PASSIVE ACOUSTIC MONITORING OF COARSE BEDLOAD TRANSPORT ON THE TRINITY RIVER

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Abstract: Passive recording of acoustic pressure levels due to interparticle interactions has the potential to serve as a proxy for coarse-grained fluvial bedload, but the technique has never been tested using a fluvial dataset. Here we report a time-series of acoustic measurements taken in the Trinity River at Douglas City during the peak release flow from May 6 to 19, 2005, in Trinity County, California. Measurements were taken at the U.S. Bureau of Land Management campground at Douglas City, using a Geospace MP-18 hydrophone, a custom-built, variable-gain (1-800x) amplifier, a National Instruments DAQCard 6036E, and Mathworks' MATLAB Data Acquisition Toolbox. Data were recorded at 64 kHz for several hours each day on ten of the fourteen days in the study period. Estimates of actual bed material fluxes were obtained at the same cross-section by Graham Matthews & Associates GMA), who used pressure-differential bedload samplers: the 6x6" Helley-Smith and a 12 x 6" Toutle River (TR-2) sampler. Flow information is available from a USGS gauge (#11525854) about 150m upstream from the site. Results show that there is a statistically significant correlation between the coarse bedload flux measured by Graham Matthews & Associates and the total acoustic power. This correlation can be shown to be independent of third variables such as bubble collapse or turbulence. Acoustic power, and by inference, bedload flux, show interesting periodicity that needs further investigation, particularly in the 4 to 15 minute frequency range.

INTRODUCTION

There has long been a need to monitor bedload fluxes in mountain streams, but few practical methods for observation. Invasive systems, such as vortex (Klingeman et al. 1979) or Birkbeck (Reid et al. 1980) samplers, are one approach, and given small enough clast sizes, Helley-Smith type samplers (Helley and Smith, 1971) can provide an alternative. During high discharge flows, however, none of the present methods is effective, and all have difficulty measuring the spatial and temporal variability of transport rate.

Recent attempts to better understand bedrock erosion in steep mountain streams (e.g. Hartshorn, et al. 2002) have underscored the need for a better method to measure bedload accurately, especially during high-flow events. The prevailing view of fluvial bedrock erosion (e.g. Slingerland et al. 1997; Howard, 1998; Sklar and Dietrich, 1998) is of a process combining both hydraulic plucking and abrasion by bedload particles. Therefore, though the erosion rate will be a complex function of the bedload transport rate, in order to make predictions about downcutting in these channels, it is necessary to have accurate measurements of the rate of availability of abrasion tools.

Collisions between moving sediment grains and between moving grains and a stationary bed produce acoustic energy within the water. This paper will describe an experiment conducted in May 2005 to record the acoustic energy produced, and to relate that energy to bedload data obtained using traditional empirical methods.

BACKGROUND

Many methods have been used to measure bedload transport since the earliest basket samplers of Ehrenberger (1931). Acoustic methods represent 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 work examined the impact of sediment on a plate (Mulhofer, 1933). Among the first to examine interparticle collisions were Johnson and Muir (1969), and later Twyoniuk and Warnock (1973), Anderson (1976) and Baenziger and Burch (1990). All of these studies reported that time-domain sound pressure levels measured by hydrophones increase with an increase in bedload transport rate. A variation on these techniques was reported by Govi (1993), who counted impulses from a passive geophone network caused by collisions of sediment grains with a poured concrete slab.

Work in the marine realm using hydrophones (e.g. Millard, 1976; Thorne, 1985, 1986; Thorne et al., 1984, 1989; Rouse, 1994; see Hardisty, 1993 for a review) has focused on wideband results, which predict a distribution of frequencies dependent on sediment size. Thorne (1986) reports that the centroid frequency of the wideband distribution decreases linearly with increasing particle diameter. Thorne (1986) also indicates that the particle size distributions calculated from this relationship relate well to visual estimates of number distributions of the mobile bed material, as determined from underwater video. According to Thorne’s relationship, typical frequencies for gravel range from about 50 kHz for very fine (2mm) to about 2kHz for very coarse (64mm). Subsequent studies (e.g. Voulgaris et al., 1994, 1995) have reported extensive field-testing of this method.

