20,000 GRAIN-SIZE OBSERVATIONS FROM THE BED OF THE COLORADO RIVER, AND IMPLICATIONS FOR SEDIMENT TRANSPORT THROUGH GRAND CANYON

David M. Rubin, Senior Scientist, USGS, Santa Cruz, CA, drubin@usgs.gov
David J. Topping, Hydrologist, USGS, Flagstaff, AZ, dtopping@usgs.gov
Henry Chezar, Photographic Technologist, USGS, Santa Cruz, CA, hchezar@usgs.gov
Joseph E. Hazel, Geologist, Northern Arizona Univ., Flagstaff, AZ, Joseph.Hazel@nau.edu
John C. Schmidt, Professor, Utah State University, Logan, UT, Jack.Schmidt@usu.edu
Michael Breedlove, Geographer, Utah State University, Logan, UT, mbreedlove@usgs.gov
Theodore S. Melis, Deputy Center Chief, USGS, Flagstaff, AZ, tmelis@usgs.gov
Paul E. Grams, Hydrologist, USGS, Flagstaff, AZ, pgrams@usgs.gov

Abstract

In the late 1990s, we developed digital imaging hardware and software for in-situ mapping of sand-sized bed sediment of the Colorado River in Grand Canyon. This new technology enables collection and processing of hundreds of grain-size samples in a day. Bed grain size was mapped using this equipment on 8 surveys of the Colorado River in Grand Canyon, for a total of more than 20,000 observations spanning 8 years. These observations document the fining of the bed when fine sand is introduced from tributaries and document the winnowing of that new sediment in the mainstem during intervening periods. The observations show how grain size varies with depth and geomorphic setting (finer in shallow depths and in lateral separation eddies), and how it varies through time. The results document that mean grain size of sand covering much of the riverbed can change substantially through time (a factor of 3). Such changes in bed sediment can be expected to cause suspended sediment concentration and flux to change by an order of magnitude for a constant water discharge.

INTRODUCTION

Background and Purpose

Previous work has shown that changes in bed-sediment grain size are as important as changes in water discharge in regulating sediment transport down the Colorado River in Grand Canyon (Rubin and Topping, 2001). For a given water discharge, suspended sediment concentrations can vary by as much as 2-3 orders of magnitude, with much of the variability attributable to changes in bed sediment (Topping and others, 2000). Because knowledge of bed-sediment grain size is key to understanding and predicting sediment transport down the river, we developed new technology to speed up the data collection and analysis, and we initiated a program to map bed-sediment grain size on 8 surveys between 2000 and 2008. The purpose of this paper is to report those observations and to use the results to interpret how sediment moves downstream from Glen Canyon Dam.

METHODS

Hardware

Grain size of sand on the bed of the Colorado River was measured using digital technology that was developed specifically for this work. The approach was to enclose a small video camera and

LED light source within a wrecking ball (Chezar and Rubin, 2004; Rubin and others, 2007), lower this instrument to the bed, take digital images of bed sediment through a window on the bottom of the housing, and determine grain size using digital image processing (Rubin, 2004). The camera in this system views the bed through a window resting flat on the bed, so images are clear regardless of water turbidity. Field of view and resolution are optimized to give accurate results for the full range of sand sizes (0.625 mm to 2.0 mm). Finer sediment is too small for the resolution of the video system, and coarser sediment contains too few grains in the field of view (roughly 1 cm^2). Consequently, the results presented below are restricted to sand-sized sediment.

Data Collection

Data collection involved navigating to each pre-planned location, lowering the video wrecking ball to the bed using an electric winch (Rubin and others, 2007, fig. 7a), and collecting multiple images of the bed (moving the wrecking ball a few cm or tens of cm between images). The first survey (August, 2000) collected approximately 350 bed images; later surveys were able to collect as many as 4000 samples. Most bed-sediment images were collected in the first 110 km downstream of Lees Ferry, where the Paria River enters the mainstem Colorado River (Fig. 1).

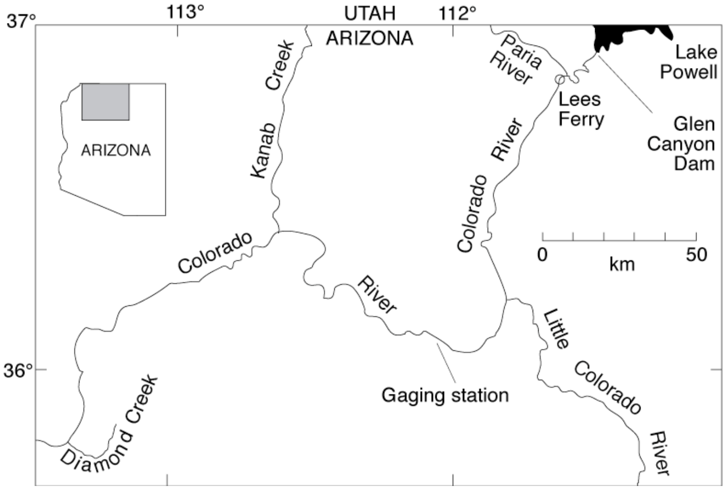


Figure 1. Map of Colorado River in study area, showing Glen Canyon Dam, Lees Ferry, and Paria River.

