USING HYDROPHONES AS A SURROGATE MONITORING TECHNIQUE TO DETECT TEMPORAL AND SPATIAL VARIABILITY IN BEDLOAD TRANSPORT

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Abstract Collecting physical bedload measurements is an expensive and time-consuming endeavor that rarely captures the spatial and temporal variability of sediment transport. Technological advances can improve monitoring of sediment transport by filling in temporal gaps between physical sampling periods. We have developed a low-cost hydrophone recording system designed to record the sediment-generated noise (SGN) resulting from collisions of coarse particles (generally larger than 4 mm) in gravel-bedded rivers. The sound level of the signal recorded by the hydrophone is assumed to be proportional to the magnitude of bedload transport as long as the acoustic frequency of the SGN is known, the grain-size distribution of the bedload is assumed constant, and the frequency band of the ambient noise is known and can be excluded from the analysis. Each system has two hydrophone heads and samples at half-hour intervals. Ten systems were deployed on the San Joaquin River, California, and its tributaries for ten months during water year 2014, and two systems were deployed during a flood event on the Gunnison River, Colorado in 2014. A mobile hydrophone system was also tested at both locations to collect longitudinal profiles of SGN. Physical samples of bedload were not collected in this study. In lieu of physical measurements, several audio recordings from each site were aurally reviewed to confirm the presence or absence of SGN, and hydraulic data were compared to historical measurements of bedload transport or transport capacity estimates to verify if hydraulic conditions during the study would likely produce bedload transport. At one site on the San Joaquin River, the threshold of movement was estimated to have occurred around 30 m^3/s based on SGN data. During the Gunnison River flood event, continuous data showed clockwise hysteresis, indicating that bedload transport was generally less at any given streamflow discharge during the recession limb of the hydrograph. Spatial variability in transport was also detected in the longitudinal profiles audibly and using signal processing algorithms. These experiments demonstrate the ability of hydrophone technology to capture the temporal and spatial variability of sediment transport, which may be missed when samples are collected using conventional methods.

INTRODUCTION

Estimating bedload transport rates and determining the timing of incipient motion is desired for a variety of ecological and engineering purposes. High-quality data, however, are often unavailable or collected too infrequently (Gomez, 2006) due to the time and expense associated with collecting physical bedload samples (Gomez, 1989, Gray et al., 2010). Sediment transport is driven by a variety of mechanisms at a range of spatial and temporal scales (Hoey, 1992). Many practitioners use empirical relations between streamflow discharge and sediment discharge rates to predict transport during unmeasured periods (Gray and Simoes, 2008). Infrequent sampling will often fail to capture temporal variability, and therefore transport relations developed from these data may not adequately predict transport rates. An example of this is provided in Figure 1. A regression equation was developed from a simple discharge-bedload relation using physical measurements of bedload between 2010 and 2013 on the San Joaquin River (Figure 1A). The predicted bedload is shown during a 2011 flood event (Figure 1B) with the physical measurements of bedload overlaid. When compared to the physical measurements of bedload, the regression equation in this example will often either underpredict or overpredict bedload (from -70 percent to 310 percent,). The cause of such error in bedload transport prediction may be attributed to one of two (or both) sources: sampling error or temporal variations in bedload transport (Gomez and Troutman, 1997). To improve estimates of sediment transport, a low-cost surrogate technique could be used to fill in the temporal gaps between physical measurements or aid in identifying erroneous samples. This is analogous to using continuous measurements from a turbidity sensor calibrated to measurements of suspended sediment concentration to calculate sediment transport rates. Hydrophones are one example of such technology which can be used for coarse bedload transport.

Hydrophones were first used to listen to sediment-generated noise (SGN) in the 1930s (Bedeus and Invicsics, 1963). Since that time, others have conducted lab and field experiments to attempt to correlate the acoustic signal to particle size and transport rates (e.g. Thorne, 1986; Rouse, 1994, Barton et al., 2010). Several surrogate sediment monitoring technologies currently exist, each with their own advantages and disadvantages (Gray et al. 2010). Advantages of

hydrophones include: (a) low cost, (b) ease of deployment (c) minimal interference with the bed, and (d) they provide a spatially-weighted average of transport over the detection area. Disadvantages include: (a) hydrophones may detect unwanted noises in addition to SGN, (b) the precise detection area is not known and may change during a flood event, and (c) the relation between particle size and sound transmission loss is also not well understood.