This previous work provides a sound basis upon which to build a system for studying coarse bedload transport in mountain streams. Previous work has suggested that site-specific calibration will be necessary because of the dependence of the signal strength upon reach geometry.

STUDY SITE AND ANCILLARY DATA

Data were collected on the Trinity River at Douglas City, Trinity County, California during the peak release flow from Trinity Dam on May 6 to 19, 2005. Measurements were taken at the U.S. Bureau of Land Management campground at Douglas City using a hydrophone case lashed to the submerged trunk of a tree. The most important priority for instrument placement was proximity to ground-truth measurements carried out by Graham Matthews and Associates, and safety concerns relating to that proximity. The site selected was on the right bank of the river, four meters downstream from the cross-stream tether used for the GMA cataraft. Observations of the GMA samples led to the estimate that the closest moving coarse bed material was approximately 10-12 meters away from the instrument during the study.

Sediment sampling occurred from May 6 to May 31. Sampling was conducted from cataraft-based sampling platforms specifically developed for sampling at sites where other methods (bridge, cableway, etc.) were not available. The catarafts were attached to temporary, tensioned cable taglines securely anchored to large trees on either side of the channel. The cable passed through a modified version of the USGS standard quick-release boat rollers mounted on 6' towers on either side of the platform, allowing boat traffic to pass. Caution signage, flagging and safety kayakers were utilized. Crews consisted of two on-river personnel specifically trained in cataraft-based sediment data collection. All crew members attended a mandatory safety/sampling technique training session and crew leaders attended the USGS Sediment Data Collection Techniques course.

Bedload measurements were collected over a range of flows and at various positions on the hydrograph spanning the release period utilizing a 6" Helley-Smith sampler (through May 11), and the Toutle River-2 (TR-2) thereafter. Both used 0.5 mm mesh collection bags. Cross sections were sampled at 12-20 verticals following standard USGS procedures (Edwards and Glysson, 1999) for Single Equal Width Increment samples. Down-times of 60 seconds were usually used at each vertical. Two passes were generally completed for each sample. Samples were logged with site identifier, date, time, sampler-type, stage, moving bed width, sampler bottom time, and stationing information. Water surface slopes were recorded for each distinct stage and sites were photographed. Each sample pass was dried and sieved at ½ phi sizes to 1 mm, below which whole phi size classes were used. After each pass was analyzed, the data were composited into single-sample particle size distributions, reporting each size fraction as percent by weight of the total sample and reporting partial mass sub-totals for < 0.5 mm, 0.5-8 mm and > 8 mm fractions. Bedload samples were processed in the GMA Coarse Sediment Lab in Arcata. Quality assurance plans are available to interested parties. Transport rates were computed for each size fraction using the sample data and the standard methods utilized by the USGS as described in Edwards and Glysson (1999). A station analysis was developed for each sampling site and was submitted along with sample data and records to the USGS for review/approval/publication in the USGS California Science Center Annual Data Report Series.

SYSTEM DESIGN

The basis of the instrumentation is a Geospace, Ltd. MP-18 hydrophone. The hydrophone has been encased in a perforated three-inch 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 exits the pipe through the tip 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 this experiment, 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 16-bit National Instruments NI-DAQCard 6036E analog-to-digital conversion card on a laptop computer. This card, controlled with Mathworks' Matlab Data Acquisition Toolbox, samples the amplified and filtered voltage at 62.5 kHz and records one-minute long samples. Each sample is separated by 2-5 seconds of time dedicated to file management. This arrangement is used because it results in 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.

RESULTS AND DISCUSSION

Theory predicts a linear relationship between acoustic power and the square-root of mass transported (Thorne, 1986). Total acoustic power was obtained by using Welch's algorithm, with 50% overlapping one-second rectangular windows, to obtain a power spectral density for each one-minute sample, which was then summed over frequency. The resulting power was then averaged over the period during which GMA were taking samples, and the resulting average powers were regressed against the square-root of the average mass tranport rates calculated by GMA. The regression was then applied to the sample data, and the results are plotted in Figure 1, along with the water discharge over the sample interval, and the GMA observations.