Other Data

Sample locations were recorded spatially in three dimensions. Coordinates in the horizontal plane were measured by tracking the boat using a shore-based laser tracking system from established survey control points (Hazel and others, 2007). Elevation of the riverbed (relative to river stage at 8000 ft^3/s; 226.53 m^3/s) was determined by comparing the depths to either the stage-discharge relations of Hazel and others (2006) or the modeled water-surface elevations of Magirl and others (2008). Geomorphic environments were determined by locating the grain-size samples on pre-existing geomorphic classification maps that identify the main channel, eddy, channel margin, and other settings.

Data Processing

For the decade during which this technology was used to collect data in Grand Canyon, the grain-size algorithm was tested using manual point counts of digital images from Grand Canyon and a variety of other geographic locations and settings (river, beach, dune, nearshore marine, and shelf), with grain sizes ranging from very fine sand to cobbles (Rubin, 2004; Barnard and others, 2007; Buscombe, 2008; Buscombe and Masselink, 2009; Warrick and others, 2009; Buscombe and others, 2010; Buscombe and others, in press). These studies reported errors of approximately 10-20% for individual measurements, which is greater error than errors in traditional lab methods. When corrected using calibration images, as for the results presented here, errors of individual values is typically less than 13%, and errors in the mean grain size of a population is even less. The approach here is to use vary large numbers of samples to reduce errors in determining the mean grain size. Data processing is relatively rapid; a trained high-school student was able to process 800 grain-size images in one day (a cost of less than $0.10 each). Because this approach is so rapid and inexpensive in both the field and lab, a given budget can measure considerably more grain-size measurements, thereby enabling 20,000 measurements in this study. A final advantage of this approach is that it measures only those grains that are exposed on the bed surface thus interacting directly with the flow.

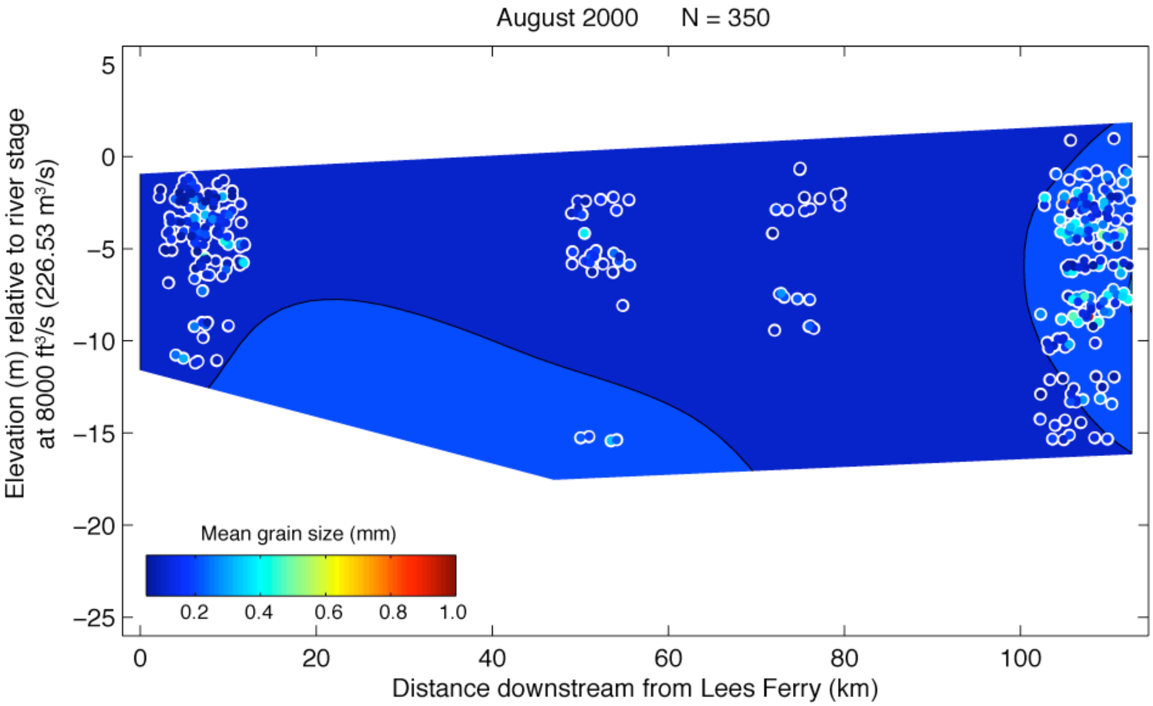
OBSERVATIONS AND INTERPRETATIONS

General Sediment Distribution Patterns

Grain sizes for more than 20000 observations are shown in Figure 2(A-H). Results show systematic variations in grain size as a function of depth, distance downriver, and time. Fine grain sizes were most widespread when surveys were conducted soon after large tributary inputs (surveys of August 2000, November 2004, and February 2008). Coarse grain sizes were most widespread at times without large recent inputs (May 2002 and May 2004).

Figure 2 (next 4 pages). Bed grain size plotted as a function of distance downriver and flow depth. Each of the 8 plots represents a different survey. Each dot shows the location of an individual grain size sample; color of the dot represents mean grain size of that sample. Because sampling density is too great to plot without most points being concealed by other points, the location of each point on the plot is shifted by a small random displacement. The background color is a smoothed surface fit to the data (color-coded using same color scale as used for individual points). In August 2000, grain size was relatively fine at all depths and all locations. From then until May 2004, bed sediment coarsened, beginning upstream and in deep water, and then progressing downstream and into shallower water. Tributary inputs later in 2004 caused the bed to fine, although not as fine as in August 2000. A high flow in November 2004 caused the bed to begin coarsening again.

