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Bedload transport measurements at the Erlenbach stream with geophones and automated basket samplers

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ABSTRACT: In the Erlenbach stream, a pre-alpine steep channel in Switzerland, sediment transport has been monitored for more than 25 years. Near the confluence with the main valley river, stream flow is monitored and sediment is collected in a retention basin with a capacity of about 2000 m^3. The basin is surveyed at regular intervals and after large flood events. In addition, sediment transport has been continuously monitored with piezoelectric bedload impact and geophone sensors since 1986. In 2008–2009, the measuring system in the Erlenbach stream was enhanced by installing an automatic system to obtain bedload samples. Movable metal baskets are mounted on a rail at the downstream wall of the large check dam above the retention basin, and they can be moved automatically into the flow to take bedload transport samples. The wire mesh of the baskets has a spacing of 10 mm to sample all sediment particles coarser than this size (which is about the limiting grain size detected by the geophones). The upgraded measuring system permits to obtain bedload samples over short sampling periods and to measure the grain size distribution of the transported material and its variation over time and with discharge. The analysis of calibration relationships for the geophone measuring system confirms findings from very similar measurements which were performed until 1999 with piezoelectric bedload impact sensors; there is a linear relationship between impulse counts and bedload mass passing over the sensors. Findings from flume experiments are used to discuss the most important factors which affect the calibration of the geophone signal. The bedload transport rates as measured by the moving baskets are among the highest measured in natural streams, with values of the order of several kilograms per meter per second. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS: bedload transport; geophone sensor; indirect measurement; calibration; steep stream; mountain stream

Introduction

The rate and timing of bedload transport is a central question in many applications in river science and engineering, yet it remains difficult to predict. In contrast to lowland gravel-bed rivers, relatively few studies have been undertaken on sediment transport in steep headwater channels, with stream gradients higher than about 5%. Flow behavior and sediment transport dynamics in these channels may be quite different from low-gradient channels (Hassan *et al.*, 2005). Steep mountain streams often experience a strong interaction between hillslope processes and the channel network, and sediment transport may be supply-limited rather than transport-limited. In addition, steep headwater streams are characterized by a wide range of sediment sizes, temporally- and spatially-variable sediment sources, and rough and structured beds with alternating sequences of steeper and flatter slopes, commonly known as steps and pools (Church and Zimmermann, 2007; Comiti and Mao, 2012). Bed morphology and channel structures may be influenced by the presence of large boulders, woody debris and bedrock constrictions. This results in large variations of channel geometry, stream flow velocity and bed roughness; the application of theoretical or laboratory-derived sediment transport equations is, therefore, problematic (Gomi and Sidle, 2003).

Many bedload transport formulas for gravel-bed rivers were developed or calibrated using data from experiments in laboratory flumes. Measured transport rates in natural streams can differ substantially from values predicted with such formulae (e.g. Bathurst, 1987; Gomez and Church, 1989; Rickenmann, 2001; Barry *et al.*, 2004). Many of the characteristics of steep streams cannot be completely reproduced in the laboratory, such as large-scale roughness and a broad sediment size distribution. Quantitative measurements of bedload transport in steep streams are rare, and often episodical (Rickenmann, 2001; Barry *et al.*, 2004; Bunte *et al.*, 2004; King *et al.*, 2004; Ryan *et al.*, 2005; Mao and Lenzi, 2007; Bunte *et al.*, 2008; Ryan and Dixon, 2008; Imaizumi *et al.*, 2009; Rickenmann and Koschni, 2010), because such measurements are laborious, expensive, and technically challenging. Overall, the necessary data to test, calibrate and validate laboratory-derived equations for natural streams is not available.

Sediment transport measurements in natural streams may be grouped into the following methods (e.g. Bathurst, 1987; DVWK, 1992; Bogen *et al.*, 2003; Ergenzinger and de Jong, 2003): (i) trapping sediment in a retention basin; (ii) morphologic method, i.e.

assessing sediment volume changes along river reaches, including measuring river delta growth; (iii) assessing the movement of (coarser) tracer particles together with estimating the active layer depth (e.g. by using scour chains); (iv) collecting moving particles; (v) indirectly determining transport intensity. Method (i) is typically limited to small streams where a retention basin is available and provides only a rough evaluation of transport rates. However, settling basins built for hydroelectric power production and equipped with weighing cells can provide more useful sediment transport data with a higher time resolution (e.g. Turowski and Rickenmann, 2009; Turowski, 2010). Method (iii) is particularly helpful for determining travel times (speed) and rest times of individual particles. The main disadvantage of methods (iii) and (iv) is that they generally cover only discrete measurements in space and time, as, for example, handheld basket samplers (e.g. King *et al.*, 2004; Ryan *et al.*, 2005). Continuous measurement of bedload transport with method (iv) typically requires maintenance and operating personnel, e.g. in the case of vortex-tube samplers (e.g. Milhous, 1973; Hayward, 1980; Tacconi and Billi, 1987), Reid-type (previously termed Birkbeck-type) slot samplers (Sear *et al.*, 2000; Habersack *et al.*, 2001; Laronne *et al.*, 2003), conveyor belts (Leopold and Emmett, 1976), weighing devices (Reid *et al.*, 1980) or the continuous monitoring of bedload volume deposited in a retention basin (Lenzi *et al.*, 1999; Mao *et al.*, 2010).

Indirect methods (method iv) to measure bedload transport rates can provide useful high-resolution data for fluvial sediment transport studies (Gray *et al.*, 2010). Indirect techniques include geophones placed in or near the streambed (e.g. Thorne and Hanes, 2002; Downing *et al.*, 2003; Froehlich, 2003, 2010; Mizuyama *et al.*, 2010a, 2010b; Rickenmann and Fritschi, 2010), hydrophones and vibrational sensors (Bänziger and Burch, 1990; Richardson *et al.*, 2003; Krein *et al.*, 2008; Møen *et al.*, 2010). Pipe-microphone acoustic systems have been deployed in Japan (Taniguchi *et al.*, 1992; Mizuyama *et al.*, 2010a, 2010b). Feasibility tests under laboratory conditions suggest a linear relationship between the number of impulses within a given amplitude range and bedload volume (Taniguchi *et al.*, 1992). Later laboratory tests showed how the number of pulses was affected by grain-size, bedload discharge, pipe length and microphone characteristics (Mizuyama *et al.*, 2010a). Bogen and Møen (2003) studied bedload transport in a laboratory channel using two acoustic sensors (frequency range 0–500 kHz) fixed beneath a steel plate. For a first test series with particle sizes d = 18–27 mm, the mean acoustic energy was found to increase approximately linearly with bedload transport rate. Møen *et al.* (2010) reported on 450 experiments with grain sizes mostly ranging from 3 to 40 mm and found that the sensor signal is considerably influenced by sediment grain size.

Non-invasive techniques have the advantage to minimize local and temporal changes in the flow field near the sensor. Some important conclusions from the International Bedload Surrogate Monitoring Workshop, held in April 2007 in Minneapolis, USA, are (Gray *et al.*, 2010): (a) indirect bedload measuring methods have the advantage of providing continuous records of bedload transport activity both in time and over a cross-section; (b) controlled laboratory experiments are important for a better understanding of the factors influencing the calibration of these measuring methods; (c) additional field calibration of the sensors is necessary to obtain a reasonable measuring accuracy.

