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Bed load measurements with a new passive acoustic sensor

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Abstract Flume experiments and field tests of acoustic bed load sensors have been carried out in three Norwegian rivers. The sensors record the acoustic energy of bed load impacts on a plate fixed to the river bed. Some of the sensors operate in a narrow ultrasonic frequency band, while others record the whole frequency spectrum from 0 to 500 kHz. The systems tested are able to monitor temporal variations in bed load transport and thereby provide additional information about the transport process. The field measurements revealed a markedly irregular pattern of bed load transport rates. The presence of a hysteresis effect indicates some similarity to suspended load transport, with the transport rate being much larger on the rising stage of a flood than on the falling stage. A large difference between maximum and mean acoustic amplitudes over a given time period reflects sporadic transport; the difference is much less when particle transport is continuous. Flume experiment results for a single fraction, 18–27 mm, produced a linear relationship between bed load transport in kg s^{-1} and acoustic energy integrated over the frequency range. Preliminary analyses indicate that a characteristic relationship exists for each size fraction within the bed load range. The present studies of the transport of different grades also indicate that each fraction may have a characteristic frequency signature. Thus, it is possible that a multivariate calibration model may predict both total load and grain size from acoustic amplitudes and frequency spectra.

Key words bed load; chemometric; field tests; flume experiment; frequency signature; Norway; passive acoustic sensor; sediment

INTRODUCTION

Bed load transport data are important to many aspects of river management. However, the pulsating and discontinuous nature of bed load movement introduces many problems for conventional methods of measuring transport rates. The introduction of continuously recording sensors therefore seems to be a way to obtain more reliable data and improve the understanding of the bed load transport process. The aim of this paper is to report the results of testing new acoustic bed load sensors in field and laboratory studies to determine their ability to measure bed load in rivers.

The physical principle underpinning the acoustic characterization of bed load described in this paper is based on the kinetic impact of particles that strike a steel plate attached to the sensor. Sound generated by particle impacts has been employed for detecting bed load movement for some time (Mulhofer, 1933) but the development of this approach has been slow in spite of its advantage in producing a continuous record.

Richards & Milne (1979) applied a piezo-electric transducer to convert acoustic energy produced by bed load particle impacts to electric signals. They concluded that the method was potentially useful for identifying bed load transport thresholds.

Banziger & Burch (1991) and Rickenmann *et al.* (1997) describe a system where impacts caused by bed load passing over a metal plate are detected by a hydrophone. Impacts above a certain threshold amplitude are recorded by a pulse counter. The volume of material deposited in an adjacent sediment trap was found to correlate with the number of pulses counted per minute.

Jagger & Hardisty (1991) investigated bed load transport by waves in a coastal environment by acoustic methods. They measured the acoustic energy generated by interparticle collisions and provided a review of former work. These experiments demonstrated that bed load transport rate can be reasonably estimated from the output voltage above background of a bandpass filtered hydrophone system.

Halstensen (2001) described mass flow rate measurements in fluid flow in industrial and technological processes using acoustic sensors. Emission of audible noise is an inherent characteristic of very many production-, manufacturing- and transport processes. Of special relevance to sediment transport phenomena are the analyses of powders, acoustic chemometric monitoring of fluidized bed granulation, and analyses of fluid flow with multicomponent mixture concentrations. An acoustic chemometric approach for prediction of powder particle size distributions, intended for on-line implementation, was presented by Halstensen & Esbensen (2000). Acoustic chemometry is described as a measurement method applying multivariate analysis to process-generated vibrations. The standard solution demands that calibration is carried out on representative reference powder samples.

The present paper discusses the results of a programme of flume experiments and fieldwork designed to test the suitability of new passive acoustic sensors for monitoring bed load transport rates in rivers. Initially, ultrasonic sensors that record within a narrow frequency band were deployed. These had been developed by a Norwegian company, ClampOn AS, to monitor the amount of sand carried in suspension by oil pumped up from reservoirs below the Norwegian continental shelf. The sensor detected the sound of particles impacting the pipeline wall at a bend. These collisions generated a characteristic frequency pattern which was analysed to estimate the total mass of sand. ClampOn (1998) adapted this pipeline instrument for NVE by altering the frequency band so that it could better detect gravel- and cobble-sized material. The use of an ultrasonic frequency band was chosen to avoid turbulence-generated noise. This first version of the modified acoustic sensor was installed and tested in three Norwegian rivers.

Subsequent laboratory experiments, described in this publication, employed a newer version of the ClampOn sensor which measures the acoustic response within a broad frequency range 0–500 kHz. An additional sensor, previously used by Halstensen (2001), was used in parallel to acquire higher resolution data in the low frequency domain (0–25 kHz). Halstensen & Esbensen (2000) had demonstrated that significant information can be extracted by use of chemometric methods in the low frequency range, despite the low signal to noise ratio.

It was assumed that information may be obtained not only from measurements of the impact energy alone, but also from the pattern of variation in the frequency domain. Several fractions in the bed load range were therefore investigated to find out if they had characteristic frequency signatures.

SENSOR DESIGN AND OPERATION

The sensor consists of an acoustic sensing device, a signal amplifier with a low-pass/-high-pass filter and a digital signal processor. In the field tests a narrow ultrasonic frequency band above 50 kHz was applied and the acoustic signal was integrated over a period of one second, with the value output in digital form as a numeric string. The water turbulence generates very little acoustic energy in this frequency range, so the output data essentially represent variation in bed load transport with very little ambient noise present in the record. In the flume studies, the acoustic signal generated by the bed load transport process was studied in a broad frequency range, employing the ClampOn and the low frequency sensors in parallel to obtain good resolution.

The low frequency sensor is at the moment a laboratory setup, consisting of a standard lightweight accelerometer, a signal amplifier, a low-pass filter and a National Instrument data acquisition card and software. Frequency spectra are calculated every second. The high frequency ClampOn sensor contains a digital signal processor which calculates the frequency spectra internally every second and communicates the result via an RS-485 line. Both sensors are attached to the underside of a 500 × 500 × 10 mm steel plate which is fixed to the riverbed or the bottom of the laboratory flume (see Fig. 1).

Vibration created by particles sliding or rolling over the plate is picked up by the sensor. In the field configuration, the sensor was connected to a Sutron 8210 datalogger (RTU) which reads the acoustic energy every two seconds. To reduce data storage space, only the mean and maximum values for each minute are stored.

In addition to the bed load reading, the logger measures water stage at 5-minute intervals. The stored data are transmitted to the office once a day using a combination

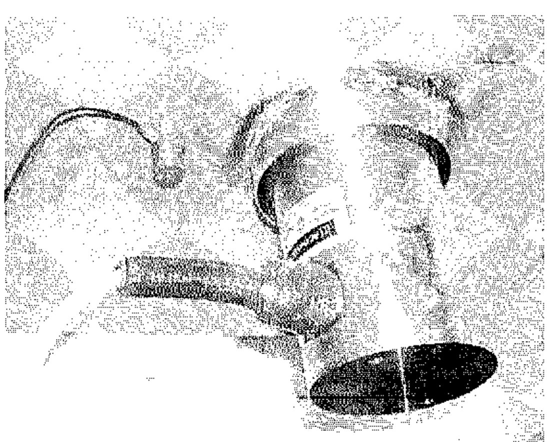

Fig. 1 Sensors installed in the laboratory test rig used in the flume studies. Right: The ClampOn sensor operating at high frequencies (0–500 kHz). Left: The low frequency 0-25 kHz sensor.

of line-of-sight radio and fixed line modems. Of the two field sites operational today, one is solar powered and the other uses mains power.

The sensor is powered by a 12 V supply using 300 mA and communicates readings through an RS-485 serial interface. The cylindrical sensor head is 20 cm high and 10 cm in diameter. All electrical components are mounted in a robust and watertight stainless steel housing.

PILOT STUDY OF SENSOR RESPONSE

During the initial stages of the project, the acoustic response of the narrow band ultrasonic sensor was tested with known quantities of sediment of different fractions. The rig consisted of a wooden channel, approximately 100 cm long and 50 cm wide, set at a 12° slope. At the top of the channel was a trough, where water flowed freely over the edge into the channel. The flow rate (1 m s^{-1}) and the slope of the channel were constant throughout the experiments and maintained approximately 1 cm of water above the sensor plate.

The result of the test of sensor response to bed load transport for the 5–8 mm fraction is shown in Fig. 2. Although the total mass tested was low in this initial experiment the result suggested a semi-logarithmic relationship between the relative acoustic amplitude and the number of particles rolling across the sensor plate. Tests of several other fractions indicated that the sensor responded differently to different size grades. Runs using 10 g, 50 g and 100 g of sediment of four grades in the 0.25–8.0 mm size range were repeated three or four times for each size grade. The sensor responded clearly to an increase in sediment load for all the size grades included in the test. The rate of increase in acoustic amplitude was, however, larger in the coarse sand fractions, when compared to the rates of increase caused by the impact of either gravel-sized or fine sand particles.

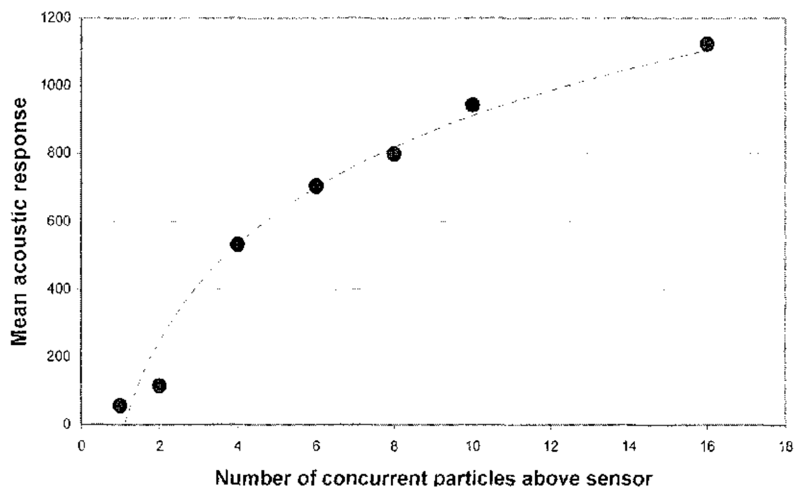

Fig. 2 Acoustic response to increasing transport of 5–8 mm gravel particles in test flume.

FIELD TESTS

Nigardsbreelv

Nigardsbreelv is the meltwater outflow from the Nigardsbre glacier and its flow is characterized by a high degree of turbulence. The river occupies a bedrock channel and the bed load carried by the river is derived from sediment supplied by the glacier. The bed load is composed of relatively coarse material; gravel fractions dominate but in addition there is a significant proportion of cobbles and boulders. Clasts are often well rounded.

Annual transport rates have been calculated from measurements of the annual rate of deposition on the delta in Lake Nigardsvatn, 0.6 km downstream from the glacier terminus. The mean annual transport rate amounts to 8000 t year^{-1}, though up to 20 000 t year^{-1} have been measured during years with particularly intense runoff.

In May 1998 an acoustic sensor was installed in a rock surface cavity on the river bed approx. 0.5 km downstream from the glacier. The cavity was covered with a steel plate, connected to the datalogger by a cable. A record covering 15–22 May 1998 is shown in Fig. 3. This is a plot of the mean values calculated for successive 15-minute periods. During the first 7 days, the discharge was subject to daily fluctuations of around 12–15 m^3 s^{-1} because of snowmelt. The acoustic record shows little bed load activity, except for some minor peaks triggered by release of short term blockages in subglacial tunnels. However, the acoustic activity increased considerably, during a flood at the end of the measurement period, but fell back to a low level during the recession phase, even though discharge remained relatively high for some time. No direct sampling of bed load was carried out, but a high rate of cobble and boulder

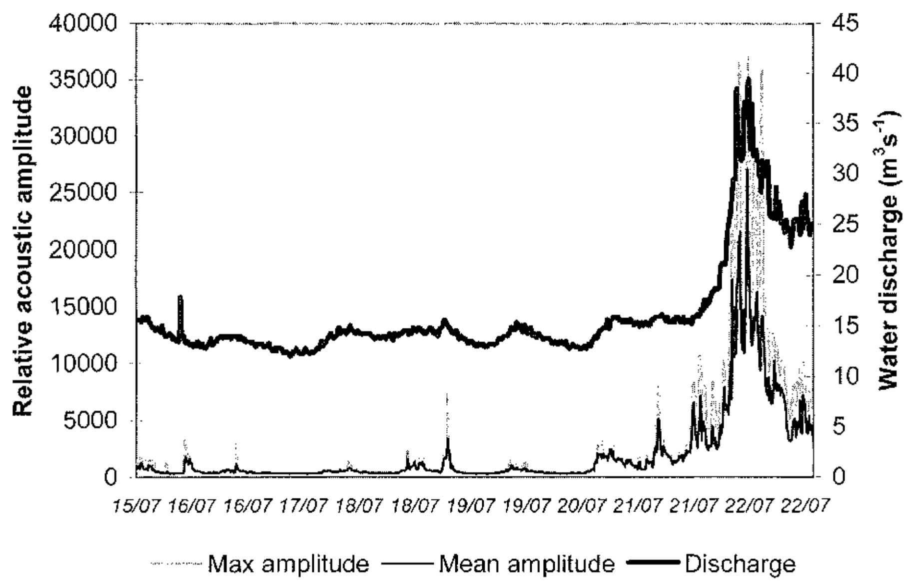

Fig. 3 Maximum and mean acoustic amplitude over 15-min intervals, and water discharge, in the river Nigardsbreelv 15–22 July 1998.

transport during the flood is revealed by the fact that the cable was heavily abraded, and eventually torn off. Further measurement in Nigardsbreelv was abandoned as an advance of the glacier caused the channel position to change.

Gråelva

In November 1999 a similar sensor was installed in the lowland River Gråelva in Trøndelag, central Norway. The sensor and the corresponding plate were built into the weir of the water discharge monitoring station. Gråelva represents a low energy environment when compared to Nigardsbreelv. The bed load is derived from a layer of gravel and cobbles on the river bed upstream of the monitoring station.

A record covering the period 10 December 1999 to 5 January 2000 is shown in Fig. 4. The measurements reveal a transport pattern essentially in agreement with bed load observations reported by authors that used sensors in other rivers (Banzinger & Burch, 1991; Rickenmann *et al.*, 1997). The bed load passes in pulses, but these do not always occur during high water discharge. If we exclude the anomalous measurement of 2 January, that may be due to an instrument error, the largest acoustic amplitudes were recorded during the rising stage of the flood event on 25 and 26 December. There was apparently little bed load activity during the falling stage except on 28 December when a small rise in discharge was accompanied by a major acoustic peak. The mean amplitude, however, remained low throughout the whole measurement period and only a small increase in acoustic amplitude was recorded during the flood on 4 January. No high amplitude events were recorded after this flood had peaked.

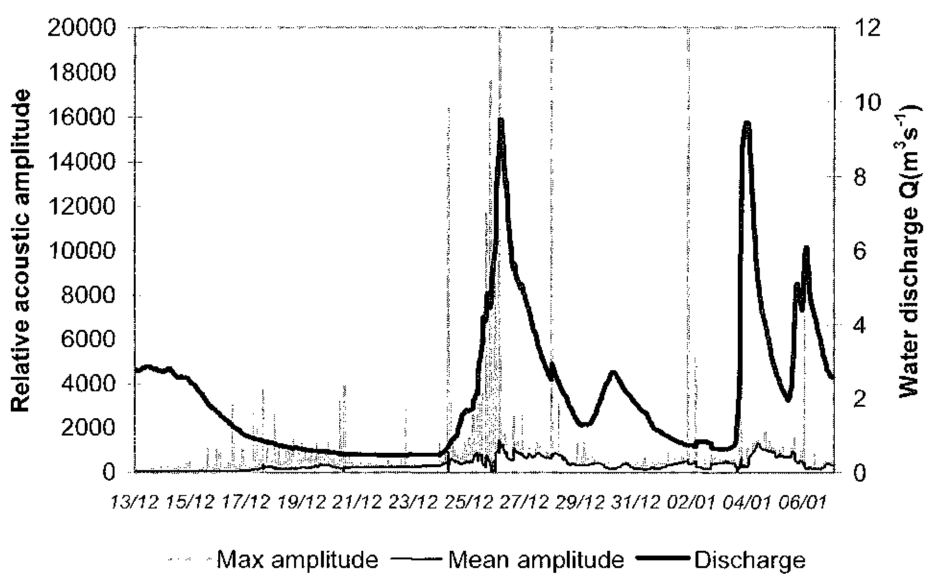

Fig. 4 Mean and maximum acoustic amplitude calculated for 5-minute intervals, and water discharge, in the River Gråelva at Børstad, from 10 December 1999 to 5 January 2000.

Bayelva

Bayelva is located near Ny Ålesund on Svalbard in the high Arctic. Most of the sediment is supplied by the Austre and Vestre Brøggerbre glaciers and by erosion in the glacier forefield.

Sediment transport and water discharge are measured at a composite Crump weir near the river outlet into the fjord. Between the monitoring station and the glaciers the river passes through several sandurs. The river bed sediment is dominated by gravel and cobble fractions derived from sandstones and is in general more angular than the clasts in the Nigardsbreelv and Gråelva rivers. In order to avoid material being deposited on the steel plate, the plate and sensor were installed at the downstream side of the weir crest. A description of the Crump weir and the suspended sediment monitoring station in Bayelva is given by Skretteberg (1990) and Bogen (1990).