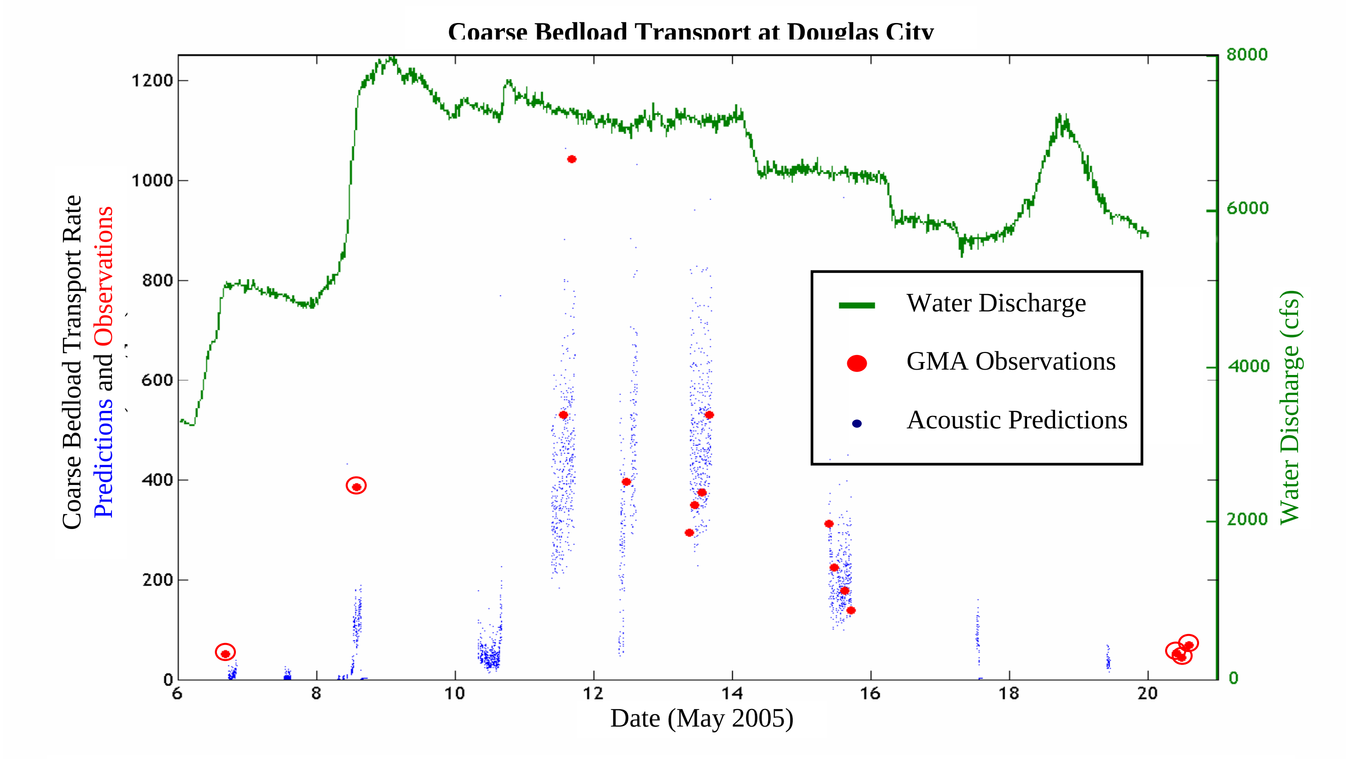

Figure 1 Predictions of coarse (>8mm) bedload transport rate from one-minute-averaged acoustic power (blue) over the study interval plotted with the water discharge (green) and GMA Helley-Smith and TR-2 observations (red). The circled GMA observations were excluded from the regression analysis because there were no contemporaneous acoustic data.

The regression used all 11 of the GMA observations for which contemporaneous acoustic data were available. Because of the paucity of data, it was impossible to reserve a test population to evaluate the effectiveness of the prediction. Figure 2 shows the regression plot, with the 95% confidence interval for the regression parameters (assuming Gaussian error). Note that the regression is linear with respect to the square-root of mass, and for clarity, the plot is drawn with respect to mass. The Pearson's correlation coefficient is 0.77, with a p-value of 0.005, indicating a significant correlation. To perform the regression, the acoustic power was averaged over the entire GMA sampling period, which was typically about 40 minutes long, under the assumption that the GMA sampling technique provides an average transport rate over the sampling interval. The results from this regression were then used to produce the acoustic prediction values from the one-minute power data that were plotted in Figure 1.

