Monitoring Coarse Bedload Transport with Passive Acoustic Instrumentation: A Field Study

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Abstract

An inexpensive method for monitoring bedload transport using commercially available underwater pressure transducers (hydrophones) is presented. In addition to the hydrophone, the system consists of only amplification and signal conditioning circuitry and a portable computer with appropriate hardware and software installed. The main advantages of the system are low cost, portability, integration of bedload motion over the reach scale and usefulness in high-flow environments, especially when very large boulders are moving. The method has drawbacks, including uncertainty in the area of integration over which transport rate is measured, and in that it is only applicable to gravel and larger particles. Because of the dependence of the acoustic signal on reach geometry, it is likely that this method will not be able to be calibrated and then forgotten, but will need constant calibration adjustments, making it more suitable for filling data gaps between samples or for extrapolating point measurements of transport rate to a whole reach than for stand-alone monitoring. Much more work needs to be done to develop this technology into an operational monitoring technique, but this study provides evidence that this technique is feasible and worthy of such development.

Introduction

There has long been a need to monitor bedload flux in mountain streams, but few practical methods for observation are available. Bed-invasive systems, such as vortex (Klingeman and others, 1979) or Reid slot (previously termed Birkbeck) (Reid and others, 1980; Lewis, 1991) samplers, are one approach, and given small enough clast sizes, pressure-difference samplers (Helley and Smith, 1971) can provide an alternative. However, during extreme conditions, available methods are not effective: pressure-difference sampling becomes dangerous, Reid samplers fill or become obstructed, and the size requirements of any sampling device in a boulder reach would be prohibitively expensive.

There is a particular need to measure the coarser fraction of the bedload in mountain streams because this fraction can play an important role in reducing reservoir capacity (Reid, 1980), as much of the fine sediment can be flushed downstream during extreme events. One can monitor check dams through time to calculate long-term fluxes, but this method is labor intensive, and does not provide real-time estimates. Sediment traps, such as Birkbeck samplers, provide excellent real-time estimates of bedload data but require significant initial investment for installation, and require frequent removal of accumulated sediment, especially during high-flow events. Generalization of these data to other, unmonitored catchments is problematic because the transport rate of the coarse fraction increases with a power of the fluid shear stress greater than one. Thus, a few infrequent events may be responsible for the bulk of the bedload yield.

In addition to the obvious engineering needs, recent attempts to better understand bedrock erosion in steep mountain streams (e.g. Hartshorn and others, 2002) have underscored the need for accurate bedload measurements, especially during high-flow events. Bedrock erosion is likely to be a complex function of both hydrodynamic variables and bedload transport rate. The prevailing view of fluvial bedrock erosion (e.g. Slingerland and others, 1997; Howard, 1998; Sklar and Dietrich, 1998; 2004) considers both hydraulic plucking and abrasion by bedload particles to be responsible. In addition, the presence of bedload sediment will inhibit bedrock erosion by shielding the bed from these processes (Sklar and Dietrich, 2002, 2004). Therefore, in order to predict erosion in these channels, it is necessary to have accurate measurements of the availability of abrasion tools.

This paper describes a method for measuring the flux of coarse bedload by recording the acoustic energy produced by collisions between moving sediment grains and between moving grains and the stationary bed. Results from measurements on the Trinity River, northern California, made in May 2005 show that the acoustic energy of grain collisions correlates well with bedload data obtained using traditional direct-sampling methods.

Background

Many methods have been used to measure fluvial bedload transport since the earliest basket samplers of Ehrenberger and Einstein (as described in Hubbell, 1964). In an attempt to capture the spatial and temporal variability of the transport rate, two major projects employed continuous sampling strategies in the late 1960s and early 1970s at Oak Creek, in Oregon (Klingeman and others, 1979) and at East Fork, in Wyoming (Leopold and Emmett, 1976). At about the same time, the development of the portable Helley-Smith sampler (Helley and Smith, 1971; Emmett, 1980) facilitated bedload estimation. One main disadvantage of the Helley-Smith sampler is that it does not provide continuous data, so temporal variability in the transport rate is difficult to capture. The need for continuous data, at lower cost than that of the methods developed at Oak Creek and East Fork has motivated the development of the pressure-pillow Birkbeck sampler (Reid and others, 1980; Harris and Richards, 1995). This sampler continuously records the weight of bedload that has fallen through a slot in the streambed. All of these methods are limited in the clast sizes they can measure.

