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Monitoring of bedload in river beds with an hydrophone: first trials of signal analyses

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ABSTRACT: A description is given of preliminary efforts in using passive acoustic detection of bedload transport in gravel bed channels. A hydrophone cell placed near the river bed records surrounding noise resulting from both flow and bedload transport. Several methods for detecting sediment components of the record are explored by signal analysis. Time-frequency analysis is suitable for the detection of pebble collisions of highest energy. The relationship between frequency of the noise of the shock and the grain size is analyzed. This relationship is associated with spectral analysis of the recordings for determining the coarsest particles under transport in given conditions.

Keywords: Bedload transport, Hydrophone, Time-frequency analysis.

The goal of this paper is the investigation and development of a simple method for bedload transport monitoring in gravel-bed rivers based on the recording and the analysis of the noise emitted by movement of bedload particles. The intent of this effort is not to quantify sediment flux, but to assess the onset of bed transport at a given cross-section of the river under different flow conditions. After a discussion on arguments for direct passive noise recording, the paper will address the detection of bedload transport monitored by hydrophone recording. It is based on original recordings and analyses, from detection of individual shock noise to the deformation of the power spectral density in the case of significant bedload flux.

1 INDIRECT OR DIRECT PASSIVE NOISE? A SHORT REVIEW OF EXISTING LITERATURE

Two different techniques are common in the use of acoustical devices for detecting the movement of coarse sediment in gravel bed channels: (i) geophones or hydrophones are used for **indirect recording** of the noise generated by the impact of gravel on an artificial object implanted into the river bed; (ii) hydrophones are used for passive audition and recording of **self-generated noise**, or the noise made by the shock of bedload when rolling and jumping over the river bed.

For **indirect recording methods**, a metallic plate or pipe is installed onto the bed or near the bed to act as a resonator. The noise of vibration of the plate or pipe when impacted by moving grains is recorded. The frequency and intensity of the impacts are conditioned by the shape and the material of the resonator. Frequency of particle collision is well identified and intensity can be related for example to the particle energy, the number of strikes and distance to the microphone. The "pioneers" of acoustic technology used such an indirect method. Mullhoffer (1933) describes what appears to be the first attempt at acoustic detection of bedload transport in rivers. The microphone was placed in a metallic box laid onto the riverbed and connected to earphones, which allow the audible detection of the presence of strikes of bed particles on the box. Mulhoffer investigated solid transport from a bridge at different locations across a section of the Inn River. His experiments were "calibrated" by sampling of bedload transport and the total flux was derived from cross-section exploration. Mulhoffer's ideas were applied in France by the Laboratoire de Beauvert in 1942 (apparently unpublished but a report is made by Labaye, 1948) and further reproduced with the same technology by Bradeau (1951) for detection of the critical discharge for the onset of bed transport. A metallic plate served as a support for the hydrophone but it is uncertain whether the plate acted as a resonator. The original idea of a couple of hydrophones for locating the shocks would suggest audition of self-generated noise by Bradeau. Mulhoffer (1933) and Bradeau (1951) had direct audition from a hydrophone but did not record the signal.

More recent investigations of indirect recording analyze the intensity of the impacts on the resonators. With an installation developed for indirect recording by Bänziger & Burch (1990), Rickenmann (1997) correlated the number of shocks with solid transport rate measured from the volume of sediment accumulated in a retention basin. In small Norwegian rivers, Bogen & Moen (2003) investigated ultrasonic frequencies from a metallic plate laid onto the river bed. Froelich (2003) analyzed the noise from strikes of bed transport against a metallic pipe in a river. In both cases a correlation was made between acoustic intensity and liquid discharge and hysteretic effects were observed. Shock counting on a pipe imbedded in a Japanese creek resulted in the similar identification (Mizuyama *et al.*, 2001).

