Overview of Five Recent Bedload Monitoring Field Experiments Using Hydrophones

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Abstract

Bedload transport rates are often desired by engineers and scientists for a variety of purposes. Obtaining useful bedload data through physical sampling, however, can be logistically challenging and expensive. Conventional bedload sampling techniques can have high uncertainty, and poor correlation of bedload transport to discharge or other easily measurable variables makes it difficult to model or predict transport rates. In recent years, there has been increased interest in surrogate monitoring techniques such as passive acoustics as a lower-cost method of collecting bedload data. Hydrophones (underwater microphones) can be used to detect the underwater sounds generated by gravel and cobble as they roll and saltate along the bed. This noise is referred to as sediment-generated noise (SGN). While the acoustic data still require calibration to physical samples, it can be used to produce a high-quality continuous record. This paper provides a brief overview and preliminary findings from five recent passive acoustic monitoring (using hydrophones) projects conducted by the US Geological Survey with other partners and cooperators, either as a stand-alone study or as part of larger sediment transport or geomorphic studies. The objectives of the passive acoustic monitoring studies were to test passive acoustic monitoring in different types of systems, determine if sediment-generated noise was correlated with bedload transport rates, and experiment with different techniques to improve correlations (such as using pairs of hydrophones). Study sites ranged from small (5-10 meters in width) channels in the Catskill Mountains of New York and a tributary creek in the Grand Canyon to a large glacially-fed river (70-meters in width) in the Cascade Range in Washington State. Bed material ranged from mixed sand and gravel to coarse cobble with small boulders. Channel slope ranged from about 0.2 percent (Trinity River, CA), to 3.5 percent (Shinumo Creek, AZ). Overall, we found that hydrophones detected SGN at all but one site; however, noise from air entrainment and water turbulence severely degraded the signal quality at two relatively steep (1.5 percent slope) cobble-bed streams. Continuous recording (versus 15-minute intervals) did not necessarily improve calibration but placing hydrophones at opposite banks helped detect lateral variability in transport and placing hydrophones at different elevations allowed improved data collection at a wider range of flows.

Introduction

Passive acoustic bedload monitoring has been an area of increasing research in recent years. This method typically uses either geophones and geoplates (e.g., Wyss et al. 2016), pipe hydrophones (Mizuyama et al., 2010) or hydrophones (e.g., Marineau et al., 2017; Geay et al.,

2017) to collect surrogate acoustic data to supplement physical bedload measurements. The advantage of using a surrogate technique is to increase the frequency of bedload measurements while also reducing the overall monitoring costs. In the studies presented here, hydrophones were used to record sounds generated by collisions of bedload particles, which are referred to as sediment-generated noise (SGN). Those acoustic data are then calibrated to transport rates from physical samples to produce continuous or near-continuous estimates of bedload transport. Passive acoustic bedload monitoring has been demonstrated in some cases to provide estimates with greater accuracy than conventional methods. However, the method is not suitable in all stream types, and there are still several issues to address before making passive acoustic monitoring an established method. These issues are generally related to underwater sound propagation and its relation to channel geometry, field installation design, and calibration. Here, we discuss preliminary results from five recent studies by the US Geological Survey (USGS) and other collaborators, as well as some of the challenges encountered.

Objectives

The objectives of these five studies generally fell into one or more of the following: 1) attempt to calibrate acoustic data to bedload measurements to determine if acoustic data can be used as a surrogate, 2) test if multiple hydrophone-recorders, more frequent sampling, and/or splitting bedload measurement transects (explained in methods) can improve calibration, and 3) explore and evaluate the passive acoustic sediment monitoring for a variety of channel types and site conditions.

Study Areas

The five study sites discussed are: Sauk River, WA; Trinity River, CA; Arroyo de los Piños, NM; Birch and Stony Clove creeks in the Esopus Creek watershed, NY; and Shinumo Creek, AZ (Figure 1). Table 1 summarizes some of the key hydraulic and hydrologic information for each site. Study areas are presented in order of stream width from widest to narrowest. The Trinity River sites are grouped together and ordered from upstream to downstream.

The Sauk River was the largest river (70-m width) monitored. The Sauk River has a gravel-cobble bed and streamflow in the Sauk River is not regulated by an upstream dam. The river is dynamic with active channel migration, gravel bars, and log jams. The largest flow of record (measured in 1855) was over 1,300 m^3/s.

The Trinity River is a gravel-bed river with a channel width of about 40 meters. Streamflow is regulated by upstream dams and controlled releases during wet years are generally limited to 340 m^3/s. Gravel injection is used to replenish gravel supply downstream of the dams (Gaeuman, 2014) and there is a long-term sediment monitoring program at four sites (acoustic monitoring took place between 2015 and 2017, but the number of sites acoustically monitored varied from 2 to 4 sites). Gravel is often injected at two locations in the river. One of those is about 1.6 km upstream from the Lewiston site (USGS Station No. 11525500) and the other is about 0.2 km upstream of the site above Grass Valley Creek (USGS Station No. 11525540).