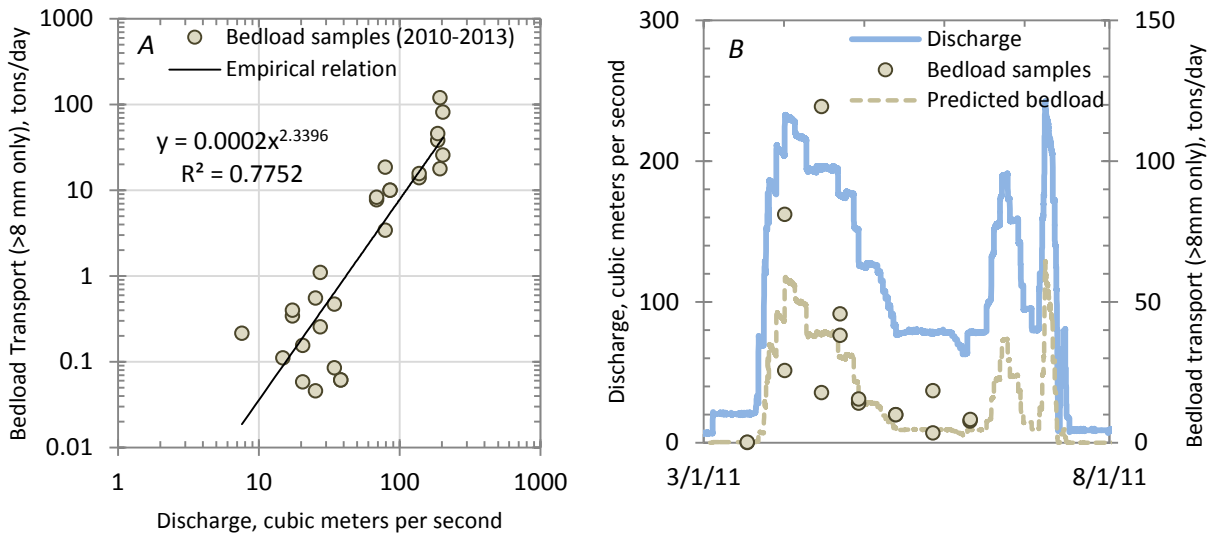

Figure 1 Example of temporal variability of bedload discharge in the San Joaquin River at Hwy 145 (USGS Site Number 11252975). Bedload measurements are plotted as a function of streamflow discharge to obtain a power law regression equation (A). The hydrograph during a 2011 flood event is shown with bedload measurements and predicted bedload discharge based on the empirical regression equation (B).

The general principle behind using hydrophones as a surrogate bedload monitoring technique is that they detect the rigid body radiations (i.e. sounds) generated by the collisions of sediment particles as the particles roll and saltate along the bed (Thorne, 2014). The sounds produced by the sediment collisions are often referred to as *sediment-generated noise* (SGN). The hydrophone uses a piezoelectric element to convert the sound pressure waves to an electrical signal. The electrical signal is proportional to the pressure acting on the piezoelectric element which is assumed to be proportional to the magnitude of bedload transport occurring near the hydrophone.

Our recent work has focused on developing a low-cost, long-term monitoring system to collect and record underwater sounds to supplement physical bedload measurements and to identify the timing of incipient motion. In addition, we developed an experimental mobile hydrophone recording system intended to measure relative spatial variability of SGN on a reach scale.

STUDY AREA

The majority of the hydrophone monitoring work was conducted on the San Joaquin River in California as part of the San Joaquin River Restoration Program (SJRRP). SJRRP is a multi-agency effort to increase populations of Chinook salmon (*Oncorhynchus tschawytscha*) in the San Joaquin River downstream of Friant Dam. This reach of the San Joaquin River consists largely of deep pools with gravel-bedded riffle clusters. There are only two major tributaries to this reach: Cottonwood Creek and Little Dry Creek. Both of these creeks are unregulated ephemeral streams. No measurable discharge occurred on the tributaries during WY 2014. Discharge on the mainstem San Joaquin River in the study area is regulated by Friant Dam. Particle-size distribution of the bed-material was measured in the San Joaquin River at hydrophone monitoring sites (using Wolman pebble counts). Median particle size (D_{50}) ranged between 26 and 80 mm on the mainstem and between 2 and 23 mm on the tributaries (which were generally a mix of sand and cobbles). Figure 2A shows the hydrophone monitoring sites on the San Joaquin River as well as the start and stop locations of the mobile hydrophone longitudinal profiles. The hydrophones were also tested on the Gunnison River, Colorado, during a spring flood event in 2014. The Gunnison River is a tributary to the Colorado River. Discharge on the Gunnison River was primarily regulated by the Blue Mesa Dam. Pitlick et al.

(1999) conducted particle-size distribution measurements at several locations along the Gunnison River. Our study reach was nearest to RM 55.6 which was measured by Pitlick et al. (1999) to have a surface D_{50} of 59 mm, and a subsurface D_{50} of 29 mm. Figure 2B shows the location of one of the hydrophone monitoring stations on the Gunnison River, as well as the start and end locations of the mobile hydrophone longitudinal profiles.