Results from the acoustic record for 14–25 July 2000 are given in Fig. 5. Water discharge variations during the period were mainly caused by temperature fluctuations giving rise to variations in snow and glacier melt. The highest acoustic amplitudes were recorded during the rising stage of the 17 June flood event. A similar pattern occurs during each of the daily discharge fluctuations. However, the amplitude of the acoustic peaks does not always match the water discharge amplitudes. During low discharges of 3-6 m^3 s^{-1} for 24–27 July the acoustic amplitudes are higher than those on the preceding days, when discharges had been significantly higher.

The sensor record of bed load transport rates in the Bayelva is quite different from that of the rivers Gråelva and Nigardselv. These differences are probably related to hydraulic and sedimentological factors.

Calibration of acoustic amplitudes against the mass of the bed load obtained with a Helley–Smith sampler was initiated in the rivers Bayelva and Gråelva. However,

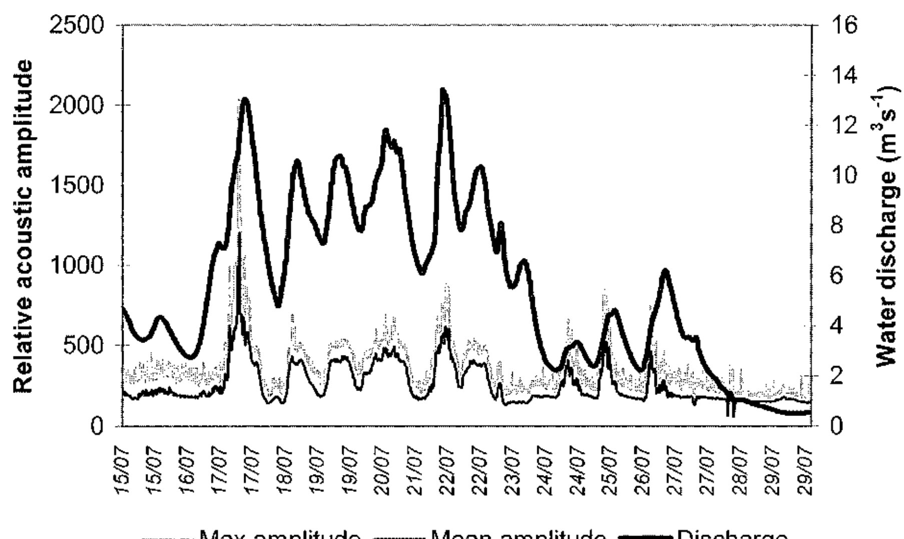

Fig. 5 Mean and maximum relative acoustic amplitude calculated for 5-minute intervals, and water discharge, in the River Bayelva 15–29 July 2000.

manual sampling in high discharges proved to be difficult at both locations. To overcome the problems encountered in the field, a full scale test rig was built. Information on the acoustic response to changes in grain size, sediment load and particle roundness was thus obtained through experiments with this test rig in the laboratory.

TESTS IN LABORATORY FLUME

The test rig consists of four main parts: sediment feeder, test flume, sedimentation basin and water recirculation pump (see Fig. 6). The rig is built mainly of waterproof plywood. A 2 m long and 0.5 m wide conveyer belt is used as the sediment feeder, and this is controlled by a computer using a frequency drive. Feeding rates from <1 g s^{-1} to >4 kg s^{-1} can be obtained. An even layer of test material is placed on the belt before each test. The total mass of the material is entered into the computer, together with the selected feeding rate.

The test material is dry fed into the flume which is approximately 4 m long, with a 0.5 × 0.5 m cross-section. The acoustic sensors are attached beneath a 0.5 × 0.5 m steel plate which extends across the flume 20 cm from its end. The sides of the flume next to the sensor are made of thick glass for visual inspection of particle movement over the sensor. A pair of hydraulic jacks is used to adjust the flume slope.

The mix of water and sediment flows into an 8 m^3 sedimentation basin. Coarse material (>2.5 mm) is separated in a 1 m^3 filter basket which can be hoisted out for easy re-use of the test material. Finer material accumulates on the bottom of the basin. At the far end of the basin a large wastewater pump feeds the now clean water back up to the top of the test flume. A simple manual butterfly valve is used to control the pump outlet, which yields a water flow in the range of 30–300 l s^{-1}. Depending on the sediment feed rate, the test duration was 20–200 s.

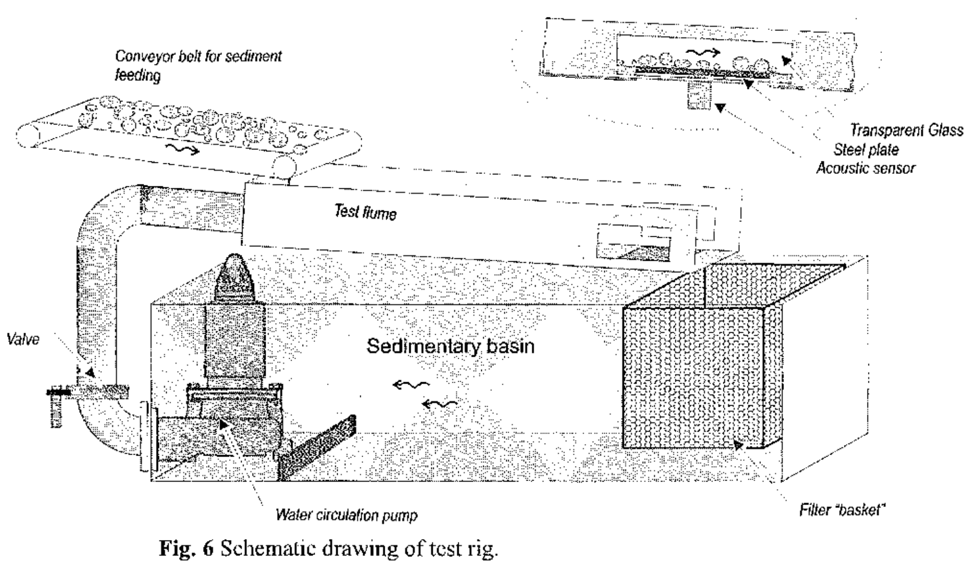

Fig. 6 Schematic drawing of test rig.

More than 100 tests have been run, varying the grain size fractions, particle roundness, bed load transport rate and water velocity. The sensor setup generates a frequency spectrum every second. Fractions within the grain size range from 3 to 136 mm were selected for the flume experiments. The experiments reported in this paper were all carried out using edged particles and a water velocity of 1.8 m s^{-1}

RESULTS OF FLUME EXPERIMENTS

It seems that a particular combination of size fraction, velocity and bed load transport rate values gives a fairly constant acoustic frequency signature.

The results of a series of tests with the 18-27 mm fraction are shown in Fig. 7 for increasing bed load transport rates between 10 g s^{-1} and 2000 g s^{-1} (Series 1 in Table 1). As the bed load transport rates increase, the frequency signature or spectrum shape is maintained, but with increasing acoustic amplitude.

Mean acoustic energy (P_a) appeared to be positively correlated with bed load transport rates (G_b). The integral of the frequency spectra was calculated for the transport rates used in this series. The mean integral value of the frequency spectra over a given time (e.g. 60 s) for the fraction 18–27 mm increased almost linearly with the bed load transport rate (Fig. 8). The best fitted regression line is $P_a = 161.92G_b + 11935$ with $r^2 = 0.9806$.

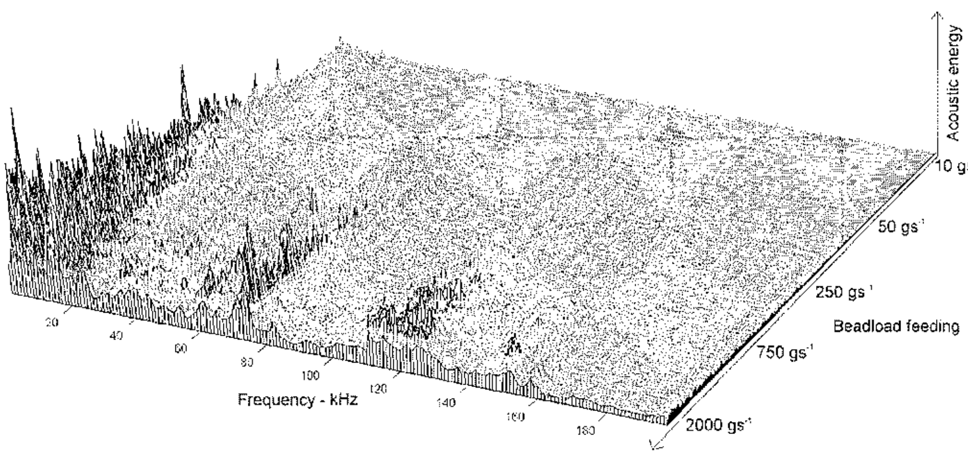

Fig. 7 Acoustic energy as a function of bed load transport rate and the frequency distribution in the 0–180 kHz range. (Series 1 in Table 1).

Table 1 Set of variables during flume experiments reported in this paper.

Flume experiment	Particle fraction (mm)	Particle roundness	Bed load transport (g s^{-1})	Velocity (m s^{-1})
Series 1	18.0–27.0	edged	10–2000	1.8
Series 2	18.0–27.0 and 4.5–8.5	edged	500	1.8

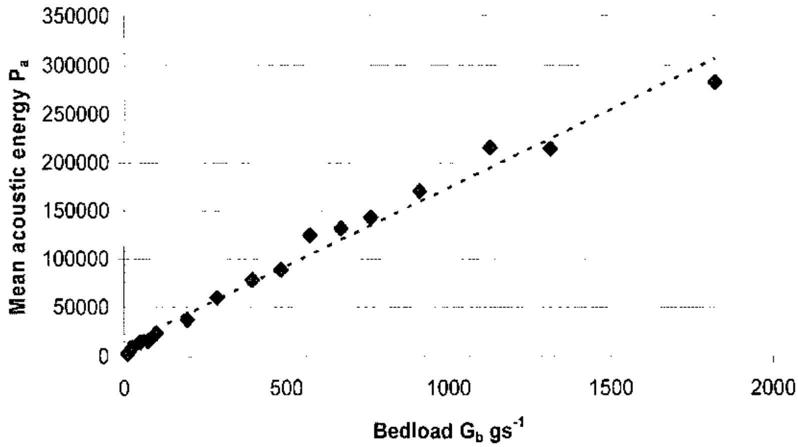

Fig. 8 Acoustic energy (expressed as the integral of the frequency spectrum) *vs* bed load transport rate for the 18–27 mm fraction. (Series 1 in Table 1).

The difference in correlation curves between this experiment and the preliminary findings shown in Fig. 2 has yet to be investigated. One possible explanation might be that the first experiment operated close to the lower detection threshold of the sensor. The experiment was also conducted with the first generation of the acoustic sensor which might have an influence on the results due to different hardware properties.

When maintaining a constant particle concentration and flow velocity, different frequency signatures were produced when fraction sizes were changed. Each fraction seems to have a characteristic frequency signature. This is illustrated by the results in the 0–30 kHz frequency band for the 4.5–8.5 mm and 18–27 mm fractions, shown in Fig. 9. This observation suggests that it is possible to develop a model for identifying and classifying different size fractions by their acoustic signature. Halstensen & Esbensen (2000) were able to estimate the particle size distribution of a powder flow by acoustic methods using multivariate analysis techniques such as Principal Component Analysis and Partial Least Squares to calibrate their model. Further

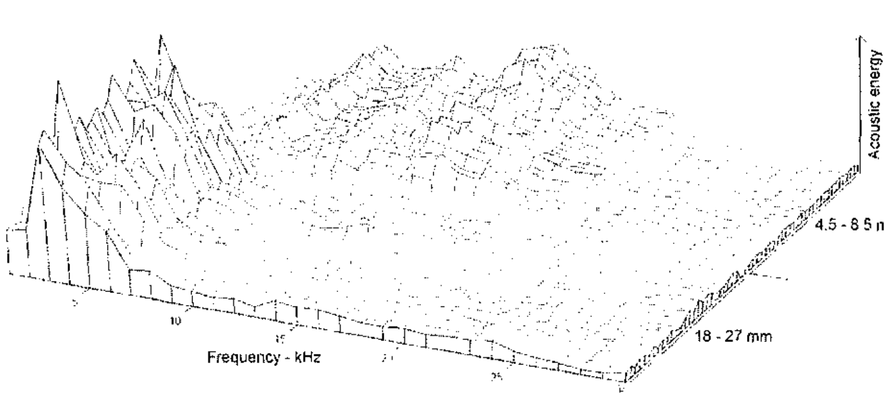

Fig. 9 Frequency signature of the 4.5–8.5 mm and 18.0–27 mm fractions (Series 2 in Table 1).

experiments and analyses are necessary to develop such a model for the estimation of bed load transport rates and size distributions. However, the results obtained so far are promising.

CONCLUSIONS

The experiments and field tests with the acoustic bed load sensor indicate that this system successfully monitors temporal variations in the rate of bed load transport. The system must be calibrated against actual samples of bed load for each measuring site.

The field measurements reveal a markedly irregular pattern of bed load transport rates in the rivers studied. There is some similarity to suspended load transport in the way that a hysteresis effect is present, namely the transport rate is much higher on the rising stage than on the falling stage of a flood.

The small difference between maximum and mean acoustic amplitudes recorded in the high energy rivers Bayelva and Nigardsbreelv most probably indicates continuous movement of bed load. In the quieter River Gråelva, there is a very large difference between the mean and maximum amplitudes. This probably represents a continuous flow of small amounts of sand with only sporadic transport of gravel or cobbles during the observation period.

Flume studies were carried out to study the acoustic response to hydraulic and sedimentological variables. Results for the 18–27 mm fraction showed that as bed load transport rate increases, the frequency signature or spectrum shape is maintained, but with increasing acoustic amplitude.

The same fraction gave a linear correlation between bed load transport and acoustic energy integrated over all frequencies. Preliminary analyses indicate that a similar relationship exists for all the size fractions in the bed load range, but that the parameters may vary for each fraction. In rivers, these parameters may possibly be modified by particle roundness and hardness, but this is still being investigated.

Studies of the transport of several fractions indicate that each of them may have a characteristic frequency signature. Thus it is possible that a multivariate calibration model can be used to calculate both the total bed load transport and its grain size distribution from frequency spectra and acoustic amplitude.

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Acoustic gravel-transport sensor: description and field tests in Little Granite Creek, Wyoming, USA

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Abstract Acoustic systems have been developed for the measurement of bed load momentum in gravel bed streams. The transducers are placed in the bed load either by a wading operator (GTS-I) or in a fixed installation embedded in the stream (GTS-II). The signals produced when particles impact the transducer are processed by an electronics unit to provide a continuous record of bed load momentum. A recent comparison of a GTS-II system with bed load traps in a small, mountain stream yielded promising results. Although the data are limited, they show that when the size of the bed load is known, corrections for grain velocity are made, and time-space averaging is sufficient, GTS measurements are roughly comparable to those made with bed load traps.

Key words bed load; bed load transport; gravel bed streams; gravel-transport sensor

INTRODUCTION

An understanding of bed load transport in gravel bed streams is needed for the assessment of the ecological and physical consequences of land-use changes in and around these systems. D & A Instrument Company is developing acoustic systems for measuring bed load in streams and on beaches to meet this need. The idea of using acoustic signals generated when entrained sediment particles strike a rigid object is not new. Sharp & O'Neill (1968) used a wire to detect sediment flowing in pipes and Downing (1981) used a similar technique to measure sand bed load in streams. In the early 1990s, this approach was extended to measure gravel bed load with a pipe containing an acoustic detector and recording electronics (Downing, 1993). In this paper, we describe further developments of acoustic devices for measuring gravel momentum and present the results of our tests in a small, mountain stream in Wyoming, USA.

SENSOR DESCRIPTIONS

The gravel-transport sensor (GTS) consists of a 1.6-mm, 17-PH4, stainless steel pressure plate covering a sheet of 0.5-mm PVDF film (PiezoFlex™, AIRMAR Technology Corp.), the acoustic detector, backed by a mass of aluminium; see Figs 1 and 2. When gravel collides with the plate, it compresses the detector until its forward

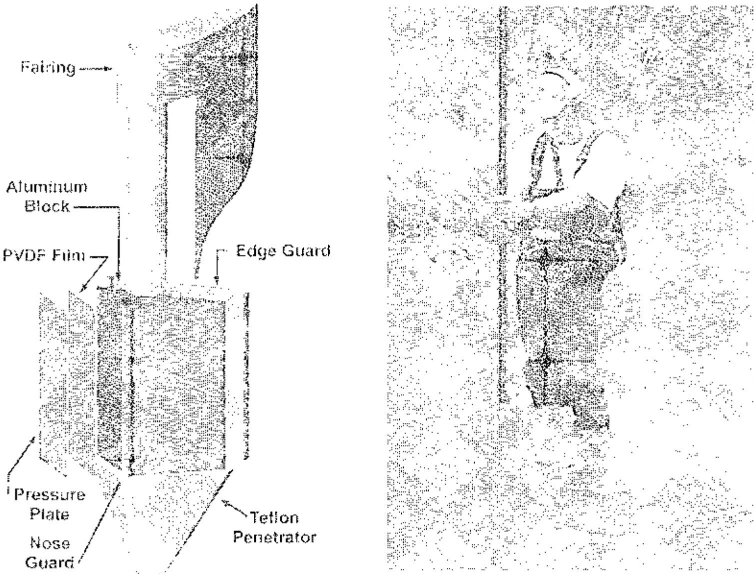

Fig. 1 Exploded view of GTS-I transducer and photograph of GTS system during a stream survey.

