ADV Point Measurements within Rapids of the Colorado River in Grand Canyon

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Abstract

Rapids on the Colorado River in Grand Canyon attract over 20,000 white-water enthusiasts a year and are considered one of the premiere collections of rapids in North America. While this collection of rapids is an important recreational resource, relatively little is known of the specific hydraulics of individual rapids. Flow measurements are occasionally made in the low-velocity reaches between rapids, but the turbulent and dangerous nature of rapids makes in-situ data collection challenging. The present study measured hydraulics within a small rapid in Grand Canyon as well as an alluvial reach of the Colorado River in Glen Canyon using a Sontek Argonaut acoustic Doppler velocimeter (ADV) [2]. The ADV was mounted near the center-front of a motor-powered 19-foot J-snout boat; the instrument sample volume was located 80 cm below the surface. The quality of the measurements was best in the slower water above the rapid and in Glen Canyon. Waves, aeration, and high-velocity water rendered specific measurements in the core of the rapid difficult as the ADV instrument could only measure velocities less than about 3.0 m/s. Nonetheless, velocity, bathymetry, and water-surface maps were constructed for the rapid and the reach in Glen Canyon. The compiled data sets can be used for predicting the erosion potential of debris fans forming the rapid and the development of numerical models to better characterize rapids.

Introduction

Rapids on the Colorado River in Grand Canyon are formed predominantly by the accumulation of coarse-grained sediment debouched from ephemeral tributaries by debris flows (Webb et al., 1989; Melis et al., 1994). The debris flows transport boulders well over 1.0 m in size into the main channel. Over time, the accumulation of debris on an active debris fan pools the river upstream of the fan, constricts the river forming the rapid, and creates a deep scour pool below the rapid. Depending upon how they are defined, roughly 200-300 rapids exist along the 380 km of river between Lee's Ferry and Lake Mead. The rapids and their associated pool-and-rapid morphology form the basic geomorphic control of the river corridor in Grand Canyon (Leopold, 1969; Howard and Dolan, 1981; Schmidt and Rubin, 1995). Sand deposition, fish habitat, and even bedrock down cutting are driven by debris fan location and the hydraulics of the resulting rapids. Despite the scientific importance of rapids on the Colorado River, relatively little quantitative data exists describing the hydraulics in rapids.

Velocity measurements in rivers are usually taken with mechanical current meters, but most current meters average flow in all directions and are ill-suited to measure flow in turbulent or rapidly flowing rivers and steams. Flow velocities in a turbulent mountain stream were collected by Smart (1994) using a pitot-static tube. More recently, electromagnetic current meters have been used to measure flow and turbulence in rivers (Roy et al., 1999). Recent developments in acoustic flow instruments has led to widespread and routine measurements of velocity and discharge in rivers (Yorke and Oberg, 2002; Morlock and Fisher, 2002). Using an acoustic Doppler current profiler (ADCP) and BoogieDopp river discharge measurement system, Cheng and Gartner (2003) measured velocity profiles that extended closer to the free surface than normally possible with an ADCP alone. Acoustic Doppler velocimeters (ADVs) are also commonly used to measure flow velocity at a point location. Lane et al. (1998) completed an extensive study of 3-D flow fields in rivers using an ADV. Detailed studies with ADVs have also been made of the 3-D flow field above a gravel-bed flume (Ferro, 2003), in scour hole abutments (Dey and Barbhuiya, 2006), and in the surf zone (Elgar et al., 2005). In an application similar to the present study, Hotchkiss et al. (2003) used an ADV to measure the fluid velocity entering a spillway weir. Yet in each application described above, maximum measured flow velocity was much less than velocity magnitudes expected in the core of Grand Canyon rapids.

Kieffer (1987) was one of the first to quantify the hydraulics of Grand Canyon rapids. She cleverly used a calibrated video camera and floating tracer particles to measure, in a Lagrangian frame of reference, velocity along trace lines through rapids. Using tracking particles for measuring flow velocity, however, has some disadvantages. First, particle trajectories cannot be controlled; also, being on the surface, particles are susceptible to jostling by waves thus reducing the particle velocity relative to the true free-stream velocity. Nonetheless, Kieffer (1987) was able to measure velocities as high as 7.5 m/s. She also made a preliminary attempt at measuring bathymetry within the rapids with mixed results. Despite these efforts, complete data sets describing river flow velocity, surface elevation, and bathymetry in rapids remain elusive. The present work attempts to build on the work of Kieffer (1987) by quantifying flow values within a Grand Canyon rapid in addition to measuring the morphology of the water surface and the bathymetry below the rapid.