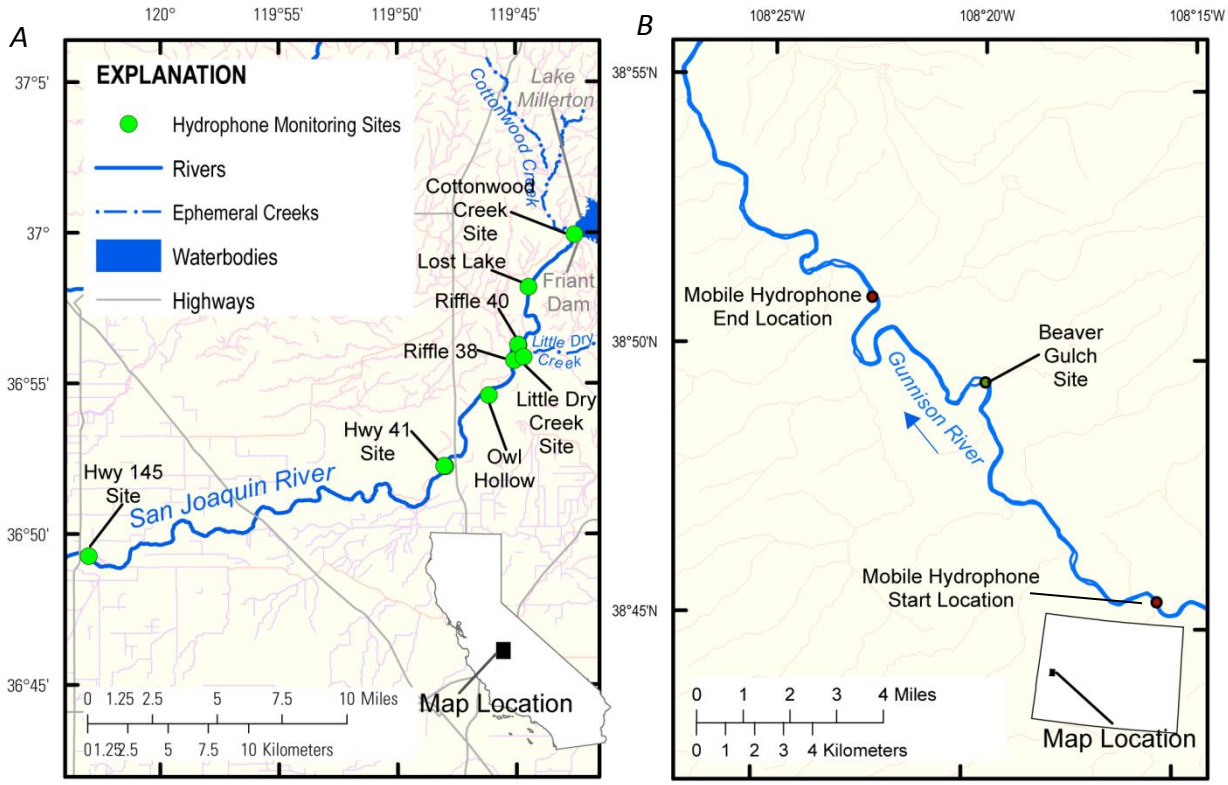

Figure 2 Study area map showing long-term hydrophone monitoring sites along the San Joaquin River, California (a), and testing locations for stationary and mobile hydrophones in the Gunnison River, Colorado (b)

METHODS

Data Collection Each hydrophone monitoring station consisted of two Aquarian H1a hydrophones and one recording system. The hydrophone recording systems were programmed to collect a 1-minute audio recording at a preset sample interval. Typically the sampling interval was set to 30 minutes; however, at the flashier tributary creeks the sampling interval was set to 20 minutes. The recording system was contained in a Pelican case and secured to the bank. The systems were capable of operating continuously for four to five weeks before they required routine servicing. Routine servicing involved downloading data and replacing batteries. At that time, the hydrophone heads were inspected (when conditions were wadable) and any debris found was removed. A pressure transducer was also installed nearby at each site to record water levels. The sensitivity of the H1a hydrophones is -190 dB re 1V/uPa (+/- 4 dB) (Aquarian Audio, 2013). The preamplifier gain was set to 14 dB, which provided a clear overall signal without clipping higher amplitude sounds.

At each site, the hydrophones were installed in the river by attaching them to a vertical piece of steel rebar approximately 30 cm above the bed. Prior to attaching the hydrophone, the rebar was driven into the bed 45-60 cm. A second piece of rebar was installed approximately 30 cm directly upstream to block debris which may otherwise accumulate on the hydrophone and result in sound transmission loss (Figure 3B). The audio cable was routed through a flexible polyvinyl chloride (PVC) conduit which was buried in a shallow trench. The PVC conduit was also secured in place using several pieces of u-shaped rebar which were driven into the bed.

Ten hydrophone recording systems were deployed across eight California sites in November 2013 (Figure 2a). Two of ten system were deployed in the tributary creeks. In addition, at two sites (Hwy 41, and Riffle 40) a hydrophone monitoring station was installed on each bank of the river in an attempt to collect a better spatial average of SGN. Due to the multi-year drought in California, peak flow during the study period was only about 37 m^3/s on the San Joaquin River, which is relatively low with minimal bed movement. In an effort to field test the hydrophone systems under a range of flow conditions, two systems were deployed on the Gunnison River, during a late-spring flood event.

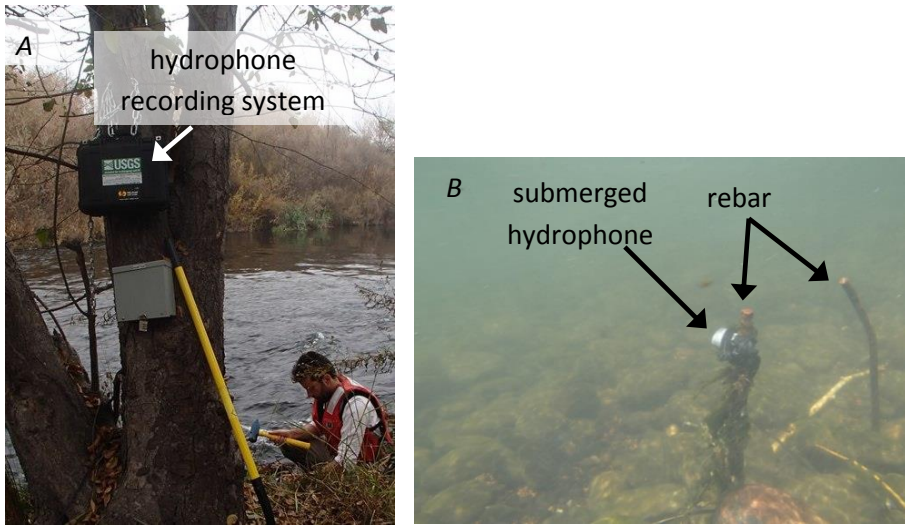

Figure 3 Photo of hydrophone recording system installed at the Owl Hollow Site (A), and photo of submerged hydrophone with additional piece of rebar installed upstream to deflect debris (B).

A mobile hydrophone system was used to record a longitudinal profile using one hydrophone mounted to a hard-shell kayak. Audio data were recorded on a portable tablet computer. Location, depth and streamflow velocity were measured using a real-time kinematics global-positioning system (RTK-GPS) and a StreamPro acoustic Doppler current profiler (ADCP). At the time of publication, GPS data were not fully processed, therefore "distance downstream" on any plots shown are approximate, and were calculated using the assumption that boat speed was constant throughout data collection. Three longitudinal profiles of underwater sounds at three different flows (303 m^3/s, 234 m^3/s, 48 m^3/s) were collected on the Gunnison River, and one longitudinal profile (at 37 m^3/s) was collected at two reaches on the San Joaquin River.