The main advantages of indirect recording methods are the possibility for localization of bed transport (obviously where it strikes the plate or the pipe) and an easy discrimination of the corresponding noise. Only bed particles coming into contact with the resonator are detected. However, as Labaye (1948) suggested, there are possible hydrodynamic perturbation resulting from the presence of an artificial device on the bed and the possibility for spurious scouring around the obstacle. In the case of a fixed resonator, an additional problem is that the resonator can become buried during bed aggradation. In order to overcome such problems, the resonator may be placed in a contracted section of the river (e.g. Rickemann, 1997) or at the edge of a weir crest (Taniguchi *et al.,* 1992). Scouring and burying could be the reason for the limitation of the use of indirect methods mainly in smaller mountain creeks where the device is often included in a weir. Burying is not reported by Krein *et al.* (2008) when using a 0.3 m x 0.3 m square steel plate in small creeks or in the bed of the large Mosele River at a flood discharge which is nearly 3000 m^3s^{-1}. On an apparently neat surface, they noticed a different signal from angular rolling stones and flat sliding cobbles.

Passive recording of **self-generated noise** does not require a resonator, and bedload noise is directly recorded with a hydrophone cell in the water column.

The literature mainly describes experiments made in controlled conditions: in flumes or even in a drum (Thorne, 1985, Thorne, 1986). Few experiments took place in real rivers. Fouli (1999) recorded hydrophone signals in a flume and in a torrent and performed spectral analysis. From flume recordings, Barton *et al.* (2010) correlated acoustic energy with bed movement intensity recorded by a video camera. Acoustic energy has been obtained from time integration, typically 2 to 3 minutes of the signal filtered in a 125 - 1600 Hz band.

This paper is concerned with passive recording of self-generated noise. This method has been preferred to an indirect recording for the following reasons: (i) The method can be implemented directly rather than require the installation of any obstacle on the bed prior to observation. (ii) It avoids perturbations from introduction of an artificial object spurious such as scour or modification of the transport. (iii) The method allows continuous measurements in the case of important aggradation or degradation of the river bottom. The risk with an obstacle is of burial in the case of aggradation of the river bed. (iv) The method can be developed and tested in various bed configurations, particularly in large rivers without the requirement for heavy installations. (v) The method can be tested, or at least easily removed, during challenging flood conditions.

It is obvious that early studies were limited by available recording and data processing possibilities; it is amazing to realize that more recent experiments do not exploit the methods of modern signal analysis. Among the most advanced is the use by Krein *et al.* (2008) of the Fast Fourier Transform for analysing indirect recordings of bed movement in a flume. The present work aims at exploring different paths for signal analysis.

2 CONDITIONS OF THE EXPERIMENTATION

A hydrophone cell was placed within the flow in the vicinity of the bank, at some distance from the river bed (approx. 0.10 to 0.20m, not too close in order to avoid direct impacts, not too far in order to detect the less energetic strikes). In first attempts, the hydrophone was manually held by the operator with a rod. For later experiments, it was supported by a fixed frame (Fig. 1a, 1b).

The typical duration of a recording is 30 seconds, digitised as a 16 bits / 44 100 Hz signal. The pass-band of the recording system is checked through laboratory experiments and covers the range [320 - 22 000 Hz]. This range is sufficient, as noises treated in this paper are within the range [500 - 15 000 Hz].

A first series of recordings was performed in the Isère River, a piedmont river with a narrow system of levees. The main characteristics of the river and its morphology are described elsewhere (Vautier, 2000; Allain-Jégou, 2002). At Lancey where recordings were made, the river width between levees is 80 m and the slope is S_0=0.001. Bed material consists of elongated pebbles with [d_{16}=20 mm, d_{50}=35 mm, d_{84}=45 mm].

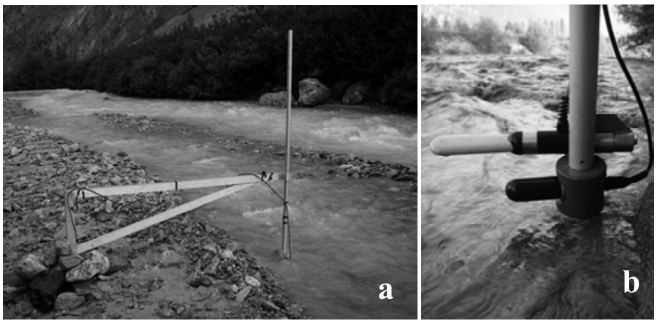

Fig.1a – The hydrophone held by a fixed frame in a mountain creek. Fig.1b – The hydrophone on the frame before immersion. In this experiment, an electromagnetic flow sensor is also used (above). During recordings, the set is oriented upstream.

