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 trap 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.

Project Summary

The goal of this project was to combine laboratory flume experiments at the National Sedimentation Laboratory (NSL) with a field campaign at Walnut Gulch Experimental Watershed in order to provide calibration data for Sediment-Generated Noise (SGN) research.

Major Results

- Waveguide effects on frequency propagation in the flume were investigated and characterized during a series of rock-towing experiments at NSL.
- Acoustic and sediment load data were collected for seven runoff events in Walnut Gulch Experimental Watershed (WGEW).
- Correlations between sediment load and acoustic signal were tested for each 1 kHz frequency band up to 11 kHz. The highest correlation was found for 10-11 kHz.
- A metric based on integrated acoustic power (IP) was defined and hypothesized to be directly proportional to total coarse sediment load by mass for an event.
- **A strong linear relationship was found between IP_{10}, integrated acoustic power in the 10-11 kHz frequency band, and all size classes of the coarse sediment load (Fig. 10).**
- Measurement of instantaneous correlation between hydrophone signals suggests that acoustic conditions in the channel during an event are not reverberant, in contrast to laboratory conditions, which bodes well for future SGN deployments.
- The strong IP_{10} relationship suggests that analogue circuits for bandpass filtering and integration may be a feasible method for reducing both data acquisition rate and data storage for SGN data.

The results of this study also suggested some important general conclusions that should be considered for future SGN research and data collection:

- Hydrophones should be deployed in pairs to allow cross correlation analysis of signal parameters, which may allow for better separation of SGN from other ambient sound.
- The development of robust streamlined housings are essential for continued development of SGN procedures. Flow noise generated around housings may be masking important parts of the frequency spectrum.

Laboratory Component: In practice, the laboratory component of the project posed the greatest challenges. The reverberant environment of the laboratory flume proved an unexpected and substantial difficulty as it created strong spatial dependencies in the sound field that subverted many simple experiments designed to clarify SGN processes. Facing these challenges suggested numerous topics for additional research.

Field Component: Two hydrophones were deployed in the Lucky Hills catchment of Walnut Gulch Experimental Watershed. Only three of the seven recorded events

were large enough to completely submerge the hydrophones. Coarse sediment load was captured in a pit trap downstream of the outlet flume and was then dried and sieved into four size classes. Suspended sediment was also sampled using a traversing slot sampler. Based on spectral analysis, a metric was developed that integrates the acoustic power in specific frequency bands over the entire runoff event. This metric shows a strong linear relationship with coarse sediment load commensurate with SGN theory published by Thorne (1985).

1. 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). Key needs for the advancement of SGN work are 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.

2. METHODS AND EQUIPMENT

All acoustic data was recorded with RESON TC4013 hydrophones amplified by RESON E6061 preamplifiers. This signal was digitized by a National Instruments 9215 data acquisition module and recorded with a custom Labview script. The hydrophones were mounted in a protective casing, illustrated in Figure 1, to protect the instrument during deployment and shield the cable between the instrument and the data acquisition equipment. The effects of the casing on the acoustic properties (directionality and frequency response) of the hydrophone are the subject of ongoing experiments. Preliminary data on the directionality of the hydrophone when deployed in the casing is also shown in Figure 1.

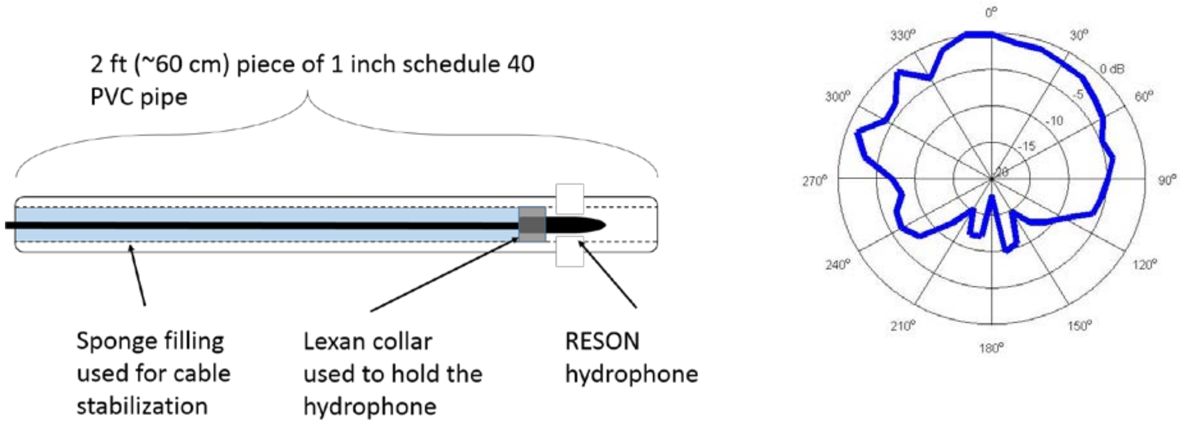

Figure 1. Schematic diagram of the hydrophone housing (left) used for both laboratory and field experiments with a polar plot (right) of the directional sensitivity of the hydrophone within the housing.

2.1. Laboratory Methods

The original set of experiments aimed to create precisely known particle movement by towing rocks over an immobile gravel substrate while recording the resulting sound. The experiment was conducted at a gravel flume at the National Sedimentation Laboratory in Oxford, MS, in conjunction with researchers from the National Center for Physical Acoustics. The basic design of the experiment was to use a programmable motorized carriage to tow particles at known speeds over a fixed gravel bed. By using the carriage to move particles rather than flowing water, the velocity of the particle was known and flow noise was eradicated.

The gravel bed, seen in Figure 2, was constructed by gluing gravel (D_{50} = 30 mm) to an 8ft by 4ft (2.4m by 1.2 m) section of ½-inch thick plywood. Five different rocks were measured for linear dimensions and mass and then tied to the motorized carriage, which was programmed to run at three different speeds. Table 1 shows the sediment flux calculated from the different combinations of rock and speed. The acoustic signal generated by the towed rocks was detected using two hydrophones. The data was filtered using a 500 Hz high-pass filter in order to eliminate the noise generated by the motorized carriage.