<u>Discrimination of Sediment-Generated Noise and Ambient Noise</u> Previous work (Jonys, 1976; Millard, 1976; Thorne, 1985; Thorne, 1986) has shown an inverse relation between the acoustic frequency of SGN and the particle size. Thorne (1986) proposed an empirical equation using those data to relate the resonance frequency of SGN and particle size (shown in Figure 4). Thorne's equation was based on particles from 0.2 mm to 43 mm. More recently, Belleudy et al. (2010) conducted experiments to measure the SGN of larger sized particles (15 to 110 mm). The hydrophones are most suited for applications in gravel-bedded rivers (Gray et al., 2010). Therefore, results from coarser particles are of particular interest, and we present a revised equation (Equation 1) using only experimental results for particles coarser than 4 mm (which includes pebbles, gravels and cobbles) (Figure 4). The following is the revised equation which provides a better approximation of experimental data for the larger sizes.

$$f_r \approx 55/D^{1.16}\ Hz \tag{1}$$

where f_r is the resonance frequency, and D is the particle diameter in meters. Assuming those results are transferable to particles in motion in a streambed, the intensity, or level, of sound in these ranges should correlate with SGN of bedload particles in transport.

Ambient noise (e.g. water motion, wind, and/or biological), however, may still overlap the same frequency range as SGN. Tonella et al. (2009), for example, found that underwater noise related to turbulence and bubble formation were most pronounced between 125 Hz and 2 kHz. Zakarauskas (1986) noted that wind noise can occur between 50

Hz and 10 kHz, but maximum wind noise is generated between 100 Hz to 1000 Hz. Therefore it is important to determine if ambient noise is present in audio recordings as well as the likely frequency range of such noise. Aural listening (i.e. listening through the ear) is particularly useful at distinguishing various sources of noise in the audible range (Camp, 1970). Aural review was combined with automated signal processing tools to analyze the audio recordings and identify if there were periods in which either ambient noise or SGN noise was dominant.

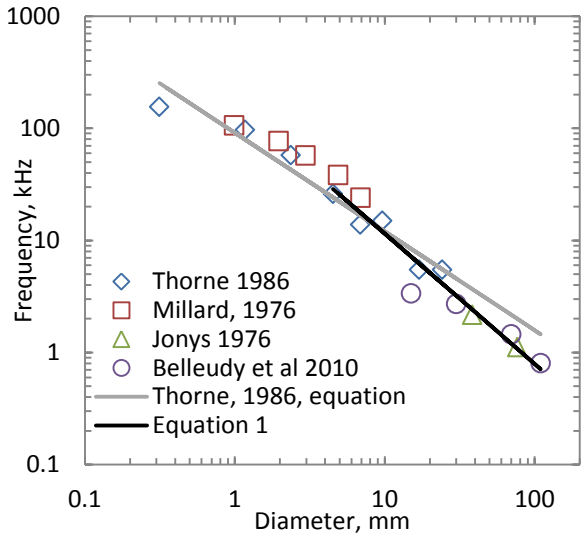

Figure 4 Measurements of acoustic frequency of sediment-generated noise (SGN) as a function of particle size. Thorne 1986 empirical equation, and Equation 1 of this study are also shown.

Signal Analysis The audio recordings were processed in MATLAB by first transforming the signals from the time domain to the frequency domain using a short-time Fourier transform to obtain the power spectral density (PSD). A spectrogram is a convenient way to display the PSD of an audio recording. Time is displayed on the x-axis, frequency on the y-axis, and the sound level for any given frequency and time is represented by color. The sound level for the recordings were averaged over a 1-minute time period. Marineau et al. (2010) found that a 1-minute sample was sufficient to average short-term temporal variability of SGN (such as a loud shock in very close proximity of the hydrophone). For the mobile hydrophone systems, however, a 1-minute time period may not be appropriate. For example, a 1-minute averaged sample may smooth over a local peak of SGN while traveling through a riffle. Therefore, the mobile audio data was split into 15-second time periods for analysis.

Hydrophones are typically calibrated in a specialized underwater-acoustics facility which involves measuring the precise voltage response of the electrical signal output to a given sound pressure at a specific frequency. Low-cost hydrophones (such as the ones used in this study) are generally not calibrated. Therefore, it is not possible to determine the exact sound pressure level from the measured voltage signal output. Sound level is generally referred to in decibels (dB), and sometimes more specifically as decibels of sound pressure level (dB SPL) where 0 dB SPL is the lower threshold of human hearing. The decibel scale is a logarithmic scale and is used because sound pressure can vary by many orders of magnitude. Since the hydrophones used in this study were not calibrated, sound levels are expressed in *dB* rather than *dB SPL*. This means that 0 dB does not necessarily correspond to the lower threshold of human hearing and also that any two hydrophones may have slightly different levels of sensitivity. Though the hydrophones are not calibrated, they can still provide useful information regarding the relative magnitude of underwater sounds. For each 1-minute sample recorded at a hydrophone monitoring station (or 15-second subsample of the mobile hydrophone recording), decibels were calculated using the following equation (Erbe, 2011) assuming cylindrical spreading sound due to shallow water (e.g. Urick, 1983):

$$dB = 10*\log(dv/FS) - M - G - S \qquad (2)$$

where dv = digital values in the .wav file, FS = full scale value (for 16-bit floating point, FS is 1), M is the digital gain of the pre-amplifier, I = hydrophone sensitivity level, expressed in dB re 1V/uPa, G = preamplifier gain setting

(in dB). Each spectrogram was calculated in MATLAB using a Hamming window, with a 1 second (44,100 sample) window size, 50 percent window overlap, and fast-Fourier transform (FFT) length of 4410.

