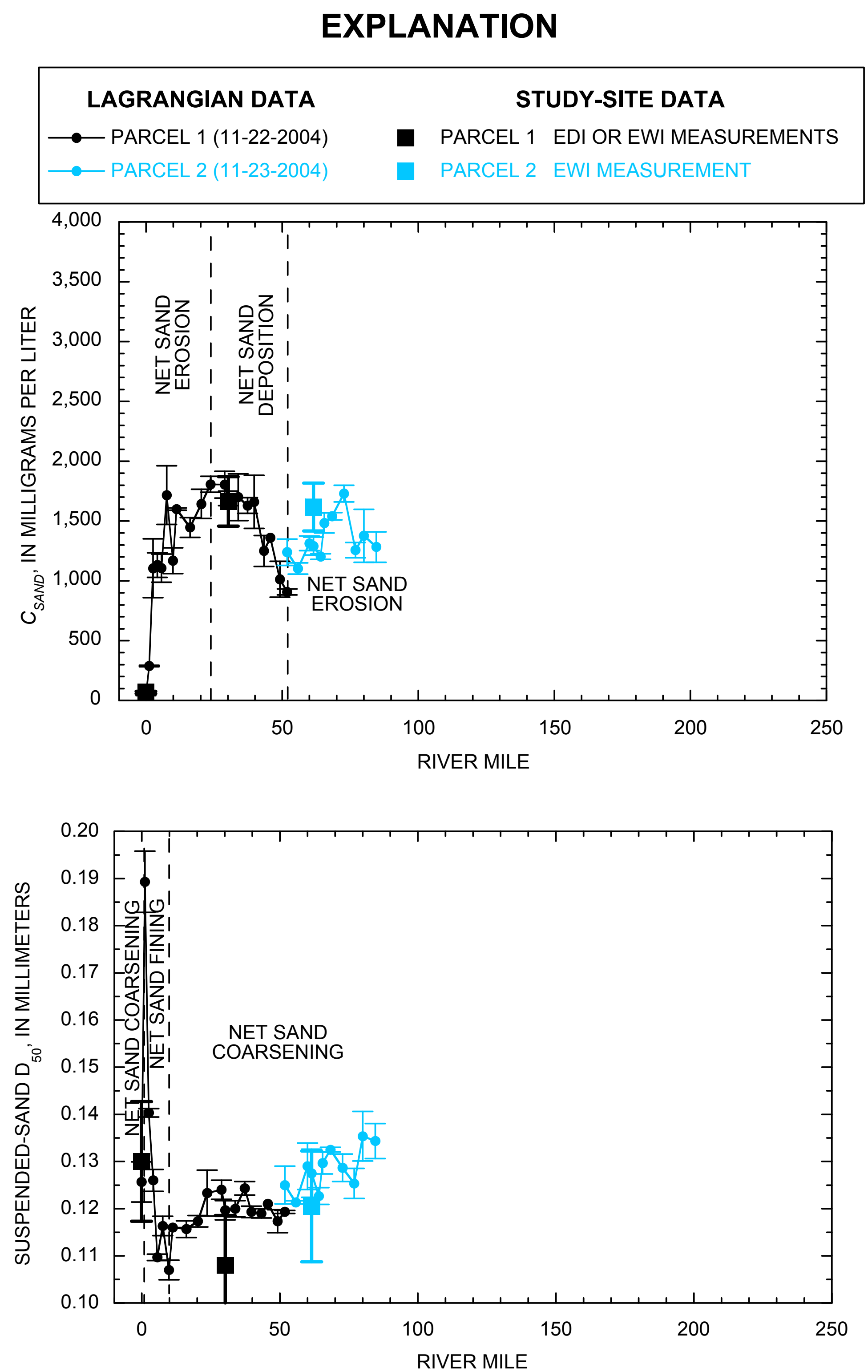
Suspended-sediment data collected during the 2004 and 2008 Lagrangian sampling programs are presented in figure 8, with each sampled parcel of water indicated by a different color. Also shown are the EDI, EWI, or calibrated pump measurements made at the study sites in close temporal proximity to the Lagrangian data in each parcel of water. Agreement is excellent between all Lagrangian and study-site suspended-sediment data except during the sampling of water parcel 5 near the River-mile 225 study site during the 2008 CFE. Although agreement is good between the Lagrangian data and data collected at this study site with respect to suspended-sand median grain size and suspended-silt-and-clay concentration, agreement is poor between Lagrangian data and data collected at this study site with respect to suspended-sand concentration.

Analysis of the Lagrangian data collected during the 2004 and 2008 CFEs allows identification of reaches of net sediment erosion or deposition, as well as identification of reaches of net change in suspended-sand median grain size. This analysis is possible by virtue of conservation of mass between the bed and the water column, and by the assumption that the spatial patterns in the suspended sediment observed in a sampled parcel of water are similar to spatial patterns in suspended sediment in other parcels of water traveling through the same reach at different times during a CFE. This assumption is most justified in cases where the flood duration is relatively short, as in the cases of the 2004 and 2008 CFEs, and in cases where step changes in concentration and grain size are relatively small during backward or forward steps in the Lagrangian reference frame. Because the discharge of water is constant during the high, steady discharge parts of the CFEs, an increase in the suspended-sediment concentration in a parcel of water traveling downstream through a reach indicates a net flux of sediment from the bed to the water column in this reach, that is, erosion of sediment in this reach. Likewise, a decrease in the suspended-sediment concentration in a parcel of water traveling downstream through a reach indicates a net flux of sediment from the water column to the bed in this reach, that is, deposition of sediment in this reach.

During the 2004 CFE, analysis of the Lagrangian data between river miles 0 and 85 indicates that net sand erosion occurred between river miles 0 and 24 in Marble Canyon, net sand deposition occurred between river miles 24 and 52 in Marble Canyon, and net sand erosion occurred between river miles 52 and 85 in Marble and eastern Grand Canyons (fig. 8*A*). The suspended sand quickly coarsened between river miles 0 and 1 (reaching its maximum value), fined between river miles 1 and 10 (reaching its minimum value), and then coarsened gradually between river miles 10 and 85 (fig. 8*A*). Net erosion of silt and clay occurred between river miles 0 and 85 (fig. 8*B*). The downward step in silt and clay concentration between water parcels 1 and 2 in fig. 8*B* does not represent net deposition of silt and clay overnight while the sampling program was in camp and merely reflect a backward step in the Lagrangian reference frame associated with

Figure 8 (next pages). Suspended-sediment measurements made during the Lagrangian sampling programs during the 2004 and 2008 CFEs. Data collected in different parcels of water are indicated by different colors. Also shown are the EDI, EWI, or calibrated-pump suspended-sediment data collected in closest temporal proximity to the Lagrangian suspended-sediment data in each parcel of water. Step changes between the data collected in the various parcels of water arise from reference-frame effects (see text for discussion). Error bars for the Lagrangian data are one standard error, indicating the 67-percent confidence interval associated with the mean values of these data among the three replicate single-vertical depth-integrated suspended-sediment samples collected at each sampling station. As in previous figures, error bars for the EDI and EWI suspended-sediment concentration and grain-size data indicate the 95-percent confidence interval associated with these measurements (incorporating the field and laboratory errors described above). *A*, Suspended-sand concentration and median grain size measured during the 2004 Lagrangian sampling program. *B*, Suspended-silt-and-clay concentration measured during the 2004 Lagrangian sampling program. *C*, Suspended-sand concentration and median grain size measured during the 2008 Lagrangian sampling program. The reason a calibrated pump measurement is used for comparison with the Lagrangian data collected in water parcel 3 is that no EDI measurement was made at the River-mile 87 study site until several hours after the Lagrangian sampling program passed this study site. *D*, Suspended-silt-and-clay concentration measured during the 2008 Lagrangian sampling program.

A


EXPLANATION
LAGRANGIAN DATA
PARCEL 1 (11-22-2004)
PARCEL 2 (11-23-2004)
STUDY-SITE DATA
PARCEL 1 EDI OR EWI MEASUREMENTS
PARCEL 2 EWI MEASUREMENT
NET SAND EROSION
NET SAND DEPOSITION
NET SAND EROSION
C SAND, IN MILLIGRAMS PER LITER
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
0
50
100
150
200
250
RIVER MILE
NET SAND COARSENING
NET SAND FINING
NET SAND COARSENING
SUSPENDED-SAND D50, IN MILLIMETERS
0.10
0.11
0.12
0.13
0.14
0.15
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0.17
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50
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150
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250
RIVER MILE

B

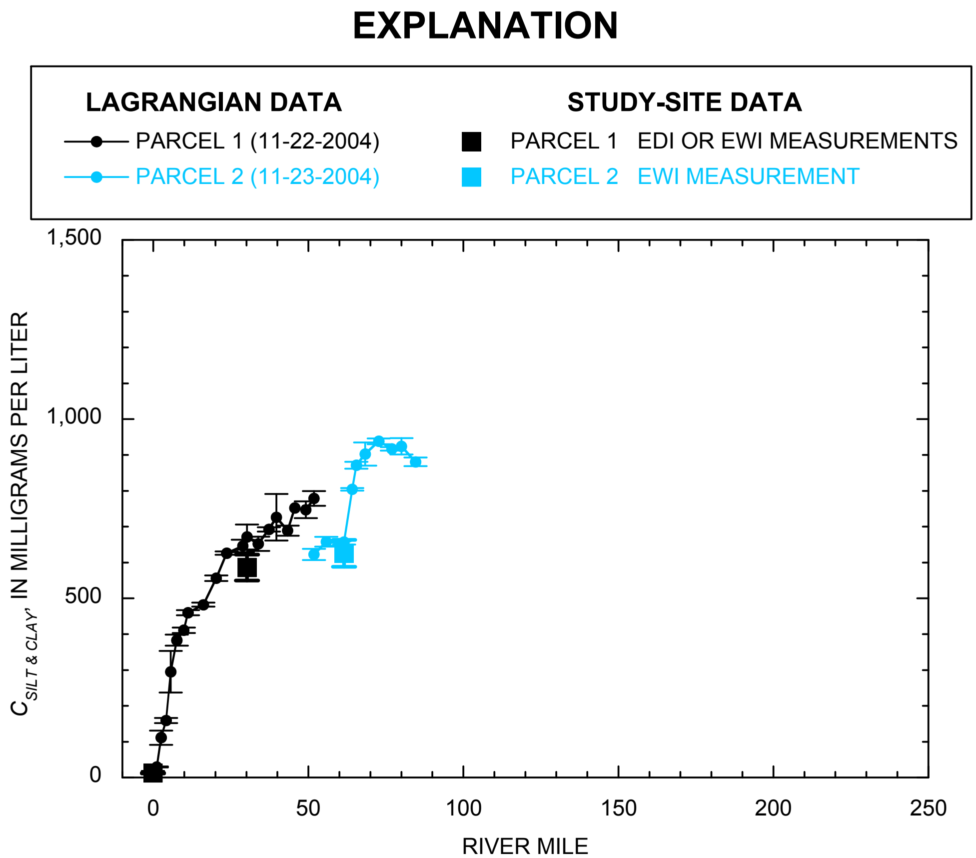
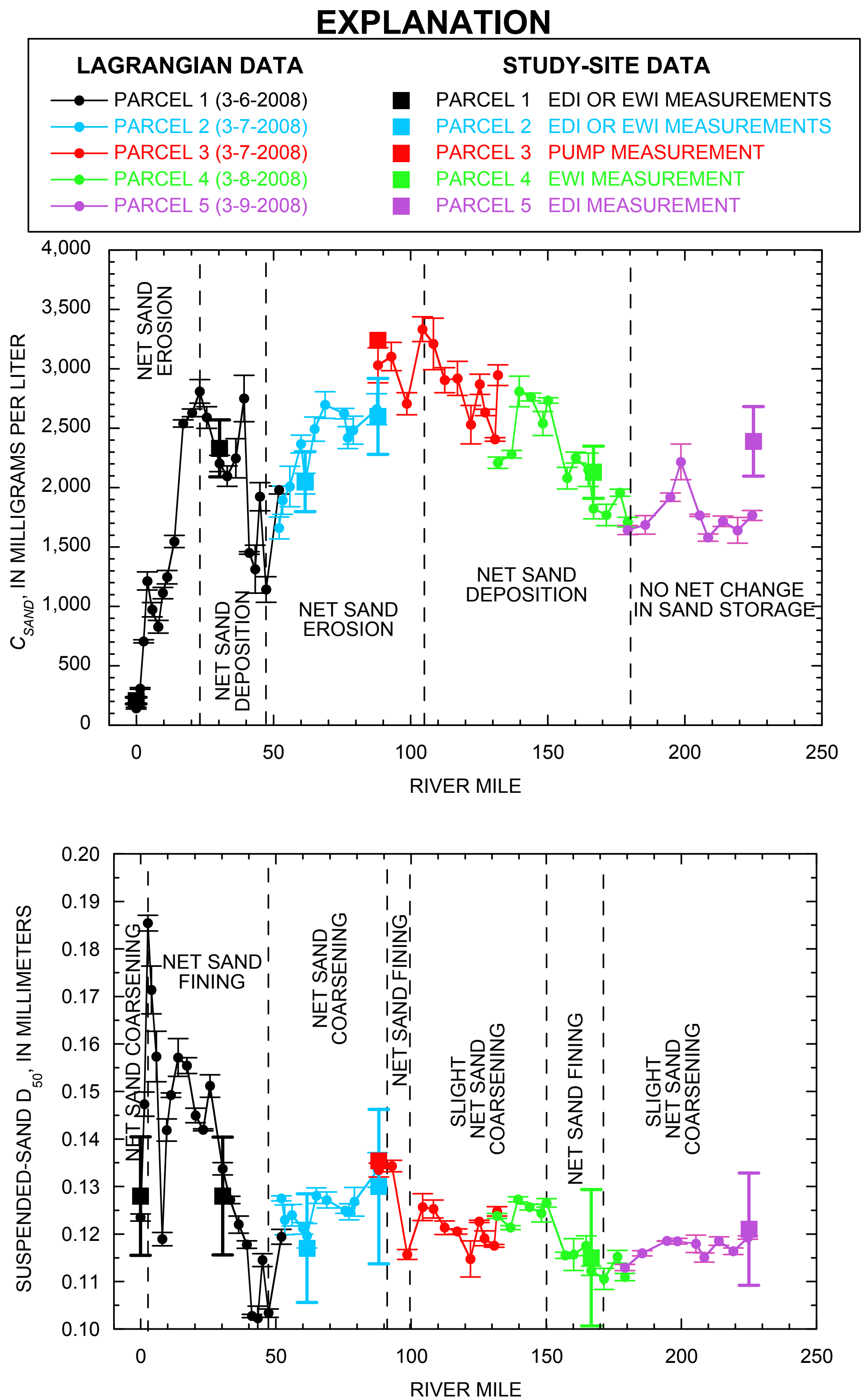


Figure 8. — Continued.

