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Original Research

Listen to the sound of moving sediment in a small gravel-bed river

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ABSTRACT

In order to assess the dynamics of rivers, a reliable characterization of bedload transport particularly during unsteady flow regimes is required. In contrast to highly energetic cases in hillslope areas, we aim to answer the question whether the usage of acoustic measurements can improve the characterization of bedload in small rivers draining low land mountains with comparatively low water discharge and bedload. In addition to the investigation of natural flood events, controlled floods were generated by releasing water from a reservoir into a small gravel-bed stream. The controlled releases allow for an evaluation of bedload solely from channel storage or bank erosion. For acoustical in-situ characterization of bedload transport, hydrophones were mounted onto the bottom side of steel plates, thus recording the impacts of sediments via the acoustic vibrations on the surface of the plates while at the same time minimizing the disturbing noise resulting from water turbulence. Corresponding bedload traps are removable boxes with open lids fixed in the riverbed so that bedload material registered by the hydrophone is trapped. The acoustic signals correlate well with the quantity of the transported material. During summer flood events the highest transport rates occur at the beginning of the rising limb featuring clockwise hysteresis. This is due to the rising transport energy of the flow and the presence of loose, unconsolidated material. During typical winter flood events bedload shows anticlockwise loops. The intensification of bedload conveyance after the runoff peak can be explained by a decreasing stability of the bed material from the beginning to the end of a transport event. Anticlockwise behavior also results from a combination of bedload exhaustion in the vicinity of the monitoring station with a delayed arrival of new material from distal sources later in the hydrograph.

1. Introduction

The transport and deposition of bedload leads to the aggradation of catchment areas of running waters or drinking water reservoir sedimentation. Material accumulations and damages to weirs or sluices are well-documented (Badoux et al., 2014; Ergenzinger & Schmidt, 1993). The understanding of the very short term variations in bedload flux as an inherent characteristic in sediment movement is relevant for practical approaches that depend on knowledge and monitoring of bedload. Frey and Church (2009) indicate that available theories often over predict the actual rate of bedload movement, making the impact prediction of natural flood events difficult. A more detailed process understanding on temporal bedload dynamics during unsteady flow would additionally enhance the scrutiny (as well as the reliability) of existing bedload formulae in order to continuously improve the planning, designing and managing of canals and rivers in future. Recording slot sampler document bedload flux continuously with relatively high temporal resolution (10–60 s) when fluxes are elevated, or lesser resolution (10–60 min) when they are low (Habersack & Laronne, 2001). Currently, bedload measuring devices have incomplete possibilities for an investigation of mass

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transport with a resolution shorter than ten seconds. Moreover, during flood events turbidity is often high and consequently high resolution optical systems are not well appropriate to investigate bedload transport (Gray et al., 2010).

As an alternative technique, this study focuses on the application of a hydroacoustic measurement system in order to describe bedload transfer rates in small mid-mountain rivers. The expected scaling relationships would be of high interest in terms of monitoring capabilities, since it would in principal allow for the characterization and quantification of bedload transport in near-real time from acoustic data. The prime research question that we wish to answer is which information can be derived from hydro-acoustics on short-term bedload transport during both controlled reservoir releases and natural flood events in a small, mid-mountain gravel-bed river. Recent studies in this study area highlight the general importance of sediment and bedload transport (Barrière et al., 2015a; Gallé et al., 2004; Krein et al., 2008; Martinez-Carreras et al., 2010a, 2010b, 2010c; Onderka et al., 2012; Petticrew et al., 2007).