Field Locations and Measurement Methods

The main challenge in making in-situ measurements of water velocity in rapids of the Colorado River in Grand Canyon is the logistical difficulty of holding an instrument in a fixed position within the flow. Most boaters are motivated to safely navigate a given rapid as quickly as possible; few are interesting in loitering. The waves in the rapids and the force of the moving water can make small errors potentially catastrophic, even in small rapids. Also, because the study area is a national park, measurement techniques cannot damage the landscape and no structures can be left behind. Vehicle access to the river is available only at Lee's Ferry and at Diamond Creek, 364 km downstream of Lee's Ferry. All field equipment is typically brought in by boat.

The site chosen for measurement in this study was Upper Rattlesnake Rapid, located 119 km below Lee's Ferry. The measurements were made in March 2005 at a river discharge of 540 m^3/s. Within the river corridor, Upper Rattlesnake is situated between the better known Unkar Rapid upstream and Nevills Rapid downstream. A debris flow at Upper Rattlesnake in 2002 changed the riffle into a small rapid.

Another site at Minus 4-Mile Bar in Glen Canyon was measured in April 2003 at a river discharge of 340 m^3/s. Glen Canyon is a bedrock controlled reach of the Colorado River just upstream from Lee's Ferry. The site is 18 km below Glen Canyon Dam and consists of a large cobble bar on river right just before a large right-trending meander. In contrast to Grand Canyon, Glen Canyon has no rapids and its fluvial geomorphology is more characteristic of an alluvial river. Due to the dam, little sand or clay is present in the reach and the bed is composed predominantly of gravels and cobbles. Measuring sites in Glen Canyon and Grand Canyon allowed a comparison of the measurement techniques on a rapid as well as in an alluvial reach.

A 10Hz Argonaut ADV manufactured by Sontek/YSI was used for velocity measurement (Figure 1). The instrument was fitted with a 3D side-looking transducer probe arrangement. ADVs operate on the Doppler principle utilizing the fact that sound reflected from particles suspended in the moving fluid is shifted in frequency according to the direction and speed of flow. By using three transmitters/receivers oriented in a spread array, the velocity of a 0.25 cc point within the flow can be calculated. The sample volume is nominally 10 cm from the probe. During this study, measured 3-D velocities consisted of the vector average of a 5-second burst of measurements (made at a 10Hz sample rate). A review of the operation of the ADV can be found in Lane et al. (1998) and Morlock and Fisher (2002).

Velocity data were post-processed using software supplied by the vendor. While the ADV software has the ability to use the instrument's built-in compass/tilt sensors to report velocity vectors in globally referenced East-North-Up (ENU) coordinates, the high velocities and extreme turbulence within the river rendered ENU coordinates suspect. Instead, velocity data reported in a raw XYZ coordinate system were used for all analysis. Because the boat was positioned facing against the river current, the instrument was oriented so that the probe looked across, or orthogonal to, the oncoming flow. The X component of velocity was defined along the predominant flow, the Y component of velocity orthogonal to the boat direction, and the Z component of velocity in the vertical. In this orientation, the maximum velocities could be measured along the axis of the boat (X component) with smaller fluctuations measured along the two remaining axes (Y and Z components). For a particular measurement location, a scalar magnitude of the overall horizontal velocity vectors, X and Y, was calculated. The boat heading, as reported by the compass in the instrument, was used to determine the direction of this horizontal velocity. Instrument specifications list the maximum velocity measurement capability to be 4.5 m/s, but small changes in the orientation of the probe relative to the flow reduced