Fig. 2 Photographs of GTS-II transducer, anchor assembly (insert) and sensors deployed with bed load traps in Little Granite Creek.

momentum is expended then it bounces back into the flow. Nearly all of the strain produced by an impact occurs in the PVDF film because of its low elastic modulus (1%) relative to the adjacent elements. Electric charge is generated by the PVDF film in proportion to the force exerted on the pressure plate and the time integral of force, the impulse, is proportional to the momentum of the impacting particles. The integral of electrical charge is therefore a direct measure of particle momentum. PVDF film was selected from several candidate piezoelectric elements because of its high sensitivity, excellent formability, and low mechanical quality (a bell has high mechanical quality), elastic modulus, and cost. Laboratory calibrations have demonstrated that transducers constructed in this way are sensitive to particle momentum in the range 0.00002–0.08 kg m s^{-1}. The lower end of this range is equivalent to a 5-mm stone moving at 0.12 m s^{-1} and the upper end represents a 100-mm stone moving at 0.06 m s^{-1}. The calibrations also show that sensitivity is very uniform over the transducer area because the pressure plate is very stiff. Tests with steel balls dropped onto a grid of 18 evenly spaced points on a GTS transducer showed that the coefficient of variation of the output was only 2.3%.

The GTS transducer has been configured for two applications (Downing, 2003). The first one, called GTS-I, is for a handheld unit deployed by a wading operator in much the same way as a Helley-Smith bed load sampler is used. Figure 1 shows an exploded view of the GTS-I transducer design. Two 54 × 105-mm PVDF elements are bonded to a block of anodized, 7075-T6 aluminium with high-strength epoxy in a 90°, open-book configuration. The leading edge of the assembly is protected from impact damage with a steel bull nose bonded into the front of the mounting block and the trailing edges are protected with an edge guard bolted to the back of the transducer. The open-book geometry was chosen so that impact angles are nearly constant. This is the angle between a particle trajectory prior to impact and the pressure plate. It is important because the correlation between particle momentum and impulse (the charge integral) depends on the impact angle. When pointed upstream, the impact angle is 45° and the cross-flow active area of the GTS-I transducer is 76 mm wide. Figure 1 also shows a GTS-I deployed in a stream. Electrical connections to the PVDF film are made through holes in the film and the leads are routed to the electronics through passages in the mounting structure.

During sampling, the operator positions the GTS-I at a point on a sample transect and steps on it to force the Teflon® penetrator into the streambed. Once in position, a switch is depressed to initiate a sample record. At the end of a sample, the switch is depressed again to stop recording. This process is repeated at several positions to complete a transect. To reduce operator fatigue, a plastic fairing (CWA Products, Ltd) is fixed to the submerged part of the device (Fig. 1) to reduce drag by about 85% relative to a cylindrical shape with the same cross section. The pole is made of carbon-fibre composite for stiffness, low weight, and low heat loss and the device can be broken down into 1.5-m lengths for shipment. The GTS-I assembly weighs 4.6 kg.

The second application is an embedded sensor mounted on an anchor assembly containing batteries, electronics, and a data logger that can record bed load transport for periods from a few weeks to several months (GTS-II). Figure 2 shows two GTS-II transducers, an anchor assembly (inset), and a stream installation beside bed load traps developed by Bunte *et al.* (2001). The construction of the sensor is similar to that described above, except that only one PDVF element is used and the active cross-section is 95 × 200 mm. The GTS-II system also has a pressure transducer for measuring depth along with momentum data.

The electronics consist of an analog signal processor, a low-power microcontroller, and a FLASH data-storage circuit. Signals from the acoustic detector are input to a charge amplifier, the output of which is fed to a fourth-order, 500-Hz, high-pass filter that removes 60-Hz and other low-frequency noise. The filter output is routed to a comparator through a variable-gain amplifier that provides electronic compensation

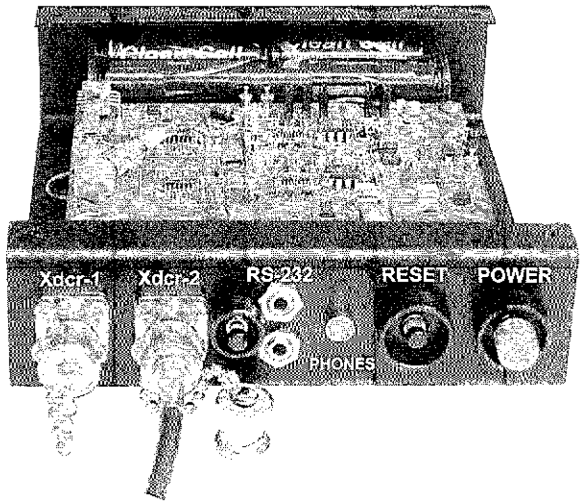

Fig. 3 GTS electronics and operator controls.

for differences in transducer sensitivity. When a signal produced by an impact rises above the comparator threshold, the comparator switches to a logic-high state until the signal returns to ground. The resulting square wave connects the signal to an integrator and triggers a pulse timer and a one shot to signal the microcontroller to digitize and record the integrator output and pulse duration. Once peak acquisition is complete, the controller resets the logic and integrator to set them up for the next pulse. The pulse acquisition time of the microcontroller is 7 ms, resulting in a maximum pulse-acquisition rate of 143 Hz. Because of FLASH memory limitations, the controller computes the average peak area and peak duration over an operator-selectable period from 1 to 60 s and stores the average values along with the number of impacts and time and date. The data FLASH can record 18 400 samples, which corresponds to a 306-h record for a sample period of 60 s. From laboratory tests with granitic and sedimentary stones, pulse durations range from 10 to 200 μs. Pulse duration is a data-quality-assurance parameter that indicates if the data are noisy and of dubious quality. The electronics and operator interface are shown in Fig. 3. The GTS-I transducers were calibrated by dropping steel balls and stones, falling at terminal velocity, on to the submerged transducers and recording the integrator counts. Integrator counts are an exact, digital measure of peak area. The calibration data for the transducers used in Little Granite Creek are shown on Fig. 4.

FIELD TESTS

The field tests were conducted in Little Granite Creek, which is an upland contributor to the Snake River system situated in the Gros Ventre range near Jackson, Wyoming, USA. Little Granite Creek is described by Ryan & Emmett (2002). Upstream of the GTS installation, the creek drains 19.7 km^2 of sandstone and interbedded sandstone and claystone. In the upper reaches, above the test site, several active landslides feed

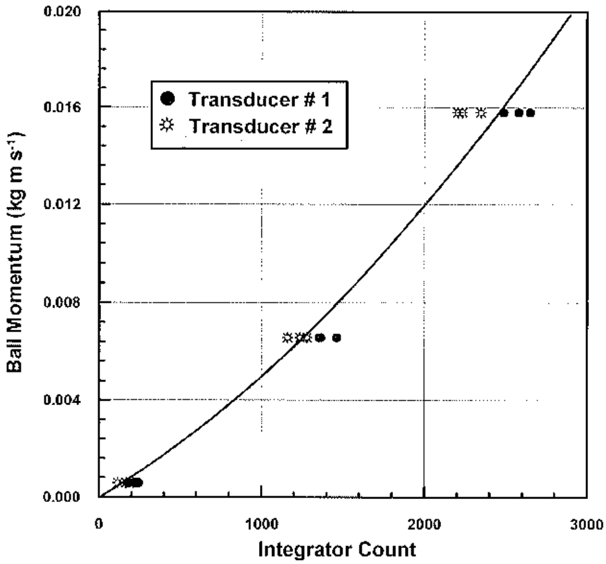

Fig. 4 Steel-ball calibrations of transducers used in Little Granite Creek (integrator counts are equivalent to peak areas).

glacial outwash and till to the creek where the channel has step-pool and plane-bed sections. The mean channel slope in the study reach is 0.021 and the local slope on the bar where samplers were deployed is 0.0115. Channel width and mean depth are 6.5 m and 0.34 m, respectively. At bankfull flow (3.4 $m^3 s^{-1}$), the mean velocity is 1.5 m s^{-1}. The streambed surface at the test location is composed of sand, gravel, and boulders and has a median grain size (d_{50}) of 49 mm determined by a pebble count.

The bed load sampler is 0.3 m wide, 0.2 high, and has a 0.9-m long trailing net with a 3.9-mm mesh. For sampling, the trap is temporarily fastened to a ground plate anchored in the stream bottom with steel rods. Sampling times are usually 1 h facilitating representative samples of a wide range of transport rates (up to seven orders of magnitude) and bed load particle sizes (4–90 mm). Two GTS-II sensors and two portable traps were installed on a submerged bar of the channel (Fig. 3) from 26 May until 9 June 2002 during snowmelt runoff. The prototype GTS-electronics box was placed on the stream bank and connected to the transducers with cables.

In order to compare the GTS record with trap samples, the data were binned each hour and the average depth, total impact counts, and the average peak areas in integrator counts were computed. Counts were then converted to average momentum using the calibration results shown in Fig. 4 and the total momentum in a 1-h bin is the product of the average momentum and the impact count. The values were divided by the cross-stream width of the transducers in metres to get bed load momentum in kg m s^{-1} per metre of bed per hour.

The GTS measures bed load momentum whereas direct samplers capture a mass of it. In order to compare GTS and bed load-sampler observations, it is necessary to factor bed load velocity into one set of the numbers. We elected to factor it into the bed load samples by using particle velocities computed from stream hydraulics and trap samples sieved in 0.5-phi size classes. Using the method described below, the velocity of each size fraction in a sample was computed and multiplied by the fraction weight to get fractional momentum. The total momentum of all fractions was then calculated. These results were divided by the trap width in metres and sampling time to get the bed load momentum per metre of bed per hour.

Equation 1, originally developed by Sekine & Kikkawa (1992) and later modified by Papanicolaou *et al.* (2002), provides a way to compute average particle velocities during saltation events from particle size, friction, critical-friction, and fall velocities. The equation was calibrated in a flume with fixed-bed roughness of uniform size, which yielded standard errors of about 14% of the mean velocity. It has not been verified in a natural stream. Critical-friction velocities were estimated using an equation given by Wilcock & Crowe (2003). Friction velocities were estimated using $U_* = (gSh)^{1/2}$ and a record of local water depth and bed slope, where: g = gravitational acceleration; S = energy gradient, nearly equal to the local bed slope; and h = local depth (Engelund & Fredsoe, 1976). Particle velocity is:

$$U_p = \sqrt{Rgd}\left[1.7\frac{U^*}{\omega}\sqrt{1-\frac{U^*c}{U^*}}+0.10\right] \tag{1}$$

Where: R = relative submerged density $(\rho_s - \rho)/\rho$; ρ = water density (kg m^{-3}), ρ_s = sediment density (2650 kg m^{-3}); d = particle diameter (m); ω = fall velocity (m s^{-1}); and U_{*c} = critical-friction velocity (m s^{-1}).

The results of the comparison for 28 May until 3 June are shown in Fig. 5. The bold trace shows the bed load momentum computed from the GTS record and the fine trace shows the water discharge measured at a gauging station 50 m upstream. Gravel began to move around noon on 28 May and continued to move intermittently until noon on 2 June. Prominent transport events occurred at 92, 113, and 128 h, the last of which was the largest one recorded. Momentum computed for the trap samples is shown by the open symbols.

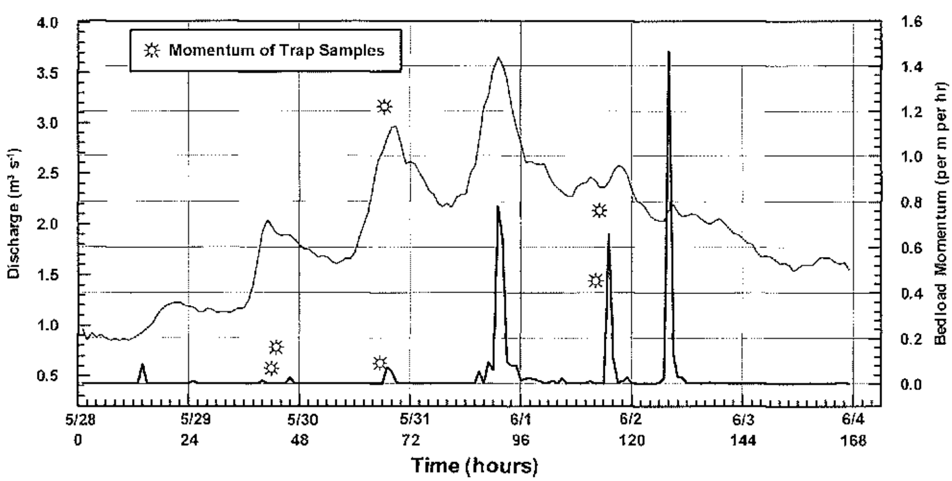

Fig. 5 Time series of discharge (fine trace), bed load momentum (bold trace), and computed momentum for trap samples (open symbols).

DISCUSSION

As the field tests have demonstrated, some bed load events occur when trap operators are not on the scene. The main advantage of the GTS-II system is that it provides a continuous record of the onset, relative magnitude, and cessation of transport events. The GTS-II is installed vertically with the bed surface located at the middle of the active transducer area, unlike some other sensors that are placed across a stream, flush with the bed. With this orientation, the bed can move up and down with accretion and erosion one half the transducer length, and moving grains will still impact the sensor. The disadvantage of the installation is that the sampling intensity is less than flush-mounted sensors. Sampling intensity is the percentage of the total bed load that is sampled. For example, a bed load sensor that spans an entire channel and monitors continuously would have a sampling intensity of 100%. Sampling intensities for the devices used at Little Granite Creek are much lower, ranging from 0.5, 2.4, to 7.5% for the Helley-Smith samplers, GTS-II sensors, and bed load traps, respectively. In many situations, continuous records from low-intensity sensors are worth more than records from high-intensity sensors with data gaps. The choice of one over the other will depend on the study objectives.

The data show general agreement with respect to magnitude most of the time. However, there is a poor correlation between the trap samples and the timing of peaks in the continuous GTS record. Sometimes the results from the two techniques agree quite well, such as for one of the samples around hour 68 and the one at hour 113, but at other times computed values differ by a factor of 14 and greater. Part of the difference is explained by the uncertainty of the particle velocities. Observations by Lee *et al.* (2000), indicate that the average velocities of saltating particles are normally distributed with a standard deviation of about 15% of the mean velocity. Time averaging should therefore remove the effects of these random velocity fluctuations. A more likely explanation for the time correlation is that transport rates vary greatly in time over the width of the channel during transport events. For example, the ratio of gravel masses trapped simultaneously about one metre apart were: 0.9, 10.9, 16.7, 30.4, 8.7, and 5.2, indicating that large differences are possible between closely spaced devices. This order of variability has been observed in transects made with Helley-Smith samplers at nearby sites and in other streams (Ryan & Porth, 1999). Although limited in scope, the test showed that GTS measurements are roughly comparable to those made with bed load traps when the size of the bed load is known, corrections for grain velocity are made, and time-space averaging is sufficient. It is clear, however, that longer sampling times extending over a wider range of transport conditions will be required to produce statistically significant calibrations.

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Monitoring bed load transport using acoustic and magnetic devices

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Abstract The work reported was undertaken in the Homerka instrumented catchment in the Polish Flysch Carpathians, where different techniques for monitoring coarse sediment transport have been applied over the past 30 years. The area is characterized by highly active erosion, sediment transport and fluvial sedimentation processes. Bed load transport has been measured using both acoustic and magnetic techniques. The acoustic (hydrophone) method permits continuous measurement and is able to provide a continuous record of coarse particle movement during flood events, which is a direct reflection of the magnitude of bed load movement. In general, bed load transport reaches a peak more rapidly than the water discharge. For a given flood discharge, the intensity of bed load transport varies between the rising and falling stages of a flood event. Coarse material bed load transport has also been measured in the Homerka catchment using magnetic tracers. In this case, magnets are cemented into holes drilled into gravel particles and an electromagnetic sensor is used to track their movement through a designated short reach. In addition, transport distances associated with individual gravel particles tagged with magnets during individual events have been documented by recovering the labelled gravel after the event using a metal detector. These magnetic tracing techniques permit the bed load transport rate associated with individual grain size fractions to be quantified.

Key words acoustic device; bed load transport; hydrophone; magnetic device; mountain streams; Polish Carpathians; sediment transport

INTRODUCTION

The high energy and active morphodynamic environment associated with mountain streams introduces important practical constraints in the application of standard techniques for measuring bed load transport. Direct classical methods for investigating bed load transport are for the most part expensive to apply, in terms of both equipment and manpower requirements. As a result, most studies applying such methods have addressed very limited objectives and have involved only short term measurements. It is difficult to use short term measurements in the interpretation of longer term sediment yields and contemporary channel system changes.

Most existing work has centred on comparisons of bed load and suspended load transport, since this is important for investigating the total sediment flux. Such studies have indicated that bed load commonly constitutes a substantial part of the total load of most mountain rivers and is generally much more important than suspended load in terms of channel development and change in such rivers (Froehlich, 1982; Pitlick & Thorne, 1987; Leopold, 1992).

