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Combining active and passive hydroacoustic techniques during flood events for rapid spatial mapping of bedload transport patterns in gravel-bed rivers

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With 7 figures

Abstract: Turbulent flow in rivers and the associated movement of sediment creates unique underwater soundscapes that can be measured passively with hydrophones while Acoustic Doppler Profilers (ADP) are an active form of hydroacoustic sampling that can be used to provide a surrogate measurement of Apparent Bedload Velocity (ABV). In our study, longitudinal profiles of ADP and sound were simultaneously measured, while floating the river in a raft on the Nyack Floodplain of the Middle Fork of the Flathead River, USA during flood events exceeding bankfull conditions. In addition, similar measurements were carried out on the Kootenai River during a prescribed flood release aimed at mobilizing gravel bed sediment to positively impact White Sturgeon spawning. Both data sets revealed spatially explicit zones of coherent ABV and bedload intensity (sound) over the two 12 km river segments. The ability to remotely and in real-time assess bedload transport for large gravel-bed rivers, on the floodplain scale, is a missing piece of information important for basic ecological understanding and applied science, specifically management decisions regarding regulated rivers worldwide. With these data sets we demonstrate a new methodology for rapid real-time spatial surveying of bedload transport in large gravel-bed rivers.

Key words: hydroacoustics, bedload transport, aquatic habitat, soundscape, gravel-bed, underwater acoustic, floodplain.

Introduction

After nearly a century of effort, it is clear that it is not possible to collect *in situ* physical samples of bedload transport in large gravel-bed rivers, especially during channel-forming flood events, much less make reliable predictions of bedload-transport rates (Gomez 2006). This fact underscores the heightened interest in developing non-invasive, surrogate means of measuring bedload transport (Barton et al. 2010). We believe that the application of combined passive and active hydroacoustic techniques holds great promise to address this practical need, and thereby begin to fill, this basic knowledge gap. Bedload transport in large gravel rivers is an important physical process that has been difficult to measure beyond what has currently been attained from studies in flumes, small streams and few isolated data sets from single locations where tether lines and other equipment have been used. Hydroacoustic technologies offer promise in addressing this age old problem, and thereby, increase our understanding of rivers from fluvial geomorphology

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to ecohydrology. Turbulent flow in gravel-bed rivers and the associated movement of sediment creates underwater sound that can be measured passively with hydrophones (Tonolla et al. 2010, Tonolla et al. 2011). Moreover, acoustic signals from particle collisions can be used to assess the intensity of bedload transport and distinguish size fraction transport based on frequency band intensity (Tonolla et al. 2011). Both of these aspects are important to modeling fluvial dynamics from bed and bank erosion, the formation of gravel bars, and mapping the spatial distribution and abundance of aquatic habitats. Such processes are pivotal to maintaining a "shifting" mosaic of habitat (Stanford et al. 2005) because the flow of water coupled with the movement and transport of gravel as bedload in rivers and streams are primary drivers of ecosystem structure and function in fluvial systems.

The movement of gravel in rivers and streams is an important regulator of aquatic ecosystem metabolism linked directly to watershed hydrology, and hence, climate change (Cronin et al. 2007). Sediment transport and associated bed scour during floods can become a catastrophic disturbance for benthic communities, drastically reducing their abundance. River bed sediments are colonized from two directions: (i) from "epigean" surface organisms (e.g. insects) which penetrate downward into the sediments and need to return to the surface to complete their life cycles, and (ii) from "hypogean" groundwater organisms (e.g. crustaceans) who colonize near-surface bed sediments by migrating upwards from deeper groundwater attracted to near-surface habitats because of the higher food availability (Brunke & Gonser 1997, Ward et al. 1998). Although it has been demonstrated that sediment dwelling invertebrates do seek such refugia during flood events, and that some migrate laterally over many kilometers to the river through the subterranean environment of the floodplain (Stanford & Ward 1988), almost nothing is known about the cues these organisms perceive to induce such behavior. We believe that the underwater sound produced by the river provides a river soundscape that both epigean and hypogean organisms can use as a cue to guide life cycle behavior patterns.

Indeed, underwater sound exhibits a lower attenuation rate compared to light and chemical substances, and it can be transmitted rapidly over long distances (Hawkins & Myrberg 1983, Rogers & Cox 1988). Furthermore, it is well known that inter- and intraspecific communication is not the only role of sound in aquatic ecosystems, but that underwater soundscapes produced by flow turbulence and sediment transport are most likely an important information source for many aquatic organisms (including fish and the adult stage of aquatic insects), as most of them are able to use acoustic cues in their environment for spatial orientation and positioning within and among suitable habitats (Slabbekoorn & Bouton 2008). Because the occurrence and duration of competent flow in streams and rivers is affected by flow regulation, any hydrologic change in rivers that reduces the spatial and temporal occurrence of bedload motion will also change ecosystem metabolism at the primary production level. Such changes may influence aquatic food web dynamics of secondary producers cascading upwards to fish thereby influencing change in the biotic community and aquatic ecosystem processes as a whole. Hence, underwater acoustic signals from the combined processes of flow turbulence and particle collisions during sediment transport can not only be used for rapid spatial mapping of active disturbance in the river (e.g. bed scour and bank erosion) but also provide an eloquent method for real-time remote monitoring of primary drivers of fluvial ecosystems. Indeed, the combination of active and passive hydroacoustic techniques may hold great promise for monitoring channel changes occurring at discharge sites, detecting bed scour near bridge pilings and pipeline crossings including validation of effectiveness of flow releases from dams either to re-naturalize rivers or lessen impacts from hydropeaking practices.

The main goal of our paper is to demonstrate the potential of combined passive and active hydroacoustic techniques, using commercially available instruments, for rapidly mapping bedload transport and the production of sound from base flow to flood conditions. We provide examples of rapid spatial mapping using both sensor data types from two rivers located in North-West USA, one a natural unregulated river during flood conditions exceeding bankfull and another a regulated river receiving a scheduled controlled flood flow release from a dam aimed at improving spawning success for White Sturgeon, an endangered fish. These methods and results are intended to appeal to a broad base of basic researchers, managers and technicians working in the fields of river engineering, fluvial geomorphology and river ecology.

Methods

Study reaches

River floodplains provide model ecosystems to test coupled hydrologic and ecologic theory (Tockner et al. 2010) and moreover they are the most endangered landscape on the planet (Tockner & Stanford 2002). Hence, we choose two floodplain sites, one on a natural unregulated river and the other located on a highly regulated one to highlight the possible application of rapid hydroacoustic mapping of complex river landscapes. Our natural river-reach is the large, well-studied Nyack Floodplain on the Middle Fork of the Flathead River in northwestern Montana, USA, which provides a suite of large-scale homogeneous bed sediment patches ranging from cobble, to cobble and gravel, gravel, gravel and sand, and sand. Moreover, we know from historical analysis of channel change that this section of river experiences annual mobile bed conditions during floods (Whited et al. 2007). In fact, sediment movement can often be heard audibly at the surface while floating.

Our regulated river reach is the Kootenai River just above the Bonners Ferry Bridge located in Bonners Ferry Idaho and downstream from Libby Dam (located in North-West Montana, USA). This section of river has been identified as important pre-dam White Sturgeon (*Acipenser transmontanus)* spawning habitat and that sturgeon recruitment has been impacted since flow regulation began (Paragamian et al. 2002, Fosness & Williams 2009). In addition, Kootenay Lake, British Columbia, Canada, creates backwater conditions in the Kootenai River that reach several kilometers upstream of the Bonners Ferry bridge (Barton et al. 2004, Barton 2009). The U.S. Fish and Wildlife Service has requested that Kootenai River stream flows be increased during White Sturgeon spawning in May and June in an attempt to help re-establish recruitment. They have requested flow releases from Libby Dam to accomplish this recruitment goal (Fosness & Williams 2009). The ability to identify the location of backwater effects, as well as validate the occurrence and location of bedload transport are important for both improving spawning conditions but also to validation of those goals for the dam operators being asked to release water. Hence, rapid spatial mapping of bedload in the Kootenai River is important for dam operations in both the US and Canada along this important international trans-boundary river.