RESULTS

Temporal Variability During WY2014, streamflow on the San Joaquin River was generally not sufficient to mobilize coarse sediment at most sites. This was evidenced by audio recordings from several sites and bedload samples collected by the California Department of Water Resources (CADWR) at four sites (Matt Meyers, CADWR, written communication). Of the monitoring sites along the San Joaquin River, the most downstream site, Hwy 145 (Figure 2A), had the smallest bed-material size (D_{50} of 26 mm) and the hydrophone monitoring station at this site detected higher levels of SGN than any other site. During a portion of the deployment, streamflow was very low (4.2 m^3/s) and the hydrophone sensors were at or just above the water surface. Figure 5 shows a spectrogram (5A) and time series of average sound levels for 1.3 to 6.7 kHz frequency range (5B). Data from only one of the two hydrophones is shown in this figure. The frequency range was calculated using Equation 1 with particle diameters of 16 to 64 mm (approximately 70 percent of the bed-material was within this size range). The data includes the period when the hydrophones were out of the water and periods when the water level was at the hydrophone. Releases from Friant Dam were increased starting in early May and held steady during most of the summer. An aural review of several audio recordings revealed that during early low-flow (4.2-11.3 m^3/s) period, the dominant noise sources was water motion. Ambient noise associated with water motion was generally below 2 kHz, but at times was as high as 5 kHz. During period of higher stage, the noise associated with water motion could not be heard in any audio recordings; therefore we concluded that the average sound levels calculated during these periods was primarily SGN. The time series data was refined to exclude low-flow periods which were dominated by ambient noise (Figures 5B and 5C). The ambient noise was easily identified by ear, but could not be discerned from SGN using the signal analysis methods employed in this study. The data from the 5-month period with sustained 36.8 m^3/s flows show some temporal variability in transport; however the elevated sound levels measured during the months of data collection prior to the reservoir releases were from ambient noise, not SGN. In the absence of physical bedload measurements, an aural review of the audio recordings was helpful in distinguishing the SGN from noise originating from other sources. Based on SGN data, coarse bedload was found to generally start and stop at this site when streamflow was around 30 m^3/s.

The hydrophone monitoring station at the Beaver Gulch Site on the Gunnison River (Figure 2B) recorded audio data during the peak of a 10-year flood event. Since the hydrophones were installed in the bank during the rising limb of the flood event, as the streamflow decreased, they were no longer submerged and thus were repositioned to continue data collection. Figure 6B shows the hydrograph with the average sound-level time series overlaid. Figures 6C and 6D show scatter plots of sound level vs discharge. The colors indicate the date starting around June 1 and ending June 10. This figure shows clockwise hysteresis in the sound level. Assuming the SGN was directly proportional to the sediment discharge, these results indicate a decrease in transport which suggests a reduction in sediment supply, bed armoring, or perhaps that the geometry of the channel changed such that sound transmission decreased with time.

Spatial Variability Two longitudinal profiles of SGN were collected in two separate reaches of the San Joaquin River during a discharge of 36.8 m^3/s. Only results from the downstream-most 2.5 km are reported (Figure 7). The spectrogram (Figure 7A) indicates that near-continuous noise was present in the lower frequencies through the entire profile. Aural review of the audio recordings suggested that the source was water noise, likely generated by either the kayak or the paddle movement. The two black rectangles in Figure 7A highlight areas where SGN was audibly detected. Figure 7B shows a time series of the average sound levels for two different frequency ranges. The lower frequency range (1.3 to 6.7 kHz) overlaps with the boat/paddler-generated noise; therefore a time-series calculated from the average sound levels in this range does little to elucidate locations of bedload transport. In the mobile recordings, however, water motion noise was detected in the slower-moving pools (during which the operator was using the paddle to propel the kayak downstream), and this noise was generally limited to less than 4 kHz. The second frequency range shown in Figure 7B (4.5 to 6.7 kHz), however, excludes most of the ambient noise, and two potential riffle clusters with SGN are easily identified in the time series (black rectangles in Figure 7B). The last figure (7C) shows longitudinal profiles of depth, velocity, and water-surface elevation for the same reach. Two sections with increased water-surface slope correspond roughly to the potential riffles identified in Figure 7B. The downstream riffle is a known riffle at the Hwy 145 Site.

