EVALUATION OF MULTIPLE-FREQUENCY, ACTIVE AND PASSIVE ACOUSTICS AS SURROGATES FOR BEDLOAD TRANSPORT

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Abstract: The use of multiple-frequency, active acoustics through deployment of acoustic Doppler current profilers (ADCPs) shows potential for estimating bedload in selected grain size categories. The U.S. Geological Survey (USGS), in cooperation with the University of Montana (UM), evaluated the use of multiple-frequency, active and passive acoustics as surrogates for bedload transport during a pilot study on the Kootenai River, Idaho, May 17-18, 2012. Four ADCPs with frequencies ranging from 600 to 2000 kHz were used to measure apparent moving bed velocities at 20 stations across the river in conjunction with physical bedload samples. Additionally, UM scientists measured the sound frequencies of moving particles with two hydrophones, considered passive acoustics, along longitudinal transects in the study reach. Some patterns emerged in the preliminary analysis which show promise for future studies. Statistically significant relations were successfully developed between apparent moving bed velocities measured by ADCPs with frequencies 1000 and 1200 kHz and bedload in 0.5 to 2.0 mm grain size categories. The 600 kHz ADCP seemed somewhat sensitive to the movement of gravel bedload in the size range 8.0 to 31.5 mm, but the relation was not statistically significant. The passive hydrophone surveys corroborated the sample results and could be used to map spatial variability in bedload transport and to select a measurement cross section with moving bedload for active acoustic surveys and physical samples.

INTRODUCTION

Background: Active acoustics, through deployment of acoustic Doppler current profilers (ADCPs), have been tested as a surrogate for bedload transport in Canada's Fraser River (Rennie and others, 2002) and the United States' Trinity River (Gaeuman and Pittman, 2007) and lower Missouri River (Gaeuman and Jacobson, 2006). However, little work has been done to evaluate the performance of multiple frequency ADCPs outside a laboratory environment and whether the response of the various frequencies can help identify types and thicknesses of bedload based on differences in perceived velocities of the moving layer and water depths.

One feature of an ADCP is that it transmits a sound wave, called a bottom track pulse, to keep track of its position as it moves across a stream (Gordon, 1996). If material is moving along the bed at a particular site, the ADCP will falsely appear to move upstream, which introduces bias in a streamflow measurement unless it is corrected (Mueller and others, 2013). If the specific location of the ADCP is known (by fixing its position or by connecting it to a differential global positioning system (DGPS)), and the apparent or false movement of the ADCP is measured over time, an apparent moving bed velocity can be inferred. Bedload transport rate can be estimated based on the apparent moving bed velocity and empirical parameters or through correlations between near-simultaneous measurements of apparent moving bed velocity and bedload samples.

The average velocity of the bedload layer depends on the various sizes and velocities of the particles. Apparent moving bed velocity should be representative of the average surface velocity within the volume measured by the ADCP; however, the measurement is influenced by the frequency of the instrument and the size of the particles. An ADCP preferentially measures reflections from particles with a diameter equal to or greater than the wavelength of the instrument's sound wave (Thorne and others, 1995). For example, a 1200 kHz ADCP should be most sensitive to particles with diameters equal to or greater than 0.8 mm, and the weighting of these particles in the apparent moving bed velocity should be greater. The use of multiple ADCPs with different frequencies should theoretically allow the computation of apparent moving bed velocities for different grain sizes. As a result, relations between bedload and apparent moving bed velocity may be developed separately for various grain size categories.

Passive acoustics, through deployment of hydrophones, have been tested as a surrogate for bedload transport in the United States' Trinity River (Barton and others, 2007) and Middle Fork Flathead River (Lorang and Tonolla, 2014) and France's Isère River (Belleudy and others, 2007). Most research with hydrophones has been focused on measuring

coarse gravel transport, and little work has been done to evaluate the ability of hydrophones to detect a wider range of bedload grain sizes. Additionally, research is needed to determine whether passive acoustics could be used in conjunction with active acoustics to optimize sampling design and development of surrogate relations.

STUDY SITE AND METHODS

The U.S. Geological Survey (USGS) has operated a sediment monitoring and hydrodynamic modeling project in the Kootenai River basin (fig. 1) since 2003 as part of the Kootenai River White Sturgeon Recovery Plan. Recovery efforts for the endangered Kootenai River population of white sturgeon require an understanding of the characteristics and transport of suspended and bedload sediment which have an effect on egg suffocation and mortality rates in the critical habitat reach of the river (fig. 1) as described in Fosness and Williams (2009). The pilot study site, Kootenai River at Crossport near Bonners Ferry, ID (USGS 12308500; fig. 1), is near the upstream end of the Kootenai River white sturgeon critical habitat. The site was selected for the pilot study based on observed conditions in 2010-12: consistent bedload at streamflows greater than 30,000 ft^3/s, a mixture of sand and gravel in bedload samples, and apparent moving bed velocities greater than 0.04 ft/s detected by ADCPs used to measure streamflow.