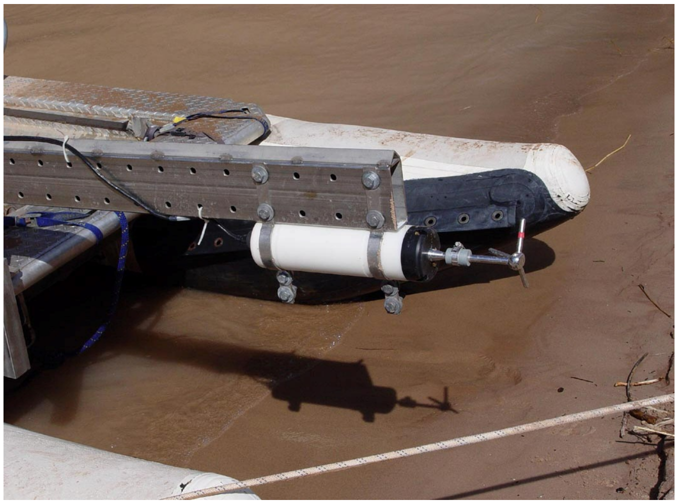

Figure 1. ADV shown mounted on rotating boom. The boom was rotated down into the water for measurements, positioning the ADV probe 80 cm below the water surface. (Photo: C. Watkins)

this maximum. If the free-stream speed exceeds the maximum velocity capability in any one of the three flow axes, the instrument will experience an “ambiguity jump,” in which case either the velocity values are reported as negative or the reported vertical velocity is well above 2.0 m/s and the corresponding horizontal components of velocity are reported to be nearly zero—a physically unrealistic condition in most rivers. Because measurements were always made with the boat positioned into the oncoming flow, any data in which the Y or Z components of velocity exceeded the magnitude in the X component of velocity were discarded as potential ambiguity jumps.

Water depth values were determined using a Lowrance X59DF fathometer that was mounted near the rear of the boat. The X59DF is a 50/200kHz instrument with a digital LCD display and a reported depth range of 400 m.

The boat was a 19-foot J-snout, consisting of two rubber tubes supporting a rigid aluminum frame. A Mercury 50-hp outboard motor powered the boat with enough speed to up-run many smaller rapids. A stainless-steel rotating boom was mounted on the front of the boat that allowed rapid deployment of the ADV instrument. When the boat was in position to make measurements, the boom was pivoted down into the river (Figure 2). All measurements were made 80 cm below the water surface. With this mounting arrangement, the boom could be quickly pulled from the water and secured at any time. This safety feature was essential to ensure the boat could be made navigation-ready in an instant. Stainless steel was chosen for the mounting boom because of its strength and non-magnetic properties. We attempted to minimize magnetic interference because the ADV has a built-in compass to reference measured fluid velocities to magnetic north. The ADV was connected to a laptop computer mounted in the boat and data were continuously fed to the laptop during each experiment. A multi-directional survey prism was placed at the top of the boom to allow the position of the instrument to be determined using an on-shore total-station surveying instrument. When making measurements, the boat was first positioned at a target location in the river and allowed to stabilize in the flow. ADV measurements were then taken for at least 15 seconds. The water depth under the boat, as reported by the fathometer, and the position of the boat measured with the total station was also recorded.

Figure 2. Photos of operation of ADV boat in quiet water above the rapid (left) and within the wave field of the rapid (right). (Photos: C. Watkins)

Finally, tetherballs were used as flow velocity tracers at Upper Rattlesnake Rapid. In a Lagrangian measurement technique analogous to the Kieffer (1987) work, the tetherballs were tossed into the water above the rapid and free-floated down the middle of the tongue of the rapid. By timing the passage of each tetherball, an average velocity in the tongue of the rapid was calculated and recorded. Fifteen tetherballs were tossed, timed, and results recorded.

Results

During the ADV measurement in Upper Rattlesnake Rapid, ambiguity jumps occurred frequently as flow velocities exceeded 3.0 m/s. In fact, measurements made in the core of the rapid typically reported vertical velocities approaching 6.0 m/s with concurrent horizontal velocities near zero—clearly, a physically unrealistic result. For Upper Rattlesnake Rapid, only 62% of all measurements were usable. In the slower water of Minus 4-Mile Bar, 87% of the measurements were salvaged.