The Swiss Federal Research Institute WSL has several hydrologic research catchments in operation in mountain areas since the 1980s (Hegg *et al.*, 2006). The Erlenbach is one of these catchments. Bedload transport observations in the Erlenbach stream are available since 1982 from regular surveys of sediment retention basins and since 1986 using piezoelectric bedload impact sensor (PBIS) systems, which were replaced by geophone sensors in 1999. PBIS and geophone sensor are indirect methods of estimating the volume or the rate of bedload transport of coarse sediment, providing continuous measurements of transport intensities for more than 25 years for the Erlenbach (Rickenmann, 1997; Rickenmann and McArdell, 2007; Turowski *et al.*, 2009, 2011; Rickenmann and Fritschi, 2010). Recently, the measurement facilities were enhanced by direct measurements made with a moving basket system. These measurements permit to: (a) obtain bedload samples over short sampling periods; (b) measure the grain size distribution of the transported material and its variation over time and with discharge; (c) obtain direct bedload measurements that can be used to improve the understanding of the geophone signals; (d) improve the geophone calibration for the Erlenbach stream. The main objective of this paper is to present the calibration of geophone measurements with continuously operating physical bedload trap data. These data and experience from flume experiments are used to discuss possible effects of the detection threshold particle size, changing grain size distribution and flow velocity on the calibration of the geophone measurements. Finally, the measured bedload transport rates are compared with data from other streams and with trends inferred from earlier observations in the Erlenbach made with the PBIS measurement system.

The Erlenbach Catchment

The Erlenbach catchment is located in the Alptal valley in the Pre-alps of central Switzerland (Hegg *et al.*, 2006). The catchment has an area of ~0·7 km^2, and the stream gradient is 18% on average and 11% along the 50 m long natural reach immediately upstream of the gauging site. Geologically, the Erlenbach basin is located in a Flysch zone. Creeping and sliding slopes along most of the channel length provide a persistent high supply of sediment to the channel (Schuerch *et al.*, 2006).

The catchment has been equipped with hydrologic instrumentation for more than 25 years (Hegg *et al.*, 2006). The hydrology of the Erlenbach catchment is characterized by both frequent high intensity storms in the summer and snowmelt events in the spring. Total mean annual precipitation is ~2300 mm, 30–40% of which falls as snow from November through April. High intensity summer rainfall events cause sharp discharge peaks of short duration. Bedload transport in the Erlenbach occurs frequently with an average of about 20 events per year, the large majority being due to summer rainstorms. The high sediment supply from creeping and sliding slopes and the fast reaction of the catchment to summer rainstorms result in this unusually frequent occurrence of sediment transporting flood events. The largest sediment transport events had associated peak discharges of 12 m^3/s (25 July 1984) and 15 m^3/s (June 20, 2007), respectively, depositing 2130 m^3 and 1650 m^3 of sediment in the retention basin (Turowski *et al.*, 2009). Although the high channel gradient and the catchment steepness do not exclude the occurrence of debris flows in principle, none have been observed in over 30 years of monitoring, and there is no geomorphic evidence of past debris-flow occurrence. Due to the sudden occurrence of the thunderstorm-triggered rainfall events, bedload transport measurements during such events are ideally made automatically, requiring no immediate presence of operating staff.

The Erlenbach channel has a pronounced step-pool morphology with some riffle and cascading reaches, and an average bankfull channel width of 3·7 m (Molnar *et al.*, 2010). The steep channel is located in alluvial and colluvial materials originating from the weathered Wägital Flysch bedrock (Winkler *et al.*, 1985), containing grain sizes ranging from clay to meter-sized boulders. Bedrock outcrops are very rare along the Erlenbach channel. Most of the catchment is on a large landslide complex, and the left bank is particularly active in supplying sediment to the channel by hillslope creep in the reach 500 m upstream of the gauging station (Schuerch *et al.*, 2006). In this reach, the steps are up to several meters high and are composed of both sediment and large woody debris and spaced at intervals of 10–50 m (Molnar *et al.*, 2010). There is evidence that the large steps were mobile during an extreme flood event of 14 July 1995 with a peak discharge of 10 m^3/s, mobilizing 1 m boulders and resulting in local erosion or deposition of several meters. Similar large changes were observed after the flood of June 20, 2007 (Turowski *et al.*, 2009; Molnar *et al.*, 2010).

Sediment Transport Measurements

Sediment retention basin surveys

In order to measure the total amount of sediment transported by the Erlenbach, a sediment retention basin with a capacity of about 2000 m^3 was built in 1982 just downstream of the gauging station. The basin is surveyed at least once a year and after large flood events. The sediment deposited in the basin was determined 49 times in the period from June 1983 to October 2010, which on average corresponds to two surveys per year. From 1982 to 2006 the sediment deposits were surveyed from a rubber boat, measuring the height of the deposits along grid points evenly spaced at 1 m intervals using a graduated rod. An error estimate was made based on 20 repeated rod measurements along the same transect, resulting in a mean volume change error of about 2·5 m^3; the volume change is equal to the sediment deposited between two successive surveys. This means that only deposit volumes larger than about 50 m^3 can be measured with an error of 5% or less. Most surveys include larger deposit volumes. Since 2006, the topography of the sediment deposits is determined with a tachymeter or a terrestrial laser scanner (TLS), after the water is drained through the bottom outlet from the basin. Two repeated TLS surveys of the deposits made on August 22, 2011 resulted in a volume difference of about 0·5 m^3 for the surveyed area of 500 m^2, indicating a substantial improvement of the accuracy of determination of the deposit volumes as compared to the rod measurements.

The measured deposit volumes, F_s, include pore spaces, and the deposit material is composed of boulders, cobbles, pebbles, gravels, sand, and silt- and clay-sized particles. The grain size distribution (GSD) of the deposits in the retention basin is variable depending on the location and on the characteristics of flood events (i.e. range and duration of discharges). Based on six grain-size samples obtained for different locations in the basin during the period 1984 to 1987, it was estimated that about 50% by volume of the deposits have a particle size $D > 10$ mm, and about 30% by volume of the deposits have a particle size $D > 30$ mm (Rickenmann and McArdell, 2007). Similarly, based on 17 grain-size samples obtained from different locations in the basin in November 2006, the estimates are 62% sediment with $D > 10$ mm, and 32% sediment with $D > 30$ mm (Ziltener, 2007). Using areal samples and a transect by number analysis of the deposits after the extreme event of June 20, 2007, the estimates are 82% sediment with $D > 10$ mm and 76% sediment with $D > 30$ mm. For the conversion of the deposit volume into a mass, a bulk density of 1750 kg/m^3 is used (Rickenmann and McArdell, 2007). The *b*-axis of the largest particles deposited in the basin was typically around 0·2 to 0·4 m for ordinary flood events, and was up to 0·63 m for the extreme event of June 20, 2007 with a peak discharge of 14·6 m^3/s (Turowski *et al.*, 2009).

The annual volumetric sediment load F_s along with the effective runoff volume, V_{re}, is reported in Figure 1. The effective runoff volume is the integral for the observation period of the stream discharge Q above the critical discharge for beginning of bedload transport of particles > 10 mm Q_c, i.e. $V_{re} = \sum(Q - Q_c)$, over the time of bedload transport as recorded by the PBIS and geophone measurements. To determine V_{re} (Figure 1), the observed values of Q_c as inferred from the geophone measurements were used; this is important in view of the large variability of Q_c in mountain streams (Turowski *et al.*, 2011). Due to irregular timing of volume surveys in the retention basin the data in Figure 1 do not correspond exactly to one year, but to a period of 10–14 months starting and ending around August.