Figure 2A



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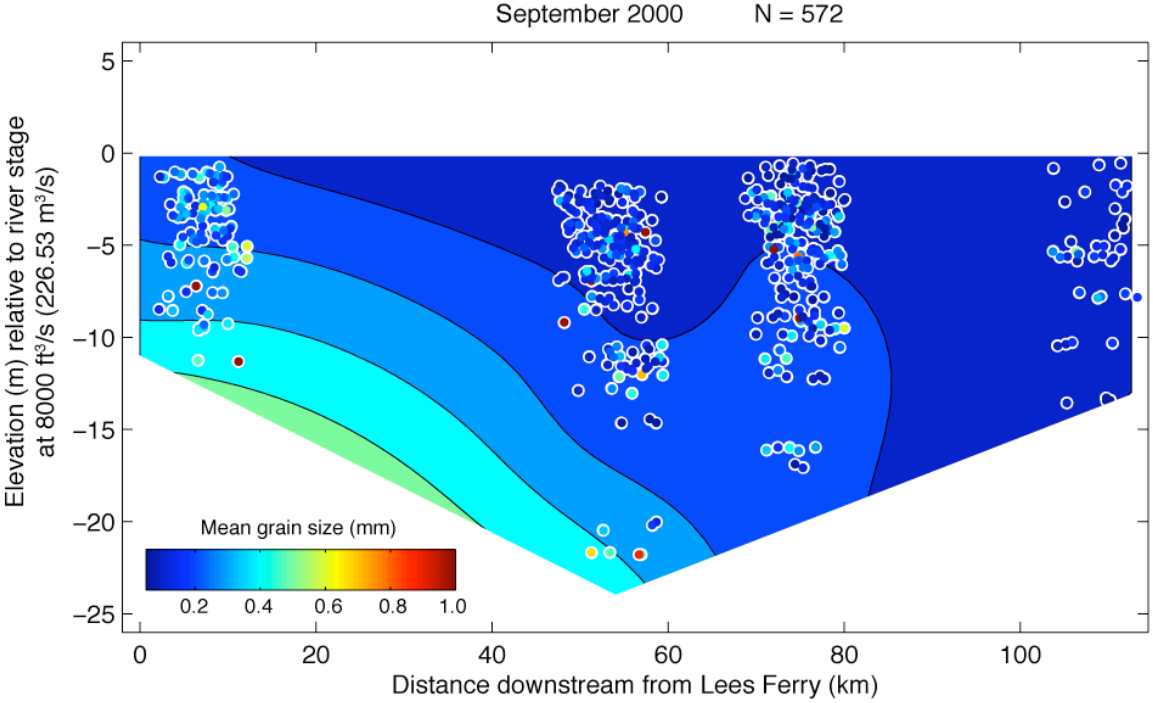

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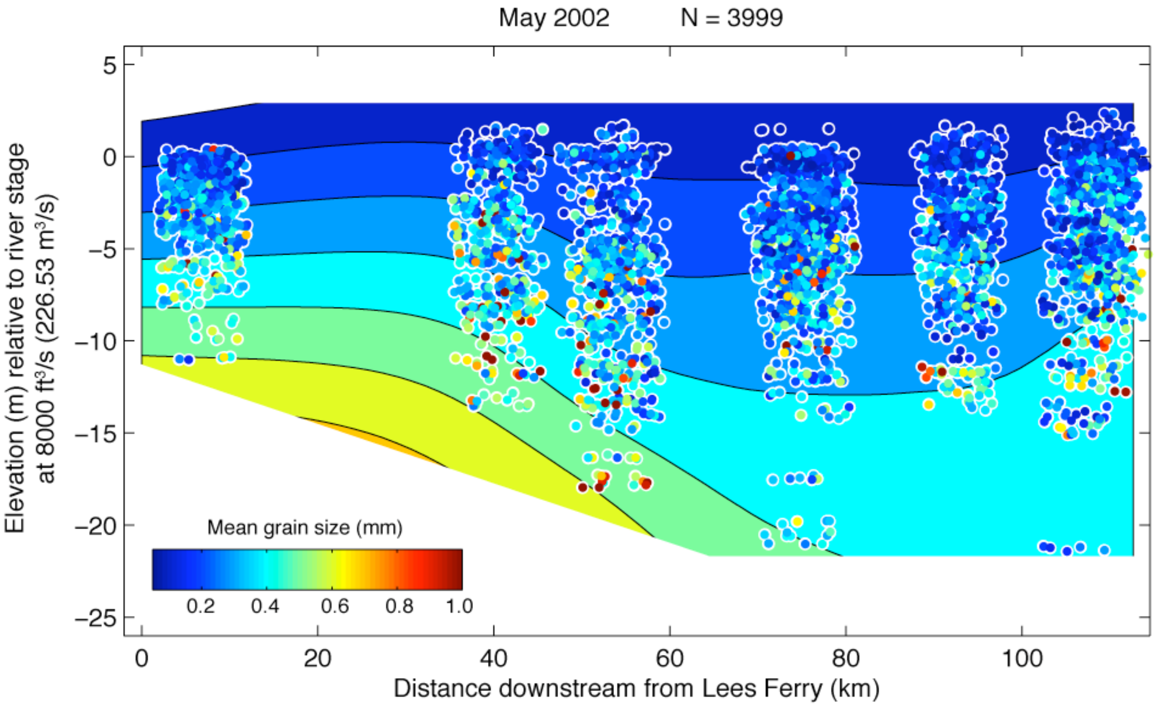