While attempts were made to minimize magnetic interference with the ADV compass, the system had problems. While the stainless-steel ADV boom was not magnetic, the stainless steel bolts that held the instrument to the boom were slightly magnetic. This problem was discovered while post-processing the data. In addition, it appeared that for the measurement session at Upper Rattlesnake, a local magnetic field developed around the boat itself. In the adjacent transects measured in the pool above the rapid, where the flow velocity is uniform and directed into the rapid below, compass headings (and in turn, the processed velocity vectors) were deflected as much as 30° depending on whether the transect was cut from river left toward river right or the other way. Before making a measurement, the boat was allowed to dwell in a location for roughly 15 seconds. This dwell offered ample time to let the boat adjust to the oncoming flow. We also know from direct observations that the flow leading into the rapid, while turbulent, is smooth and uniform. Because the ADV was mounted forward and centered on the boat, our only remaining explanation for this compass artifact is the presence of a magnetic field, probably generated from the boat motor. This problem was intermittent and not observed at Minus 4-Mile Bar. Due to the error induced in the ADV compass by the magnetic bolts and this apparent magnetic field, a compass correction was required for each site. This correction was applied to all the data from a site until the velocity vectors flowing into the study section were pointed reasonably downstream. The correction at Minus 4-Mile Bar was -40° and the correction at Upper Rattlesnake was -35°. This compass correction does not affect the reported velocity magnitudes, only the direction of the velocity vector as shown in the flow-field maps.

The velocity flow field and the bathymetry from Minus 4-Mile Bar are shown in Figure 3. Roughly 13 transects were made covering a distance of just over 1.1 km. The river centerline is shown, expressed as a distance in miles above Lee's Ferry. As the flow enters the study reach, a wide, shallow, 1-2 m deep section with low velocities (around 1.0 m/s) is pinched by a long cobble bar that forms along the right side of the river. The flow is pushed to the left and accelerates to over 2.0 m/s. The depth in this faster section of the channel increases to roughly 5.0 m. The flow then curves toward the right in a meander bend with a deep channel near the outer bank and reduced flow velocities. The greatest depth measured at this site, 6.8 m, occurred in this meander bend; velocities here drop to below 1.0 m/s. Overall, the highest velocity measured at Minus 4-Mile Bar was 2.26 m/s and all velocities appeared to be within the capability of the instrument. It is interesting to note that in the clear

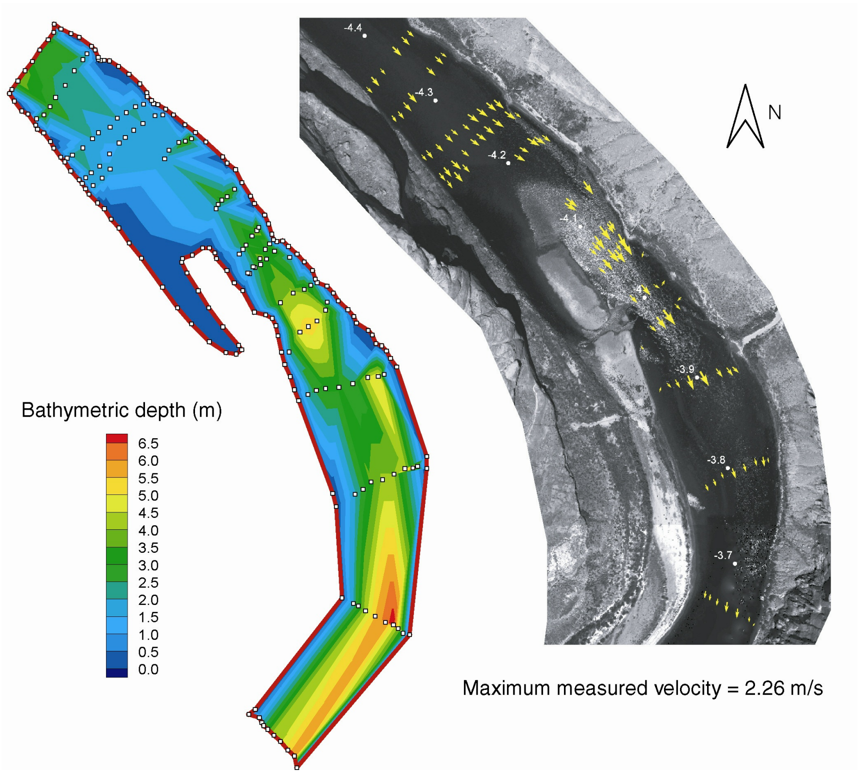

Figure 3. Bathymetry (left) and velocity (right) maps of Minus 4-Mile Bar in Glen Canyon. River miles relative to Lee's Ferry are indicated with the white dots. The greatest depth measured was 6.8 m, on the outside of the bend.

