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Correcting acoustic Doppler current profiler discharge measurement bias from moving-bed conditions without global positioning during the 2004 Glen Canyon Dam controlled flood on the Colorado River

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Abstract

Discharge measurements were made by acoustic Doppler current profiler at two locations on the Colorado River during the 2004 controlled flood from Glen Canyon Dam, Arizona. Measurement hardware and software have constantly improved from the 1980s such that discharge measurements by acoustic profiling instruments are now routinely made over a wide range of hydrologic conditions. However, measurements made with instruments deployed from moving boats require reliable boat velocity data for accurate measurements of discharge. This is normally accomplished by using special acoustic bottom track pings that sense instrument motion over bottom. While this method is suitable for most conditions, high current flows that produce downstream bed sediment movement create a condition known as moving bed that will bias velocities and discharge to lower than actual values. When this situation exists, one solution is to determine boat velocity with satellite positioning information. Another solution is to use a lower frequency instrument. Discharge measurements made during the 2004 Glen Canyon controlled flood were subject to moving-bed conditions and frequent loss of bottom track. Due to site conditions and equipment availability, the measurements were conducted without benefit of external positioning information or lower frequency instruments. This paper documents and evaluates several techniques used to correct the resulting underestimated discharge measurements. One technique produces discharge values in good agreement with estimates from numerical model and measured hydrographs during the flood.

A need exists to better understand variations in river discharge and their effects on riparian plants and animals, sediment transport, sandbar changes, and recreational activities in the Colorado River within Marble and Grand Canyons, Arizona. To help meet this need, discharge measurements were made by acoustic Doppler current profiler (ADCP) at two locations on the Colorado River to study downstream effects of the 2004 controlled flood release from the Glen Canyon Dam.

Acoustic Doppler current profilers have been used for about 25 years to make measurements of the vertical structure of water currents in all bodies of water ranging from deep oceans to shallow rivers. An ADCP determines water velocity profiles by transmitting sound pulses at a fixed frequency and measuring the frequency (or phase) shift of acoustic echoes reflected back from scatterers (plankton and sediment) in the water (Simpson 2001). Doppler shifted echoes are then converted to along (acoustic) beam velocity components. Finally, the ADCP transforms the along beam velocities to north/south, east/west, and vertical velocity components using trigonometric relations. Velocity profiles are determined by range gating echoes so that velocities are determined at preset intervals (bins) along the acoustic path. When the instrument is oriented facing down and measurements are made from a moving vessel in order to provide estimates of river discharge (Simpson and Oltmann 1990) relative instrument position is determined using separate bottom track acoustic pings.

While ADCPs provide the capability to make accurate, rapid, safe, and cost-effective measurements of river discharge (Yorke and Oberg 2002) under most conditions, high-suspended sediment concentrations, particularly during high river flows can be problematic for ADCP measurements. There are two reasons for problems. First, suspended sediment tends to attenuate the ADCP signals, thus reducing effective measurement range; the degree of attenuation and range reduction

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is a function of instrument frequency such that high frequency instruments are affected more than low frequency instruments. Under extreme situations, this may result in loss of bottom track positioning information. The second condition caused by high sediment may be more problematic. During high sediment and flow conditions, a layer of near-bed sediments may be moving downstream above the actual riverbed (bed load) that the ADCP bottom track pings incorrectly interpret as the actual bottom. The instrument assumes (for calculation purposes) that it is moving, and the riverbed is not. The effect of bed motion during discharge measurements is to bias the discharge measurements low because velocity measurements are biased low (there is an effective upstream motion of the boat due to downstream bed motion) (Yorke and Oberg 2002). Also, since the ADCP interprets the moving bed as the bottom, actual water depths may be somewhat deeper than calculated, which may further bias the calculated discharge. The presence of bed motion is checked for prior to ADCP discharge measurement. If bed motion is present, the instrument position can be determined by using a satellite global positioning system (GPS), if available. Another possible solution is use of a lower frequency instrument that might better determine the actual riverbed (and thus the vessel position). This approach depends on the direct relation between acoustic frequency and attenuation of acoustic signal from suspended sediment as previously described. One promising method of correcting discharge measurements for moving bed when GPS is unavailable is the “loop method” in which the ADCP is moved across stream and then returned to its starting point (Mueller and Wagner 2006). If recommended procedures are followed, and there is no loss of bottom track during transects back and forth across the river, the method can be used to determine the mean moving-bed velocity and to correct the final discharge and mean velocity. However, as previously noted, some loss of bottom track and accompanying velocity profile measurements may occur because of high absorption and scattering of acoustic signal where substantial bed sediment is present. When this occurs, the “loop method” is inappropriate, and some other method of correcting measured discharge for moving bed must be employed.