Figure 2. The flume test-section configured for the rock-towing experiments. Gravel substrate shown has been rigidly fixed to an underlying plywood bottom set atop a layer of sand. Individual particles (Table 1) were then towed across the substrate using the instrument cart above the flume in the photo.

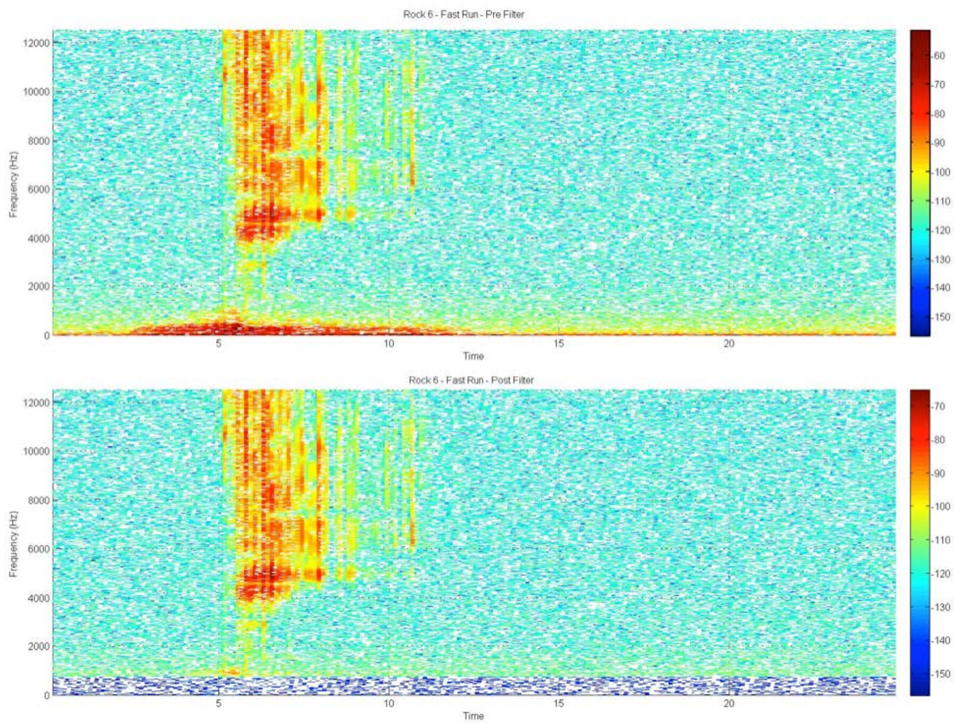

Figure 3. Spectrograms of acoustic signal during rock-towing before and after application of a 500 Hz high-pass filter. In the upper panel the low-frequency signal generated by the instrument carriage can be seen before, during, and after the high-frequency particle-on-particle interactions as the towed rock comes within range of the hydrophone. In the lower panel, the low frequency noise has been eliminated.

Table 1. Rock-dragging experimental runs.

Run #	Rock #	Mass (kg)	Dimensions (mm)	Speed (m/s)	Flux (kg/s)
1	1	0.1846	66 x 56 x46	0.082	0.0071
2	1	0.1846	66 x 56 x46	0.3	0.0260
3	1	0.1846	66 x 56 x46	0.56	0.0485
4	2	0.0894	61 x 35 x 31	0.082	0.0034
5	2	0.0894	61 x 35 x 31	0.3	0.0126
6	2	0.0894	61 x 35 x 31	0.56	0.0235
7	3	0.1249	65 x 47 x 28	0.082	0.0048
8	3	0.1249	65 x 47 x 28	0.3	0.0176
9	3	0.1249	65 x 47 x 28	0.56	0.0328
10	4	0.1767	80 x 50 x 33	0.082	0.0068
11	4	0.1767	80 x 50 x 33	0.3	0.0249
12	4	0.1767	80 x 50 x 33	0.56	0.0465
13	5	0.3236	85 x 70 x 47	0.082	0.0125
14	5	0.3236	85 x 70 x 47	0.3	0.0456
15	5	0.3236	85 x 70 x 47	0.56	0.0851

2.2. Walnut Gulch Field Campaign

2.2.1. Site Characterization

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 4 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).

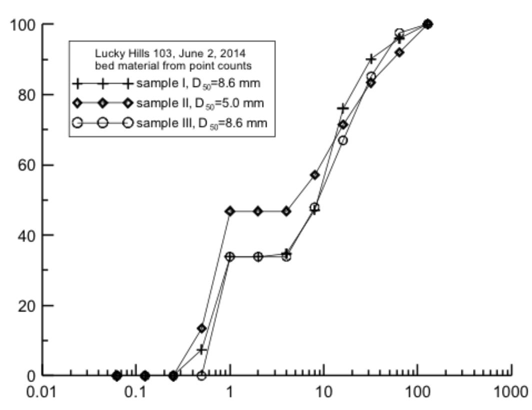

Figure 4. **Left: Particle size distribution (mm) from three samples taken along the**

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.

2.2.2. Instrumentation

Two RESON TC4013 hydrophones with RESON E6061 preamplifiers were deployed in the watershed immediately upstream of the Santa Rita style measuring flume at the watershed outlet. Due to the low flow depths anticipated during runoff events, the hydrophone housing was installed within 2 cm of the bed and oriented downstream. Each hydrophone was deployed in a PVC housing affording moderate directionality in the measured acoustic signal (Figure 1). Sound level was sampled at a rate of 25 kHz, using a computer with a multi-channel data acquisition card. The hydrophones were manually activated by a technician at the onset of precipitation (prior to the appearance of runoff) and sampled through the entire hydrograph.

Coarse sediment was collected at the outflow of the measuring flume using a 75cm deep rectangular pit trap. 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 show a bimodal distribution with very little mass occurring in the 1-10 mm range. Thorne (1985, 1986) empirically found that peak emission frequency and equivalent spherical diameters of natural marine sediments approximately followed the relationship

$$f_{peak} = 209/D^{0.88}$$

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.