2. State of the art

Monitoring of bedload movement with hydrophones, piezoelectric sensors, geophones (ground vibrations), stage sensors used for debris flow velocity and acoustic pipes was demonstrated by Bänziger and Burch (1990), Belleudy et al. (2010), Burtin et al. (2008), Krein et al. (2008) or Mizuyama et al. (2010a). Different devices and methods of monitoring debris-flow (e.g. endwise vertical measurements in the river banks) or bedload transport (e.g. horizontal pipe system, impaction plates for different scales or river cross sections) have been described (e.g. Arattano & Marchi, 2008; Itakura et al., 2005; Rickenmann et al., 2013), and mostly case studies with ground vibration sensors or methods to measure the velocity of debris-flow with image processing techniques are considered. The application of piezoelectric sensors for the characterization of bedload transport was primarily tested in alpine torrents (Hegg & Rickenmann, 1998). The main focus of these investigations relies on the registration of impulses produced by bedload particles upon contact with metal plates. The same applies to the studies of Richards and Milne (1979) or Rickenmann (1994), who investigated the bedload conveyance in mobile riverbeds. An impulse is detected when the generated acoustic signal exceeds some pre-defined amplitude threshold, and the counted number of impulses provides a representation over time of bedload transport. A considerable disadvantage of this impulse counting system is that its sensitivity depends on the predefined threshold value. Additionally, only coarse gravel material can be detected. Main outcomes of these studies are that the beginning and ending times of transport can be determined acoustically and that bedload movement can only be measured when a certain critical shear stress is exceeded. Further studies in various catchments around the world came to similar conclusions (e.g., Bogen & Moen, 2003; Downing et al., 2003; Froehlich, 2003; Mizuyama et al., 2003; Richardson et al., 2003). Turowski and Rickenmann (2009) report on bedload data and acoustic impulse measurements from the Pitzbach in Austria. In another paper, Turowski and Rickenmann (2011) analyze the relationships between bedload movement rates, water discharge and sensor response. They outline that an indirect measurement of bedload transport solely with sensors as a proxy for bedload transport - such as for instance a piezoelectric sensor measuring acoustic signals - is in most cases unsuitable to develop a rating curve of bedload transport rates. Nevertheless, reliable sensors such as the Swiss plate geophone can be used to estimate sediment yields of individual events, although the main part of these experiments focusing on torrent channels in mountain environments (Rickenmann & McArdell, 2007; Rickenmann et al., 2012). The same research team concluded that such a bedload impact sensor results are in agreement with bedload volumes estimated using the survey of material stored in corresponding retention basins or captured with bedload basket traps (Rickenmann et al., 2014). Recently, Turowski et al. (2013) made a first attempt of evaluating the energy delivered to the streambed by moving bedload using the plate system. The detection of bedload movements in laboratory flume experiments with a plate geophone set-up similar to that used in the present study has been demonstrated by Krein et al. (2008). They distinguished homogeneous masses of different grain sizes, for which movement of material down to the fine-sand fraction can be detected. The Japanese pipe hydrophone has been shown to register the transport of granules (8 mm) and likely down to sand particles (1–2 mm) (Mizuyama et al., 2010a, 2010b). Belleudy et al. (2010) applied a passive hydrophone monitoring approach in the French Alps, placing a hydrophone near the riverbed to record surrounding noise resulting from water flow and bedload transport. They concluded that the method is unsuitable when the sound energy produced by the bedload on the riverbed is too low or the impacts are too numerous. Slot samplers are useful for research purposes- amongst others to calibrate acoustic bedload sensors- as they are too expensive and laborious for standard bedload monitoring (Gray et al., 2010). Laronne et al. (2003) presented detailed advantages and limitations of different monitoring devices for bedload flux. Within this context, the general relationship between suspended solid concentrations and/or bedload with the river discharge during storm events has been studied intensively in hydrology. Most studies on such hysteresis effects describe clockwise or positive hysteresis loops (Asselman, 1999; Krein & De Sutter, 2001; Mao, 2012; Mao et al., 2014; Oeurng et al., 2011; Solo-Gabriele & Perkins, 1997).

3. Material and methods

3.1. Area of investigation

The area of the Olewiger brook basin near the city of Trier (Germany) is about 24 km^2 (Fig. 1a and b). Devonian shales with quartz and diabase veins dominate the basin geology of the Northern Hunsrück Mountains. The river cross sections are mainly rectangular shaped with relatively large width/depth ratios (3 m/0.5 m at measurement site), and vertical river banks in argillaceous material. The channel slope of the investigated river reach is about 1.5%. A picture of the measurement site and the position of the hydrophone can be taken from Barrière et al. (2015a); additional illustrations of the measurement equipment are highlighted by Krein et al. (2014). The gravel-bed Olewiger brook exhibits well defined sequences of riffles and pools along its longitudinal profile. At the riffle with the measurement system surface river bed substrate is characterized by a D_{50} of 8.7 ± 3.9 mm and a D_{90} of 32.9 ± 9.6 mm. We sampled the upper 10 cm of the river bed at 15 locations with a shovel (Bunte & Abt, 2001). For the sieving of the collected bedload material and river bed material a vibratory sieve shaker AS 450 (RETSCH) is used. Further information about stream bed morphology and sediment characteristics are detailed elsewhere (De Sutter et al., 2000; Krein & Schorer, 2000; Petticrew et al., 2007).