The first recording used for the analysis was made during a flood. The discharge at the time of the recording was 805 m^3s^{-1} and is the order of magnitude for peak discharge during a ten-year return flood. Intense bedload transport was recognized audibly from the surrounding flow noise. It was composed of clear shocks as well as a more confused bottom noise similar to the one that could be made by a continuous sheet of rolling sediment. Although subjective, ear detection served in this demonstration as the reference for comparison with automatic detection of the presence of bedload transport. Our subsequent efforts were oriented towards an automatic treatment of the signal with various analysis techniques.

3 TIME-FREQUENCY ANALYSIS FOR INDIVIDUAL SHOCK DETECTION

Figure 2 displays a sample of the recorded wave (signal intensity, *I* vs. Time). *I* is the signal delivered by the electronic chain and is proportional to the sound intensity). In this example, the listener recognized three characteristic shocks during this period.
The timing of these shocks is indicated in Figure 2 by vertical arrows. There was minimal change in the signal at these recorded times. Hence the representation by intensity is not very well-suited for shock counting and analysis.

A second representation is built where we define *P*, the 'instant power' of the signal as *P=I2-P0*, where *I2* is the square value of the average signal intensity during time interval Δt. A good discrimination of shocks requires that time interval Δt be shorter than the characteristic duration of a shock which has been estimated from our recordings to be of the order of 3.10^{-3} s. The choice made was $\Delta t = 10^{-3}$ s.

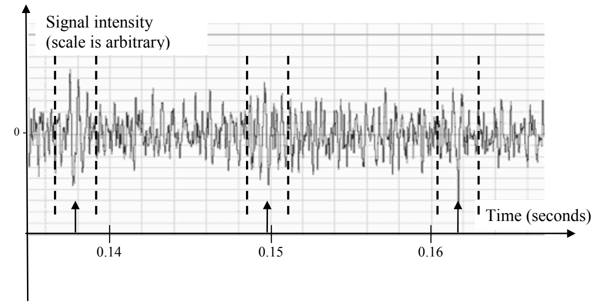

Fig.2 – Recorded sound intensity wave from hydrophone. Vertical arrows point to audibly detected shocks which presumably arise due to collision with moving bed grains. Dotted lines give an indication of the duration of the perturbation induced by each shock.

P0 is the average value of *I2*. Hence *P* is proportional to the noise power recorded by the hydrophone.

During a shock, sound energy is produced during a very short time interval and the 'instant power' should show a peak value. The same wave sample shown in Figure 2 is represented by the 'instant power' in Figure 3. 'Instant power' displays peak values at the occurrence of shocks as identified audibly, thus confirming the presence of moving grains. However, on other recordings the method does not allow identification of every audibly detected shock. A more refined analysis is required to overcome such a limitation.

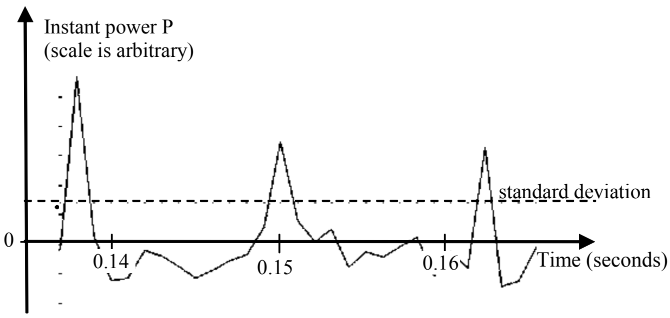

Fig.3 – 'Instant power' of recorded sound *P=I2-P0* ,
I2 = square value of the average noise intensity during time interval $\Delta t = 10^{-3}$ s , *P0* is the average value of *I2*.
The horizontal dotted line indicates standard deviation.