Passive acoustic methods offer an opportunity to obtain spatially-integrated and continuous measurements of bedload fluxes, even during extreme transport events. They have been proposed many times over the past century in various forms. The earliest passive acoustical studies, conducted in the early 1930s, considered the impact of sediment on the vertical face of a steel box (Bedeus and Ivicsics, 1964). Some subsequent investigations have examined interparticle collisions (Johnson and Muir, 1969; Tywoniuk and Warnock, 1973; Anderson, 1976), finding that time-domain sound pressure levels measured by hydrophones increased with an increase in bedload transport rate. However, most recent studies have investigated the impacts of sediment with bed-mounted metal plates. Long-term studies monitoring the acoustic energy produced by sediment collisions with a flush-mounted plate in Switzerland were begun by Bänziger and Burch (1990), and continued by Rickenmann and Hegg (Rickenmann, 1997; Rickenmann and others, 1997; Hegg and Rickenmann, 1998, 2000). A similar device measuring the acceleration of a metal plate caused by sediment collision has been investigated in

Norway by Bogen and Møen (Bogen and Møen, 2001). Using a similar approach, Govi (1993), counted impulses caused by collisions of sediment grains with a poured concrete slab with a geophone network.

In the marine realm, wideband hydrophone response has been used to evaluate the distribution of acoustic frequencies generated by colliding sediment (e.g. Millard, 1976; Thorne and others, 1984; Thorne, 1985; 1986; Thorne and others, 1989; see Hardisty, 1993 for a review; Rouse, 1994; Voulgaris and others, 1994, 1995). Thorne (1986) performed experiments with artificial sediment grains in a rotating drum, and reported that the centroid frequency of the wideband distribution decreased linearly with increasing particle diameter. He also used a tripod-mounted platform that included two hydrophones, a closed-circuit video camera, and electromagnetic current meters stationed on the bed of a tidal channel. Thorne found that the particle size distributions calculated from this relationship related well to visual estimates of the size distributions of the moving bed material, as determined from underwater video. According to Thorne's relationship, typical frequencies of the acoustic signal generated by gravel impacts range from about 50 kHz for very fine (2 mm) to about 2 kHz for very coarse (64 mm) particles.

Recently, attention has also been given to the role that active acoustic methods such as those proposed by Rennie, Villard, Kostaschuk and others (see Rennie and others, 2002; Kostaschuk and others, 2004; Villard and others, 2005) may play in the analysis of bedload transport in sand-bedded systems. However, because of the dependence of active sensors on scattering by the target material, it is unlikely that these methods will be applicable to coarse-bedded systems.

Thus, previous work suggests that is theoretically possible to monitor coarse bedload transport in mountain streams using the acoustic signal of grain impacts.

Acoustic System Design

The basis of the acoustic instrumentation in this study is a Geospace, Ltd. MP-18 hydrophone, which has a flat response for frequencies below about 2 kHz. The hydrophone has been encased in a perforated 7.62-cm PVC pipe, the interior of which is filled with pieces of permeable foam. The ends of the pipe are plugged with streamlined wooden caps, one of which can be removed for access. The cable to the hydrophone leaves the pipe through the downstream cap, minimizing stress on the cable in a high-flow environment. The hydrophone is connected to an adjustable-gain amplifier, which allows for on-site adaptation to the sampling environment. For most of the measurements reported here, the gain was set at 800X, but 325X was used for some of the early samples. This amplifier also includes an analog low-pass anti-aliasing filter that passes signals below 26 kHz. The filtered signal is fed to a sixteen-bit National Instruments NI-DAQCard 6036E analog-to-digital conversion card on a laptop computer. Mathworks' Matlab Data Acquisition Toolbox is used to control the sampling. One-minute long samples of the amplified and filtered voltage at 62.5 kHz are recorded. Each sample is separated by two to five seconds of time dedicated to file management. This arrangement is used because it yields sample sizes within the memory constraints of a personal computer without subsetting or subsampling. The system is not designed to run unattended, but only minor modifications would be necessary to make it so.

The costs of the system are primarily equipment costs, as there is only minimal personnel cost expected for this system in an operational mode. Equipment costs are approximately \$4000 for computer (\$1000), software (\$2000), and data acquisition card (\$1000), and \$500 for each hydrophone deployed, and approximately \$500 for amplification for each channel. Additional costs for weatherproofing, and for securing the system against theft or vandalism should also be considered.