3. RESULTS & DISCUSSION: Laboratory Experiments

Linear dimensions of the rocks used for the experiments ranged from 28 mm to 85 mm, while the mass ranged from 89 g to 324 g. If the average of the three linear dimensions is used to assign a representative particle size, then the representative particle size ranged from 42 mm to 67 mm. Each rock was towed at three speeds over the gravel bed with three replicates for each towing speed. Figure 5 shows the results of the rock-towing experiments. Linear regressions are also shown. For very small transport rates such as these, the data should appear approximately linear, though generally Thorne (1985) predicts a square root relationship between SGN and mass rate.

The SGN signal recorded for each rock at a given speed was consistent across the three runs for Rock 3 and Rock 5. Rocks 1, 2, and 4 displayed much larger variance between runs, particularly at the highest speed. Rocks 1 and 4 were the closest to each other in mass and linear dimensions but resulted in very different regressions. Frequency analysis of the data indicates that the energy generated by the particles was mostly between 3 kHz and 10 kHz, with a significant amount of energy located at 5 kHz.

A major difficulty revealed in these experiments was that of the “reverberant” nature of the flume environment. The walls of the flume (in contact with air on one side) and the water surface act as very efficient acoustic reflectors. In addition, with a speed of sound in water of approximately 1500 m/s and a flume test-section approximately 15m in length, the time between sound emission and reflection from the end of the flume would be less than 1/100 of a second. The flume therefore behaved as a large rectangular resonance cavity for any sustained sound source. The effect of reverberation was to produce a highly correlated and complex sound field in which small changes in the position of the hydrophone or sound source resulted in substantially different results.

Ongoing efforts to expand and improve the rock-towing experiments revealed numerous questions about the absorption and propagation of SGN signals in water-filled channels that have become objects of further study. Within the context of this project, initial investigation of the “measurement volume” of a hydrophone became the focus of a second proposal funded by FISP under the direction of Daniel Wren. This work included the development of a repeatable mechanical sound source using a hydraulic arm and impact plate that generates an impulse-like emission that mimics the sound from a single particle interaction. Details of this work will follow in a future report.

While the premise of the rock-towing experiments shows promise, preliminary experiments were inconclusive pending further investigation into the acoustic properties of natural and synthetic channels.

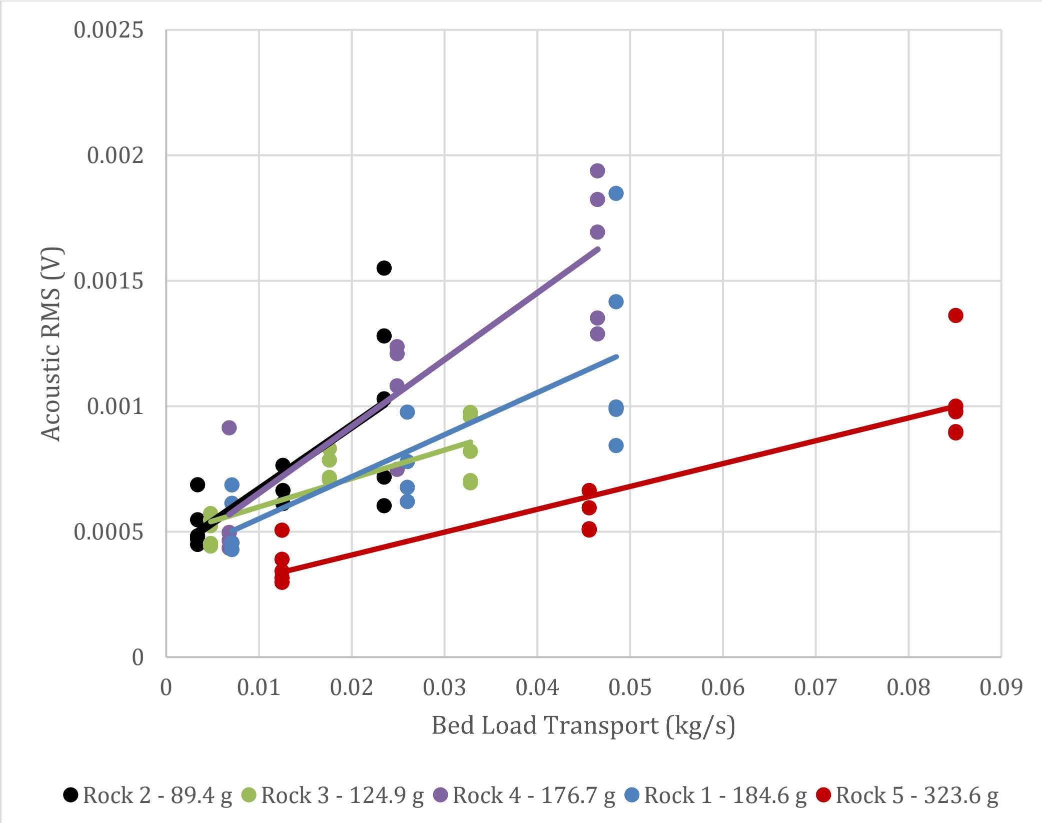

Figure 5. Results from rock dragging experiment showing linear correlation between RMS and bed load transport which is dependent on particle size.

4. RESULTS & DISCUSSION: Walnut Gulch Field Campaign

Seven runoff events occurred in the field campaign between August 1 and September 8, 2014 in the Lucky Hills catchment. Acoustic data and sediment load were collected for all seven events. The hydrophones were activated manually prior to each runoff event at the appearance of precipitation. In four of the events, stream stages were not sufficient to submerge the hydrophones. For events of August 1, August 15, and September 8, 2014, the hydrophones were submerged during the runoff peaks and provided quality SGN data.

4.1. Sediment Load

Coarse and fine sediment loads were collected separately using a pit sampler and a traversing slot sampler, respectively, both attached to the flume at the outlet of the catchment. Coarse sediment samples were removed, dried, and sieved into four size fractions. Fine sediments were dispersed, sieved, and dried during analysis. Figure 6 shows the relationship between sediment transport rate and runoff rate for the sediment collected in the traversing slot sampler, including particles up to approximately 8 mm in diameter.