This paper describes a method of successfully correcting biased river discharge measurements made by ADCP in the presence of moving bed and intermittent bottom track when external positioning information such as GPS is unavailable. The paper begins with a description of ADCP discharge measurements made under those conditions during the Glen Canyon Dam controlled flood in 2004. The remainder of the paper discusses the results of several techniques used to correct the measurements for bias from moving-bed conditions.

Materials and procedures

ADCP discharge measurements were made at two locations on the Colorado River as part of research conducted during the Glen Canyon Dam controlled flood in November 2004.

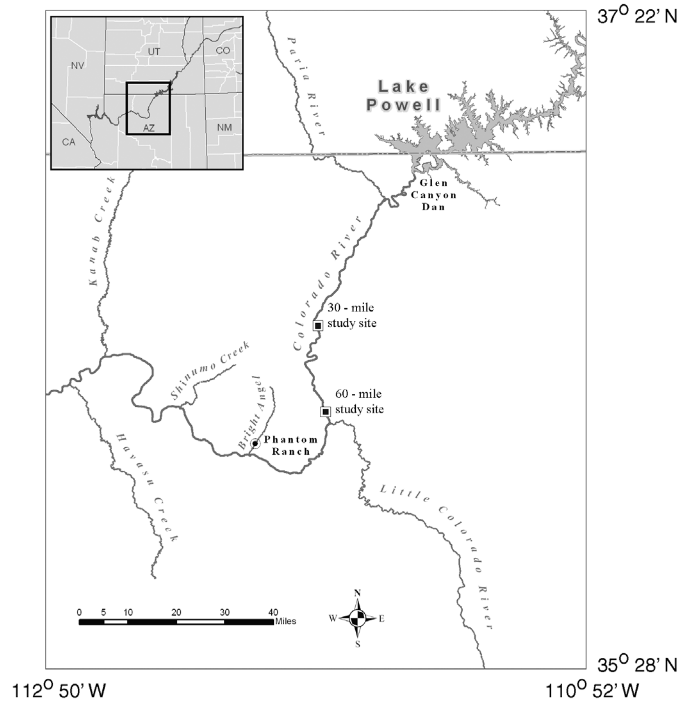

Fig. 1. Map of the Colorado River below Glen Canyon Dam showing locations of study sites at RM30 and RM60 where ADCP discharge and moving-bed test measurements were taken during the 2004 controlled flood from Glen Canyon Dam.

Study sites were located at tag lines strung near river mile 30 (RM30) and river mile 60 (RM60), co-located with existing U.S. Geological Survey (USGS) measurement sites (Fig. 1). Boat positions for water samples, moving-bed tests and discharge measurements at RM30 and RM60 sites were accomplished by positioning the vessel at known locations below the tag lines. River width was about 70 m, average depth about 6 m, maximum depth about 7 m, and maximum velocity about 120 cm/s at RM30 prior to dam release. At RM60, the river was about 102 m wide and 3 m deep prior to dam release. Maximum depth was about 4 m and maximum velocity about 150 cm/s. During time of peak flows, mean river depth was about 10 m at RM30 and about 6 m at RM60. Maximum speeds typically approached 245 cm/s at RM30 and 275 cm/s at RM60.

