MEASUREMENTS OF VELOCITY PROFILES AND SUSPENDED-SEDIMENT CONCENTRATIONS IN A COLORADO RIVER EDDY DURING HIGH FLOW

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Abstract: Measurements of velocity profiles and suspended-sediment concentration were made in a recirculating eddy along the Colorado River in Grand Canyon during a high flow release from Glen Canyon Dam in November 2004. The objectives of the measurements were to test an acoustic Doppler current profiler (ADCP) within these environments, to roughly characterize the velocity and concentration structure in the eddy, and to test some assumptions of previous numerical modeling approaches. Results indicate that ADCPs can be useful tools for characterizing the velocity structure of recirculating eddies. The velocity profiles are useful for evaluating some of the assumptions that have been made in previous modeling efforts. In particular, the measurements indicate significant rotation of horizontal velocities vertically through the water column as well as significant vertical velocities; neither process can be simulated with depth-averaged, two-dimensional flow models. However, it is still unknown how important these features are for sediment transport and eddy morphology.

INTRODUCTION

Fine-sediment deposits along the Colorado River below Glen Canyon Dam (fig. 1) have been the subject of numerous studies because of their importance to recreational river users, riparian vegetation, and potential importance as physical habitat for juvenile native fish. Completion of Glen Canyon Dam in 1963 greatly reduced the fine sediment supply to Grand Canyon and has resulted in erosion of these deposits (Rubin et al., 2002, Wright et al., 2005); as a result, restoration and maintenance of fine sediment deposits in Grand Canyon is a primary goal of the Glen Canyon Dam Adaptive Management Program (U.S. Department of the Interior, 1996).

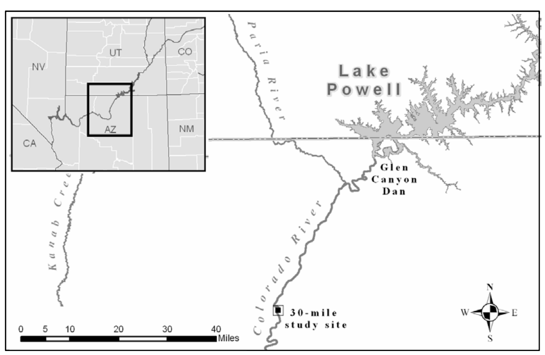

Figure 1. Location map showing 30-mile study site (45 miles from Glen Canyon Dam).

Fine-sediment deposits typically occur downstream from channel constrictions created by tributary debris fans. Flow separates immediately downstream from the constriction and reattaches to the bank at some point downstream, forming a recirculating zone (eddy) near the shore with relatively low velocity that is conducive to sediment deposition. Schmidt (1990), Schmidt and Graf (1990), and Rubin et al. (1990) described the basic processes of recirculating flow and sedimentation along the Colorado River in Grand Canyon; Schmidt et al. (1993) documented an experimental investigation of similar processes.

Along with the considerable field and laboratory efforts to characterize fine-grained depositional areas, several modeling studies have been undertaken that attempt to simulate the fate of fine-grained sediments in the Colorado River under varying discharges and sediment supply conditions. Wiele et al. (1996) and Wiele (1998) describe development of a numerical model and its application to simulate deposition in reaches of the Colorado River below the confluence with the Little Colorado River (river mile 62, 77 miles below Glen Canyon Dam) following significant flooding and sediment inputs from this tributary in 1993. The model simulates the flow field as two-dimensional and vertically averaged; suspended sediment is modeled through use of the advection-dispersion equation which yields the three-dimensional concentration field, though it is not a full three-dimensional solution because of the two-dimensional depth-averaged flow field. Bed evolution is obtained from flux divergences in suspended- and bed-load transport. Model predictions were found to be in relatively good agreement with measured changes in topography. This model has been subsequently applied to study the effects of sand concentration on deposition rates (Wiele et al. 1999) and to study sand deposition in archaeologically significant reaches of the Colorado River (Wiele and Torrizo 2005).