PBIS and geophone measurements

Sediment transport at the Erlenbach stream has been continuously monitored with a PBIS array since 1986 (Bänziger and Burch, 1990; Rickenmann and Fritschi, 2010). The array of nine sensors spans the width of an entire cross-section and is mounted flush with the surface of a check dam immediately upstream of the retention basin. The PBIS system was developed to measure continuously the intensity of bedload transport and its relation to stream discharge. In the original system, the core of the sensor was a piezoelectric crystal, which generated a small electrical potential when deformed. To standardize the sensors, the piezoelectric crystals were replaced with geophones at the end of the year 1999, reducing the number of active sensors to six (Figure 2a). Both the piezoelectric and the geophone sensor are fixed in a cylindrical aluminum case mounted on the underside in the middle of a 0·36 m long, 0·50 m wide, and 0·015 m thick steel plate (Figure 2b). The sensors are acoustically isolated from the frame and the other plates using elastomer elements. During sediment transport, gravel particles slide, roll or saltate over the steel

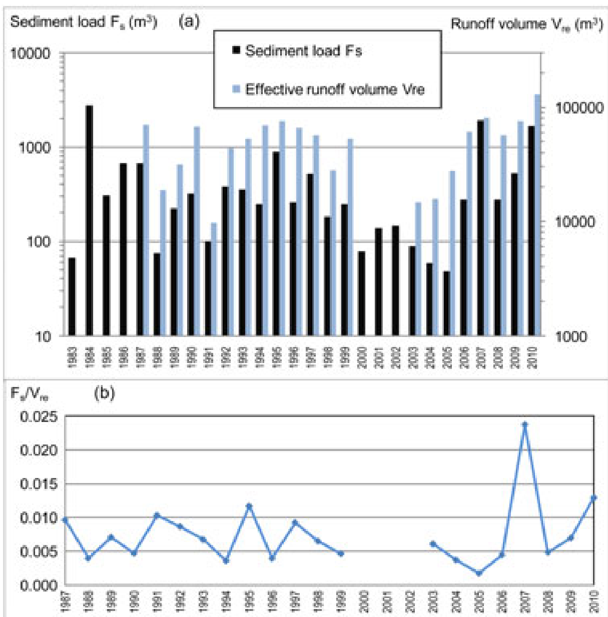

Figure 1. (a) Annual sediment load F_s and effective runoff volume V_{re} at the Erlenbach. Sediment volumes include pore spaces and fine material. Due to irregular volume surveys in the retention basin the data points do not correspond exactly to one year, but to a period of 10–14 months, typically starting and ending in the period September to mid-October when the high intensity rainfall season is over. (b) The same data shown as ratio of F_s/V_{re}, indicating a high transport efficiency in the year 2007, dominated by the extreme flood event of June 20, 2007. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

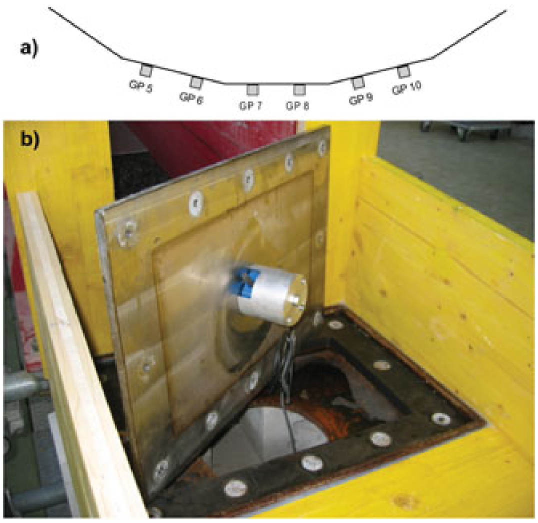

Figure 2. (a) Schematic cross-section (view downstream) at the drop structure showing lateral distribution and labeling of geophone sensors in operation since the year 2000. (b) Geophone sensor in a cylindrical aluminum housing screwed to the underside in the center of a stainless steel plate. The plate is screwed into a steel profile (which is mounted flush with the flow section of the check dam), and the rubber material acoustically isolates neighboring steel plates. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

plate. The plate transmits the impact shocks to the deforming piezoelectric crystal, or to the inertial mass moving in a coil of the geophone sensor, and thereby an electrical potential is produced. The sensor is a standard geophone, using a magnet in a coil as inductive element. The magnet moves with the steel plate and induces a current in the coil which is proportional to the velocity of the magnet. Whenever the voltage exceeds a preselected threshold value, the shock is recorded as an impulse. For the PBIS system, the threshold value was set at 0·2 V, whereas for the geophone sensors it is generally set at 0·1 V. The two threshold values are not directly comparable since the signal of the PBIS had to be electrically amplified. When more than six impulses are registered in a minute (an arbitrarily selected triggering value), the sum of impulses per minute is stored together with the actual water stage. Piezoelectric and geophone sensors are well suited for acoustic bedload transport measurements because of their stable operating characteristics, robust nature and the large electrical output generated by relatively small mechanical forces.

The piezoelectric sensors were fabricated in the workshop of the WSL institute. To check the performance of the sensors among each other and with time, a rubber sphere with a steel core was dropped from a defined height above the steel plate. To obtain comparable signals from the different piezoelectric sensors, the signal was electronically amplified before entering an electronic circuit counting the number of impulses passing above the selected threshold voltage. After about 10 years of operation in the Erlenbach, some of the piezoelectric sensors started to deteriorate and had to be replaced. The PBIS were in operation at the Erlenbach during the period 1986–1999. The new geophone sensors are commercially available, are probably more reliable and may also have a longer lifetime than the previously installed piezoelectric sensors. We use the 20DX geophone from Geospace Technologies (Houston, Texas) in a PC801 LPC Land-case.

The signal of a PBIS and a geophone sensor were compared by dropping particles with weights from 53 to 435 g from a height of 10 cm above the steel plate at different locations along three transects, laterally oriented to the main flow direction. If the particle was dropped onto the center of the plate the maximum amplitude and the frequency of oscillations were somewhat larger for the geophone than for the PBIS, while for all other impact locations the PBIS clearly showed a larger frequency of oscillations, and also larger maximum amplitudes for particles up to 240 g (Figure 3). Based on the regular surveys of the deposits in the retention basin, the total impulse counts recorded with the geophone system are about half of the number of impulses recorded with the PBIS system for a given bedload mass having passed the sensors in the Erlenbach stream.

Based on laboratory experiments using the PBIS and sediment from the Erlenbach (Etter, 1996) and on field tests during lower flows, the critical size for registering an impulse with the PBIS was estimated at about 14 to 38 g, corresponding to a mean diameter of 10 to 30 mm for an ideal sphere of quartz material (Rickenmann and McArdell, 2007). According to the same laboratory experiments using the PBIS, the number of impulses per unit mass decreased approximately linearly with D, for mean particle sizes (b-axis) ranging from 40 to 200 mm (Etter, 1996). Recent laboratory experiments using the geophone sensor and sediment from the Erlenbach were made with a flow velocity of 2·3 m/s which corresponds approximately to the flow velocity in the Erlenbach at a discharge of 0·4 m^3/s, representing flow conditions near the beginning of bedload transport. These flume tests indicate that number of impulses per unit mass strongly increases for uniform-sized particles with mean weights increasing from 25 to 50 to 75 g, with a corresponding mean b-axis of 26, 31, and 37 mm (Böckli, 2011). Thus the threshold particle size or weight appears to be somewhat larger for the geophone than for the PBIS.

Bedload sampling with moving basket system

The moving basket system was installed in the years 2008 and 2009, and it took the first bedload sample during a flood on July 7, 2009. The devices permit obtaining bedload samples

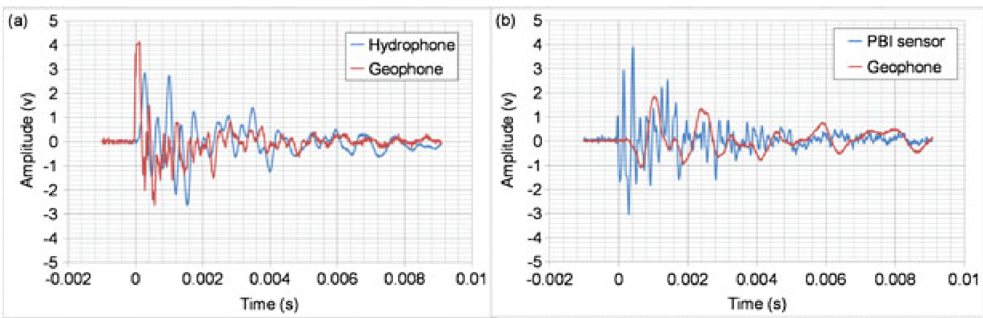

Figure 3. Comparison of the signals of a hydrophone and a geophone sensor produced by a single particle dropped from a height of 10 cm onto the steel plate for (a) a 240 g particle dropped onto the center of the plate and (b) a 120 g particle dropped onto a corner position of the plate. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

over short sampling periods, determining the grain size distribution of the transported material and its variation over time and with discharge, and improving the understanding of the geophone signal by providing a direct comparison with the geophone data at short timescales.