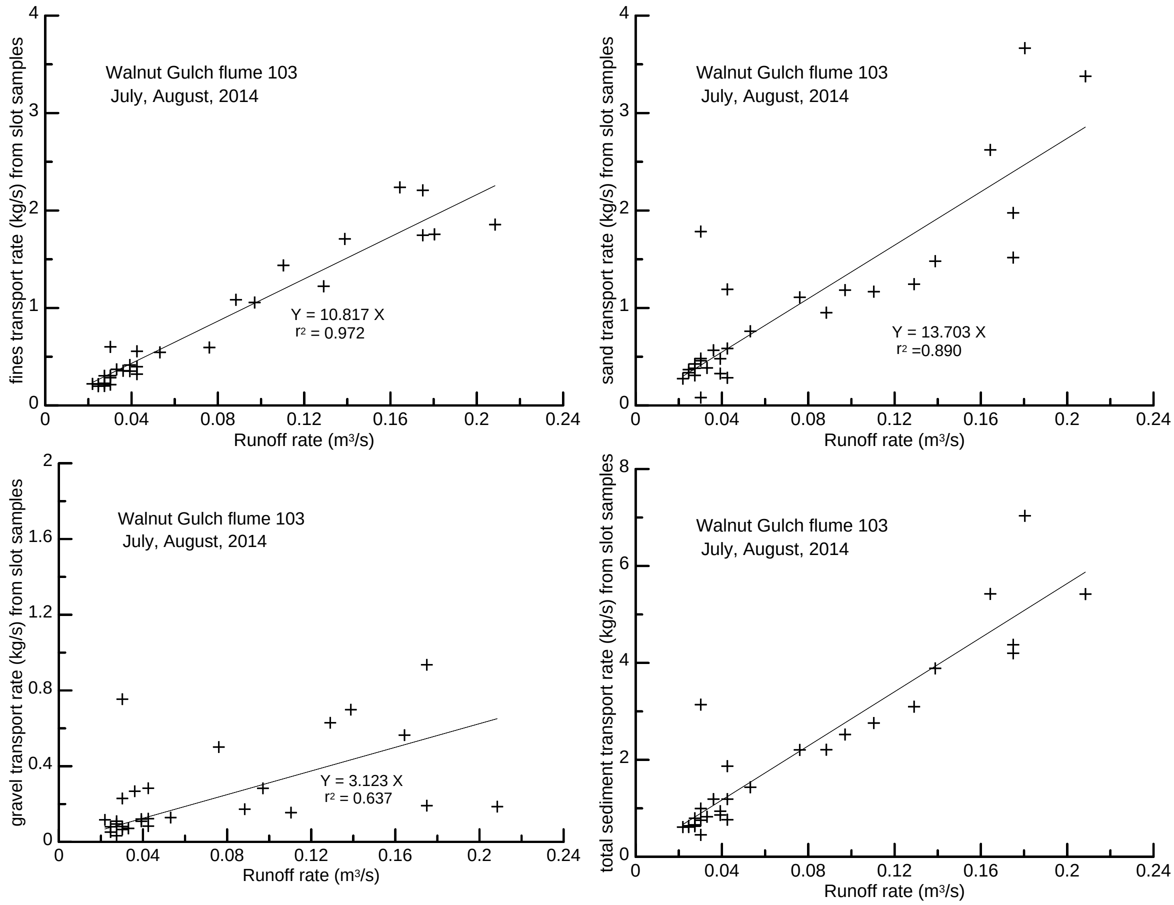

Figure 6. Fine sediment load versus runoff rate collected from the traversing slot sampler in the Lucky Hills watershed (Walnut Gulch flume 103) for fines, sand, gravel and total sediment.

The coarse sediment load results from the pit sampler are summarized in Table 2 and in Figure 7. Coarse sediment loads ranged from 0.13 kg to 444 kg for events ranging in duration from 28 minutes to over 5 hours. Stages were expectedly low with an average peak stage of 12.7 cm and maximum stage of 26 cm.

Table 2. 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

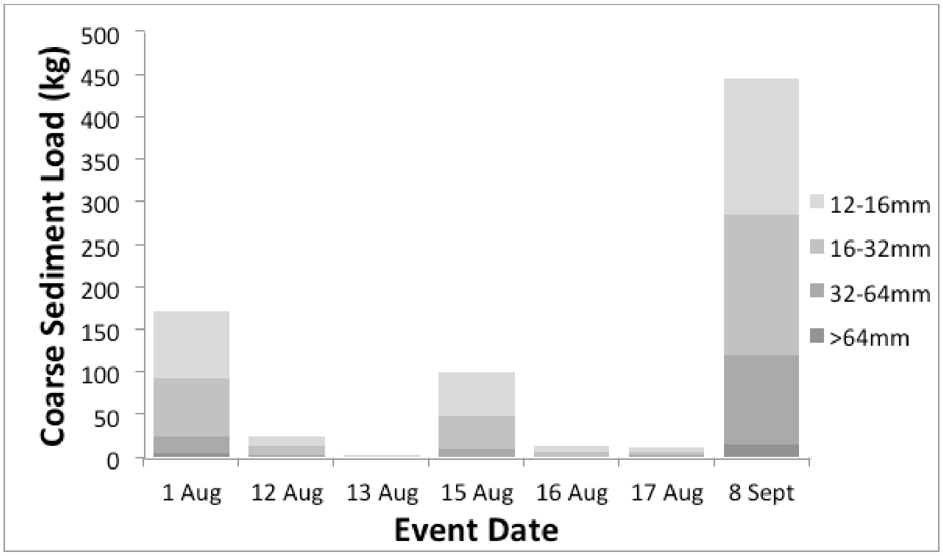

Figure 7. Coarse sediment load by size fraction collected in the pit sampler for the seven runoff events monitored in 2014 in the Lucky Hills catchment. Coarse sediment was collected in a pit trap below the outlet flume and sieved for size fractions.

Table 3. Percent of total coarse sediment load (mass) by size class for each event.