Active and passive hydroacoustic data recording

Velocity profiles and flow depths were simultaneously recorded using two different manufactures Acoustic Doppler Current-Profilers (ADP); one with nine multi-frequency (3.0 and 1.0 MHz) transducers (M9, SonTek/YSI) and one with four 1.2 MHz transducers (RDI, Workhorse). The M9 was used on both the Kootenai River and the Nyack while the RDI was only used on the Nyack. This active hydroacoustic sampling was used to continuously measure flow-velocity and depth. In addition calculated ABV as explained below.

Passive hydroacoustic signals were recorded by a pair of co-located hydrophones, amplified, and stored on a digital recorder (for details see Tonolla et al. 2010). The hydrophones were secured parallel to each other and facing upstream on a small metal rod (~40 cm length) mounted on the frame of the raft or jet boat next to the ADP at ~30 cm depth.

For the Nyack we used data collected in 2008 with the RDI deployed from an inflatable raft and over three discharge levels ranging from base flow (~30 m^3 s^{-1}) to bankfull (~350 m^3 s^{-1}) and a 10-year return interval flood (~855 m^3 s^{-1}) to illustrate the extent of river bed mobility along the 12 km longitudinal thalweg-transect that existed that year. By floating the same path for each discharge and using a Real Time Kinematik (RTK) survey grade Global Positioning Systems (GPS) with the rover attached to the raft and the base station within our float we were able to accurately determine both position and elevation of the bed tied to common datum and select sections of river where the float paths were perfectly overlain. Additionally, on May 22 and 23 of 2012 we repeated the same 12 km river thalweg/centerline floats four times over two days, where discharge was relatively stable ranging from 396 to 420 m^3 s^{-1} (bankfull conditions), continuously collecting both active and passive hydroacoustic data. We used two rafts where the lead raft sampled the thalweg with both a M9 and hydrophones. A second raft followed the first with the RDI sampling river-right for the first two runs and then river-left of the lead raft for two runs. Our goal was to examine the repeatability of the Apparent Bedload Velocity (ABV) and sound measurements.

Over May 17 and 18 of 2012 we collected both passive and active hydroacoustic data on the Kootenai River during a scheduled flow release of approximately 1132 m^3 s^{-1}. During the same time a team from the US Geological Survey (USGS) was also on the river collecting moving bedload material along a cross-river transect by lowering a traditional sediment trap while maintaining position with the boat engine. They were partially successful in collecting large volumes of gravel, hence we know that sediment transport was active and that our mapping revealed where in the river that transport was occurring, at what levels of intensity and what size fractions in a broad sense were composing the moving bed.

Our first collection scheme on the Kootenai River was comprised of a series of seven parallel float lines between the river banks collected while floating for approximately 0.5 km on a jet-boat (with the engine off) and using the M9 with a GPS base station in RTK mode and the hydrophones deployed over the side of the boat. Once a longitudinal transect was completed we would jet back up the river and start a new longitudinal transect slightly offset from the previous transect with the float path dictated by the flow. In this case, our goal was to laterally cover as much of the water surface as possible to assess spatial variability in flow, bedload transport, and sound in the same reach as the USGS. We also collected a single longitudinal transect that extended 12 km above the Bonners Ferry Bridge maintaining a river center ship track with the motor idling.

Data analysis and noise reduction of passive hydroacoustic signals

Passive hydroacoustic signals were evaluated with a short-term third-octave band analysis over 31 frequency bands (0.020–20 kHz), and a temporal resolution of 1.1 s (three Fast Fourier Transformation frames), and then combined in 10 octave bands (0.0315–16 kHz). All data were expressed on a logarithmic scale as dB values relative to one micro Pascal (dB re 1 μPa) as a reference. The calibration was performed with a Brüel and Kjaer calibrator which generates a highly reproducible nominal sound level of 166 dB at 0.25 kHz. For a more comprehensive description of sound analyses please refer to Tonolla et al. (2009) and Tonolla et al. (2010).

Cross-spectrum analyses were used to minimize uncorrelated background noise between the two hydrophones providing an elevated signal-to-noise ratio (for details see Tonolla et al. 2009). The use of octave bands instead of third-octave bands resulted in the reduction of the spectral resolution; thus significantly lowering the uncertainty (for details *see* Tonolla et al. 2009, Tonolla et al. 2010). All the sound data have been subjected to a 15 second low pass filter to reduce episodic noise produced while floating with the raft and the jet boat, and to increase the reliability of the recorded data. However, noise produced by motors in the Kootenai River, as well as noise produced by passing trains, were all recorded and left in the time-series as an indication of their occurrence and over-all effect on the recorded passive hydroacoustic signals produced by the river. We discuss and compare these effects with recordings made without such influences.

ABV calculation and error assessment

An ADP determines water column velocity by assessing the Doppler shift of the return backscatter signal which bounces off of suspended particles advected with the flow. The shift in frequency has been shown to be linearly related to the advection velocity (Brumley et al. 1991, Simpson 2001). In this paper we focus on the mean water column flow velocities that are output from the two manufactures software (both report depth accuracies within 1 % of the measured range and 0.25 % of the measured flow velocity). To determine ABV from a moving boat requires corrections for boat velocity (Rennie et al. 2002, Jamieson et al. 2011). This can be done by either determining boat velocity using Differential GPS (DGPS) for the RDI or M9 (data presented in Figs 1–5) or by deploying a GPS base station and using the M9 in the RTK mode (Figs 6 and 7). The most accurate method for determining boat velocity (BV) is to use the bottom tracking mode (BT) which uses the Doppler shift concept for the echo sounding off the bed (Gaeuman & Jacobson 2006). However, if the bed is moving then both BV and the water column velocity estimates will be biased towards lower values. Hence, under mobile bed conditions, ABV can be approximated if the actual boat velocity is known by DGPS or RTK positioning and then using the following:

$$ABV = BV_{GPS} - BV_{BT}.$$

The ABV signal is not an unbiased estimate for a variety of reasons but the signal remains large and of great value to many disciplines working in rivers, especially if spatial maps can be made. Much research remains to be completed in terms of accurate assessment of ABV error with the hope of pinpointing the relative contribution of many possible sources. We estimated ABV error from the noise floor of ABV time-series by examining the spectrum at high frequencies where the variance is approximately constant (e.g. Bendat & Piersol 2000). For this paper we estimated the error by first plotting the spectrum and looking for flatness at high wavenumbers and from that estimate determine the spectral energy (S_n) value. This can be done by visually (as we have done) inspecting the plotted spectra for flatness and reading the S_n off the Y-axis, digitally it is done by summing the spectral values and then multiplying the wave number resolution (wavenumber spacing). This approach provides a quick assessment of ABV error in terms of it being small or large relative to the ABV estimates for each ADP profile. Step two is to then to calculate the standard deviation of the noise

$$\sigma_{noiseb} = \sqrt{s_n / 2\Delta}$$

where Δ is the sampling frequency and plot those values on the ABV time-series (Figs 2, 3 & 5). This approach allows a simple and easy assessment of total error from all sources. Because we are collecting longitudinal transects down the river over relatively long time periods (hours) we end up with robust time-series assessment of error. This approach does not tell us where the major sources of error might lie but knowing the source of error is not so important when changes in the bed and channel are occurring at high rates. In such conditions ABV measures are big signals relative to the noise of the sampling technique. This may not be true under near flow competence levels where sediment entrainment threshold conditions are just beginning to be reached and much of the bed is not mobile.

