SEDIMENT-GENERATED NOISE (SGN): COMPARISON WITH PHYSICAL BED LOAD MEASUREMENTS IN A SMALL SEMI-ARID WATERSHED

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Abstract: Passive acoustic techniques for the measurement of Sediment-Generated Noise (SGN) in gravel-bed rivers present a promising alternative to traditional bedload measurement techniques. Where traditional methods are often prohibitively costly, particularly in labor requirements, and produce point-scale measurements in time and space under highly heterogeneous conditions, acoustic techniques offer the potential to inexpensively monitor gravel movement quasi-continuously over larger spatial scales. While acoustic methods show great potential, significant work is required to provide a general relationship between acoustic signals and physical bedload sampling under field conditions. We addressed this problem by deploying hydrophones for monitoring SGN in the Lucky Hills subwatershed of the USDA-ARS Walnut Gulch Experimental Watershed for the 2014 runoff season (July-September). Bedload was collected using a pit sampler attached to a supercritical Santa Rita-style measuring flume at the catchment outlet. Results of the comparison of physical measurements with SGN monitoring are shown for three runoff events. The field results are compared with expectations derived from theory and laboratory experiments to suggest improvements and new directions for future SGN investigations.

INTRODUCTION

Conventional measurements of bed load are difficult, time consuming, often of unknown accuracy, and expensive. Consequently, data on the rate of bed load transport of most streams is lacking. There is an ongoing need for low-cost instrumentation that can be deployed to work autonomously in remote locations. One promising technology that has been used as a surrogate for bedload in the past is recording sound made by particles transported by flow, which will be referred to as Sediment Generated Noise (SGN), and converting the acoustic energy into a transport rate (Gray et al. 2010). The equipment needed for the recording is relatively inexpensive and is amenable to customization into a self-contained unit. Previous work has examined sound propagation in shallow natural environments (Forrest et al. 1993; Forrest 1994) and the potential for SGN monitoring in large rivers (Barton 2006). A key need for the advancement of SGN work is a broader database of acoustic signal in different hydraulic settings and the development of data analysis techniques. For this information to be useful, the acoustic data needs supporting independent sediment load measurements that can be used in the

interpretation of the acoustic data. Our work was supported by the Federal Interagency Sedimentation Project and represents an effort to improve the techniques used to convert SGN to rates of bed load transport. Here, we describe a field test in a natural channel within the Walnut Gulch Experimental Watershed, near Tombstone, Arizona. The results include a detailed analysis of the frequency content of the acoustic signal and correlation of load with specific acoustic bandwidths.

METHODOLOGY

Data were collected in the Lucky Hills watershed, a 9.1 acre subwatershed of the United States Department of Agriculture (USDA), Agriculture Research Service (ARS) Walnut Gulch Experimental Watershed near Tombstone, Arizona. Average annual precipitation for the watershed over the period 1961-2013 was 356 mm yr^{-1} with approximately two-thirds of annual precipitation occurring during the summer monsoon season (July-September). Soils in the watershed are primarily sandy loam with a large fraction of coarse material composed of fragmented rock. Figure 1 shows the particle size distribution of bed material taken near the outlet of the Lucky Hills watershed. Further characterization of the study area is available in Ritchie et al. 2005.