Nelson and McDonald (1996) and Nelson et al. (1994) presented a modeling approach that stresses the need to model secondary flows in addition to the two-dimensional depth-averaged flow field. They argue that advective transport of sediment into the eddy near the bed can be an important mechanism that can only be accounted for by including secondary flows. This transport is a result of tilting of the vortices (by the vertical velocity gradient) that are shed from the separation point, leading to rotational structures with flow out of the eddy near the surface and into the eddy near the bed. Since sediment concentration is highest near the bed and lowest near the surface (when Rouse number is low), this leads to a net advective transport of sediment into the eddy. McDonald and Nelson (1996), McDonald et al. (1994), and Nelson (1991) document field and laboratory studies that demonstrate this transport mechanism. Also, Nelson and McDonald (1996) present numerical simulations with and without secondary flows and show that the simulations with secondary flows yield better agreement with laboratory measurements. Though transport by secondary currents must certainly be important under some conditions, it is not yet clear that it is an important transport mechanism for Colorado River eddies during high flow. Indeed, the model of Wiele et al. (1996), which relies solely on turbulent dispersion to transport sediment into and out of eddies, was shown to perform well for the cases studied; it is noted that these cases were quite large depositional events. Further investigation is required to better constrain these transport mechanisms for Colorado River eddies. Recent modeling efforts using large eddy simulation (Akahori and Schmeeckle, 2005) provide a promising start.

Despite the considerable efforts to characterize and model the fine-grained sediment deposits along the Colorado River in Grand Canyon, relatively few detailed field measurements of the velocity and concentration structure of recirculating eddies have been made. Schmidt (1990) presented a comparison of main channel and within eddy average velocities based on measurements at three sites on the Colorado. McDonald and Nelson (1996) and McDonald et al. (1994) document measurements of flow velocities in three recirculating zones by employing a system of mechanical current meters designed to collect velocity profiles and turbulence intensities. While enough good data were collected to characterize mean depth-averaged recirculating flow patterns, significant contamination from suspended organic matter precluded analysis of vertical velocity profiles and turbulence intensities. These data were also used by Rubin and McDonald (1995) to document nonperiodic pulsations in velocity resulting from the vortex shedding.

The study described herein details the collection of velocity and suspended-sediment-concentration data during a high-flow experiment on the Colorado River at a single site approximately 45 miles downstream from Glen Canyon Dam (30-mile site, fig. 1). The high-flow experiment consisted of a 60-hour peak-flow release from the dam of about 1,160 m^3/s (41,000 ft^3/s). The experiment was designed to redistribute sand from the channel bed to eddy sandbar environments that have been eroding since construction of the dam (Webb et al., 1999, Wright et al., 2005, U.S. Department of the Interior, 2004). The objectives of the study described here were to: 1) test the application of an acoustic Doppler current profiler (ADCP) within these environments, 2) roughly characterize the velocity and suspended-sediment-concentration structure at the study site, and 3) use the data to evaluate some of the assumptions of previous modeling approaches. It was, however, beyond the scope of this investigation to quantify the effects of secondary flows on sediment transport in Colorado River eddies during high flow.

METHODS

A 600 kHz ADCP manufactured by RD Instruments[1] was used to collect vertical profiles of three-dimensional velocities at three locations within the eddy. Depth-integrated suspended-sediment samples (Edwards and Glysson 1999) were collected simultaneously at each location; main-channel suspended-sediment samples were also collected on an hourly basis during this time period. All measurements were made mid-day on November 23 which was the second day of the high-flow experiment peak. The ADCP was programmed to sample using Water Mode 1 (RD Instruments, 2003) utilizing a 30 cm resolution bin size.

The three locations for stationary measurements were selected in order to characterize velocity structure and sediment concentration at locations expected to exhibit a range in hydrodynamic and sediment-transport conditions (fig. 2). Sample locations shown in fig. 2 are approximate and based on field landmarks and aerial photographs. Station 1 was located in the return channel (which exhibited upstream flow near the bank); station 2 was located near the eddy fence (i.e. the interface between the main channel and eddy); and station 3 was located near the reattachment point. Because river conditions precluded anchoring, positions were maintained during measurements by maneuvering the boat. This resulted in some variations in position locations especially at station 2. Bottom tracking was used to remove boat motion from the velocity data. Also, station 2 had to be located further into the eddy than desired due to large depths, high suspended-sediment concentration, and moving bed conditions directly within the eddy fence which precluded reliable velocity profiles at the desired sample location.

RESULTS

Measurements of single-ping ADCP velocity profiles were averaged to provide vertical profiles of mean horizontal velocity and direction, vertical velocity, and error velocity (horizontal/vertical orientation and direction from true north were determined by roll, pitch, and heading sensors internal to the ADCP). Averaging times were as follows: 308 sec at station 1, 422 sec at station 2, and 315 sec at station 3. The ADCP sample rate was about 2.2 Hz. Error velocity is an estimate of measurement quality; it is the difference between the two vertical velocities calculated using two different three-beam solutions (the ADCP has four beams). Profiles with error

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[1] Use of trade, product, or firm name is for descriptive purposes only and does not imply endorsement by the U.S. Geological Survey.

velocities greater than 0.81 m/s (three times the expected single-ping standard deviation of 0.27 m/s) were discarded prior to averaging. Because ADCPs cannot measure all the way to the bottom nor very near the surface (Gartner and Ganju, 2002), the center of the shallowest measurement bin was about 1 m below the water surface and the deepest measurement bin was at least 6 percent of total water depth above the bottom.