Integration and mapping approach

We have developed a Matlab-based data-integration tool that allows us to synchronize latitude and longitude positions from DGPS that provides up to 10 cm in horizontal accuracy or by using a RTK GPS providing centimeter-level accuracy with the suite of hydroacoustic data collected while floating. The first step in the integration procedure is to linearly interpolate between each ADP data value (e.g. three-dimensional orthogonal velocity components) with the most shoreward ADP profiles taken as the water edge. Once the water's edge is determined the program logarithmically interpolates to the edge and bottom using the ADP data and linearly interpolates between bins. A grid can then be overlaid, and a kriging approach (e.g. Matheron 1963, Matheron 1973) used to further smooth between interpolated data points producing a 3-D interpolated hydraulic and hydroacoustic data cube at the resolution the data was collected. In summary, in this data integration and mapping approach we used three methods; 1) linear integration between ADP profiles 2) logarithmic interpolation between profiles, the shore and the river bottom and 3) a kriging approach to further smooth between interpolated points. This procedure allows production of spatially explicit hydroacoustic maps presented in Fig. 7.

Results

In 2008, by floating the same thalweg-path of the Nyack floodplain over three discharge levels and using a RTK-survey grade GPS, we were able to accurately assess changes in bed elevation on the order of a meter (Fig. 1). In this way we know that our surrogate measures of ABV and sound recordings resulted from bedload transport otherwise bed elevation changes on order of a meter could not have occurred. During each float ABV was determined with relatively high velocities yet the spatial distribution were sporadic (occurring in locations of active headcutting where transverse bars crossed the main channel) at low flows and more consistently active bed at higher flows (Fig. 2). As expected, a decreasing ABV error with increasing discharge was found (dashed lines Fig. 2).

The four floats collected in 2012 in the river thalweg/centerline of the Nyack floodplain during relatively stable bankfull flow conditions were remarkably similar in the recorded soundscapes (Fig. 3 top 4 panels) as well as in estimated ABV (Fig. 3 bottom 2 panels); thus confirming the repeatability of hydroacoustic measurements. The areas in orange to red, high sound pressure levels in the 140 to 150 dB range repeatedly occurred in the 2 to 8 kHz frequency range and also correlated well with the zones of highest ABV values in the thalweg (Fig. 3). These are also areas where the sound of cobbles and gravel colliding could be distinctly heard with the human ear while collecting the data.

The pattern of sound intensity, across the frequency spectrum, varies spatially in a very coherent manner along each of the 4 longitudinal transects (Fig. 3 top 4 panels). In particular bands of less intense sound pressure levels are seen as green-to-yellow stripes in the high frequency spectrum in the first half of each float. These areas coincide with changes in the river flow pattern with the first band occurring at the location of a large boulder barb built into the river by the railroad with the intent to deflect flow away from the bank (Fig. 3, ~1.5 km downstream distance). The other narrow sets of green-to-yellow bands (at ~4 km) reflect deep glides of water down stream of scour pools that formed in the river and the major light green band (at ~6 km) occurs at a bedrock confluence with another smaller stream (Fig. 3 top 4 panels). This area of the river is deep (~6 m) and was also characterized with a smooth surface, yet consisting of a fast moving glide. At low flows these areas are slow moving relatively deep pools in the river.

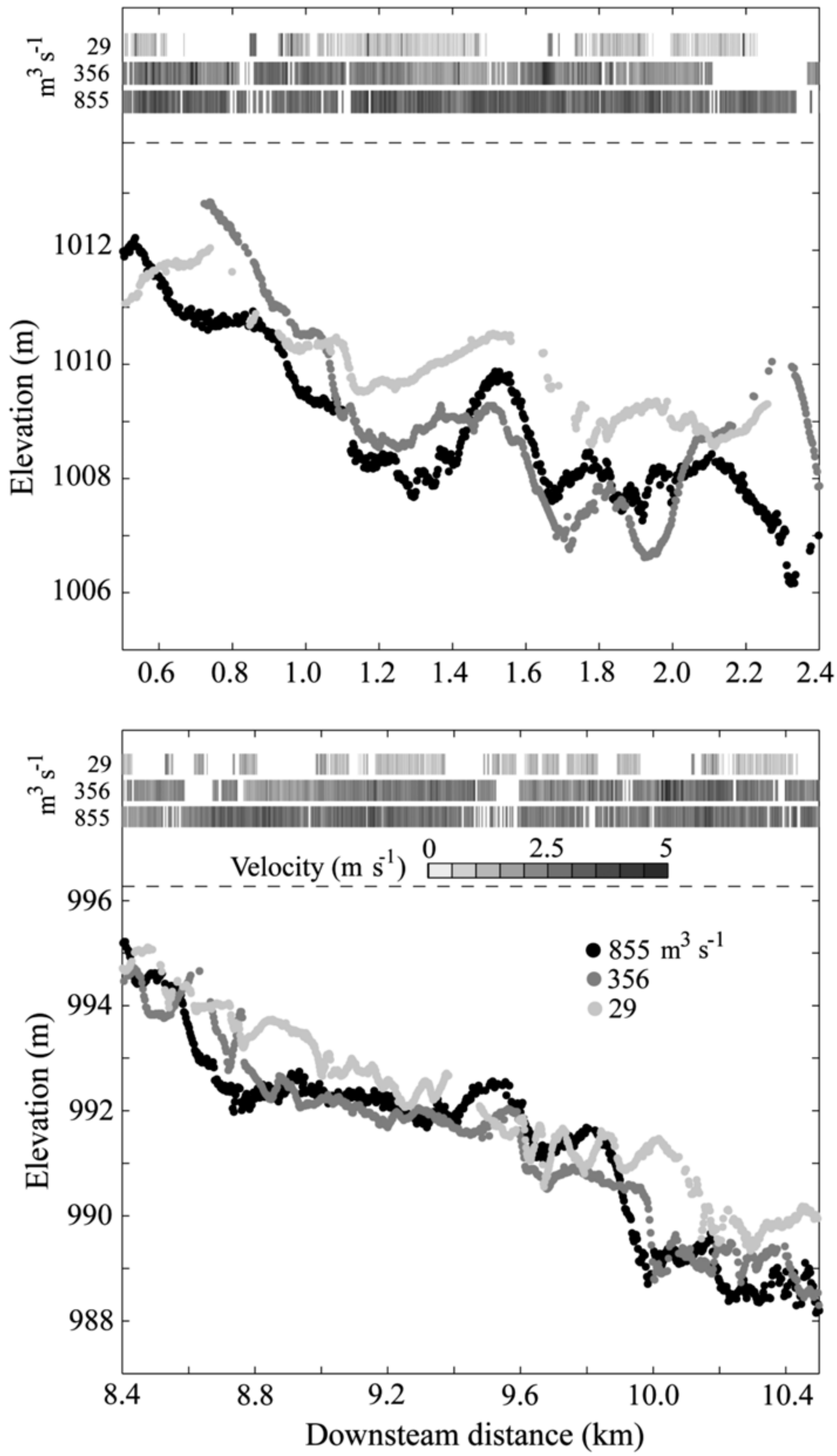

Fig. 1. Time-series plots of bed elevation change due to net erosion and deposition occurring on the Nyack in 2008. Top panels in each plot show the bottom boundary water velocity for each discharge measured ranging from base flow (29 $m^3\ s^{-1}$) to 10 year flood event (855 $m^3\ s^{-1}$). These represent sections of the river where all 3 ADP floats covered exactly the same path allowing for comparison.