The time-frequency analysis (Flandrin, 1998, Flandrin, 1999), or *windowed Fourier transform*, which performs a Fourier transform on limited portions of the original wave signal was applied. In comparison with the basic Fourier transform, the time frequency analysis allows the treatment of non-stationary signals. The time-frequency analysis produces a decomposition of the signal intensity as a function of time and frequency. A typical representation of the analysis is the spectrogram or time-frequency representation (TFR).

Figure 4 displays TFR of the same portion of the acoustic signal as in Figure 2 and Figure 3.

The three shocks which had been previously identified appear as three clear areas on the TFR. For example, the central clear dot between times 0.148 s and 0.152 s shows that a high energy was released with a noise frequency in the interval 1000 - 3000 Hz.

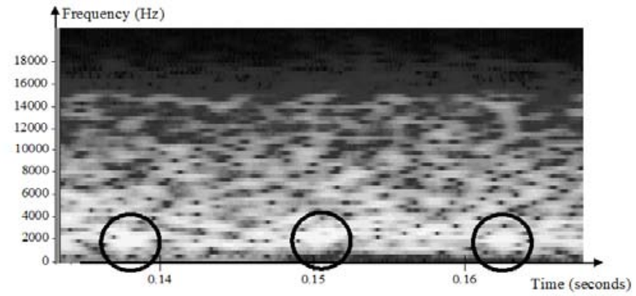

Fig.4 – Spectrogram or TFR – dark : low sound intensity / clear: high intensity. Black circles point out shocks of bedload material

As the calculation of 'instant power' (Fig. 3) took the entire spectral range of the noise into account, this time-frequency analysis permits a similar calculation of the 'instant power' (amount of energy which is released in a given period of time Δt) on discrete frequency ranges [ν, $\nu+\Delta\nu$]. It is then possible to discriminate the 'instant power' produced on a selected range of frequencies.

Individual shock detection was attempted from filtering 'instant power' $P_{\nu 1,\ \nu 2}$ within the frequency range of audible shocks [ν_1=1000 Hz; ν_2=3000 Hz]. A criterion was devised for the selection of a 'power' peak as characteristic of a shock. After optimization on a sample of the original recording, using audible detection as well as TFR examination, it was determined that a shock is detected only when $P_{\nu 1,\ \nu 2}$ becomes larger than 1.8 times its standard deviation.

This finding is useful because it allows the counting of shocks from a hydrophone recording. Counting has been tested on several samples of the original recording; the average value was 153 shocks per second. The counting of shocks seems to be a suitable method for the investigation of the flux and rhythm of bedload movement. In its present development, it does not allow the quantification of bedload transport because the domain where sediment movement is detected has not been determined.

Another limitation of the method occurs at lower discharges, when bedload transport is less intense and shocks have less energy. Therefore, individual shocks are more difficult to identify by listening or by 'instant power' detection. An example of the hydrophone recordings at the same cross-section on the Isère River (discharge Q=356 m^3s^{-1}, only twice its mean annual value) is shown in Figure 5. Several peaks of 'instant power' value are indicated but discrimination between these minor bedload shocks and other noise of short duration is not possible by listening nor by TFR examination. The energy of bedload shocks is insufficient at such mild flow conditions.

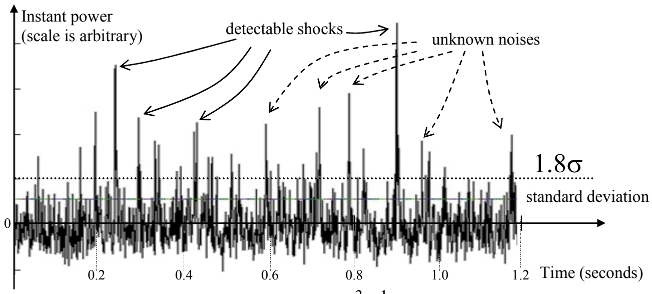

Fig.5 – 'instant power' (356 m^3s^{-1}). For intermediate discharges, shock energy from bed particles shocks is not significantly different from energy from other noises in the same frequency range [1000-3000 Hz]. 'Detectable shocks' are energy peaks identified without doubt by listening. The dotted line at 1.8σ indicates the discrimination chosen for the counting of the shocks.