The main element of the system are cubic metal baskets with a side length of 1 m and a volume of 1 m^3, installed on an iron rail fixed on the downstream wall of the large check dam above the retention basin (Figure 4). Due to the sporadic occurrence of bedload transporting floods (typically during summer thunderstorms) it was necessary to design an automatic sampling system. The metal baskets can be automatically moved into the flow by an electric winch. The movement is triggered according to a predefined range of flow rates and a minimum number of geophone impulses. The baskets can be stopped in line with and downstream of two neighboring geophone plates at the centerline of the overflow section. The wire mesh has a spacing of 10 mm to sample all sediment particles coarser than this size. The weight increase of the accumulating sediment is measured by two force sensors installed in the lower basket supporting structure, and this information is used in combination with the geophone recordings to determine when to move a basket laterally away from the flow. In addition, the weight increase gives an indication about the

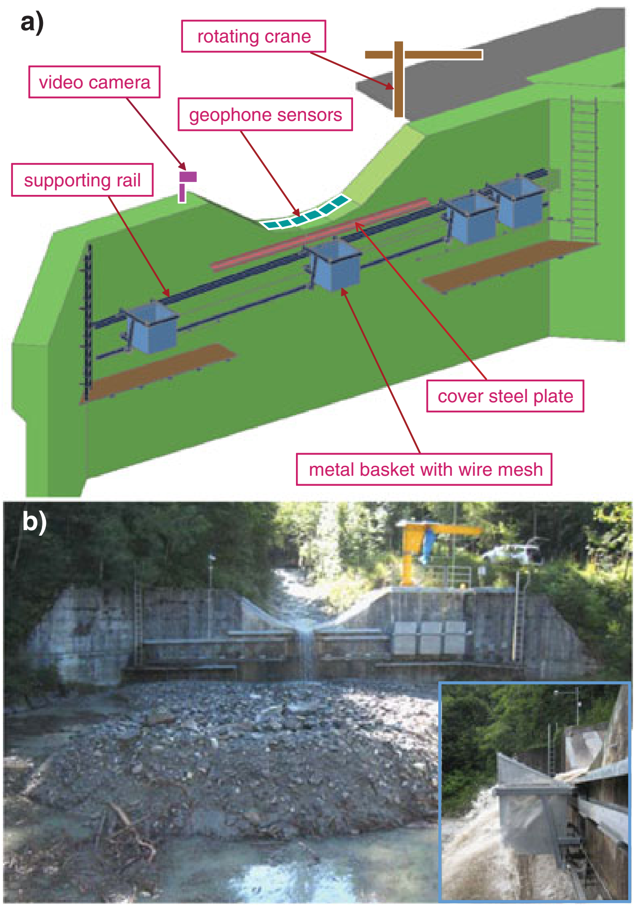

Figure 4. (a) Schematic illustration of the bedload measuring system in the Erlenbach stream. The metal baskets are automatically moved into the flow according to flow conditions and geophone recordings. The force due to the caught sediment is recorded by sensors installed in the lower supporting rail, and this information is used to determine when to move a basket laterally out of the flow. The geophone sensors are mounted underneath the metal plates installed at the overflow section of the check dam. (b) View from the sediment retention basin upstream onto the check dam with the overflow section and the metal baskets. The inset photograph shows a metal basket in sampling position along the centerline of the approach flow channel. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

temporal variation of sediment transport during the sampling period. For this study, only time-integrated weights were used in data analysis. A cover steel plate is fixed onto the downstream side of the check dam, above the supporting rail; this cover prevents particles settling onto the rail and blocking the movement of the basket, and it guarantees catching all particles also at smaller discharges.

The geophone sensors are installed along the crest of the drop structure. This guarantees a close time correspondence of the recorded geophone signal and the sediment sampled in the basket. Typically, a basket is in position to sample until filled to about 20% of its volume, corresponding to around 200 kg of sediment. This guarantees that all particles passing the geophone sensor are collected; a larger filling degree would increase the risk of previously collected particles to be re-entrained by the impinging water jet. Three baskets are available to take automatic samples during a flood event. After an event, the baskets are lifted to a working area behind the check dam with a crane, and the total weight of the sampled sediment is determined with an electronic scale. There, a particle size analysis is made by using a portable electric sieving machine, and the weight of each size fraction is measured. Typically, the sieve analysis is made when the particles are still wet; based on nine sediment samples subsequently dried in the laboratory, an average water content of ~2% was determined. Due to the limited number of samples and the small water content, no correction was made for the analysis presented later. The total weight of woody material caught in the basket is also measured, and the weight and dimensions of larger pieces are recorded.

The sampling efficiency of the metal baskets was tested successfully in scaled laboratory experiments at WSL before the installation of the prototype. The laboratory experiments were performed at a scale of 1:5 to test the drainage of the water flow through the wire mesh and to qualitatively check the performance of the baskets to collect bedload particles. The system is primarily designed to work at discharges up to about 1·5 m^3/s, corresponding approximately to the annual peak discharge. The final design of the baskets includes a wedge-type wire mesh with a front height of 0·5 m which is put on top of the cube-sized basket (Figure 4b); this ensures in principle a 100% sampling efficiency also for higher discharges up to about 6 m^3/s, if no damage to the basket structure occurs. According to the previous PBIS and geophone measurements, the bedload transport intensities show a very high variability (scatter) and a steep increase in transport rate with flow for Q smaller than about 2 m^3/s (Hegg and Rickenmann, 1999). Also, grain size distributions may be expected to change considerably with increasing discharge in this range. For discharges up to 1 m^3/s, the PBIS of the two plates next to the centerline of the drop structure recorded 88% of all impulses during the period 1986–1999. The sediment samples in the 1 m wide metal basket placed at the centerline guarantee a good match with the geophone signal recorded by these two plates covering the same width. At water discharges of several m^3/s, high sediment transport rates may completely fill a basket within a few seconds, which would rapidly reduce catch efficiency. In addition, the basket would be exposed to high water pressures and potential impact forces of large stones or boulders in transport. The upper limit for a proper functioning of the basket sampling system from an operational point of view is yet to be determined from experience. To control qualitatively the performance of the sampling system, a video camera is installed on the check dam to obtain a lateral view of the operating basket system. A beam light allows video capture at night.

Data recording system

Discharge at the Erlenbach stream is continuously recorded at 10 minute intervals at a gauging station located about 30 m upstream of the sediment retention basin, as well as at a V-shaped weir downstream of the basin. At the upstream gauging station flow stage is measured at the end of triangular-shaped concrete apron. Rainfall in the catchment is continuously recorded at 10 minute intervals with a rain gauge situated close to the stream channel about 550 m upstream of the retention basin. In case of a runoff event with bedload transport detected by the PBIS (1986–1999) or geophone (since 2000) system, discharge, rainfall, and impulses for several steel plates are recorded at one-minute intervals, as long as there is no cessation of bedload transport during more than five minutes, i.e. if no geophone impulse is recorded for five minutes the geophone system stops recording.

During the operation of the moving basket system, the full geophone signal is recorded by an analog-digital converter with a measuring frequency of 10 kHz for the period of bedload basket sampling, and additionally stored on a computer system. The weight increase due to the collected sediment is measured by two force sensors (Figure 5). The abrupt change in weight force allows the sampling time to be determined, and could be further used to obtain a finer temporal resolution of the geophone calibration measurements, for conditions when the discharge and the associated force component onto the basket remain approximately constant during the sampling period; the water jet impinging on the perforated walls of the basket exerts an additional force on the sensors which is difficult to quantify. Since the installation of the moving basket system in 2009, additional parameters characterizing the full geophone signal are preprocessed on a computer and stored at one-minute intervals during a bedload transport event: in addition to the impulse count (as done previously), the root mean square value, and the maximum signal amplitude is determined at one-minute intervals.