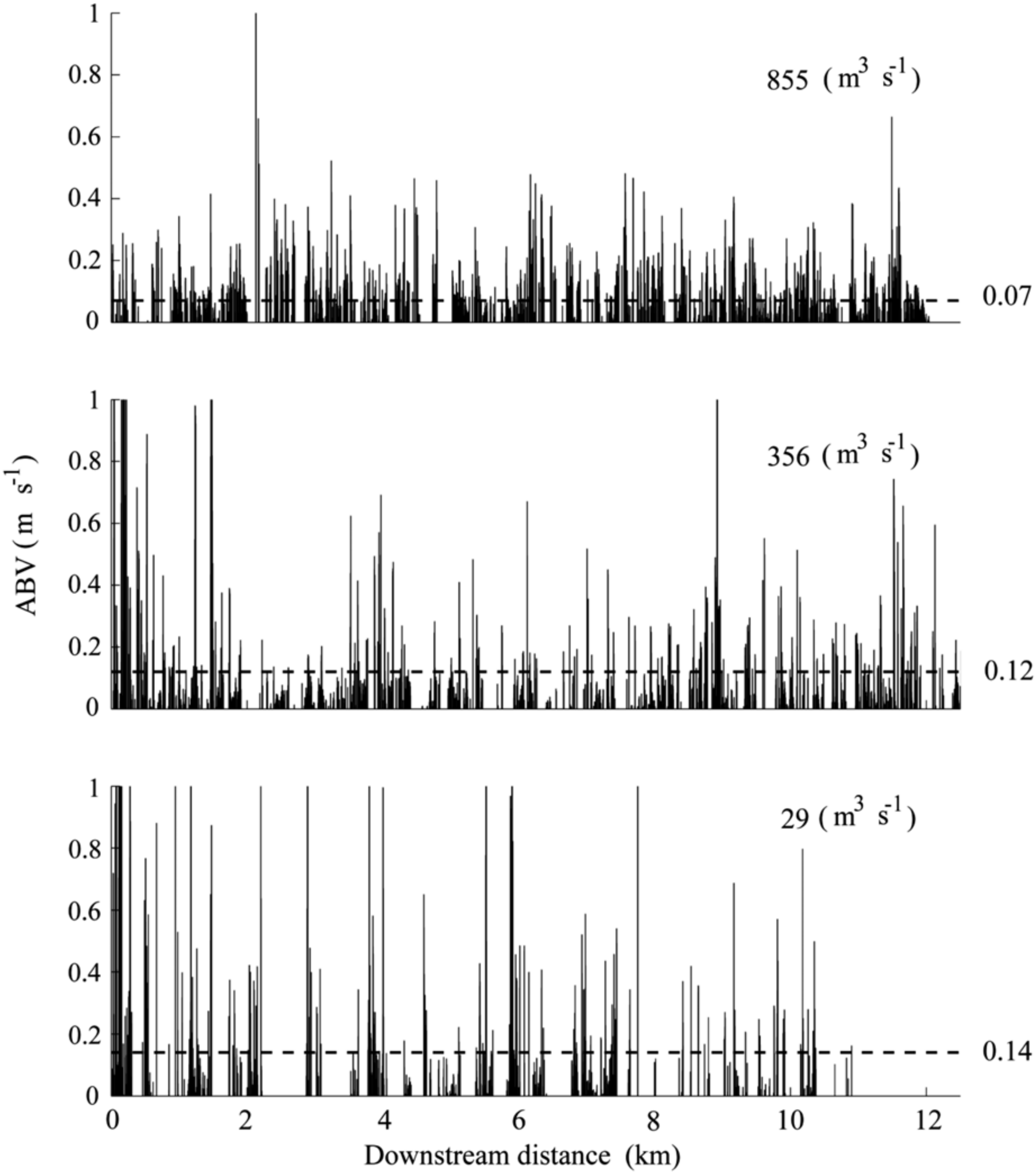

Fig. 2. A time-series plot of ABV data collected in 2008 on the Nyack using a 4 beam RDI 1.2 MHz ADP and over 3 discharges from base flow (bottom) to near bank full (middle) and flood conditions (top). The dashed lines show potential total ABV error. The spectral approach takes into account all potential sources of error which is our main focus rather than portioning out the error between various sources.

The ABV data collected with the second raft river differed in magnitude by a factor of 2 in respect to the data collected in the thalweg (Fig. 3 bottom 2 panels). This can be partially explained by difference in flow path taken by each raft but for the most part the spatial pattern in the longitudinal direction is very similar. The M9 with its vertical beam plus 8 other side beams and dual frequency may very well produce a more accurate estimate of bottom track determined water velocity, whereas the RDI without a vertical beam and only 4 beams total and one frequency may have a bias towards higher ABV values (Fig. 3 bottom ABV panel). Taking the most conservative estimate of error from the M9 and only plotting those data above

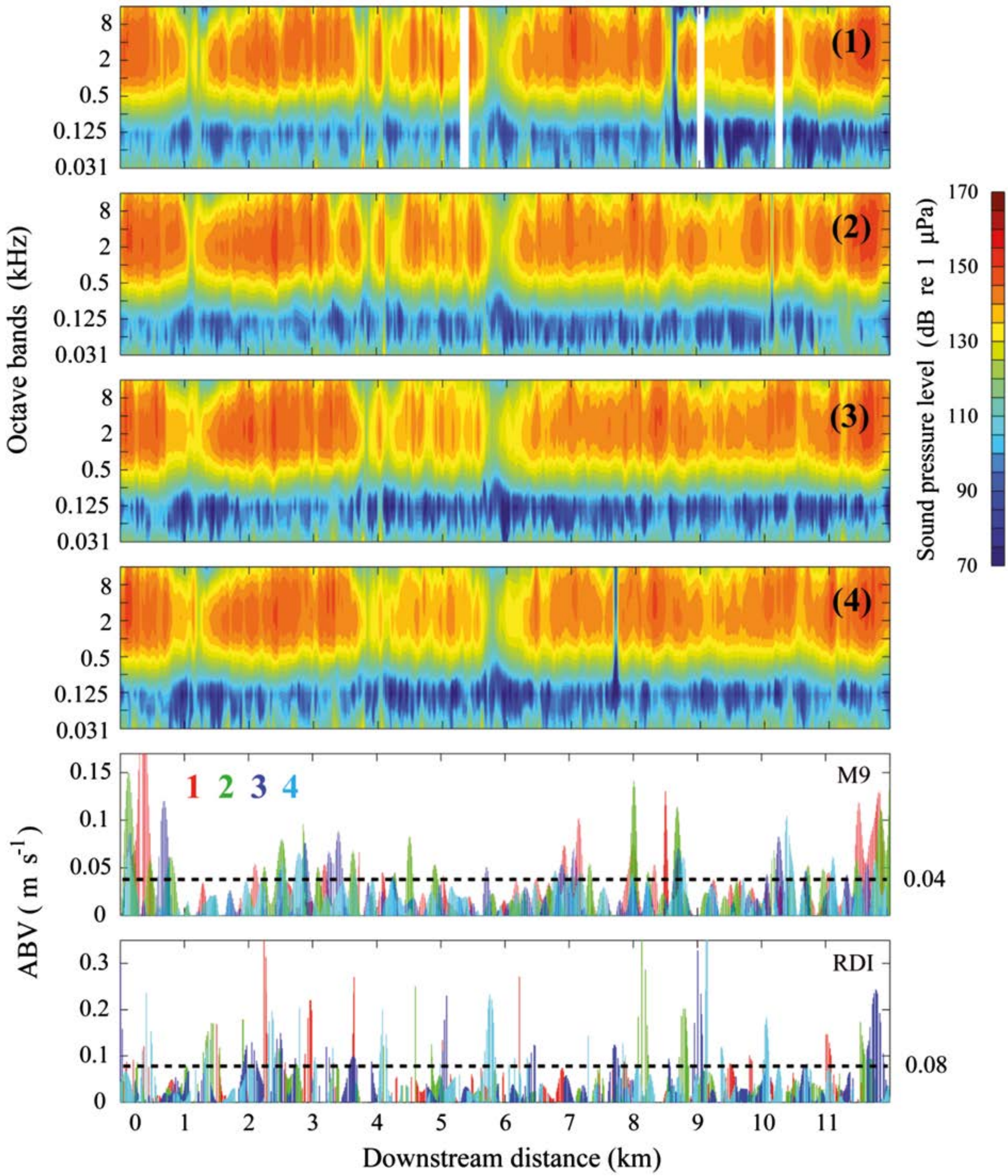

Fig. 3. Time-series plots of sound (top 4 panels) and ABV (bottom 2) collected during peak 2012 flooding on the Middle Fork of the Flathead River, from 12 km floats through the Nyack Floodplain. The different colors in the ABV plots correspond with the 4 different floats (1–4 top to bottom on sound panels). M9 ABV data was collected in the thalweg, RDI ABV data was collected river-right for the first two runs and then river-left. Dashed lines with corresponding ABV error are plotted. White bars in the top panel and blue spikes in the first, second and fourth panel are from physically lifting the instrument package from the water in an attempt to avoid submerged flow obstructions.

our spectra-determined ABV threshold, yields a map of bedload motion for the entire 12 km longitudinal axis of the river during flood conditions that exceeded bankfull (Fig. 4). Plotting the data in this fashion shows that much of the main channel of the river bed is experiencing bedload transport (Fig. 4).