Field data collection for the pilot study was conducted May 17-18, 2012, during a controlled release of about 14,800 ft^3/s from Libby Dam (fig. 1) and fairly steady streamflow around 38,000 ft^3/s at the study site. All sampling and ADCP equipment were deployed from a jet boat. Four ADCPs with frequencies ranging from 600 to 2000 kHz (fig. 2) were used to measure apparent moving bed velocities and streamflow depths at 20 stations across the river:

- Teledyne RD Instruments (TRDI) 600 kHz Rio Grande
- TRDI 1200 kHz Rio Grande
- TRDI 2000 kHz StreamPro
- SonTek/Xylem multi-frequency RiverSurveyor M9 (1000 kHz beams used)

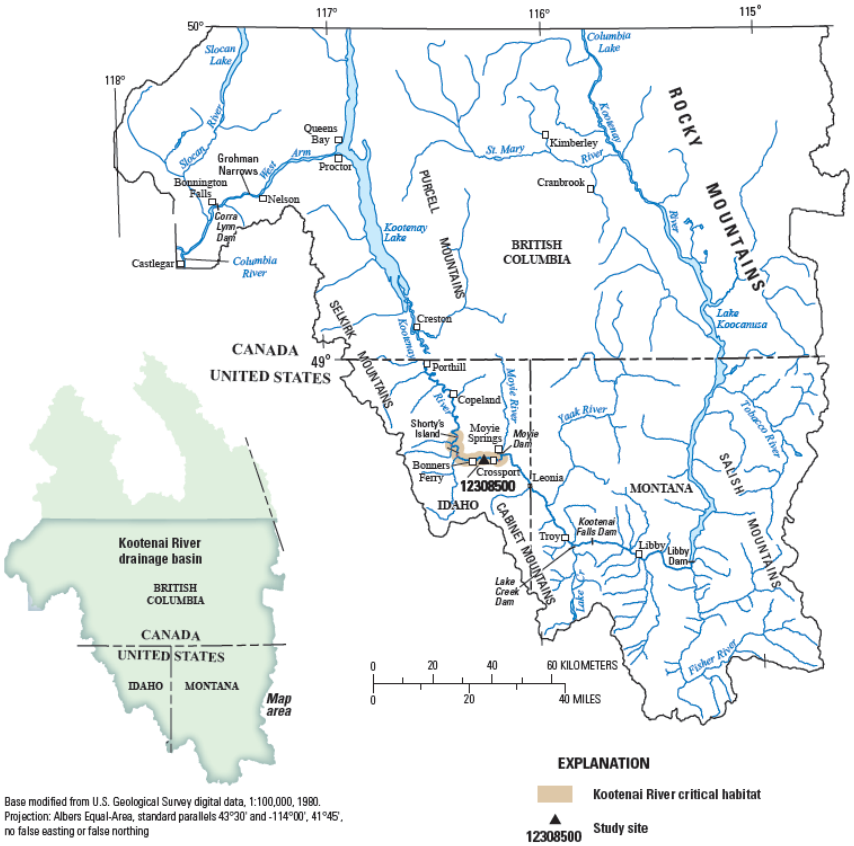

Figure 1 Map showing location of pilot study site, Kootenai River at Crossport near Bonners Ferry, Idaho (USGS 12308500).

Figure 2 Mounting configuration for ADCPs used to measure apparent moving bed velocities in the Kootenai River at Crossport near Bonners Ferry, Idaho (USGS 12308500), May 17-18, 2012. ADCPs are (from left to right): TRDI StreamPro, TRDI 600 kHz Rio Grande, TRDI 1200 kHz Rio Grande, and SonTek/Xylem RiverSurveyor M9.

All ADCPs except the TRDI StreamPro were equipped with DGPS equipment. Use of a DGPS requires a compass within the ADCP. For the TRDI StreamPro, the compass is contained within the electronics housing, which is separate from the ADCP transducer. The electronics housing must be aligned in a specific way relative to the transducer if the compass is to be used, which was not possible during the study. The compasses in all other ADCPs that were used were calibrated according to manufacturer recommendations and USGS policies in Mueller and others (2013) prior to further data collection.

The ADCPs were deployed to collect stationary moving bed tests for 5 minutes at each station. USGS personnel were unable to anchor the boat during ADCP data collection because of safety considerations and difficulty in attaching the anchor in the cobble substrate. The boat was held as stationary as possible during each moving bed test but some movement was unavoidable. Apparent moving bed velocities were calculated by determining the apparent distance moved upstream according to the ADCP's bottom track pulse. Apparent moving bed velocities for the TRDI StreamPro were taken directly from the stationary moving bed tests assuming boat position was held relatively steady (no "real" upstream movement). For all other ADCPs, the apparent moving bed velocities were calculated relative to actual boat movement determined from DGPS (equation 1):

$$V_{mb} = \frac{DU_{BT} - DU_{DGPS}}{T} \quad (1)$$

Where

V_{mb} is the apparent moving bed velocity in ft/sec,
DU_{BT} is the distance the ADCP appears to move upstream in ft when referenced to bottom track,
DU_{DGPS} is the distance the ADCP moves upstream in ft when referenced to DGPS, and
T is the duration of the test in seconds.

For all ADCPs equipped with DGPS, the National Marine Electronics Association (NMEA) "Global Positioning System Fix" (GGA) string was selected over the "Track Made Good and Ground Speed" (VTG) string as the best DGPS reference.