THE STUDY AREA

The work reported in this contribution was undertaken in the Homerka instrumented catchment in the Polish Flysch Carpathians, where different techniques for monitoring sediment transport have been applied over the past 30 years (Froehlich, 1982, 1995). The Homerka stream drains a catchment area of 19.6 km^2 with a longitudinal slope of 53.3‰. The catchment has a mean discharge of 0.350 $m^3 s^{-1}$, a mean annual flood discharge of 9.15 $m^3 s^{-1}$ and a mean annual rainfall of 909 mm. The area is characterized by highly active erosion, sediment transport and fluvial sedimentation processes. Fluvial processes are dominant, and the channel network is being actively deepened. Extreme floods exert an important control on the fluvial system and are highly significant as geomorphologically effective events (Froehlich, & Starkel, 1994).

Bed load transport along the Homerka stream is characterized by significant spatial variability, in response to variable sediment supply related to the occurrence of bedrock channels, bed armouring and hillslope mass movements. The armoured surface layer consists of grain sizes with a D_{50} of 55 mm.

PROBLEMS ASSOCIATED WITH BED LOAD TRANSPORT INVESTIGATIONS IN MOUNTAIN STREAMS

Geomorphologists and hydrologists are constantly seeking improved methods for measuring bed load transport, in order to quantify sediment yields from drainage basins more accurately. The results from individual field investigations are, however, difficult to compare, because of the considerable range of measurement techniques and sampling procedures employed (Wohl, 2000). There is a particular need to develop improved techniques for monitoring bed load transport in mountain streams.

Any sampler placed in the flow will perturb local hydraulic conditions. Direct bed load transport measurements, particularly during floods, are also extremely difficult, because of a number of problems, including high flow velocities, the large quantities of sediment being transported, the wide range of grain sizes involved, and dangerous field conditions. Furthermore, the thresholds for the initiation and cessation of bed load transport are highly variable in high-energy mountain streams (Wohl, 2000).

Bed load transport in mountain streams is also often characterized by waves of different frequency and amplitude, which again pose great problems for measurement programmes (Ergenzinger *et al.*, 1994; Bunte, 1990). Furthermore, grain sizes that normally move as bed load, may be transported as suspended load during extreme flood events. Macroturbulence may be responsible for the suspension of large blocks and cobbles (e.g. Leighly, 1934; Matthes, 1947; Froehlich, 1982). Large boulders are frequently moved by catastrophic floods, but there is evidence that they also move in floods lying within the normal flood range (Vaughn, 1990). During low and intermediate magnitude flood events, when a stream is not competent to transport the coarser bed material fractions, the finer, mobile fractions are selectively removed from the active layer. When the tractive force exceeds the critical value for the maximum grain size, all fractions are transported.

ACOUSTIC (HYDROPHONE) BED LOAD TRANSPORT MEASUREMENT

Numerous studies have attempted to use acoustic devices to measure bed load transport (e.g. Bedeus & Ivicsics, 1964; Tywoniuk & Warnock, 1973; Richards & Milne, 1979; Froehlich, 1982; Bänzinger & Burch, 1990; Rickenmann, 1994). The author has successfully used the acoustic method to provide a continuous record of bed load transport in the Homerka instrumented catchment, and an acoustic device was designed and constructed and successfully deployed at the gauging station on the Bacza stream, a tributary of the main Homerka stream (Froehlich, 1982). The device permits the continuous detection of coarse particle movement during flood events and the resulting record can be used to derive information on the magnitude of bed load transport. Early experimental investigations commenced in 1972 and an upgraded recording system has been in operation since 1975. In the past 29 years, 75 events have been documented.

The acoustic device comprises three steel pipes containing the microphones placed horizontally on the channel bed, a signal processing unit, an oscilloscope, an analogue recorder and a computer (Fig. 1). The system has been installed within a straight reach in the lower part of the Bacza stream. Field tests have demonstrated that the sensor does not interfere with the natural hydraulic conditions. Each steel pipe is 6 m in length and 42 mm in diameter, and these pipes have been installed on the channel bed at a distance of 10 m from each other. The small capacitive microphones have a flat frequency response over the range 20–35 kHz and, in order to determine the optimum configuration and specification, the author tested both different microphones and also steel and plastic pipes of different diameter.

The microphones detect sound (acoustic waves) transferred through the pipes after its generation due to collisions with the moving gravel. The acoustic noise has a frequency in the range 20–60 Hz. The signal-processing unit has a low frequency amplifier and six noise filters. The data logging system is based on recording of the signal output current. Power is supplied from external high-capacity lead-acid batteries connected to the power supply. The device described above is still experimental and has its own particular advantages and limitations.

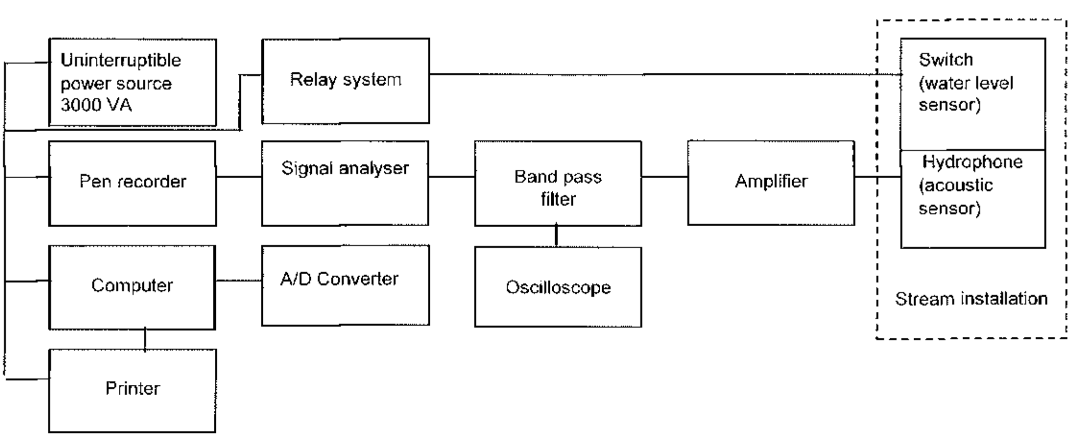

Fig. 1 The primary elements of the acoustic (hydrophone) system.

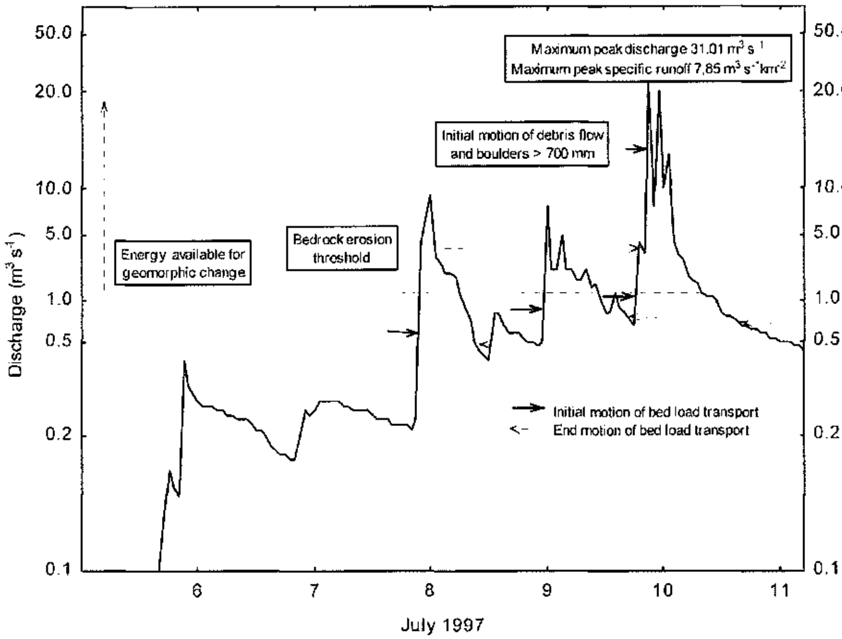

Fig. 2 Thresholds for the initiation and cessation of bed load transport during a series of flood events in early July 1997.

The initiation of particle movement represents a key component of the bed load transport process. However, Froehlich (1998) has reported that the threshold discharge, above which transport commences, may vary through time and the investigations undertaken in the Homerka catchment, using both acoustic and magnetic tracer techniques, have emphasized that the threshold discharge for initiation of bed load transport cannot be treated as a single definitive value (cf. Fig. 2).

The relationship between water discharge and the rate of bed load transport can be analysed using continuous measurements of water discharge and the continuous record of the acoustic signal provided by the coarse sediment. In general, sound intensity increases with transport rate and the frequency of the acoustic signal is inversely proportional to the diameter of the moving particles. The signal pattern is a complex hierarchic system reflecting both the pulsed nature of bed load transport and the noise generated by moving bed load. The transport rate increases rapidly and reaches its maximum value very soon after an increase in the magnitude of the flow renders the bed unstable. The threshold discharge for initiation of bed load transport varies between flood events. It is possible to recognise the discharge threshold for both initiation of bed load transport during the rising limb of a flood and for the cessation of transport during the falling limb (Fig. 2).

In general, bed load transport reaches a peak more rapidly than the water discharge, and for a given flood discharge, the intensity of bed load transport will vary between the rising and falling stages. This is reflected in the shape of the hysteretic loop characterizing the relationship between bed load transport and discharge (e.g. Froehlich, 1982; Bathurst, 1987; Schöberl, 1991; Rickenmann, 1994; Moog & Whiting, 1998). Each flood is characterized by a loop with a different shape, in a

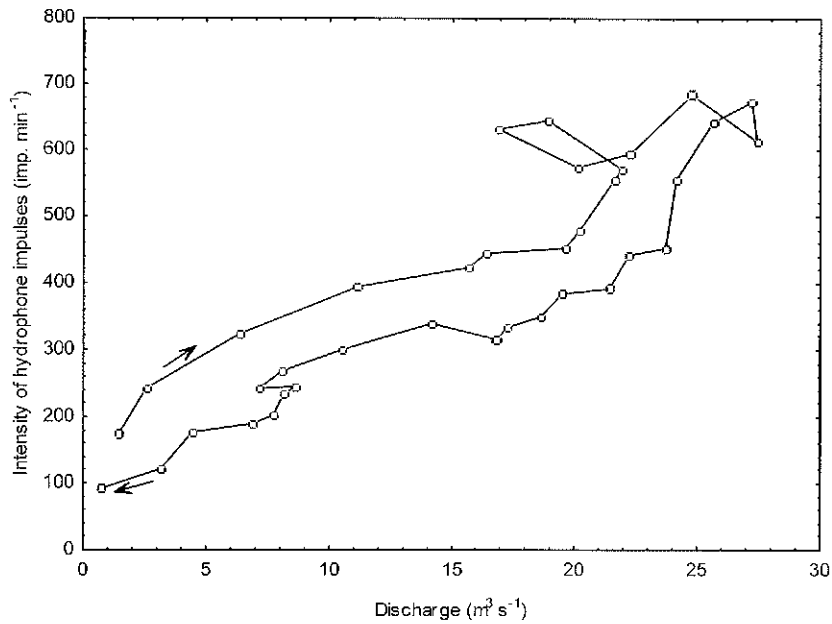

Fig. 3 The relationship between the intensity of hydrophone impulses generated by transported particles and water discharge.

similar way to the hysteresis curves reported for suspended sediment transport (Fig. 3). It is therefore impossible to establish a single rating relationship between bed load transport rate and water discharge that can be applied to all events (Froehlich, 1982). Bed load transport is non-uniform and unsteady and can fluctuate over an order of magnitude, for given flow conditions. In general, more bed load is transported by discharges associated with the first exceedance of the threshold for initial motion in a particular year and the sequence of floods and their associated inter-arrival times play an important role in controlling the pattern of bed load transport in subsequent events (Froehlich, 1982, 1998). The role of the relaxation time is still poorly understood.

The acoustic device can also be used to estimate the magnitude of the bed load discharge, if it can be calibrated. Independent measurements of bed load discharge were obtained using periodic surveys or emptying of the sedimentation basins upstream of concrete weirs and drop structures and these were used to establish the calibration relationship between the cumulative impulse count and the total amount of sediment moved, presented in Fig. 4. The particle size distributions of the sediment trapped in the sedimentation basins was determined using large sieves.

THE USE OF MAGNETIC TRACERS FOR MEASURING BED LOAD TRANSPORT

The use of magnetic tracers affords a means of establishing the bed load transport rate during flood events associated with individual size fractions (e.g. Ergenzinger & Conrady, 1982; Ergenzinger & Custer, 1983; Hassan *et al.*, 1984; Reid *et al.*, 1984;

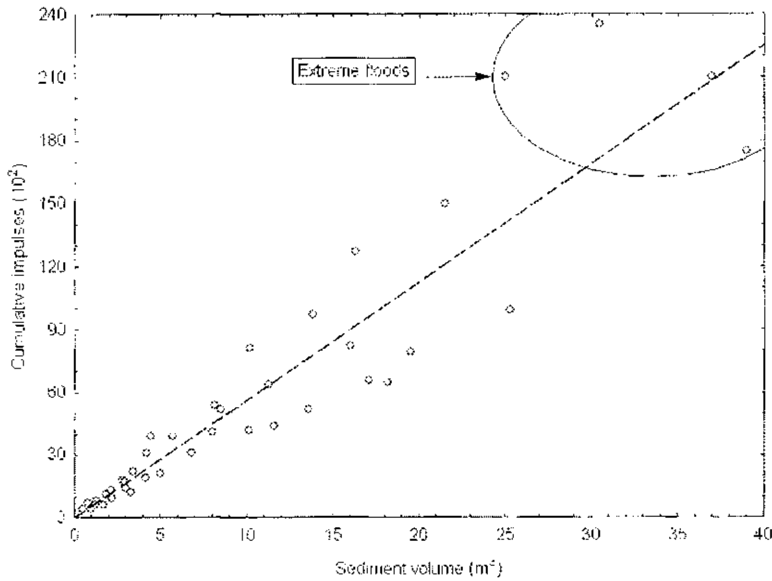

Fig. 4 A calibration relationship between cumulative hydrophone impulses and the volume of bed load transported during an event.

Ergenzinger *et al.*, 1994). Two approaches to the use of magnetic tracers can be distinguished. In the first, the more conventional passive approach, individual gravel clasts of varying size are tagged with magnets and placed at known positions within a river reach. By relocating the tagged clasts after individual events, it is possible to establish the distance of travel. This approach permits the effects of grain size and particle density and shape on transport distance to be explored (e.g. Hassan *et al.*, 1984). In the second, or active, approach, the actual timing and speed of movement of the tagged particles within a study reach is recorded as they cross magnetically sensitive coils installed across the river channel (cf. Reid *et al.*, 1984). Although the individual gravel particles are usually tagged by implanting magnets into the clasts, Ergenzinger & Custer (1983) also reported the successful application of the approach to a stream where the coarse bed load was naturally magnetic.

Coarse material bed load transport has been investigated within the Homerka catchment using both magnetic approaches. In each case, small magnets were cemented into holes drilled into gravel clasts of different sizes using an epoxy resin. Early experimental work with an active bed load transport sensor commenced in 1982, when a measuring system designed and constructed by the author, was installed at a gauging station on the Homerka stream (Fig. 5). The device consists of two magnetically sensitive coils (copper windings on an iron core), each 4 m in length. These coils were installed across the channel bed, separated by a spacing of 30 m (cf. Reid *et al.*, 1984). The movement of the tagged gravels during a flood is registered by their passage over the coil, which affects the magnetic field, causing a change in the inductance of the coils. According to the Faraday principle, a voltage peak is induced and the signal is detected, amplified and transmitted to a receiver and then to recorder. The median diameter of the bed material in the experimental reach is 64 mm. Magnets

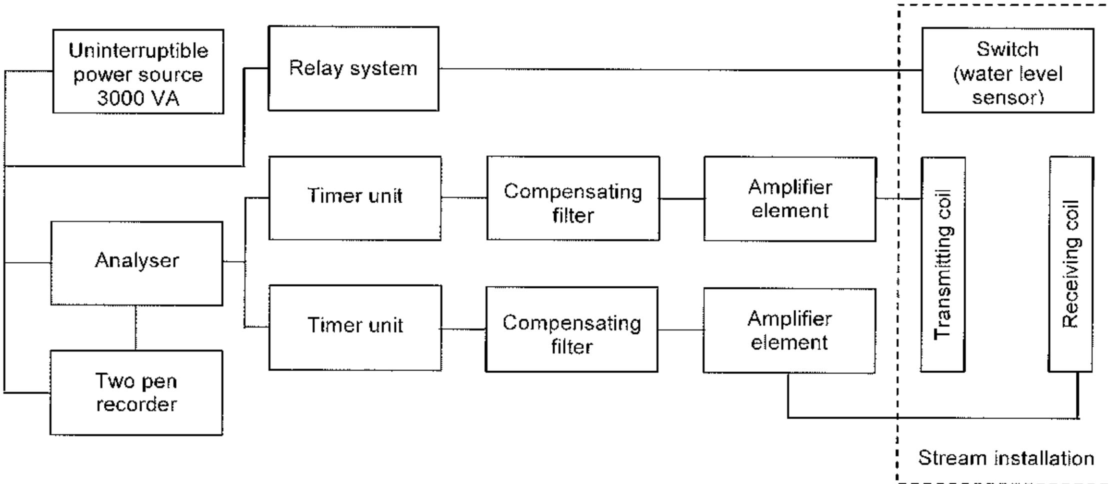

Fig. 5 The primary elements of the electromagnetic system used for monitoring bed load transport.

of different size were inserted into different sized gravel clasts, permitting the movements of clasts of different size to be distinguished (Fig 6). The tagged gravels were also painted to facilitate their recovery after an event. After every flood, the gravels were relocated using a portable metal detector. Recovery rates ranged from 12 to 85%. Some typical results generated by this measurement system are depicted in Fig. 7.