Two different ADCPs, both manufactured by Teledyne RD Instruments, were used during this study. (Use of trade, product, or firm name is for descriptive purposes only and does not imply endorsement by the U.S. Geological Survey.) A 600 kHz ADCP was used at RM30 and a 1200 kHz ADCP was used at RM60. There are several modes of ADCP operation available; selection depends upon the water depth and other considerations. An evaluation and detailed discussion of the ADCP modes can be found in RD Instruments, Inc (1999) and RD Instruments, Inc (2003). Typically, the highest sampling rate and smallest usable bin-size consistent with instrument frequency and accuracy requirements are chosen to give maximum spatial resolution of velocity distribution. During this study, both ADCPs were programmed to sample using Water Mode 1 using one water track ping and one bottom track ping for each measurement. A 25 cm blank distance was used for both instruments. A blank distance (in which no usable data are available) is required because these instruments use the same transducers to both transmit and receive. A short time interval is necessary for acoustic ringing to dissipate before the transducers can receive usable information. Also, there is evidence of flow distortion near the transducers such that some small distance is required before reliable velocity data can be determined (Gartner and Ganju 2002). The 600 kHz ADCP was programmed with a 50-cm bin size, thus the center of the first bin was located at 108 cm below the water surface; the 1200 kHz ADCP was programmed with a 25-cm bin size. The center of the first bin in the 1200 kHz data were at 91 cm below the water surface. Each single-ping velocity measurement was saved.

The ADCPs were mounted on the side of aluminum boats with transducers oriented down and submerged just below the water surface. The boats were positioned for measurements relative to tag lines strung across the river at the desired locations. Thus, boats could be kept stationary for averaged velocity profile measurements or driven back and forth under the tag line for a traditional moving-boat ADCP discharge measurement because of good visual reference in spite of the lack of reliable bottom track or GPS position information.

A single transect to measure river discharge took approximately 2 min at RM30 and 3 min at RM60. Normally, a single discharge measurement consists of four transects with two pairs of left-to-right bank and right-to-left bank sets (USGS, Tech. Memo 2002). In this case, discharge measurements consisted of anywhere from two to six transects depending on river conditions.

As previously described, the existence of a moving bed is determined prior to discharge measurements. Typically, this is accomplished by anchoring the measurement vessel at one or two locations in the river cross-section where moving bed is likely to be present and then making velocity measurements for a period (usually 5-10 min). If a moving bed is present, the resulting apparent upstream boat motion divided by measurement time provides an estimate of moving-bed velocity at that location in the cross section; it is not representative of a mean for the whole cross section. Moving-bed tests provide both the biased (measured) current speed and the bed motion speed. Unbiased current speed can be calculated at the test location by correcting the biased speed with bed motion speed or setting the instrument reference in the data processing software to be “none” rather than “bottom track,” as long as ADCP is essentially not moving in space.

River conditions prevented anchoring during this study; however, vessel positions were maintained visually relative to fixed locations on the tag lines by careful boat maneuvering against current. Although it is not possible to determine exactly how much variation in boat motion occurred during the moving-bed tests, it is unlikely that this is a source of bias in results. During moving-bed tests prior to peak flow, when bottom track measurements were successful, boat motion typically varied within about ± 1-2 m, and total distance traveled was typically less than 1 m using this technique. Because of increased water depth during peak flow, the boats were even closer to the tag lines, which provided a very good visual reference for boat operators. Based on boat position relative to the tag line, boat motion that occurred during moving-bed tests conducted at peak flow would have averaged to near zero similar to measurements at low flow when bottom track operated successfully.

Water samples were collected at five (roughly equally spaced) locations in the river cross section numerous times during this study to determine suspended sediment concentrations. For convenience, ADCP moving-bed tests were performed at the same times and locations, which provided an excellent set of data for potential use to adjust discharge measurements for moving bed bias. Initial measurements showed no moving bed prior to dam release at either site however moving-bed conditions began after dam release as the flow rose from about 8000 cubic feet per second (cfs) (226.6 m^3/s) to the planned release of 41,000 cfs (1161.1 m^3/s) (U.S. Department of Interior 2002). (The USGS reports river discharge in English units; equivalent values in metric units are provided.)