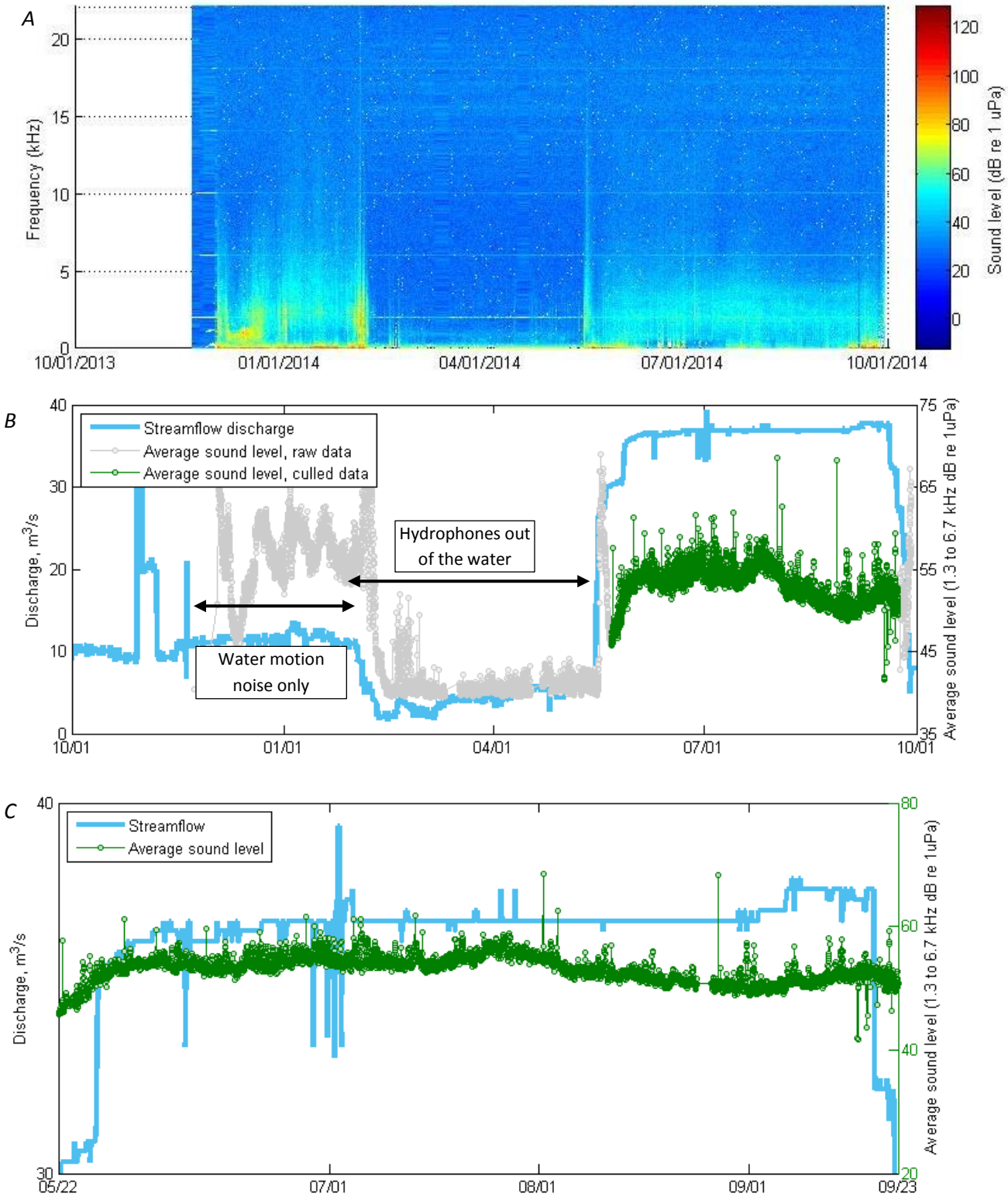

Figure 5 Spectrogram (A) and time-series of raw and refined data overlaid on the hydrograph (B) recorded in the San Joaquin River, California at Hwy 145 monitoring site, WY2014. A close-up of the period when sediment-generated noise was detected is also shown (C).

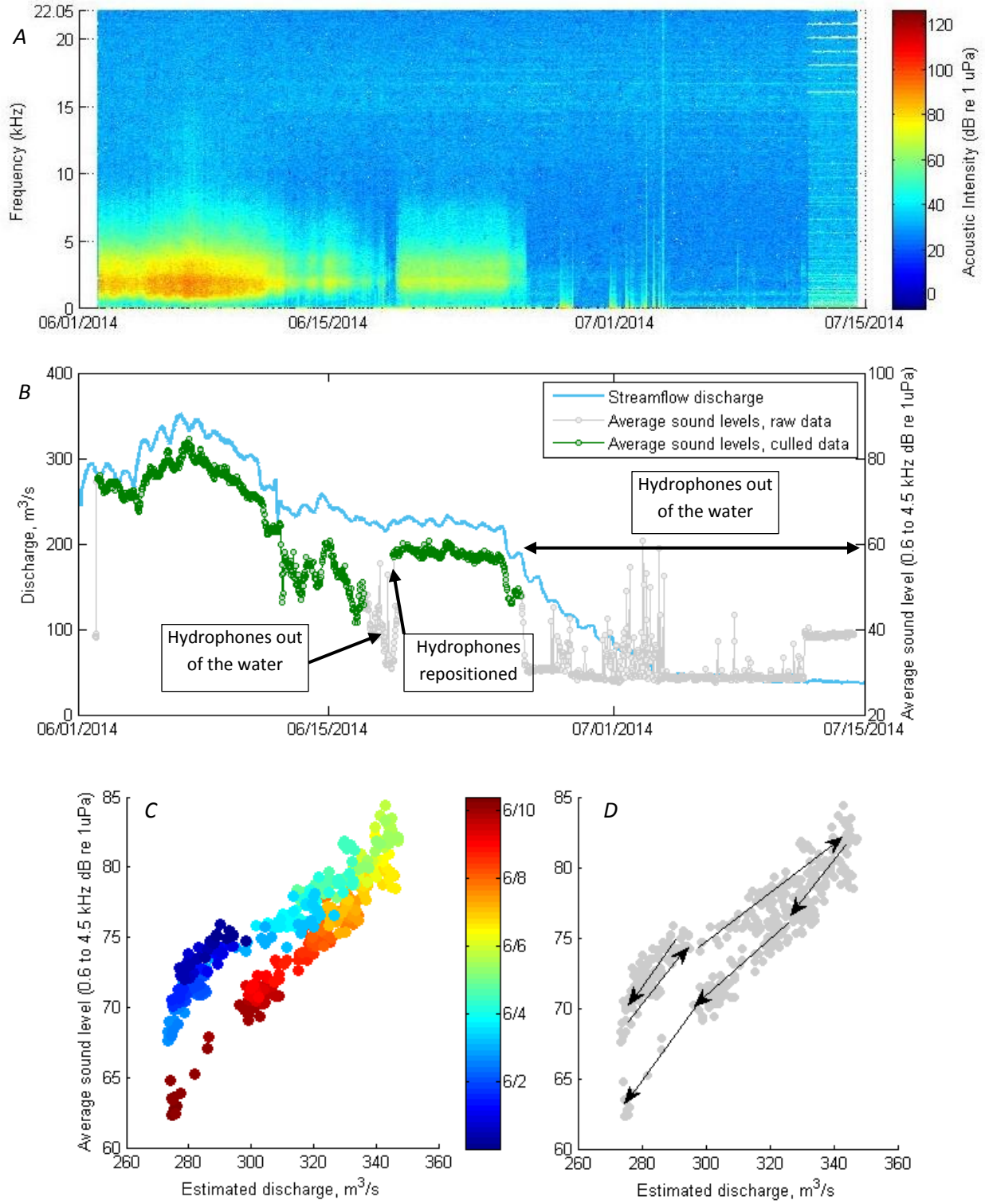

Figure 6 Spectrogram (A) and time-series (B) of 1-minute averaged sound level (0.6-4.5 kHz) in the Gunnison River, CO, Beaver Gulch Site. Scatterplot (C, D) of days 1-10 showing clockwise hysteresis of sediment-generated noise