Results

Geophone calibration

Previously, PBIS or geophone signals accumulated over a runoff event could only be compared with sediment deposits in the retention basin accumulated during the event (Rickenmann, 1997; Rickenmann and McArdell, 2007). Thus, the sum of impulses was compared to relatively large bedload volumes. The new moving basket system for bedload measurements allows a more systematic investigation of the geophone calibration relationship of the Erlenbach site. In particular, geophone signals can now be compared with bedload samples taken over shorter time intervals and associated with smaller bedload masses and a more precise grain size distribution as compared to the measurements of the sediment deposits.

For the period of 2009 to 2010, 27 bedload transport measurements are available from the moving basket system. Results of the new calibration measurements for the two central geophone sensors (geophone plates GP7 and GP8, Figure 2a) are illustrated in Figure 6. The number of geophone impulses, IP, divided by the mass of sediment particles larger than 9·5 mm, *M* (in kilograms), collected in the moving baskets system is shown versus the mean discharge, Q_m, during the sampling period in Figure 6a. Apart from a relatively constant range of 2·2 to 4·3 impulses per kilogram of bedload, there appear to be outlier data points with less than half or more than twice as many impulses for the same bedload mass. The three measurements of group D_1 are associated with the smallest values of Q_m = 442–480 l/s and thus with the smallest transported particles, many of which are below the detection limit for the recording of geophone sensor impulses. On average those low flow samples contain only about 25% particles (by weight) larger than 20 mm (see also Figure 9 and section on bedload transport later). For the measurement labeled as D_2 the time limits and the number of impulses are only known approximately, because data with high temporal resolution were not recorded, and impulse sums were estimated from the data at the 60 second resolution. The two measurements of group D_3 had relatively short sampling times of 12 and 17 seconds, whereas for all the other measurements the sampling time

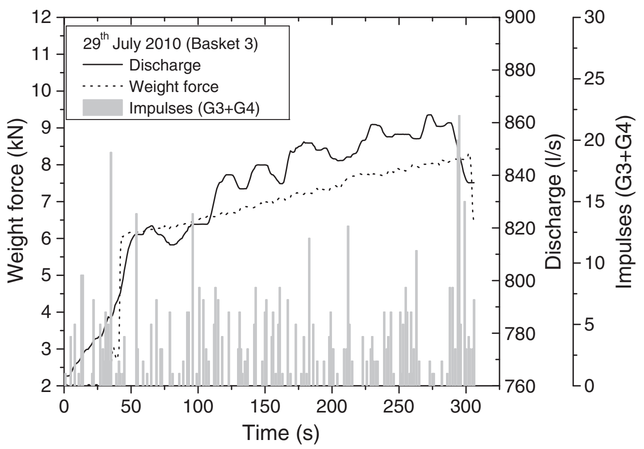

Figure 5. Example of the measurements of discharge, geophone impulses recorded by the two central sensors, and weight force due to the caught sediment in the basket during the sampling period. The sharp changes in weight force allow the average sampling time to be determined.

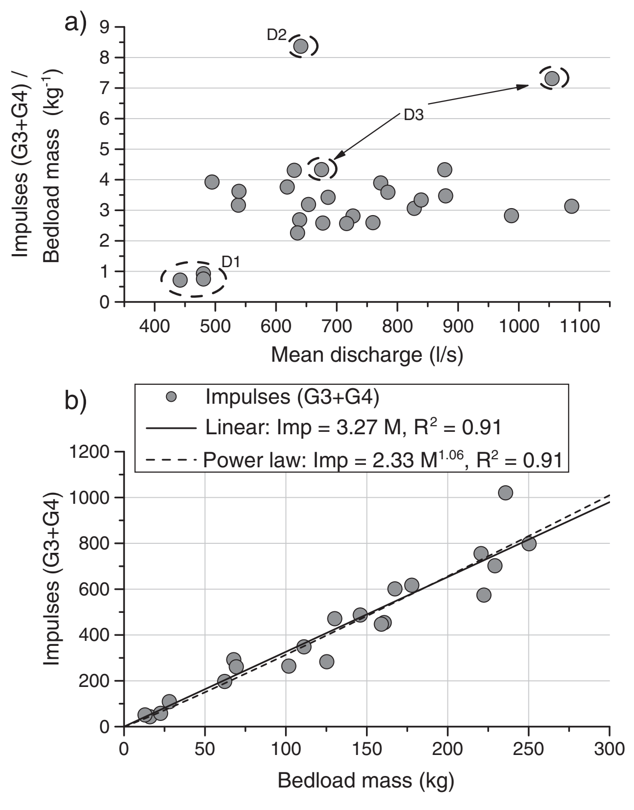

Figure 6. (a) Calibration measurements for the two central geophone sensors, showing number of geophone impulses (IP) divided by the mass of sediment particles larger than 9·5 mm (*M*) caught with the moving baskets system versus the mean discharge during the sampling period. The data groups labeled as D_1, D_2, and D_3 denote less reliable data (outliers) for the geophone calibration. (b) Calibration measurements for the two central geophone sensors, showing number of geophone impulses (IP) versus mass of sediment particles larger than 9·5 mm (*M*) caught with the moving baskets system. The six measurements identified as outliers in Figure 6a are excluded from this diagram and were not used for the regression.

was 57 to 292 seconds. The time for a basket to move completely into the measuring cross-section is about seven to eight seconds. Therefore the uncertainty about partial sampling effects is relatively high for the two samples with the shortest sampling times. For the quantitative analysis of the geophone calibration, the six 'outlier' samples (of groups D_1, D_2, and D_3) are excluded, and Figure 6b shows the number of geophone impulses IP versus the sample mass *M*, along with two possible regression lines. The data can be equally well fitted with a linear relation and a power law function, both relations having a relatively high correlation coefficient R^2. The linear calibration relationship is:

$$\mathrm{IP} = k_B \ M \tag{1}$$

where $k_B = 3{\cdot}27$ 1/kg and $R^2 = 0{\cdot}91$.

Note that the data of Figure 6 represent time-integrated measurements, i.e. the sum of geophone impulses and the bedload mass accumulated over the sampling time. A comparison of calibration measurements for the geophones in the Erlenbach including different methods of measuring sediment transport measurements is shown in Figure 7. For the data from the retention basin, the impulses of all six sensors (geophone plates GP5 to GP10, Figure 2a) were summed, and the deposited sediment volumes were used to estimate the mass of particles larger than 10 mm. For the 10 measured sediment deposits (data period 2003–2010), the following linear calibration relationship is obtained, if a proportion of 50% of sediment with $D > 10$ mm is assumed:

$$\mathrm{IP} = k_S \ M \tag{2}$$

where $k_S = 1{\cdot}63$ 1/kg and $R^2 = 0{\cdot}99$. For the basket samples, all measurements including the three outlier groups are shown in Figure 7. The two linear calibration relationships for the basket samples and the retention basin differ by a factor of 2·0, i.e. more impulses are registered for the basket samples for a given bedload mass. The reasons for this difference of the coefficient in Equations 1 and 2 are not yet clear. For the derivation of Equation 2 and comparison with Equation 1, a relatively large uncertainty is associated with the determination of the bedload mass of

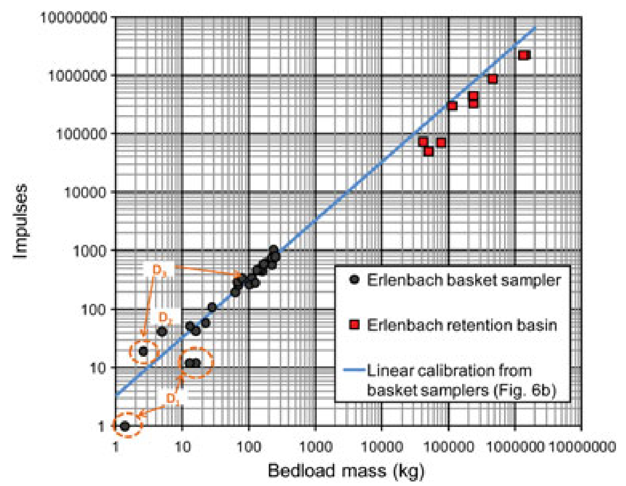

Figure 7. Comparison of calibration measurements for the geophones in the Erlenbach for different methods of sediment transport measurements. For the basket samplers, the impulses relate to the two central sensors, and all measurements including the outlier groups of Figure 6a are shown here. For the retention basin, the impulses of all six sensors were summed, and the deposited sediment volumes were used to estimate the mass of particles larger than 9·5 mm. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

particles larger than 9·5 mm of the entire deposits in the retention basin. The proportion of material coarser than this size is based on a limited number of deposit samples in the retention basin. The considerable variability of the estimated proportion of 50% of sediment with $D > 10$ mm (see section on Sediment retention basin surveys earlier) induces an important uncertainty in the interpretation of the geophone calibration based on the retention basin volume surveys. The GSD of the deposits varies both with location in the basin and with the sequence and magnitude of the bedload transporting flood events.