Results of moving-bed tests varied widely with time and distance across the river at both RM30 and RM60. Thus, the location and speed of maximum or minimum bed movement varied although the mean of all five tests in each cross section remained relatively constant during peak flow. During the moving-bed tests, the maximum bed movement occurred at two different locations at RM30 and three different locations at RM60. The average difference between bed movement at an individual test site in the cross section and the mean of the five tests done in the same cross section was about 54% at RM30 and about 52% at RM60. Maximum differences ranged from –87% to + 170% at RM30 and –100% to + 114% at RM60. Such variability points out the importance of making multiple moving-bed tests at carefully chosen locations in the river cross section prior to making discharge measurements.

Assessment

Neither lower frequency instruments nor GPS signals (because of terrain limitations) were available to compensate for moving-bed conditions during this study. Therefore, moving-bed conditions resulted in uncorrected discharge measurements (closed square symbols in Figs. 2 and 3) being biased low by approximately 16% (600 kHz ADCP at RM30) and 25% (1200 kHz ADCP at RM60) relative to expected discharge of 41,000 cfs (1161.1 m^3/s) during time of peak flow from the Glen Canyon Dam release. For comparison, the modeled (Wiele and Griffin 1997) hydrographs are also shown in Figs. 2 and 3.

Both the accuracy of results and the speed of correction method are important considerations in post processing these

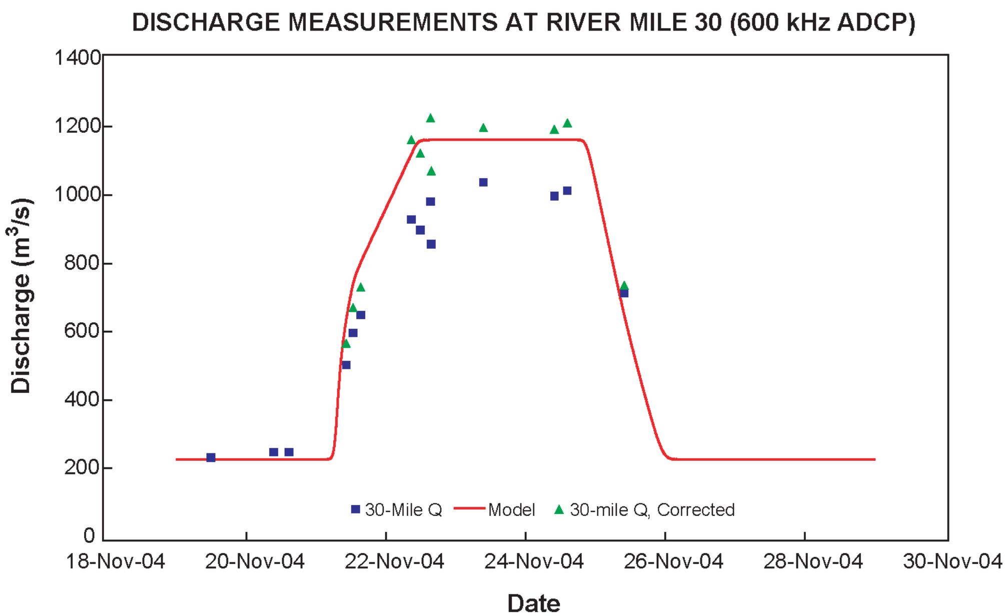

Fig. 2. Graph showing modeled and measured discharge at RM30. ADCP measurements at 600 kHz include uncorrected values and those from the CDMB correction method using speed correction from moving-bed tests and the biased (measured) discharge.

data sets to correct for the existing bias. Sub sectioning each transect using discharge measurement software was considered but deemed too time consuming because there were hundreds of individual discharge measurements made during this study.