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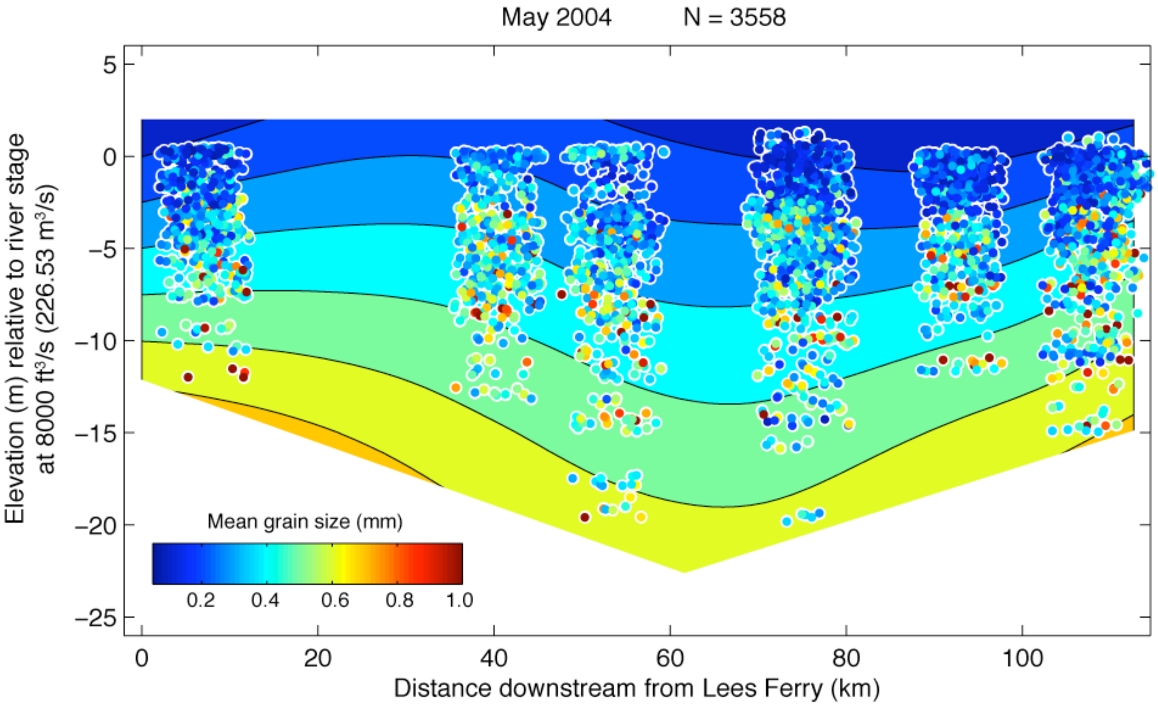

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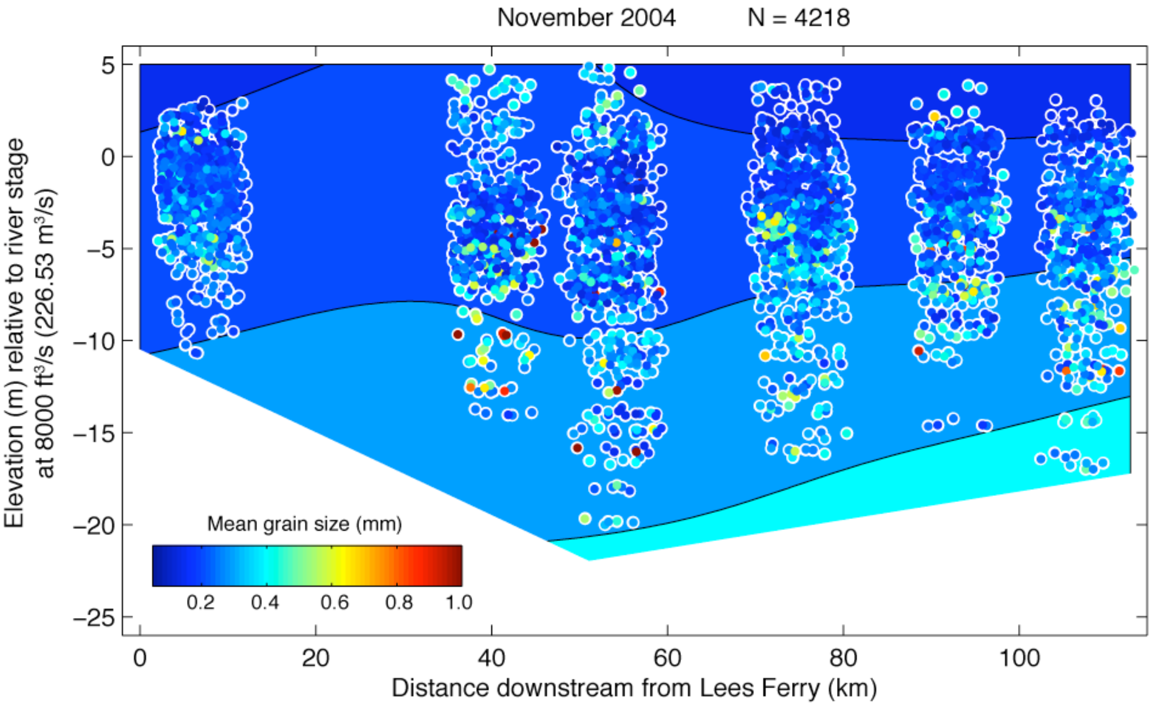