Bedload transport

Bedload transport rates q_b [in kg/(m s)] as measured by the basket samplers are shown as a function of discharge *Q* in Figure 8a. Regarding the quality of the measurements, the same data of the three 'outlier' groups identified earlier in the section on geophone calibration are marked in Figure 8. For the analysis of the bedload transport rates q_b, the two samples of the 'outlier' groups D_2 and D_3 may be considered to be less reliable, for the reasons mentioned earlier. In comparison, the bedload transport intensities as determined by number of impulses IP per sampling time *T*, IP/*T*, of the central geophone sensors are presented in Figure 8b. The variation of IP/*T* with *Q* shows a similar pattern as in the case of q_b and *Q*, reflecting the correlation between IP and *M*, as given in Figure 6.

The coarsening of the GSD of the transported material with increasing discharge and bedload transport rate is illustrated in Figure 9. For this analysis, the GSD of 25 measurements (excluding outliers D_3) were averaged for the following discharge classes, with *n* being the number of basket samples per class: 400–499 l/s ($n = 4$), 500–599 l/s ($n = 2$), 600– 699 l/s ($n = 8$), 700–799 l/s ($n = 5$), 800–899 l/s ($n = 4$), 900–1099 l/s ($n = 2$). For the averaging, the sampled mass for each grain size class was weighted within each discharge class by the relative sampling time. The GSD for these six discharge classes are presented in Figure 9a. Generally, larger discharges result in coarser transported bedload material, although for individual measurements there is variability, and any two basket samples collected at different flows do not necessarily confirm the general trend. With a doubling of *Q* from 450 to 900 l/s, the D_{50} grain size increased nearly two-fold from 17·5 to 30 mm, while the D_{84} grain size almost quadrupled from 25 to 90 mm. Similarly, a coarsening trend of the transported

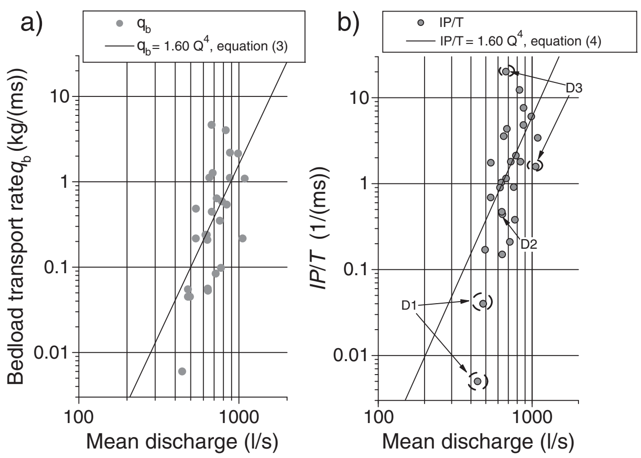

Figure 8. Bedload transport measurements shown as a function of discharge in the Erlenbach. (a) Transport rates measured by the basket samplers (for particles larger than 9.5 mm), and (b) Transport intensities as determined by number of impulses of the central geophone sensors per unit sampling time. The power-law regression lines were fitted based on a fixed exponent of 4.

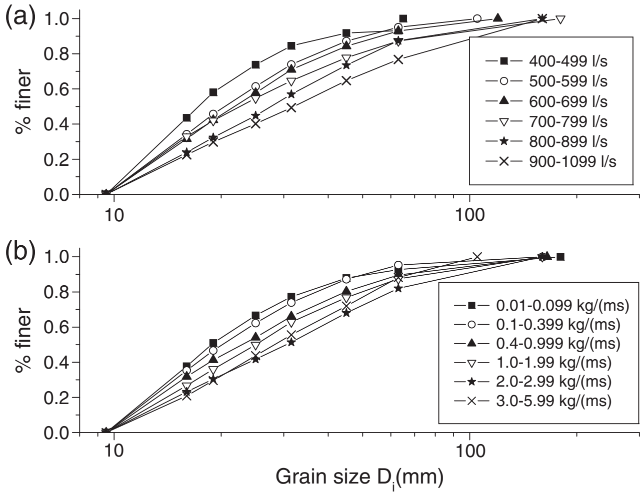

Figure 9. Grain size distributions of bedload transport measurements taken by the basket samplers. For better visibility of trends, the grain size distributions were averaged for classes of both (a) discharge and (b) transport intensities. Class limits are shown in the respective inset legends.

bedload material is observed, if the 25 measurements are averaged for the following classes of bedload transport rates q_b (Figure 9b), with n being the number of basket samples per class: 0·01–0·099 kg/(m s) ($n = 8$), 0·1–0·399 kg/(m s) ($n = 5$), 0·4–0·999 kg/(m s) ($n = 5$), 1·0–1·99 kg/(m s) ($n = 4$), 2·0–2·99 kg/(m s) ($n = 2$), 3·0–4·99 kg/(m s) ($n = 1$). In this case, the largest class does not fit the general trend, which may be due to the fact that it consists of only one basket sample. In both Figures 9a and 9b there is a trend for a flattening of the GSD curve with increasing Q or q_b.

Discussion

Geophone calibration

For indirect bedload transport measurement systems, field calibration measurements appear to be necessary, in addition to flume experiments (Gray *et al.*, 2010). Different factors may affect the signal response of such a measurement system; for the PBIS system, particle size and shape, mode of movement, detection threshold and flow velocity were identified as the more important factors (Rickenmann and Fritschi, 2010). Here we discuss how some of these factors may also affect the calibration of the geophone measurement system.

Based on laboratory experiments using a PBIS and sediment from the Erlenbach and on field tests during lower flows, it was previously estimated that the critical particle size for registering an impulse must be larger than 10 mm to 30 mm for a perfect sphere of quartz material (Etter, 1996; Rickenmann and Fritschi, 2010). Similar flume experiments with sediment from the Erlenbach indicate that the threshold for a geophone sensor may be somewhat larger in the range of particle sizes (b-axis) from 20 to 40 mm (Böckli, 2011). For the basket samples, the three measurements associated with the lowest ratio of IP/M (group D_1 in Figure 6a) and IP/T are all in the lowest discharge class (400–499 l/s), which includes four measurements. The mean GSD for this discharge class indicates that about 60% of the material is smaller than 20 mm and about 82% is smaller than 30 mm (Figure 9a). In comparison, the mean GSD for the discharge class 500–599 l/s indicates that about 48% of the material is smaller than 20 mm and about 71% is smaller than 30 mm. For all measurements in this and the larger discharge classes the calibration coefficient IP/M is of the same order of magnitude (Figure 6a). The increase of the calibration coefficient k_B above a discharge threshold of about 500 l/s is thus in agreement with the finding from the flume experiments that the geophone signal response becomes much stronger (and thus the number of impulses per unit mass increases) for particle sizes increasing from 20 to 40 mm.