C



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D

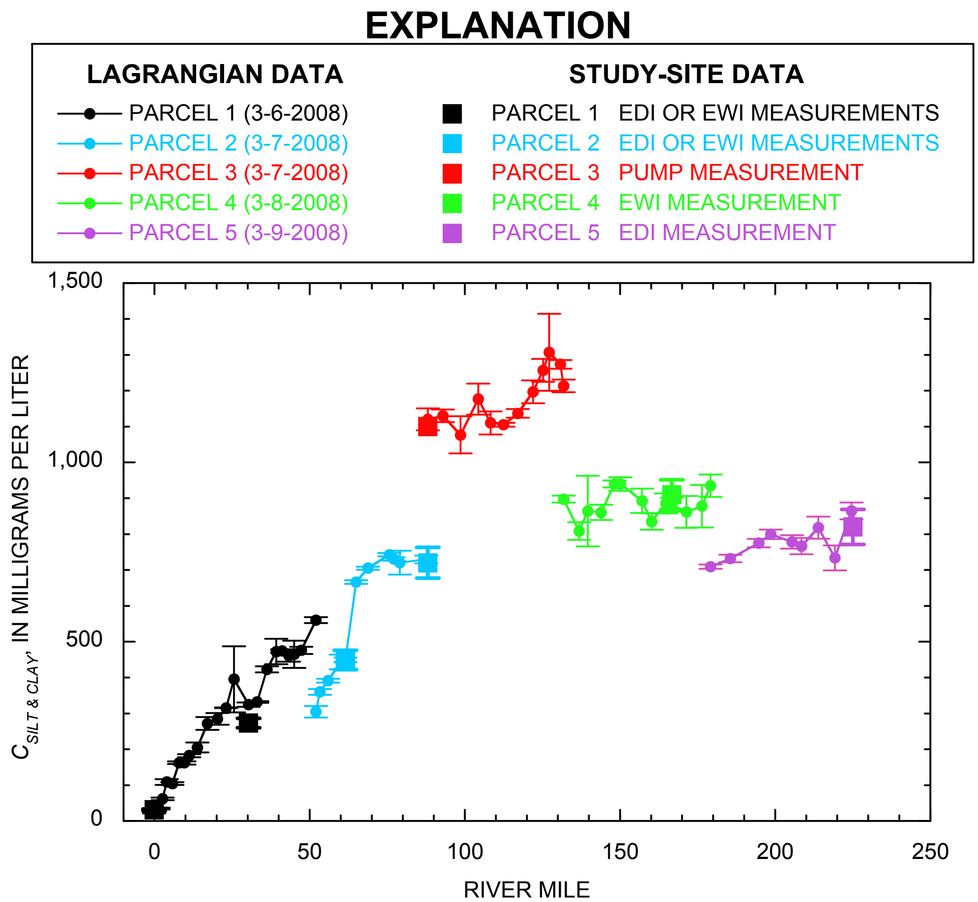

Figure 8. — Continued.

switching from water parcel 1 to 2. Note that this step change is much larger than and opposite in sign to the associated step changes in suspended-sand concentration and median grain size between these two water parcels in figure 8*A*.

During the 2008 CFE, analysis of the Lagrangian data between river miles 0 and 225 indicates that net sand erosion occurred between river miles 0 and 24 in Marble Canyon (identically as during the 2004 CFE), net sand deposition occurred between river miles 24 and 47 in Marble Canyon (very similar to what happened during the 2004 CFE), net sand erosion occurred between river miles 47 and 105 in Marble and eastern Grand Canyons, net sand deposition occurred between river miles 105 and 179 in Grand Canyon, and no net change in sand storage occurred between river miles 179 and 225 in Grand Canyon (fig. 8*C*). As during the 2004 CFE, the suspended sand quickly coarsened between river miles 0 and 2.5, reaching its maximum value (fig. 8*C*). However, downstream from river mile 2.5, the longitudinal patterns in suspended-sand median grain size were far more complicated during the 2008 CFE than during the 2004 CFE. Although the suspended sand fined dramatically between river mile 2.5 and 8 (similarly as during the 2004 CFE), the suspended sand then coarsened substantially between river miles 8 and 13.5 before fining to its minimum value near river mile 42. Thus, the longitudinal patterns in suspended-sand median grain size were very different in upper Marble Canyon between the 2004 and 2008 CFEs. Downstream from river mile 47, however, the longitudinal patterns in suspended-sand median grain size were similar (at least through the end of the 2004 Lagrangian sampling program near river mile 85). During the 2008 CFE, suspended-sand median grain size was characterized by three long reaches of gradual coarsening (between river miles 47 and 91, 100 and 150, and 171 and 225) separated by two short reaches of abrupt fining (between river miles 91 and 100, and 150 and 171). It is important to note that these two prominent downward steps in suspended-sand median grain size are real because they do not coincide with breaks in camp between the different sampled parcels of water (that is, they are not a result of backward steps in the Lagrangian reference frame). As during the 2004 CFE, net erosion of silt and clay occurred during the 2008 CFE over the entire reach sampled. During the 2008 CFE, this was the reach from river mile 0 to 225 (fig. 8*D*). The upward and downward steps in sand concentration and silt and clay concentration between the water parcels in figures 8*C* and 8*D* are merely reference-frame effects. The downward steps in sand concentration and silt and clay concentration between water parcels 1 and 2, and between 3, 4, and 5 arise from the decrease in sand concentration and silt and clay concentration over time during the 2008 CFE at all locations along the Colorado River (that is, backward steps in the Lagrangian reference frame associated with switching between these different parcels of water). The upward step in sand concentration and silt and clay concentration between parcels 2 and 3 is an artifact of these two water parcels being sampled simultaneously by two field crews[17] (that is, a forward step in the Lagrangian reference frame associated with switching from water parcel 2 to 3). Thus, this upward step also arises from the decrease in sand concentration and silt and clay concentration over time during the 2008 CFE at all locations along the Colorado River.

Direct comparison of the Lagrangian data collected during the 2004 and 2008 CFEs shows the similarity in Marble and eastern Grand Canyons in the longitudinal patterns in suspended-sand concentration and the large differences in Marble Canyon in the longitudinal patterns in suspended-sand median grain size between the two CFEs (fig. 9). The peaks and troughs in suspended-sand concentration occurred at essentially the same locations in Marble and eastern Grand Canyons

[17] Water parcel 3 was sampled beginning at the River-mile 87 study site in the morning on March 7, whereas water parcel 2 was sampled ending at the River-mile 87 study site in the afternoon of March 7.

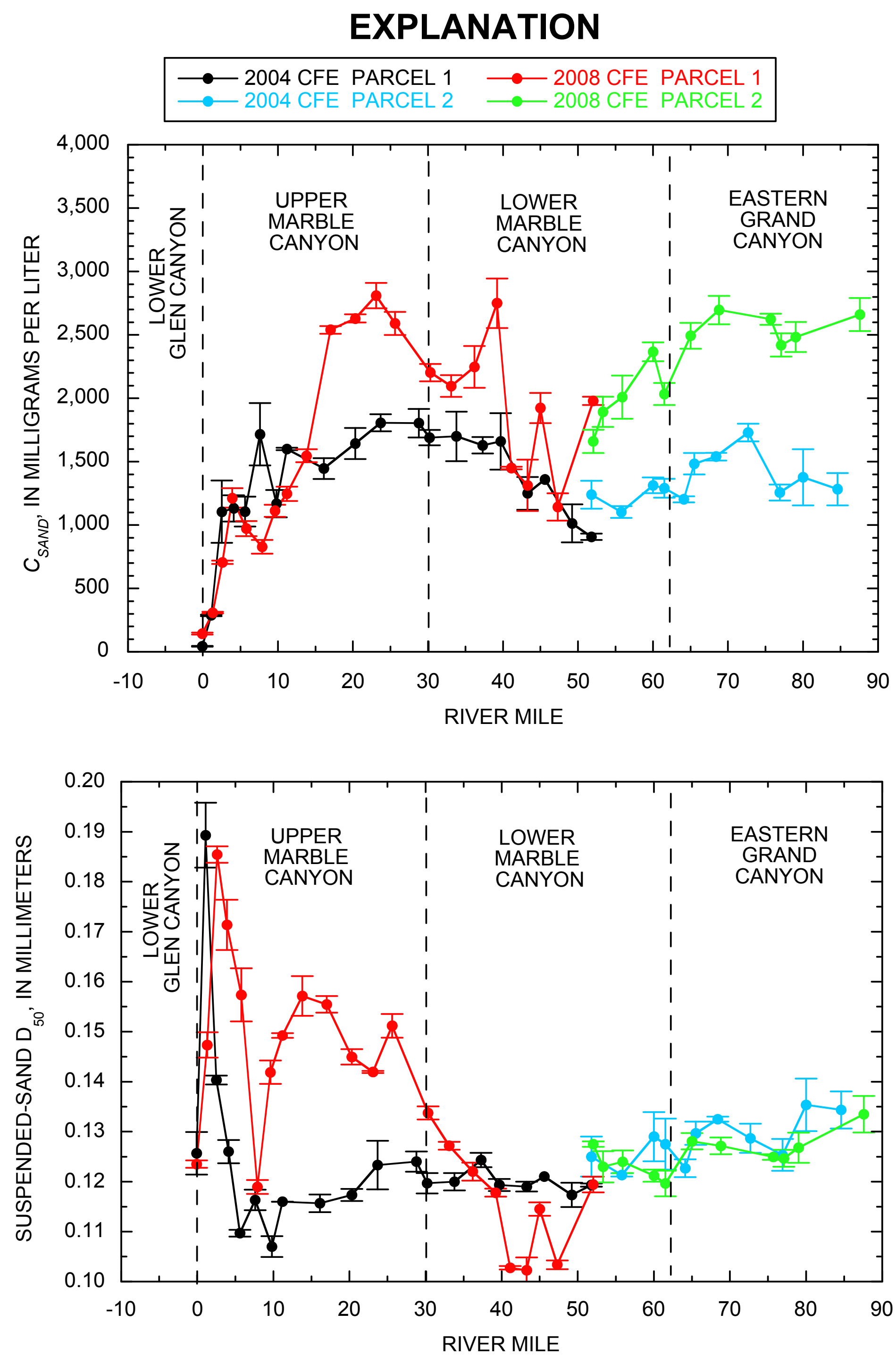

Figure 9. Comparison of suspended-sand concentration and grain size measured in the Lagrangian sampling programs during the 2004 and 2008 CFEs. Data collected in different parcels of water are indicated by different colors. Step changes between the data collected in the various parcels of water arise from reference-frame effects (see text for discussion). Error bars for the Lagrangian data are one standard error, indicating the 67-percent confidence interval associated with the mean values of these data among the three replicate single-vertical depth-integrated suspended-sediment samples collected at each sampling station.

during these two CFEs, thus indicating similar longitudinal patterns of net sand erosion and deposition. However, the magnitudes of the differences between the peaks and troughs in suspended-sand concentration are much larger during the 2008 CFE than during the 2004 CFE, with much higher suspended-sand concentrations during the 2008 CFE. This indicates that, although the locations of net sand erosion and deposition were similar, the magnitudes of the net sand erosion or deposition in these locations were much larger during the 2008 CFE than during the 2004 CFE. Between about river miles 2 and 50, the longitudinal patterns in and the magnitudes of the suspended-sand median grain size were very different during the two CFEs. In general, the suspended sand was much coarser during the 2008 CFE than during the 2004 CFE over most of this reach, except between about river miles 40 and 50 where it was finer during the 2008 CFE than during the 2004 CFE. Downstream from river mile 50, the suspended-sand median grain size was essentially identical during the two CFEs. It is informative to examine the data in figure 9, keeping in mind the previous reviews and analyses of the influences of reach-averaged τ_b, reach-averaged bed-sand median grain size, and reach-averaged bed-sand area on suspended-sand concentration and median grain size. Given that the likely maximum difference in reach-averaged τ_b at steady, high discharge between the two CFEs is only about 10 percent[18] at any individual Lagrangian sampling station, the only realistic physical mechanism that can explain the larger suspended-sand concentrations associated with either equivalent or larger suspended-sand median grain size between the two CFEs is greater reach-averaged bed-sand area (that is, a larger amount of sand of equal or greater median grain size on the bed). Thus, during the 2008 CFE, much more sand had to be present on the bed than during the 2004 CFE between river miles 14 and 35 and between river mile 51 and at least 85. This observation will be explored further in more sophisticated physically based analyses later in this report.