4 GRAIN SIZE AND SHOCK NOISE FREQUENCY

An experiment was carried out to determine whether the grain size characteristics of bedload can be identified from our hydrophone recordings. For assessment of the potentialities of the method, controlled conditions were preferred in order to minimize uncertainties. The study was conducted in a rectangular basin which had been dug in soil. The cavity shape was a 1m deep cube. It was lined with a plastic cover and filled with water. The bottom was covered with pebbles and same material was poured from underwater onto the bottom. The hydrophone was hung in the centre of the cavity and recorded the ambient noise of shocks during the pouring. Several runs were made with well sorted and regularly shaped granite pebbles.

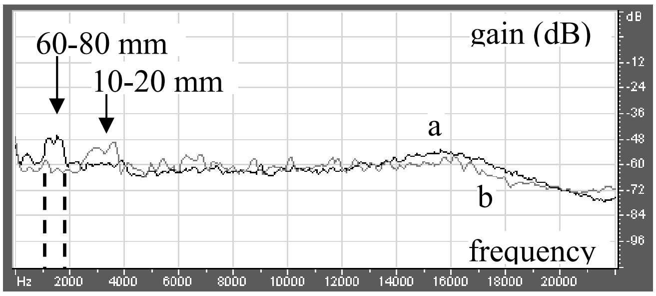

Fig.6 – Power spectral densities or PSD from basin experiments, (a-black) : 60mm-80mm pebbles, (b-grey) : 10mm-20mm pebbles. Arrows point characteristic shock frequencies.

From the recordings, samples were selected, each of them corresponding to a single shock/collision, thus artificially increasing shock occurrence and allowing a simple spectral analysis. A graphic representation of the power spectral density (PSD) of one such recording is plotted in Fig. 6.

The sediment in this experiment had diameters *d* within the range [60 - 80 mm] and a characteristic hump on the PSD curve has been identified within the range [1100 - 1800 Hz]. Two small peaks can be identified on the hump, probably due to some difference in the pebbles involved in this particular shock.

The experiment was repeated with other available collections of the same granite pebbles. Characteristic signatures were identified and the corresponding frequencies were plotted (Fig. 7).

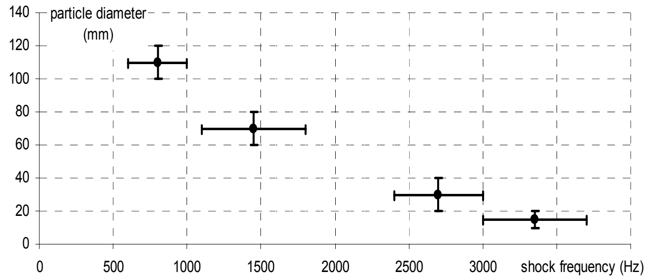

Fig.7 – Characteristic frequencies of shocks of individual granite pebbles. Vertical bars indicate the grain size range of each experiment and horizontal bars indicate the characteristic frequency range.

Similar results were obtained by others (e.g. Thorne, 1985, Thorne, 1986, Fouli, 1999). Indeed, basic dimensional analysis leads to a proportionality of noise frequency with 1/*d*. However, the theoretical value of the frequency of pulsation of a spherical homogeneous solid body (ν in eq. 1, from Dahlen & Tromp, 1998), leads to frequency values about 400 times the measured frequency (ν=456 kHz for *d*=70mm)

$$\nu = 0.82\pi \frac{C}{r} \qquad (1)$$

where C is the celerity of compression waves in the solid (C=6200 m.s^{-1} in granite) and $r=d/2$ is the radius of the sphere. A similar comparison is presented in Thorne (1985) with theoretical vibration frequencies larger by several orders of magnitude than recorded frequencies.

Bed material in real rivers, and especially in the Isère River bed often are flat shaped. Hence, automatic determination of the grain size of transported sediment is more complex; Fouli (1999) has warned of the influence of shape characteristics on noise frequency.