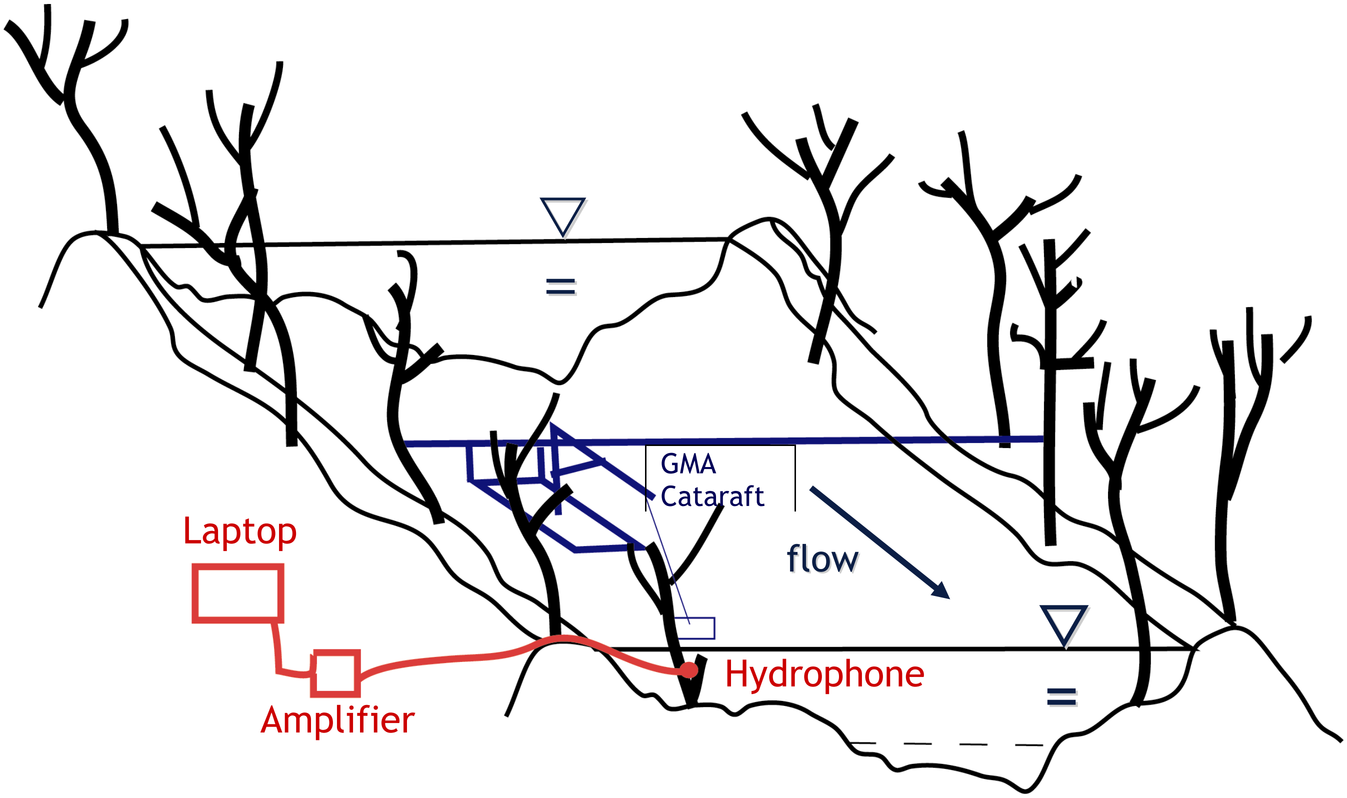

Figure 1. Schematic diagram of measurement setup. The hydrophone (in protective case) was installed about four meters downstream from the GMA cataraft installation. Shielded cable connected the hydrophone to amplification and data recording units located over the berm.

Examination of the Area of Integration

A potential limitation of this method is that it yields a weighted spatial average of the transport rate. The weighting function is equivalent to the transmission loss with range, r, of the acoustic signal. In fresh water and for frequencies considered in this analysis (less than 30 kHz), over the ranges of hundreds of meters that are likely to be important, the effects of absorption and scattering are several orders of magnitude smaller than spreading losses. If the simple assumption of spherical spreading is used, an r-1 law can be applied to predict power as a function of range (in shallow water a cylindrical spreading law: r-½ may be more appropriate). The effective range of the hydrophone system is determined by the distance at which the power received from the sediment transport is equal to the power received from ambient noise sources in the river. These ambient sources may include turbulent noise around the hydrophone (reduced, but not eliminated by the instrument design), bubble collapse and cavitation noise, as well as typically small volumes of noise introduced into the river by the banks or from the air above. The impedance contrast between air and water and between rock and water makes the transfer of acoustic energy between these media relatively inefficient, however. This ambient noise floor is unlikely to be constant for different discharges, and it is difficult to measure because of the impossibility of measuring acoustic noise in the high-flow river without sediment transport. It will also depend heavily upon the channel geometry, so measurements in a flume environment will not carry over into the field. These limitations bar the calculation of the absolute area of integration for the study site.