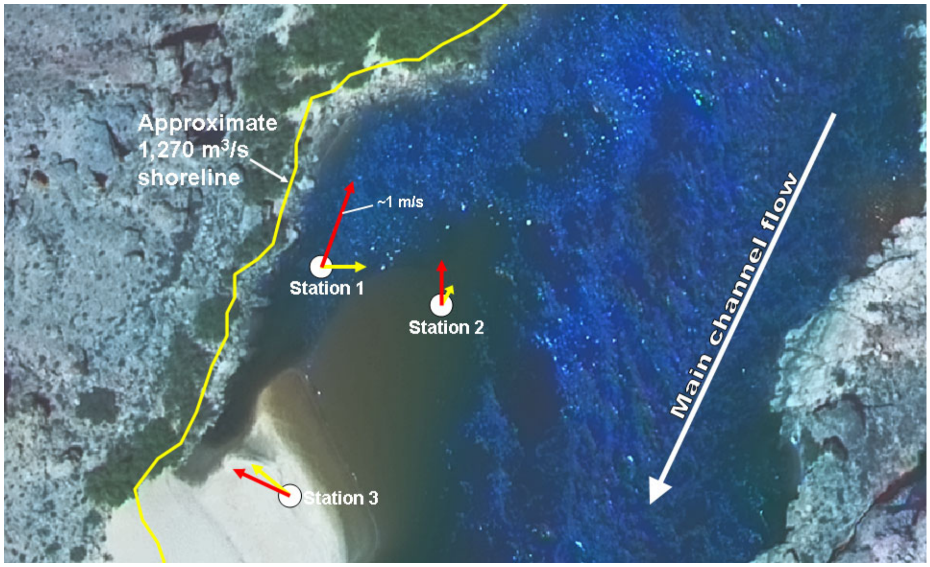

Figure 2. Aerial photograph (May 2002, at 227 m^3/s) showing the measurement locations.

Results of the ADCP measurements are shown in figs. 2 through 5. In fig. 2, arrows indicate approximate near-surface (red) and near-bed (yellow) horizontal velocities. Velocity profiles measured at station 1 (return channel) indicate that flow is primarily parallel to the bank in a direction opposite to main-channel flow. Near-surface horizontal velocity is approximately twice the near-bed velocity and, interestingly, the horizontal velocity rotates clockwise about 70º through the vertical such that near-surface velocity is approximately parallel to the bank while near-bed velocity is nearly perpendicular to the bank, directed toward the main channel (fig. 2). Vertical velocities ranged from about 7 to 15 cm/s directed downward, increasing slightly from surface to bed (fig. 3). Depth was approximately 6 m.

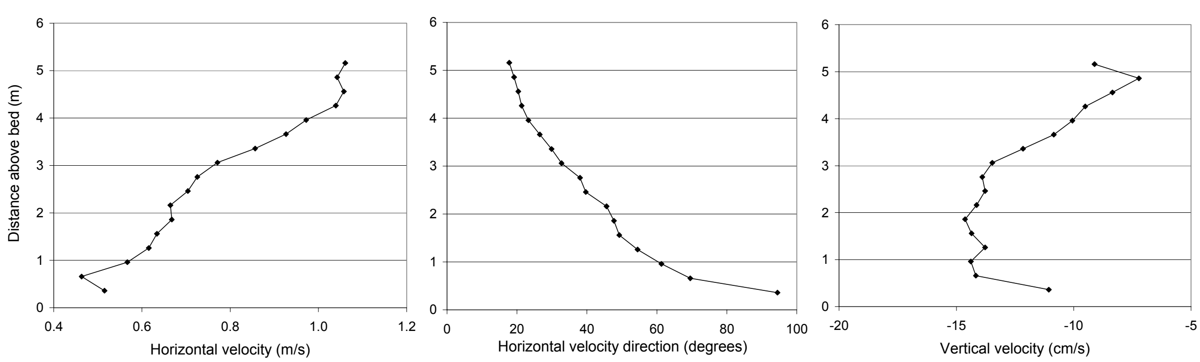

Figure 3. ADCP measured velocity profiles at station 1.