The other study areas had smaller channels. Birch and Stony Clove creeks (tributary creeks in the Esopus Creek Watershed, NY) are about 10 m in width, with steeper gradients, and their mixed beds are mostly gravel to large cobble. Arroyo de los Piños is an ephemeral stream which is a tributary to the Rio Grande. Its bed is composed mostly of sand- to gravel-sized material and

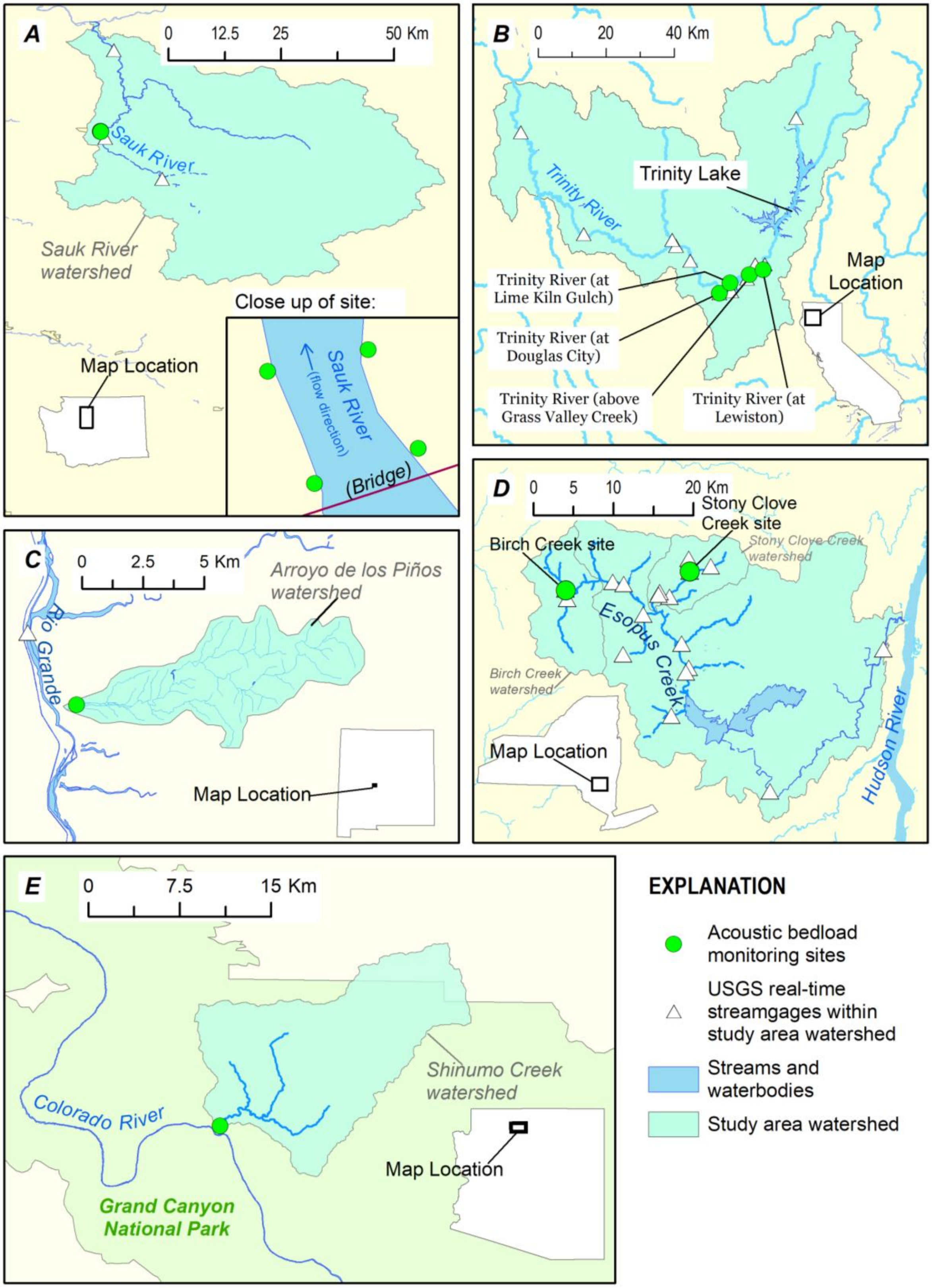

Figure 1. Study area sites: Sauk River, Washington (A), Trinity River, California (B), Arroyo de los Piños, New Mexico (C), Esopus Creek watershed, New York: Birch and Stony Clove creeks (D), and Shinumo Creek, Arizona (E).

flow events generally last only a few hours but stream depth can exceed 1 m during extreme events. Shinumo Creek, AZ, is a small gravel-cobble bed creek, tributary to the Colorado River. Following a 2015 post-wildfire debris flow (Schenk et al., 2017), the channel was filled with sand and gravel to near bank-full height, but the majority of in-channel fine sediment was evacuated in the subsequent 2 years of spring snowmelt high water (Schenk, 2018).

Table 1. Summary site information for 6 acoustic bedload monitoring sites, arranged by channel size. USGS streamgage site ID in parenthesis. D_{50} is median grain size.