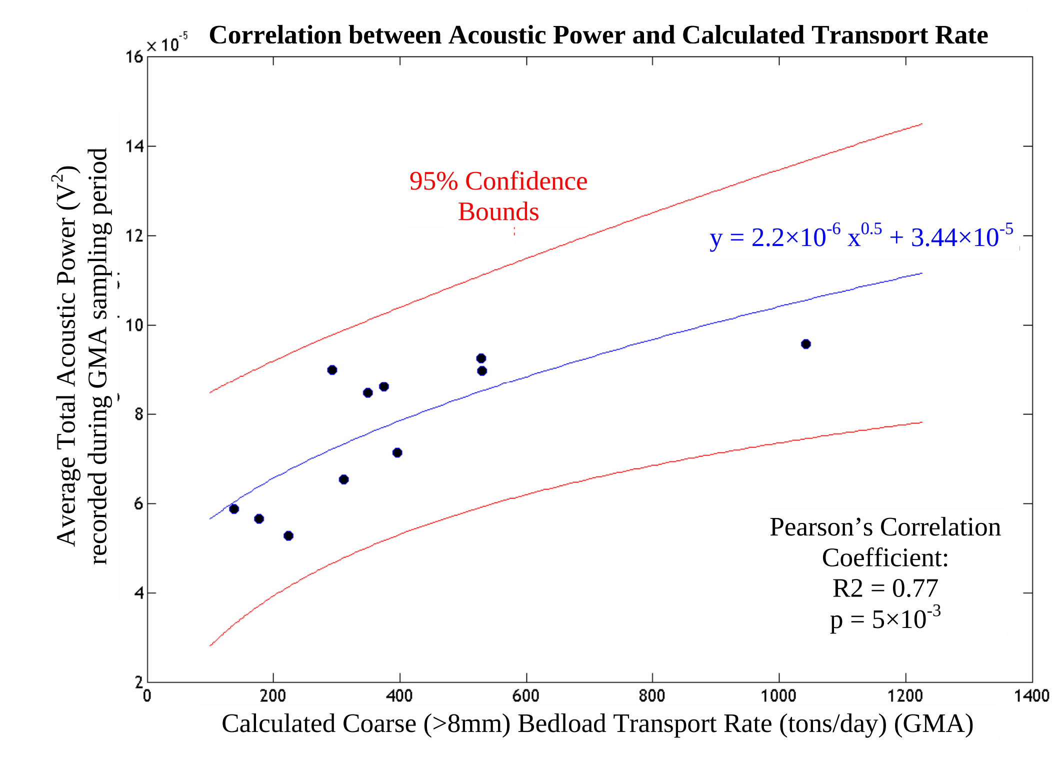

Figure 2 Correlation plot between average acoustic power and bedload transport rate.

It has been suggested (e.g. Hardisty, 1993) that acoustic noise will correlate strongly with discharge, because of bubble collapse and turbulence-induced noise. Figure 3 shows the relationship between discharge and acoustic power. The explanation for the dramatic rise in acoustic power well after the peak in water discharge cannot be attributed to water discharge, as the rising and falling limb values, for the same discharge, are distinct populations on this plot. We attribute this rise to bedload, 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. We conjecture that the coarse sediment sources for this site are the deltas of Indian and Weaver Creeks located from 2.5-3 miles upstream. Over the year, rain-event driven flooding progrades these deltas into the Trinity. It is only during the dam-release flows that this material gets transported downstream, and we speculate that this delay in the peak coarse-material transport rate corresponds with the arrival of the deltaic material. These distances and delays correspond to an average celerity of between 0.9 and 1.2 cm/s, which are well within the range given in the literature for bedload sheet migration.