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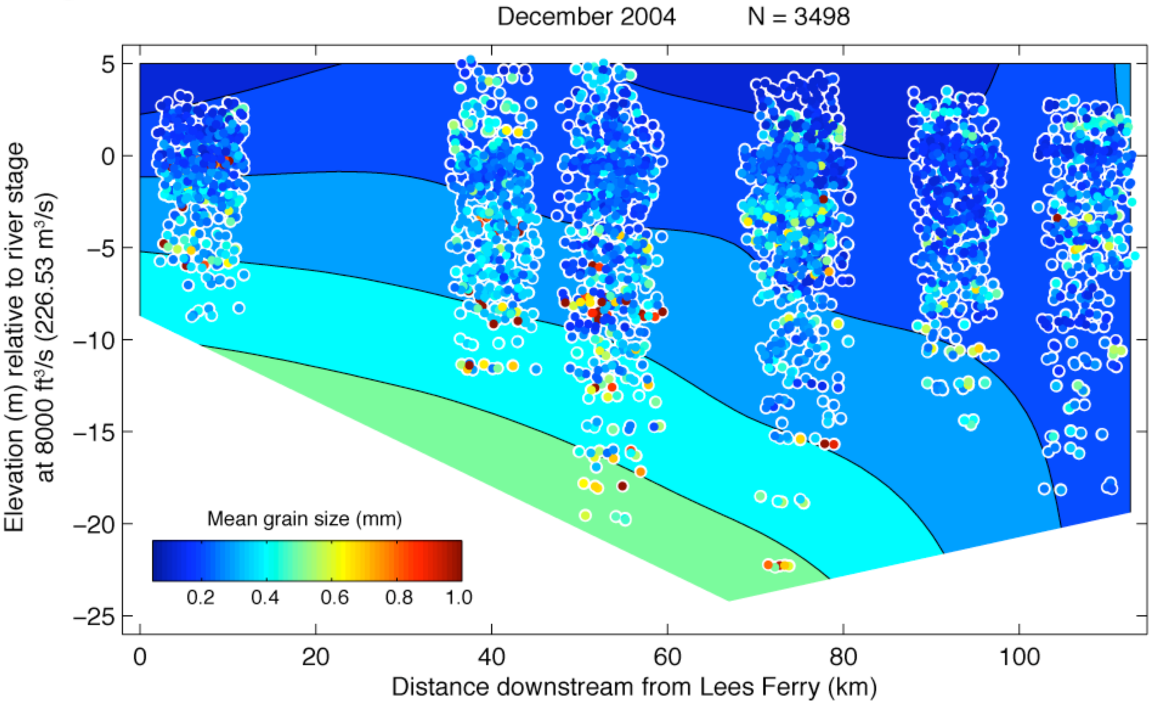