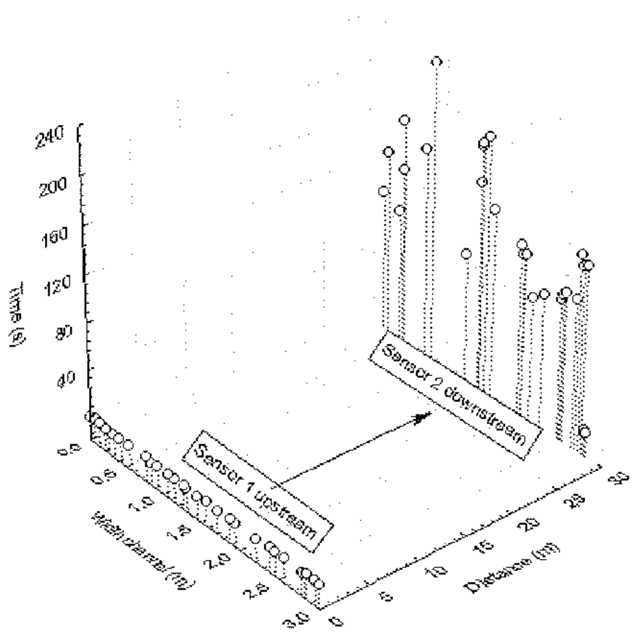

Fig. 6 Results obtained from the electromagnetic system used for measuring bed load transport during a flood occurring on 20 July, 2001.

Recording of the locations of the tagged clasts within the Homerka channel system after successive events also provided a means of documenting the transport distances of tagged clasts of different size during individual events. However, the results obtained for the first event after the emplacement of the labelled gravel were not considered to be representative, since it is almost impossible to relocate a tagged gravel clast in exactly the same position as it occupied prior to removal for labelling. The transfer of gravel particles through the Homerka channel system was shown to be influenced by both flood magnitude and duration. Transport distances for single gravel clasts during an event with a magnitude equivalent to the mean annual flood ranged from 5–140 m. The smaller clasts were found to have significantly lower transport distances than the larger particles. The coarsest fractions (>600 mm) of the bed material only become mobile during extreme floods and the results are presented in Fig. 7 show that under similar flow conditions individual clasts moved varying distances in successive steps. These results clearly demonstrate the stochastic nature of the entrainment and movement of individual particles in a step-pool mountain stream. This stochastic behaviour assumes increasing importance during extreme flood events. The consequent lack of a clear relationship between distance of movement and particle size has been reported in many field experiments. Little is currently known about the movement of large particles through the channel systems of catchments at different scales.

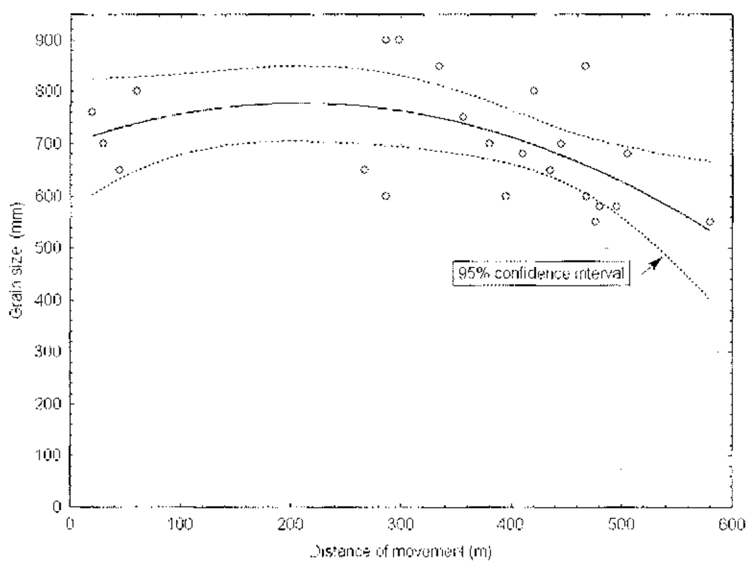

Fig. 7 The relationship between transport distance and the grain size of magnetically tagged coarse bed load particles for a flood occurring during the period 9–11 July 1997.

CONCLUSIONS

The results from the investigations described in this contribution demonstrate that acoustic and magnetic approaches to investigating bed load transport both provide valuable and complementary results. These results emphasise the complexity of bed load transport in mountain streams. Both the threshold discharges for initiation and cessation of bed load transport and the volume of bed load transported can vary significantly between individual flood events. Equally, the lack of a clear relationship between transport rate and discharge emphasises the stochastic nature of bed load transport and the importance of pulse transfer.

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Bed load measurements with a passive magnetic induction device

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Abstract The Bed load Movement Detector (BMD) is installed on the O'Ne-ell Creek, a gravel bed stream, with a forced pool-riffle morphology, in the upper Fraser River basin in northern British Columbia, Canada. The device records the passage of individual particles across the full width of the channel. At the peak of the 1999 nival flood sediment movement, approximately 3×10^5 particle passages per hour were detected. The transport rate increases as the stage and water discharge increase. Bed load movement in this flood involved nearly all of the stream bed, but the point of most intense transport varied across the channel throughout the flood. During one week of flood discharge, 14.41×10^6 particles were recorded passing the BMD. We estimate that this is approximately equivalent to 7.88 m^3. Pulses of sediment movement are apparent at a variety of time scales ranging from diurnal to seconds. While the spasmodic character of the sediment transport is most pronounced at scales of 5 min to 1 h, there is no stable periodicity in the record.

Key words bed load; bed load movement sensors; fluvial geomorphology; gravel bed streams; pool-riffle morphology

INTRODUCTION

In the last decade there has been an increase in interest in the measurement and visualization of bed load movement in streams. As a result, there have been a series of new developments in bed load movement sensing apparatus including: devices based on repeated measurements of the stream cross-section (Ergenzinger, 1992), repeated bed load sampling using Helly-Smith samplers or net samplers (Bunte, 1990, 1996), Birkbeck-type slot samplers with pressure pillows (Lewis, 1991; Harris & Richards, 1995; Garcia *et al.*, 2000; Sear *et al.*, 2000), magnetic induction devices (Bunte, 1996), acoustic Doppler velocity devices (Rennie *et al.*, 2002), and hydrophones and impact sensing devices (Bänzinger & Burch, 1990; Rickenmann *et al.*, 1997). These devices either sample the pattern of movement across the stream width, or the pattern and quantity of movement through time. We report on recent developments using a bed load movement detector that produces continuous records of clast movement across the channel width in a format which permits visualization of changing transport patterns through time.

METHODS

Bed load movement was monitored from 1993 to 1999 on a small stream in the headwaters of the Fraser River in northern British Columbia, Canada, as part of the Stuart-Takla Fish–Forestry Interaction Project (Macdonald *et al.*, 1992). The investigation entailed three components: (a) tracer studies, to obtain information on the distance of travel and depth of burial of clasts; (b) repeated topographic surveys, to develop volumetric estimates of nival and summer flood events; and (c) a passive magnetic bed load detection device spanning the channel to record the passage of coarse clastic material. This paper will discuss the results of the Bed load Movement Detector (BMD) from the 1999 nival flood event.

In 1997 the BMD device was installed in the riffle section of a small forest channel. The device consists of an array of 82 magnetic sensors set in an aluminium housing, mounted on an adjustable frame that may be raised or lowered to compensate for changes in stream bed elevation (Fig. 1). The sensing surface is set flush with the stream bed. The sensors (Fig. 2) are disc-shaped (4 cm high × 8 cm diameter) and spaced 10 cm apart along the 8.2 m length of the device. Ferromagnetic minerals in particles passing over the sensors induce small electrical currents. Sufficient magnetism is found in most igneous and metamorphic rocks that moving particles, of pebble and cobble size, can be detected. The apparent lower size limit of detectable particles, under laboratory conditions, is 1–2 mm. The signal duration is proportional to the size of the clast and the velocity of transport. The signals generated from passing particles are sampled at 100 Hz by a data acquisition system and stored on a computer hard drive.

The BMD is a significant improvement of earlier magnetic bed load detection devices. Ergenzinger & Conrady (1982) and Reid *et al.* (1984) employed single coil detectors to record the passage of tracers with embedded magnets. Ergenzinger & Custer (1983) built an instrument with two 1.25 m rods wound with copper wire

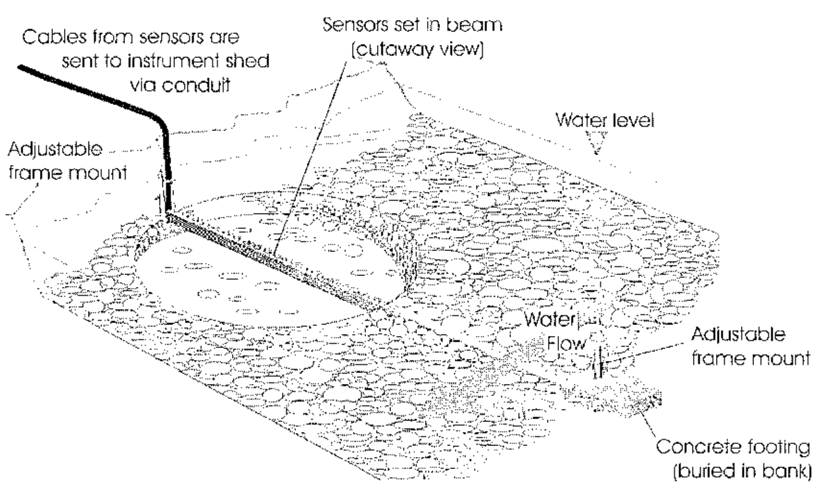

Fig. 1 Diagram of the Bed load Movement Detector. The device is buried flush with the stream bed surface. Vertical adjustment can be made with threaded rods on the frame mounts.

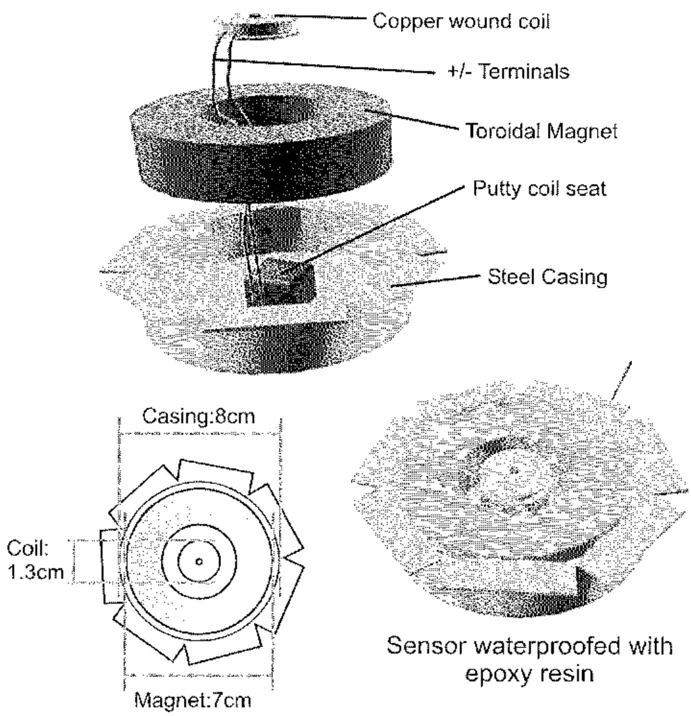

Fig. 2 The Bed load Movement Detector sensor shown in exploded view, sensor dimensions, and the assembled product.

placed horizontally within the stream bed, that could detect the passage of naturally magnetic andesite clasts >32 mm. In 1986 a more sensitive device was developed which used 1.55 m units of micro-coil assemblies extending across Squaw Creek, Montana (Custer *et al.*, 1986; Bunte, 1996).

All of these devices used strip chart recorders, which can record no more than several signals per second and a few sensor channels. The practical limit of resolution of the strip recorder system at Squaw Creek may be 200 h^{-1} (Bunte, 1996).

The BMD has a sensor that is several orders of magnitude more sensitive than earlier devices. The spacing of sensors at 10-cm intervals permits recognition of lateral variation at a scale comparable to the largest clasts transported. The sampling rate of 100 Hz permits recognition of about 10 particle passages per second on each sensor. The theoretical maximum number of passages discernable with the BMD is about $3 \times 10^6 h^{-1}$. Actual maximum rates measured are about four-fold less due to a variety of factors including: low rates of transport at the stream margins, and to some extent, saturation of the sensors when more than one particle passes simultaneously across the sensor, a situation that is likely during intensive transport, since most recorded particles are smaller than 1 cm. Finally, the use of a data acquisition system allows data to be recorded and analysed on computers, which permit sophisticated signal detection algorithms to be employed. Further details of the construction and calibration of the BMD can be found in Tunnicliffe *et al.* (2000) and Tunnicliffe (2000).

The Bed load Movement Detector is installed on O'Ne-ell Creek at a site 8 m wide with a slope of 0.013, and a peak discharge about 15 $m^3 s^{-1}$. The channel has a forced pool-riffle morphology with abundant large woody debris. The reach is in an approximate equilibrium, with no marked tendency for aggradation or degradation over the past 10 years. The sampled reach has a coarse gravel bed with a mean grain size of 42 mm. The largest clasts are approximately 300 mm. Clast lithologies and thus magnetic properties are extremely variable. This work and similar field experiments suggests that approximately 30% of the rocks in O'Ne-ell Creek yield sufficient ferrous material to obtain a voltage response greater than 1.7×10^{-4} V (noise threshold of the data acquisition system) from a sensor. This proportion of detectable lithologies can be increased substantially using more sensitive voltmeter instrumentation.

Bed load movement occurs annually during the peak of the snowmelt flood in May or June and during short floods following intense summer storms. O'Ne-ell Creek has relatively little suspended sediment transport. At the study site, the stream bed could be visually observed from a catwalk over the stream for much of the 1999 flood. Particles in motion could be observed and captured with a basket sampler. At the peak of the 1999 nival flood sediment movement, approximately 3×10^5 particle passages were detected per hour (Fig. 3).

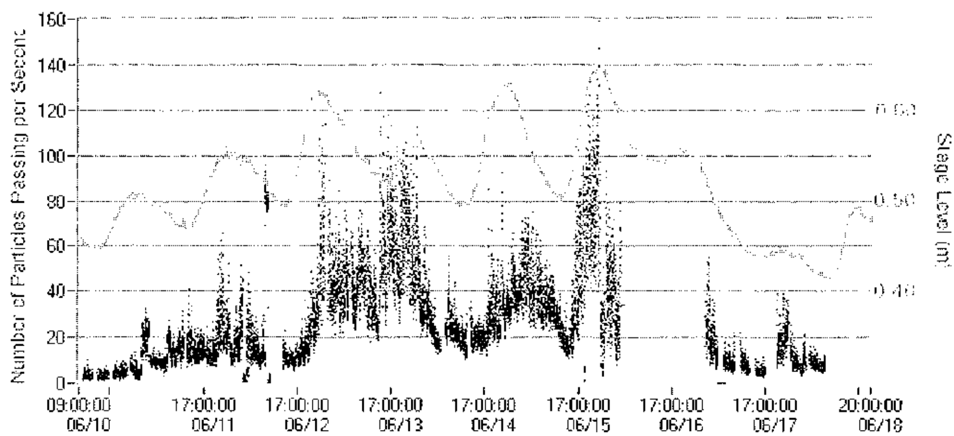

Fig. 3 Rates of particle transport (number of particles s^{-1}) over the course of the flood.

OBSERVATIONS

The 1999 flood was unusual. A cool cloudy spring and high snow accumulations resulted in the snowmelt period being prolonged over about six weeks. Peak discharge was relatively low. Stream flows were just below that sufficient to initiate bed load movement from 25 May to 9 June. During this time sporadic movement of only single particles and bursts of finer material was observed. Between 10 June and 12 June the rate of entrainment increased, and the sensors detected "batches" of larger-sized material crossing the device. Sampling with a small basket net yielded maximum particle sizes of 20–30 mm. Particle counts ranged from 0 to 35 s^{-1}. As the stage rose during the afternoon and evening of 12 June, increasingly intense pulses of sediment passed

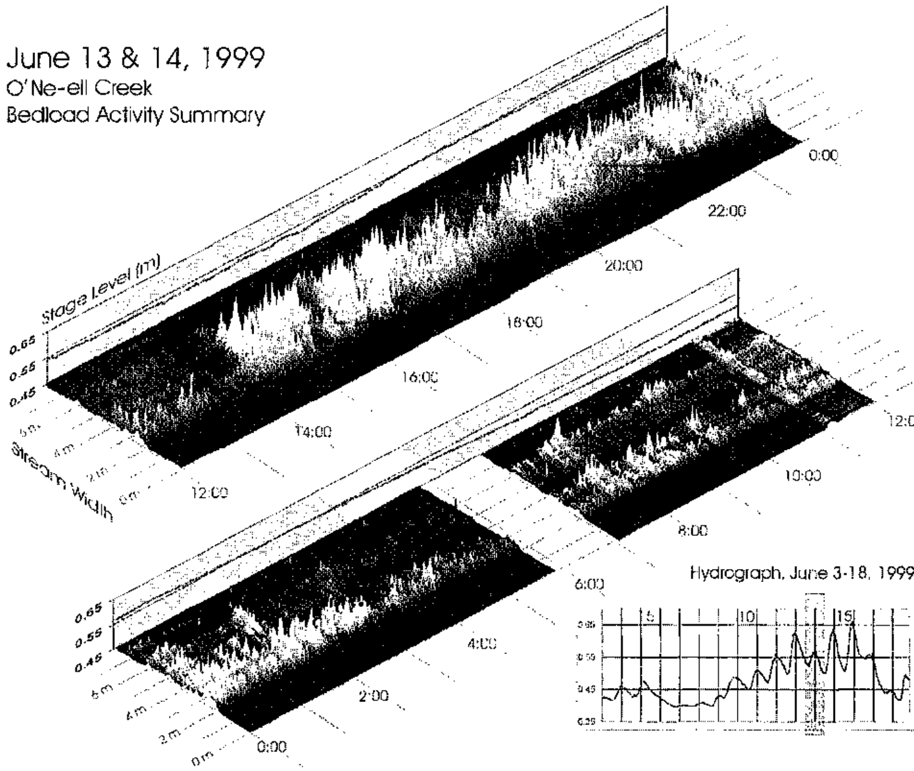

Fig. 4 Summary of bed load movement 13–14 June 1999. Bed load movement commences abruptly with increase in stage at about 14:00 h on 13 June. Pulses of sediment movement of variable intensity and duration continue to 00:30 on 14 June. As the overall sediment flux declines in the early morning, bed load movement is confined to one to three streets. One hour of data were missed at 06:00 h while hard drive files were transferred.

over the device. Inter-granular collisions, and the sheer volume of material in motion, often blurred the distinction of passing particles. Rates exceeding 60 particles s^{-1} were recorded during about 10% of the total event. Maximum counts of up to 150 particles s^{-1} were attained at the peak of transport activity. At times, the material seemed to pass in steady sheets. The activity continued until about mid-day on 13 June, when the amount of material in transit subsided for a few hours and then resumed and reached a maximum on the evening of 13 June. There was clearly an abundant supply of material entrained by the high flows, and the bed load discharge continued even as the stage level dropped during the mid-day period of 13 June.