Immediately before or after ADCP data collection, bedload samples were collected at each of the 20 stations using an Elwha US-ER1 sampler with a 0.5 mm bag mesh size. Additionally, an underwater video camera was attached to the bedload sampler to monitor its orientation and performance at four stations. Samples were collected utilizing USGS methods for single equal width increment (SEWI) samples (Edwards and Glysson, 1999), but samples were not composited. Each station's sample was separately analyzed for mass in 12 grain size categories from 0.063 mm to 128 mm. Bedload was calculated according to equation (2) adapted from Edwards and Glysson (1999):

$$Q_b = K\left(\frac{W_t}{T_t}\right)M_t \quad (2)$$

Where

Q_b is the bedload in tons/day,
K is a conversion factor calculated as 86,400 sec/day x (1 ton/907,200 g) x (1 ft/N_w), where N_w is the width of the sampler opening in ft, or 0.67 ft,
W_t is the width of the stream represented by each station in ft, or about 23 ft on average,
T_t is the total time the sampler rests on the bed at each station in seconds, or 60 s, and
M_t is the mass of sample from each station in grams.

Sampling was repeated on May 18 at three stations that were measured on May 17 that had the highest apparent moving bed velocities and most bedload collected. Overall, 23 samples were attempted, but because no material was present in one sample collected near the left bank, data from 22 samples were available for analysis. USGS personnel intended to repeat sampling at all 20 stations but were unable to do so within the short time frame of the controlled release out of Libby Dam.

Simultaneous with the sample and ADCP data collection, UM scientists measured the sound frequencies (0.020−20 kHz; then combined in 10 octave bands from 0.0315 to 16 kHz) of moving particles with a pair of co-located Brüel and Kjaer 8103 hydrophones, amplified and connected to a digital recorder, along longitudinal transects in the study reach. The hydrophones were mounted parallel to each other at about 1 ft depth below water on the frame of a jet boat (a separate boat from the one used to collect bedload samples and ADCP data).

RESULTS AND DISCUSSION

Bedload Characteristics: Total bedload from the composite of all stations contained 3 percent sand and 97 percent gravels, with less than 0.5 percent organics. Sand was considered to include sediment retained on 0.063 to 1 mm sieves, and gravel was considered to include sediment retained on 2 mm and larger sieves, according to the Wentworth scale (Wentworth, 1922). Throughout this paper, bedload is referenced by how much material was retained on that sieve size (for example, "2 mm bedload" is bedload comprised of grain sizes passing through the 4 mm sieve but retained on the 2 mm sieve).

The most sand bedload at any station was measured at station 7, about 160 ft from the right bank (fig. 3). About 20 percent of the total bedload in the sample collected at station 7 was sand. The most gravel bedload was measured at stations 8 and 9, 180 to 203 ft from the right bank. Overall, nearly all the measured bedload was in the right 35 to 45 percent of the cross-section. The gravel bedload measured at station 1 is suspected to be the result of the sampler scooping bed (non-moving) gravel because (1) sampler control was difficult because of turbulence caused by a

submerged tree, and (2) the gravel sizes measured (16.0-31.5 mm) are unlikely to be transported by the low stream velocities observed at station 1.

Overall, bedload size distribution was unimodal and contained a much higher percent of gravel than expected. The largest sediment mass was observed in the grain size categories of 8.0 and 16 mm. Fairly equal proportions of sands were measured in the 0.5 and 1.0 mm size categories. Any sands less than 0.5 mm were assumed to be attached to other particles or were present in the bag due to occlusion of the 0.5 mm mesh openings from other particles. As a result, sand particles smaller than 0.5 mm were not considered in relations with acoustic data. None of the samples contained sediment in the 63 and 128 mm (gravel) grain size categories.