Interpretation of the individual acoustic records reveals several interesting periodicities in the acoustic noise, and by inference, in the bedload transport (Fig. 4). In particular, the lowest

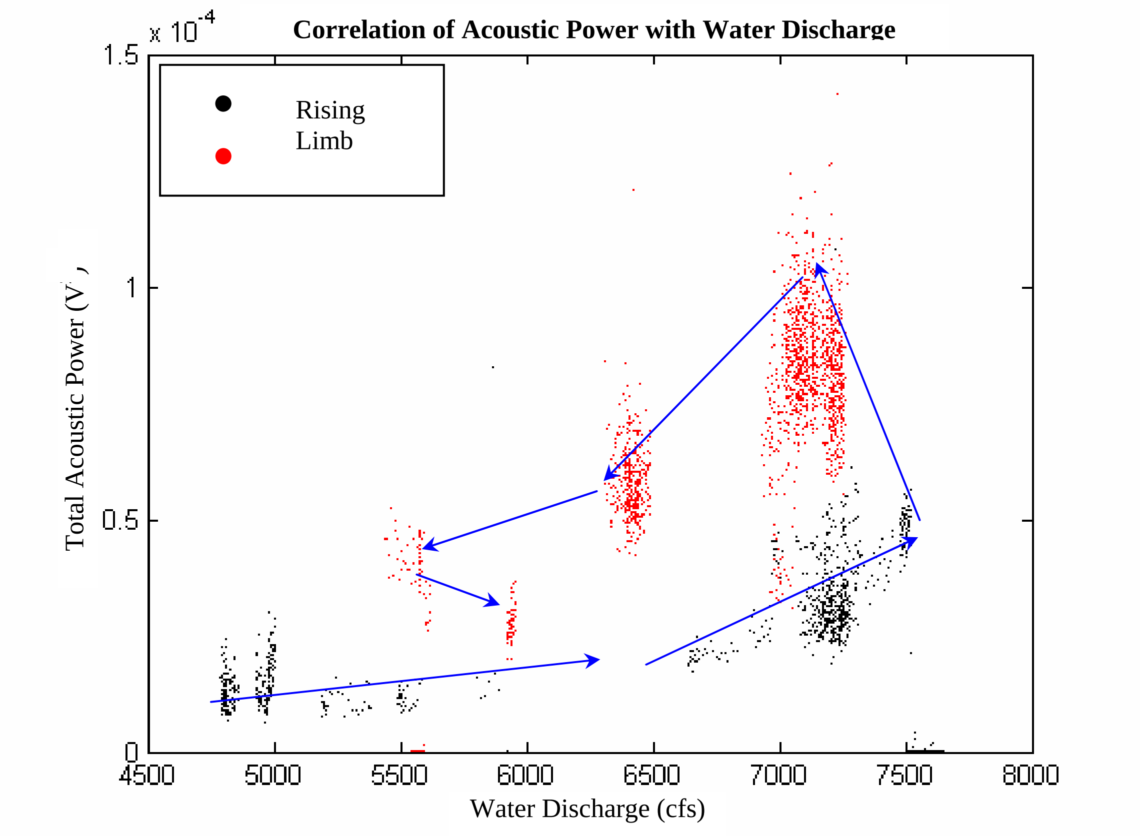

Figure 3 Relationship between acoustic power and discharge. The blue arrows indicate the approximate progression of time through the flood. The peak of the flood was assumed to fall