With the ample availability of material for transport, the "batch" effect became less conspicuous as more intense pulses of sediment passed over the BMD. In the intervals between pulses, the transport rate dropped substantially. A condensed record of 24 h at this peak stage is shown in Fig. 4.

The final portion of the bed load transport event, 14–17 June, featured one or two narrow transport zones, 1–2 m wide, which migrated laterally by about 1 m. Material in transport, observed and sampled non-quantitatively, was sand to small pebble size.

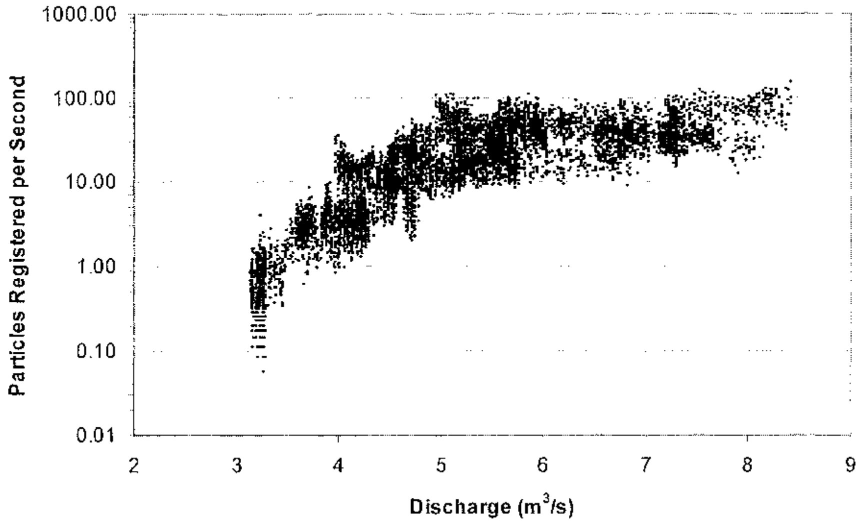

Fig. 5 The number of particle counts per second counted by the BMD as a function of stream discharge.

The bed load streets seen at the end of the nival flood were active while a sandy gravel bank was being eroded about 75 m upstream (about 9 stream widths).

Figure 5 shows that for any given flow, the transport rate (it must be emphasized that this is measured as particles detected per minute, not mass) varies within roughly an order of magnitude. The transport rate increases with discharge, up to roughly 5 $m^3 s^{-1}$, at which point the slope in the relation seems to flatten. This may be due to depletion of the material available for transport during the 1999 flood, or saturation of the sensors due to multiple clasts crossing the 10 cm sensors simultaneously. But, in part, the decline in the rate of increase of the number of particles in transport is counteracted by an increase in the maximum size of particle transported, so that the volume in transport increases faster than the count of particles.

Temporal variation in transport rates

Pulses of sediment movement occurred during the flood at a variety of scales. Snowmelt flows in O'Ne-ell Creek show a clear diurnal discharge cycle. As the stream power increased each evening, from 12 June to 17 June, high rates of coarse bed load movement commenced. The transport commences abruptly (Fig. 5), presumably as clusters and patches of the stream bed disassemble and are entrained (Kuhnle & Southard, 1988; Brayshaw *et al.*, 1983).

Within the frame of this daily cycle, the transport rate considerably vacillates on a time scale measured in minutes, independent of channel flows. We examined the pulsation of the sediment transport record with Fourier analysis to identify periodicity in the pulsation record. Fisher's test of significance in harmonic analysis (Fisher, 1929; Nowroozi, 1967; Kuhnle & Southard, 1988) showed that the amplitude of most peaks in the range of interest (minutes to hours) on the Fourier spectra were not significantly

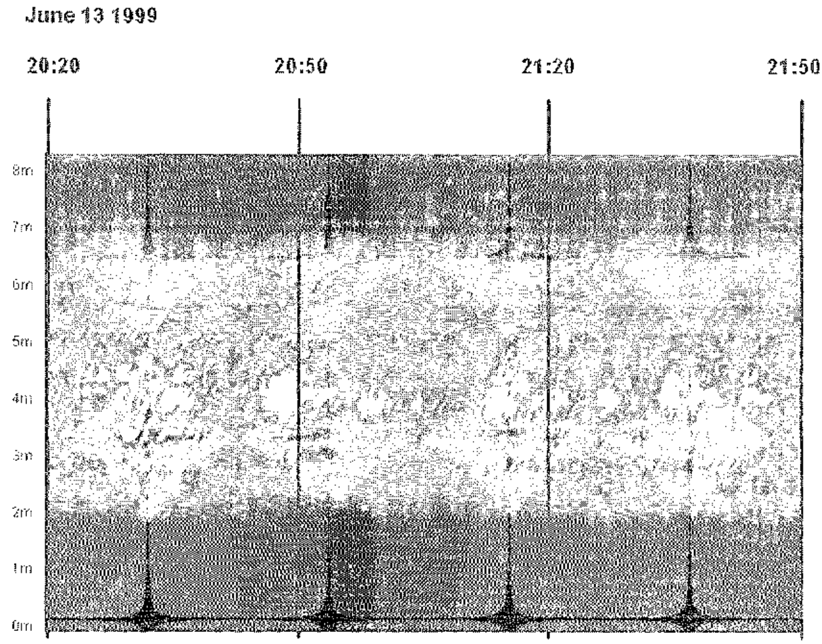

Fig. 6 Transport of pulses of sediment past the Bed load Movement Detector during 90 minutes of high transport rates.

different from random noise at the $\alpha = 0.05$ level. Although previous authors (Gomez *et al.*, 1989; Kuhnle & Southard, 1988; Whiting *et al.*, 1988) have attributed this kind of variation to the migration of bed form elements such as bed load sheets, bars or ripples, it is not clear from our limited observations of upstream conditions that this is the operating mechanism in the forced pool-riffle morphology of O'Ne-ell Creek. Figure 6 shows a summary of an hour and a half of bed load activity, with at least 10 distinct surges in bed load activity.

At the finest scale, that of seconds, particle movement is concentrated into "batches". Batches are present during intervals of both low and high transport rates, although at the highest transport rates, size and number of individual particles becomes difficult to determine because a mixture of sand and gravel particles are moving across each sensor simultaneously.

Lateral instability in the transport record

Over the course of the 1999 flood, bed load movement involved nearly all of the stream bed. The channel cross-section at the BMD site is relatively flat, since the device was sited midway along a riffle section. To characterize the locus of transport (the point of maximum bed load transport activity), total signal intensity for each sensor channel was summed for each sampling session, generally about 3 h (Fig. 7). Over the course of the flood, the locus of greatest transport migrated widely across the channel and back. Early and late in the flood, when small volumes of bed load were in

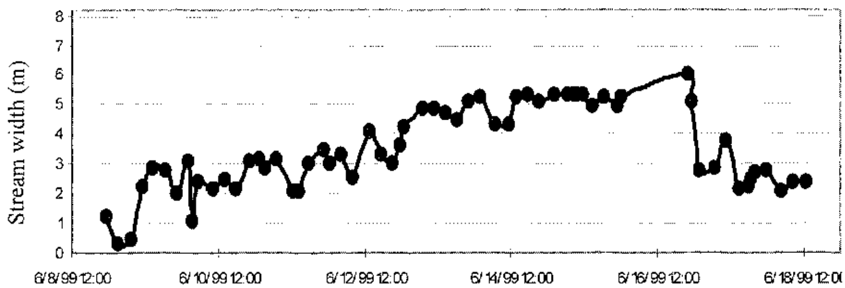

Fig. 7 The wandering locus of transport in the 1999 nival flood. The locus of transport moved substantially throughout the event, starting within roughly 1 m of the right bank (9 June) and drifting to within 2 m of the left bank (15–16 June).

motion, the lateral field of transport tended to be narrow and located in the deeper part of the channel; during the peak of the nival flood, most of the channel was simultaneously active.

Not only does the locus of transport wander across the stream bed, and the width of the transport zone change, but the intensity of transport varies as well. The continuous record of transport can be conceptually divided into portions of intensive transport, active transport and marginal transport (Fig. 8). Contours in the lower part of Fig. 8 show the number of particles per second passing each of the 82 sensors for the duration of the flood. During this flood, most of the stream cross-section experienced marginal bed load transport rates of <1 particle s^{-1}. Intensive transport (≥4 particles s^{-1}) did not occur in more than 25% of the stream width at any time.

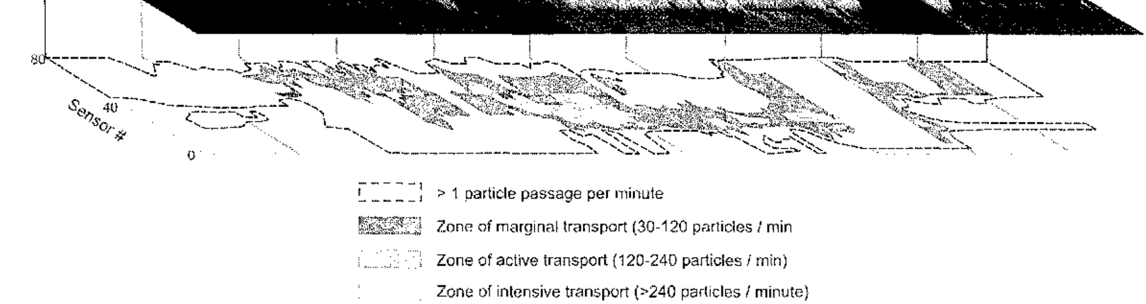

Fig. 8 Bed load transport activity during the 1999 nival flood. The upper half of the diagram is a hydrograph of flood discharge. The lower half of the diagram shows intensity of transport during 10 days of the nival flood. Transport is represented by the cumulative voltage during 30-s intervals. Three intensities of transport are contoured: marginal transport (<1 event s^{-1}), active transport (1–4 events s^{-1}), and intensive transport (>4 events s^{-1}).

The 1999 nival flood produced modest changes in the stream bed. Previous studies of nearby reaches, using repeated total station surveys (Poirier, 2003), show modest alteration of nearly all of the stream bed during nival floods, with complex patterns of scour and fill averaging one to two clasts thick.

Estimate of transport volumes

During the flood, 14.41×10^6 particle signals were recorded by the BMD at O'Ne-ell Creek. We attempted to estimate the volume of transport making a number of simplifying assumptions, including: (a) that the variation in magnetic intensity is uniform for various size clasts, and is similar in character to the bed material; (b) that the material in transport has the same composition and size distribution as the stream bed; (c) that 30% of the moving particles are detected; (d) that only particles >4 mm are detected; and (e) that intervals of peak sensor response represent single sediment particles. With these assumptions the estimated volume is 7.88 m^3. Independent estimates for transport rates on this stream and in similar reaches in a stream in the adjacent watershed were determined in previous years by repeated detailed mapping of the stream bed and by magnetic tracer studies (Gottesfeld, 1998; Poirier, 2003). These estimated transport volumes agree within a factor of two (Table 1).

Table 1 Transport volume estimates for O'Ne-ell and Forfar Creek Nival Floods. Forfar Creek is a similar watershed immediately north of O'Ne-ell Creek with about 60% of the peak flow.

Transport volume estimates for O'Ne-ell and Forfar Creeks (m^3)			
Stream reach	Tracer study 1992–1996[1]	Morphologic method 1996–1997[2]	BMD 1999
Forfar 1050	2.88	3.06	
Forfar 1545	12.70	3.82	
O'Ne-ell 925		6.76	
O'Ne-ell 1550	16.86	8.99	
O'Ne-ell BMD Site			7.88

[1] Gottesfeld (1998), Gottesfeld, unpublished data.
[2] Poirier (2003).

DISCUSSION

The bed load transport patterns shown in Figs 3, 5 and 6 have a number of interesting features. We see a clear threshold effect as competent flow is reached at about 3 $m^3 s^{-1}$. There is diurnal forcing in the bed load discharge record with high transport rates attained near midnight as the peak of the previous day's snowmelt passes.

The large quantity of data recorded at 100 Hz permit analysis of the timing of pulses of sediment moving past the instrumented stream cross section. Although the pattern of bed load transport shows pulses lasting several minutes throughout, and pulses are often spaced 5 min to an hour apart, there is no stable, coherent periodicity in the 1 min to 1 h range. Instead movement is chaotic, and is perhaps best thought of as jams in the congested flow of material (Langbein & Leopold, 1968) Pulsing at the finest scale (batches) may result from the disaggregation of clusters.

Much of the diversity of response in bed load discharge is probably related to supply, i.e. upstream stochastic phenomena. This is to be expected since pulses of sediment are derived from varying distances upstream, they disperse during transport both laterally and along the path of transport and, on a finer scale, there are innumerable complex interactions among particles in movement and the irregular stream bed. The width of the transport zone varies greatly during the flood. Lateral dispersion of sediment pulses as they move downstream is inevitable, so that intervals where much of the channel width is active likely reflect periods of augmented supply from further upstream. Periods of narrow transport reflect nearby sources. With exhaustion of supply late in the flood, gravel streets which derive from small areas of supply not far upstream, become conspicuous. The width of passing pulses is also related to the size of bed forms which disassembled upstream. Small clusters would be expected to have narrow signatures that widen during downstream translocation.

Thus, while the BMD shows a number of important improvements over previous bed load detection systems, it faces a number of similar challenges. Noise from a number of external sources (such as an on-site generator) is problematic. However, the difficulties attributed to vibration, reported by Custer *et al.* (1987), appear to be minimal. The signals generated by the instrument contain limited information on the particles passing, and thus particle counts remain only a coarse approximation of rates of bed load flux. At present we are unable to separate the velocity and size components in the sediment passage record. In a stream with simpler bed load lithology the amplitude of the voltage response of the sensor would provide a scale for clast volume and permit calculation of apparent velocity. Problems related to simultaneous passage of several particles across each sensor would be alleviated by decreasing the size of the sensors. The additional data acquisition burden and need for a generator on site can be met using the more powerful laptop PCs currently available.

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Erosion and Sediment Transport Measurement in Rivers: Technological and Methodological Advances (Proceedings of the Oslo Workshop, June 2002). IAHS Publ. 283, 2003.

Measurement of bed load with the use of hydrophones in mountain torrents

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Abstract Sediment transport in mountain torrents is more affected by sediment production such as landslides, bank erosion and torrent bed erosion, than by water runoff. Therefore sediment transport rate cannot be estimated theoretically using sediment transport equations. This is why we have to measure sediment transport rate in the field in the mountain torrents. Wash load and suspended load can be measured using various kinds of samplers, whereas the direct measurement of bed load is difficult. Bed load samplers that have been used in mild rivers are not applicable in mountain torrents where the flow velocity is high and the bed surface is rough. Hydrophones are more appropriate for mountain torrents. Steel pipes are installed on torrent beds or on the spillways of sabo (erosion and sediment control) dams. The number of times that sand and gravel particles hit the pipes are counted by the microphones. This system has worked well in mountain torrents. The measurement system, some observed results and preliminary analysis are reported.