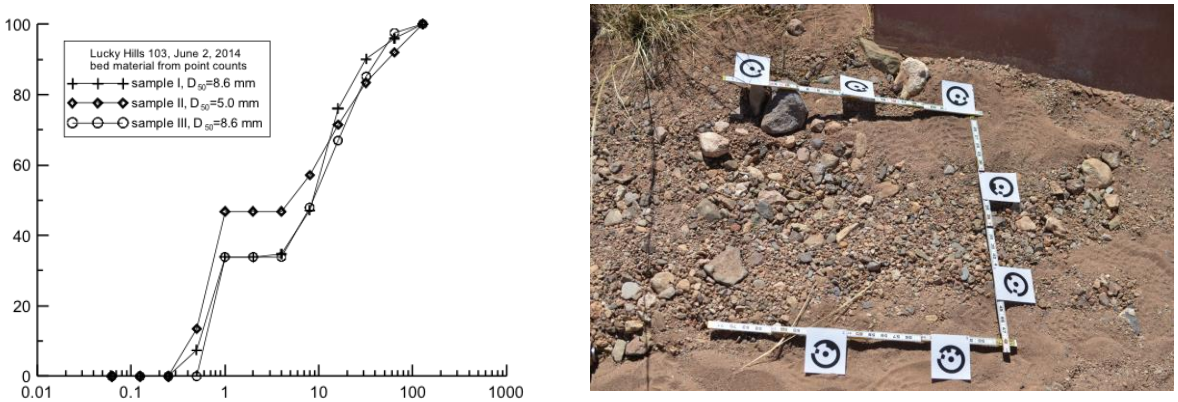

Figure 1 Left: Particle size distribution (mm) from three samples taken along the Lucky Hills watershed main channel. Large fractions of sandy loam and coarse angular material resulted in a bimodal size distribution. Right: Photo of typical coarse sediment deposits along the ephemeral channel.

Two hydrophones were deployed in the watershed immediately upstream of the Santa Rita style measuring flume at the watershed outlet (Figure 2). Due to the low flow depths anticipated during runoff events, the hydrophone housing was installed within 2 cm of the bed oriented in a downstream direction. Each hydrophone was deployed in a PVC housing affording moderate directionality in the measured acoustic signal. Hydrophones and amplifiers from Teledyne Reson were used to record sound at a rate of 25 kHz, using a computer with a multi-channel data acquisition card. The hydrophones were manually activated at the onset of precipitation prior to the appearance of runoff and sampled through the entire hydrograph.

Figure 2 Left: The Santa Rita style flume at the outlet of Lucky Hills subwatershed. This view faces upstream from the outfall (where the pit sampler was later placed) toward the hydrophone mount (post seen in the upstream channel). Right: Photo of the PVC housing of the downstream hydrophone (mounting post visible in center of left photo).

Coarse sediment was collected at the outflow of the measuring flume using a 75cm deep rectangular pit sampler. The walls of the sampler were constructed with 3 mm perforated sheet steel to allow water and finer particles to pass through during a runoff event. After each event the bulk load was removed from the pit trap, dried, and sieved into four size classes using ½", 16 mm, 32 mm, and 64 mm sieves. The size range for coarse sediment collection was chosen based in part on both the particle size characteristics of the site and on expected acoustic emissions from particles based on earlier studies. The particle size distributions derived from channel sediments shown in Figure 1 show a bimodal distribution with very little mass occurring in the 1-10 mm range. Thorne (1985, 1986) found that peak emission frequency and equivalent spherical diameters of natural marine sediments approximately followed the relationship

$$f_{peak} = 209/D^{0.88} \tag{1}$$

where the frequency, *f*, is given in Hz and diameter, *D*, in meters. Accordingly the expected peak emission frequency for a 10 mm particle should be approximately 12 kHz which is very near the resolving limit of our 25 kHz sample rate.

RESULTS

Seven runoff events were monitored between August 1 and September 8, 2014 (Figure 3). The total coarse sediment load (>12mm) for each event ranged from 0.13 kg to 444 kg, peak stage from 1.5 cm to 26 cm, and runoff duration from 28 minutes to 5.25 hours (Table 1). The size distribution of the coarse sediment load for each event is summarized in Figure 4 and Table 1. In each of the larger events, the intermediate coarse fractions (16-64 mm) represented the majority of the sampled mass.