Event	>64 mm	32-64 mm	16-32mm	1/2"-16mm
1 Aug	2%	12%	41%	46%
12 Aug	2%	11%	40%	48%
13 Aug	0%	0%	38%	62%
15 Aug	1%	8%	40%	51%
16 Aug	0%	8%	37%	55%
17 Aug	6%	9%	31%	55%
8 Sept	3%	24%	37%	36%

4.2. SGN Acoustic Data

Figure 8 shows the hydrographs and one-second rms acoustic signals for the three largest recorded events from each deployed hydrophone. The acoustic instrumentation performed very well and provided two channels of quality data for all but the last event (September 8), during which the upstream hydrophone was completely buried by sand.

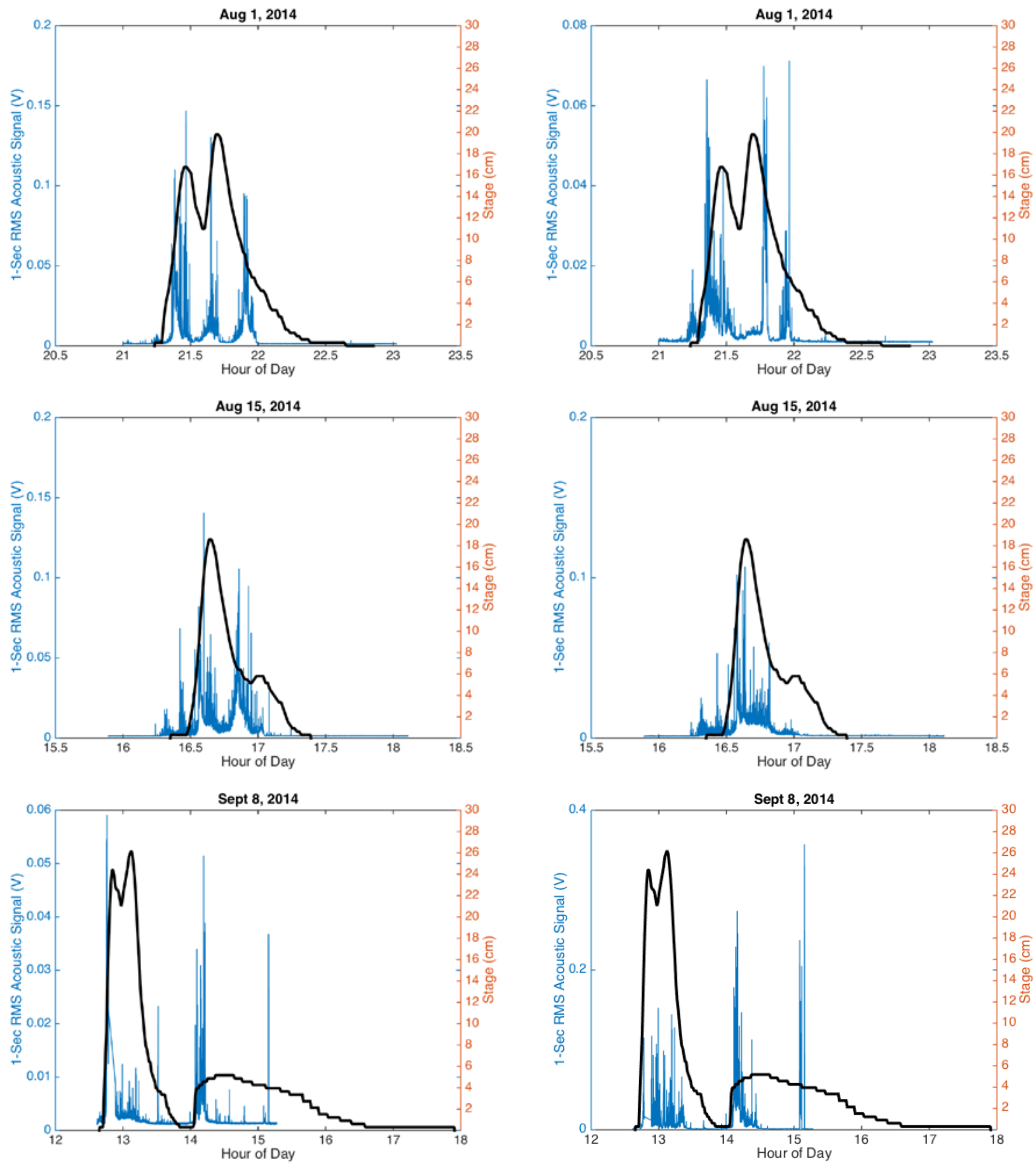

Figure 8. Hydrographs and RMS acoustic signal for the three recorded events during which the hydrophones were fully submerged. The columns represent the upstream (left) and downstream (right) hydrophone signals for each event. The downstream hydrophone was positioned immediately upstream of the throat of the Santa Rita flume at the outlet, while the second hydrophone was approximately 2m further upstream.

4.2.1. Hydrophone Submergence

While the hydrophones were mounted very near the bed, it was still necessary to determine when the hydrophones were fully submerged in order to properly analyze the resulting acoustic data. One could not simply look at the acoustic signal alone because rainfall, thunder, and wind noise were all recorded by the hydrophone before it became submerged. A number of metrics were used to estimate the stage at which the hydrophones were first fully submerged. As can be seen in Figure 8, a spike in the acoustic data appears around a stage of 7 cm – 8 cm for each event. We hypothesized that this spike corresponded to the water surface reaching the face of the hydrophone, maximizing noise from rain-splash and water surface disturbances (e.g., waves). To confirm this hypothesis, we also examined the correlation between the upstream and downstream hydrophone signals. Figure 9 shows that the hydrophone signals were highly correlated when not submerged but displayed consistently very low correlations for the interval when the hydrophones were submerged (see, Aug 1 and Aug 15 events). The sudden transition from high to low correlations suggests both that a sudden change in the acoustic environment occurred (i.e., submergence) and that the underwater environment is largely uncorrelated and thus not strongly reverberant, unlike laboratory flume conditions. Correlation for the Sept 8 event is not shown because only one hydrophone yielded useful data for that event. For the four shallower events, decreases in correlation can be seen but without a distinct region of low correlation (with the exception of a short window on Aug 12). The regions characterized by large, rapid fluctuations in the correlation appear to be coincident with periods of rainfall when the hydrophones were not submerged. These analyses both suggest a stage threshold of approximately 7 cm to 8 cm for the hydrophone to be submerged. For the analyses that follow, we used a slightly more conservative estimate of 9 cm as our minimum stage. The period of SGN data collection was thus limited to the portions of the hydrograph for which stage was greater than 9 cm.