Key words bed load; hydrophones; measurement; mountain torrent

INTRODUCTION

Actual sediment outflow rate depends not only on sediment transport capacity, but also on movable sediment volume in the mountain streams. In most cases the amount of sediment on the torrent beds and torrent banks is limited. Torrent beds are often covered with armour coats. During low discharge periods the actual sediment transport rate is smaller than the sediment transport capacity that is estimated by the sediment transport equations for sediment grain size, torrent gradient and flow discharge or flow depth. When the flow discharge rate exceeds a certain critical condition for the incipient motion, or rainfall exceeds its critical condition for landslides or debris flow occurrence, sediment is produced and supplied to the torrent. The sediment transport rate increases sharply and approaches the sediment transport capacity. The actual sediment transport has to be observed to determine the reasonable sabo (erosion and sediment control) plan. Monitoring of the sediment transport rate is necessary to operate the sediment control gates of the sabo dams that are under development. Suspended load is relatively easy to measure because sampling with samplers or suction tubes is available. However, the measurement of bed load is difficult. Some bed load samplers have been used mainly in subcritical flow. It is difficult to set the samplers on the torrent bed, because the bed is rough with large rocks and the flow velocity is high. Hydrophones counting impacts or the sound of sand and gravels against plates or pipes are appropriate in mountain torrents, as they do not measure the absolute sediment transport rate, but the relative sediment transport rate (intensity). Hydrophones with pipes and a microphone were developed for isolated mountain torrents and were installed on the bed of slit sabo dams. The system and observed data using them are reported in this paper.

HYDROPHONE SYSTEM

Hydrophone systems have been adopted in several locations. For example, a hydrophone system with a steel plate and seismometer is used in Switzerland (Rickenmann, 1992). Our hydrophone system consists of a hydrophone sensor; a steel pipe with a microphone inside. In this case, we used a pressure-type water level gauge, a data logger, a battery charged by solar batteries and a cellular phone to transmit the data (Fig. 1). Hydrophone signals are logged after a 10 times amplification by a preamplifier. The data is recorded after amplifying 32 times at Channel 5, 16 times at Channel 6, 8 times at Channel 7, 4 times at Channel 8, 2 times at Channel 9 and once at Channel 10, respectively. The number of pulses are counted during each 5-min period.

SET-UP OF HYDROPHONE

A set consisting of a hydrophone and a pressure water level gauge was set up at a slit of a slit sabo dam. A slit sabo dam is a sabo dam with one or more vertical slits. It dams up water during high water and causes inflowing sediment to be deposited temporally at the upper reach of the dam. When the discharge decreases, the deposit

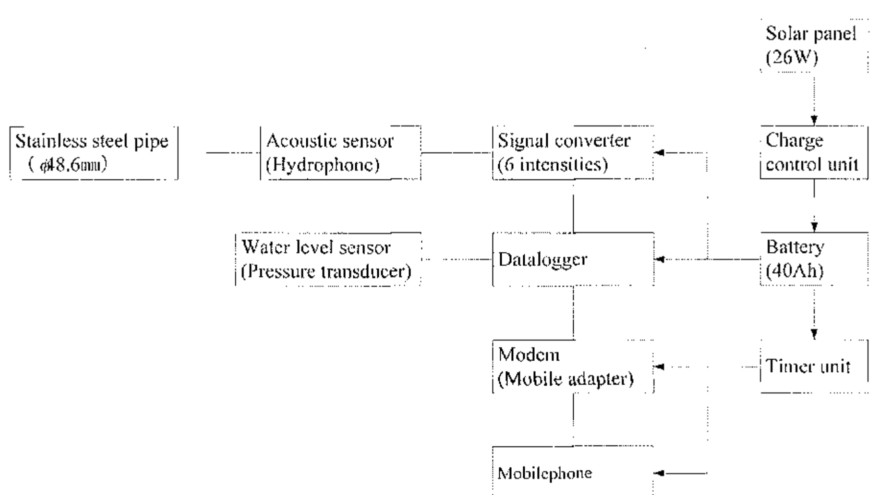

Fig. 1 Block diagram of the hydrophone system.

disappears gradually as the trapped sediment is eroded and released downstream. Although the behaviours of slit sabo dams is known through flume experiments and computer simulations, their real function must be verified in the field. The hydrophones were applied to measure the real sediment outflow from the slit sabo dams.

The hydrophone was installed at Tsuno-ura Karyu slit sabo dam (Figs 2 and 3) constructed by Tateyama Sabo Work Office in the Joganji River. The sabo dam is 13.5 m high and has two slits; 16.0 m wide and 7 m high. Channel gradient at the dam site was originally 1:28. The planned deposition gradient is 1:56. The drainage area at the dam is 131.53 km^2. A 6-m long steel pipe was set at the bottom of the slit as a hydrophone sensor. A signal was recognized by Channel 5, but not by Channel 6 when a 1.0 cm diameter stone was dropped from a height of 1.5 m. A 2-cm diameter stone dropped from a height of 0.5 m was recognized by both Channel 5 and Channel 6.

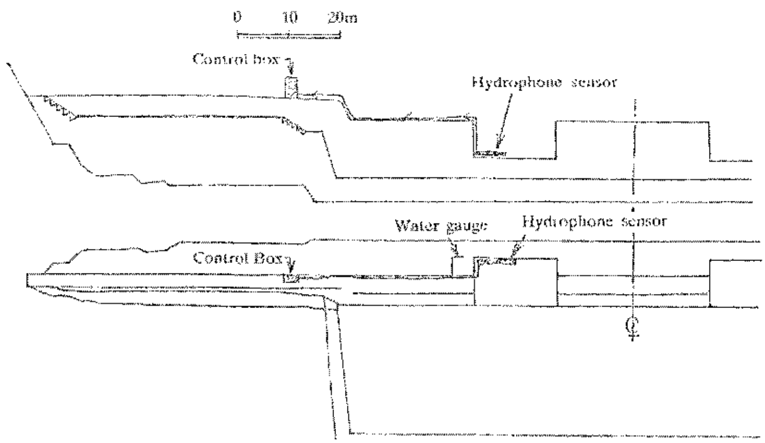

Fig. 2 Installation of the hydrophone and a water level gauge at the Tsuno-ura Karyu slit sabo dam.

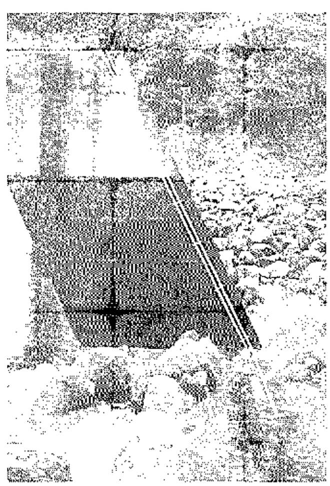

Fig. 3 Sensor pipe of the hydrophone installed on the slit of a sabo dam.

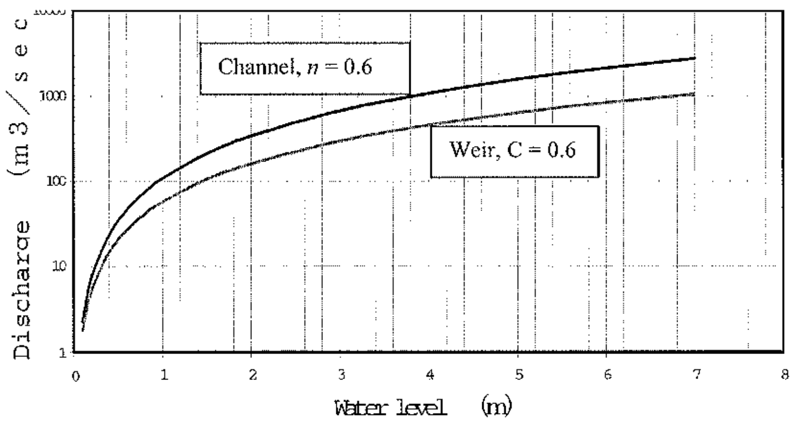

Fig. 4 Stage–discharge curve at Tsuno-ura Karyu slit sabo dam.

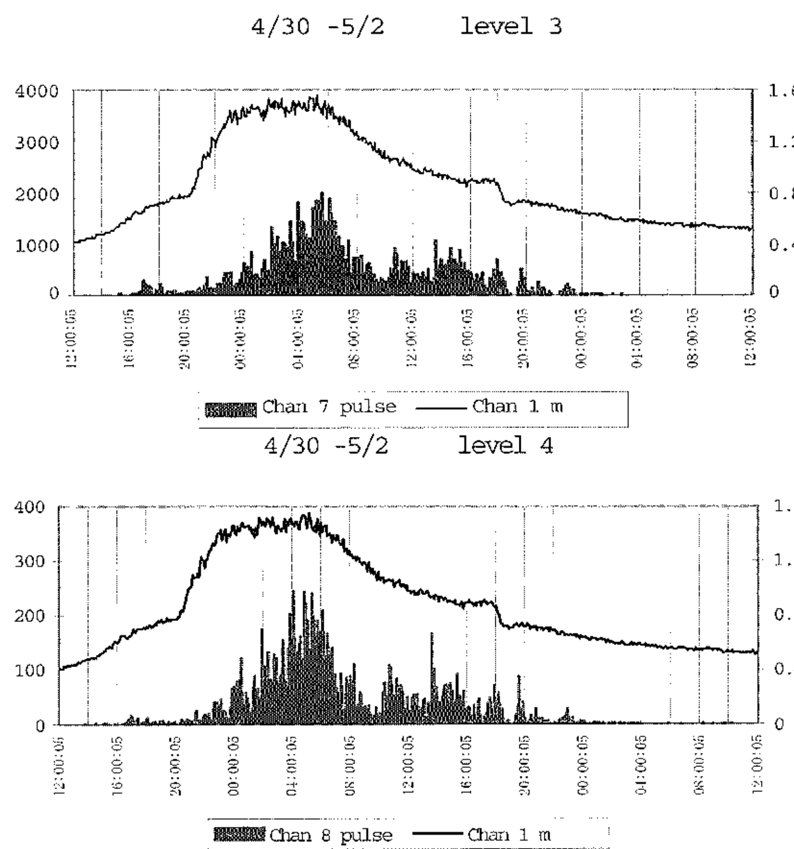

Fig. 5 Records of water level and input pulses of the hydrophone every 5 min on 30 April 2002.

The water level can be converted into flow discharge rate (Fig. 4, where Manning's n and a discharge coefficient are assumed as 0.04 and 0.6, respectively).

Measurements are necessary to obtain an accurate stage–discharge (H-Q) curve. The data obtained is stored in the data logger and is then transmitted to the work office through a cellular phone. The power for the system is supplied from a solar battery.

RESULTS OF MEASUREMENTS

The measurement at Tsuno-ura Karyu slit sabo dam started from 16 June 2001. It will be continued except during snow seasons. Measured data of incoming signals and water level of a storm on 30 April 2002 are shown as examples (Fig. 5). Pulses are counted every 5 min. The storm was not large enough to dam the flow. The recorded impulses correspond well to the flow level. The data on Channel 5 may include some noise.

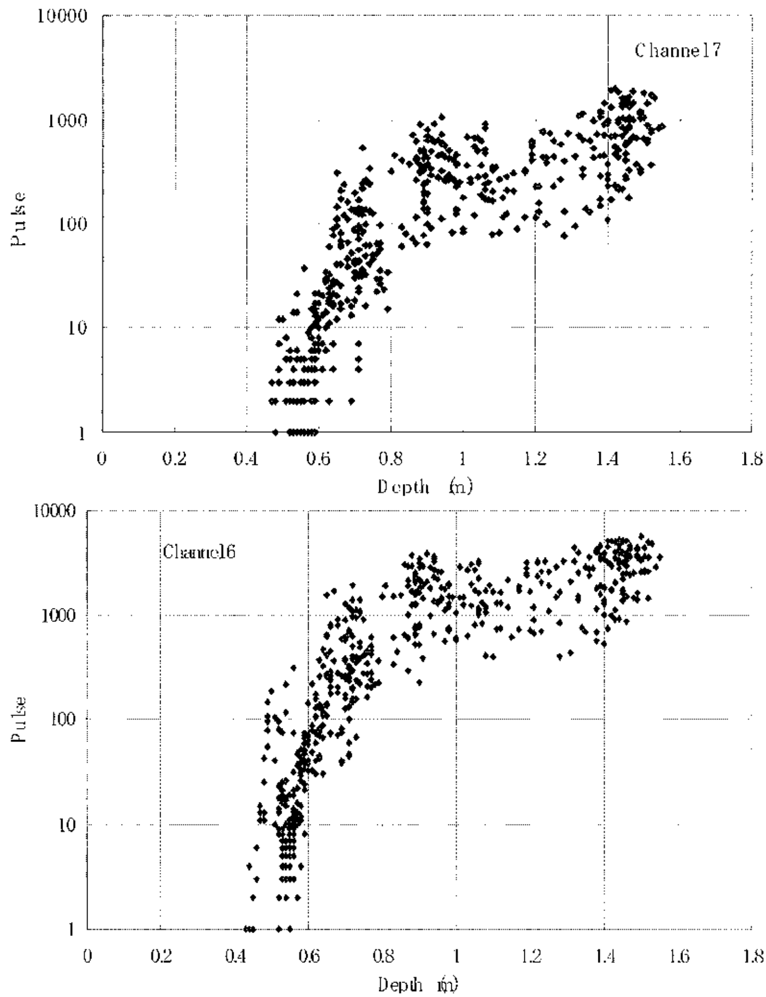

Fig. 6 Relationship between water level and recorded pulses.

PRELIMINARY ANALYSIS OF THE OBSERVED RESULTS

The relationship between the flow depth and the number of pulses are shown in Fig. 6. It indicates that sediment starts to move when the flow depth is larger than 50 cm. When impulses start to be recorded the water level changes with the gain of channels. Grain size of sediment could be estimated by analysing recorded signals.

CONCLUSIONS

It can be demonstrated that the hydrophone is appropriate for measuring bed load transport rates in mountain torrents, although the method does not indicate absolute values. As the record of the hydrophone is in proportion to sediment discharge rate (Rickenmann, 1992), absolute values can be estimated if the total sediment discharged volume is surveyed downstream. The hydrophones are planned to be set along several sections of the main river and the mouths of the branches of the Joganji River. Turbidity meters will also be installed.

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An instrument to record sediment movement in bedrock channels

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Abstract High energy bedrock channels pose particular practical difficulties in the measurement of bed load transport. An instrument has been developed to address these problems which detects the acceleration of a steel plate fixed to a rock riverbed upon being struck by a clast, and counts the impacts. The instrument has been shown to be reliable in the extreme environment presented by bedrock channels, and to provide high quality data. Three bed load sensors were deployed simultaneously in a cross section of a bedrock channel over a period of 50 days. The data obtained show that bed load is routed along well defined narrow areas of the channel. The threshold of initial motion is variable between events, while that for cessation is more constant. Within each event, bed load transport rates are hysteretic, with a higher threshold for initiation of motion than for cessation. Transport rates show strong general trends and they exhibit stochastic behaviour, demonstrating the pulsing of bed load.

Key words abrasion; bed load; bedrock channel; critical shear stress; impact sensor; northwest England; sediment transport

INTRODUCTION

Measurements of initial motion and bed load transport are difficult in alluvial streams but pose a particular problem in high-energy bedrock rivers. Not only is expensive instrumentation at risk of being destroyed, but suspension cables and support frames are usually inadequate to allow successful deployment, and pit traps used in gravel bed rivers are impractical in bedrock channels. In addition, there is considerable risk to the safety of researchers in such environments. These problems may be addressed by the development of instrumentation which is robust during high-flows, but which is deployed safely during low-flows. A long sampling period, with a high frequency sampling interval, is required as sediment transport will not occur immediately after deployment, but only when a flood wave passes through the system. Such a period and frequency of sampling has the advantage of allowing high resolution continuous data to be collected from many consecutive events, and from several locations simultaneously, without the need for repeated visits or the intensive input of labour, in contrast to handheld or movable bed load traps. Continuous data are necessary for determining thresholds of initial motion (Habersack *et al.*, 2001). Finally, the system needs to be cheap to allow for replication and for inevitable instrument losses in such hostile environments.

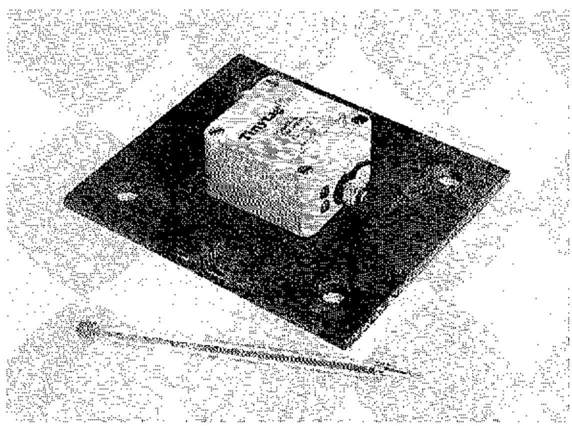

Fig. 1 Impact sensor and impact plate shown in inverted position.

INSTRUMENT DETAILS AND LIMITATIONS

An instrument has been developed to detect the acceleration of a steel plate fixed to a rock riverbed upon being struck by a clast, and to count the impacts detected within fixed intervals of time. An integral acceleration sensor and logger unit in a watertight housing is attached to the underside of the steel plate (Fig. 1), and fits into a recess chiselled into the bedrock. The device is relatively small; the logger unit is 8 × 6 × 3.5 cm, and the plate is 15 × 13 cm by 6 mm thick. A small plate is preferred to reduce the probability of multiple impacts. The plate is secured with four commercially available masonry screws. The internal battery is replaceable and lasts for over 6 months, although data begins to overwrite at 54 days at the sampling frequency used in this study. A version with a small external sensor is also under development for laboratory-flume experiments with sand size particles. At the time of writing the cost of the field unit is around £400.

There are limitations to the device which need to be considered. These are:

(a) The device must be installed in very low water because it is necessary to drill into the bed.

(b) The device must be removed promptly at the end of the period of interest to prevent overwriting of data.