β Analysis

Physical suspension processes in a river provide a more representative "sample" of the average bed sedimentologic conditions upstream from a measurement cross-section than do bed-sediment measurements made only at that single cross-section (Rubin and others, 2001). For typical flow conditions in the Colorado River in Marble and Grand Canyons, the spatial scale over which suspended sand equilibrates with the bed ranges from about 600 m to well over 1 km (Topping and others, 2007a). Therefore, an appropriate analysis of the suspended-sand data can yield information on changes in the reach-averaged grain size of the sand on the surface of the channel bed, banks, and eddy sandbars upstream from the suspended-sand measurement location in exactly the proportion these environments are "sampled" by the suspended sand. Rubin and Topping (2001, 2008) developed such a technique to analyze suspended-sediment data based on theory and tested this technique against data from flumes and rivers. Their parameter "β" is a nondimensional measure of the average bed-surface grain size that interacts with the suspended

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[18] As previously discussed, a substantial change in sand-patch thickness over 20 percent of the bed in a kilometer-long reach would likely result in an approximate 10-percent difference in reach-averaged τ_b at constant water discharge. Although differences greater than 10 percent in reach-averaged τ_b at constant discharge may have occurred in certain individual reaches between the two CFEs, such greater differences would require substantial changes in sand-patch thickness over more of the bed than are suggested by available bathymetric and bed-textural data. Therefore, a 10-percent difference in reach-averaged τ_b at constant discharge is deemed the likely maximum for typical reaches.

sand at a given flow condition. The parameter β was derived for beds composed of 100 percent sand, and uses the concentration and grain size of the sand in suspension to compute the spatially averaged upstream grain size of the sand on the bed. The definition of β is given as

$$\beta = \frac{D_b}{D_{b-ref}}, \tag{15}$$

where D_b is the spatially averaged median grain size of the bed-surface sand at an instant in time and $D_{b\text{-}ref}$ is the reference median grain size of the sand on the bed surface. For broad and narrow log-normal bed-sand grain-size distributions and for cases with and without dunes on the bed, Rubin and Topping (2001, 2008) found that

$$\beta = \left(\frac{C_{SAND}}{C_{ref}}\right)^{-0.1}\left(\frac{D_s}{D_{s-ref}}\right), \tag{16}$$

where C_{SAND} is the concentration of suspended sand observed during a single measurement, C_{ref} is the reference concentration of sand in suspension, D_s is the median grain size of suspended sand observed during a single measurement, and $D_{s\text{-}ref}$ is the reference median grain size of sand in suspension. This result was computed using the suspended-sediment theory reviewed by McLean (1992). The reference concentration and median grain sizes in the denominators of equations 15 and 16 can be set equal to the average concentration and median grain sizes over any specified time interval.

For the same reasons that a proper physically based analysis of the suspended sand can provide a more representative and physically meaningful sample of the reach-averaged bed-sand grain-size distribution in the reach upstream from a measurement cross-section, a similar analysis of the suspended sand could provide a more physically meaningful measure of the reach-averaged area of the sand on the bed that is interacting with the flow and in equilibrium with the suspended sand at the given measurement location. In addition, such an analysis could actually provide a better relative measure of the bed-sand area than any other approach. For example, side-scan sonar data have been used extensively to estimate bed-sand area in the Colorado River in lower Glen, Marble, and Grand Canyons (Anima and others, 1998; Schmidt and others, 2007). However, these data are complicated to work with because (1) they require highly sophisticated data collection, (2) identification of bed sand in the sonar data is highly interpretive, and it is difficult to distinguish flat sand beds from flat beds composed of fine gravel, and (3) it is impossible to identify sand interstitial to cobbles and boulders on the bed (this could be most of the sand in some reaches). Multibeam sonar data have also been extensively collected with a secondary goal of measuring bed-sand area (Kaplinski and others, 2009), but these data have the same associated problems as the side-scan-sonar data. Video transects have also been collected with the goal of identifying bed-sediment type (for example, Anima and others, 1998), and although these data involve the least interpretation, it is only possible to map small parts of the bed with the video-transect technique. Thus, as with the reach-averaged bed-sand grain-size distribution, it is perhaps best to let the physics of suspended-sand transport provide a measurement of the reach-averaged area of the sand on the bed. This new analysis builds strongly on the work of Rubin and Topping (2001) and extends their work for conditions of constant reach-averaged τ_b.

The analysis described below is the simplest possible suspended-sediment analysis for detecting changes in reach-averaged bed-sand area and neglects several potentially important physical effects. Although this approach will not likely provide an absolute measurement of the reach-averaged bed-sand area, it at least provides a measure of reach-averaged bed-sand area that is coupled to the sand transport. As shown below, such an approach is possible for detecting differences in reach-averaged bed-sand area upstream from the same measurement cross-section between or over periods of constant reach-averaged τ_b. In addition, such an approach can also be used to detect differences in reach-averaged bed-sand area upstream from different measurement cross-sections between or over periods of similar water discharge as long as the reach-averaged τ_b at these different cross-sections is similar. Finally, this approach can be used to area-correct the computations made using equation 16 such that they take into account the influence of changes in bed-sand area on the β estimates of bed-sand median grain size.

As stated previously, at constant reach-averaged τ_b, differences in the grain-size distribution of the sand in suspension at a given cross-section can only be explained by changes in the reach-averaged grain-size distribution of the sand on the bed upstream. Under conditions of constant reach-averaged τ_b, reach-averaged bed- and suspended-sand median grain size are positively correlated (equation 7), reach-averaged bed-sand median grain size and suspended-sand concentration are negatively correlated when reach-averaged bed-sand area is constant (equation 4), reach-averaged bed-sand area and suspended-sand concentration are positively correlated for constant reach-averaged bed-sand median grain size (equation 4), and reach-averaged bed-sand area and suspended-sand median grain size are uncorrelated (equation 7). Thus, under conditions of constant reach-averaged τ_b, the only mechanism that can explain a change in suspended-sand concentration without a change in suspended-sand median grain size is a change in reach-averaged bed-sand area. Because the influence of reach-averaged bed-sand area on suspended-sand concentration is typically much smaller than is the influence of reach-averaged bed-sand median grain size, the formulation of β in equation 16 provides a reasonably good estimate of reach-averaged bed-sand median grain size upstream from a measurement cross-section when changes in reach-averaged bed-sand area are either small or change systematically with water discharge or reach-averaged τ_b (as during rising limb of floods in the Colorado River in Marble and Grand Canyons). However, this formulation can result in substantial error in the estimates of reach-averaged bed-sand median grain size in situations where reach-averaged bed-sand area changes are larger than about a factor of 10. This is the case, when one uses equation 16 to compute β in a spatial sense to compare reach-averaged bed-sand median grain size over the entire length of the Colorado River in lower Glen, Marble, and Grand Canyons, a reach over which large changes occur in the upstream sand supply and, therefore, reach-averaged bed-sand area.

Sensitivity of β in equation 16 to changes in reach-averaged bed-sand area at constant reach-averaged τ_b can be evaluated by holding both grain-size terms in equation 16 constant, holding the reference concentration term in the denominator constant, and by varying only the concentration term in the numerator to account for changes in reach-averaged bed-sand area relative to the initial reach-averaged bed-sand area associated with $\beta = 1$. This is justified based on the reasoning of Topping and others (2007a), who argued, on the basis of the flume experiments of Grams (2006) and Grams and Wilcock (2007), that the depth-averaged suspended-sand concentration scaled approximately linearly with changes in reach-averaged bed-sand area such that, for the same flow and grain-size conditions, a reach-averaged bed-sand area of 50 percent would result in a depth-averaged suspended-sand concentration that is approximately 50 percent of the depth-averaged suspended-sand concentration associated with a reach-averaged bed-sand area of 100 percent. For example, if for a reach-averaged bed-sand area of 100 percent, the concentration term in the numerator of equation 16 were 1,000 mg/L, this concentration term would decrease to 750 mg/L for a reach-averaged bed-sand area of 75 percent, 500 mg/L for a bed-sand area of reach-averaged bed-sand area of 50 percent, and 100 mg/L for a reach-averaged bed-sand area of 10 percent. As discussed in detail in Topping and others (2007a) and above, this is perhaps an oversimplification of the problem, but it does provide insight into the effects of changes in reach-averaged bed-sand area on β. Results from this sensitivity analysis are shown in figure 10. As shown in figure 10, a factor of 2 change in reach-averaged bed-sand area at constant reach-averaged τ_b only results in a change in β of 7 percent, as previously suggested by Rubin and Topping (2001).

Relative differences in reach-averaged bed-sand area between two times or locations of constant reach-averaged τ_b can be computed by solving a modified version of equation 16, where the suspended-sand data collected over a specified time interval at only one time or location are used to compute the reference terms, C_{ref} and $D_{s\text{-}ref}$, in the denominator. Hereafter, the term "reference condition" is used to define the specified time interval at the one time or location over

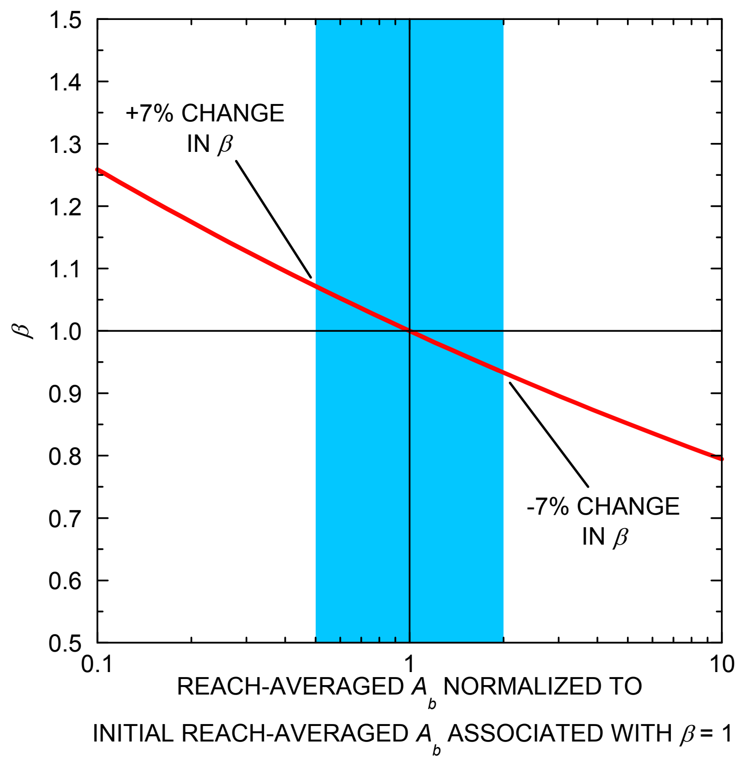


Figure 10. Influence of changes in reach-averaged bed-sand area, A_b, on β. Horizontal solid line indicates initial value of β associated with initial reach-averaged A_b and a given reach-averaged bed-sand median grain size; vertical solid line indicates initial reach-averaged A_b normalized by itself. Blue band encompasses region within a factor of 2 change in reach-averaged A_b relative to this initial value. Red curve is computed by holding bed- and suspended-sand median grain size and reach-averaged τ_b constant and changing suspended-sand concentration by only changing reach-averaged A_b. Factor of 2 changes in reach-averaged A_b are associated with only ±7 percent changes in β, as indicated by the intersection of the red curve with the edges of the blue band.

which these reference terms are computed. Based on the results from the sensitivity analysis in figure 10, a more-general form of equation 16 that incorporates effects of variable reach-averaged A_b is

$$\beta_A = \beta\left(\frac{A_b}{A_{b-ref}}\right)^{0.1} = \left(\frac{C_{SAND}}{C_{ref}}\right)^{-0.1}\left(\frac{D_s}{D_{s-ref}}\right)\left(\frac{A_b}{A_{b-ref}}\right)^{0.1}, \quad (17)$$

where β_A is the reach-averaged D_b normalized by reach-averaged D_{b-ref} for variable reach-averaged A_b. Using the same convention as in equation 16, A_{b-ref} is the reference reach-averaged A_b (averaged over the same time interval as C_{ref} and D_{s-ref}). As with the original β-approach derived by Rubin and Topping (2001, 2008), which computes a reach-averaged bed-sand median grain size normalized by the reference reach-averaged bed-sand median grain size, this new β_A-approach does not directly compute reach-averaged bed-sand area but can, for conditions of constant or near-constant reach-averaged τ_b, compute a reach-averaged bed-sand area normalized by the reference reach-averaged bed-sand area. Therefore, because reach-averaged bed-sand area is correlated with upstream sand supply, this approach can compute relative differences in the upstream sand supply during two time periods at the same location or between two different locations, but cannot compute the actual upstream sand supply. This new β_A-approach does provide guidance, however, on (1) the accuracy of the previously presented sand budgets in estimating changes in the total upstream sand supply to the reaches (including changes in background sand storage) antecedent to the 2004 and 2008 CFEs and (2) the utility of using only the simple analyses in the previous sections of coupled changes in suspended-sand concentration and grain-size between different CFEs and between different reaches during the same CFE to infer relative differences in upstream sand supply.