Therefore, it is necessary to calibrate each site where this technology is deployed by comparison of acoustic records with traditional sampling techniques, such as pressure-difference sampling.

To investigate the role of reach geometry in controlling the observed signal strength, we conducted numerical experiments using a probabilistic bed collision model. The results of these experiments show that the reach geometry, particularly the relative distance of impacts to the sensor will play an important role in the signal strength. Because of this limitation, in situ calibration of the instrument will be necessary at each site. (Barton, 2006) An array of hydrophones, possibly using both banks of the channel, should be able to eliminate the ambiguity caused by lateral shifts in transport location.

The relative insignificance of scattering and absorption over distances of interest is important as these properties are frequency dependent, and should therefore depend upon grain size. The transmission loss, however, should be dominated by grain-size independent spreading loss. Numerical modeling has shown that changes in diameter of the moving sediment have a minimal effect on the ability of the system to estimate bedload transport rates.

Study Site and Ancillary Data

The Trinity River watershed comprises 7640 km² of the Trinity Alps of Northern California. The basin is forested, though heavily logged in the past half-century. The Trinity and Lewiston dams, constructed in 1961 as part of the U.S. Bureau of Reclamation Central Valley Project, restrict flow from the upper 1860 km² of the basin. Channel flushing release flows have been conducted for several years at this site, mainly driven by salmon fisheries interests. Douglas City, located 25 km downstream from Lewiston Dam, was selected as the test site for this study, as ongoing sediment sampling was in place, and because relatively coarse sediment had been observed in transport during previous floods. In addition, flow information was available from a USGS gauge (#11525854: Trinity R. at Douglas City) located 150 m upstream from the site. Sediment size distribution data has not yet been published for this site. However, analysis of provisional data from the pressure-difference sampling conducted at the time of this study shows a strongly bi- or tri-modal distribution, with one coarse mode and one or two fine modes. Table 1 shows parameters of representative size distributions taken during the dam release.

Table 1. Representative sediment size distributions. The pebble count data was collected and analyzed by Wes Smith for Graham Matthews & Associates in August, 2006, during low water.

Mean Time of Sample	**Water discharge m^3s^{-1}**	**D_{15} mm**	**D_{50} mm**	**D_{85} mm**
Bedload 08 May 2005 14:00	210.	0.75	3.2	27
Bedload 11 May 2005 16:00	204	2.8	11.2	34
Bedload 13 May 2005 11:00	203	1.5	38	86
Pebble Count 12 Aug 2006	n/a	30	64	144

Acoustic data was collected over the peak discharge of the release, from 6 to 19 May 2005, during which time, the channel width varied from 31.7 to 56.4 m, and the water depth varied from 2.13 to 2.89 m. The channel cross-section at this site and at these stages is approximately trapezoidal, with water depth reaching 85% of its maximum within 15 m of each bank. A substantial body of literature exists on sediment studies on the Trinity River (e.g. Wilcock and others, 1996a; Wilcock and others, 1996b), though most of previous descriptions focused on study sites upstream from Douglas City.

In order to test the method, two simultaneous, independent estimates of bedload were made on the same study reach. Measurements were taken with a hydrophone case anchored in the river bed on the right bank of the river and four meters downstream of a tethered cataraft used by Graham Matthews and Associates (GMA) to obtain bedload measurements using pressure-difference samplers. Observations by GMA indicate that the closest moving coarse bed material was located approximately 10-12 m from the hydrophone during the study.

Pressure-difference sampler data were selected as the control data for this experiment because they represented the best available dataset in an environment with predictable high-flow events. High temporal and spatial resolution sampler data, such as that available from Birkbeck samplers, was not available in a dam-release setting with high flow, pavement breaking events. Pressure-difference bedload transport data were collected during the Trinity flow release from 6 to 31 May 2005. Sampling was conducted from cataraft-based sampling platforms (6-m inflatable tubes supporting a deck, crane and towers) that were specifically developed for use on the Trinity River at sites where infrastructure for high flow sampling (bridge, cableway, etc.) was not in place. Two different samplers were used: a 0.15- by 0.15-m Helley-Smith sampler (3.22 expansion ratio), and the 0.30- by 0.15-m Toutle River 2 sampler (1.4 expansion ratio) (Childers, 1992).

Transport rates were computed for each size fraction using the standard methods of the USGS as described in Edwards and Glysson (1999).

Statistical analysis of the acoustic data collected during the pressure-difference sampling period and data collected immediately before or after a sampling period showed no significant bias caused by the noise produced by the pressure difference sampler. Qualitative analysis in the field also indicated that the sounds produced by the sampler on the bottom were insignificant compared with the noise of the gravel movement in the area of integration.