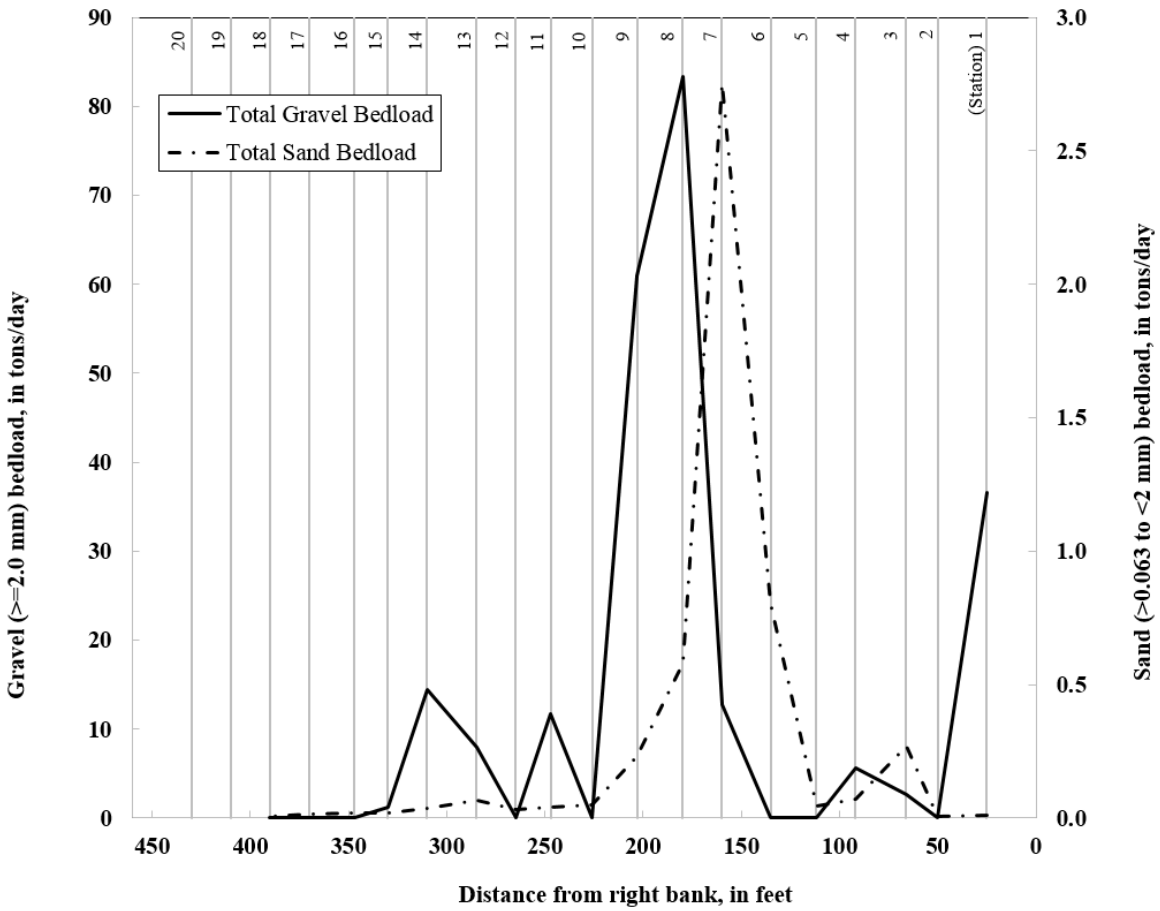

Figure 3 Total gravel and sand bedload at each station measured in the Kootenai River at Crossport near Bonners Ferry, Idaho (USGS 12308500), May 17, 2012.

Bedload Sampler Performance: Underwater video camera reconnaissance of the bedload sampler, attempted at stations 1-4, showed that the sampler often turned sideways or backwards when deployed, which raises concerns about sampler performance. The camera and accessory cable were tested in different configurations (fig. 4) in an attempt to reduce their hydraulic drag and resulting effect on sampler orientation. After several attempts the camera was removed because a proper sampler orientation could not be attained and meaningful bedload samples could not be collected. After camera removal, collected bedload samples made sense based on observed substrate and velocity distribution in the cross-section, which suggests that the sampler oriented correctly without the presence of the camera. Post-study consultation with other bedload sampling experts revealed that the weight distribution of the sampler may not have been ideal to handle the added weight and hydraulic disturbance due to the video camera (Smokey Pittman, Graham Matthews and Associates, written commun., 2013). The video reconnaissance of the bedload sampler showed some concerning behavior, which could be further verified through controlled experiments in a laboratory flume or in a river where water clarity allows direct observation of the sampler on the bed.

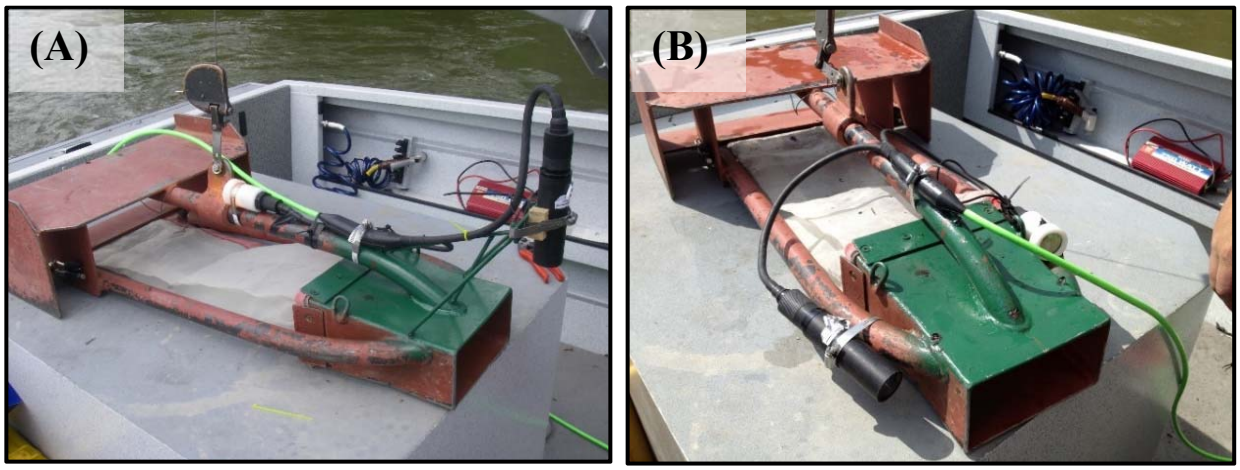

Figure 4 Elwha US-ER1 sampler used to measure bedload in the Kootenai River at Crossport near Bonners Ferry, Idaho (USGS 12308500), May 17-18, 2012. An underwater video camera was temporarily attached to the sampler, (A) looking down on the sampler opening and (B) attached to the lateral sampler supports, to evaluate sampler performance and orientation.

Active Acoustic Relations: Apparent moving bed velocities were low (0.001-0.064 ft/sec) during the selected sampling event due to the unforeseen low percentage of sands in the total bedload. In theory, sand should be more detectable by the ADCPs than gravels for the frequencies tested. Apparent moving bed velocities greater than 0.04 ft/sec were measured at only 5 stations. An apparent moving bed velocity of 0.04 ft/s is used as an uncertainty threshold for correcting ADCP streamflow measurements for moving bed using a loop correction described in Mueller and others (2013). Average apparent moving bed velocity among all instruments and sampling stations was 0.013 ft/s. As a result, uncertainty was high in identified relations between bedload and apparent moving bed velocities for all ADCPs. However, some patterns emerged in the relations that show promise for future studies.