Site and (streamgage ID)	Channel width (m)	Dominant bed-material sizes[a] and D_{50} [in mm]	Slope (percent)	2-year flow (m^3/s)	Drainage area (km^2)
Sauk River, Washington					
Sauk River at Darrington, WA, (12187500)	70	Sand, gravel, cobble, small boulders [–]	0.5	480	760
Trinity River, California					
Trinity River, at Lewison, CA (11525500)	40	Gravel-cobble [55–60]	0.17	170	1,860
Trinity River above Grass Valley Creek (11525540)	38	Gravel-cobble [29–72]	0.13	*unknown*	1,970
Trinity River below Lime Kiln Gulch (11525655)	43	Gravel-cobble [41–52]	0.28	195	2,100
Trinity River at Douglas City (11525854)	46	Sand, gravel, cobble [42–62]	0.3	220	2,410
Arroyo de Los Piños, New Mexico					
Arroyo de los Piños, NM	10	sand (1/3), gravel (2/3) [2.5–4]	1.3–1.7	*unknown*	32
Esopus Creek watershed, New York					
Stony Clove Creek at Janssen Road, NY (01362336)	9–10	Sand-cobble & small boulders [58–95]	1.5	*unknown*	24
Birch Creek at Big Indian, NY, (013621955)	10	Sand-cobble & small boulders [64–80]	1.6	12	32
Shinumo Creek, Arizona					
Shinumo Creek, AZ	5	Sand-gravel, boulders also present [29]	3.2–3.7	*unknown*	221

[a] Particle size classifications are defined as: sand (<2 mm), gravel (2 to <64 mm), cobble (64 to <256 mm) and boulder (256 mm or larger). –, not reported.

Methods

At each site at least one audio recorder was used with two hydrophones to record files (.wav format) at 44.1 kHz. The system, which was developed by the USGS (Marineau et al. 2015) recorded files that were 1-minute in duration and were generally collected at 15-minute sampling intervals. The newer systems (2017 and later) also supported a feature that allowed continuous (i.e. consecutive 1-minute recordings). This feature was utilized at sites during physical bedload sampling. At the Arroyo de los Piños site, runoff events only lasted a few hours, so the systems here were programmed to only record in continuous mode. The systems also used an external liquid detection sensor. The system was programmed to check this sensor (which was placed at an elevation slightly above base flow) frequently. If liquid wasn't present, the system would go to into standby mode for a set amount of time. If liquid were present (indicating a high flow event), then the system would go into recording mode and record at the pre-programmed sampling frequency. The recording system was kept on the bank out of the water (Figure 2). Using a liquid-detection sensor to trigger recording allowed the devices to remain in the field for months on battery power.

Figure 2. Examples of hydrophone installations: Sauk River, WA (left photo), Stony Clove Creek, NY (right photo)

For the Trinity River sites, typically only one recorder was installed at a site. However, at one of the Trinity sites (Lewiston) a recorder was installed on each bank to determine if lateral variability could be detected. At Stony Clove Creek, Birch Creek and Arroyo de los Piños two recorders were installed, typically on opposing banks. At the Sauk River, four recorders were installed (one pair on each bank, separated by about 60-70 m).

Bedload samples at Trinity River, Sauk River, and Esopus Creek Watershed sites (Stony Clove Creek and Birch Creek) were collected with a TR-2 (Childers, 1999) or Elwha sampler (Childers et al., 1999) using the Equal Width Increment (EWI) method (Edwards and Glysson, 1999). Bedload samples at the Arroyo de los Piños site were collected using three slot samplers (Berkman et al, 2006). Several other sediment surrogate methods were being tested at the Arroyo de los Piños site, see Varyu et al. (2019) for details). Traditionally, bedload measurements are collected using the EWI method and consist of about 10-20 subsamples (verticals) which are composited across the entire transect to create a single bedload measurement. To capture the lateral variability in transport rates and explore ways to improve surrogate calibration, the sampling protocol was modified at the Trinity River and Sauk River. At the Trinity River, the subsamples were composited into thirds (rather than the full transect). Bedload from each side of the channel and middle could be compared to the sediment-generated noise (SGN) recorded by the hydrophone on the corresponding bank. At the Sauk River, the mass of each subsample (wet weight) was recorded prior to compositing. This provided greater spatial resolution in the bedload.

Audio recordings were processed using discrete Fast Fourier transform (using a Hamming Window). Sound was recorded with a sampling frequency of 44.1 kHz with 16-bit integer resolution. See Marineau et al. (2016, 2017) for detailed description of audio processing. Results from a single 1-minute audio recording are in the form of a power spectral density (PSD) function which shows the sound-level pressure (in $\mu Pa^2/Hz$, which can be converted to decibels re 1V/µPa) at each frequency. Examples of PSD for various flows during an event on the Trinity River at Lewison, CA, are shown in Figure 3.

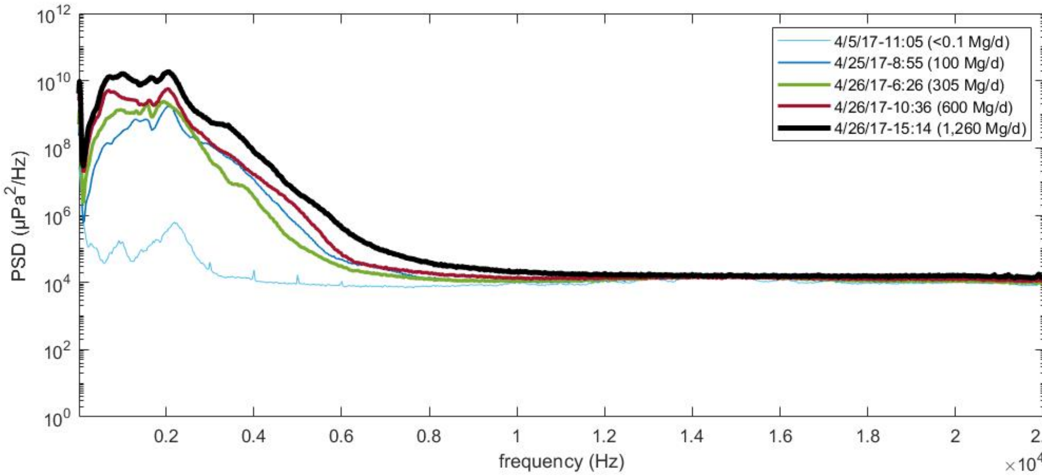

Figure 3. Examples of power spectral density (PSD) estimates under different streamflow and bedload transport conditions at the right bank of the Trinity River at Lewiston, CA.