3.2. Measurement equipment

The hydrophone is mounted onto the bottom side of a stainless steel plate (50 cm × 50 cm). The contact plate with the hydrophone has been installed in the riverbed so that its upper surface is adjusted to the level of the sediment surface. The hydrophone fixed onto the bottom of the plate is located in a cavity below the plate and is thus not in contact with the river bed. The hydrophone and plate are acoustically isolated from the subjacent fixing by rubber vibration cushions. The hydrophone is designed in such a

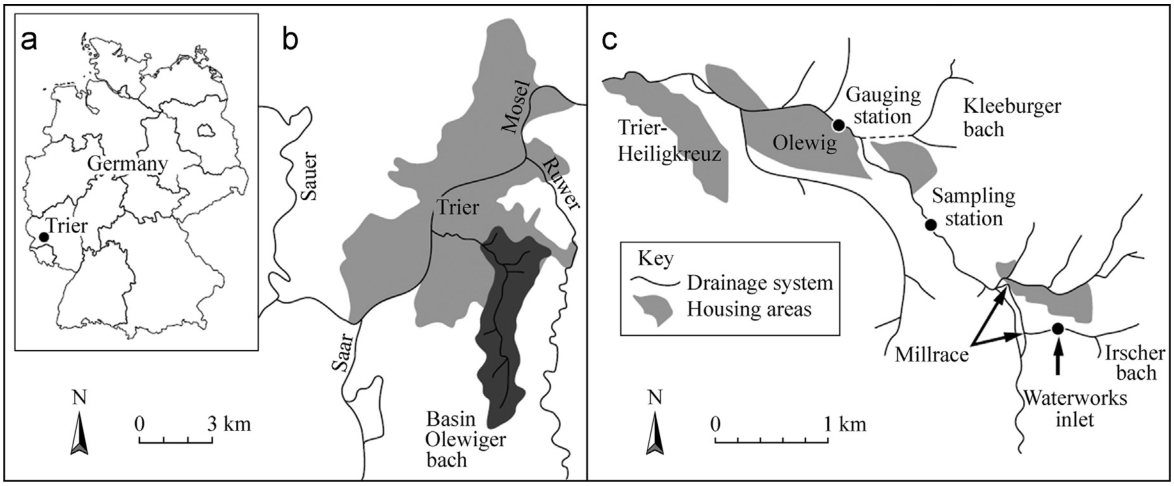

Fig. 1. Maps of the field site locations in the Olewiger Bach basin in the region of Trier, Germany. (a) Location of the investigation site within Germany, near the city of Trier. (b) Regional setting of the Olewiger Bach basin. (c) Zoom on the details of the basin. Note that the location of the waterworks inlet and the sampling location, co-located with the hydroacoustic observation site, are separated by 2 km of channel traversed by the release flow.

way that it only records the mechanical friction on the surface of the metal plate below which it is fixed by screws. The remaining signals of the flowing water are located in higher frequencies than the bedload transport. They are beyond the 20 kHz of the hydrophone and are therefore not registered at all. The benefit of this setup lies in the fact that acoustic noise resulting from the water turbulence in the river is efficiently excluded.

The ITC-4001 hydrophone system is a flexural disc transducer mounted in a robust housing. It records acoustic signals in the sonic frequency range (kilohertz) with high signal-to-noise ratio and shows a recording range between 1 Hz and 20 kHz with a stable, linear frequency response. The signals are recorded by means of a data recorder (Zoom H-4N portable wave-recorder). Start and stop trigger signals are controlled by a level sensor with magnetic float submerged in water (MEDER ELECTRONIC, LS03 series). When the magnetic float registers a rising water level by closing the contact, the recording procedure is started as soon as a pre-defined threshold level is reached and constantly exceeded. Audio data files are stored on 32 GB SD-Cards; fifty hours storage time is possible. Similar to a previous study (Krein et al., 2008), the raw data are stored in the usual wave-format. For our investigations, we selected a sampling rate of 44.1 kHz with a depth of 16 bits.

Bedload traps consist of a box with an open lid (50 cm × 30 cm) fixed permanently into the riverbed. Directly after registration by the piezoelectric plate system, bedload sediment falls through a slotted plate covering a plastic box set within a formed iron-barred box in the stream bed. After sieving, the material fractions are weighed and set in a correlation with the corresponding sound and seismic signals, as the measure of the mass of transported sediment.