Apparent moving bed velocities measured by the 1200 kHz ADCP had the best statistically significant, though scattered, linear relations with sands in the 0.5 – 1.0 mm size categories and very fine gravels in the 2.0 mm size category (table 1, fig. 5). The 1000 kHz ADCP showed similar, though slightly more scattered, relations with sands and very fine gravels. The 2000 kHz ADCP showed statistically significant relations with individual bedload grain size categories 0.5 and 1.0 mm but not 2.0 mm and larger. No statistically significant relations were found between bedload transport for gravels 4.0 mm and larger and apparent moving bed velocities measured by any ADCP, which was expected. However, apparent moving bed velocities measured by the 600 kHz ADCP related better to gravels in the 8.0 to 31.5 mm grain size categories than the other ADCPs (correlation = 0.46, R^2 = 0.21; p-value = 0.11 (table 1)). Otherwise, use of a range of frequencies did not improve the ability to define relations for individual bedload size categories.

Apparent moving bed velocities measured by the 1200 kHz ADCP had the best relations with sand and very fine gravel bedload of all tested ADCPs. The highest apparent moving bed velocities were measured by the 1200 kHz ADCP at 4 stations located 135-203 ft from the right bank. Samples collected from these stations contained 89 percent of the total sand and very fine gravel bedload measured in the cross-section.

Relations between apparent moving bed velocities measured by ADCPs with frequencies in the 1000-1200 kHz range and sand and very fine gravel bedload transport show promise for future work, but further testing is needed during an event when total bedload consists of a greater percentage of transport in these size categories and apparent moving bed velocities are consistently higher than 0.04 ft/sec.

Table 1 Regression statistics of selected relations between apparent moving bed velocities measured by acoustic Doppler current profilers and bedload in various grain-size categories in the Kootenai River at Crossport near Bonners Ferry, Idaho (USGS 12308500), May 17-18, 2012.

[A table entry of "--" indicates the regression was not statistically significant at a significance level of 0.10. The regression model between the 600 kHz Rio Grande and gravel bedload is shown because it is noteworthy and discussed in the text, even though it is not statistically significant at a significance level of 0.10. Regression model form developed in all cases is log(bedload) = m(log(V_{mb}))+b, where m is the regression slope and b is the regression constant. Abbreviations: V_{mb}, apparent moving bed velocity; kHz, kiloHertz; mm, millimeter; n, number of samples used in regression; R^2, coefficient of determination; SE, standard error; p, statistical significance or probability that the two compared variables are linearly related by chance]

Bedload grain size classification (Wentworth, 1922)	Bedload grain size (mm)	Acoustic Doppler current profiler															
		600 kHz Rio Grande				1000 kHz RiverSurveyor M9				1200 kHz Rio Grande				2000 kHz StreamPro			
		n	R^2	SE	p	n	R^2	SE	p	n	R^2	SE	p	n	R^2	SE	p
Coarse sand	0.5	--	--	--	--	22	0.35	4.6	0.004	22	0.41	4.3	0.001	[1]15	0.24	5.3	0.066
Very coarse sand	1.0	--	--	--	--	22	0.28	4.6	0.012	22	0.36	4.2	0.003	[1]15	0.22	5.3	0.077
Very fine gravel	2.0	--	--	--	--	[2]21	0.16	5.8	0.071	[2]21	0.35	4.6	0.005	--	--	--	--
Fine gravel	4.0	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Medium gravel	8.0	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Coarse gravel	16	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Very coarse gravel	31.5	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Coarse to very coarse sand	0.5 to 1.0	--	--	--	--	22	0.31	4.7	0.007	22	0.39	4.3	0.002	[1]15	0.24	5.3	0.066
Coarse sand to very fine gravel	0.5 to 2.0	--	--	--	--	22	0.30	5.1	0.008	22	0.38	4.6	0.002	[1]15	0.22	6.0	0.074
Medium to coarse gravel	8.0 to 31.5	[3]13	0.21	5.4	0.11	--	--	--	--	--	--	--	--	--	--	--	--

[1]Some data points were removed from the regression with the 2000 kHz StreamPro because the StreamPro reported downstream instead of upstream movement at those stations.
[2]Bedload in the 2.0 mm grain size category was not present in one sample.
[3]Bedload in the 8.0 to 31.5 mm grain size categories was not present in nine samples.