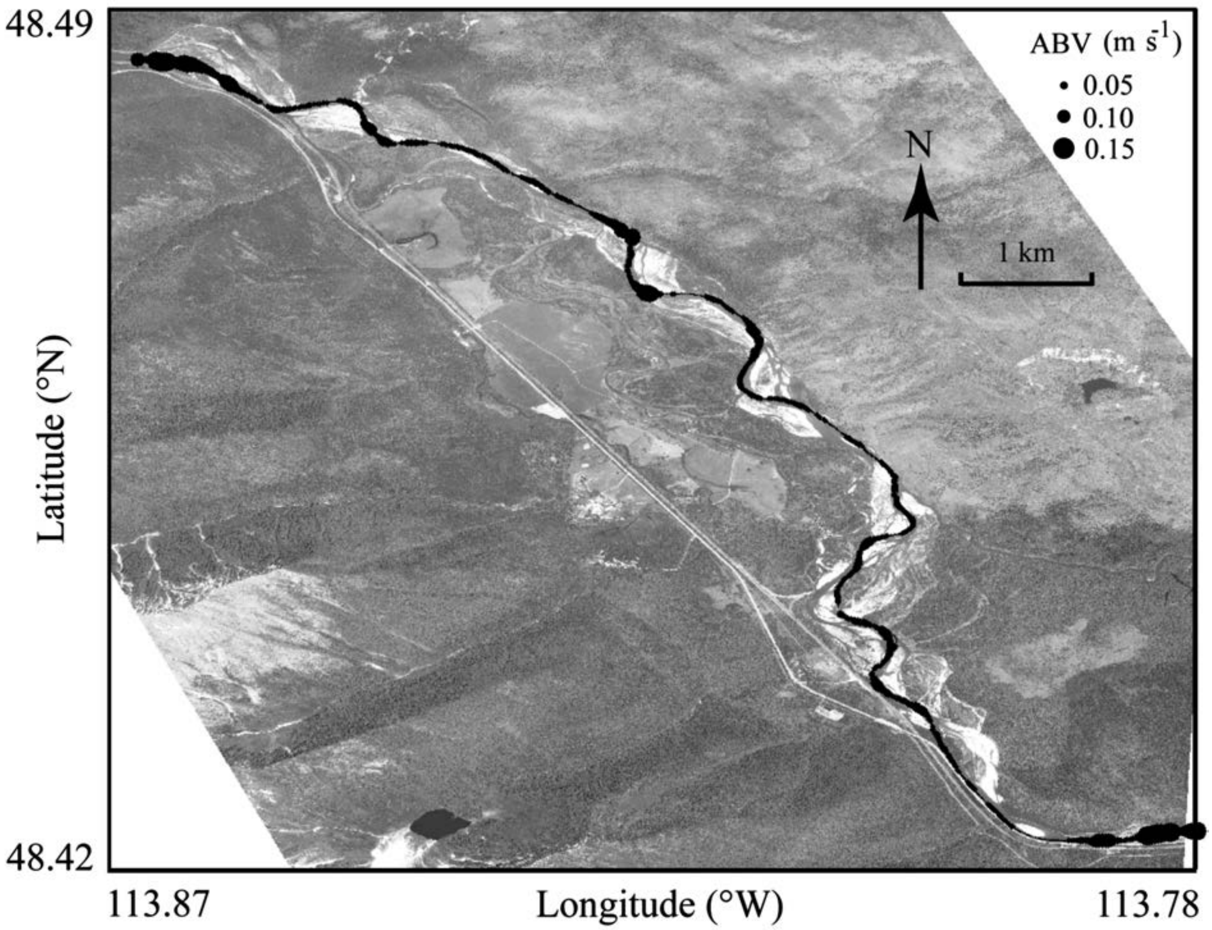

Fig. 4. A map showing three categories of ABV data plotted on an August 2012 satellite image of the Nyack Floodplain. This is the M9 data binned into categories that are shown as a continuum time-series in Fig. 3. Flow direction is from lower right to upper left.

The longitudinal transect collected in 2012 in the river thalweg/centerline of the Kootenai River during the scheduled dam flow-release showed good correlation between zones of high flow velocity and high sound pressure levels over the frequencies between 2 and 8 kHz (Fig. 5). We believe this result is associated with gravel/pebble transport and that the very highest frequencies (8 to 16 kHz) are associated with a sand dominated size fraction. Kootenay Lake downstream produces a backwater effect in this reach and this was indicated by the sudden drop in flow velocity and sound in the 2 to 8 kHz range (Fig. 5, ~9 km downstream distance) and is interpreted as a subsequent decrease in gravel and pebble transport. The ABV plot shows that sediment transport was occurring over the entire reach (Fig. 5 middle panel). The fact that sound pressure levels dropped suddenly (Fig. 5 bottom panel) in this backwater affected reach coupled with a measured moving bed (Fig 5 middle panel) indicates that the bedload layer most likely was dominated by sand and silt which does not produce as high levels of sound from inter-grain collisions as a mixture of sand and gravel. These findings underscore the value in collecting both active and passive data. Had only the ADP data been collected none of the interpretations about what grain sizes, comprised the bedload, could have been inferred.

ABV estimates were quite variable in spatial extent (Figs 6 bottom panel & 7). Physical sampling revealed an increase in sand transport across locations moving from river left to right (pers. Comm. USGS). In general, the passive hydrophone surveys corroborated these results. The hydrophones recorded the greatest response in the expected frequency range for gravel (2–8 kHz) and where the highest and most concentrated estimates of ABV occurred (Fig. 7 dots). The passive hydroacoustic response also recorded an increase in sound pressure level especially in the frequency range 8–16 kHz, from left to right across the river (Fig. 7 bottom to top) which could be related to increased sand transport.