Most of the SGN is in the lower frequency ranges (0.5 to 6 kHz). The sound level or sound pressure level for any given recording can be integrated over the entire frequency range or over a more narrowly selected frequency range to obtain a value which would then represent the SGN at that time. The values of SGN during bedload sampling can then be used to establish an empirical relation between SGN and bedload. Figure 4 in the results section shows an example time series of estimated bedload at the Trinity River at Lewiston site during controlled upstream dam releases.

The error around the bedload for the Trinity River was calculated from an experiment by GMA Hydrology Inc. (Pittman, 2018) in which six sequential vertical samples were collected at the same cross-section station over a 29-minute period (Pittman, 2018). During those six vertical subsamples, bedload ranged from 60 to 429 Mg/day.

Results

Sauk River near Darrington, Washington, WY 2018

At the Sauk River, in WY2018, several high flow events occurred, the largest was in November and was roughly 850 to 1,100 m^3/s. This is an estimate based on upstream and downstream streamgages. The event eroded a 30-m section of the right bank where the upstream right bank hydrophones were located. The same event also buried two of the three other hydrophone pairs. Hydrophones were recovered and reset or replaced in the following months (except for the upstream right bank recorder which was completely lost). Partial records of acoustic data were available from the remaining three recorders. Generally, SGN was much higher on the left side of the river. Bedload measurements were collected on two separate occasions (February 5 and May 9) and partial acoustic records were collected over a period of several months (example shown in Figure 9). For each measurement, 2 to 4 subsamples were collected at each location across the transect. The results show that about 60 to 75 percent of the total bedload occurred at only 3 of the subsample locations, all of which were near the left side of the channel. Total bedload from the four measurements collected on May 9 varied from about 500 Mg/day to nearly 1,700 Mg/day (Figure 4). Approximately one-third of the bedload was coarse (>8 mm). During the 4-hour period of bedload sampling, stage only varied by about 5 cm and SGN did not vary substantially (Figure 5).

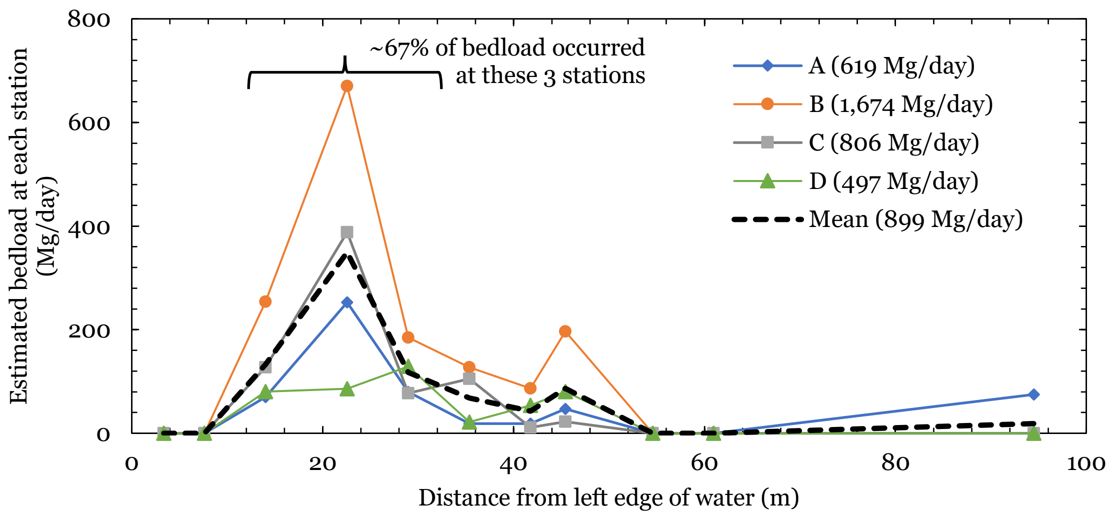

Figure 4. Repeated vertical bedload sampling across entire cross-section of Sauk River, May 9, 2018, showing temporal and spatial variability. Each station (vertical) was sampled 4 times before moving to the next station. Most of the bedload transport occurred at 3 of the sampling stations and transport rates ranged from 497 to 1,674 Mg/day.