Solving equation 17 requires a reduction in the number of unknown quantities from 2 to 1. As written, the unknown quantities in equation 17 are β_A and the ratio $\left(\frac{A_b}{A_{b-ref}}\right)$. Because reach-averaged bed-sand area is treated independently of both reach-averaged bed-sand median grain size and suspended-sand median grain size, it is possible to solve equation 17 for the ratio $\left(\frac{A_b}{A_{b-ref}}\right)$ by setting $\beta_A = 1$, replacing D_s with D_{s-ref}, and then modifying C_{SAND} to account for the difference between D_s and D_{s-ref}. At constant reach-averaged τ_b, $C_{SAND} \propto D_s^{-2}$ (Rubin and Topping, 2001). Therefore, the factor used to modify C_{SAND} to account for the difference between D_s and D_{s-ref} can be written as

$$\delta = \left(\frac{D_{s-ref}}{D_s}\right)^{-2}. \quad (18)$$

After making the appropriate substitutions and rearrangements, equation 17 becomes

$$\left(\frac{A_b}{A_{b-ref}}\right) = \left(\frac{\delta C_{SAND}}{C_{ref}}\right). \quad (19)$$

Again, as with β as a measure of reach-averaged bed-sand median grain size, this measure of bed-sand area is only appropriate in a reach-averaged sense over the kilometer-long reach scales over which suspended sand equilibrates with bed-sediment conditions in the Colorado River in the study area (Topping and others, 2007a). Unlike β, however, which can be applied for conditions of changing reach-averaged τ_b, this measure of bed-sand area requires constant or near-constant reach-averaged τ_b to result in reasonably accurate estimates of differences in reach-averaged bed-sand area.

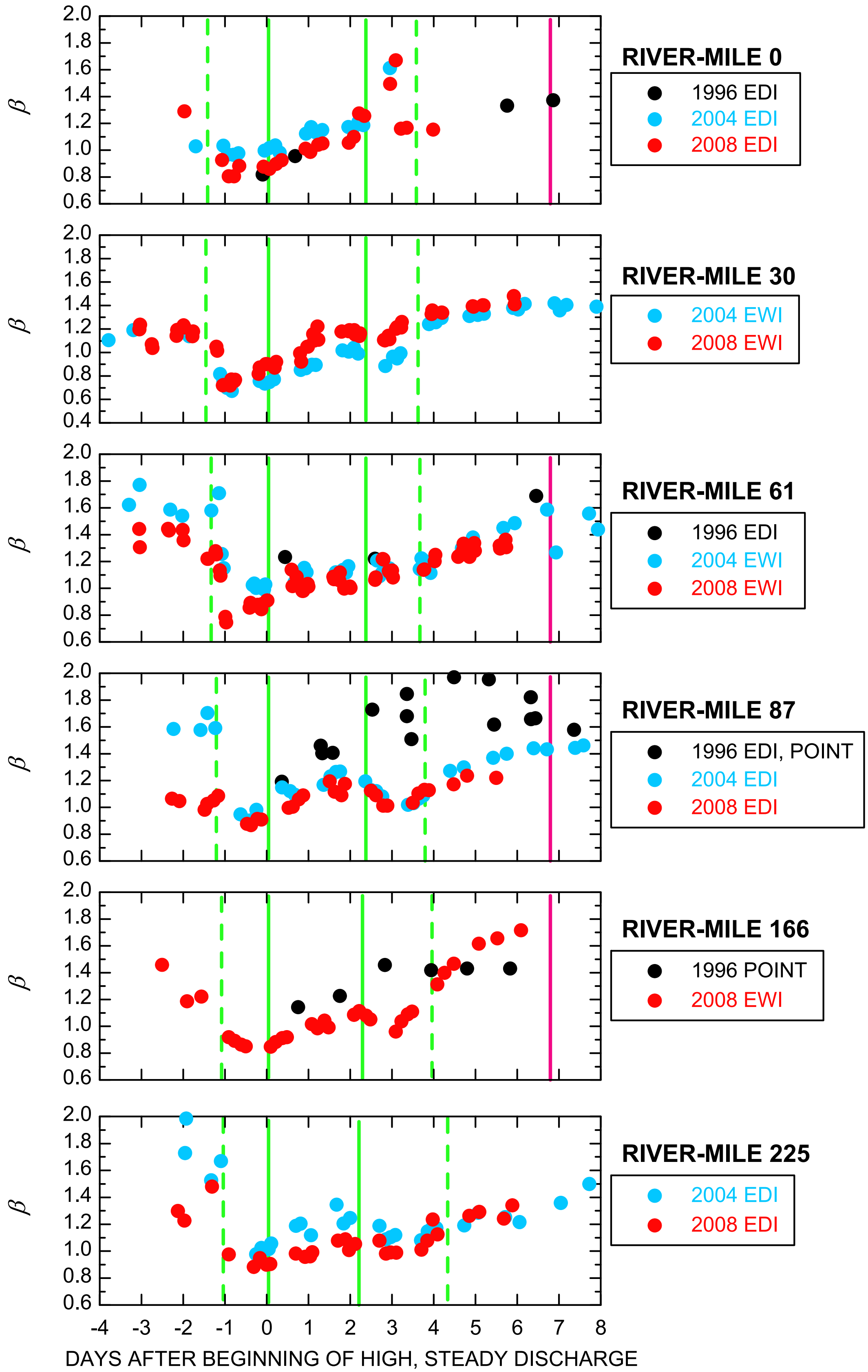
By virtue of the relative insensitivity of β to changes in reach-averaged bed-sand area (fig. 10), β computed using equation 16 can be used directly as an indicator of changes in reach-averaged bed-sand median grain size when changes in reach-averaged bed-sand area are less than about a factor of 2 (fig. 10). However, when greater changes in reach-averaged bed-sand area occur, substantial error can be introduced into β-estimated reach-averaged bed-sand median grain size. For example, when reach-averaged bed-sand area decreases by a factor of 5 at a constant reach-averaged bed-sand median grain size, β computed by equation 16 will be 17 percent too high, and when reach-averaged bed-sand area increases by a factor of 5 at a constant reach-averaged bed-sand median grain size, β computed by equation 16 will be 15 percent too low. This effect can be corrected for by using equation 17 to solve for β_A, when reach-averaged τ_b can be assumed to be constant to within about 10 or 20 percent.

Values of β at Each Study Site During All CFEs

Values of β computed using standard β analysis (conducted using equation 16) of the suspended-sand data collected at each study site during all three CFEs are shown in figure 11. At each study site, the reference condition was set equal to days -2 through 5 of the 2008 CFE (that is, the 7-day period from 2 days before the beginning of high, steady discharge to 5 days after the beginning of high, steady discharge during the 2008 CFE). This data-collection period encompassed the entire flood hydrograph for the 2004 and 2008 CFEs. Because data were only collected at every study site during the 2008 CFE and were collected with the most consistent methods during the 2008 CFE, this approach allowed better direct comparison of β values between the different CFEs. Only the best (that is, lowest error) physical measurements of suspended-sand concentration and grain size were used in this analysis, that is, only data collected using the EDI, EWI, or point-sampling methods.

The tendency at each site is for β to decrease during the rising limb of each CFE and then subsequently increase, continuing to increase even after recession of each CFE. Because changes in reach-averaged bed-sand median grain size dominate over changes in reach-averaged bed-sand area on influencing β, these changes in β most likely arise from fining of the bed and then subsequent coarsening of the bed upstream from the measurement cross-sections. These same patterns were typically observed in the bed-sediment data collected at only the measurement cross-sections (figs. 4 and 5). The amount of bed fining during the rising limbs varies from site to

Figure 11 (next page). Values of β at each study site during all CFEs. At each study site, data were shifted in time such that zero time is the beginning of high, steady discharge during each CFE. Except at the River-mile 30 study site, β was as fine or finer during the 2008 CFE than during the other two CFEs. β generally fined during the rising limb of each CFE and then subsequently coarsened. Solid green vertical lines indicate the beginning and end of high, steady discharge at each study site during the 2008 CFE. Dashed green vertical lines indicate the beginning of the rising limb and end of the recession at each study site during the 2008 CFE. Solid pink vertical lines indicate the end of high, steady discharge at each study site during the 1996 CFE. Beginning of high, steady discharge during the 1996 CFE indicated at each study site by the leftmost solid vertical green line.


RIVER-MILE 0
1996 EDI
2004 EDI
2008 EDI
RIVER-MILE 30
2004 EWI
2008 EWI
RIVER-MILE 61
1996 EDI
2004 EWI
2008 EWI
RIVER-MILE 87
1996 EDI, POINT
2004 EDI
2008 EDI
RIVER-MILE 166
1996 POINT
2008 EWI
RIVER-MILE 225
2004 EDI
2008 EDI
β
DAYS AFTER BEGINNING OF HIGH, STEADY DISCHARGE

site during each CFE, but the bed coarsening follows similar patterns at each study site during at least the 2004 and 2008 CFEs. Bed coarsening during the 1996 CFE likely follows different patterns from those during the 2004 and 2008 CFEs at some sites because of the much longer duration of the 1996 CFE.

Values of β were generally smaller during the 2008 CFE than during the 1996 and 2004 CFEs downstream from upper Marble Canyon. From the River-mile 61 study site through the River-mile 225 study sites, β was smaller during the 2008 CFE at each study site than during the 1996 and 2004 CFEs. At the River-mile 0 study site, β was approximately equal during the 1996 and 2008 CFEs, but smaller during both of these CFEs than during the 2004 CFE. At the River-mile 30 study site, β was smaller during the 2004 CFE than during the 2008 CFE. These relative differences in β between the CFEs at each study site only disagree with relative differences in bed-sediment data between the CFEs at the River-mile 30 study site. Thus, as already discussed, the response of the bed-sand median grain size at the measurement cross-section at the River-mile 30 study site was likely not representative of that in the kilometer-long reach upstream. Except at the River-mile 0 study site, β during the 1996 CFE tended to be larger than during the 2004 and 2008 CFEs at all other sites where data were collected in 1996.

Because reach-averaged bed-sand median grain size dominates over reach-averaged bed-sand area in influencing β, these analyses indicate that, with the exception of at the River-mile 30 study site, substantial parts of the bed upstream from the measurement cross-sections were finest during the 2008 CFE and were coarsest during the 1996 CFE. These results do not necessarily track with the known levels of enrichment in the upstream sand supply computed from sand budgeting nor do they necessarily agree with inferred levels of enrichment in the upstream sand supply estimated from the simple coupled analyses of suspended-sand concentration and grain size in the previous sections of this report. For example, both the sand budgeting and the simple coupled analyses of suspended-sand concentration and grain size suggest that upper Marble Canyon was more enriched with respect to sand before the 2008 CFE than it was before the 2004 CFE. Results from the β analysis, in contrast, indicate that, at least upstream from the River-mile 30 study site, the reach-averaged median grain size of the bed sand in this reach was consistently finer during the 2004 CFE than it was during the 2008 CFE. This will be addressed further below in β analysis of the data from the Lagrangian sampling programs. As shown in the "Theoretical Background" section of this report, reach-averaged bed-sand median grain size and upstream sand supply may be typically negatively correlated, but this relation is not required. This is pursued further in the next few analyses.

Estimation of Differences in Reach-Averaged Bed-Sand Area in the Reaches Upstream from Each Study Site During Each CFE and Between CFEs

To compute the relative differences in reach-averaged bed-sand area in the reaches upstream from each study site, the EDI, EWI, and point-sample data collected at each site were reanalyzed using the approach outlined in equations 17 through 19. To proceed with this analysis, reach-averaged τ_b was assumed to be constant among the various study sites. Although this assumption may not be valid at low discharges, it is likely valid in the discharge range from 42,000 to 45,000 ft^3/s on the basis of the analysis of pre-dam suspended-sand data collected at the River-mile 0 and 87 study sites (the two of the six study sites that are most different from each other) in Topping and others (2000a). This analysis will allow better relations to be developed between upstream sand supply, reach-averaged bed-sand median grain size, reach-averaged bed-sand area, and suspended-sand concentration during CFEs. Because of the complexities outlined in the "Theoretical Background" section of this report in regard to (1) the different relations between upstream sand supply and reach-averaged bed-sand area at very different discharges of water and (2) the transient effects of sand redistribution on the bed on reach-averaged bed-sand area following large changes in discharge, back-calculated changes in reach-averaged bed-sand area could only be computed using suspended-sand data collected during the first day of a CFE at similar discharge (that is, the only data that could be analyzed were those collected at the same relative time after a large discharge change has occurred during a CFE). This approach avoided effects that could result in apparent negative correlations between upstream sand supply and bed-sand area. To proceed with this analysis, suspended-sand concentrations and median grain sizes were first averaged over the first day of high, steady discharge at each study site during each CFE. For these analyses, the reference condition was set equal to the first day of high, steady discharge at the River-mile 87 study site during the 2008 CFE, with C_{ref} set equal to 2,740 mg/L and $D_{s\text{-}ref}$ set equal to 0.125 mm in equations 18 and 19. The ratio $\left(\frac{A_b}{A_{b-ref}}\right)$ was then computed at each study site using the "first-day" averaged suspended-sediment concentrations and median grain size and these values of C_{ref} and $D_{s\text{-}ref}$. By this approach, the ratio $\left(\frac{A_b}{A_{b-ref}}\right)=1$ for the River-mile 87 study site during the first day of high, steady discharge during the 2008 CFE, and $A_{b\text{-}ref}$ became the reach-averaged bed-sand area in the kilometer-long reach upstream from the River-mile 87 study site during the first day of high, steady discharge during the 2008 CFE. This allowed direct comparison between the reach-averaged bed-sand areas computed for all reaches upstream from each study site during any one CFE and between all CFEs.