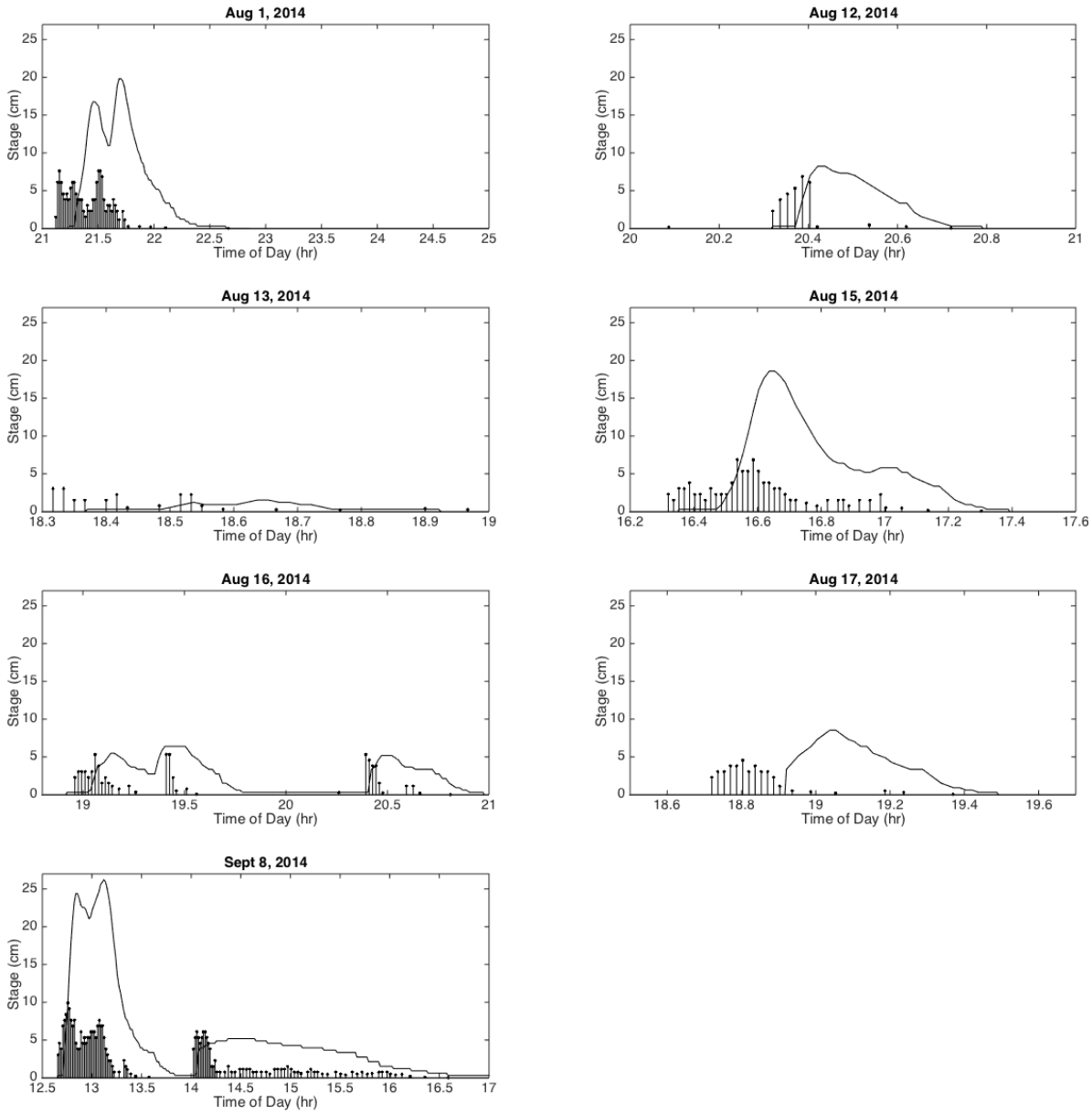

Figure 3 Hydrographs of the seven runoff events from Lucky Hills subwatershed monitored in August-September 2014. The stem plots overlaid show the occurrence of precipitation (heights shown are 1/10 of rain rate in mm/hr) at Rain Gage 83 near the center of the watershed.

Figure 5 shows a sample hydrograph from the flow event on August 15. The acoustic data for these events is also shown, represented by the integrated acoustic signal (volts) over one minute bins. There is an initial peak in the acoustic data associated with flow-induced noise around the instrument housing as the hydrophones were submerged (at ~8cm stage) followed by a period of elevated acoustic activity during the peak of the hydrograph until the stage again falls below the submergence level of the instrument. Three of the events (August 1, August 15, and September 8) reached depths significantly above 8cm which provided the target acoustic data with the hydrophone fully submerged.