There are two general approaches to compensate for moving-bed bias in ADCP discharge measurements. The first method depends on estimating a new discharge from calculated or known values for mean speed, depth, and width (referred to herein as MSDW methods). MSDW methods are quick and simple and seem promising in a situation where (1) the river walls are generally vertical; (2) the bottom is measured by ADCP and is relatively flat; and (3) the river width is known from tag-line markings. The second approach involves correcting the measured discharge for moving bed (referred to herein as CDMB methods). CDMB methods are potentially more complex because additional post-processing

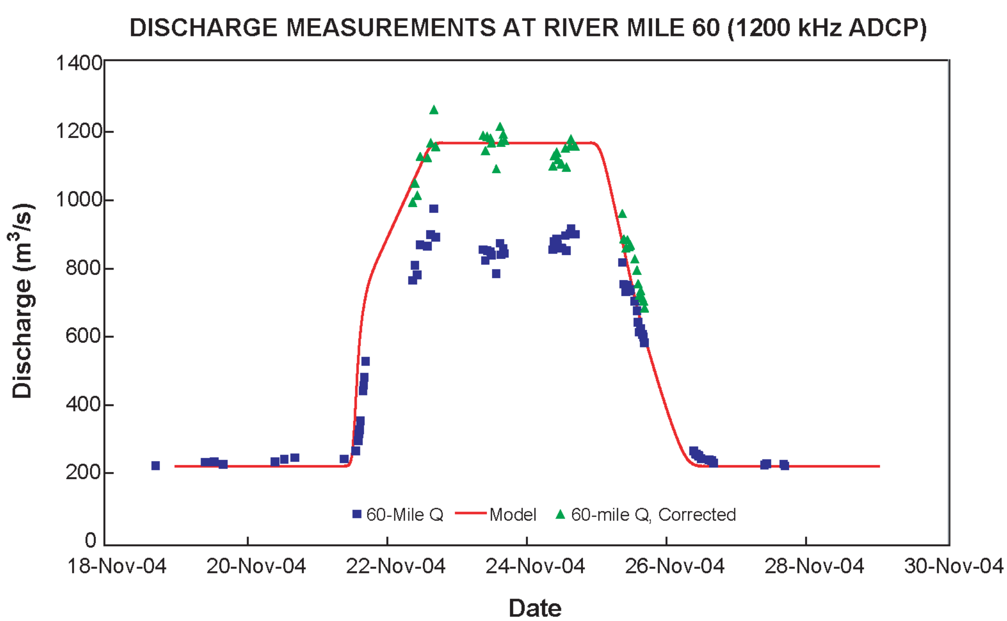

Fig. 3. Graph showing modeled and measured discharge at RM60. ADCP measurements at 1200 kHz include uncorrected values and those from the CDMB correction method using speed correction from moving-bed tests and the biased (measured) discharge.

or subsectioning of ADCP discharge measurements may be needed, as well as corrections to speed measurements based on errors from the moving bed. Nevertheless, CDMB methods that use discharge and moving-bed measurements that span the entire river (less any unmeasured edges) such as the "loop method" are potentially more accurate. However, as previously noted, the "loop" technique is not suitable unless bottom track information is continuous. Both the 600 and 1200 kHz ADCPs frequently lost bottom track at some locations in the river during measurements in this study, probably because of excessive bed load, turbulence, and debris near bottom.

Several methods of estimating or correcting discharge are described and evaluated in the following sections. Two MSDW methods that estimate discharges calculated from actual river widths, measured mean depths, and (corrected) mean current speeds are able to improve results somewhat but are not optimal. One CDMB method that utilizes correction factors determined from bed motions measured at multiple river locations to correct the biased ADCP discharge measurements does provide acceptable estimates of the river discharge.

MSDW correction methods using estimates of averaged bed motion—The initial technique used to calculate a corrected discharge from mean water speed and mean river depth and width utilizes the five bed motion measurements made prior to a discharge measurement to correct mean speed. Several methods have been used to determine a mean value for the five moving-bed measurements to be used to correct the mean speed. Methods include using a spline fit, an average of the five measurements, an average of seven measurements (including 0 cm/s at the left and right water edge), and an area-weighted average of the five measurements. Once the mean water speed is corrected with a mean value for bed motion, the new mean water speed is used in conjunction with the known river width and the mean cross section depth to calculate a new value for river discharge for each river transect. The best results are obtained using an area weighted average of five bed motion measurements however the corrected discharges are still about 13% low for the 600 kHz ADCP and about 14% low for the 1200 kHz ADCP. Thus, discharges that are calculated from mean river speed (corrected with moving-bed speed), mean river depth, and known river width are improved over the uncorrected discharge measurements but still have generally poor agreement with the assumed value of 41,000 cfs (1161.1 m^3/s) during times of peak flow from the dam release.

