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Bed load measurements with a new passive acoustic sensor

JIM BOGEN & KNUT MØEN
Norwegian Water Resources and Energy Directorate (NVE), PO Box 5091 Maj.,N-0301 Oslo, Norway
jbo@nve.no

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

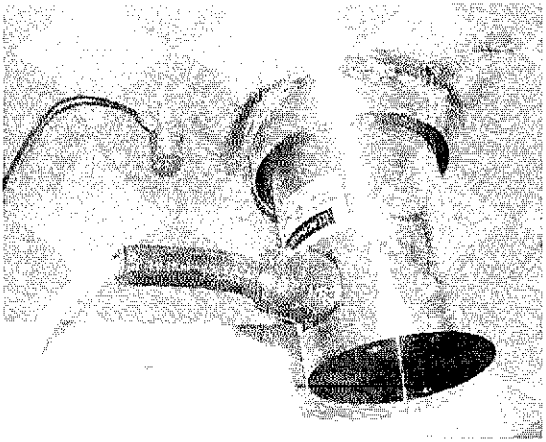

Fig. 1 Sensors installed in the laboratory test rig used in the flume studies. Right: The ClampOn sensor operating at high frequencies (0–500 kHz). Left: The low frequency 0-25 kHz sensor.

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.

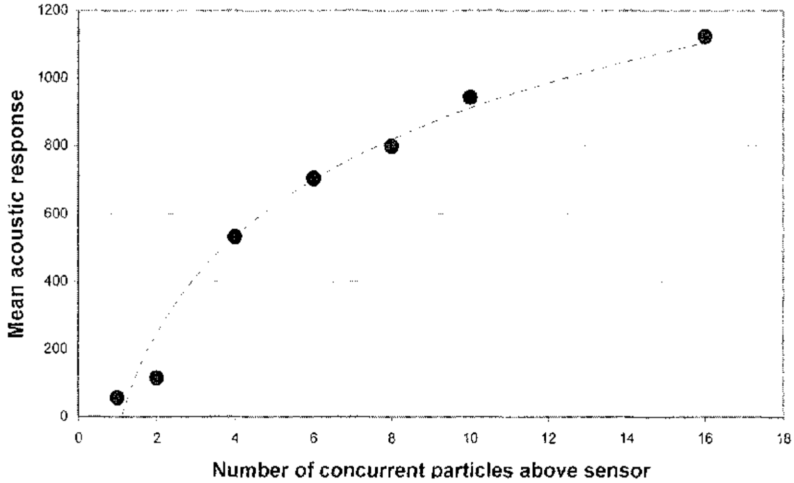

Fig. 2 Acoustic response to increasing transport of 5–8 mm gravel particles in test flume.

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

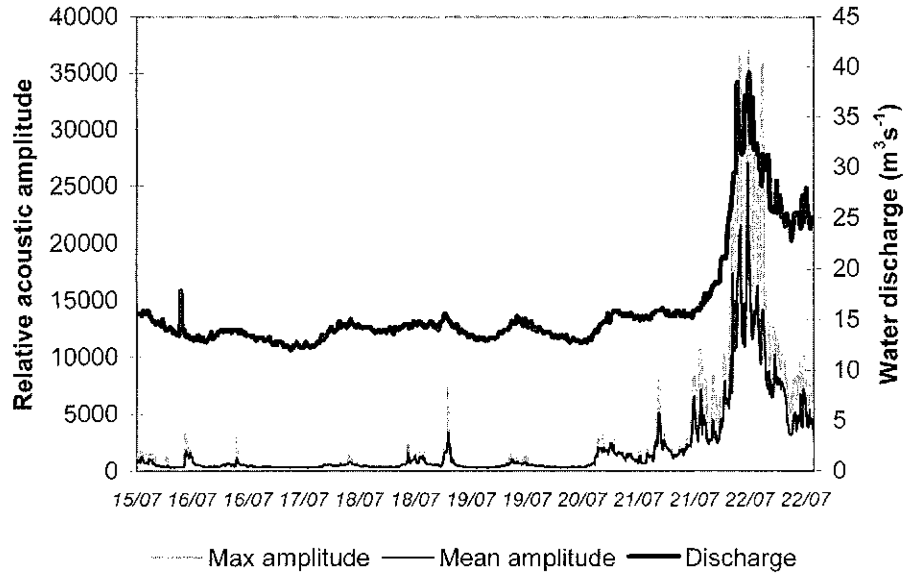

Fig. 3 Maximum and mean acoustic amplitude over 15-min intervals, and water discharge, in the river Nigardsbreelv 15–22 July 1998.

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.