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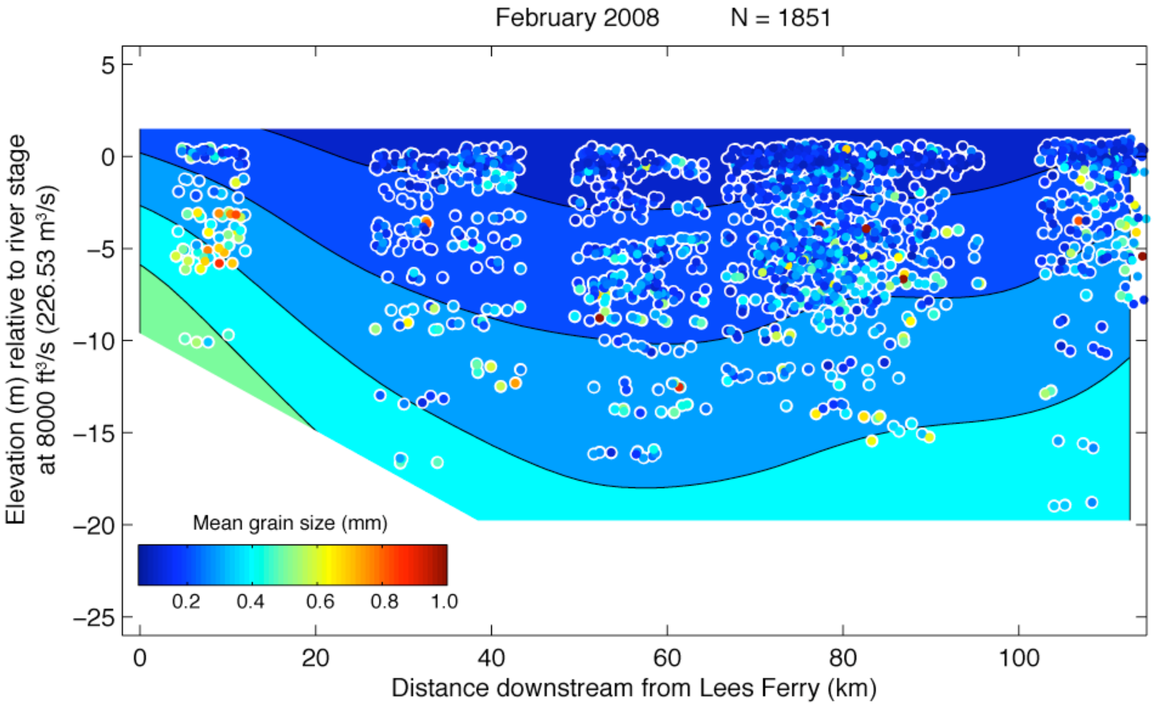
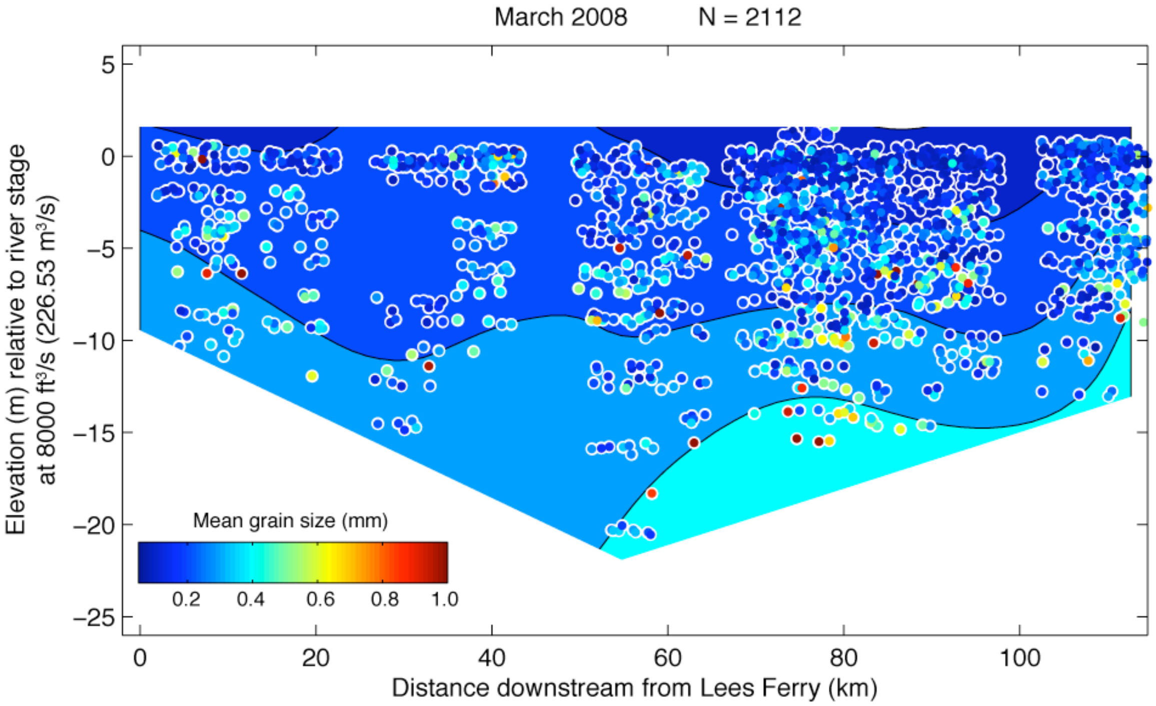


Figure 2H



Grain Size of Sand as a Function of Depth

Grain size is coarser in deep water than in shallow water (Fig. 3), which is consistent with what has been observed routinely in ancient fluvial deposits (Allen, 1970). The variation of size as a function of depth is substantial. Mean grain size at an elevation of -20 m (20 m below stage at 8000 ft^3/s or 226.53 m^3/s) is approximately 0.4 mm, whereas mean grain size at an elevation of 5 m (5 m above the reference stage) is approximately 0.2 mm. This spatial trend is inferred to reflect a greater shear stress in deep water that is more effective in winnowing the bed.

Variability of grain size in deep water is also greater than in shallow water (on a linear scale, although not on a log scale). The grain size that is one standard deviation coarser than the mean increases from approximately 0.29 to 0.61 mm with depth, but the grain size that is one standard deviation finer than the mean increases only from 0.11 mm to 0.23 mm with depth (Fig. 3). Consequently, the range of grain sizes is greater in deep water. These results summarize observations from all eight surveys. Depth-related differences in grain size are not constant, however; they vary from one survey to another, as discussed below.