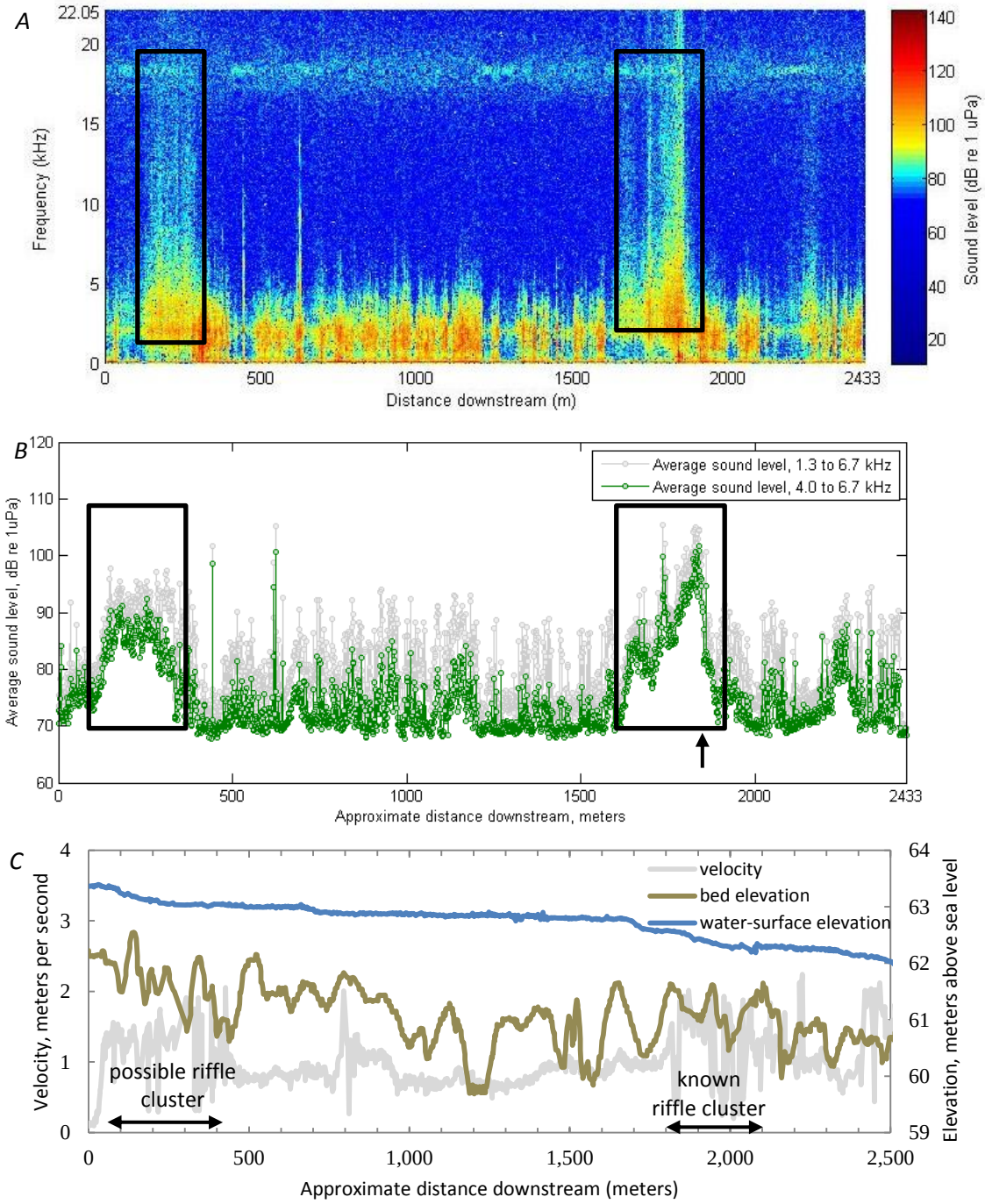

Figure 7 Longitudinal profile of San Joaquin River, California (2.5 km reach near Hwy 145) shown as spectrogram (A), time-series of average sound level for two different frequency ranges (B), and bed elevation, water velocity, and water-surface elevation (C). Boxes indicate periods in which bedload was audibly detected. Vertical arrow indicates approximate location of hydrophone monitoring station at the Hwy 145 Site.