5 INTERPRETATION

As discussed previously, time-frequency analysis performed on the Isère River recording made during the flood at discharge Q=805 m^{3}s^{-1} identified individual shocks the frequency of which has been evaluated by progressive filtering within the interval [1000 - 3000 Hz] where we are still able to recognize the shock noise that is characteristic of bedload transport audibly but is not clearly identified by time-frequency analysis.

Our interpretation is that time-frequency analysis, as determined using the described analysis, is only suitable for the detection of the most energetic shocks generated during transport of the coarser sediment (d_{95}=60 mm measured by Vautier, 2000). Finer material is transported as bedload at such flow conditions but with a very high intensity, thus rendering the application of time-frequency analysis unsuitable for the detection of the frequent shocks.

A graphic representation of this interpretation is made on the sketch of Figure 8. The representation uses a Qs (bedload sediment discharge) vs θ relationship (where θ is the dimensionless shear stress, assuming a critical value θc for initiation of transport as in the formulation of Meyer-Peter & Müller (1948). The Qs vs. θ relationships are sketched for d_{min} and d_{max}, the respective the minimum and maximum grain sizes of the bedmaterial.

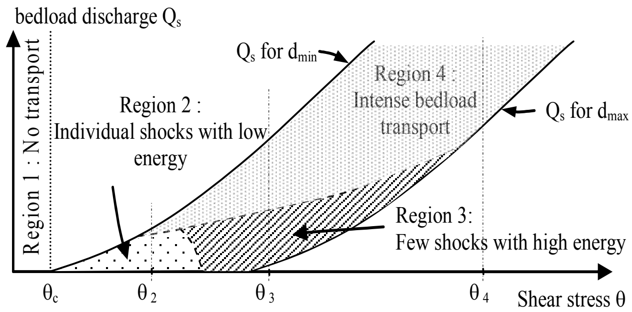

Fig.8 – Different regions for shock detection

Several likely progressive regions can be identified on this sketch:

Region 1: the shear stress is lower than the critical shear for the finest sediment: there is no transport.

Region 2: for shear stress θ_2, only the finest grain-size sedimentary particles are transported. Shock energy is low and the discrimination from other noises is difficult

Region 3: for higher shear stresses θ_3, the coarsest bed material is transported. Corresponding bedload is low but with relative high energy. Corresponding shocks can be discriminated from the surrounding noise by time-frequency analysis.

Region 4 corresponds to the same shear stress θ_3 but considering finest bed material. For higher stresses it could concern the whole range of bed-material. Intense bedload transport and discrimination of individual shocks is not possible by time-frequency analysis.

Region 2 could be identified with Phase I of bedload transport as it was described by Jackson & Beschta (1982). A typical recording was performed at Lancey at a discharge Q=356 m^{3}s^{-1} (Figure 5). The recording was undertaken at the upstream extremity of a transverse riffle bar. It is assumed that, apart from suspended material, only the finest gravel particles were moving on the coarser, armoured cobble bed of the bar [d_{16}=20 mm, d_{50}=35 mm, d_{84}=45 mm]. It is worth noticing that the discharge Q=356 m^{3}s^{-1} is exceeded 20 days a year on average. Such a discharge is significantly below the discharge with 1.5-year return period which has served for a reference discharge by Ryan *et al.* (2002) for assessing the different phases of bedload transport. For shear stress θ_3, regions 3 and 4 can be identified with Phase II intense bedload transport as described by Jackson & Beschta (1982). The recording at Lancey for Q=805 m^{3}s^{-1}, nearly the 10-year return period discharge, can be considered as characteristic of Phase II. Its audition presents at the same time the clear energetic shocks from the coarsest particles and a more confused roll from finer particles in movement above the river bed.

6 ADDITIONAL SPECTRAL ANALYSIS

Due to the relative scarcity of shocks in region 3 (Figure 8), the signal from the recording can be considered *non-stationary*. The time-frequency analysis is adapted for such non-stationary signals. The density of shocks is larger in region 4 and the shock noise makes a stationary signal. Therefore, a basic Fourier analysis on the entire recording is adapted and is more convenient as it allows a better discrimination of the different frequencies because the Heisenberg-Gabor inequality (Flandrin, 1998, Flandrin, 1999) is no more a constraint. The purpose of this section is the discrimination on the power spectral distribution of characteristic shock energies from the surrounding flow noise. In what follows, developments are devised from a limited number of experiments. As a result, they lead to hypotheses rather than to real conclusions.