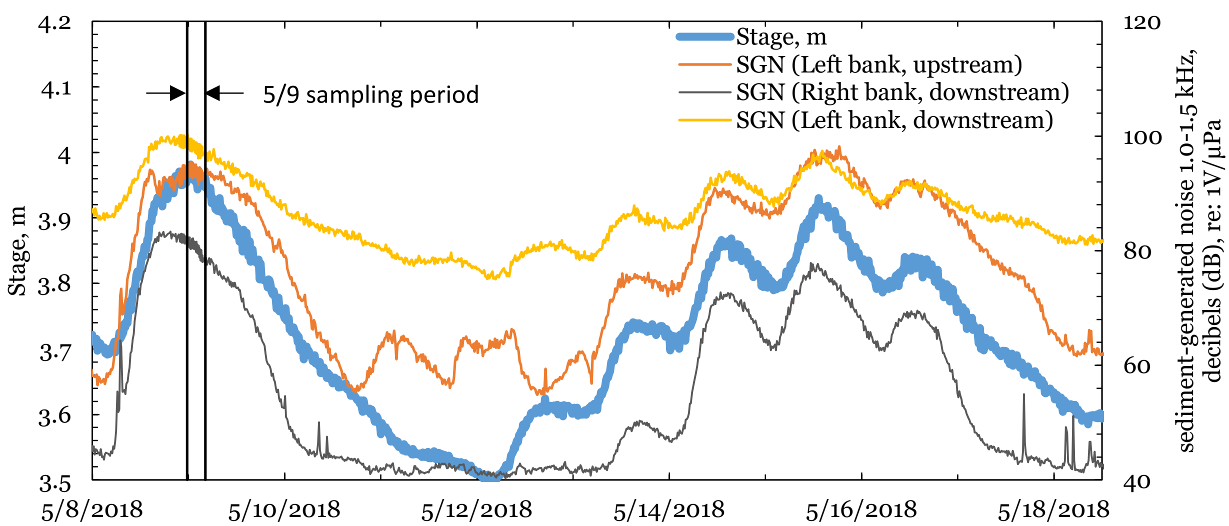

Figure 5. Time series of sediment generated noise at three locations along a short reach of the Sauk River, WA (right-bank upstream hydrophone was destroyed in an earlier flood).

Trinity River at Lewiston, California, WY 2016-2017

The Trinity River had the largest bedload sample set including multiyear results. Results (which include three other sites) from WY2015-16 can be found in Marineau et al. (2016, 2017). At the Trinity River, Lewiston site, 64 bedload samples were collected in WY2016. All stations across the transect were composited together for those samples. In the following year (WY2017), 19 bedload samples were collected with separate compositing of the left, middle, and right sections of the channel. Of those two years, streamflow discharge had the highest peak in WY2017 at 340 m^3/s. A relation was developed between the SGN on each bank and the bedload samples. Pearson's r was used as a measure of the correlation between SGN from each bank and coarse (>8 mm) bedload (Table 2). For WY2017, correlation was also measured between SGN from each bank and the bedload measured in each section of the channel. Most (67 percent) of the bedload transport occurred in the middle section while the rest was divided evenly (~16 percent) to each side.

Table 2. Correlation (measured by Pearson's r) between SGN and coarse (>8mm) bedload. Bedload measurements in WY2016 were not composited by channel section.

SGN recorder	Left Channel	Middle Channel	Right Channel	Total channel
		WY2016[a]		
Left bank				0.67
Right bank				0.85
Average of both banks				0.77
		WY2017[b]		
Left bank	0.61	0.75	0.56	0.86
Right bank	0.40	0.51	0.65	0.65
Average of both banks	0.56	0.69	0.61	0.82

[a] 64 bedload measurements (each transect counted as a measurement) collected; bedload transport rates ranged from 4.7 to 590 Mg/day
[b] 19 bedload measurements collected; bedload transport rates ranged from 139 to 1592 Mg/day

In WY2016, the highest correlation of total bedload was with the SGN recorded from the right bank, however, this switched in the following year. This is likely due to most of the transport occurring in the center of the channel rather than on one side. Using the acoustic record from the left bank only, a continuous record of bedload was created (Figure 6).

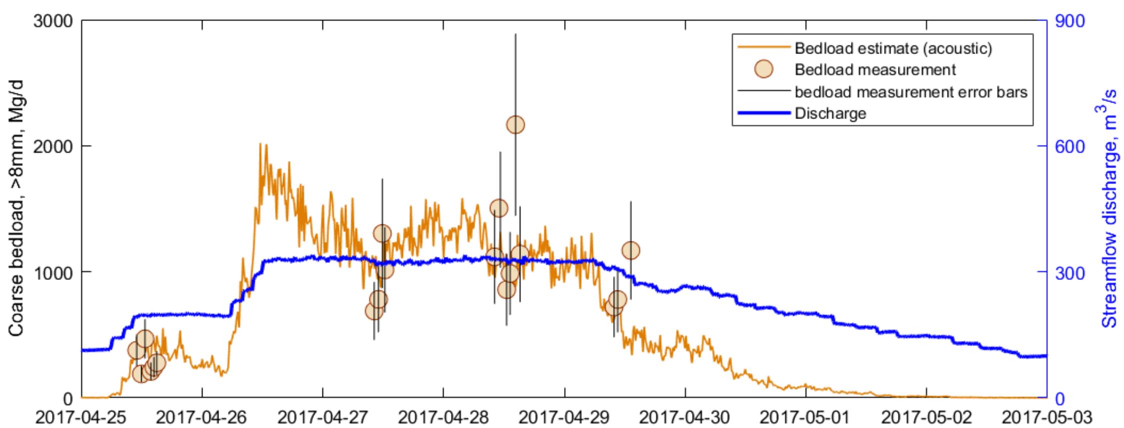

Figure 6. Example time series of acoustic-based bedload estimates with bedload measurements and streamflow discharge, Trinity River, Lewiston, CA. Vertical error bars represent standard deviation from repeated vertical sampling bedload experiment (Pittman, 2018).