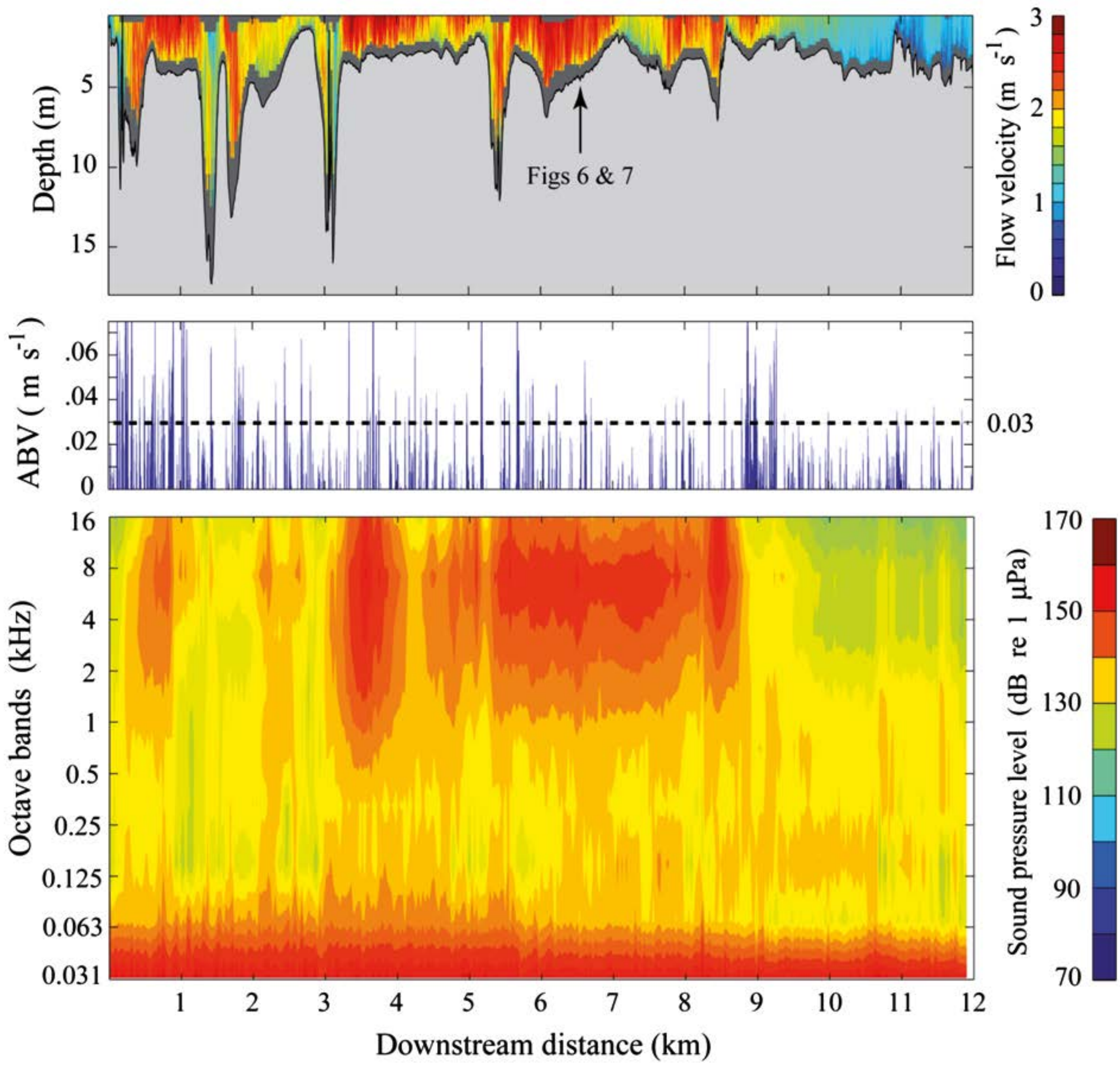

Fig. 5. A three panel plot of a 12 km longitudinal transect collected along the thalweg of the Kootenai River with the transect ending at the Bonners Ferry Bridge in Bonners Ferry Idaho. The top panel shows the vertical velocity profile through the water column, middle panel ABV with estimated error (dashed line) and bottom panel the frequency distribution of sound intensity.

Not only does the river soundscape and patterns in bedload transport vary in the downstream direction but there is also a high degree of lateral variation (Figs 6 & 7). Starting the engine on the jet-boat, to keep the boat from ramming into a fallen tree, was recorded by the hydrophones, mainly in the low frequency range (0.063 to 0.25 kHz, Fig. 7 top panel). The boat engine seems to raise the ambient sound level over all frequencies (especially the lower ones) and looks to reduce the differences between the frequencies. However, this noise seems to least impact sound generated in the sediment transport range (1 kHz and higher). A train passed during collection of center line data and for nearly the whole duration (Fig. 7 middle panel). It was slow moving and very loud which seem to clearly be recorded by the hydrophones but mainly in the lower frequencies below 1 kHz (Fig. 7 middle panel). The location of the USGS boat to our passing was recorded (Fig. 7 black lines) as we drifted by with the closest paths occurring at locations represented in panels 2 and 3 counting up from the bottom in Fig. 7. The sound from the passing boat was recorded by the hydrophones, but once again mainly impacting the lower frequencies below 1 kHz and not impacting the sediment transport frequencies ≥ 2 kHz (Fig. 7).

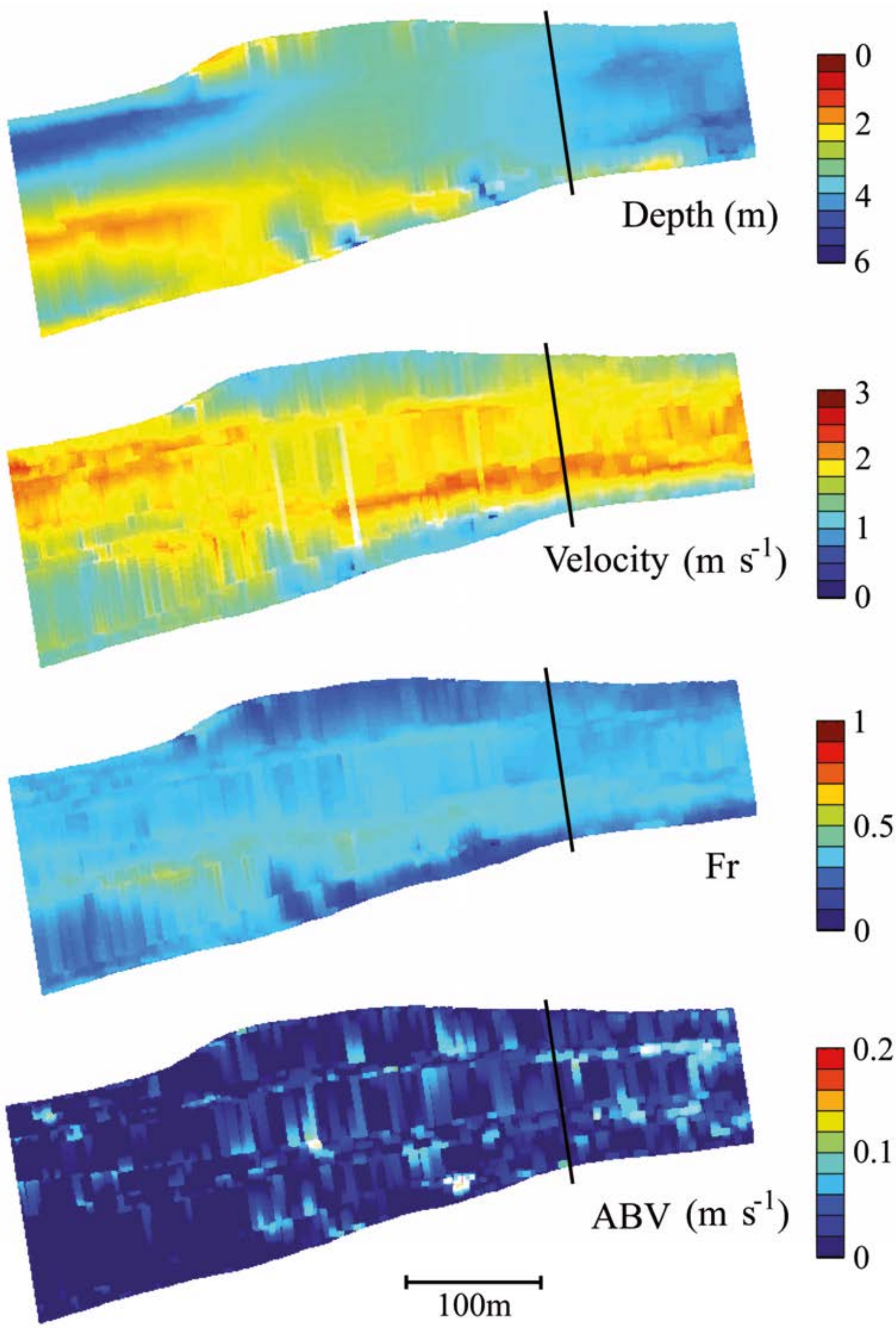

Fig. 6. Panel map showing spatial integrated plots of ADP data with depth (top panel) velocity (second panel from top) Froude Number (*Fr* third panel from top) and ABV (bottom panel). The black line represents the approximate location of the USGS lateral sampling transect. Flow direction is from right to left.