Flow noise spectrum seems to be a constant for a given cross-section. Two recordings were performed at low and medium discharges at the same cross section of the Isere River. The power spectral density (PSD) of each of these two recordings is plotted in Fig. 9.

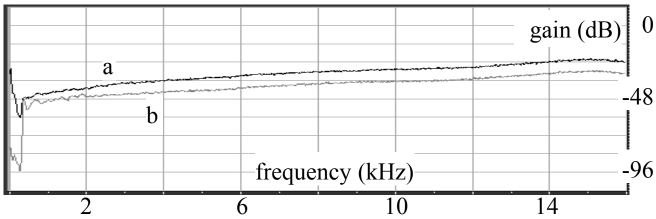

Fig.9 - Power spectral densities from Isère Campus section (a-upper curve) : 355 m^{3}s^{-1}, (b-lower curve) : 217 m^{3}s^{-1}

The two recordings show similar spectral characteristics. The PSD representations are nearly parallel curves, with different energies (dB) but with the same frequency distribution. The higher of the two discharges in shown on the upper curve, representing a higher energy level relative to the lower discharge. At low discharge (curve b), the discharge is so low that the recording is from flow noise alone. For medium discharge (curve a), few audible shocks may be recognized by a trained listener but the bed transport is low and likely derives from fine gravel in Region 2 (see Fig. 8). In either case, the spectral signature is mainly issued from flow noise in this cross-section. Such a signature appears to be characteristic of a given cross-section as recordings made at other sections do not have the same frequency distribution.

A case where bedload noise can be identified from the PSD. Two other PSD representations from a couple of recordings at low and high discharges show the deformation of the curve due to bedload transport (Fig. 10). These were obtained from recordings presented at another cross-section (see Figs. 1-5). The bedmaterial consists of elongated pebbles [d_{16}=20 mm, d_{50}=35 mm, d_{84}=45 mm]. The lower curve plot was obtained with the same recording as in Fig. 5. The discharge (Q=356 m^{3}s^{-1}) is twice the mean annual value and rare bedload shocks of the gravel produce low energy responses. The upper curve plot was obtained in the same section with the recording made during the decennial flood discharge (Q=805 m^{3}s^{-1}). The spectral distribution of energy is similar for frequencies in the range 5000 Hz < ν < 15000 Hz (the comparison is limited because the gain of the DAT recorder was not controlled during the recording and the relative position of curves in the vertical direction is uncontrolled). The damping of high frequencies during the flood may be related to high suspended sediment concentrations in such flood conditions. For frequencies ν < 5000 Hz, important bedload transport of the coarsest bed material in flood conditions produces a noticeable increase in energy, visible in Fig.10 by a higher spectral energy on curve (a). Filtering of the signal and elimination of high frequencies in noise recording makes a clearer audition of shocks.

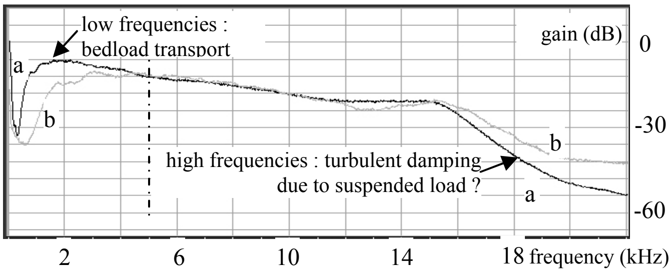

Fig.10 - Power spectral densities from Isère Lancey section at (a) 805 m^3s^{-1} and (b) 356 m^3s^{-1} .On (a) the deformation of PSD for low frequencies is due to bed-load transport. As the gain is uncontrolled, the relative position of the curves cannot be compared.