water of Glen Canyon, the signal strength of the instrument was unusually low—typically below 100 counts. Signal strength is an internal instrument metric that reports the strength of the return signal from particles in the water; one count equals 0.72 dB. Signal strength is a function of the amount and type of particulate matter in the water. In Grand Canyon, where suspended sediment is much higher, signal strength ranges from 180 to 200.

Overall velocity magnitudes in Upper Rattlesnake Rapid (Figure 4) are much higher and more variable than in Glen Canyon. Velocities were successfully measured in the smooth water above the rapid, but nearly all measurements from the core of the rapid were unusable due to ambiguity jumps. Below the rapid, waves and turbulence jostled the boat, and ambiguity jumps were common. In all, 63 velocity measurements were made at Upper Rattlesnake with a peak value of 3.19 m/s. Figure 4 also shows the velocity direction switch in the alternating transects of the upper pool that we attribute to a boat-based magnetic field.

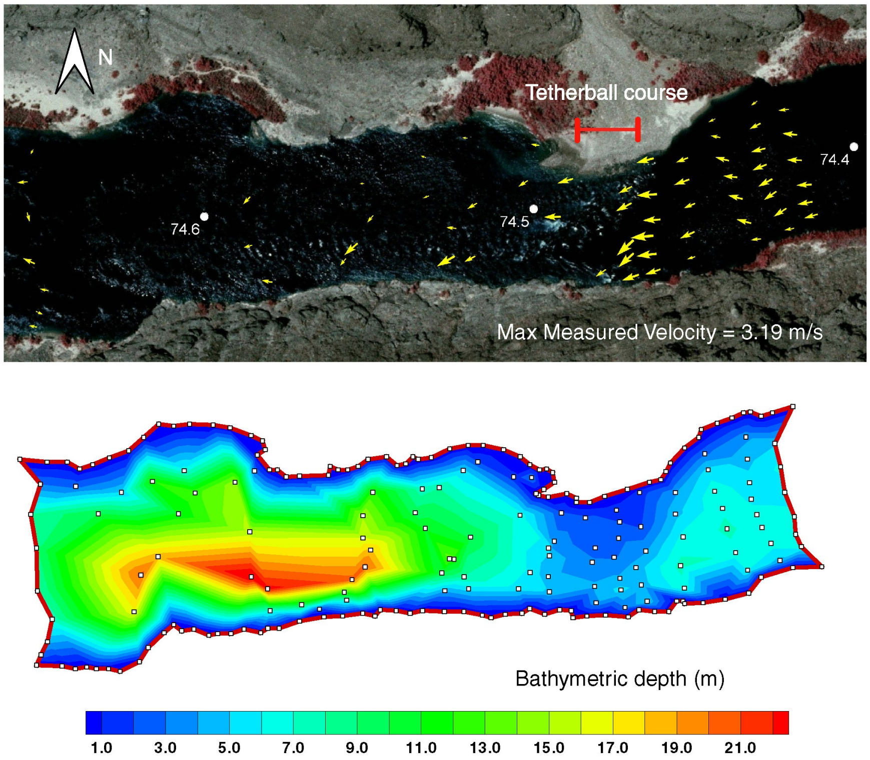

Figure 4. Velocity (top) and bathymetry (bottom) maps from Upper Rattlesnake Rapid. River miles relative to Lee's Ferry are indicated with the white dots. The 30 m tetherball course is shown. The maximum depth of 23.4 m is found in the scour hole below the rapid.