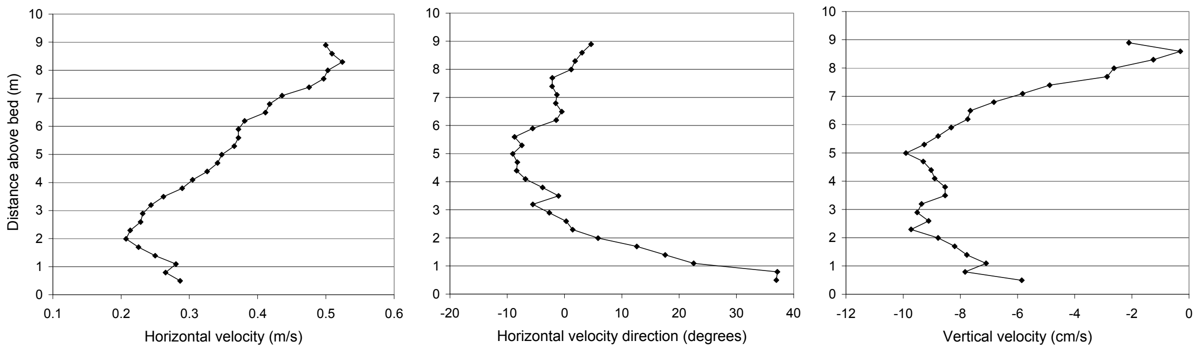

Figure 4. ADCP measured velocity profiles at station 2.

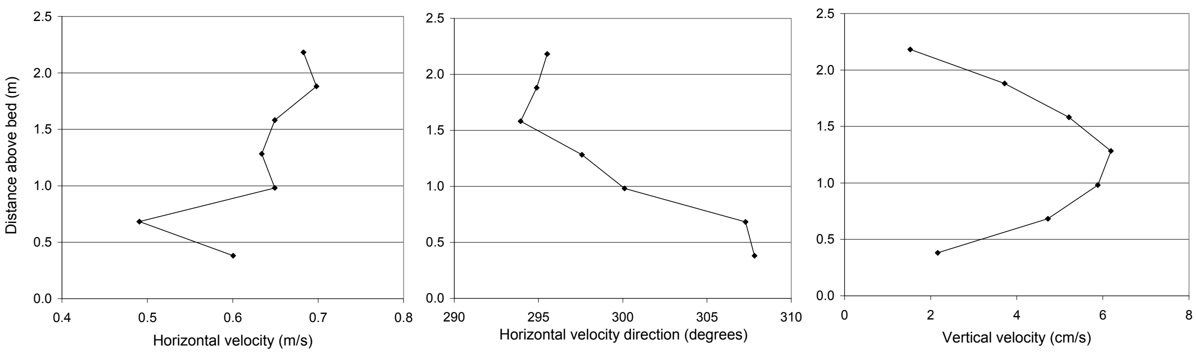

Figure 5. ADCP measured velocity profiles at station 3.

Velocity profiles at station 2 (eddy fence) indicate that it was located inside of the recirculation zone such that horizontal velocity is directed opposite to the main-channel flow. Horizontal velocities were approximately half those at station 1 with a similar decrease from surface to bed. About 30º of clockwise rotation from surface to bed was measured, primarily in the bottom 1-2 m of the profile. Vertical velocities ranged from almost zero near the surface to 6-10 cm/s in the lower half of the profile, oriented downward. Depth was approximately 10 m.

Station 3 (near reattachment point) velocity profiles indicate that horizontal flow was toward the bank, perpendicular to main-channel flow. In contrast to stations 1 and 2, horizontal velocity was nearly constant in the vertical with little rotation occurring from surface to bed (<15º). Vertical velocities were directed upward (opposite to those at stations 1 and 2) and show a peak of about 6 cm/s at mid-depth. Depth at this location was about 3 m.

Caution must be used in interpreting the vertical velocities. At station 1 the calculated error velocities (not shown) were generally small and random except near bottom where values approached those of the measured vertical velocities. Station 2 error velocities show values in the bottom 3 m of water to be of the same order of magnitude as vertical velocities and, rather than being random, they include a clear positive bias. Error velocities at station 3 were small and without bias with the exception of the bottom bin. Thus, vertical velocities very near the bottom at station 1 and in the bottom 3 m at station 2 may not reflect actual water velocities. Further, some of the measured vertical velocity may be due to sediment particles settling through the measurement volumes. One of the assumptions of ADCP operation is that the water is flowing at the same speed and direction as the materials providing the backscattered signal for Doppler information. It is known that fine sediment accumulated in this eddy during this period. While the two effects (real water motion and settling sediment particles) cannot be reliably separated, it is noted that the calculated settling velocity of suspended sediment typical of this location (~0.1 mm) is only about 1 cm/s, significantly less than most measured vertical velocities.