Results and Discussion

Theory and laboratory experiments predict a linear relationship between total acoustic power and the transported mass of bedload (Jonys, 1976, Thorne, 1986 #15). Total acoustic power was estimated by averaging sixty rectangular-windowed, one-second power spectral densities to obtain a power spectral density for each one-minute sample, which was thereafter numerically integrated over frequency between 10 and 14809 Hz. To test the correlation between total acoustic power with bedload transport rate, the acoustic power was averaged over the entire GMA sampling period, which was typically about one hour, under the assumption that the GMA sampling technique provides an estimate of the average transport rate over the sampling interval.

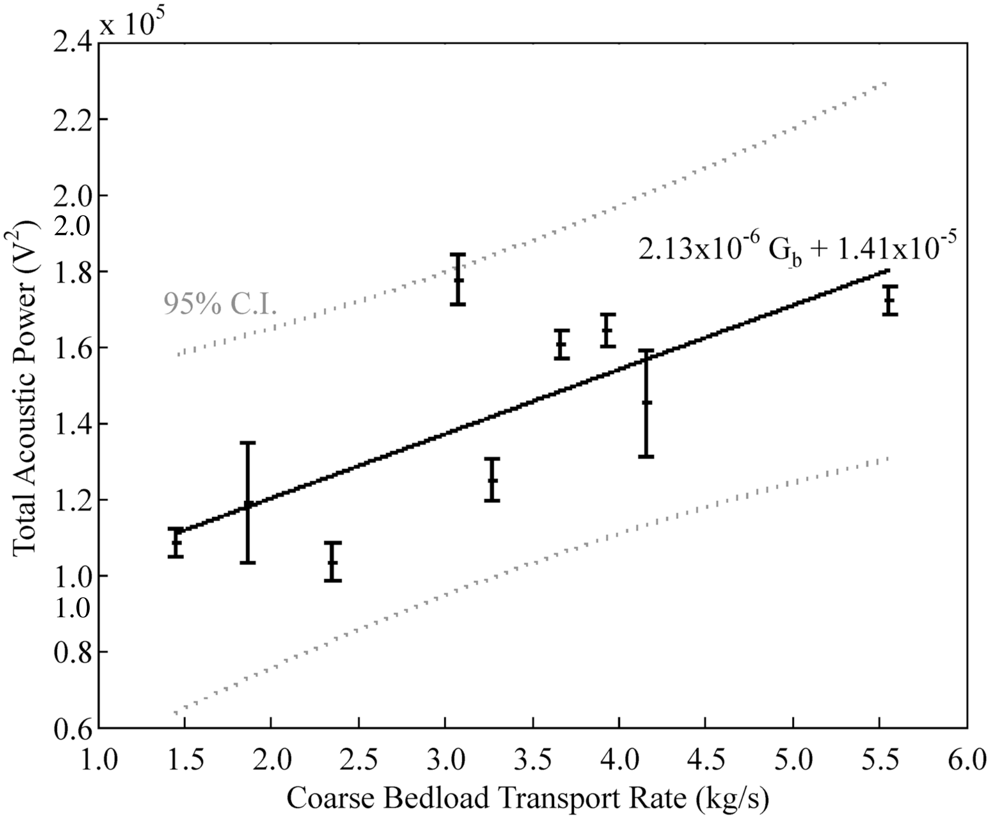

Figure 2. Correlation plot between temporally-averaged total acoustic power (totaled over the frequency range of 10 to 14809 Hz) and bedload transport rate from the Toutle River 2 sampler. Error bars show ±2 standard errors of the temporal mean. The Pearson's correlation coefficient R is 0.758, with a p-value of 0.0180. Confidence interval for the regression parameters assumes Gaussian error. See text for details.

A least-squares linear regression of total acoustic power as a function of bedload transport rate was performed using the nine GMA TR-2 observations for which contemporaneous acoustic data were available (Figure 1), under the assumption that acoustic pressure is linear with respect to amplifier output voltage. Only the nine TR-2 measurements were used because anecdotal evidence from field researchers suggests that the TR-2 and the 0.15-m Helley-Smith may not yield equivalent measurements of bedload transport. These anecdotal reports are consistent with results obtained by Vericat et al. (2006) for smaller pressure-difference sampler sizes. The three TR-2 measurements from 20 May were not included because there was no acoustic data collection on that date. The relationship is linear with respect to mass; Pearson's correlation coefficient is 0.76, with a p-value of 0.018 indicating a significant correlation. Because of the paucity of data, it was impossible to reserve a test population for rigorous evaluation of the effectiveness of the prediction; however, a qualitative evaluation is possible using the seven remaining GMA observations. The trapping efficiency of the TR-2 for grain sizes as large as those in the Trinity River has not been evaluated (Childers, 1992), and the dataset acquired in this study is not sufficient to perform such an analysis. It is likely to be biased (see Vericat and others, 2006), but as the largest available portable sampler, it must be treated as the best available data.