4.2.2. Relating Acoustic Signal to Sediment Load

Thorne (1985) reasoned from experiments on glass spheres in a rotating drum that the rms sound pressure level should be proportional to the square root of the mass of spheres in the rotating drum. Since the drum was rotating, the rms sound pressure level should actually be proportional to the square root of the mass *rate*. At a given time, therefore, the mass rate passing the hydrophone should be proportional to the square of the rms SPL.

Based on Thorne's work on peak emission frequencies from particle collisions in natural sediments, we also hypothesized that the SGN signal would be frequency dependent and that much of the total SPL, particularly at low frequencies, may be attributable to sources other than bed load. We therefore computed power spectra for each event to examine the correlation between the acoustic signal in specific frequency bands and the sediment load. To do this, the time series of hydrophone voltage for each event was divided into 2-minute segments. A power spectrum was estimated for each 2-minute segment and integrated over 1kHz bands from 0-11kHz to give the total acoustic power (variance) in each frequency band for the two minute segment of data. The total power in each frequency band thus has units of [V^2]. By Thorne's theory, this should then be proportional to the mass flux rate during the 2-minute time interval. Multiplying the power by a time interval should then be proportional to the total mass passing the hydrophone in a given time interval. We therefore integrated the total power in each frequency band over the time interval for which the hydrophones were submerged to estimate the total mass passing the hydrophone. For brevity we term the latter quantity “integrated power” or IP_x which can be expressed as

$$IP_x = \sum_{i=1}^{N} \Delta t_i \int_{x\ kHz}^{x+\Delta \mathrm{x}\ kHz} S_{t_i}(f)df$$

where *S(f)* is the power spectrum as a function of frequency, Δt is the time interval over which each spectrum is estimated, *x* is the lower bound of the frequency band of interest, Δx is the width of the frequency band (1 kHz here), and *N* is the number of time intervals during the submerged measurement period. The quantity IP_x should then be directly proportional to the total mass collected in the pit sampler in the same interval. The next step was to determine whether particular frequency bands display higher correlations with sediment load.

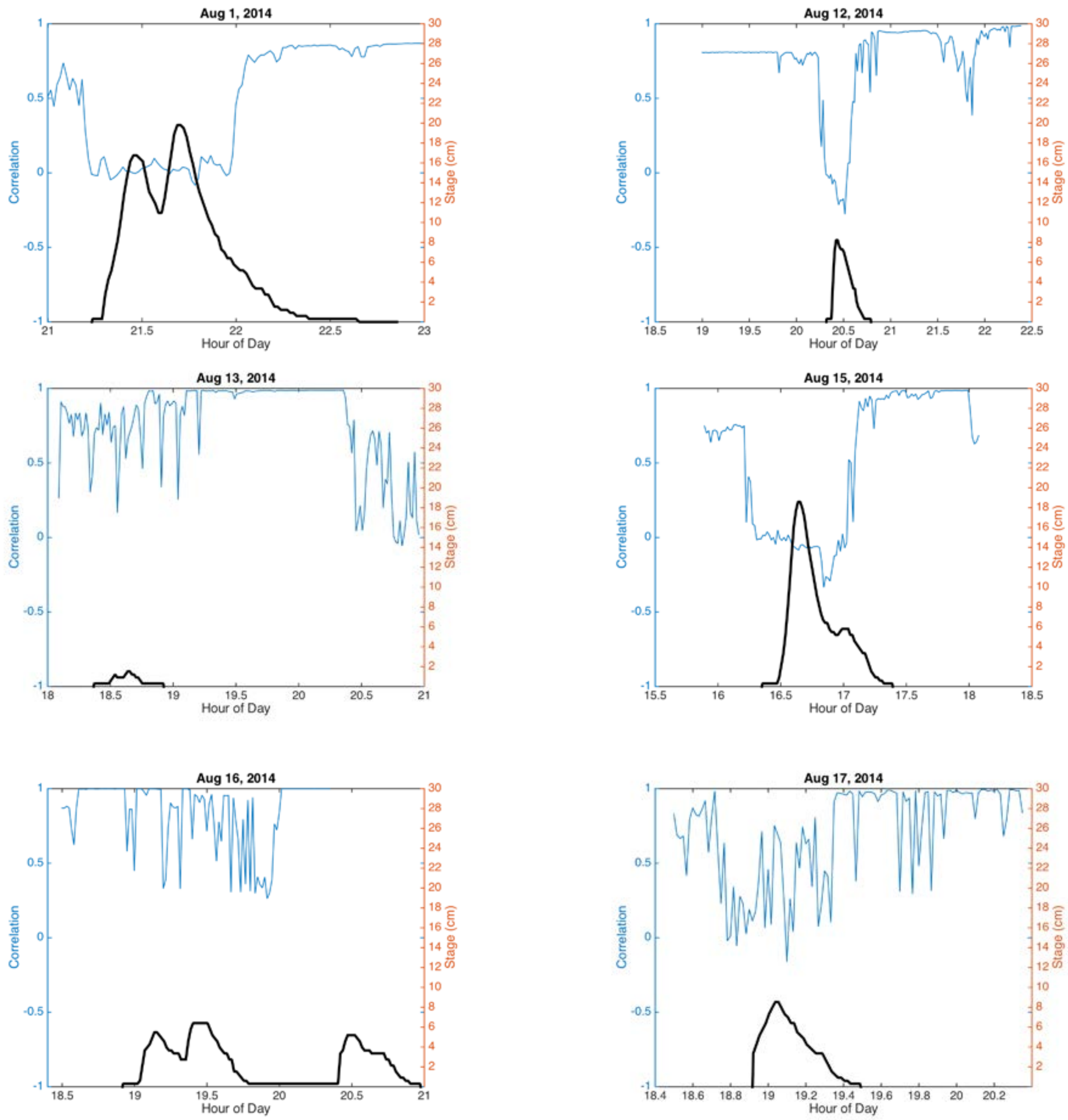

Figure 9. Linear correlation between the two hydrophone signals through the hydrographs of the three events during which hydrophones were submerged.