Results of the depth-integrated suspended-sediment-concentration measurements are shown in fig. 6. For silt and clay, concentrations in the eddy correspond closely with those in the main channel; the maximum difference is only about 10%. Silt and clay concentrations within the eddy also show very little variability. This indicates that these sizes were being transported into and out of the eddy at approximately equal rates such that very little deposition was occurring at the time of the measurements. Sand concentrations exhibit significantly more variability, though is it difficult to know if this is real or measurement error. As with silt and clay, sand concentrations within the eddy are similar to main channel concentrations. Sand concentrations within the eddy do exhibit a structure that could be interpreted as reflecting deposition in the eddy. Concentration (and grain-size) was highest at stations 2 and 3 and drops off significantly at station 1 (>50 percent difference between stations 2 and 1). This suggests that sand was depositing in the eddy center during this time period. Sand at station 1 was also finer than at stations 2 and 3 suggesting that the coarsest material was settling out of suspension. Again, it is difficult to interpret these data in the context of measurement error (not known precisely for this environment), particularly given the degree of scatter in the main-channel sand concentrations evident in figure 6. A more rigorous sampling approach is required to better understand the temporal and spatial variability of the concentration field, possibly utilizing optical or acoustic techniques; however, those approaches may also be limited by inherent measurement errors.

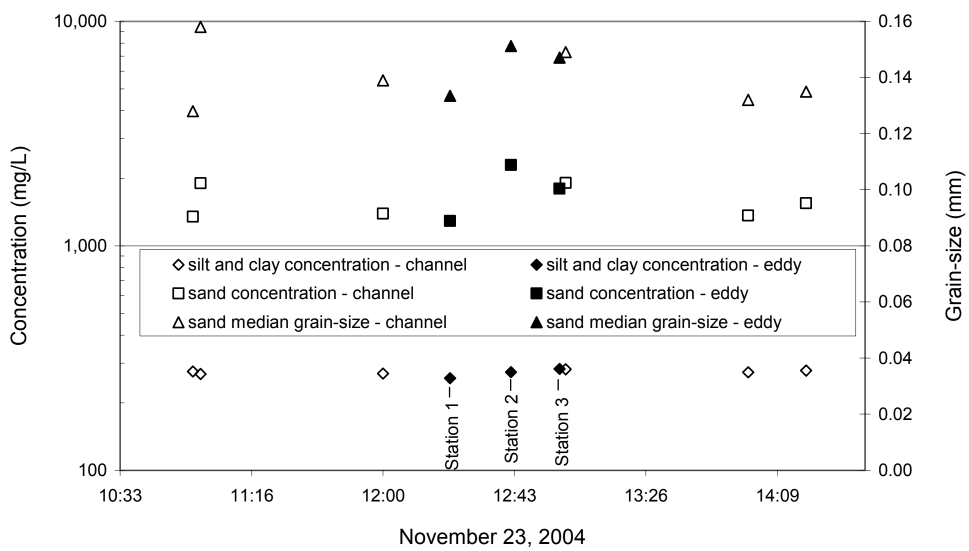

Figure 6. Measured silt/clay and sand concentrations and median sand grain-size in the main channel and at three locations within the recirculating eddy.

CONCLUSIONS

The ADCP can be a useful tool for characterizing the velocity structure of recirculating eddies. Difficulties with velocity measurements were encountered near the eddy fence due to large water depths in combination with high suspended-sediment concentrations and a moving bed. The moving-bed problem can be overcome through use of a differential global positioning system, a technology that is becoming more feasible in remote canyon environments such as Grand Canyon. The combination of large depth and high suspended-sediment concentration resulted from the unusually high flow; measurements during more typical conditions would likely be more successful in the eddy fence, a region critical to understanding sediment-exchange mechanisms. The study succeeded in roughly characterizing the velocity and suspended-sediment structure within the recirculating zone; however, significantly more effort would be required to fully characterize the suspended-sediment field, in particular, and results may still be difficult to interpret due to the combination of small differences in concentrations and inherent measurement errors. Finally, the velocity profiles indicate that 2D flow models may be too constrained under some conditions such that fully 3D flow and sand transport models would yield more accurate results. In particular, the measurements indicate significant rotation of horizontal velocities vertically through the water column (~70º at station 1, ~30º at station 2) as well as significant vertical velocities, also with some vertical structure. Depth-averaged, two-dimensional flow models, such as that developed and applied by Wiele et al. (1996), by definition cannot simulate these flow features. However, it has not yet been determined how important these features are for sediment transport and morphology within recirculating eddies. Further field investigations in combination with more rigorous modeling approaches (e.g. Akahori and Schmeeckle, 2005) are required to improve our understanding of these mechanisms.

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