In the case of this recording, it can be estimated from the comparison with the PSD representation obtained for the smaller discharge (curve b) that the coarsest moving particles produce energy at about 800 Hz. Because the conditions in the river differ from those in the 'basin experiment', the grain size/frequency relationship presented in Fig. 7 cannot be used to determine the characteristic diameter of the coarsest particles on movement based on signal frequency. When available, this determination of the grain size distribution of bedload using acoustic techniques will be helpful to geomorphologists and engineers in their analysis of the behaviour of gravel beds during floods.

Spectral analysis was also performed on many other recordings. Among them, in many instances shear conditions were likely (schematized) like those of region 2 (Fig. 8), and listening by ear gives no doubt about the occurrence of bedload. Nevertheless, shock energy generated by small particles is low and the number of recorded shocks is insufficient to modify the power spectral distribution which is mainly constructed of noise generated by the moving water (e.g. in Fig. 9).

7 CONCLUSIONS AND PERSPECTIVES

The objective of the paper has been evaluation of the potential of passive sound recording in determining critical conditions for the initiation of bedload transport for different size fractions of the bed material. Different techniques were used for analyzing the signal obtained by *in situ* hydrophone recording of the sound of flow and coarse grain transport.

Calculation of instant power improved our listening-alone ability to identify shocks with high energy. Improved precision was further obtained with time-frequency spectral analysis which allows quantification of shocks generated by intense bedload transport. However, the method is unsuitable where the shock energy is too low or when the shocks are too numerous. Spectral analysis may give a good qualitative estimation of the presence of bedload transport of the coarsest particles within bed-material. Each of these methods may deliver its part of information about the bedload from hydrophone recordings. Further refinements of the methods are needed in determining the flux of bedload from spectral analysis.

Future efforts in this area include:

(i) Additional data collection. The exploration and hypotheses presented in this paper are derived from a small number of recordings and were seldom confirmed by repetitive experiments. The priority is collection of a range of recordings in controlled conditions.

Bedload transport shocks can be detected, but there is no possibility to determine whether they take place a few centimetres from the hydrophone or in a larger zone. This certainly depends on the one hand on flow conditions and intensity of the turbulence and on the other hand on the sensitivity of the recording system. In mountain streams, whirls, cascades and hydraulic jumps produce very noisy environments and bedload movement is sometimes difficult to detect even with a trained ear. In milder conditions the surrounding noise is less important and the hydrophone used in these experiments has proved to be highly sensitive (e.g. by detection of oars of passing rowing boats more than 50 m away or even the noise of a passing truck on a nearby bridge).

In most of the recordings, the hydrophone was hung in a vertical position by its connecting cable. A more stable and controlled position is performed in present recordings (Fig. 1) but it has not been investigated whether it is a better configuration in terms of sensitivity. The support rod certainly induces significant additional flow noise at frequencies different from those of bedload, but which must be minimized nevertheless. The necessity of additional devices for improving the directivity of noise detection should also be tested, preferably under controlled conditions in a flume.

(ii) Refine methods. The authors do not claim to be specialists in signal analysis. The investigations which have been performed are basic and would benefit from additional assessment by those further trained with this method. It is hoped that the investigations have demonstrated the potential of the method. We have identified several limitations and questions which suggest that further refining of the method is needed:

Can an efficient filtering eliminate other perturbing noises, or at least improve bedload transport detection?

Optimization of time-frequency analysis is needed for a better discrimination of frequencies, and to allow counting in the case of intense transport.

Quantification of signal energy: (i) improvement of methods for counting; (ii) could it be related to bedload energy and the velocity of particles, as suggested by Taniguchi *et al.* (1992) ?

Following an idea from Bradeau (1951), location of shocks by correlation of simultaneous recordings of shocks with several hydrophones.

(iii) Assess sound properties with direct measurement of bedload. Systematic measurements of bedmaterial properties and velocity will be performed for the next experiments for the assessment of shear conditions in relation to signal properties. A simple installation is shown in Fig. 1c with an electromagnetic flow sensor associated with the hydrophone on the support rod. Ryan et al. (2005) mentioned the difficulty as *"to make progress toward development and validation of surrogate technologies until there is a way to adequately quantify the rates of bedload transport"*. Despite limitations and sometimes low confidence in some of the classical methods, field comparisons are necessary with direct measurement of the bedload such as physical samplers or particle tracking.

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