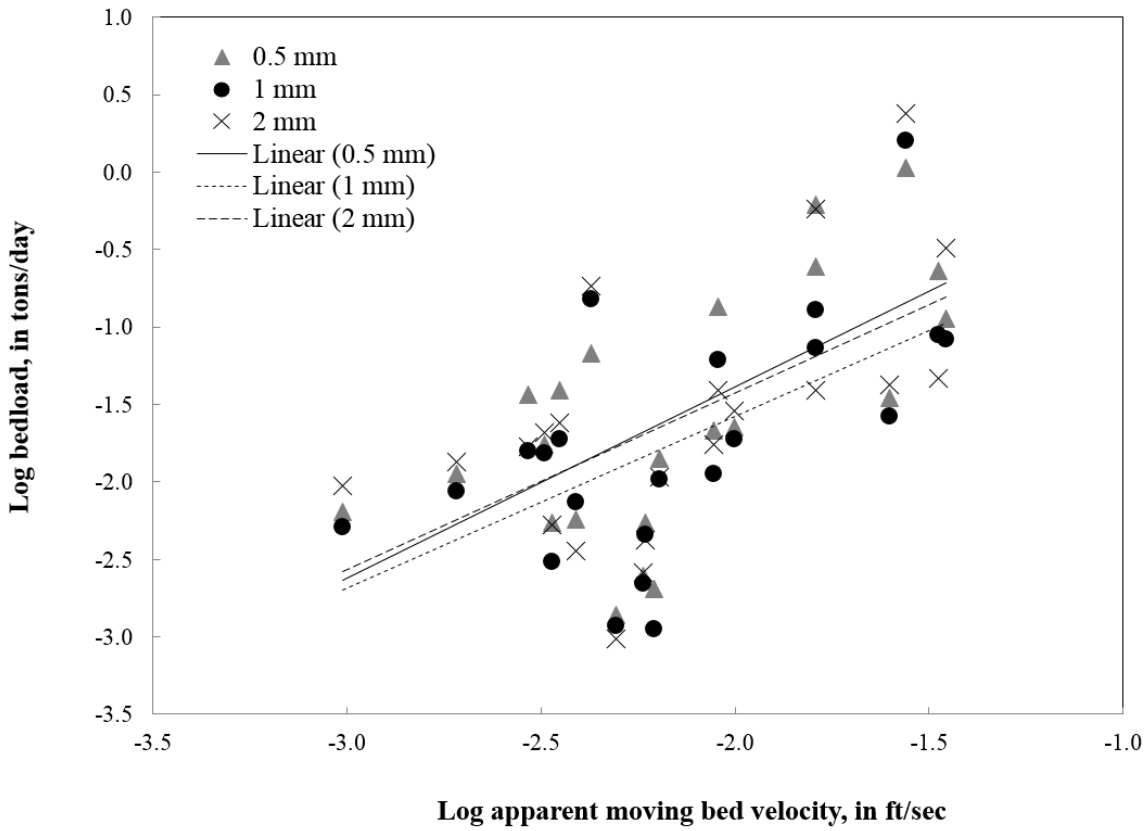

Figure 5 Selected linear relations between apparent moving bed velocities measured by the 1200 kHz TRDI Rio Grande ADCP and bedload at individual stations sampled in the Kootenai River at Crossport near Bonners Ferry, Idaho (USGS 12308500), May 17-18, 2012.

Active Acoustic Depth Differences: Streamflow depth readings from each ADCP were compared at each station, and an overall cross-sectional area was calculated based on each ADCP's depth readings using the USGS AreaComp2 program (Lant and Mueller, 2012). Differences in depth and area readings among ADCPs were examined for patterns in an attempt to determine thickness of bedload layers in various size categories. Safe anchoring was not possible during the pilot study, and, as a result, considerable uncertainty exists when comparing average depths among ADCPs because of movement of the boat. Additionally, each ADCP measured depth in a slightly different ensonified area due to their mounting configuration on the boat (fig. 2) and differences in beam angle and diameter.

Depths measured by the 600 kHz ADCP resulted in the largest cross-sectional area, which was expected because the acoustic signal strength of the 600 kHz ADCP is higher than the other ADCPs and is able to penetrate finer material moving near the bed. No clear patterns were observed between cross-sectional area and the other ADCP frequencies. Overall, the coefficient of variation among cross-sectional areas calculated from the various ADCP depths was 0.6 percent, which is small compared to the uncertainties mentioned above. Future testing would benefit by selecting a site where anchoring could be ensured; however, the other mentioned uncertainties would likely still exist.

Passive Acoustic Surveys: Selected results of the passive acoustic hydrophone surveys along longitudinal transects in the study reach are presented here as they relate to the active acoustic (ADCP) and bedload sample data in the pilot study cross-section. Further details on the results of the hydrophone surveys are presented in Lorang and Tonolla (2014).

In general, the hydrophone surveys corroborated the bedload sample results and apparent moving bed velocities measured by the ADCPs. Lorang and Tonolla (2014) state that frequency responses from 2 to 8 kHz probably correspond with gravel bedload transport and 8 to 16 kHz correspond with sand bedload transport. The hydrophones recorded highest response in the expected frequency range for gravels (2-8 kHz) where the highest gravel transport was sampled about 180-200 ft from the right bank (3rd panel from top, fig. 6) and highest response in the expected frequency range for sand (8–16 kHz) where the highest sand transport was sampled about 160 ft from the right bank (2nd panel from top, fig. 6). The hydrophones also recorded a high response in the 2-6 kHz frequency range about 300-350 ft from the right bank at the sampling cross-section (3rd panel from bottom, fig. 6) that seems to correspond with an increase in gravel transport measured in the bedload samples at station 14 (fig. 3). All of the ADCPs reported lower than average apparent moving bed velocities in this area. In the future, passive acoustic surveys could be used to measure spatial variability of bedload in a river reach and could aid in selecting locations with moving bed for sample and active acoustic data collection.