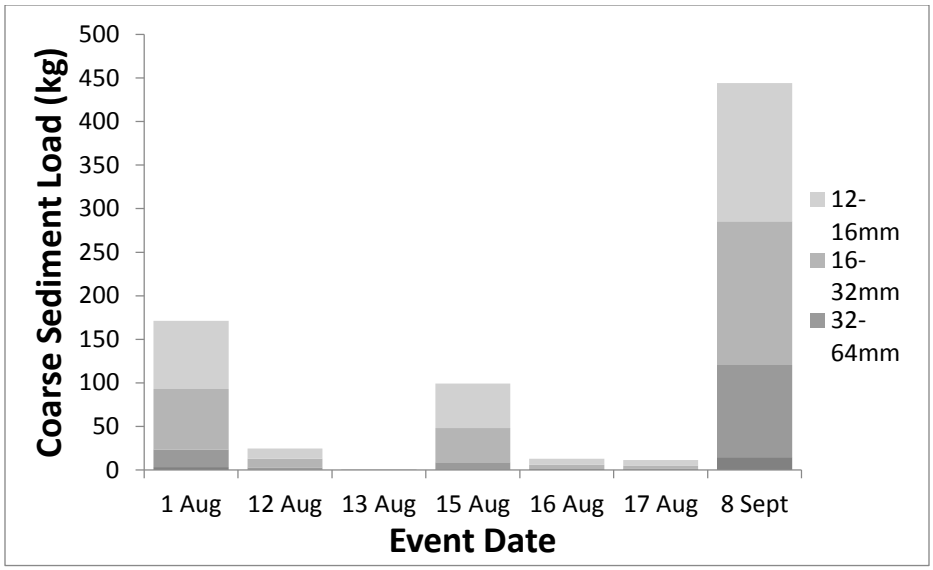

Figure 4 Coarse sediment load by size fraction for the seven runoff events monitored in 2014 in the Lucky Hills subwatershed. Coarse sediment was collected in a pit trap below the outlet flume and sieved for size fractions.

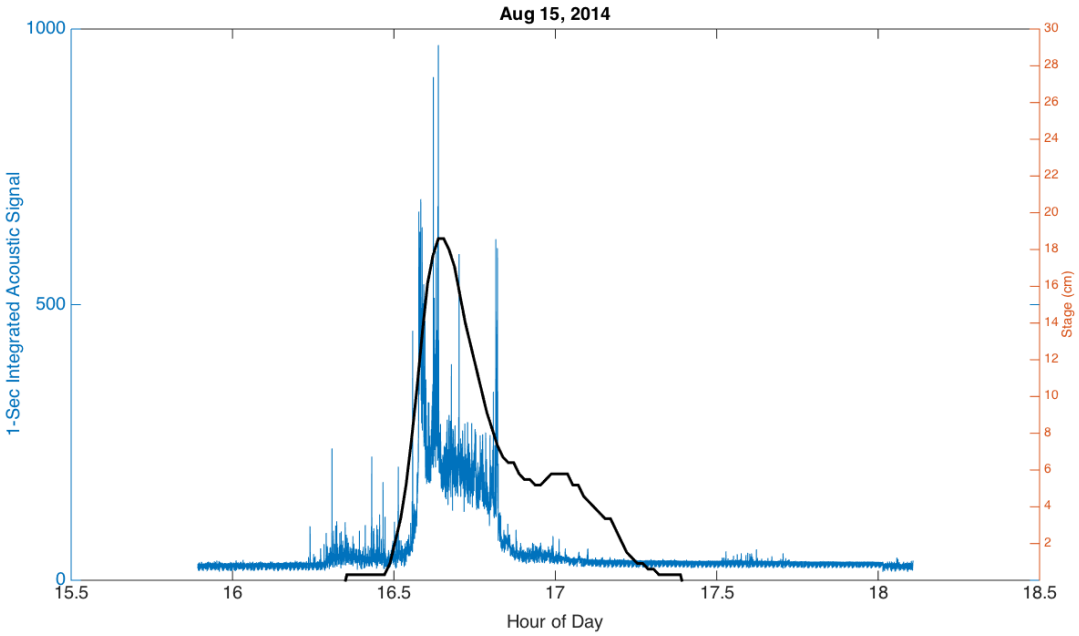

Figure 5 Hydrograph (black) and concurrent rectified acoustic signal (25kHz sampled voltage summed over one-second bins) for the August 15, 2014 runoff event. Note the rain noise prior to the rise in the hydrograph, and spikes in acoustic signal around stages of 8-10cm as the instrument was submerged and later reemerged associated with flow noise generated by the instrument housing.