MSDW correction method using course and distance made good estimates—The second approach using mean water speed and mean river depth and width to calculate corrected discharge employs an estimate of the moving-bed speed that is representative of the entire measured cross section in order to correct the mean water speed. Because boat position was always maintained below the tag line for discharge measurements, actual courses and distances made good across the river during each pair of measurement transects are known. These can be compared to courses and distances made good (as calculated by ADCP software). Simple trigonometry relations and the elapsed time of measurements provide the mean difference of current speed (the moving bed) during the measurement. The bed motion is added to the mean speed to determine a corrected mean speed that, together with the actual river width and mean depth, is used to calculate a new discharge. With this technique, the calculated value of moving bed is an average for the entire cross section unlike the previously described technique, which used an average bed movement calculated from measurements at five locations in the river. ADCP discharge measurements corrected by this method have a bias of about 9% low for the 600 kHz ADCP and 7% low for the 1200 kHz ADCP during the time of peak flow. Results are better than the technique previously described but still fall short of accurately describing river flow under these flood conditions. This technique uses an approach somewhat similar to the "loop" method for quantifying the moving bed. However at least some of the error is the result of loss of bottom track in sections of the river transects.

CDMB correction method using speed correction from moving-bed tests and the biased (measured) discharge—The approaches previously described to calculate corrected discharge from corrected mean speed, mean depth, and actual river width appear inadequate. Therefore, a technique of correcting the actual (biased) discharge measurement using bed motion is evaluated.

As a first step, the moving-bed tests are evaluated to determine if their location and number are adequate to provide useful corrections to the measured discharge. Adequacy of moving-bed tests is checked by using the biased water speeds from those measurements to estimate discharge in a manner similar to a conventional current meter measurement using subsection areas and average velocities (Rantz and others 1982) although with far fewer river subsections than normally used. If those calculated discharges using the biased speeds from the moving-bed tests are in reasonable agreement with the biased moving boat discharge measurements done at about the same time, then it suggests that the differences between the biased and unbiased speeds from the moving-bed tests can be used to calculate correction factors to revise the biased moving boat discharge measurements. This is an appealing approach because the moving boat discharge measurements are missing many velocity profiles because of loss of bottom tracking; however, moving-bed tests always provide profiles of mean water speed because they were conducted over several minutes during which there were always some usable measurements. The estimate of unbiased water speed during the moving-bed test can be calculated from the biased speed plus the bed speed or directly from the ADCP if the instrument (rather than bottom track) is used as the frame of reference during post processing.

The biased moving boat discharge measurements and the discharges calculated from the sum of the subsection areas at each moving-bed test site multiplied by the biased mean velocities from the moving-bed tests compare favorably (within 2% at site RM30 and within 5% at site RM60). As expected, there is somewhat more scatter and difference at RM60 where the higher frequency ADCP was used. Nevertheless, these results indicate that the location and number of moving-bed tests are probably sufficient to define the moving bed in the cross sections and thus, are probably sufficient to correct the biased moving boat discharge measurements.