By this analysis, reach-averaged bed-sand area during the 2008 CFE increased between the River-mile 0 and 30 study sites, then decreased slightly between the River-mile 30 and 61 study sites, and then increased to its maximum value at the River-mile 87 study site. Downstream from the River-mile 87 study site, reach-averaged bed-sand area gradually decreased to be slightly less at the River-mile 225 study site than it was at the River-mile 30 study site (fig. 12). Thus, the reaches with likely greatest upstream sand supply during the 2008 CFE were eastern and east-central Grand Canyon. During the 2004 CFE, reach-averaged bed-sand area increased more gradually between the River-mile 0 and 87 study sites than during the 2008 CFE and then remained essentially constant between the River-mile 87 and 225 study sites. The greatest increase in reach-averaged bed-sand area during both the 2004 and 2008 CFEs occurred between the River-mile 0 and 30 study sites in upper Marble Canyon, although this increase was much less during the 2004 CFE than during the 2008 CFE. This is consistent with the previously presented mass-balance sand-budgeting results that showed that upper Marble Canyon had the greatest enrichment in the upstream sand supply during the sand-budgeting accounting periods antecedent to both the 2004 and 2008 CFEs. During the 1996 CFE, reach-averaged bed-sand area increased between the River-mile 0 and 87 study sites, and then decreased between the River-mile 87 and 166 study sites. As in the 2004 and 2008 CFEs, the greatest increase in reach-averaged bed-sand area during the 1996 CFE occurred in Marble Canyon. However, in contrast to the 2004 and 2008 CFEs, the increase in reach-averaged bed-sand area in eastern Grand Canyon (between the River-mile 61 and 87 study sites) was as large as that within Marble Canyon. This large increase in reach-averaged bed-sand

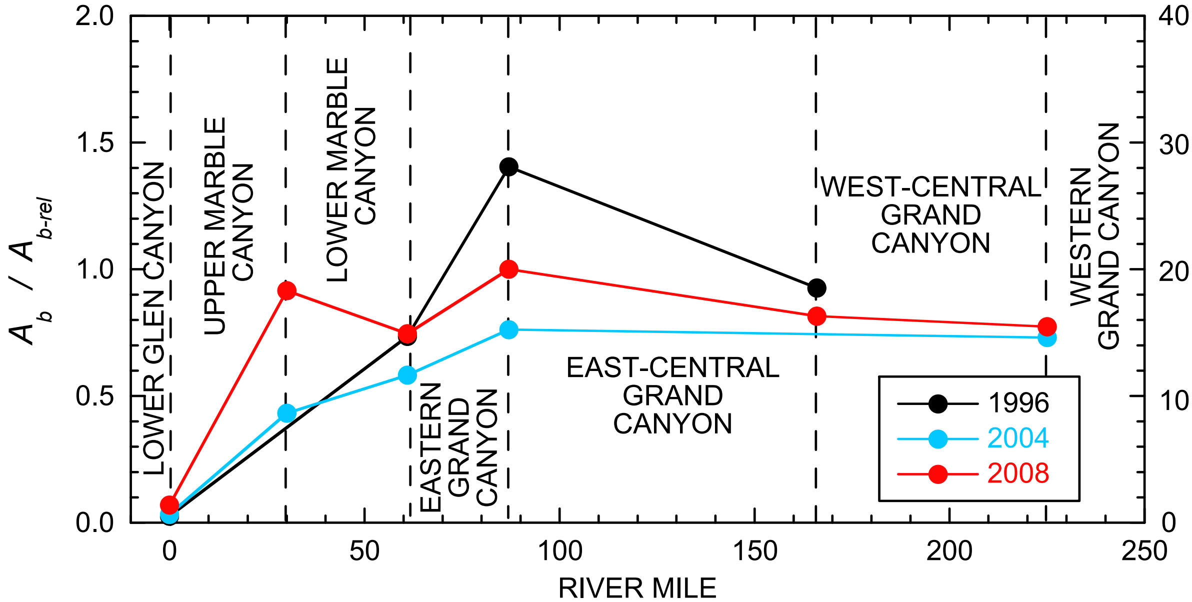


Figure 12. *β*-based computation of reach-averaged bed-sand area in the kilometer-long reaches upstream from each study site during each CFE. Study reaches are indicated, separated by vertical dashed lines.

area in eastern Grand Canyon could have been the legacy of the coarse tail of the extremely large inputs of sand that occurred from the Little Colorado River during January-March 1993 (Wiele and others, 1996; Topping and others, 2000b). Although much of these sand inputs from the Little Colorado River were likely exported downstream from this reach before the 1996 CFE because of the relatively large dam releases between the 1993 and the 1996 CFE, it is likely that part of the coarse tail of these extremely large sand inputs was still in eastern Grand Canyon during the 1996 CFE (Topping and others, 2000b).

Throughout lower Glen, Marble, and Grand Canyons, reach-averaged bed-sand area was likely greater during the 2008 CFE than it was during the 2004 CFE (fig. 12). However, in only lower Glen Canyon was reach-averaged bed-sand area likely greater during the 2008 CFE than it was during the 1996 CFE. Reach-averaged bed sand area was likely about equal during the 1996 and 2008 CFEs in lower Marble Canyon (upstream from the River-mile 61 study site) and reach-averaged bed-sand area was likely greater during the 1996 CFE than it was during the 2008 CFE in much of Grand Canyon (upstream from the River-mile 87 and 166 study sites). Reach-averaged bed-sand area during the 2004 CFE was likely less than that during the 2008 CFE in all reaches and it was likely less than that during the 1996 CFE in all reaches except lower Glen Canyon. Because no suspended-sand data were collected at the River-mile 30 study site during the 1996 CFE, it is impossible to compare reach-averaged bed-sand area in upper Marble Canyon between the 1996 CFE and the 2004 and 2008 CFEs. Among the three CFEs, the minimum and maximum values of reach-averaged bed-sand area both likely occurred during the 1996 CFE, with the minimum value occurring in lower Glen Canyon (upstream from the River-mile 0 study site) and the maximum value occurring in eastern Grand Canyon (upstream from the River-mile 87 study site).

Combination of the results from this analysis with modeling results from Topping and others (2007a) allows conversion of the relative values of reach-averaged bed-sand area, $\left(\frac{A_b}{A_{b-ref}}\right)$, to approximate fractional values of reach-averaged bed-sand area, A_b (fig. 12). Using a more sophisticated physically based suspended-sediment model than the simple β-based analysis in this section of this report, Topping and others (2007a) computed that the reach-averaged bed-sand area in the kilometer-long reach upstream from the River-mile 87 study site during day 1 of high, steady discharge during the 1996 CFE was approximately 25 percent, and during day 1 of high, steady discharge during the 2004 CFE it was approximately 18 percent. The difference between these two numbers is a factor of 1.4. For comparison, by the simple β-based analysis in this report, the difference in reach-averaged bed-sand area at the River-mile 87 study site between days 1 of the 1996 and 2004 CFEs is only somewhat larger at a factor of 1.8. Because these differences are similar (1.8 is only 29 percent larger than 1.4) whereas the approaches used to arrive at these differences are very different in complexity (yet still physically based), this result lends further support to the utility of using simple β-based analysis to estimate relative differences in reach-averaged bed-sand area. Best-fit between the two approaches was achieved by setting $A_{b\text{-}ref}$(the reach-averaged fractional bed-sand area during the reference condition) equal to 20 percent. When making conclusions based on values of A_b computed by this approach, it is important to remember that these values of A_b are not unweighted, linear geometric spatial averages, but rather are estimates of the fractional bed-sand area in a reach weighted by how the suspended sediment interacts with (that is, "samples") the bed sand over kilometer-long reaches at assumed constant reach-averaged τ_b. Therefore, these values of A_b are perhaps best used, not as an exact measure of the percentage of sand on the bed in a reach, but rather in a relative sense in evaluations of (1) how the relative amount of sand on the bed changes longitudinally over long reaches or (2) how the relative amount of sand on the bed in a reach differs between CFEs.

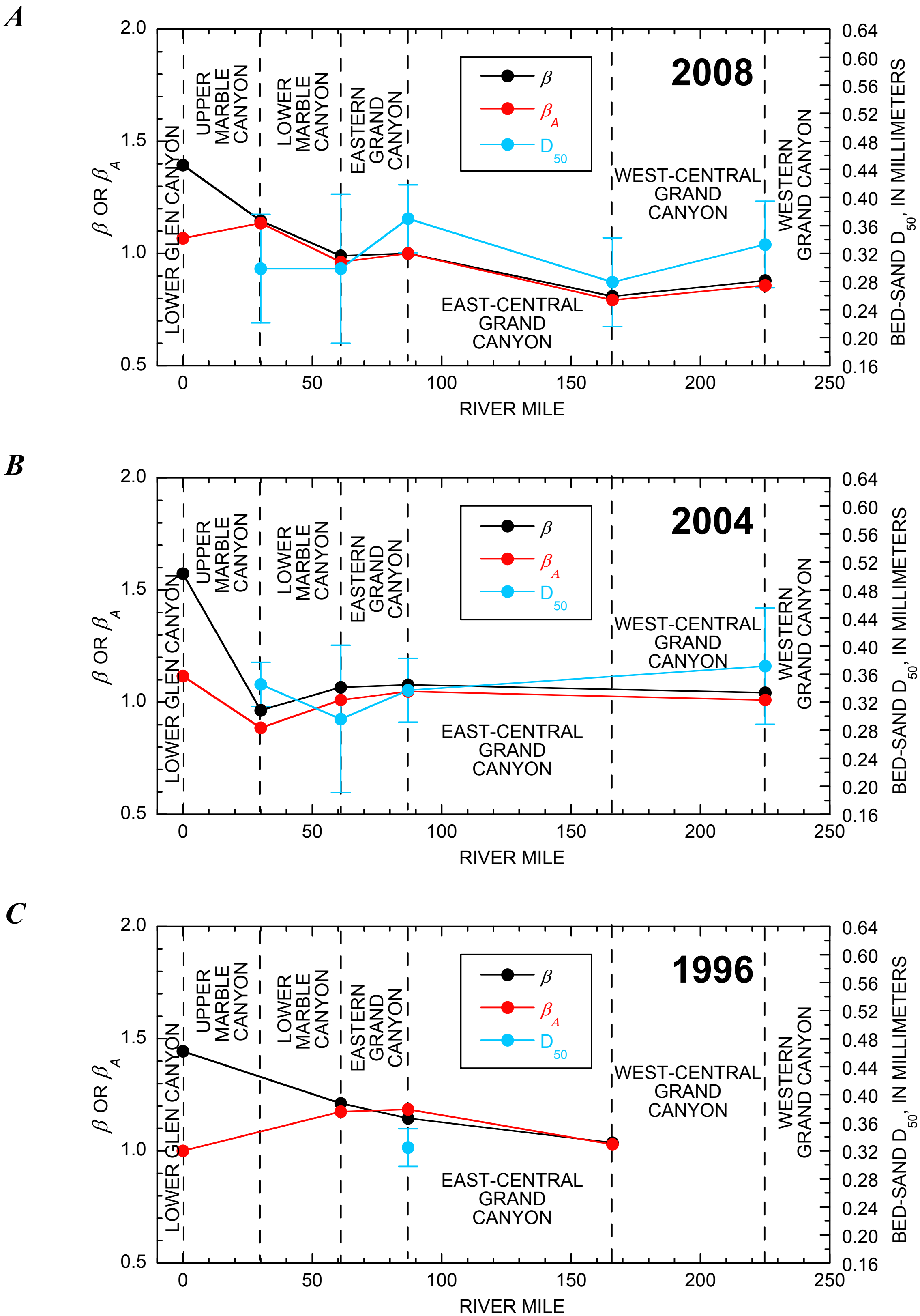
Values of β at All Study Sites During Each CFE

To compute the relative differences in reach-averaged bed-sand median grain size in the reaches upstream from each study site, the EDI, EWI, and point-sample data collected at each site during day 1 of high, steady discharge were analyzed using both a standard β analysis as described by equation 16 and a “sand-area-corrected” β_A analysis as described by equation 17 using the values of $\left(\frac{A_b}{A_{b-ref}}\right)$ computed in the previous analysis and presented in figure 12. To proceed with this analysis, as in the previous analysis, suspended-sand concentrations and suspended-sand median grain sizes were first averaged over the first day of high, steady discharge at each study site during each CFE. For this analysis, as in the previous analysis, the reference condition was set equal to the first day of high, steady discharge at the River-mile 87 study site during the 2008 CFE. β and β_{A} values were then computed using the "first-day" averaged suspended-sediment concentrations and median grain size, and these reference-condition values of C_{ref} and $D_{s\text{-}ref}$. By this approach, both $\beta = \beta_{\mathrm{A}} = 1$ for the River-mile 87 study site during the first day of high, steady discharge during the 2008 CFE. This allowed direct comparison of reach-averaged bed-sand median grain size in all reaches upstream from each study site during any one CFE and between all CFEs. Results from this analysis with comparisons with the mean bed-sand median grain sizes measured at the measurement cross-sections at each site during day 1 of high, steady discharge during each CFE are shown in figure 13. These comparisons indicate general good agreement at the 95-percent confidence interval between β_A and the mean bed-sand median grain sizes measured at the cross-sections at all study sites during all CFEs when the reference reach-averaged median grain size of the bed-sand, $D_{b\text{-}ref}$, is set equal to a reach-averaged bed-sand median grain size of 0.32 mm.