Discussion and Conclusions

Our main objective with this research was to demonstrate that both active and passive forms of hydroacoustic measurements could be useful in many different disciplines of riverine science and management where mapping the bedload transport is a common and a pivotal theme. The discussion that follows focuses on the need for new methods for bedload sampling, sampling challenges, questions of repeatability, and

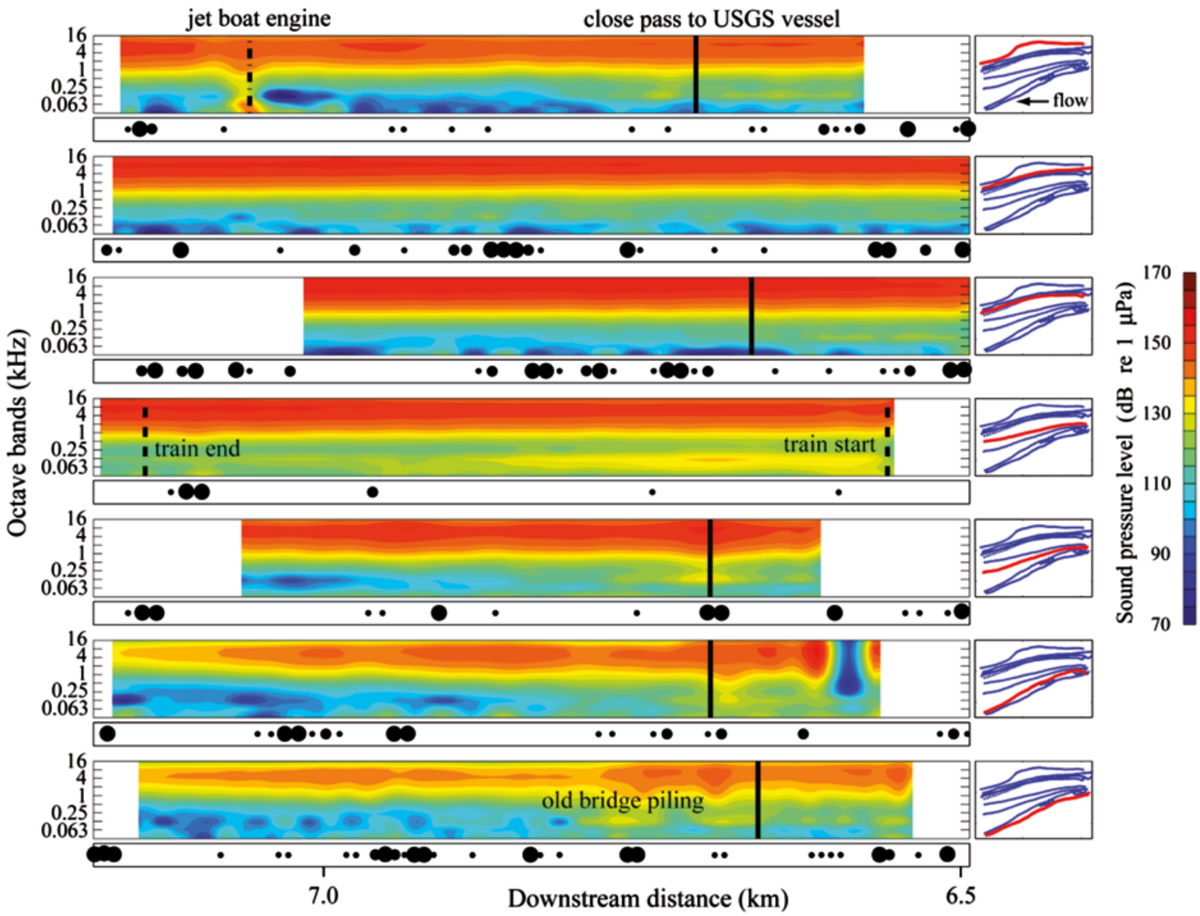

Fig. 7. Lateral variation in sound moving from river left to right of the Kootenai River with vertical bars indicating the occurrence of noise from engines, nearby boats and a passing train. Panels at right show position in the river relative to bank with red line corresponding to the sound plot to the left. Dot size relates relative ABV magnitude as scaled in Fig. 4.

highlights some ecohydrological applications. The discussion is meant to provide further insight to the possibility of rapid mapping of rivers using these commercially available hydroacoustic instruments rather than provide the answers per say to specific research questions. This is a new emerging technology, a frontier, and our goal at this point was to inform a broad audience of what we have found in our first attempts to gather such data and make sense of it. A key message that we discuss is the importance of taking the longitudinal Lagragnian view of rivers to better augment what we know from single point data and that collected at gauging stations.

Bedload sampling challenges: the need for hydroacoustic methods

In gravel-bed rivers, bedload transport is mainly comprised of particles that range in size from cobbles to pebbles and where actual movement occurs by sliding, rolling, or saltation (e.g. skipping) of bed particles that both exchange momentum with the bed lowering threshold entrainment levels, (Lorang & Hauer 2003) but also creates sound that can be used to assess the intensity of bedload transport as demonstrated herein (Figs 3, 5 & 7). Often sand and finer grains are involved and that portion of the material flux is referred to as the wash load which creates its own sound at higher frequencies. In addition the sand may be temporarily suspended and thereby interfere (e.g. by scattering) with the transmission of sound created by the underlying gravel collisions. Hence, the transition from suspended sediment carried with the flow of water downward through the water column towards the stationary part of the bed is a complex processes that is difficult to sample with traditional physical techniques (Gaeuman & Pittman 2007, Turowski et al. 2010) but also may impact the sound pressure levels recorded. This complexity associated with the surrogate approach will require more directed research.

Bedload transport in gravel-bed rivers occurs mainly during bankfull discharge or higher flood levels when working on or in the river and physically gathering direct samples is at best difficult. This underscores the reason bedload data from flooding gravel-bed rivers is essentially non-existent. Traditional sediment samplers, used over the past eight decades, include some kind of physical trapping device that is either lowered to the bed (box and basket samplers), pressure difference sampler (e.g. Helley-Smith, Elwha) or some type of trap permanently installed in the bed (Barton et al. 2010). However, these approaches to physically trapping sediment can only be practically applied in small streams and flumes and only at site specific locations. In large rivers where depths are several meters and flow velocities necessary to mobilize the bed reach velocities > 2 m s^{-1} (e.g. Figs 1, 5 & 6) the ability to control position of the sampler along the bed is extremely difficult. Hence, for large rivers deploying and operating a physical sampler on the bed is both dangerous and difficult during flood events when channel-forming bedload transport is occurring. In addition, the presence of a sampler disturbs both the local flow field and bed-load transport rate (Barton et al. 2010) which adds another unknown source of uncertainty to the actual undisturbed rate of bedload transport that is known to have wide spatial and temporal variability (Rennie & Miller 2004, Clayton & Pitlick 2007). These facts require a large number of samples distributed in both time and space for adequate representation of bed-load transport rate (Rennie & Church 2010) which is impossible to achieve with traditional physical samplers. Therefore, it is not hard to understand that such measurements are rarely undertaken even though two- and three-dimensional morphological modeling requires spatially distributed data for testing and calibration (Rennie & Church 2010).

Ironically, measurement of bedload is commonly required for assessment of many hydraulic engineering actions ranging from river restoration activities, flow regulation (e.g. hydropeaking), channel works (bank armoring, bridge, piers, and pipeline crossings), and for a fundamental ecological understanding. To meet this requirement the most common approach is low flow surveys of the river bed and channel before and after flood events. Alternatively, hydroacoustic instruments coupled with downstream langrangian sampling (i.e. going with the flow) may provide accurate surrogate measurement of bedload transport as it occurs (*sensu* real-time monitoring; Figs 1–7).