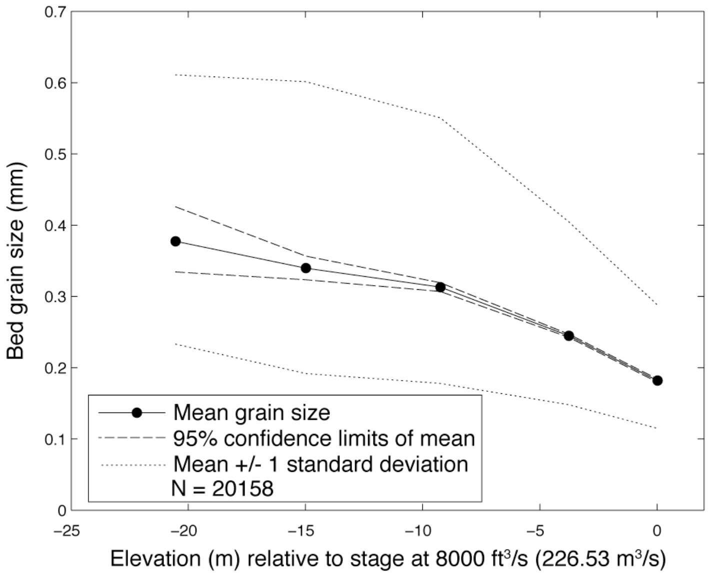


Figure 3. Mean bed grain size plotted as a function of depth relative to river stage of 8000 ft^3/s (226.53 m^3/s). Sediment in deep water tends to be coarser than in shallow water. The plot is based on 20,158 grain-size observations from the 8 surveys shown in Figure 1. Statistics were calculated in log space. The standard deviation (dotted line) is large relative to differences in the mean (solid line), but the error in the mean (dashed line) is small because of the very large number of samples used to evaluate each point.

Differences in Grain Size as a Function of Geomorphic Setting

Grain size in the main channel is generally coarser than in eddies, even when controlled for flow depth (Fig. 4). At depths of 5-15 m below the 8000 ft^3/s (226.53 m^3/s) stage, mean grain size in the channel is roughly 0.3-0.35 mm whereas mean grain size at those depths in eddies is 0.1-0.2 mm. This variation in grain size with setting is consistent with previous work that has measured lower flow velocities in eddies (Schmidt and others, 1993).

Changes in Grain Size with Distance Downriver

Although spatial changes in grain size are dramatic in the field (for example, cobbles and boulders in rapids and sand in many pools), mean grain size of sand averaged over long reaches and averaged for all surveys varies little with distance downriver (Fig. 5). Mean grain size averaged over all surveys is 0.24 mm +/- 15% for all reaches. We do not know the extent to which this lack of substantial spatial variability is a result of a non-random sampling scheme.

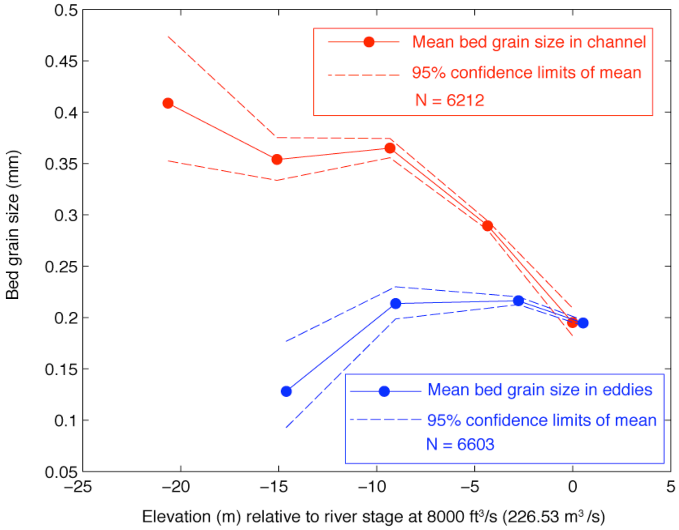


Figure 4. Mean bed grain size plotted as a function of depth in the main channel and in lateral separation eddies. Grain size in the channel is considerably coarser than in eddies. Statistics were calculated in log space.

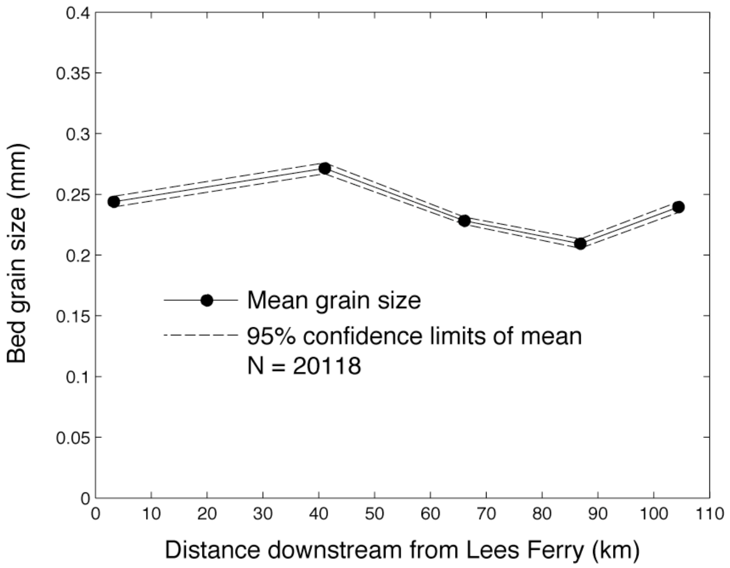


Figure 5. Mean bed grain size as a function of distance downriver, averaged from 20118 observations from 8 surveys. Grain size varies little with location (0.24 mm +/- 15%).