The sediment transport rates (as a function of discharge) also changed over time. Figure 7 shows a plot of acoustic-based bedload transport estimates as a function of discharge, color coded by the date. Clockwise hysteresis is apparent; on the initial rising limb of the hydrograph (4/26/17-4/27/17) the transport rates were about an order of magnitude higher than on the falling limb (4/29/17-5/5/17).

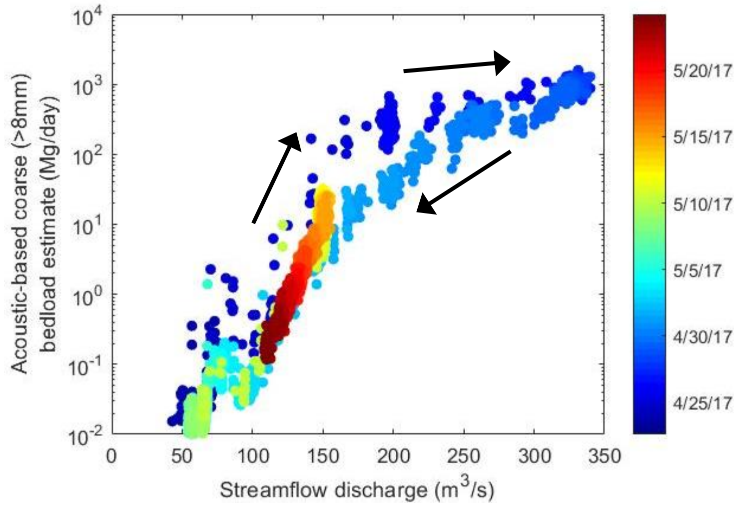

Figure 7. Acoustic-based bedload estimates vs streamflow discharge showing hysteresis and temporal variability at Trinity River, Lewiston, CA, 2017; bedload can sometimes vary by an order of magnitude for a given streamflow.

Conventional bedload rating curves were developed using streamflow discharge as the predictor variable. A comparison was made between two years of bedload data at the Lewiston site in Figure 8. The hydrophones were located at approximately the same place in both years. The plot on the left shows bedload as a function of SGN while the plot on the right shows bedload as a function of discharge. Power-law regression lines show that the empirical relation of bedload to discharge changed between these two years, whereas the relation between bedload and SGN was relatively constant.

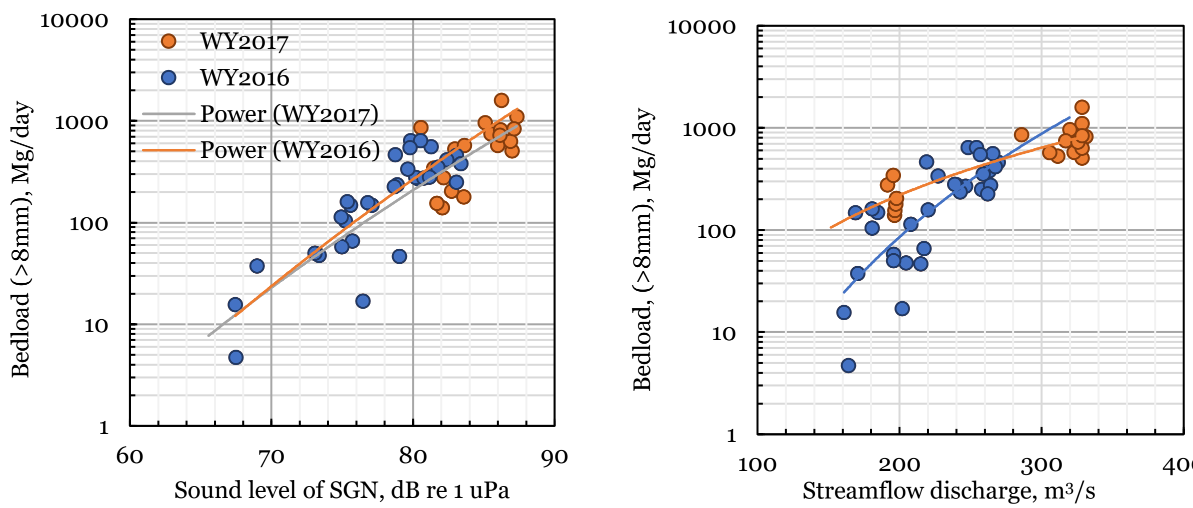

Figure 8. Comparisons of SGN vs bedload (left panel) and streamflow discharge vs bedload (right panel) for two consecutive years at same site with power-law regression lines for each year shown; Trinity River at Lewiston, CA. Gravel is sometimes injected approximately 1.6 km upstream from this site.

Arroyo de los Piños, Socorro, New Mexico, WY 2018

At the Arroyo de los Piños site, a large runoff event occurred about a week after the hydrophones were installed. One recorder (right bank) was fully operational during the event and recorded about 4 hours of audio data. Sediment samples were only collected at the very beginning of the event not collected during this event; however, other experimental surrogate methods were in operation in addition to the hydrophones (Stark et al, 2019). During this event, both hydrophones recorded a similar surge in SGN during the peak of the event (Figure 9). After that subsided, a second surge occurred only in the upper hydrophone while SGN recorded from the lower hydrophone remained relatively flat. Raw recordings from the lower hydrophones sounded muted, suggesting that aggradation had buried them during the event and subsequent scour possibly re-exposed them later.