This analysis indicates that the greatest enrichment of the upstream sand supply in a reach antecedent to a CFE is not uniquely related to reach-averaged bed-sand median grain size and can be associated with either the finest or coarsest bed sand in any reach during that CFE. During the 2008 CFE, reach-averaged bed-sand median grain size increased slightly between the River-mile 0 and 30 study sites, then generally decreased in the downstream direction between the River-mile 30 and 166 study sites, and then increased slightly between the River-mile 166 and 225 study sites (fig. 13*A*). Thus, during the 2008 CFE, the finest reach-averaged bed sand was present in east- and west-central Grand Canyon, and the coarsest reach-averaged bed sand was present in upper Marble Canyon. Note that upper Marble Canyon was the reach with the greatest sand enrichment during the mass-balance sand-budgeting accounting period antecedent to the 2008. Thus, during the 2008 CFE, the greatest enrichment in the upstream sand supply was associated with the reach with the coarsest reach-averaged bed sand. During the 2004 CFE, reach-averaged bed-sand median grain size decreased in the downstream direction between the River-mile 0 and 30 study sites, then increased slightly between the River-mile 30 and 61 study sites, and then remained essentially constant between the River-mile 61 and 225 study sites (fig. 13*B*). Thus, during the 2004 CFE, the finest reach-averaged bed sand was present in upper Marble Canyon, with coarser and similar reach-averaged bed sand present everywhere else. Note that, as during the 2008 CFE, upper Marble Canyon was also the reach with the greatest sand enrichment during the mass-balance sand-budgeting accounting period antecedent to the 2004. Thus, during the 2004 CFE, the greatest enrichment in the upstream sand supply was associated with the reach with the finest reach-averaged bed sand. During the 1996 CFE, reach-averaged bed-sand median grain size increased between the River-mile 0 and 61 study sites, increased slightly between the River-mile 61 and 87 study sites, and then decreased between the River-mile 87 and 166 study sites (fig. 13*C*). Thus, during the 1996 CFE, the finest reach-averaged bed sand was present in lower Glen Canyon and east-central Grand Canyon, and the coarsest reach-averaged bed sand was present in eastern Grand Canyon.

Reach-averaged bed-sand median grain size was typically finest during the 2008 CFE and typically coarsest during the 1996 CFE (fig. 13*D*). Reach-averaged bed sand was likely coarser at the River-mile 61 and 87 study sites during the 1996 CFE than it was at any other site during the 1996 CFE, and coarser than it was at any site during the 2004 and 2008 CFEs. Except at the River-mile 0 and 30 study sites, reach-averaged bed-sand median grain size was finest at all study sites

Figure 13 (next page). Results from β and β_A analyses of reach-averaged bed-sand median grain size in the kilometer-long reaches upstream from each study site during all CFEs. $\beta = \beta_A = 1$ is equivalent to reach-averaged bed-sand D_{50} = 0.32 mm at all study sites during all CFEs. Error bars indicate the 95-percent confidence interval in the mean median grain size of the bed sand measured at the measurement cross-section at each study site on day 1 of high, steady discharge during each CFE. Study reaches are indicated, separated by vertical dashed lines. Comparison of β, β_A, and bed-sand D_{50} (*A*) during the 2008 CFE, (*B*) during the 2004 CFE, and (*C*) during the 1996 CFE. *D*, Comparison of β_A or bed-sand D_{50} at each study site during all CFEs.


A
2008
β
β_A
D_50
LOWER GLEN CANYON
UPPER MARBLE CANYON
LOWER MARBLE CANYON
EASTERN GRAND CANYON
EAST-CENTRAL GRAND CANYON
WEST-CENTRAL GRAND CANYON
WESTERN GRAND CANYON
β OR β_A
BED-SAND D_50, IN MILLIMETERS
RIVER MILE
B
2004
C
1996

D

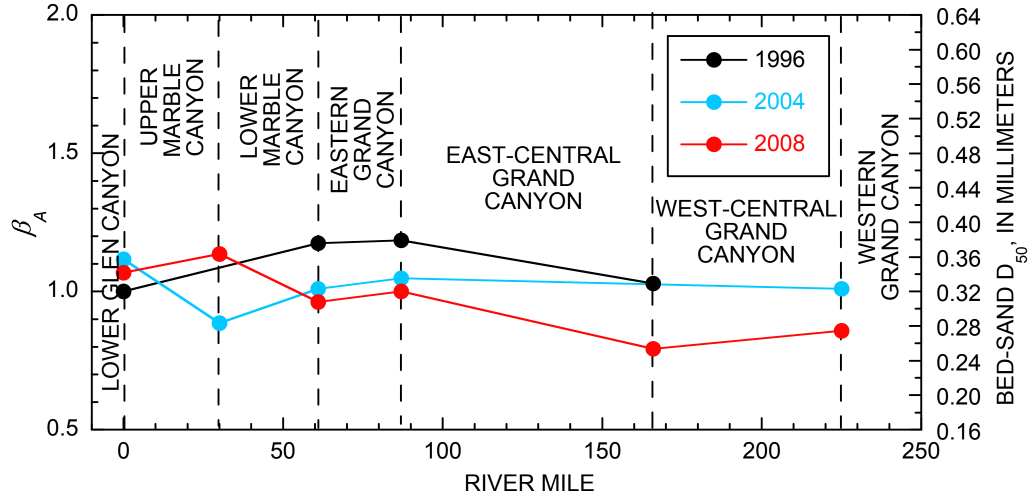


Figure 13. — Continued.

during the 2008 CFE; and, except at the River-mile 0 study site, the reach-averaged bed-sand median grain size was coarsest at all study sites during the 1996 CFE. Among all study sites during all three CFEs, reach-averaged bed-sand median grain size was finest at the River-mile 30 study site during the 2004 CFE and coarsest at the River-mile 87 study site during the 1996 CFE. Except in upper Marble Canyon, reach-averaged bed-sand median grain size was generally intermediate during the 2004 CFE relative to during the 1996 and 2008 CFEs. At the River-mile 0 study site, reach-averaged bed-sand median grain size was coarsest during the 2008 CFE and finest during the 1996 CFE. Because monitoring data indicate that greater enrichment of the upstream sand supply in lower Glen Canyon occurred before the 2008 CFE than before the 2004 CFE, and the reach-averaged bed-sand median grain size at the River-mile 0 study site was coarser during the 2008 CFE than during the 2004 CFE, lower Glen Canyon during the 2004 and 2008 CFEs is another example of how coarser reach-averaged bed sand can be associated with a greater upstream sand supply.

β Analysis of Data Collected During the Lagrangian Sampling Programs, with Estimation of Relative Differences in Reach-Averaged Bed-Sand Area Between the 2004 and 2008 CFEs

To provide a more complete estimate of the longitudinal distribution of bed-sand median grain size and bed-sand area during the 2004 and 2008 CFEs, the data collected in the Lagrangian sampling programs were analyzed using both standard β analyses and "sand-area-corrected" β_A analyses. To be consistent with the previous analyses, the reference condition was set equal to the first day of high, steady discharge at the River-mile 87 study site during the 2008 CFE, with C_{ref} set equal to 2,740 mg/L, $D_{s\text{-}ref}$ set equal to 0.125 mm, and $A_{b\text{-}ref}$ set equal to 0.2 in equations 17 through 19. This also allowed ultimate conversion of β_A to the reach-averaged D_{50} of the bed sand by multiplying β_A by 0.32 mm (the best-fit D_{50} value for $D_{b\text{-}ref}$ determined by the previous analysis). As in the previous analyses, constant (or, at least, near-constant) reach-averaged τ_b is assumed at constant water discharge among the different sampling stations to allow computation of $\left(\frac{A_b}{A_{b-ref}}\right)$, A_b, and β_A. Because discharge was constant among all of these sampled stations, and the variability in flow depth and depth-averaged velocity at and among these sampled stations was reasonably small, reach-averaged values of τ_b at the same sampling station during the 2004 and 2008 CFEs and among the various sampled stations during each CFE were deemed similar enough to proceed with this analysis.

Results from this analysis indicate that, except in parts of uppermost Marble Canyon and a short section of lower Marble Canyon, reach-averaged bed-sand area was considerably greater throughout Marble Canyon and all of eastern Grand Canyon during day 1 of the 2008 CFE than it was during day 1 of the 2004 CFE (fig. 14). The results from this analysis also generally agree with the values of reach-averaged bed-sand area computed in the prior analysis at only the study sites, but also illustrate that the longitudinal variability in reach-averaged bed-sand area is likely much greater than is captured by the analysis of reach-averaged bed-sand area at only the study sites. The longitudinal density of information on reach-averaged bed-sand area is, of course, much greater in the analyses of the Lagrangian data than in the analyses of only the data from the study sites. During the day 1 of the 2008 CFE, reach-averaged bed-sand area likely increased substantially in the downstream direction from only a few percent at river mile 0 to its highest value of approximately 29 percent at river mile 17. With the exception of between river miles 40 and 47, where a local minimum occurred in computed reach-averaged bed-sand area, during the 2008 CFE reach-averaged bed-sand area likely generally increased downstream from river mile 17 to about river mile 93, where it attained its second highest value of about 26 percent. It then decreased,

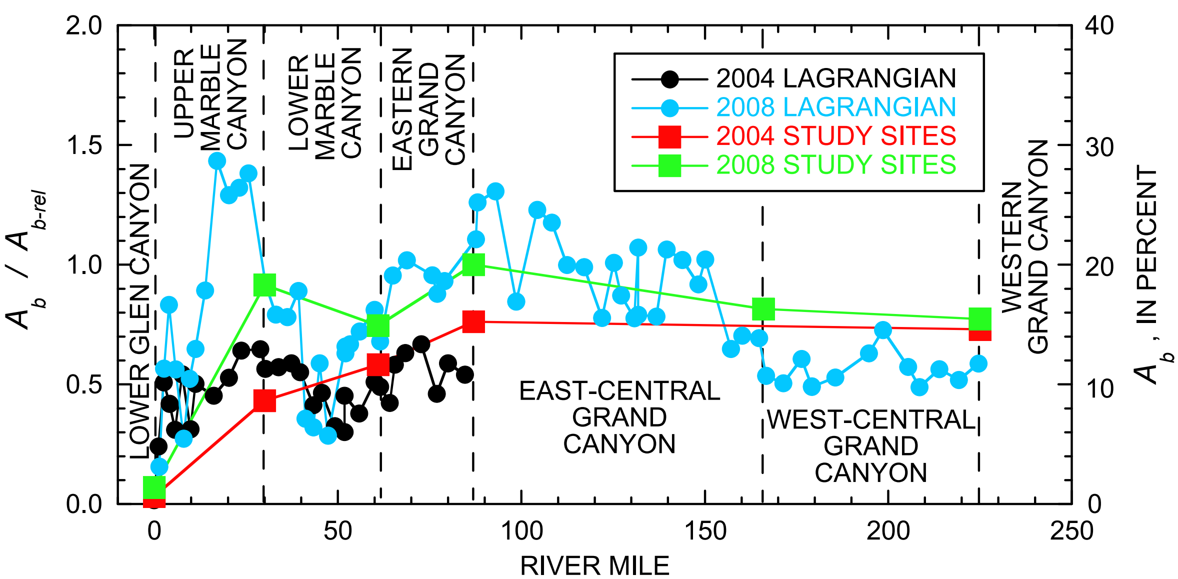
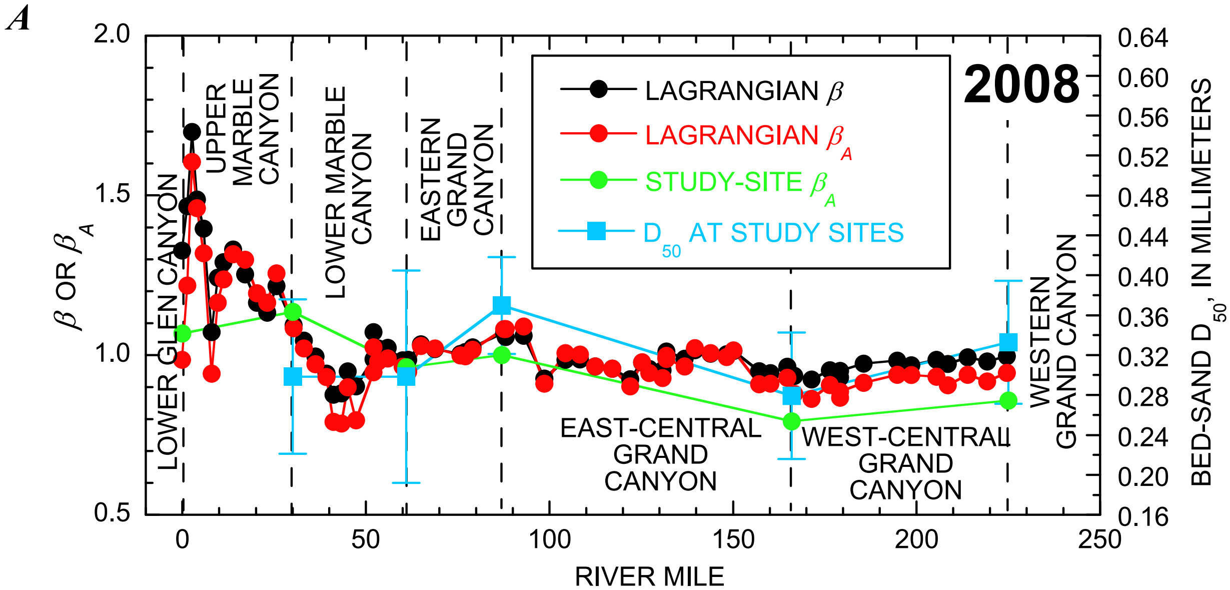


Figure 14. β-based computation of reach-averaged bed-sand area calculated using the suspended-sand data from the 2004 and 2008 Lagrangian sampling programs. Values of reach-averaged bed-sand area from figure 12 computed using the data from the study sites shown for comparison. Study reaches are indicated, separated by vertical dashed lines.

with large longitudinal variability, to about 12 to 16 percent at river mile 225. Again, as discussed in the previous analysis of reach-averaged bed-sand area at the study sites, it is important to remember that these computed values of A_b are not unweighted, linear geometric spatial averages, but rather are estimates of the fractional bed-sand area in a reach weighted by how the suspended sediment physically samples the bed sand over kilometer-long reaches at assumed constant reach-averaged τ_b.