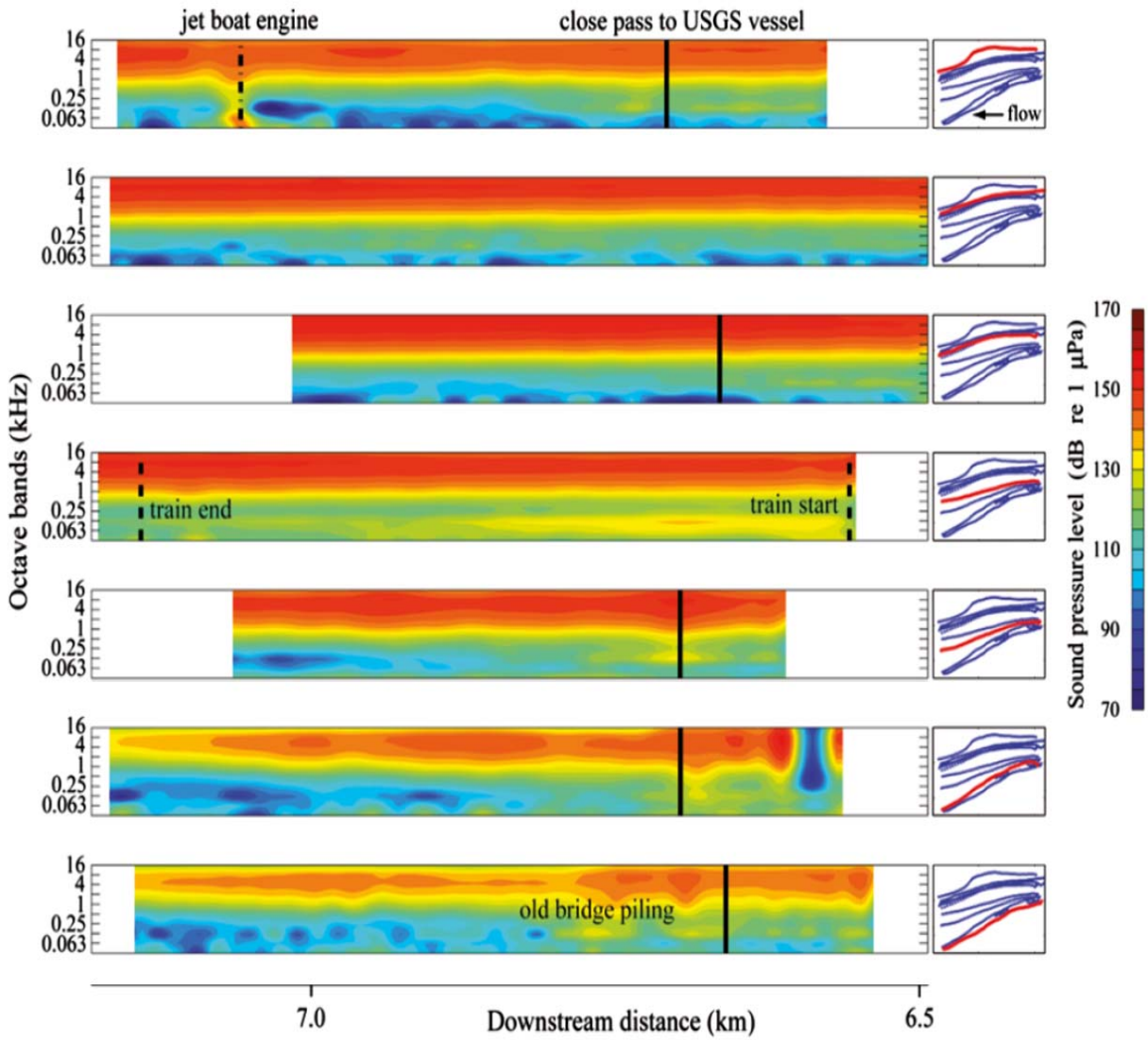

Figure 6 Lateral variation in sound moving from river left to right of the Kootenai River with vertical bars indicating the occurrence of noise from engines, nearby boats and a passing train. Panels at right show position in the river relative to bank with red line corresponding to the sound plot to the left. The solid vertical black bars generally indicate the location of the USGS cross-section for sample and ADCP data collection at Crossport near Bonners Ferry, Idaho (USGS 12308500), May 17-18, 2012. Reproduced with permission from Lorang and Tonolla (2014), www.schweizerbart.de.

SUMMARY

The USGS, in cooperation with UM scientists, evaluated the use of multiple-frequency, active and passive acoustics as surrogates for bedload transport during a pilot study in the Kootenai River at Crossport near Bonners Ferry, Idaho (USGS 12308500), on May 17-18, 2012. Four ADCPs with frequencies ranging from 600 to 2000 kHz were used to measure apparent moving bed velocities at 20 stations across the river. Bedload samples were collected at each station with an Elwha US-ER1 sampler immediately before or after the ADCP data collection. At four sampling stations, an underwater video camera was used to monitor performance of the bedload sampler. Additionally, UM scientists measured the sound frequencies (0.020−20 kHz; then combined in 10 octave bands from 0.0315 to 16 kHz) of moving particles with a pair of co-located hydrophones along longitudinal transects in the study reach. USGS scientists attempted to correlate apparent moving bed velocities measured by the active acoustics (ADCPs) and qualitatively compare frequency response from the passive acoustics (hydrophones) with the sample data at each station to determine whether surrogate relations could be developed for various bedload grain-size categories.