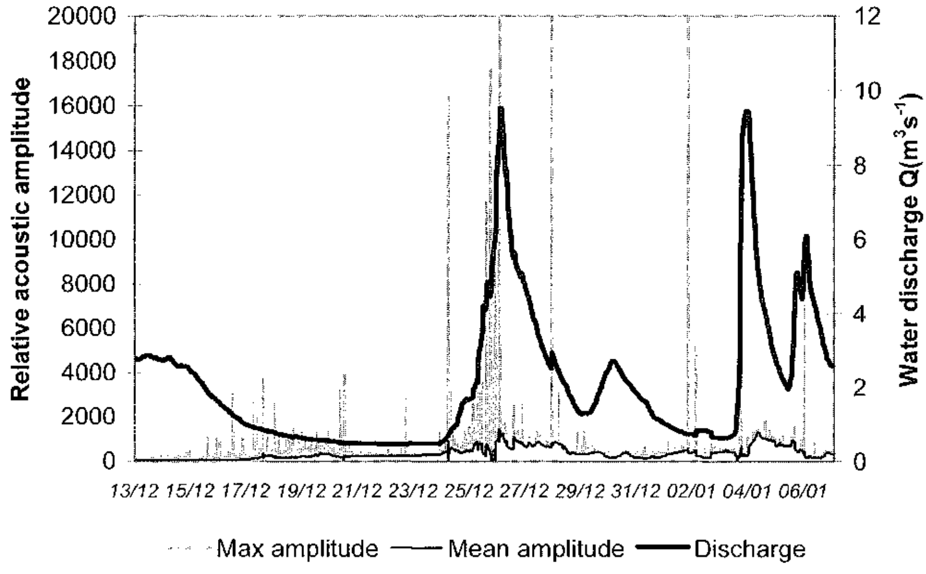

Fig. 4 Mean and maximum acoustic amplitude calculated for 5-minute intervals, and water discharge, in the River Gråelva at Børstad, from 10 December 1999 to 5 January 2000.

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,

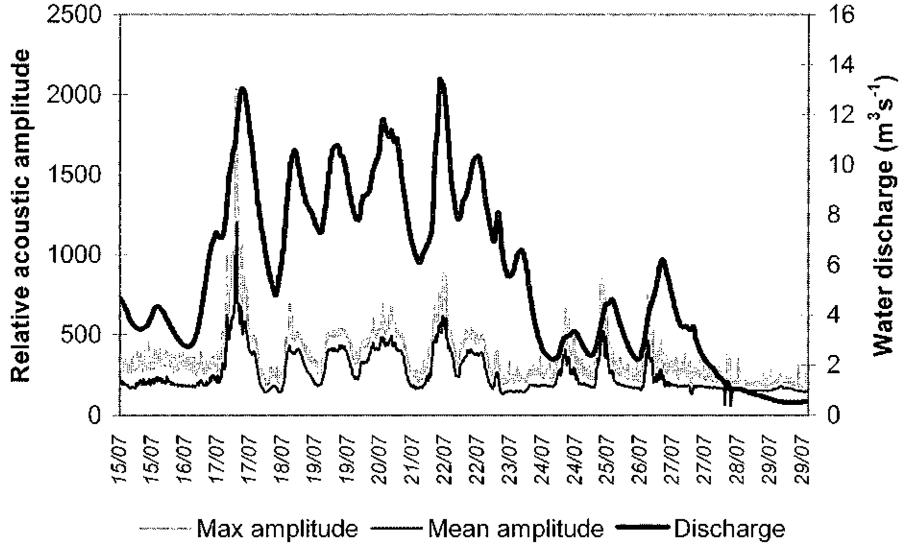

Fig. 5 Mean and maximum relative acoustic amplitude calculated for 5-minute intervals, and water discharge, in the River Bayelva 15–29 July 2000.

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.

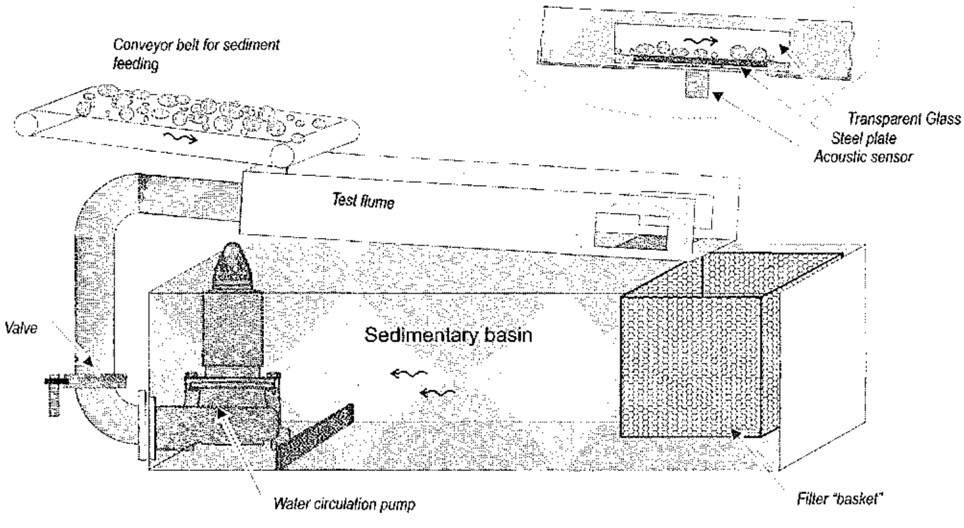

Fig. 6 Schematic drawing of test rig.