The two linear calibration relationships derived from either the basket samples or from the sediment deposit volumes show a difference by a factor of 2·1 (Figure 7; Equations 1 and 2). A part of this difference may be due to the proportion of fine material within the deposits, which is difficult to quantify and which may be larger than it was assumed for the comparison. If a linear calibration relation is determined for the moving basket samples for particle sizes $D > 19$ mm (instead of $D > 9{\cdot}5$ mm), the coefficient in Equation 1 is $k_B = 5{\cdot}20$ 1/kg and $R^2 = 0{\cdot}92$. For the data from the retention basin the mass of particles larger than 20 mm can be roughly estimated as 40% of the total deposited sediment mass. If the impulses of all six geophone sensors are linearly related to the 10 measured sediment deposits (data period 2003–2010) for this case, the coefficient in Equation 2 is $k_S = 2{\cdot}03$ 1/kg and $R^2 = 0{\cdot}99$. Thus, using a threshold particle size of 20 mm, the two linear calibration relationships for the basket samples and the retention basin differ by a factor of 2·6, a slightly larger difference than for a threshold particle size of 10 mm

Mean flow velocities at the Erlenbach are estimated to vary between 2·3 to 3 m/s for discharges varying from 0·4 to 1 m^3/s (Böckli, 2011). For higher flow stages the size limit, above which a particle can cause a sufficient signal, may be somewhat larger since higher bed-parallel flow and particle velocities and higher turbulence may result in longer saltation lengths and thus in a lower proportion of particles of the critical size range impacting on the plate and being detected by the geophone sensors. Recent laboratory experiments using a geophone sensor and a quartz sphere with 89 g weight and a diameter of 40 mm indicate that the number of impulses decreased to about one third if the flow velocity increased from 1·9 to 2·7 m/s (Hegglin, 2011). Previous flume experiments with the PBIS and sediment from the Erlenbach demonstrated that the particle shape and the mode of movement (sliding, rolling, saltating) also affect the number of impulses (Etter, 1996). This effect was also confirmed in flume experiments with the geophone sensor and sediment from the Erlenbach (Turowski and Rickenmann, 2009; Böckli, 2011). For a given stream and a given discharge, the type of particle movement is expected to average out if a sufficient number of particles are being moved. However, if increasing flow changes the sediment composition and the approach flow velocity onto the sensor plate, this may be associated with a possibly important change of the geophone signal response, resulting for example in a change of the linear calibration coefficient k_B in Equation 1.

The basket measurements indicate that the number of geophone impulses is linearly correlated with the mass of the bedload samples (Figure 6b). This observation is in agreement with a previous analyses of the PBIS measurements in the Erlenbach based on the sediment deposits in the retention basin (Rickenmann and McArdell, 2007) and in the Pitzbach (Austria) based on the sediment deposits in the settling retention basin of a water intake structure (Rickenmann and McArdell, 2008). The PBIS study in the Pitzbach stream indicates that the quality of the (linear) calibration between the number of impulses recorded by the sensor per unit time and the transported bedload volumes increases if the measurements are averaged or integrated over longer time periods with bedload transport. However, a considerable scatter was observed for small bedload volumes or short time intervals (Rickenmann and McArdell, 2008).

Figures 8a and 8b may be used to indirectly determine a linear calibration relation for the geophone system, if power law relations with the same exponent can represent the data in both figures reasonably well. Based on a regression analysis (using log transformed values), the exponents are 4·26 for the data in Figure 8a and 3·82 for the data in Figure 8b, excluding the outlier groups for the data IP/*T* versus *Q*. If the exponent is fixed at four for both data sets, the following best fit power-law relations are obtained:

$$q_b = 1{\cdot}60Q^4 \tag{3}$$

$$\mathrm{IP}/T = 6{\cdot}00Q^4 \tag{4}$$

where q_b is in kg/(m s), Q is in m^3/s, and and *IP/T* is in number of impulses/(ms). From these two equations, a coefficient $k_B = 3{\cdot}75$ 1/kg can be deduced, which is similar to the value of $k_B = 3{\cdot}27$ 1/kg in Equation 1 determined from the direct calibration (Figure 6b). Including the error estimate for both coefficients in Equations 3 and 4, the resulting geophone system calibration coefficient is $k_B = 4{\cdot}69$ 1/kg (maximum) or $k_B = 2{\cdot}87$ 1/kg (minimum). Similarly, if the exponent is fixed at five to fit power-law relations to both the data in Figures 8a and 8b, the resulting geophone system calibration coefficient is $k_B = 3{\cdot}97$ 1/kg. Thus, if a bedload transport rating function (such as the one in Figure 8a) is known from a different time period (and has not changed since then) than the geophone measurements, it would be possible to determine a calibration of the geophone system using an impulse rate versus discharge function (such as the one in Figure 8b), given that both function can be described with a power law with the same exponent.

Given the fact that the flume experiments with sediment from the Erlenbach indicate a non-constant value of k_B (Equation 1) with varying particle size (see earlier), it is surprising that both the basket and the retention basin data result in a linear correlation between number of impulses and bedload mass. From measurements in a mountain stream with a gradient of 2%, Bunte (1992) showed that for gravel bedload with $D > 11{\cdot}2$ mm there are approximately linear relationships between the number of particles transported in a given 0·5 phi size fraction and total bedload transport rates; adding the number of all transported particles per sample yielded a linear relationship between the sum of all particles and total transport rates. Bunte and Abt (2001) found the following empirical equation to be valid for a large number of streams:

$$m_i = 0{\cdot}00307\, D_i^{2.98} \tag{5}$$

where m_i is mean particle weight (in grams) for a given retaining sieve size class D_i (in millimeters). Equation 5 was applied to the data of the sieve analyses from the Erlenbach basket samples to estimate the number of particles per size class and for the entire sample. Then the number of impulses is found to correlate approximately linearly with the number of particles N_p:

$$\mathrm{IP} = k_p N_p \tag{6}$$

where the coefficient in Equation 6 is $k_p = 0{\cdot}092$ and $R^2 = 0{\cdot}83$ for a particle threshold size $D_i > 9{\cdot}5$ mm, and $k_p = 0{\cdot}604$ and $R^2 = 0{\cdot}92$ for a particle threshold size $D_i > 19$ mm. Despite the roughly linear correlation between IP and N_p, the reason for the approximately linear calibration relation in terms of IP and *M* (Equations 1 and 2) remains unclear, given the non-constant value of k_B with varying particle size, and changing GSD with changing flow strength and bedload transport rate (Figure 9). To better understand the geophone calibration further systematic flume experiments are necessary.

Some recent geophone measuring installations in Austrian streams have been equipped with computers to register the complete signal. These streams have channel widths of several tens of meters, and special constructions are provided to sample the bedload either with Helley–Smith or slot-type samplers. At the Drau River the weight of bedload particles deposited in a trap immediately downstream of a sensor plate is continuously recorded (Habersack *et al.*, 2010), and these accurate calibration measurements also indicate a linear relationship between geophone impulses and bedload mass (Seitz *et al.*, 2010). A comparative study to analyze the calibration relationships of the geophone system at different sites is under way, to further investigate the effect of particle properties (grain size, distribution and shape) and flow conditions on the geophone signal.

The Japanese pipe-microphone acoustic system was calibrated with direct bedload transport measurements using slot samplers in the gravel-bed river Nishi-takiga-tani and in the mountain river Ashi-arai-tani (Mizuyama *et al.*, 2010b). Similar to the Erlenbach geophone measurements, linear calibration relations were obtained between the number of impulses and bedload transport rates, which varied between about 0·01 and 3 kg/(m s). According to Mizuyama *et al.* (2010b), the performance of the pipe system is acceptable for low bedload discharges if the signal is summed over sufficiently long time periods and if the grain-size is larger than 4 mm (unless thinner pipes are used); the performance is good for intermediate bedload discharges; and for elevated bedload discharges there is a potential problem with signal-damping when different amplification levels of the original signal have to be used.

Overall, the main advantages of the geophone measuring system are similar to those for the earlier used PBIS system (Rickenmann and Fritschi, 2010): (a) continuous estimation of bedload transport intensities; (b) detection of bedload entrainment and cessation thresholds; (c) robust technique requiring very little maintenance; (d) relatively low costs for instruments and installation; and (e) for longer observation periods and larger bedload volumes a reasonable accuracy is obtained for the calibration relationships, given the natural variability of bedload transport in mountain streams. The disadvantages of the geophone measuring system can be summarized as follows (Rickenmann and Fritschi, 2010; Turowski and Rickenmann, 2011): (a) a calibration of the system is necessary; (b) no information on GSD of the transported particles can be obtained so far; (c) the limiting particle size which can be detected is larger than for the Japanese pipe-microphone system; (d) the influence of hydraulic conditions and sediment properties on calibration are only poorly known at present; and (e) changing flow intensities are likely to change the size distribution of transported bedload particles, which may result in a more complex calibration relation than the one obtained for the Erlenbach under the investigated flow conditions.