The acoustic signal recorded over the course of the hydrograph is a composite of: (1) rain drop noise striking the instrument before it was submerged and the water surface after submergence; (2) elevated flow noise near the time of submergence when the water surface was at the hydrophone; (3) flow noise around the instrument housing while the instrument was submerged; and (4) acoustic emissions from particle collisions. Bjorno (1994) studied the acoustic spectra of rain splash on a free water surface and found that the acoustic energy peaked near 15 kHz with a minimum near 5 kHz. Flow noise around the instrument housing was recognizable by ear during and after submergence and displayed characteristic frequencies in the 0-2 kHz band. With these observations suggesting a window of opportunity where noise generated by particle impact would not be mixed with sound from other sources, we focused analysis on frequencies in the range 3 kHz – 11 kHz. Figure 6 shows the correlation over the three largest events between the coarse sediment load and the integrated acoustic signal in each of eight 1-kHz frequency bands beginning at 3 kHz. Each data point in Figure 6 is the correlation over three events between sediment load and SGN amplitude for a frequency band. In all cases the correlations are high, but the larger size fractions show both higher correlations and more structure as a function of frequency band with a peak near 5-6 kHz. Employing Thorne's relationship for peak emission frequency (equation 1), this would correspond to a particle size of approximately 24 mm which is notably near the median of the coarse fraction in Figure 1. The lack of frequency dependence in the correlation in the 12-16 mm particle size class suggests that the signal was made up of a combination of particle impact other flow-generated noise. It is logical that SGN and 12-16 mm load are still well-correlated, but the greater energy generated by the impacts of larger particles provide a better picture of how transport changed with passage of the hydrograph. Finally, while three events make a sparse data set, the overall high correlations in Figure 6 as well as the linear relationship shown in Figure 7 show a very promising relationship between coarse sediment load and integrated acoustic signal in the 5-6 kHz band for the three events.

Table 1 Coarse sediment load and runoff statistics for the seven monitored events.

Event	**Runoff**		**Coarse Sediment Load** (kg)				
Date	Duration (hr)	Peak Stage (cm)	>64mm	32-64mm	16-32mm	12-16mm	Total
Aug 1	1.4	19.8	3.31	20.27	69.45	78.07	171.1
Aug 12	0.47	8.2	0.42	2.62	9.82	11.73	24.59
Aug 13	0.55	1.5	0	0	0.05	0.08	0.13
Aug 15	1.03	18.6	0.81	8.04	39.29	50.9	99.04
Aug 16	2.05	6.4	0	1.08	4.8	7.13	13.01
Aug 17	0.57	8.5	0.66	1.06	3.53	6.32	11.57
Sept 8	5.25	26	14.64	105.86	165.05	158.7	444.25