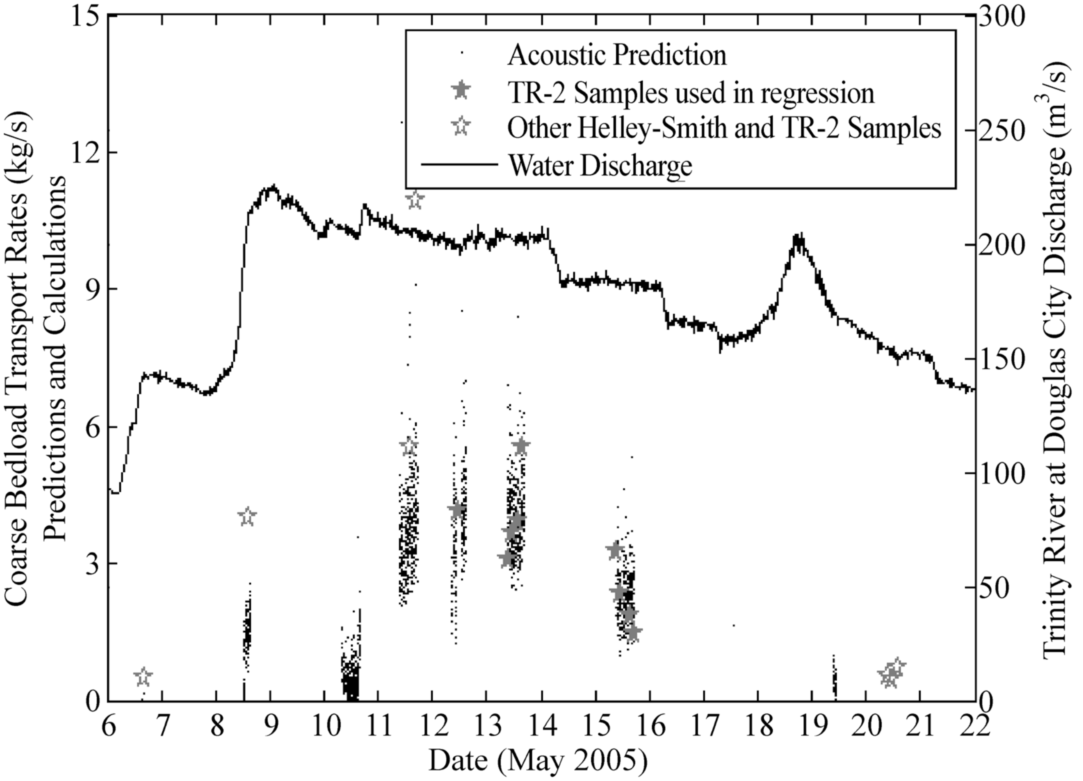

Figure 3. Predictions of coarse (>8 mm) bedload transport rate from one-minute-averaged acoustic power (small dots) over the study interval plotted with the water discharge (solid line) and GMA Helley-Smith and TR-2 observations (solid and hollow stars). The solid stars are those points that were used in the least-squares regression shown in Figure 1.

The linear best-fit model was used to predict bedload fluxes during the entire acoustic sampling period. Results are plotted in Figure 2, along with the water discharge over the measurement interval, and sixteen GMA observations during this period. Heavy rains and the presence of large quantities of woody debris on the river on 8 and 9 May 2005 have restricted the sampling during the peak of the flood. As a result, the GMA transport rate estimate for 8 May is based on a partial sample. Except for three of the four Helley-Smith measurements, the GMA observations sit well within the range occupied by the acoustic predictions. On days when multiple GMA observations were made, the range of values reported by GMA is consistent with the range of values predicted by the acoustic method. It is worth noting here that under close examination the cloud-like appearance of the acoustic data (Fig. 2) resolves itself into definite oscillations (Fig. 3), with two or three data points on each peak, suggesting that the variance is not entirely random.