Current technologies and mapping abilities of combined active and passive hydroacoustic instruments provide signals measured from bedload transport that are large with relatively small levels of noise especially when scaled against the broader impacts for fields of ecology and river management. The actual values of ABV might be very important to a researcher trying to model bedload flux through the floodplain, however, a river ecologist interested in mapping disturbance might ignore the absolute ABV values altogether and prefer the data be plotted as relative disturbance indices where ABV velocities would be categorized into high, medium and low levels of bed disturbance (e.g. Fig. 4). Indeed, the river ecologist could then map disturbance patterns through km-long reaches over the rising and falling limb of hydrographs. These relative disturbance maps could be used to help explain the spatial pattern of stream respiration or patterns of aquatic insect distribution and behavior, where the actual velocity of the bed sediment would not provide a higher level of information to the basic questions being asked. Likewise, the manager of a dam could use the same disturbance maps to assess flow releases or patterns of related hydropeaking impact.

In conclusion, using off the shelf ADP's it is now possible to measure ABV on the order of m s^{-1} and map at a resolution of 1 m^2 over many km of river hence uncertainty measurements on the order 0.1 m s^{-1} really are not relevant to the questions many researchers and river managers are addressing. However, as Rennie & Church (2010) so rightfully state: "*Uncertainty assessment is essential because if uncertainty exceeds the magnitude of the mapped quantity, then it cannot be asserted with confidence that the mapped spatial distribution is meaningful*". Therefore, we must continue to verify the ratio of signal to noise we are addressing.

Repeatability of Lagrangian sound recording

A second major question that we wanted to address with our 2012 data collection on the Nyack was the repeatability of the combined approach when flood discharge conditions were relatively stable. When floating during flood conditions over 12 km it is difficult to follow the same float path exactly, or maintain the same boat orientation which controls the relative orientation of both the hydrophones (a pair) and that of the ADP. However, the spatial coherence and relative magnitude of sound over all frequencies was remarkable (Fig. 3). The cross-spectrum analyses minimized uncorrelated background noise between the two hydrophones and provided a better signal-to-noise ratio (Tonolla et al. 2009). In addition, because we were floating with the current, turbulence related sound produced at the hydrophone heads was reduced. Furthermore, we detected changes in bed elevation, on the order of a meter, due to either net erosion or deposition processes between floats (Fig. 1). These large changes in bed elevation lend confidence that our ABV estimates are real and most likely under estimates of actual transport rates. We also know from historical photographs that the river actively migrates (Whited et al. 2007).

Other researchers have placed single hydrophones behind boulders and outcrops to reduce the noise effect (Barton et al. 2010, Belleudy et al. 2010). However, work in a laboratory flume (Tonolla et al. 2009) demonstrated that sheltering effects from flow obstructions are significant, and that individual soundscapes within river and river-habitats can be clearly distinguished from one another (Tonolla et al. 2010, Tonolla et al. 2011). Therefore, where in the river one listens determines the nature of the sound pressure levels and the variance of the acoustic signal recorded. We observed this "location effect" very clearly by recording repeatable coherence over multiple floats, general ABV coherence with areas of high sound intensity above approximately 1 kHz, and general high ABV velocity indicating that most of the river had active bedload transport, although there were both temporal and spatial differences (Fig. 3).

The bottom panel in Fig. 3 is ABV measured with the RDI instrument deployed from a second raft following the lead raft that had both the sound equipment and the newest multiple frequency M9 ADP. The lead raft attempted to stay in the channel thalweg and/or river center while the following raft floated river-right for two runs and then river-left of the lead raft for two runs. ABV values differed in some areas indicating lateral variance as expected but the same general longitudinal trends were apparent (Fig. 3). This approach of using multiple rafts floating together allows very cohesive mapping of both the lateral and longitudinal variance in river bed disturbance.

Tonolla et al. (2011) found levels of overall and frequency-dependent sound intensity to vary between different rivers and as a function of sites within any given river reach, and assumed the differences to be related to the organization of turbulence and to sound due to variations in bedload size fraction. Similarly as in Tonolla et al. (2010) and Tonolla et al. (2011) in this study we also associate the underwater sound generated by bedload transport with an increased sound pressure levels in the high frequencies (2–16 kHz). However, in all these studies, it was not determined if sound production was a function of the available bed material, nor if sound spectrum varies with bed composition, changes at a single location, or from river to river. Effectively addressing these two questions depends on knowing the size distribution of substrate material available for transport during floods and two assumptions: (i) that the size distribution of particles comprising the bedload comes from the immediate bed area when hydroacoustic measures are taken; and (ii) that the bedload size distribution is skewed towards smaller grains until fully mobile bed conditions are reached when size distribution of the bedload and surface layer of the substrate should be similar. These are both important questions to keep in mind when interpreting single data collections, however ABV estimates combined with sound recordings (Figs 3, 5 & 7) provide extremely valuable first order measures of flow hydraulics and bedload transport over broad (km) scale reaches.

Lateral variance in the soundscape (Fig. 7) is ultimately a function of variance in flow turbulence induced in part by the interaction with the bed and bank, obstructions to the flow like the old bridge piling (Fig. 7 bottom panel) and spatial variance in sediment transport. Mapping water depth, h, to visualize the bathymetry, the spatial variation in mean flow, V, and energetic indices like the Froude (Fr) number

$$Fr = V \big/ \sqrt{gh}$$

where g = gravity all coupled to the spatial pattern of bedload transport (Fig. 6) are physical templates that should aid ecological studies as well as decision making related to river management. When this information collected over varying substrate size compositions (cobbles, gravel, sand) and over varying discharge levels is then further coupled with passive measures of the hydroacoustic soundscape (Fig. 7), the most complete physical template available can be made.

In conclusion, these data collections and graphs represent 5 days of field work, and hence underscore the ability to rapidly assess and map river attributes by combining both active and passive hydroacoustic techniques and moreover underscore the ability to real-time map processes that are active during the passing of a flood wave. Coupling both active and passive hydroacoustic approaches will greatly increase our understanding of fluvial geomorphology and ecology.

Lagrangian ecological view of rivers: applications for passive and active hydoacoustics

Most analysis of flow in rivers as related to both ecological and physical questions are based on time series compiled for a single site per river. However, Larned et al. (2010) propose that a hydrological gradient concept based on longitudinal profiling as demonstrated in this paper (rather than relying totally on computer model generated ones) could serve to join two approaches to river ecology, a phenomenological approach that focuses on spatial patterns in communities, habitats and other ecological variables (e.g. Maiolini & Lencioni 2001), and a functional approach that focuses on causal relationships between ecological variables and physical drivers (e.g. Snelder & Lamouroux 2009). We agree with Larned et al. (2010) that longitudinal flow variation including sediment flux and soundscapes within river segments has been neglected in fluvial hydrology and ecology, and would indeed be happy to see other researchers looking at rivers from a downstream perspective.

The ability to assess bedload transport for gravel-bed rivers, on the floodplain scale, is a major missing piece of knowledge both for basic fluvial geomorphic-ecological understanding but also applied science as related to management decisions regarding flow release from dams in regulated rivers in the US and worldwide (Robinson 2012). In the management arena interest is focused on potential re-naturalization of rivers through prescribed flow releases that mimic floods and rework bed sediments (Lorang et al. 2005, Lorang et al. 2013). While millions of dollars are spent annually on experimental flood releases from dams aimed at mobilizing bed sediments to improve the physical quality of downstream aquatic habitats, monitoring success of flow releases remains unresolved. The example from the Kootenai River in Idaho (Fig. 5) shows great promise for evaluating the effectiveness of flow releases.

Therefore we conclude that coupling passive and active approaches to hydroacoustic mapping of river with greater spatial coverage will provide two major benefits for those interested in reducing impacts from hydropower generation: (i) monitoring flow releases to achieve desired goals; and (ii) obtaining data that should reduce the controversy among stakeholders. Controversy is high because water is an extremely valuable commodity. We know floods are beneficial but without a means of providing real-time spatial assessment of effectiveness, dam operators are reluctant to release water to mobilize bed sediments without verification and rightly so.

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