Computations of reach-averaged bed-sand area during the 2004 CFE are more limited because the Lagrangian sampling program did not extend downstream from river mile 85. During day 1 of the 2004 CFE, reach-averaged bed-sand area likely increased in the downstream direction from river mile 0, as during the 2008 CFE, but attained a value of only about 10 percent at river mile 2. Reach-averaged bed-sand area then remained essentially constant during the 2004 CFE until river mile 39, where it began to decrease to a low of about 6 percent near river mile 50. It then began to gradually increase, reaching a high value of about 15 percent at the River-mile 87 study site. Because no suspended-sand data were collected between the River-mile 87 and 225study sites during the 2004 CFE, it is impossible to compute reach-averaged bed-sand area between these study sites with any certainty during the 2004 CFE. However, because the computed reach-averaged bed-sand area at the River-mile 225 study site during the 2004 CFE is also only 15 percent, and very little sand was supplied by tributaries to the reach between the River-mile 87 and 225 study sites during the sand-budgeting accounting period antecedent to the 2004 CFE, it is unlikely that reach-averaged bed-sand area was greater than about 15 percent in east- and west-central Grand Canyon during the 2004 CFE. The computations of reach-averaged bed-sand areas in figure 13*B* combined with the relatively large magnitude of the tributary sand inputs during the sand-budgeting accounting period antecedent to the 2008 CFE suggests that, given the present tributary sand supply and dam releases in the Colorado River downstream from Glen Canyon Dam, reach-averaged bed-sand area over long reaches probably does not typically exceed about 30 percent, even under highly sand-enriched conditions. This result is also consistent with the results in Topping and others (2007a) that show that only under pre-dam sand supply and discharge conditions were values of reach-averaged bed-sand area likely to greatly exceed 30 percent, during the annual period of sand accumulation in Marble and Grand Canyons under the lower discharges that preceded the rising limb of the annual snowmelt flood (Topping and others, 2000a).

As in the β-based analysis of data at the study sites, the agreement between β and D_{50} is improved when β is corrected for bed-sand-area effects (fig. 15). Interestingly, β_A computed using the Lagrangian data agrees better with the bed-sand D_{50} at the study-site measurement cross-sections than does β_A computed using the study-site data. This analysis indicates that during day 1 of the 2008 CFE, reach-averaged median grain size of the bed sand likely coarsened in the downstream direction from about 0.32 mm at river mile 0 to about 0.52 mm at river mile 2.5. With some downstream longitudinal variation (with a pronounced local minimum near river mile 8), the reach-averaged median grain size of the bed sand likely then fined to about 0.25 mm near river mile 42. Downstream from this location, the reach-averaged median grain size of the bed-sand likely coarsened slightly to about 0.35 mm near river miles 87 to 93. It then fined abruptly (the first of two pronounced downward steps in grain size), reaching a value of about 0.30 mm near river mile 98 before coarsening slightly to about 0.33 mm near river miles 140 to 150. A second abrupt decrease in grain size occurred between river miles 150 and 157. Downstream from river mile 157, the reach-averaged median grain size of the bed sand remained approximately constant, varying only between about 0.29 and 0.32 mm. It is important to note that these downward steps in



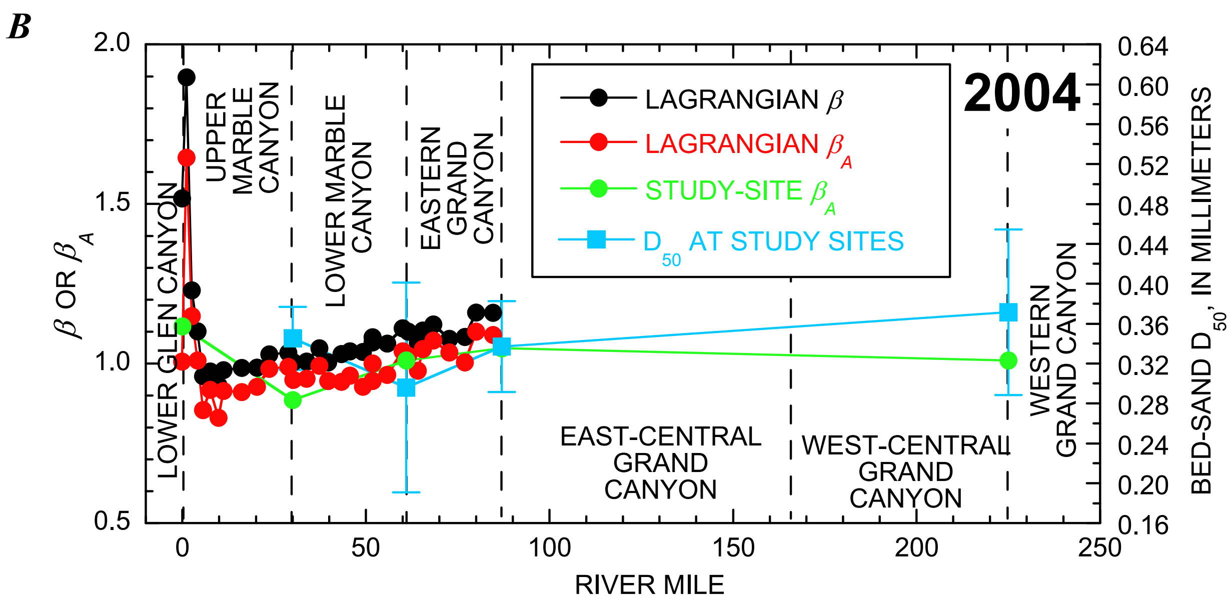


Figure 15. Results from β and β_A analyses of reach-averaged bed-sand median grain size using the suspended-sand data from the 2004 and 2008 Lagrangian sampling programs. Values of β and β_A computed using the data from the study sites, and bed-sand D_{50} measured at the study sites from figure 13 shown for comparison. As in figure 13, $\beta_A = 1$ is equivalent to reach-averaged bed-sand $D_{50} = 0.32$ mm. Error bars indicate the 95-percent confidence interval in the mean median grain size of the bed sand measured at the measurement cross-section at each study site on day 1 of high, steady discharge during each CFE. Study reaches are indicated, separated by vertical dashed lines. Comparison of β, β_A, and bed-sand D_{50} (*A*) during the 2008 CFE and (*B*) during the 2004 CFE.

computed bed-sand median grain size do not coincide with the sampling breaks between the different parcels of water sampled during the 2008 CFE. The downstream longitudinal pattern in reach-averaged bed-sand median grain size was quite different during day 1 of the 2004 CFE. During the 2004 CFE, as during the 2008 CFE, reach-averaged bed-sand median grain size coarsened abruptly from about 0.32 mm at river mile 0 to about 0.53 mm near river mile 1.5. In contrast to the 2008 CFE, however, reach-averaged bed-sand median grain size during the 2004 CFE fined substantially and quickly downstream from river mile 1.5, reaching the minimum value of about 0.27 mm between river miles 5 and 10. During the 2004 CFE, reach-averaged bed-sand median grain size then likely coarsened at an almost constant rate between river miles 10 and 87, reaching a value of about 0.35 mm at the River-mile 87 study site.

Substantial differences in computed reach-averaged bed-sand area and bed-sand median grain size are evident within lower Glen, Marble, and eastern Grand Canyons between the 2004 and 2008 CFEs (fig. 16). Except at only 3 of the Lagrangian sampling stations common to both the 2004 and 2008 CFEs, there was likely considerably more sand present on the bed during the 2008CFE than during the 2004 CFE. Computed reach-averaged bed-sand area during the 2008 CFE was about a factor of 3 greater than during the 2004 CFE at river mile 0 at the downstream terminus of lower Glen Canyon. Near river mile 17, there was likely also a factor of 3 more sand on the bed during the 2008 CFE than during the 2004 CFE. Between river miles 23 and 85, there was likely on average about 50 percent more sand on the bed during the 2008 CFE than during the 2004 CFE. Between river miles 2 and 36, the reach-averaged bed-sand median grain size was

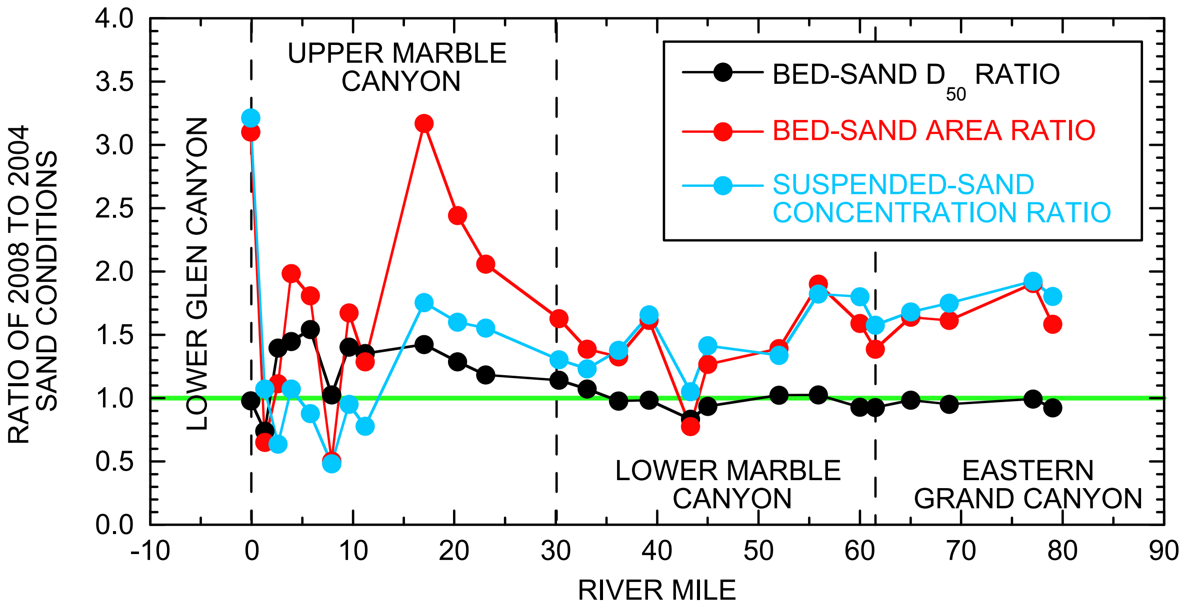


Figure 16. Ratio of 2008 CFE to 2004 CFE sand conditions from lower Glen Canyon through eastern Grand Canyon computed using the suspended-sand data collected at sampling stations common to both the 2004 and 2008 Lagrangian sampling programs. Horizontal green line indicates a ratio of one, that is, the line of zero change in sand conditions between the two CFEs. Shown are the ratios for reach-averaged bed-sand median grain size, reach-averaged bed-sand area, and suspended-sand concentration. Values plotting above the green line are greater during the 2008 CFE than during the 2004 CFE, whereas values plotting below the green line are greater during the 2004 CFE than during the 2008 CFE.

generally finer during the 2004 CFE than it was during the 2008 CFE, whereas between about river miles 39 and 80, the reach-averaged bed-sand median grain size was approximately equal during the 2004 and 2008 CFEs. At the downstream terminus of lower Glen Canyon at river mile 0, reach-averaged bed-sand median grain size was likely also approximately equal between the two CFEs. As discussed at length above, reach-averaged bed-sand median grain size dominates over reach-averaged bed-sand area in regulating suspended-sand concentration. Thus, in reaches where the bed was much finer during the 2004 CFE than during the 2008 CFE and where reach-averaged bed-sand area was only slightly less during the 2004 CFE than during the 2008 CFE, suspended-sand concentration was typically greater during the 2004 CFE than during the 2008 CFE (mostly in uppermost Marble Canyon between river miles 2 and 12). At all other locations, suspended-sand concentration was much greater during the 2008 CFE than during the 2004 CFE because reach-averaged bed-sand area was likely much greater during the 2008 CFE than during the 2004 CFE, and reach-averaged bed-sand median grain size was not that different between the two CFEs.

Comparison of Computed Reach-Averaged Bed-Sand Area, Reach-Averaged Bed-Sand Grain Size, Known Levels of Sand Enrichment, and Mean Suspended-Sand Concentration in Each Reach During the 1996, 2004, and 2008 CFEs

To provide guidance in the design of possible future controlled floods, and to provide guidance on possible improvements to monitoring the status of sediment resources in and along the Colorado River in GCNP, it is informative to compare reach-averaged bed-sand area, reach-averaged bed-sand median grain size, measured levels of sand enrichment, and observed suspended-sand concentrations during the three CFEs. Because sandbar-deposition rate depends strongly on suspended-sand concentration (for example, Schmidt and others, 1993), and suspended-sand concentration at constant discharge depends on bed-sand grain size and area, future controlled floods may be viable as management tools for sustainably rebuilding sandbars only if these floods can be designed to maintain the highest possible concentrations of suspended sand for specific different antecedent sand-supply conditions. This final analysis will provide some guidance for that effort. The parameters compared at each study site between the 1996, 2004, and 2008 CFEs in this analysis are: (1) EDI, EWI, and point-sample-measured suspended-sand concentration averaged over the last few hours of the rising limb and the entire high, steady discharge part of the flood hydrograph[19] (figs. 4, 5, 7); (2) sand enrichment[20] computed for each CFE by combining the antecedent sand enrichment values for each reach (table 3) with the measured sand loads entering the upstream end of each reach during the CFE (table 6); (3) reach-averaged bed-sand area computed using the study-site β-based analysis in figure 12; and (4) reach-averaged bed-sand median grain size computed using the sand-area-corrected study-site β analysis in figure 13. Because the magnitudes of these parameters differed greatly among the various study sites during the three CFEs, these parameters were normalized by their values during the 2004 CFE for the comparison between the 2004 and 2008 CFEs, and they were normalized by their values during the 1996 CFE for the comparison between the 1996 and 2008 CFEs. This nondimensionalization allowed better comparison of these parameters among the study sites by removing the effect of

[19] Because the duration of high, steady discharge during the 1996 CFE was much longer than during the 2004 and 2008 CFEs, only the suspended-sand concentrations measured over the first 3 days of high, steady discharge during the 1996 CFE were averaged for this comparative analysis.