(c) Saturation occurs at about three counts per second. Impacts which occur less than one third of a second apart cannot be distinguished. This works out at 1800 counts in the 10 min counting interval used in this study. The logger response is not likely to be linear as saturation is approached. The highest recorded count in the results presented below is 1850. This recording, and others of similar magnitude, may therefore be approaching saturation.

(d) Calibration of the loggers is problematic because they do not measure a single property of the clasts, but a combination of the speed and size of the clast (i.e. momentum). Calibration has not yet been attempted. The loggers therefore do not at present measure an absolute rate of bed load transport. Use of the impact sensors is therefore only a semi-quantitative technique, but it does give a measure of the relative intensity of bed load transport.

However, importantly, the instrument has been shown to be reliable and rugged in the extreme environment presented by bedrock channels in flood, and to provide high quality data on the initial motion and transport of bed load.

FIELD SITE

Three bed load impact sensors were installed in Birk Beck (Cumbria, northwest England). The study reach is a bedrock channel in cross-bedded sandstone and conglomerate with a plane bed. There are scattered small cobble bars and the banks are partially vegetated. The reach-average channel gradient is 1.2% and the channel width is about 10 m. The sensors were mounted in a straight line across the channel on a left-hand bend (Fig. 2). In the study reach, the right bank is actively eroding whereas a small bar is accumulating on the left bank.

Within the channel there are occasional linear patches or "tracks" which are lighter in colour than the surrounding channel floor. These tracks are stripped clean of algae, and represent regions of enhanced abrasion of the bed. Two sensors were mounted near the channel centre 1.1 m apart, one in an abraded track and one outside it, to determine whether this qualitative visual difference in the appearance of the bed was reflected in bed load transport rates. The third sensor was mounted near the actively eroding right-hand margin of the channel (Fig. 2) in order to detect whether bed load, which is mainly cobble-sized, was concentrated on the outside of the bend by inertia effects.

RESULTS

The instruments recorded data for a period of 50 days from January to March 2002. During this period, 26 flood events occurred in which bed load movement was

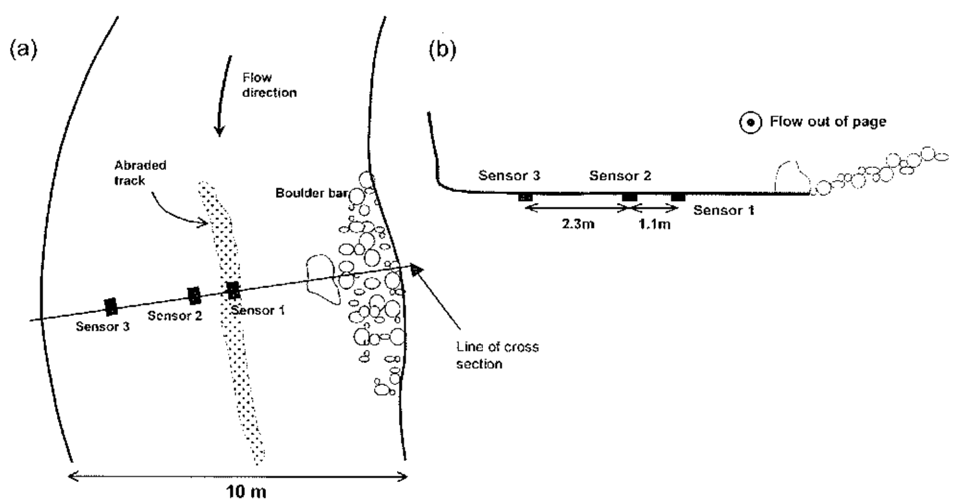

Fig. 2 Schematic diagrams of sampling site. (a) Plan view, (b) cross section.

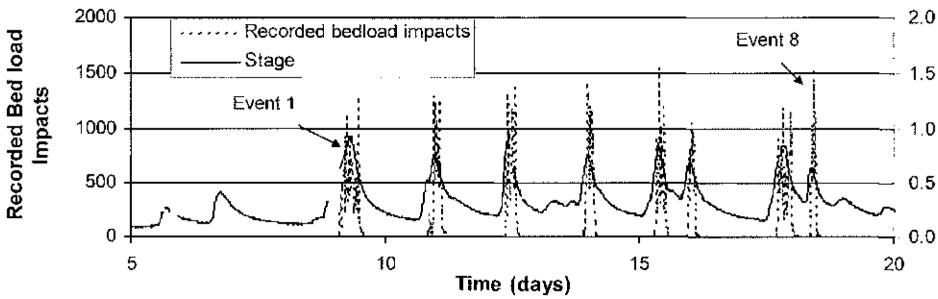

Fig. 3 Time series showing stage and recorded bed load impacts on sensor 1 for events 1 to 8.

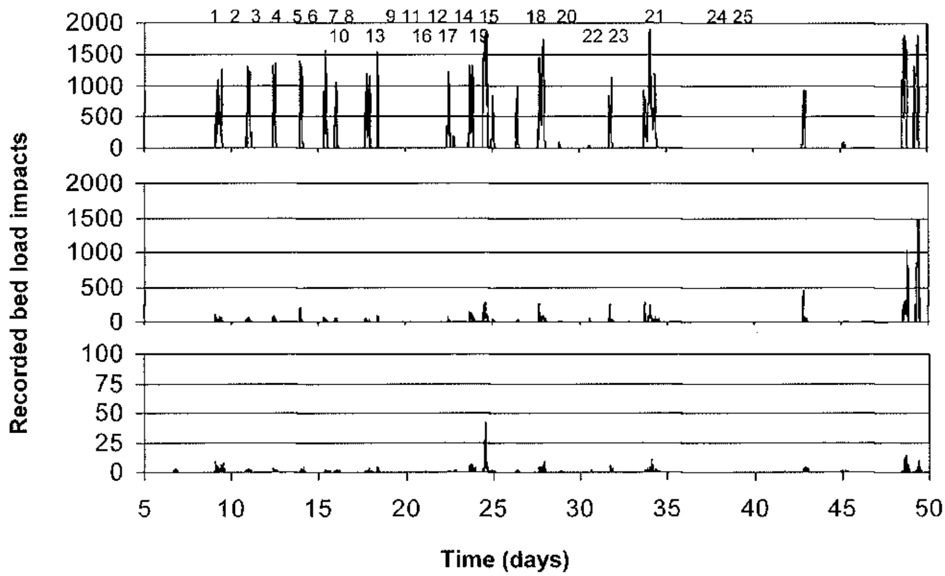

Fig. 4 Comparison of the records of sensors 1 (top), 2 (middle) and 3 (bottom). Event numbers are shown in the top graph (event 26 not shown).

detected, and these were numbered for reference purposes. The basic data time series for some of the events, showing the stream hydrograph and recorded bed load impacts from sensor 1 (in the abraded track), is illustrated in Fig. 3. Note the correlation between stage and recorded bed load impact rate, and the intermittent nature of detected bed load transport. The record period includes an "extreme" flood (Event 12) during which flow velocities of 3.5 m s^{-1} were directly measured. During this event, coarse gravel including large cobbles and rounded boulders up to 1 m in diameter were moved through the test section. The largest tabular block known to have moved measured $1.5 \times 1.0 \times 0.5$ m.

An uncalibrated pressure sensor, deployed in the same manner as the impact sensors, initially produced useful results but was later destroyed. However, all three impact sensors deployed survived and gave excellent results. In view of the failure of the pressure sensor, stage data were obtained from two non-invasive ultrasonic water level sensors mounted above the river. Subsequently, shear stress was calculated for the reach immediately upstream of the bed load sampling section through the slope × depth product, depth being determined from a knowledge of the distance from each water level sensor to the bedrock surface.

The main uses of the data have been: (a) comparison of simultaneous differences in transport intensities in different regions of a channel; (b) the detection of the thresholds of sediment motion and cessation; and (c) relative intensities of transport through time. Figure 4 compares the records from the three bed load sensors. It can be seen that the number of recorded impacts within the abraded track (sensor 1) is much greater than that recorded elsewhere within the central channel area but outside the abraded track (sensor 2), which is in turn much greater than the number of recorded impacts in the right-hand margin of the channel, on the outside of the bend (sensor 3). As a result of the low number of impacts recorded by sensors 2 and 3, all subsequent analysis was performed on the record of sensor 1.

Recorded bed load impacts for all events are plotted against shear stress in Fig. 5. This shows the existence of a threshold for detected bed load transport at 40–50 N m^{-2}, but no clear relationship between bed load activity and shear stress. It is important to note that the thresholds of motion represented in the data are thresholds of *detected* motion rather than absolute thresholds of transport because it is possible that at shear stresses below 40–50 N m^{-2}, clasts were in transport which had too low a momentum to be detected.

Figure 6 shows the data for selected individual events, and now relationships are visible. The curves are variable but follow a pattern. Each curve is hysteretic, with a higher threshold for initial motion than for cessation of transport in any single event, and with equal transport rates occurring at a lower shear stress during falling stage than in rising stage. Thresholds for initial motion are highly variable between events at 40–100 N m^{-2}, whilst thresholds for cessation of transport are more constant at 40–50 N m^{-2}. In fact, despite the variability of the rising limbs of the curves between events, the falling stage curves often overlie each other in the region just above the threshold for cessation of transport.

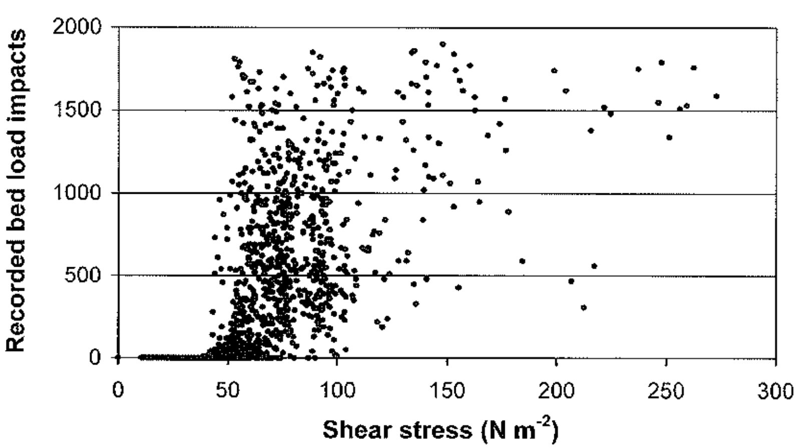

Fig. 5 Recorded bed load impacts from sensor 1 *vs* shear stress for all events.

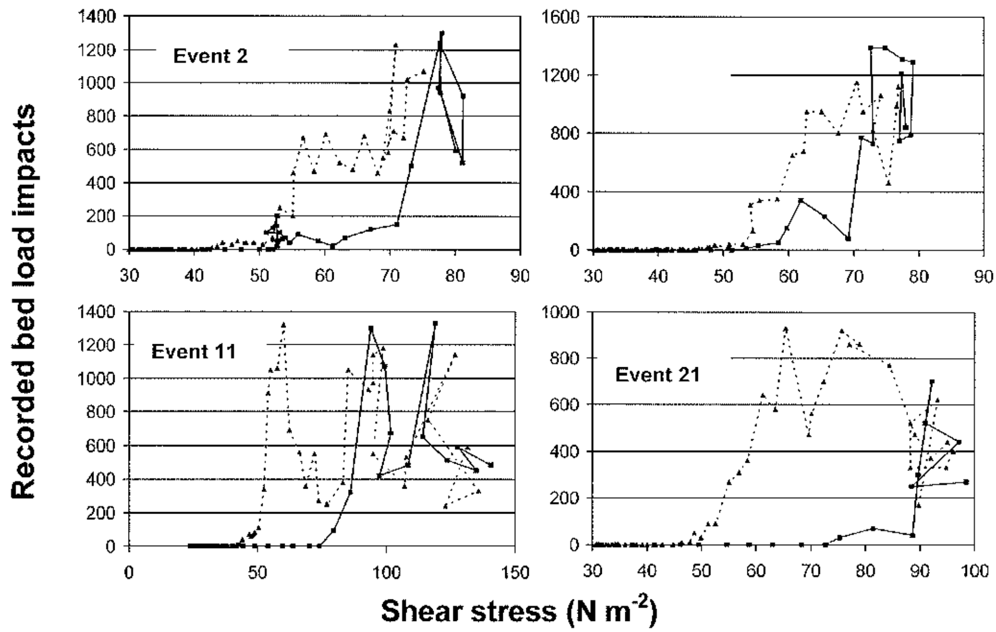

Fig. 6 Recorded bed load impacts from sensor 1 *vs* shear stress for selected events. Solid lines and dashed lines represent rising stage and falling stage data, respectively.

During rising stage, the curves show a trend for increasing bed load transport with stage above the threshold. During the falling stage, transport rates are at first generally either flat or show a gradual decrease, followed by a rapid decrease as the transport threshold is approached from above (Fig. 6, events 2 and 4). This response of bed load transport during the early part of the falling limb of the hydrograph is by no means universal. However, transport rates may continue to rise and peak during this time (Fig. 6, event 21). Despite the existence of these trends, a notable feature of the curves is the absence of a deterministic relationship between bed load transport rate and stage, and the highly scattered, apparently stochastic nature of the data (see Fig. 6, event 11 for an extreme example).

DISCUSSION

The bed load impact sensors are uncalibrated, but it is possible to estimate the size of the smallest grains which they were able to detect at this particular site. Adopting a Shield's parameter of $\theta = 0.045$, the observed threshold of 40–50 N m^{-2} for the cessation of bed load transport indicates a minimum detectable grain size of 55–70 mm. This estimate is very approximate because it is a threshold for the cessation of transport rather than for initial motion, and because the bed load consists of isolated grains moving across a plain bed rather than across packed grains. However, it does show that the impact sensors detect the motion of coarse bed load, and are not sensitive to the transport of sand and fine gravel.

The highly scattered or variable nature of bed load flux observed in Birk Beck has also been reported by many studies in gravel bed rivers (e.g. Brayshaw, 1985; Reid *et al.*, 1987; Gomez *et al.*, 1989; Young & Davies, 1991; Hoey, 1992; Batalla, 1997; Garcia *et al.*, 2000), and illustrates the pulsing nature of bed load. The pulsing of bed load in alluvial reaches is sometimes claimed to be cyclic (e.g. Young & Davies, 1991), and is generally interpreted as being due to the passage of bedforms (Gomez *et al.*, 1989; Young & Davies, 1991; Hoey, 1992; Batalla, 1997). However, this is not a realistic interpretation in the present case with sparse cobble bed load and a bedrock floor. Reid *et al.* (1987) attributed the pulsing of bed load in the absence of bedforms to be due to the passage of kinematic waves of particles, which represent streamwise differences in the concentration of particles in a traction carpet. Further work in Birk Beck will be required to identify the exact nature of bed load motion.

Temporally variable thresholds of initial motion, found in this study, have also been reported from gravel bed rivers (e.g. Garcia *et al.*, 2000). Variation in critical shear stress in gravel bed rivers for bed material of similar size and shape is attributed to packing effects (Brayshaw, 1985; Powell & Ashworth, 1995) and the form resistance generated by bedforms and channel topography (Buffington & Montgomery, 1999; Millar, 1999). The stochastic nature of the data and the variable thresholds of initial motion call into question the value of deterministic predictive formulae of bed load flux and bed load rating curves. Various bed load equations were tested by Batalla (1997) and Habersack *et al.* (2001) and were found to perform poorly, in some cases extremely so. The difference between critical shear stresses for initial and final motion observed at Birk Beck was also found by Reid *et al.* (1985) in their study of Turkey Brook, although the difference they found (on average, a factor of 3) is greater than that in Birk Beck.

Bed load is apparently routed along well-defined and narrow pathways within the channel (i.e. the abraded tracks), as shown by the much higher number of impacts recorded by sensor 1. This indicates that the qualitative observations of the intensity of abrasion within the tracks, based on the stripping of algae from the bed, are supported by the quantitative data from the impact sensors. Furthermore, the difference in abrasion intensity between algae-covered and bare areas of the channel floor can be explained by differences in abrasion by bed load, although the intensity of abrasion by suspended load may also vary between these areas. The extremely low number of impacts recorded by sensor 3 show that bed load momentum and channel curvature are insufficient to concentrate bed load on the outside of the bend in the study reach; there are clearly other more important effects which determine bed load routing.

No clear trends over the period of the record can be identified, either in terms of the threshold of initial motion or the magnitude of the bed load events, nor do the very large events or the period of inactivity between events appear to have any effect on the subsequent events. However, these observations may reflect the relatively short length of the monitoring period; a longer study period and rigorous time series analysis may reveal trends or patterns. For example, event-by-event exhaustion effects, in which a high fluid discharge in the previous flood produced a low magnitude bed load event subsequently, were found in a 6-year study by Carling & Hurley (1987). Reid *et al.* (1985) found that periods of inactivity allowed for bed consolidation, increasing the critical shear stress for the next bed load event, and leading to the restriction of bed load transport to the recession limb of the flood wave. No such pattern is observed in the present data where transport generally occurs on both limbs of the hydrograph, although the hysteretic nature of the transport curves does indicate that most material is moved on the recession limb.

CONCLUSIONS

A new robust bed load sensor has been developed for deployment in high-energy bedrock channels. The instrument has provided high-quality data on initiation and cessation of motion of bed load. In addition, the variation of relative transport intensity during individual flood events has been recorded at a fine time-resolution enabling the detection of pulsing in bed load motion and distinct hysteretic behaviour when comparing the waxing and waning limbs of hydrographs. By comparing the records of three bed load sensors deployed simultaneously in different parts of the channel, it has been shown that bed load is routed along well defined, narrow pathways.

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