Changes in Grain Size Through Time

Although grain sizes averaged for all surveys are relatively constant downriver, grain sizes vary considerably from survey to survey and from reach to reach on individual surveys. The temporal variability is evident when controlling for either depth (Fig. 6A) or distance downriver (Fig. 6B). Temporal variability (quantified by the mean standard deviation for all 5 reaches shown in Fig. 6B) is 0.53, whereas spatial variability (mean standard deviation for all 8 surveys) is 0.37. Relatively little tributary sediment was supplied to the mainstem from August 2000 to May 2004, resulting in winnowing and coarsening.

In the summer and fall of 2004, large inputs of fine sand from the Paria River (Fig. 1) caused the bed of the Colorado River to fine and also led to an experimental release of water (41,000 ft^3/s; 1175 m^3/s) from Glen Canyon Dam in November 2004. That flow caused the bed to become coarser (when surveyed in December 2004), but not as coarse as it had been in May 2004. The coarsening was greater in deep water (Fig. 6A) and at upstream locations (Fig. 6B). Subsequent tributary inputs between 2004 and 2008 again caused the bed to fine at all depths (Fig. 6A) and in all reaches downriver (Fig. 6B). Another experimental release of (~1175 m^3/s) in March 2008 did not cause detectable coarsening (Fig. 6B), perhaps because of tributary inputs during this time.

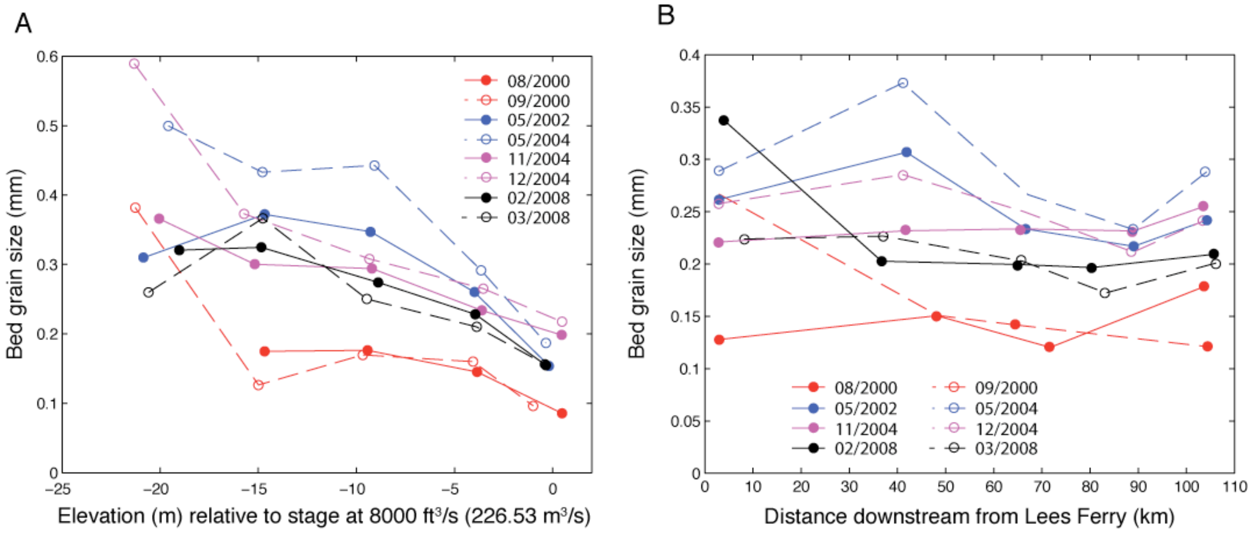


Figure 6. Plots showing temporal changes in grain size. (A) Changes in grain size as a function of depth for 8 surveys. Grain size increases with depth for all 8 surveys. Changes through time are comparable in magnitude to the changes with depth. (B) Changes in grain size as a function of distance downriver for 8 surveys. Changes through time are an order of magnitude greater than the mean downriver variability for all data (Fig. 5).

IMPLICATATIONS FOR UNDERSTANDING AND MODELING SEDIMENT TRANSPORT

Technology developed for this work enabled rapid and relatively inexpensive bed-sediment grain-size mapping, allowing an unprecedented number of samples. The large number of samples documented system-wide changes in grain size in response to tributary inputs and intervening periods of winnowing of the bed.

Previous work has shown that suspended-sediment concentrations in the Colorado River in Grand Canyon vary by several orders of magnitude for a given water discharge (Topping and others, 2000; Rubin and Topping, 2001). The observations reported here document changes in bed grain size of approximately a factor of 3. Because suspended-sediment concentration varies inversely with the square of grain size (summarized in Rubin and Topping, 2001), the observed changes are not sufficient to explain why concentration would vary by more than about one order of magnitude for a given water discharge. In addition to causing fining of mean grain size on the bed, tributary inputs likely cause other changes in bed-sediment properties. For example, new inputs are probably more poorly sorted when first supplied by tributaries and thus contain a higher proportion of the fine tail of a grain-size distribution than is evident from the mean alone. In addition, new inputs of fine sand may increase the areal coverage of sand on the bed (particularly the areal distribution of the finest fractions); the more widespread distribution of finer grain sizes is likely to include areas where shear stress is higher (as in deeper water), which can also increase the concentrations more than if the fine sands were restricted to locations with low shear stress (as happens after the bed has been winnowed).

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