3.3. *Artificial flood experiments*

Artificial flood events are used to investigate bedload transport by the replication of similar type runoff experiments during different seasons. These experiments take place in the Northern part of the catchment (Fig. 1c). A drinking water reservoir in the neighboring Ruwer catchment serves as the source of the discharged water. The municipal waterworks regulate the discharge through releases from this reservoir. Artificial floodwater is fed directly into the Irscher brook, a tributary of the Olewiger brook (Fig. 1c). Outstanding advantages of this approach are that the reservoir water can be released at a known discharge to produce a well-defined flood wave in the downstream area of the study basin and that the introduced water shows very low suspended sediment concentrations (<2 mg l^{-1}) (De Sutter et al., 2001; Krein & De Sutter, 2001; Kurtenbach & Krein, 2007). Additionally, these controlled releases permit the installation of equipment for monitoring conditions before, during and after the generation of the simulated flood waves. To simulate typical convective summer events – characterized by steep gradients and relatively short falling limbs in our study area – artificial floods with rectangular shapes were initiated. During the field experiments, discharge, water level and turbidity dynamics were determined via pre-existing stage discharge relationships, Ultrasonic Doppler velocity and water depth meters (Unidata Starflow systems) as well as YSI 600 OMS multiparameter sondes.

Fig. 2 illustrates the amount of water from the waterworks discharge unit and the corresponding water level variations 2 km downstream exemplified for the experiment on April 30th 2013. The first wave with a duration of 30 min and 140 l s^{-1} maximum introduced discharge is divided by a break of 1.5 h from a second event of 30 min with a maximum introduced discharge of 280 l s^{-1}.

4. Results on hydroacoustic signal total power

Fig. 3 illustrates the power spectral densities (PSD, in dB/Hz) of the hydroacoustic data during the second, artificially generated flood event of April 30th 2013. A time-frequency representation is useful to gauge the noise baseline of the hydroacoustic recording. The piezoelectric hydrophone acts as a sediment vibration sensor, detecting each single impact on the steel plate. A wide frequency range covering the sonic frequency band from 0.1 to 10 kHz characterizes the bedload transport signature starting on the rising limb. The most powerful frequencies are located around 1 kHz. The background noise due to water turbulence (first thousand seconds) is characterized by a much lower power level, which shows that the system is able to provide a high signal-to-noise ratio acoustic representation of bedload material transported over the steel plate.

4.1. *Scaling with bedload quantities*

In order to investigate whether a relationship exists between the material and the signal amplitude, gravel-stones that produce

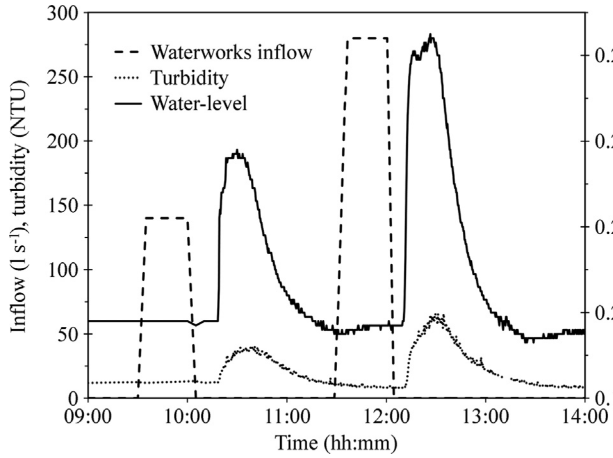

Fig. 2. Two artificial flood events on April 30th 2013 – waterworks discharge unit effluence and corresponding flood event with turbidity 2 km downstream of the waterworks.