To further confirm the validity of the moving-bed tests, they have been reprocessed setting the ADCP measurement frame of reference to "none" in the discharge measurement software. Setting instrument reference to "none" assumes that the ADCP was stationary (as it essentially was) and that the measured flow is the result of river flow only; there is no boat motion component and water speeds are theoretically unbiased. Total river discharge values are recalculated with the new, unbiased water speeds combined with the measurement subsection areas. Comparisons are made between those discharges and the river flow estimates (these results have been omitted from Figs. 2 and 3 for clarity). Although there is a small bias, these results compare favorably. Discharge values are within about 5% at RM30 with the largest difference (about 12%) occurring on the falling hydrograph. About 2/3 of the numerous moving-bed tests performed at RM60 have been processed in this manner. Results are within about 1% on the rising hydrograph, within about 5% at the peak and within about 18% on the falling hydrograph. In all cases the estimates of discharge from the ADCP moving-bed test data are higher than those from the model (rather than lower as with the other correction methods). Although biased slightly high, estimates may be more correct than model results based on measured hydrographs at Lee's Ferry and Grand Canyon gage (figure not shown), which suggest discharge at RM30 and RM60 was probably closer to 42,000 cfs (1189.4 m^3/s) than the expected 41,000 cfs (1161.1 m^3/s). Some of the difference on rising and falling hydrograph may be the result of a slight phase error in the model. Comparisons of measured and modeled discharge include an apparent phase shift; modeled values for flow tend to lead the field measurements by a few hours on both the rising and falling limbs of the hydrograph at both RM30 and RM60.

With confidence in the usefulness and accuracy of the moving-bed tests based on the results of the previous exercises, a set of correction factors are determined to be applied to the ADCP moving boat discharge measurements. The percent difference between the unbiased and biased water speeds (determined with ADCP reference set "none" and ADCP reference set "bottom track") is used to determine a correction factor for each moving-bed test. Alternatively, a similar correction could be determined directly from the unbiased speed (sum of biased speed plus bed motion) and the biased speed. An area-weighted average of correction factors from the five locations across the river is then determined for each set of moving-bed tests. For simplicity during peak flows (41,000 cfs or 1161.1 m^3/s) daily average values of the percent differences are determined. These correction factors range from about 13% to 25% for the 600 kHz ADCP and about 17% to 38% for the 1200 kHz ADCP. The discharge measurements corrected using these factors are shown in Figs. 2 and 3 (closed triangle symbols). On average, corrected values agreed with modeled results within 1.6% at RM30 and –0.3% at RM60. In addition, examinations of Figs. 2 and 3 indicate that, as previously discussed, the modeled values for flow tend to lead the field measurements by a few hours on the rising and falling limbs of the hydrograph at both RM30 and RM60.

Comments and recommendations

During time of predicted peak flow, the corrected ADCP discharge measurements at RM30 average 41,635 cfs (1179.1 m^3/s) and at RM60 average 40,581 cfs (1149.3 m^3/s). In the case of the 1200 kHz ADCP measurements at RM60, the corrected discharge measurements are somewhat lower than the average of the 5-section measurements (43,805 cfs or 1240.6 m^3/s) that provided the speed relations used to correct the moving boat measurements. Using more or fewer correction values or averaging them differently might improve results, however, using a daily average calculated from 4 moving-bed tests at site RM60 is thought to be a reasonable approach during times of relatively constant flow. Corrected values are in general agreement with the expected dam release estimate (41,000 cfs or 1161.1 m^3/s) and stage-discharge estimates (42,000-42,500 cfs or 1189.4-1203.6 m^3/s) of flow. They are the best that can be determined given the severe field conditions of high suspended sediment and debris concentrations, substantial bed movement, and enhanced turbulence present at both sites during the high flow conditions.

These results indicate that, at least under these field conditions, a correction factor based on the difference between the biased and unbiased water speeds determined from well placed moving-bed tests can be applied to minimize bias in moving boat discharge measurements made under moving bed conditions; even if GPS is unavailable, and there are some periods when bottom track information is lost. However, the number and location of moving-bed tests is important to determine appropriate correction factors because of the potential for substantial variations in bed movement across the river. The method of correcting for biased speeds provides results that are superior to computing a new estimate of discharge from single values of corrected mean speed, mean depth, and known width.

There are a number of approaches to overcoming the problem of moving bed induced bias in discharge determined by Doppler profiler. These approaches include, in descending order of choice, the use of GPS to determine instrument location, the use of lower frequency instrument, and the use of the "loop" method to determine bed movement. However, when these methods are unavailable or unsuitable, quality of discharge measurements can still be improved through use of correction factors determined from moving-bed tests as long as those tests and the resulting correction factors reasonably represent the actual moving-bed conditions in the river.

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