We then examined the linear correlation between the integrated power in each 1k Hz frequency band and the sediment load (by fraction). Table 4 shows the resulting correlations with maximum values for each size fraction shown in red. For all size fractions the maximum correlation occurred in the 10 kHz – 11 kHz frequency band. According to Thorne's formula for peak emission frequency this would correspond to a particle size of approximately 12 mm, at the lower limit of the load collected in the pit sampler. The increased correlation for higher frequencies may be, however, partly attributable to signal-to-noise ratio. The total power in the high frequency bands can be several orders of magnitude lower than the power in lower frequency bands. Contributions from flow noise and rain drops likely dominate this low frequency signal, potentially masking any SGN in those bands. The higher frequency bands may thus provide a higher signal-to-noise ratio for SGN versus other acoustic sources. Therefore, while peak emission frequencies predicted for our particle sizes may be closer to 4.5 kHz (30mm diameter), the 10 kHz component of this emission may be more easily detected relative to other sound sources.

Table 4. Linear correlation between the integrated power spectrum over 1kHz bands for the period during which the hydrophone was submerged (depth > 9cm) and the coarse sediment load. The maximum correlation for each size fraction is shown in red.

Coarse Fraction	Spectral Band (kHz) 0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11
Total	0.88	0.89	0.91	0.92	0.90	0.89	0.88	0.89	0.92	0.95	0.96
>64mm	0.97	0.97	0.98	0.98	0.98	0.97	0.97	0.97	0.99	0.99	1.00
32-64mm	0.97	0.98	0.98	0.99	0.98	0.98	0.98	0.98	0.99	0.99	0.99
16-32mm	0.86	0.86	0.89	0.90	0.88	0.87	0.86	0.87	0.90	0.94	0.95
1/2"-16mm	0.80	0.81	0.84	0.85	0.83	0.82	0.81	0.82	0.85	0.89	0.91

Figure 10 shows the results of integrating the total power from each 2-minute segment in the 10 kHz – 11 kHz band over the entire period during which stage was greater than 9 cm, i.e., IP_{10}. It should be noted that this quantity has no simple spectral interpretation and is derived explicitly from Thorne's theoretical relationships between acoustic power and mass flux. Further, the size of the time intervals may be chosen to be longer or shorter than two minutes. The 2-minute interval was chosen to provide sufficient data for the estimation of the power spectrum while also dividing the data into small enough segments so as to be quasi-stationary.

In the figure, all seven events have been plotted. The four events in which the hydrophones were not submerged have been assigned an $IP_{10} = 0$. We show them on the graph to demonstrate sediment load that passed in these smaller events. In all cases, these loads were very small compared to the three events for which $IP_{10} > 0$.

In all cases, a strong correlation was found between IP_{10} and the sediment load fraction. The relationship was nearly perfect for the sediment load with diameters greater than 32 mm. Smaller diameters between ½" and 32 mm also showed strong linear correlations. For the smaller fractions, however, this relationship may be derivative of correlation with the larger fractions. Note particularly that, for diameters less than 32 mm, the intercept on the graph becomes increasingly negative. Since a negative value of IP_{10} has no physical meaning, there are two possibilities. The relationship between IP_{10} and sediment load could be strongly nonlinear and threshold-like for small diameters and small loads, but this does not yield an obvious physical justification. It is more likely that for high sediment loads, the load fraction from smaller diameters is highly correlated with the load in the larger diameters while these larger diameters are highly correlated with IP_{10}. Thus, *when the greater-than-32 mm fraction is mobilized,* the IP_{10} for this fraction becomes a good proxy for the smaller diameter load fraction. If this is true, since smaller particles are transported earlier in an event, then we might expect that, as the particle diameters get much smaller than 32 mm, the sediment load threshold before IP_{10} begins to show a linear relationship will get larger. This trend is exactly the pattern in the data.

While IP_{10} may not be directly correlated with sediment load for the finer fractions, it does suggest that the IP_{10} intercept as a function of particle diameter may be a characteristic function of channel bed load material that could be used to estimate bed load fractions from SGN data. More practically, this seems to imply that the intercept on the total load relationship might be dependent on the bed material size distribution so that this quantity might conceivably be parameterized from bed material samples.