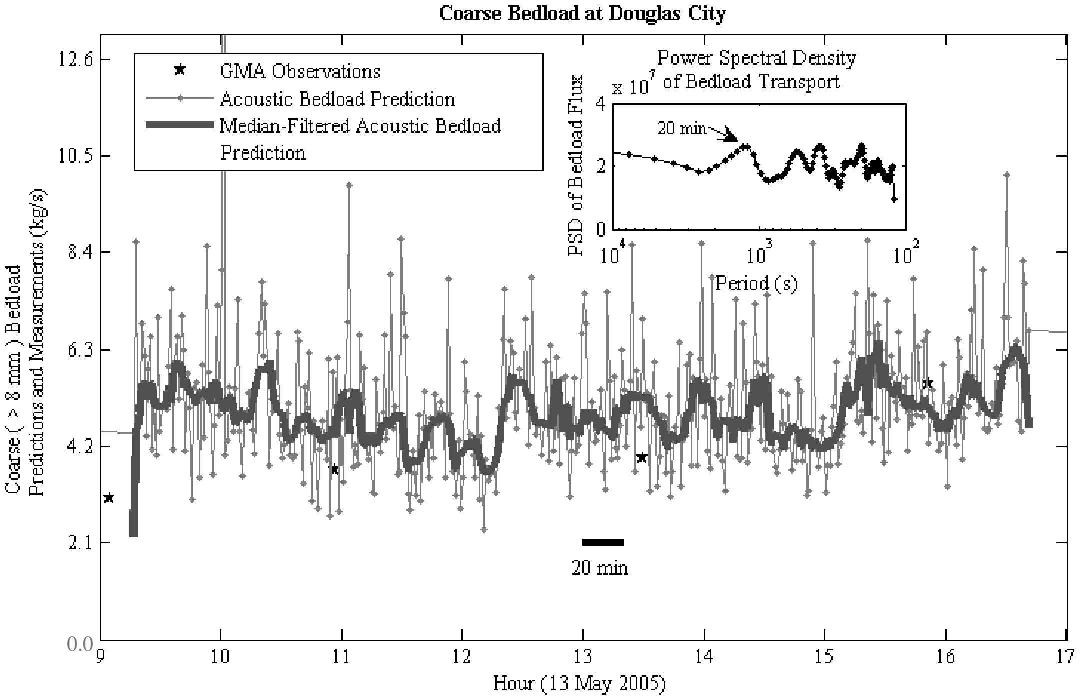

Figure 4. Detail of bedload transport predictions for 13 May 2005. The grey dots are the one-minute predicted values; the thin lines are interpolations as a visual aid. The thick curve is the result of a 10-minute moving window median filter. Inset is the power spectral density of the one-minute data. Note that the inset horizontal axis is descending in period.

It has been suggested (e.g. Clifford and others, 1990) that acoustic noise will correlate strongly with discharge because of bubble collapse and turbulence-induced noise. Figure 4 shows the relationship between acoustic power and water discharge. The dramatic rise in acoustic power well after the peak in water discharge cannot be attributed to hydraulic noise, which we postulate would be the same for identical discharges on the rising and falling limbs of the hydrograph. We attribute this power rise to increased bedload transport during the falling stage, although the hysteresis pattern in this plot is reversed when compared to the traditional view of sediment transport in a flood. A review of the GMA data from Douglas City during the 2004 release shows a similar pattern in the days immediately surrounding the peak flow. This type of hysteresis loop (counterclockwise) is consistent with a system that experiences a delay in sediment supply to the study site (Nistor and Church, 2005). If we assume a bedload migration rate of between 0.009 and 0.012 m/s, which is well within the range given in the literature for bedload sheet migration (e.g. Whiting and others, 1988), the delay in sediment supply observed in the hysteresis loop is consistent with that which would be observed for a slug of sediment moving downstream from the Indian Creek delta.