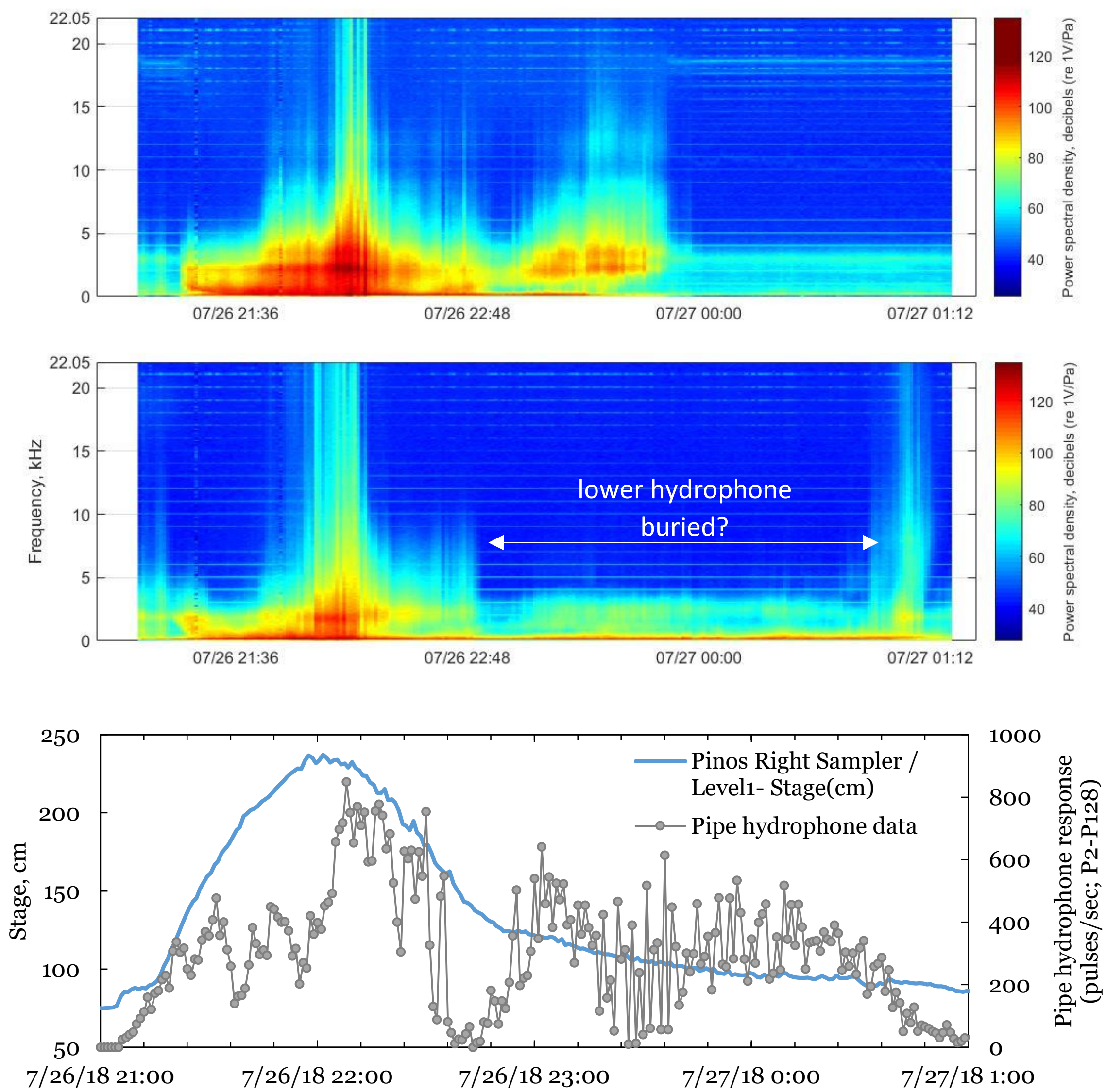

Figure 9. Acoustic data from right bank Arroyo de los Piños, NM, July 2018. Top panel is from the upper hydrophone, middle panel is from the lower hydrophone. The bottom panel shows stage and pipe hydrophone data during the same event (Stark et al. 2019).

Summary bedload data collection information

Table 3. Summary of bedload data collection information from each study

Site	Water years monitored	Bedload samples and sampler	Highest flow (m^3/s) or stage (m) during monitoring	>8 mm bedload measurement range (Mg/day)	Bedload/ SGN signal present?
Sauk River, Washington					
Sauk River at Darrington, WA	2018	6 samples using TR-2	1,120 m^3/s (estimated[a])	206–2,400 ~33% coarse[b]	Yes
Trinity River, California					
Trinity River at Lewiston	2016-17	19–64 samples using TR-2	340 m^3/s (4/26/2017)	3–1,442 ~82% coarse[b]	Yes
Trinity River above Grass Valley Creek	2015-16	14–53 samples using TR-2	283 m^3/s (5/10/2016)	4-2204 ~79% coarse[b]	Yes
Trinity River at Lime Kiln Gulch	2016	72 samples using TR-2	300 m^3/s (5/10/2016)	5-1034 ~67% coarse[b]	Yes
Trinity River at Douglas City	2015-16	13–53 samples using TR-2	314 m^3/s (5/10/2016)	19-3420 ~62% coarse[b]	Yes
Arroyo de los Piños, New Mexico					
Arroyo de los Piños, NM	2018	~27 samples per event from 3 slot samplers[d]	~ 1.6 m (7/26/2018)	[measured in kg/s·m][d] ~34% coarse	Yes
Esopus Creek watershed, New York					
Stony Clove Creek, NY	2017-18	8 samples using Elwha	35 m^3/s (7/24/2018)	1.7–38.3 ~40% coarse[b]	Yes[c]
Birch Creek, NY	2017-18	3 samples using Elwha	16.7 m^3/s (8/17/2018)	0.03–0.3 ~17% coarse[b]	No[c]
Shinumo Creek, Arizona					
Shinumo Creek, AZ	2015	1 sample using BLH-84	1.18 m (3/23/2016)	4.9 ~25% coarse[b]	Yes