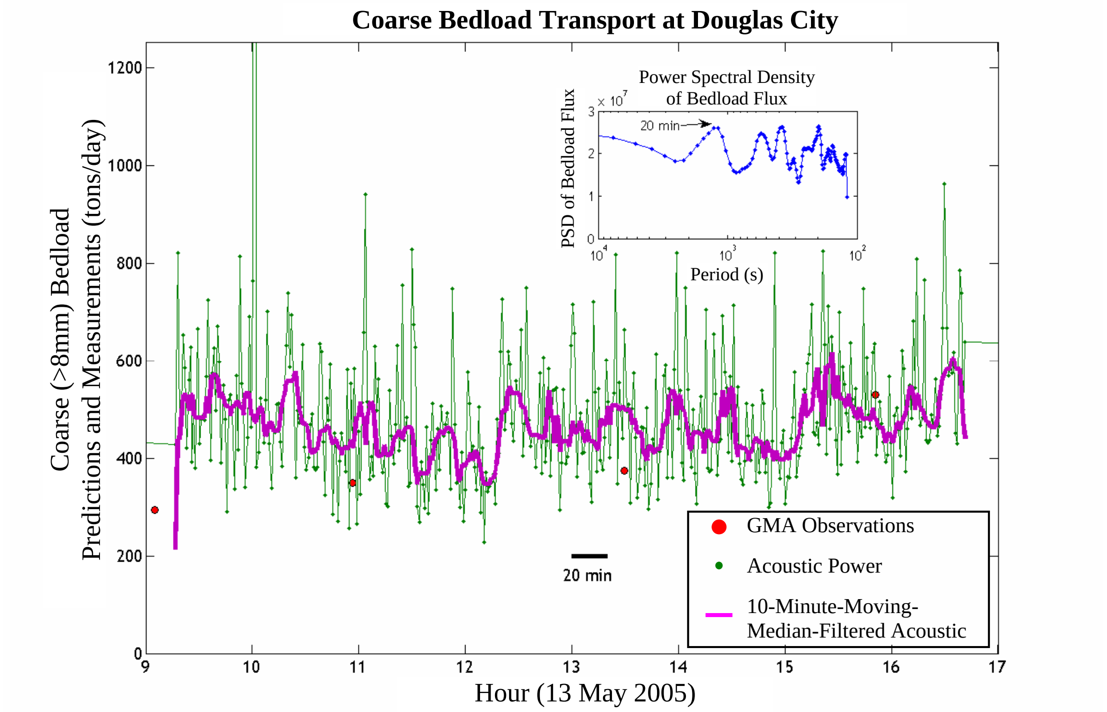

Figure 4 Detail of bedload transport predictions for 13 May 2005. The green dots are the predicted values, the lines are interpolations. The purple curve is the result of a 10-minute moving window median filter. Inset is the power spectral density of the one-minute data. Note that the horizontal axis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

frequency peak that is captured by the spectral analysis, at a period of about 20 minutes, is consistent with those reported in the literature (e.g. Whiting et al, 1988) for periodic bedload sheets.

CONCLUSIONS

Although the data are limited, it is clear that there is a statistically significant correlation between acoustic power and bedload transport. The correlation cannot be attributed to a third variable dependent on discharge such as 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, there were five GMA samples that were not included in 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 contemporaneous bedload transport observations.

REFERENCES

Anderson, M.G. (1976). “An inexpensive circuit design for the acoustic detection of oscillations in bedload transport in natural streams,” Earth Surface Processes and Landforms, 1(3), pp 213-217.

Baenziger, R., and Burch, H. (1990). “Acoustic sensors (hydrophones) as indicators for bed load transport in a mountain torrent,” in Lang, H., and Musy, A. (eds.), Hydrology in Mountainous Regions I — Hydrological Measurements; The Water Cycle: Proc. of Two Symposia Held at Lausanne, August, 1990, IAHS-AISH Publication 193, pp 207-214.

Edwards, T.K., and Glysson, G.D. (1999). Field Methods for Measurement of Fluvial Sediment, U.S. Geological Survey Techniques of Water Resources Investigation, Bk. 3 Ch. C2, 89 p.

Ehrenberger, R. (1931). “Direkte Geschibemessungen an der Donau be Wien und deren bischerige Ergehuisse,” Die Wasserwirtschaft, 34, pp 1-9.

Govi, M., Maraga, F., Moia, F. (1993). “Seismic detectors for continuous bed load monitoring in a gravel stream,” Hydrological Sciences Journal, 38, pp 123-132.

Hardisty, J (1993). “Monitoring and modeling sediment transport at turbulent frequencies,” in Clifford, N.J., French, J.R., and Hardisty, J. (eds.), Turbulence: Perspectives on Flow and Sediment Transport, John Wiley and Sons, New York, pp 35-59.

Hartshorn, K., Hovius, N., Dade, W. B., and Slingerland, R. L. (2002). “Climate-driven bedrock incision in an active mountain belt,” Science, 297, pp 2036-2038.

Helley, E.J. and Smith, W. (1971). Development and calibration of a pressure-difference bedload sampler. U.S.G.S. Open File Report.