[20] Note that data needed to compute sand enrichment were not collected before the 1996 CFE.

different reach lengths between study sites. These four dimensionless parameters are compared in table 8.

Table 8. 2008 CFE parameters at each study site normalized by their values during the 2004 CFE and during the 1996 CFE.

Study site and associated upstream reach	2008 CFE parameters normalized by their values during the 2004 CFE			
	Suspended-sand concentration	Sand enrichment	Reach-averaged bed-sand area	Reach-averaged bed-sand median grain size
River-mile 0 (lower Glen Canyon)	2.2	Positive number of unknown magnitude	2.1	0.96
River-mile 30 (upper Marble Canyon)	1.3	3.1	2.1 (*large enough to offset opposing effect on concentration of coarsening bed-sand grain size*)	1.28 (*coarsening should cause decrease in suspended-sand concentration*)
River-mile 61 (lower Marble Canyon)	1.5	2.0	1.3	0.95
River-mile 87 (eastern Grand Canyon)	1.6	2.7	1.3	0.95
River-mile 225 (combined east- and west-central Grand Canyon)	1.6	2.7	1.1	0.85
Study site and associated upstream reach	**2008 CFE parameters normalized by their values during the 1996 CFE**			
	Suspended-sand concentration	Sand enrichment	Reach-averaged bed-sand area	Reach-averaged bed-sand median grain size
River-mile 0 (lower Glen Canyon)	1.7	No data	2.7 (*large enough to offset opposing effect on concentration of coarsening bed-sand grain size*)	1.07 (*coarsening should cause decrease in suspended-sand concentration*)
River-mile 61 (combined upper and lower Marble Canyon)	1.7	No data	1.0	0.82
River-mile 87 (eastern Grand Canyon)	1.3	No data	0.7 (*not large enough to offset opposing effect on concentration of fining bed-sand grain size*)	0.84
River-mile 166 (east-central Grand Canyon)	1.2	No data	0.9 (*not large enough to offset opposing effect on concentration of fining bed-sand grain size*)	0.77

Predictions of eddy-sandbar deposition rates in a reach during a controlled flood require predictions of suspended-sand concentration. Such predictions require (1) knowledge of either the antecedent sand enrichment or reach-averaged bed-sand area and (2) knowledge of the reach-averaged bed-sand median grain size. Comparison of the dimensionless parameters in table 8 indicates that measured sand enrichment and reach-averaged bed-sand area are always positively correlated, as expected at constant discharge. Because measured sand enrichment and reach-averaged bed-sand area are always positively correlated at constant discharge (table 9), reach-averaged bed-sand area is the best proxy for sand enrichment when the data needed to compute sand enrichment by mass-balance sand budgeting are unavailable, for example, before the 1996 CFE. Reach-averaged bed-sand median grain size is a less reliable proxy for sand enrichment because reach-averaged bed-sand median grain size and area are negatively correlated in only 5 out of 9 cases (table 9). Correlations between these three parameters and suspended-sand concentration, however, are more complicated. As shown in tables 8 and 9, greater reach-averaged bed-sand area (and therefore likely greater sand enrichment) can coincide with lower suspended-sand concentration when the reach-averaged bed-sand median grain size is coarse, for example in Grand Canyon upstream from the River-mile 87 and 166 study sites during the 1996 CFE (figs. 5, 12, 13). This is because reach-averaged bed-sand median grain size exerts a stronger nonlinear control on suspended-sand concentration than does reach-averaged bed-sand area.

It is possible to have situations where greater sand enrichment leads to larger amounts of coarser sand in a reach, for example, in eastern Grand Canyon during the 1996 CFE and in upper Marble Canyon during the 2008 CFE. These situations are most likely to reoccur in these two reaches because they are located immediately downstream from the two largest sand-supplying tributaries. As already discussed, at some finite time interval after a large tributary sand-supplying event, the finer sand will be winnowed from the bed in the reach downstream from the tributary, leaving only the coarse tail of the grain-size distribution of sand supplied during this tributary flood to be mixed with the bed sand that existed in this reach before the tributary flood. In the coarse-bed, greater-bed-sand-area cases during the 1996 CFE, the sand that covered more of the bed in eastern and east-central Grand Canyon was too coarse to result in higher suspended-sand concentrations at the River-mile 87 and 166 study sites than during the two subsequent CFEs (figs. 5, 12, 13). Thus, it was possible for lesser amounts of finer sand on the bed to result in suspended-sand concentrations at the River-mile 87 and 166 study sites that were higher during the 2008 CFE than during the 1996 CFE (fig. 5). In the coarse-bed, greater-bed-sand-area cases during the 2008 CFE, the sand that covered more of the bed in upper Marble Canyon was not too coarse to result in lower suspended-sand concentrations than during the 2004 CFE (figs. 5, 12, 13). Thus, during the 2008 CFE in upper Marble Canyon, the effect on suspended-sand concentration arising from more than 3 times greater reach-averaged bed-sand area relative to during the 2004 CFE (fig. 16) was enough to overcome the opposing effect on suspended-sand concentration arising from coarser bed sand (figs. 5, 12, 15).

Therefore, in the design of future controlled floods, knowing just total "sand enrichment" in each reach of the Colorado River in lower Glen, Marble, and Grand Canyons is not enough to ensure sufficiently high suspended-sand concentrations to result in high eddy-sandbar deposition rates during a controlled flood; one must also know the relative grain size of the bed sand in each reach. This is important because if suspended-sand concentrations are not high enough during a controlled flood, eddy sandbars either will not gain sand or, in the worst-case scenario, will erode, as observed during the 1996 CFE in Marble Canyon (Hazel and others, 1999; Schmidt, 1999; Topping and others, 2006a). The sand-transport monitoring program maintained by the USGS on

Table 9. Signs of relations between the 2008 CFE parameters normalized by their values during the 2004 CFE and normalized by their values during the 1996 CFE.

[Parameter states that opposed larger suspended-sand concentration during the 2008 CFE than during the 2004 CFE or during the 2008 CFE than during the 1996 CFE indicated by red type. Parameter states that promoted larger suspended-sand concentration during the 2008 CFE than during the 2004 CFE or during the 2008 CFE than during the 1996 CFE indicated by green type. Identical signs in adjacent columns indicate positive correlation between parameters in these columns.]

Study site	Sign of relation between normalized suspended-sand concentration during 2004 and 2008 CFEs and each of the following		
	Normalized sand enrichment	Normalized reach-averaged bed-sand area	Normalized reach-averaged bed-sand median grain size
River-mile 0	+	+	-
River-mile 30	+	+ (*dominates over bed-sand grain size in this case*)	+ (*opposes bed-sand area!!!*)
River-mile 61	+	+	-
River-mile 87	+	+	-
River-mile 225	+	+	-
Study site	**Sign of relation between normalized suspended-sand concentration during 1996 and 2008 CFEs and each of the following**		
	Normalized sand enrichment	**Normalized reach-averaged bed-sand area**	**Normalized reach-averaged bed-sand median grain size**
River-mile 0	No data	+ (*dominates over bed-sand grain size in this case*)	+ (*opposes bed-sand area!!!*)
River-mile 61	No data	+	-
River-mile 87	No data	- (*opposes bed-sand grain size!!!*)	- (*dominates over bed-sand area in this case*)
River-mile 166	No data	- (*opposes bed-sand grain size!!!*)	- (*dominates over bed-sand area in this case*)

the Colorado River in Grand Canyon National Park measures suspended-sand concentration and grain size every 15 minutes at the River-mile 30, 61, 87, 166, and 225 study sites. In addition to being used to compute sand enrichment, these data can be analyzed using the β-based analyses described in this report to provide information on reach-averaged bed-sand median grain size in each reach. Thus, information on sand enrichment and reach-averaged bed-sand median grain size (the two parameters most needed to predict suspended-sand concentrations during a controlled flood) can be provided to managers for optimized design of future controlled floods to most efficiently rebuild eddy sandbars.

Finally, the analyses in this report suggest that post-1996 dam operations may be resulting in net scour of sand from Grand Canyon. Although suspended-sand concentrations were higher at all study sites during the 2008 CFE than during either the 1996 or 2004 CFEs, these higher concentrations were not necessarily associated with greatest sand enrichment occurring during the 2008 CFE. Although (1) more sand was likely present on the bed during the 2008 CFE in lower Glen Canyon than during either the 1996 or 2004 CFE and (2) more sand was likely present on the bed during the 2008 CFE in Marble and Grand Canyons than during the 2004 CFE, equal or lesser amounts of sand were likely present on the bed during the 2008 CFE in lower Marble Canyon and much of Grand Canyon than during the 1996 CFE. Among the three CFEs, the greatest level of sand enrichment in lower Glen Canyon occurred during the 2008 CFE, and this was a result of the combination of the largest tributary sand inputs and second-lowest dam releases occurring antecedent to the 2008 CFE. Among the three CFEs, however, more sand was likely present on the bed in Grand Canyon during the 1996 CFE than during either the 2004 or 2008 CFE. Therefore, among the three CFEs, the greatest level of sand enrichment in Grand Canyon occurred during the 1996 CFE, and this was a result of either (1) a temporary increase in the amount of sand on the bed following the extremely large inputs of sand to this reach during the January-March 1993 Little Colorado River floods, or (2) long-term scour of sand from this reach during dam operations. Thus, although the analyses in this report can provide guidance in the design of future controlled floods, further experimentation (with controlled floods and intervening dam releases) and monitoring are required to evaluate whether controlled floods can utilize the existing tributary sand supply to rebuild eddy-sandbars in a sustainable manner, or if dam operations with or without controlled floods will result in long-term scour of sand from the Colorado River in GCNP.

Conclusions

The major conclusions from this study are as follows.

1. Although suspended-sand concentrations were higher at all study sites during the 2008 CFE than during either the 1996 or 2004 CFE, these higher concentrations were only associated with more sand on the bed of the Colorado River in lower Glen Canyon. More sand was likely present on the bed of the river in Grand Canyon during the 1996 CFE than during either the 2004 or 2008 CFE. It remains unclear as to whether ongoing dam operations are resulting in long-term net scour of sand from Grand Canyon.

2. Nothing observed in the sediment-transport data collected during the 2008 CFE refuted any of the conclusions in Topping and others (2006a). In their analysis of sediment-transport and bar data collected during the 1996 and 2004 CFEs, Topping and others (2006a) concluded that

   > results from the 1996 controlled-flood experiment indicate that, during sediment-depleted conditions, sand deposited at higher elevations in downstream eddy sandbars is derived from the lower-elevation parts of upstream sandbars. Thus, controlled floods conducted under these conditions result in decreases in total eddy-sandbar area and volume (especially in Marble Canyon).

   They also concluded that compared to the 2004 CFE,

   > in future controlled floods, more sand is required to achieve increases in the total area and volume of eddy sandbars throughout all of Marble and Grand Canyons. Annual tributary inputs of sand much larger than one million metric tons occur, but are relatively rare. Therefore, “more sand” could be achieved directly by augmentation from sand trapped in the reservoir impounded by Glen Canyon Dam or perhaps indirectly by following each large tributary input of sand with short-duration controlled floods. Frequent short-duration controlled floods under sand-enriched conditions could result in the downstream propagation (into the downstream half of Marble

Canyon and into Grand Canyon) of the gains in total eddy-sandbar area and volume observed in the upstream half of Marble Canyon during the 2004 controlled-flood experiment.

The relatively high level of sand enrichment from tributaries antecedent to the 2008 CFE is not a frequent occurrence. Therefore, the 2008 CFE could not address the key question implied in the last two sentences of the conclusions excerpted from Topping and others (2006a), that is, whether sandbars can be sustainably rebuilt in the Colorado River in Grand Canyon National Park through use of controlled floods with more typical levels of sand enrichment. The answer to this question remains unknown and will require future experimentation and monitoring.

3. Although the 2008 CFE did not answer this key question, it did allow collection of the most comprehensive sediment-transport dataset collected during a controlled flood to date, and thus helped provide answers to key process-related questions. Analysis of the suspended- and bed-sediment data collected during the 1996, 2004, and 2008 CFEs indicates that, although greater levels of antecedent sand enrichment generally lead to higher suspended-sand concentrations during a controlled flood, this is not always the case by virtue of the opposing physical effects of reach-averaged bed-sand grain size and area in regulating suspended-sand concentration. Greater levels of sand enrichment will lead to greater reach-averaged bed-sand area, but will not always lead to finer reach-averaged bed-sand grain size. Because the reach-averaged bed-sand grain-size distribution exerts an opposing and stronger nonlinear control on suspended-sand concentration than does reach-averaged bed-sand area, greater levels of sand enrichment can produce lower suspended-sand concentrations during a controlled flood than can lower levels of sand enrichment when a smaller area of the bed is covered by finer sand. Larger suspended-sand concentrations during a controlled flood are required to produce higher eddy-sandbar deposition rates. Therefore, design of controlled floods for optimal sandbar deposition in the Colorado River in Grand Canyon National Park should not be based only on threshold levels of sand enrichment, but also on reach-averaged bed-sand median grain size. The analyses present in this report suggest that reach-averaged bed-sand median grain size could be estimated before future controlled floods using β. A lesser amount of finer sand on the bed could easily result in higher eddy-sandbar deposition rates during a controlled flood than could a larger amount of coarser sand on the bed.

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