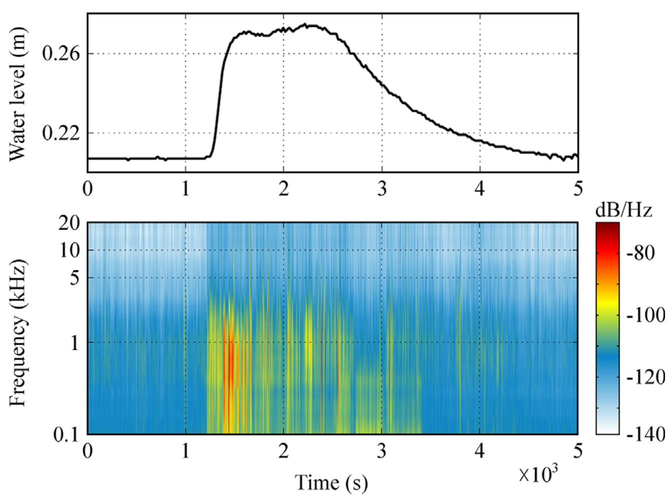

Fig. 3. Second artificial flood event of the April 30th 2013 experiment – Hydro-acoustic time-frequency map (PSD) of the second event. The first thousand seconds represent baseflow conditions. The time window used for PSD calculations is approximately 12 s (2^{19} samples) with 75% window overlap, using a rectangular window function tapered by a 10% cosine function.

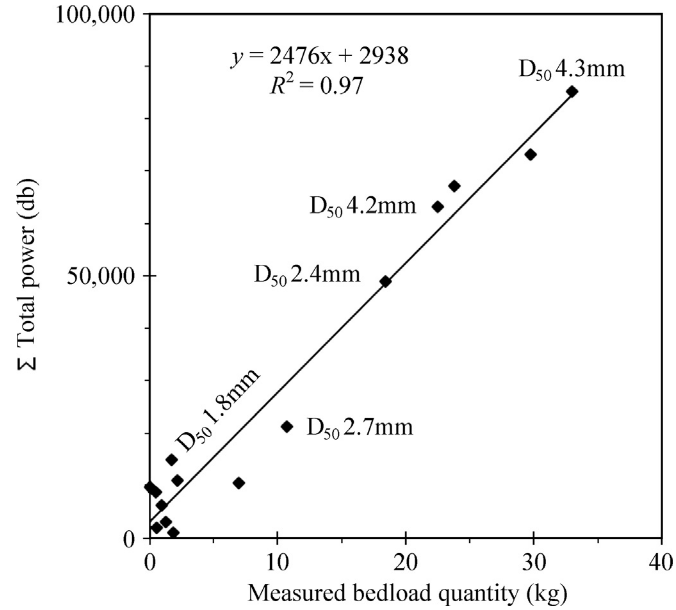

Fig. 4. Correlation of total power (dB) with bedload of single flood events.

noises are taken from the sampler. Their sizes, shapes, and weights are determined in the laboratory. The bedload sampler traps material that is moved across the plate. The total power of the hydro-acoustic signals, expressed in dB, is strongly correlated with the amount of trapped material (Fig. 4).

We can show that these signals scale well with the quantity of the transported material. The D_{50} of the bedload material is between 1.8 mm and 4.3 mm, increasing with the quantity of the trapped material. Bedload is finer than the average D_{50} of Olewiger brook river bottom material (8.7 mm) indicating selective erosion of smaller particles from the local riffle or from the upstream pool. As noticed by Krein et al. (2008) with similar equipment, the signal amplitude does not only depend on the mass and size of the transported material but is also strongly affected by the shape and the motion (sliding, rolling, saltation) of the stones. Hence, for similar D50 and quantities, the variability of the total power value could be significant depending on hydrodynamic conditions. In Fig. 4 we can observe that this variability is predominant for low bedload quantities and small D50. Indeed, when the bedload quantity in the trap is lower than 2.5 kg, corresponding to low D_{50} (< 2 mm), we realize a high uncertainty in the correlation while above this minimum bedload mass and D_{50} the total power is well correlated with the total mass. The authors noticed that this relationship is not well constrained in this low transport periods, with a large scattering of the dataset and the need of some amplitude correction. The approach appears to be not sensitive enough to smaller particles (lower than 1.5 mm) that play an important role under these conditions. Using the Swiss plate geophone, Rickenmann et al. (2012) observe similar outliers in a calibration relationship between number of impulses and bedload mass. The acoustic signature of the bedload transport being highly complex due to the numerous factors influencing it, such uncertainty is inherent to this kind of passive and local measurements. This calibration relationship is useful to estimate the total bedload mass after one single flood event but cannot be used to describe the temporal variation of bedload transport.

4.2. Evidence of hysteresis behavior between rising and falling limbs

Fig. 5 shows the time-series of total power, here expressed in dBFS (Decibels relative to full scale), during two artificial flood events. It is important to note that such total power values cannot be transformed into bedload mass using the previous relationship (Fig. 4). Indeed, this calibration is only applicable for the total power level integrated over the entire flood event and is not consistent with instantaneous (minutes range) values of acoustic power corresponding to very few material transported. However, it seems relevant to assume that high power level should correspond to a stronger bedload transport, as done for instance by Mao et al. (2014) who relate the number of impulses recorded on a pipe with the amount of bedload transport.