Some patterns emerged in the preliminary analysis which show promise for future studies. Apparent moving bed velocities were much lower than expected (average less than 0.04 ft/sec), and 97 percent of the total bedload was gravel, which in general was too large to be detected in most of the ADCP measurements but was detected by the hydrophones. Apparent moving bed velocities measured by the 1200 kHz ADCP had the best statistically significant, though scattered, linear relation with sands and very fine gravels in the 0.5-2 mm size range (highest $R^2 = 0.41$). Apparent moving bed velocities measured by the 600 kHz ADCP had a positive correlation (+0.46) and weak linear relation ($R^2 = 0.21$) with gravels in the 8.0 to 31.5 mm size range, but the p-value of the regression (0.11) was just above the threshold for statistical significance (0.10) selected for this study. Significant relations could not be developed between apparent moving bed velocities for any ADCP and sample data in individual bedload size categories of 4.0-31.5 mm. Relations between apparent moving bed velocities measured by ADCPs with frequencies in the 1000-1200 kHz range and bedload transport of sands and very fine gravels show promise for future work, but further testing is needed during an event when total bedload transport consists of a greater percentage of sands and apparent moving bed velocities are consistently higher than 0.04 ft/sec.

The passive hydrophone surveys generally corroborated the sample results. The hydrophones recorded highest response in the expected frequency range for gravels (2-8 kHz) and sand (8-16 kHz) where the most gravel and sand transport, respectively, was measured in the cross-section. In the future, active and passive acoustics used together show promise for bedload characterization. Passive acoustics could be used to characterize types and location of bedload transport in a river reach and to select an appropriate cross-section for collection of active acoustic and physical sample data, possibly resulting in development of surrogate relations, particularly for the sand fraction of bedload transport.

Underwater video reconnaissance of the bedload sampler showed that the sampler often turned sideways or backwards when deployed, which raises concerns about sampler performance. The camera was attached to the sampler in several different configurations in an attempt to reduce the camera's hydraulic drag. After several attempts, the camera was removed because it likely altered the hydraulic characteristics of the sampler, preventing proper alignment with streamflow. However, questions remain about the true performance and orientation of the sampler, which could be answered through controlled experiments in a laboratory flume or in a river where water clarity allows direct observation of the sampler on the bed.

REFERENCES

Barton, J.S., Slingerland, R.L., Pittman, S., and Gabrielson, T.B. (2007). "Monitoring coarse bedload transport with passive acoustic instrumentation: a field study," *in* Gray, J.R., Laronne, J.B., and Marr, J.D.G., "Bedload-surrogate monitoring technologies," U.S. Geological Survey Scientific Investigations Report 2010-5091, p. 266-282, available only online from http://pubs.usgs.gov/sir/2010/5091/papers/listofpapers.html.

Belleudy, P., Valette, A., and Graff, B. (2007). "Passive hydrophone monitoring of bedload in river beds: first trials of signal spectral analyses," *in* Gray, J.R., Laronne, J.B., and Marr, J.D.G., "Bedload-surrogate monitoring technologies," U.S. Geological Survey Scientific Investigations Report 2010-5091, p. 266-282, available only online from http://pubs.usgs.gov/sir/2010/5091/papers/listofpapers.html.

Edwards, T.E., and Glysson, G.D. (1999). "Field methods for collection of fluvial sediment," U.S. Geological Survey Techniques of Water-Resources Investigations Book 3, Chapter C2, 89 p. http://water.usgs.gov/osw/techniques/Edwards-TWRI.pdf.

Fosness, R.L., and Williams, M.L. (2009). "Sediment characteristics and transport in the Kootenai River white sturgeon critical habitat near Bonners Ferry, Idaho," U.S. Geological Survey Scientific Investigations Report 2009-5228, 40 p.

Gaeuman, D., and Jacobson, R.B. (2006). "Acoustic bed velocity and bedload dynamics in a large sand-bed river," J. Geophys. Res., 111, F02005.

Gaeuman, D., and Pittman, S. (2007). "Relative contributions of sand and gravel bedload transport to acoustic Doppler bed-velocity magnitudes in the Trinity River, California, in Bedload-Surrogate Monitoring," in, Gray, J.R., Laronne, J.B., and Marr, J.D.G., eds, Proceedings of the International Bedload-Surrogate Monitoring Workshop, April 11-14, 2007, Minneapolis, Minnesota.

Gordon, R.L (1996). Acoustic Doppler Current Profiler Principles of Operation: A Practical Primer. RD Instruments, San Diego, California.

Lant, J., and Mueller, D.S. (2012). "Stage area rating application – AreaComp2," U.S. Geological Survey software user's guide, accessed February 22, 2013 at http://hydroacoustics.usgs.gov/software/AreaComp2_Users_Guide.pdf.

Lorang, M.S., and Tonolla, D. (2014). "Combining active and passive hydroacoustic techniques during flood events for rapid spatial mapping of bedload transport patterns in gravel-bed rivers," Fundam. of Appl. Limnol., 184(3), p 231-246, www.schweizerbart.de.

Mueller, D.S., Wagner, C.R., Rehmel, M.S., Oberg, K.A., and Rainville, F. (2013). "Measuring discharge with acoustic Doppler current profilers from a moving boat", ver. 2.0, December 2013, U.S. Geological Survey Techniques and Methods, book 3, chap. A22, 95 p.

Rennie, C.D., Millar, R.G., and Church, M.A. (2002). "Measurement of bed load velocity using an acoustic Doppler current profiler," J. Hydraul. Eng., 128(5), 473–483.

Thorne, P.D., Waters, K.R., and Brudner, T.J. (1995). "Acoustic measurements of scattering by objects of irregular shape," J. Acoust. Soc. Am. 97(1), 242-251.

Wentworth, C.K. (1922). "A scale of grade and class terms for clastic sediments," Journal of Geology, v. 30, p. 377-392.