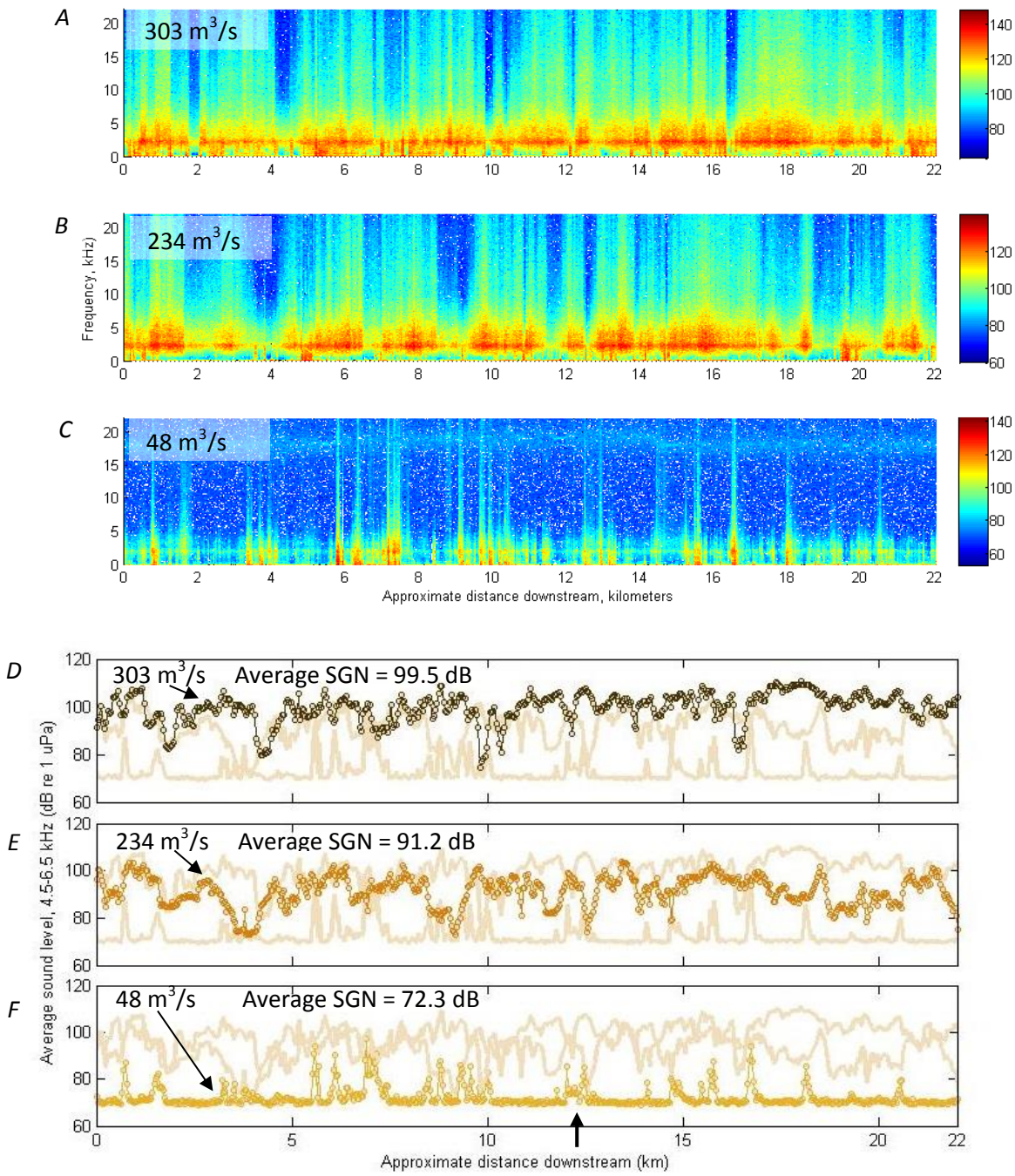

Figure 8 Spectrograms (A-C) and fifteen-second averaged sound level (D-E) recorded from mobile hydrophone system at three different flows: 303 m^3/s, 234 m^3/s, and 48 m^3/s Gunnison River, Colorado. Vertical arrow indicates approximate location of hydrophone monitoring station at the Beaver Gulch Site.

Longitudinal profiles of audio recordings were collected in the Gunnison River at three flows: 303 m^3/s, 234 m^3/s, 48 m^3/s (Figure 8). These time-series were calculated from the same frequency range as the San Joaquin River time series to reduce any potential influence of boat/paddle noise. During the higher flows, elevated sound levels were recorded over most of the reach, suggesting that most or all of the bed was at least partially mobilized. During the lowest flow, only discrete sections of the river had transport occurring. Between these sections were quiescent pools which have an ambient noise floor of about 70 dB.

Statistical information of the longitudinal profiles is also shown in Figure 8D-8F. Generally, average sound levels of SGN decreased with lower flows, however, there was still a high degree of spatial variability at all flows. Critical discharge (i.e. discharge that initiates bedload transport) in this reach, was estimated to be between 195 m^3/s and 269 m^3/s (Pitlick et al., 1999).

CONCLUSIONS

The results from this first year of data collection demonstrate that the hydrophone recording system can be used to collect high-resolution surrogate sediment data in gravel-bedded rivers. The sound level of the signal recorded by the hydrophone is assumed to be proportional to the magnitude of bedload transport as long as the acoustic frequency of the sediment-generated noise (SGN) is known, the grain-size distribution of the bedload is assumed constant, and the frequency band of the ambient noise is known and can be excluded from the analysis. These data can be calibrated and used to fill temporal gaps between physical bedload measurements or as a stand-alone qualitative measure of the timing and variability of transport. At one site on the San Joaquin River, the threshold of movement was estimated to have occurred around 30 m^3/s based on SGN data. The results from the Gunnison River show a clockwise hysteresis during a flood event, which may not be detected using traditional physical sampling at typical sampling return intervals. Previous research has found that gravel transport can occur in waves at different temporal and spatial scales. Pairing physical samples with high-resolution surrogate data may provide a method to determine if a particular sample was collected at high or low point of a sediment wave, and reduce error in estimates of sediment transport. These data may be calibrated to physical samples to obtain a continuous, quantitative estimate of bedload transport. Previous attempts (e.g. Barton et al., 2010) have attempted to relate the average acoustic intensity over a large frequency range to bedload flux. Future work should compare the acoustic signal of SGN in known mixtures from laboratory or field experiments.

The initial testing of the mobile hydrophone system shows that it could be a useful tool to identify fine-scale spatial variability in sediment transport over large reaches, something that is not possible using conventional sampling techniques. This type of qualitative information may be applicable for verifying localized transport in a hydraulic or sediment transport model. Quantifying the transport rate occurring in any particular place, however, has additional challenges; primarily that changes in depth and channel geometry will affect sound transmission and spatial variability in bedload particle-size distributions will change the acoustic signature of the SGN.

Finally, for both the stationary and mobile hydrophone systems, methods are needed to identify and reduce noise from non-sediment sources. Noise reduction may be achieved physically (e.g. changes in the hydrophone mount configuration, hydrophone placement), or through various signal processing tools. In this study, the relative magnitude of transport was quantified by calculating the average sound level over certain frequency ranges. By adjusting these (as was done for the mobile hydrophone data on the San Joaquin River), ambient noise can be excluded from the final results. In the case of the hydrophone monitoring station at the Hwy 145 Site on the San Joaquin River, the selected frequency ranges span bedload noise as well as background noise from water motion. At this site, a different mount style or site may reduce unwanted noise. Future work will consider alternative hydrophone locations and mount configurations to determine which combination will provide optimal performance.

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