[a]Discharge at the Sauk River at Darrington gage (Station No. 12187500) was discontinued July 2017. Streamflow estimate here is mean of the next upstream and downstream gages.
[b]"% coarse" is defined as the percent of the total bedload with particles having diameter >8 mm.
[c]Audio signal quality degraded by excessive water-turbulence and air-entrainment noise.
[d]Slot-samplers were used to record continuous bedload data during 4 events in WY2018, acoustic monitoring occurred during 2 of those events; bedload transport rates recorded during those events ranged from 1.0 to 16.5 kg/second-meter

Esopus Creek Watershed (Birch and Stony Clove creeks), New York, WY 2018

At the Birch and Stony Clove creek sites, the largest event in WY2017 was about a 2-year recurrence interval event. Audio recordings from that event revealed that the hydrophones detected very little SGN. However, listening to the raw audio files indicated a significant amount of noise, likely from water turbulence due to air entrainment around the large cobbles and small boulders. More testing is needed in this type of stream to determine if larger events would produce enough sediment-generated noise in the underwater soundscape for passive acoustic bedload monitoring to be useful.

Shinumo Creek, Grand Canyon National Park, Arizona, WY 2016

Shinumo Creek was one of the steepest channels monitored with hydrophones. Prior to the acoustic bedload monitoring study, the creek experienced a large post-wildfire flood which filled the channel with sediment (Schenk et al, 2017); much of it was gravel-size. The combination of readily available sediment supply and relatively steep channel (~3.5 percent slope) created conditions for sediment to be easily transported even during modest runoff events. A clear SGN signal was detected at this site during three runoff events; the largest was on 7/27/2018 with a water depth of about 1.6 meters (Table 3). The creek is located in a remote part of Grand Canyon National Park, AZ, and therefore only one bedload sample was collected during this study.

Discussion

The study on the Trinity River has provided a range of results and insights into the methods for acoustic data collection such as site selection, hydrophone placement, recorder placement, and bedload sampling protocols. The four sites on the Trinity generally have similar sized bed-material; therefore, other sites were tested to gain further insight into acoustic data collection. These other sites included a much larger, unregulated gravel-bed river, two steep gravel/cobble-bed creeks, and an ephemeral sand/gravel-bed creek. These deployments have provided valuable information on hydrophone performance in a wide range of conditions and serve as a guide for future improvements in the methods.

Location of bedload transport within the channel appears to be a significant factor in site calibration. At the Trinity River at Lewiston site most (67 percent) of the bedload transport was in the middle third of the channel and as a result, SGN did not show a particularly strong correlation to bedload in the left or right third of the channel. However, acoustic data at another Trinity River site (Marineau et al., 2017) showed a high correlation when the hydrophones were placed adjacent to the thalweg, where (presumably) most transport occurs. Alternatively, at the Sauk River, while fewer bedload measurements were collected, about 60-75 percent of the bedload occurred in only 3 subsamples, all of which were near the left bank. The SGN recorded on this side of the river was also much louder than that on the right bank. While there were not enough samples to calibrate the Sauk River acoustic data, the available data suggest that hydrophones on the left bank detected a greater portion of the bedload and that using pairs of hydrophones (i.e. one recorder on each bank) and compositing subsamples by lateral subsection of the transect may improve calibration efforts at some sites.

Hydrophone burial appears to be an issue in smaller creeks as well as larger dynamic rivers. The lower hydrophone at the Arroyo de los Piños and multiple hydrophones in the Sauk River were buried. To strike a balance between hydrophone burial during large events, and hydrophones not being submerged during low-flow events, hydrophones can be placed at two elevations along the bank: one low on the bank and another near mid-bank.

Lastly, the sampling frequency, which has typically been 15- or 20-minute intervals, was adjusted to sample continuously (every minute) at Arroyo de los Piños (due to the short-lived runoff events) and continuously at the Sauk River and Esopus creeks during sampling. In the latter two studies, the continuous audio recording was to determine if capturing all the short-term temporal variability would improve site calibration. At the Sauk, the level of SGN changed only gradually. Thus, over a 1–2-hour bedload sampling period, a 15-minute series of audio samples would have been sufficient. The bedload response and transport mechanisms will likely vary from site to site, therefore, we recommend collecting and evaluating continuous recordings initially at a new site.

In conclusion, while results are pending for the study areas with smaller creeks, passive acoustic monitoring appears to work well for measuring sediment-generated noise in gravel-bed rivers. The findings and recommendations documented herein can be used to guide installations and sampling protocols at new sites.

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