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 $r^2 = 0.9806$.

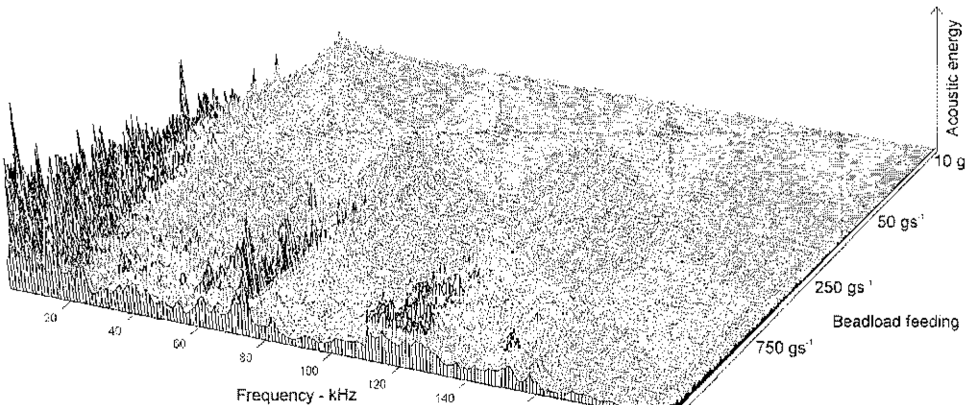

Fig. 7 Acoustic energy as a function of bed load transport rate and the frequency distribution in the 0–180 kHz range. (Series 1 in Table 1).

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

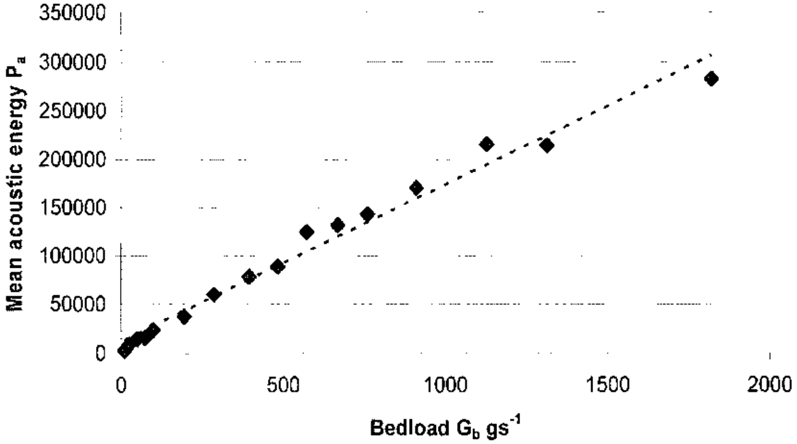

Fig. 8 Acoustic energy (expressed as the integral of the frequency spectrum) *vs* bed load transport rate for the 18–27 mm fraction. (Series 1 in Table 1).

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

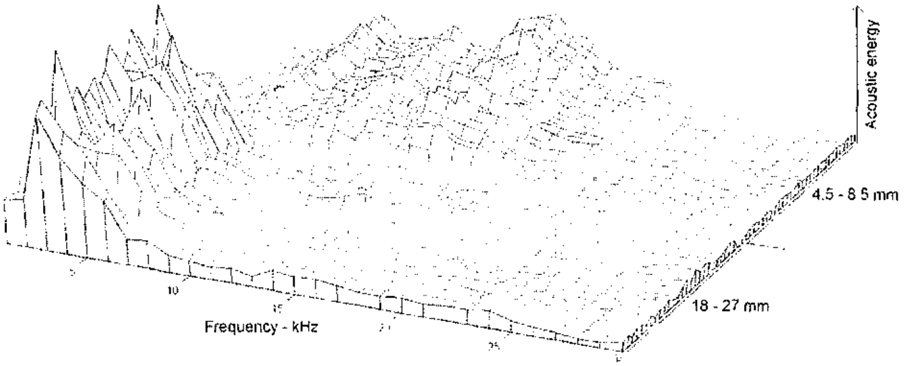

Fig. 9 Frequency signature of the 4.5–8.5 mm and 18.0–27 mm fractions (Series 2 in Table 1).

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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