Howard, A.D. (1998). “Long profile development of bedrock channels: Interaction of weathering, mass wasting, bed erosion, and sediment transport,” in Tinkler, K. and Wohl, E.E., (eds) 1998, Rivers Over Rock: Fluvial Processes in Bedrock Channels, Geophysical Monograph Series 107, Am. Geophysical Union, Washington, D.C., pp 297-318.

Johnson, P., and Muir, T.C. (1969). “Acoustic detection of sediment movement,” Journal of Hydraulic Research, 7, pp 519-540.

Klingeman, P.C., Milhous, R.T., and Heinecke, T.L. (1979). Oak Creek vortex bedload sampler. Oak Creek Sediment Transport Report F2, Water Resources Research Institute, Oregon State University, Corvallis.

Graham Matthews & Associates (2004). WY2004 Flow Release Sediment Transport Monitoring Report, Report for Trinity River Restoration Program, US Bureau of Reclamation, Shasta Lake, CA.

Millard, N.W. (1976). “Noise generated by moving sediments,” in Proc. of the Conference on Recent Developments in Underwater Acoustics 31 March-1 April 1976, Institute of Acoustics, London, UK.

Mulhoffer L. (1933). “Untersuchungen uber der Schwebstoff und Geschiebefurung des Inn nachst Kirchbichl, Tirol,” Wasserwirtschaft, pp 1- 6.

Reid, I., Layman, J.T., and Frostick, L.E. (1980). “The continuous measurement of bedload discharge,” Journal of Hydraulic Research, 18, pp 243-249.

Rouse, H.L. (1994). “Measurement of bedload gravel transport; the calibration of a self-generated noise system,” Earth Surface Processes and Landforms, 19, pp 789-800.

Slingerland, R., Willett, S.D., and Hennessey, H.L. (1997). “A new fluvial bedrock incision model based on the work-energy principle,” EOS Transactions, Am. Geophysical Union 78(46), p F299.

Sklar, L.S. and Dietrich, W.E. (1998). “River longitudinal profiles and bedrock incision models: Stream power and the influence of sediment supply,” in Tinkler, K. and Wohl, E.E., (eds) 1998, Rivers Over Rock: Fluvial Processes in Bedrock Channels, Geophysical Monograph Series 107, Am. Geophysical Union, Washington, D.C., pp237-260.

Thorne, P.D. (1985). “The measurement of acoustic noise generated by moving artificial sediments,” Journal of the Acoustical Society of America, 78, pp 1013-1023.

Thorne, P.D. (1986). “Laboratory and marine measurements on the acoustic detection of sediment transport,” Journal of the Acoustical Society of America, 80(3), pp 899-910.

Thorne, P.D., Heathershaw, A.D., and Triano, L. (1984). “Acoustic detection of seabed gravel movement in turbulent tidal currents,” Marine Geology, 54, pp M43-M48.

Thorne, P.D., Williams, J.J., and Heathershaw, A.D. (1989). “In situ measurements of marine gravel threshold and transport,” Sedimentology, 36, pp 61-74.

Tywoniuk, N., and Warnock, R.G. (1973). “Acoustic detection of bed-load transport,” Proc. of Hydrology Symposium at University of Alberta, Edmonton, May 8 and 9, 1973, Department of Environment Natural Resource Council, Canada, pp 728-735.

Voulgaris, G., Wilkin, M.P., and Collins, M.B. (1994). “Shingle movement under waves & currents: An instrumented platform for field data collection,” in Arcilla, A.S., Stive, M.J., Kraus, N.C. (eds.) Coastal Dynamics ’94, American Society of Civil Engineers, pp 894-909.

Voulgaris, G., Wilkin, M.P., and Collins, M.B. (1995). “The in situ passive acoustic measurement of shingle movement under waves and currents: instrument (TOSCA) development and preliminary results,” Continental Shelf Research, 15(10), pp 1195-1211.

Whiting, P.J., Dietrich, W.E., Leopold, L.B., Drake, T.G., and Shreve, R.L. (1988). “Bedload sheets in heterogeneous sediment,” GEOLOGY, 16 (2), pp 105–108.