Hence, the corresponding time series exhibit variable bedload reactions with higher transport in the rising limb of the hydrographs than in the falling limb for the same flow rate. The corresponding hystereses are clockwise. This is due to the rising transport energy of the flow and the pre-event presence of loose, unconsolidated material. According to Mao (2012) a possible bed restructuring (lower vertical roughness, clast rearrangement) could exist during the rapidly falling limb of hydrographs. Consequently, a better sorting of the material of the bed surface are likely the cause of the reduced mobility of sediments, and thus of the reduced sediment transport rate during the falling limb of the hydrographs. The investigation of bedload-generated seismic signals at the Cho-Sui River in Taiwan

(Hsu et al., 2011) additionally reveals that the relationship between seismic amplitudes and water level demonstrates clockwise hysteresis when significant bedload transport occurs. This may be caused by material depletion or early sediment supply from a tributary in a downstream point.

The investigation of natural flood events in the Olewiger brook provides indications that long-lasting spring precipitations of low intensity cause a singular broad discharge maximum typical of advective events (Fig. 6a). During these so-called winter flood events, the bedload transport primarily shows anticlockwise hysteresis. The intensification of bedload conveyance in the aftermath of the discharge peak can be explained by differences in the stability of the bed material at the beginning (higher stability) and at the end of a transport event (looser packing) (Kuhnle, 1992). The counter clockwise hysteresis also occurs when bedload from an upstream storage site works its way to the sampling location later in the hydrograph (Moog & Whiting, 1998).

In the summer season, multi-peaked flood waves – traceable back to the chronological sequence hydraulically connected, contributing source areas – are characteristic to the catchment area. These flood waves are characterized by a steep gradient and a relatively short falling limb (Fig. 6b). During such summer flood events, the highest transport rates occur at the beginning of the rising limb, most likely due to the rising transport power of the flow and the presence of loose, unconsolidated material, leading to clockwise hysteresis.

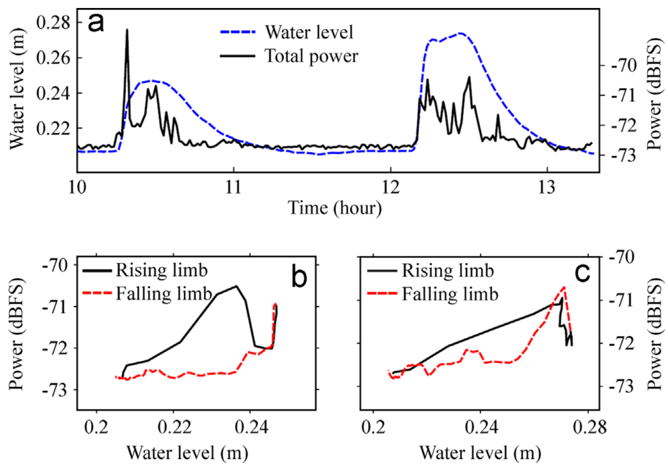

Fig. 5. Water level and hydroacoustic total power (dBFS) for two artificial flood events on April 30th 2013. b) and c) Clockwise hysteresis of total power for the first and second flow wave respectively. Average power calculation was performed on one-minute time intervals corresponding to the water level registration time. The dBFS (Decibel relative to full scale) corresponds to a relative level unit of the recorded signal digitized to 16-bits (32,768 values), 0 dBFS corresponds to the maximum while −90.3 dBFS is the noise floor (minimum value) for a 16-bit sample.

5. Discussion

In the framework of specific impacts on plate/pipe systems, Rickenmann and McArdell (2007) and Rickenmann et al. (2012) conclude that piezoelectric bedload sensor results are in agreement with bedload volumes estimated using the survey of material stored in corresponding retention basins or captured with bedload basket traps. The main part of these experiments is focused on torrent channels in mountain environments. Our results confirm that these relationships can also be found in small rivers of the low mountain range where only some kilograms of bedload are transported during small flood events. The lack of the present approach is to provide a unique quantitative information for the entire flood event and do not exploit the high temporal resolution of such measurements system.