The measurement of bathymetry at Upper Rattlesnake was successful. A total of 101 depth measurements were made throughout the rapid complex producing a map of the river bottom (Figure 4). River depths leading into the rapid were 6-8 m, and a deep scour hole of 23.4 m was measured below the rapid. This deep scour hole is comparable to scour holes measured on other large rapids in Grand Canyon (Howard and Dolan, 1981), suggesting that the Upper Rattlesnake was once a larger rapid. The depth in the shallowest part of the rapid was 4.15 m, and a sub-aqueous debris mound is visible at the tributary mouth. While a number of researchers have measured depth traces floating through rapids (Leopold, 1969; Randle and Pemberton, 1987), to the best of our knowledge, this is the first bathymetry map measured directly in the core of a Grand Canyon rapid. The fathometer used in the study was a capable instrument. While it would occasionally fail in the largest, most turbulent and aerated zones, it generally was able to return data for almost every part of the rapid surveyed.

Tetherball speeds were measured at Upper Rattlesnake just before the ADV run. The average velocity of all 15 tetherballs was 3.94 ± 0.09 m/s. The tetherball course was 30 m long and integrated the velocity of the path of the tetherballs leading into the middle of the rapid.

Discussion

Figure 5 shows a composite of velocity measurements as a function of river mile for both study sites. At Minus 4-Mile Bar, velocities slowly increase from roughly 1.2 m/s to a maximum of 2.26 m/s over a span of 600 m. This maximum velocity occurred where the cobble bar constricts the flow. Within Upper Rattlesnake Rapid, flow velocities accelerated more quickly; rising from a free-stream value of roughly 2.0 m/s to over 3.19 m/s in a distance of 25 m. Flow velocities in the rapid rise well above 3.5 m/s and are at least 3.94 m/s, the value measured with tetherballs tracers. Direct measurements of flow in the core of the rapid could not be made with the ADV instrument. Kieffer (1987) measured flow velocity in Grand Canyon rapids as high as 7.5 m/s, and the peak flow in Upper Rattlesnake Rapid probably approaches 6 m/s.

As a byproduct to collecting velocity and bathymetry data, the morphology of the water surface was also determined. Figure 6 shows the water-surface profiles of both sites. The fall in water surface through Minus 4-Mile Bar occurs mostly just upstream of the cobble bar. The slope is small, just 0.4 m in 800 m. Comparing Figures 5 and 6, the greatest velocities occur near the bottom of the long fall at Minus 4-Mile Bar. In contrast, the greatest velocities in Upper Rattlesnake Rapid occur at the top of the fall. The overall drop through Upper Rattlesnake Rapid is 0.8 m and occurs within 65 m. The higher consumption of river energy in this rapid (i.e., dissipation of stream power) offers a simple explanation as to why Upper Rattlesnake contains large breaking waves and high turbulence while Minus 4-Mile Bar does not.

Conclusions

This study attempts to use modern acoustic instrumentation to directly measure flow velocities in a rapid on the Colorado River. Valuable flow data in all but the highest-velocity regions of Upper Rattlesnake Rapid in Grand Canyon were recorded and mapped. Within the alluvial reach of Minus 4-Mile Bar in Glen Canyon, a comprehensive flow field of velocity vectors was successfully map. In addition, extensive bathymetric mapping was successful for both study sites. In the case of Upper Rattlesnake Rapid, the resulting depth chart is the best and most comprehensive data set reported for a rapid in Grand Canyon. Finally, the 3-D water-surface elevations measured in each study reach offer a valuable morphological data set that can be used to characterize the river and its free surface.

One of the goals of this study was to measure top velocities in the core of Grand Canyon Rapids. While the ADV did measure flow velocities in Glen Canyon and the slower sections of Grand Canyon, the instrument as configured was unable to measure many higher velocities found within rapids. The instrument chosen used a side-looking probe arrangement; a downward-looking probe arrangement would have been better at measuring horizontal velocities and may have had a higher upper limit than 3.0 m/s. Either way, the ADV family of instruments has an upper measurement limit of 4.5 m/s and cannot measure peak velocities of Grand Canyon rapids.

For future research, the goal of directly measuring velocities in the core of rapids remains important. Such data would lead to insight into the transport processes that distribute coarse-grained sediment in bedrock-controlled rivers. ADCPs may be a more appropriate tool for measurement purposes, although turbulence and bubbles in the rapid may create challenges. It is likely that a fundamentally different flow measurement technique is needed.