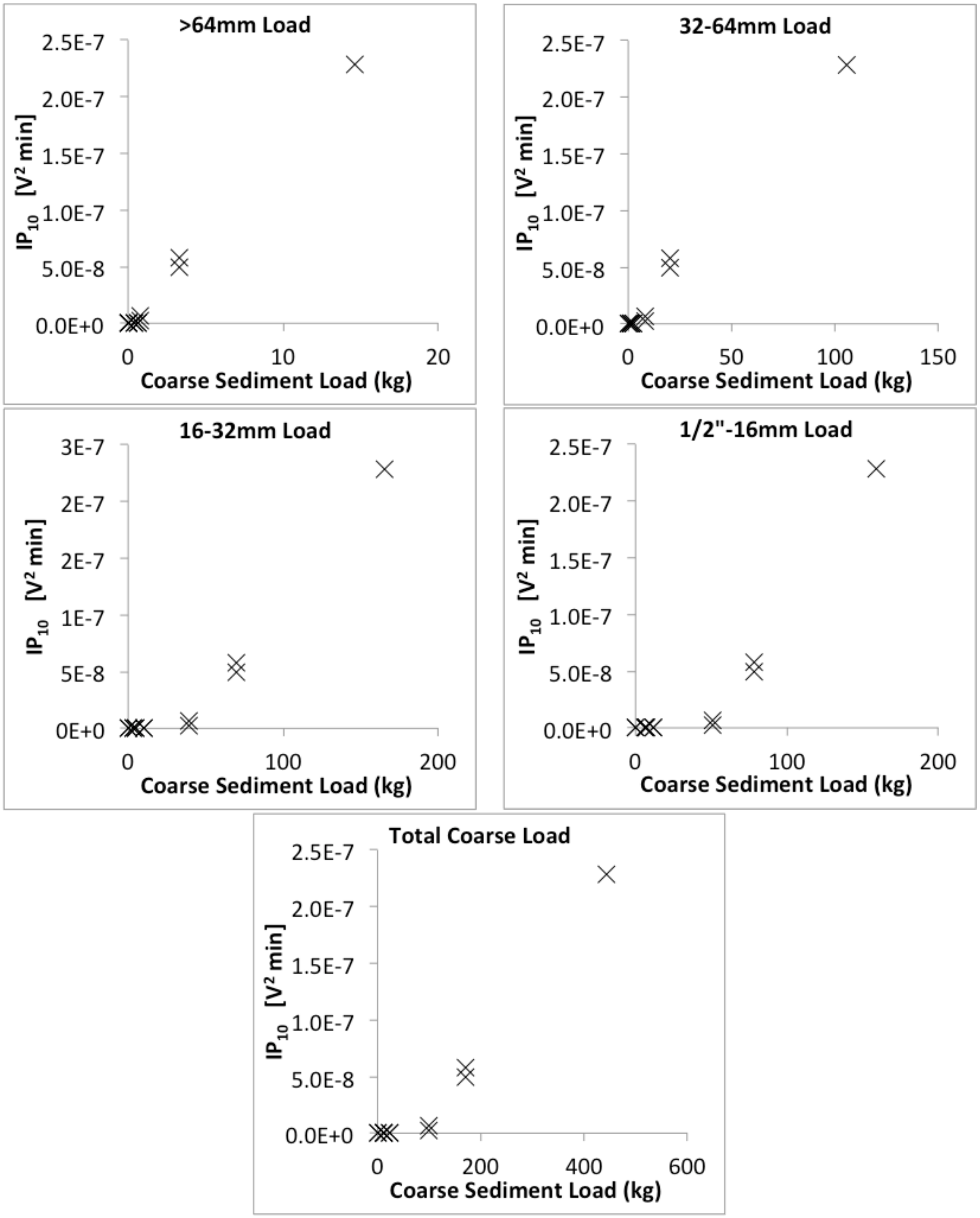

Figure 10. Plot of *IP_{10}*, the acoustic power in the 10-11 kHz spectral band integrated over periods when the hydrophone was fully submerged (stage > 9cm), versus coarse sediment load. Each panel shows a different coarse sediment fraction. Correlations are shown in Table 1. Three events involved stages in excess of 9cm (Aug 1, Aug 15, Sept 8). Points show data for each of these events for both hydrophones except for the upstream hydrophone on Sept 8 which was buried by sand load. Events for which no hydrophones were not submerged are also shown with *IP_{10}*=0 to display sediment loads for those events.

5. Conclusions

A set of flume experiments was conducted using rocks towed over an immobile gravel substrate in an attempt to calibrate SGN measurements using known sediment transport rates in the absence of noise contamination from turbulent water flow. These experiments highlighted challenges of SGN monitoring, such as quantifying the acoustic measurement footprint of the hydrophone and accounting for complex boundary interactions, neither of which have been investigated in detail to date. Each of these has become the subject of continued work.

The field campaign in the Lucky Hills catchment of the Walnut Gulch Experimental Watershed resulted in acoustic and sediment load data from seven runoff events. In three of these events runoff stages were sufficient to provide useful SGN data from submerged hydrophones. The data for these three events provide a high quality data set that combines total sediment load from physical samples with time series of the underwater soundscape during runoff events. A metric based on integrated acoustic power (IP) was derived from theoretical considerations wherein it was hypothesized that IP should be linearly related to total sediment load. This metric was calculated for 1 kHz frequency bands for each of the three runoff events and regressed against total sediment load by fraction. Results were striking and are summarized as follows:

- Within our measurement band of 0-12.5 kHz, the highest correlations with sediment load were found for the metric in the 10 kHz – 11 kHz frequency band (IP_{10})
- The metric IP_{10} showed remarkable consistency between the two independent hydrophones
- IP_{10} explained 99% of the variance in total sediment load for diameters greater than 32 mm, which constituted 21% of the total coarse sediment load recorded for those three events (Figure 10)
- Correlation with total sediment load for all diameters greater than ½” was nearly as good as the >32 mm data but is likely derivative of correlations between the coarsest fractions and finer fractions as a percent of total load (Table 3).

The results of this study also suggested some important general conclusions that should be considered for future SGN research and data collection:

- Multiple transducers should be deployed at a site to allow cross correlation analysis of signal parameters, which may allow for better separation of SGN from other ambient sound.
- The development of robust, streamlined housings are essential for continued development of SGN procedures. Flow noise generated around housings may be masking important parts of the frequency spectrum.

Products & Deliverables

1. Project final report
2. Extended abstract and presentation for SEDHYD 2015 conference
3. Peer-reviewed Manuscript: "A review of passive acoustic monitoring of bed load for fluvial applications"(submitted to *Journal of Hydraulic Engineering*)
4. Peer-reviewed Manuscript (in prep): "Monitoring bed load using sediment-generated noise in an ephemeral semi-arid stream"
5. Core Data: Two channels of hydrophone response for the seven runoff events plus coarse sediment load
6. Supplementary Data: Time-lapse video of selected runoff events

All products will be archived at the National Sedimentation Laboratory in a documented file structure and are available by request from the lead author.

Future Related Work

1. Characterization of acoustic properties and soundscape of natural stream reaches
2. Deployment of hydrophones in Goodwin Creek Experimental Watershed to record acoustic data from intermittent coarse bed load in a perennial stream
3. Development of hydrodynamic hydrophone housing to reduce flow noise
4. Extension of the Walnut Gulch campaign for an additional 1-2 seasons to confirm the IP_{10} relationship with 10-20 additional data points.

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