Qualitative analysis of the temporal variations of bedload transport can be performed by calculating the instantaneous total power on short time intervals (minutes range). While during summer floods the highest transport rates occur at the beginning of the rising limb, the bedload transport shows anticlockwise hysteresis during winter floods. The intensification of transport after the runoff peak can be explained by a higher stability of the bed material at the beginning of a winter erosion event and a looser packing in the falling limb featuring a corresponding break-up of an armoured layer. This counter clockwise hysteresis could

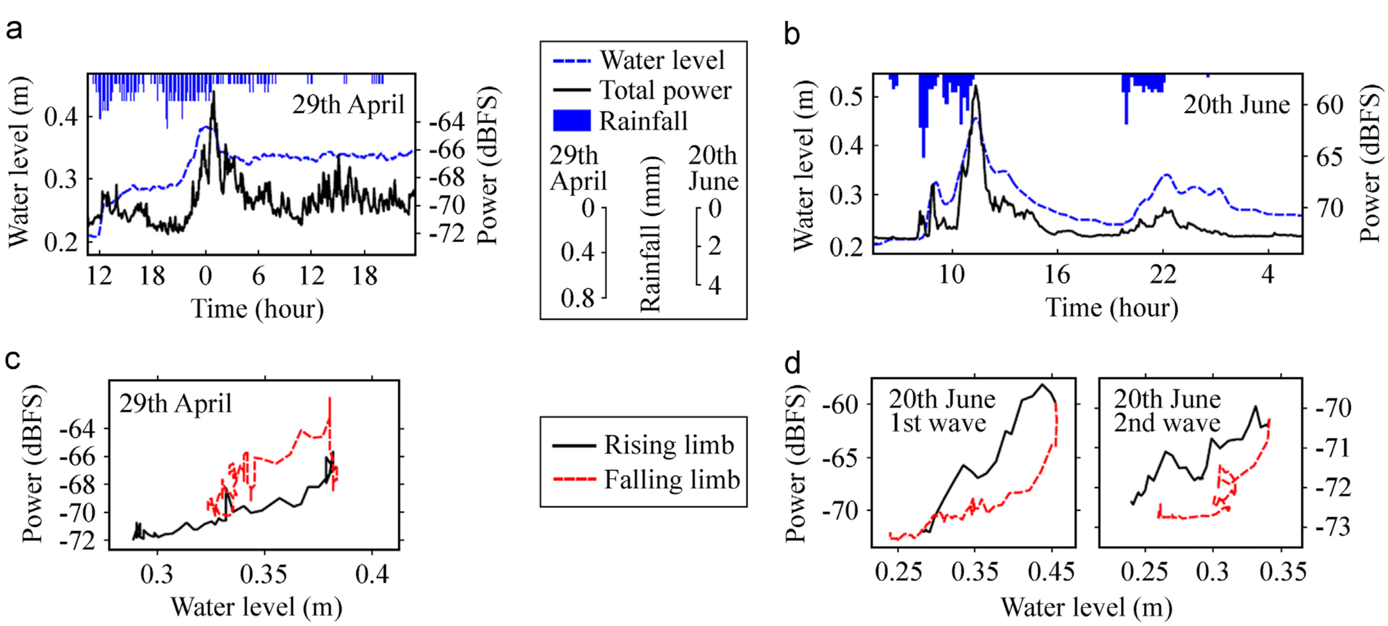

Fig. 6. Water level, rainfall and hydroacoustic total power (dBFS) for (a) A typical advective rainfall event (April 29th 2013) and (b) Two characteristic convective rainfall runoff events (June 20th 2013). (c) and (d) Hysteresis of total power for the advective and convective events respectively. Average power calculation was performed on five minutes time intervals corresponding to the water level registration time.

also be detected when bedload in the vicinity of the monitoring station is exhausted and new material from more distal sources – for instance from an upstream part of the riffle or an upstream pool – reaches the monitoring station later in the hydrograph.

Krein et al. (2008) conclude that the shape of the grains is decisive for the motion of the stones and thus also for the interaction with the contact plate. Stones with equally long axes, i.e. compact ones, have the lowest variability in the patterns of their motion and also in the signal patterns they produce. Flat stones, however, offer variable options to the attacking forces and may pass over the contact plate in very different modes, generating changing sound patterns. From the analysis of the sound patterns and from visual observations, three different forms of bedload motion could be identified: saltation, rolling and sliding. The modes of moving across the plate are related to the shape of the stones. Identical structures of the signal pattern of the bedload movement were identified that can be explained by the kinetics of flood waves.