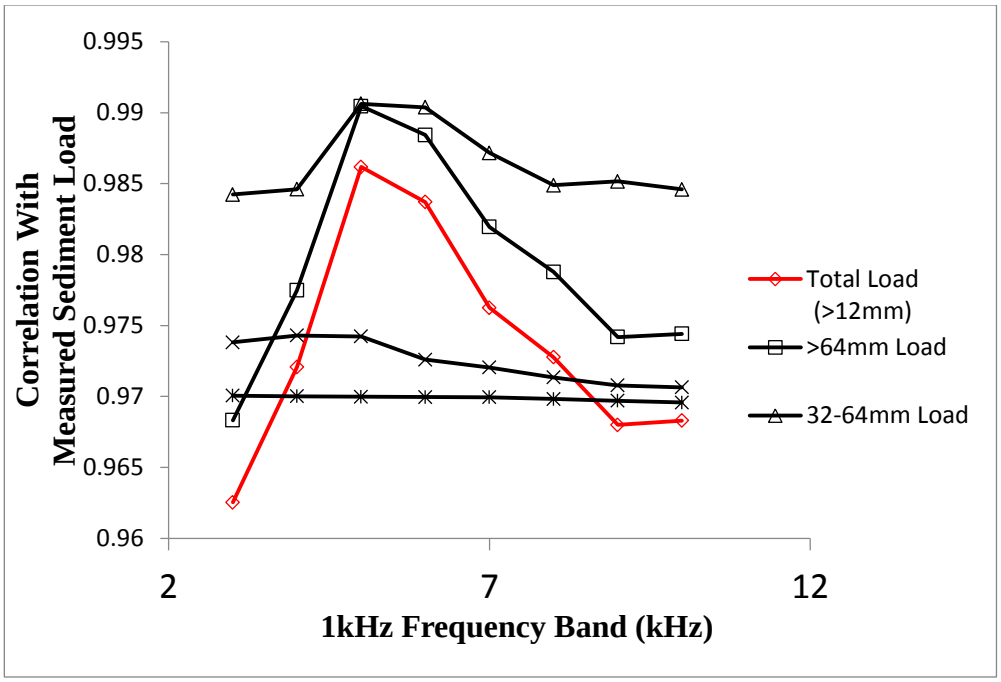

Figure 6 Correlation between coarse sediment load data and integrated acoustic signal for three runoff events (Aug 1, Aug 15, Sept 8). The power spectra of the acoustic data were integrated in 1 kHz bands from 3 kHz to 10 kHz to examine correlation with each size class of total sediment load. Correlation for the coarsest fractions is strongest in the 5-6 kHz frequency range.

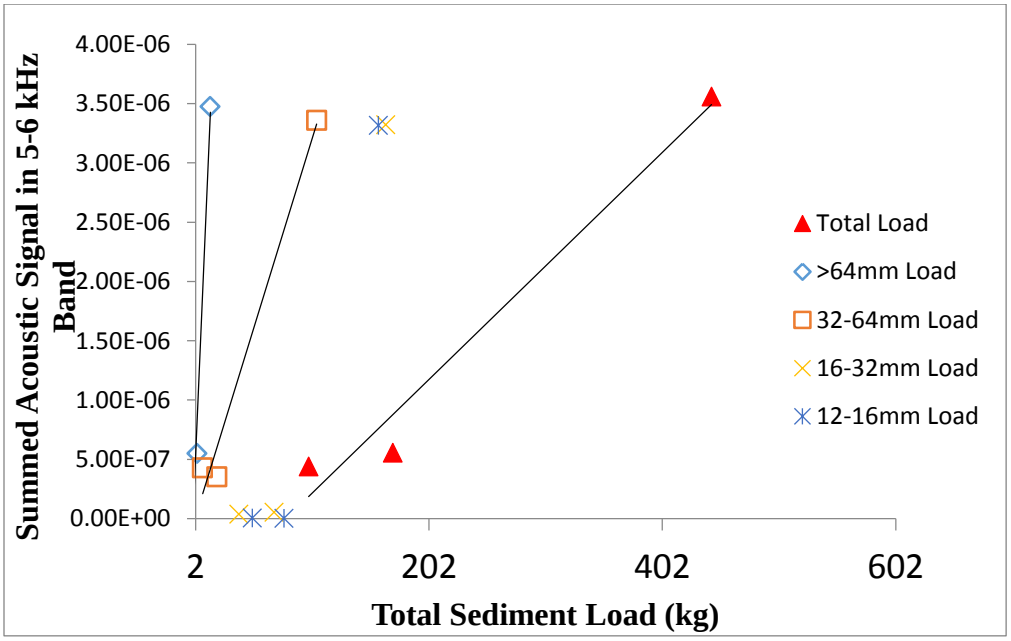

Figure 7 Relationship between integrated acoustic signal in the 5-6 kHz band versus coarse sediment load for the three largest runoff events.

CONCLUSION

We deployed hydrophones in a flashy ephemeral watershed in southeast Arizona to evaluate the potential for using passive acoustic measurements to monitor coarse sediment transport in streams. This location provided discrete flow events during which the entire coarse sediment load of the stream could be captured for analysis and characterization. While shallow flows reduced the number of events that completely submerged the hydrophone, the results of the three large flow events shown in Figures 6-7 are a high quality acoustic data set with known sediment loads. In particular, the frequency range 3 kHz-11 kHz provides a useful window that is below the peak frequencies of rain splash but above the dominant frequencies of flow noise. Correlation between total sediment load and integrated acoustic signal was high for all size classes across the frequency range of interest with a peak for the large size classes in the 5-6 kHz band.

This study has implications for future efforts to use SGN as a surrogate for bedload in flashy streams.

- Development of hydrodynamic housings for hydrophone deployment would further reduce flow noise around the instrument and simplify data analysis.
- Further study of the frequency content of acoustic phenomena such as raindrop impact may help in the separation of SGN from sound generated from other sources.
- It may be possible to use the low frequency data from the hydrophone system as an indication of flow strength, increasing the usefulness of data collected in remote deployments.

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