Sediment transport in the Erlenbach

There is some correlation between the measured sediment deposit volumes, F_s (in m^3), in the retention basin and the effective runoff volume, V_{re} (in m^3) (Figure 1). From the 35 sediment survey periods for which PBIS or geophone measurements are available (Figure 10), the following regression equations were obtained:

$$\mathrm{F_s} = 0{\cdot}0093\ \ V_{re} \tag{7}$$

$$F_s = 0{\cdot}00002\ \ V_{re}^{\,1.55} \tag{8}$$

A linear function was assumed for Equation 7 having a correlation coefficient squared of $R^2 = 0{\cdot}45$, and a power law function was assumed for Equation 8 for which $R^2 = 0{\cdot}49$. These relationships confirms findings from other studies in steep streams (Rickenmann, 1997, 2001; D'Agostino and Lenzi, 1999; Lenzi *et al.*, 2004) indicating that a simple bedload transport equation

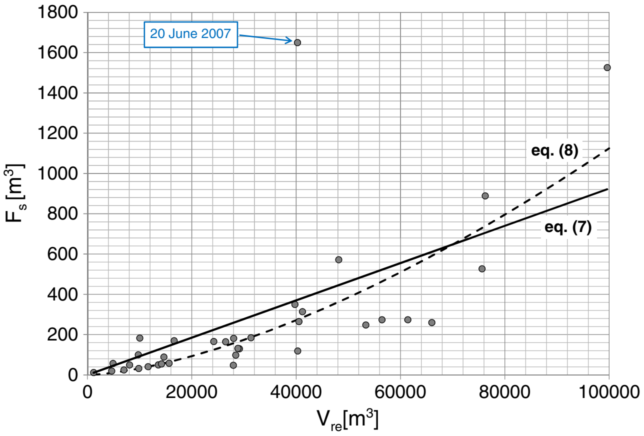

Figure 10. Sediment load F_s versus effective runoff volume V_{re} at the Erlenbach for the 35 sediment survey periods for which PBIS or geophone measurements are available. Also shown are the linear and power law regression Equations 7 and 8 for these data. The extreme flood event of June 20, 2007 produced 96% of the geophone impulses recorded during the respective period, and this event indicates a larger transport efficiency than periods reflecting 'ordinary' events. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

in terms of discharge (e.g. Schoklitsch, 1962; Rickenmann, 1997, 2001, 2012) can be integrated over the flood event to roughly estimate the total transported sediment load. According to the earlier PBIS measurements, the increase of total bedload transport Q_b with discharge Q in the Erlenbach follows approximately a power law with an exponent of five up to about $Q = 2\,m^3/s$ (or $Q/Q_c \cong 4$) (see also Figure 8a), while for larger discharges Q_b increases approximately linearly with Q (Hegg and Rickenmann, 1999). The strongly non-linear increase of transport Q_b with discharge Q below a threshold of about $Q/Q_c \cong 4$ may partly explain the larger exponent and somewhat higher R^2 value of Equation 8 as compared to Equation 7, although the total transported sediment load appears to be dominated by the time periods near peak flows, many of which are close to or above the threshold of $Q/Q_c \cong 4$. However, two further factors are also very important with regard to the absolute level of sediment transport or the ratio F_s/V_{re} for single runoff events: (a) a rough streambed morphology and low relative flow depths are associated with high flow resistance, thus reducing the sediment transport capacity as determined by bedload transport equations developed for flow conditions with essentially grain resistance dominating flow resistance (e.g. Comiti *et al.*, 2009; Zimmermann, 2010; Chiari and Rickenmann, 2011; Nitsche *et al.*, 2011; Rickenmann and Recking, 2011); (b) sediment supply and availability of movable material is also likely to control sediment transport of flows in steep channels with often high shear stresses: for example, a destabilized streambed after the occurrence of extreme flood events may be the reason for increased sediment availability and higher transport levels (Lenzi *et al.*, 2004; Turowski *et al.*, 2009), resulting in a larger ratio F_s/V_{re} than on average for the same stream, as is also illustrated in Figure 1b for the extreme event of June 20, 2007. If a discharge based bedload transport equation is used (e.g. Rickenmann, 2001), consideration of factor (a) will essentially change the predicted coefficient in Equation 7 (Rickenmann, 2012). Regarding factor (b), a limited sediment supply will similarly reduce the coefficient in Equation 7, while a variation of the threshold discharge for begin of bedload transport (e.g. Turowski *et al.*, 2011) will affect the value of V_{re} in Equation 7.

The bedload transport rates as measured by the moving baskets are among the highest measured in natural streams, with values of q_b of the order of several kg/(m s). These transport rates were associated with moderate discharge levels with recurrence intervals of less than one year. The determination of recurrence intervals of flood peaks in the Erlenbach is based on a generalized extreme value statistic (Liechti, 2008). Based on a mean flow duration curve determined for the years 1982 to 2007, the range $Q = 0{\cdot}4$–$1{\cdot}0\,m^3/s$ corresponds to flow durations in the range of 3·1 days to 6·2 hours per year. Comparable bedload transport rates were also observed in the Nahal Esthemoa in Israel (Powell *et al.*, 2001) and in the Rio Cordon in Italy (Lenzi *et al.*, 2004). Given the data in Figure 8a, maximum values of q_b of the order of several 10 to several 100 kg/(m s) may be expected during peak flows in the Erlenbach. In fact, during the June 20, 2007 flood in the Erlenbach, 1650 m³ of sediments were transported within 214 minutes (Turowski *et al.*, 2009), resulting in an average sediment transport rate of 61 kg/(m s), for a deposit bulk density of 1750 kg/m³, and a stream width of 3·7 m.

Conclusions

A moving basket system for taking bedload samples was installed in the years 2008 and 2009 in the Erlenbach stream. For the period 2009 to 2010, it successfully took 27 samples of bedload material for grain sizes larger than 9·5 mm, from which bedload transport rates and GSDs were determined. The samples were taken for short time intervals and for discharges with a recurrence interval of less than one year. The indirect measurements of bedload transport with geophone sensors were analyzed in terms of number of impulses, i.e. the number of peaks above a threshold value in the oscillating signal caused by particles impacting on the steel plate. The 27 observations with both geophone sensor and basket samples with bedload masses from about 10 to 240 kg result in a strong linear calibration relationship between number of impulses and bedload mass. This linear calibration relationship is in general agreement with earlier investigations using the PBIS system, a similar indirect measuring system. The older in-house PBIS system was found to be more sensitive than the newer system using commercially available geophone sensors. The two linear calibration relationships for the geophone measurements derived from the basket samples and the sediment deposit volumes in the retention basin differ by about a factor of two. Part of the difference may be due to the proportion of fine material within the deposits, which is difficult to quantify and which may be larger than it was assumed for the comparison. Together with experience from the similar PBIS system used previously in several streams, it can be concluded that the geophone sensors are a robust and useful indirect measuring system for bedload transport including coarser particles in movement. The main limitations of the system are the need for calibration, lacking information on transported grain sizes, and the minimum detectable particle size.

The bedload transport rates q_b as measured by the moving baskets are among the highest rates measured in natural streams, with values of q_b of the order of several kg/(m s) which were also observed in the Nahal Esthemoa in Israel and in the Rio Cordon in Italy. The volumes of the sediment deposits in the retention basin were determined over longer time periods including typically several flood events. For the period from 1986 to 2010, 35 measurements of sediment deposit volumes show a correlation with the effective runoff volume, indicating that a discharge-based bedload transport equation can roughly predict the total sediment load transported during a flood event. The comprehensive and continuous measurements in the Erlenbach stream provide valuable data for further investigations on sediment transport in a steep headwater catchment.

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