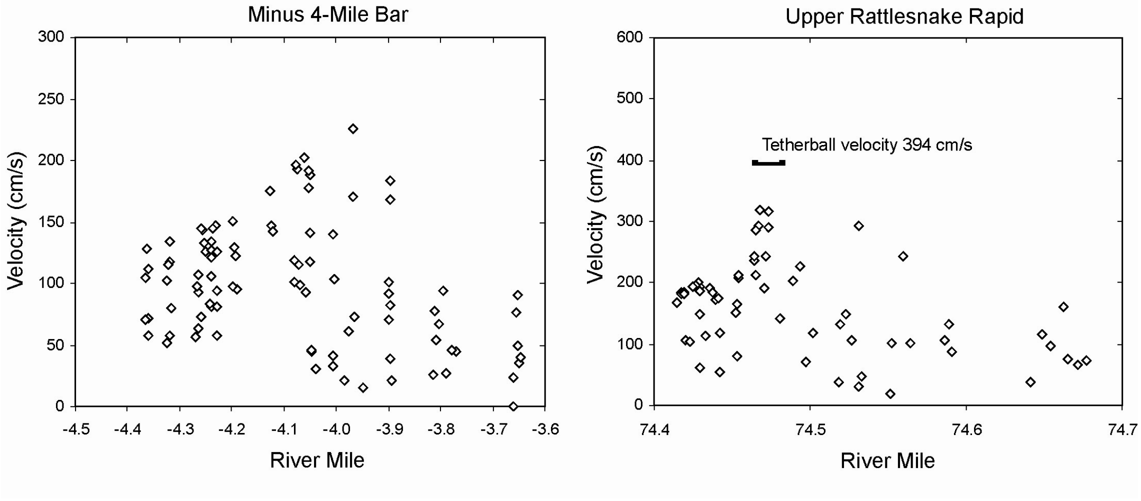

Figure 5. Graph showing horizontal velocity values for Minus 4-Mile Bar (left) and Upper Rattlesnake Rapid (right). Note the axes are at different scales. Also included on the Upper Rattlesnake graph is the surface velocity from the 15 tetherballs.

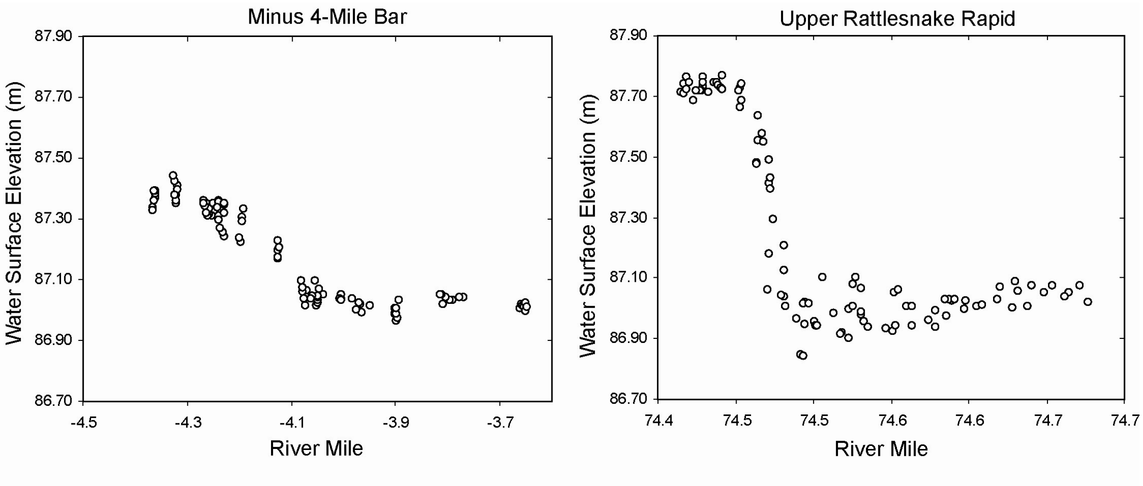

Figure 6. Graph showing water-surface profile for Minus 4-Mile Bar (left) and Upper Rattlesnake Rapid (right). The elevations are expressed in similar relative vertical scales, but the horizontal scales are different.

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