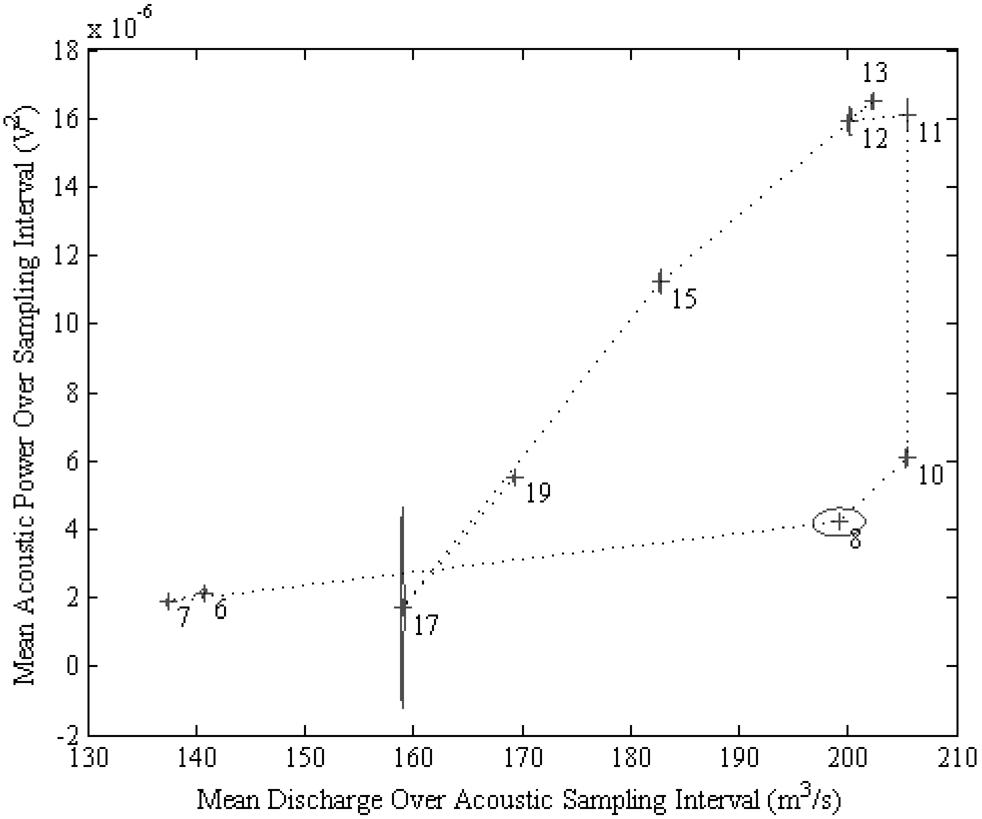

Figure 5. Relationship between mean acoustic power and mean discharge. Each daily value was calculated by averaging the acoustic samples collected on that day, and averaging linear interpolations of the 15-minute discharge data for each acoustic data point. The numbers indicate the date in May 2005. The ellipses indicate two standard errors of the means. Relatively few data points were collected on 17 May, because of rain, which may partly explain the large uncertainty in the data on that date.

Smoothing of the one-minute predictions, using a ten-minute moving-window median average (which reduces the importance of sudden spikes of limited duration), reveals distinct peaks and troughs in the power of the acoustic signal, and by inference, in the bedload transport (Figure 3). Interpretation of the spectral content of the one-minute predictions shows several interesting periodicities in the bedload transport rate. In particular, the lowest frequency peak that is captured by the spectral analysis, at a period of about 20 minutes, is consistent with peak frequencies reported in the literature (e.g. Whiting and others, 1988) for periodic passage of bedload sheets. Higher frequency peaks may be related to periodicity in turbulent bursting phenomena known to play a significant role in bedload transport (Heathershaw and Thorne, 1985).

Conclusions

Although the data are limited, a statistically significant correlation exists between acoustic power and bedload transport. The correlation cannot be attributed to a third variable dependent on discharge such as entrained-bubble collapse or turbulence, because the acoustic power during the rising limb was strongly separated from that during the falling limb. The few data points of traditional data collected did not allow a test population for the relationship that was developed. However, five GMA samples were omitted from the regression analysis because there were no acoustic data acquired contemporaneously. Although no rigorous test is possible with this data, it is encouraging to note that these acoustic predictions are consistent with proximate bedload observations.

Excluding transient acoustic spikes, the observed range of the acoustic data appears to result from short-term trends, rather than Gaussian scatter. Spectral analysis of the one-minute data shows several discrete frequency peaks; the lowest of these fall within the range of frequencies observed for bedload sheets.

If this model for the relationship between acoustic power and bedload transport rate is effective, we can make several observations about the bedload transport in the Trinity River at Douglas City during floods. The hysteretic relationship observed is consistent with delayed introduction of bedload material into the study reach. This delay can be explained by the travel-time necessary for bedload material to arrive at the reach from two tributary deltas.

Given the acceptance of large uncertainties by bedload transport community in the use of traditional samplers (This acceptance is supported by the fact that the BL85, a pressure-difference sampler, is the only sampling device approved for use by the U.S. Geological Survey for routine monitoring of coarse bedded streams), these results suggest that acoustic sampling can provide a predictive tool within these uncertainties—often set at a factor of two. The lower cost and higher temporal resolution of this method can augment a traditional sampling campaign and limit the number of sample points necessary for characterization of the bedload transport history.

Acknowledgements

This study was partly funded by grant EAR 01-26131, awarded to R.L. Slingerland, T.B. Gabrielson and N. Hovius by the National Science Foundation. It would not have been possible without logistical assistance from John R. Gray, U.S. Geological Survey and Andreas Krause, Trinity River Restoration Project. Niels Hovius provided insightful comments on the manuscript. Thanks are also due to Knut Møen and Celso Garcia for helpful reviews.

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