According to Wyss et al. (2013) the signals registered by the Swiss plate geophone contain information about the transported grain size, for example by relating the maximum amplitude of the signal over a certain time interval during a calibration measurement with collected material to the maximum b-axis of the transported particles. Barrière et al. (2015a) analyzed the waveform frequency and amplitude attributes of the first signal arrival, which is directly proportional to the force and the contact time that the bedload imposes on the plate. Frequency and amplitude are key parameters, since they are related to the grain size/mass distribution of transported bedload sediments (high frequency/low amplitude correspond to small grain size and vice versa). Recorded signals after impacts exhibit complex waveforms due to boundary reflections. To identify and characterize the first arrival, they use a high-dimensional signal decomposition method based on the chirplet transform in order to obtain a laboratory-derived relationship between impact signal properties and transported grain size using flume experiments.

Other techniques based on seismological measurements, where seismometers are installed in the vicinity of the river systems, highlighted similar hysteresis patterns. Govi et al. (1993) performed in a case study in the Italian Alps a field experiment with a continuous recording of bedload transport rates in a coarse alluvial channel, using high sensitivity seismic detectors. The corresponding mechanisms of bedload transport were inferred from single micro seismic impulse peaks occurring before and after the discharge peak. Hsu et al. (2011) conclude that the observed clockwise hysteresis of the seismic signal intensity during flood events of the Cho-Shui River in central Taiwan can be explained by the disturbance of bed armor during the rising limbs of storm events and subsequent reformation during the waning stages. Burtin et al. (2008) describe that bedload transport by larger rivers is an important contributor to their seismic noise. They observed a wide range of frequencies indicating that the frequency content of the river's seismic noise can potentially help to characterize the nature of the bedload and its type of. As independent measurements of bedload were not available in their studies they could not conduct the relevant analysis. Burtin et al. (2010) associate the river seismic sources to the impacts of sediment particles on the channel bed. The distributions of the signals are in good agreement with incision rates along the trans-Himalayan Trisuli River. For a short test of this technique we installed one broadband seismometer close to the river (Olewiger Bach, Trier, Germany) for the artificial flood event of April 30th 2013. The drawback of this site is that it is located at the edge of an urban area, with a busy road near-by. As a result, the hydroacoustic signals are well registered during the artificial flood event, whereas the seismic signal is overlapped by strong transient interferences generated by anthropogenic noise. However, Barrière et al. (2015b) recently showed the potential of monitoring seismically a similar low-altitude rural stream by successfully extracting the seismic signature of the sediments motion during a flood event within an environment disturbed by constant human activities.

6. Conclusions and outlook

The potential advantages of acoustical bedload investigation techniques are the possibility to assess bedload transport during high turbidity, a high temporal resolution in real time, the observation under undisturbed conditions, and a chance to measure materials down to the sand fraction. We herewith present a quantitative calibration between total power and total mass useful to estimate the total amount of transported material as well as an analysis of the hysteresis behavior of bedload transport with high temporal resolution. In order to explain the different sediment transport and bedload reactions during similar flood events, it is of crucial importance to assess the antecedent hydrological conditions (e.g. Kurtenbach & Krein, 2007). Series of flood events show that bedload transport is supply-limited and not transport limited. Riffle and pool-sequences are sources and sinks for the material. There are two hypotheses on how the length of the antecedent dry weather period determines the transported bedload quantities. The longer such a dry weather period lasts, the higher will be the accumulation of material because there is only very limited depletion of bedload material by flood events before the experiment. In addition, consolidation of material during such periods without floods could lead to armoured riverbeds. In contrast, the presence of antecedent storms could lead to a lack of overall bed stability, which can be thought to enhance the process of sediment movement. More flood events need to be investigated in order to get clearer insights into the question regarding the importance of variable hydrological conditions.

Recent investigations of hydroacoustic signals focus not only on the mass of transported material but also on the size of single particles (Rickenmann et al., 2014). Barrière et al. (2015a) show time-series of this kind together with corresponding uncertainties. They used an advanced signal processing technique – the chirplet atomic decomposition – to improve the characterization of bedload transport by analyzing in detail the frequency/amplitude attribute pairs of each single grain impact. Moreover, in this study the instantaneous median grain diameter D50 has been estimated from impact amplitude and frequency characteristics using a laboratory-derived calibration curve for D50 higher than 1 mm. The impact-plate set-up thus provides localized information on the order of magnitude of transport rates and the grain size distribution of bedload material moving over the plate.

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