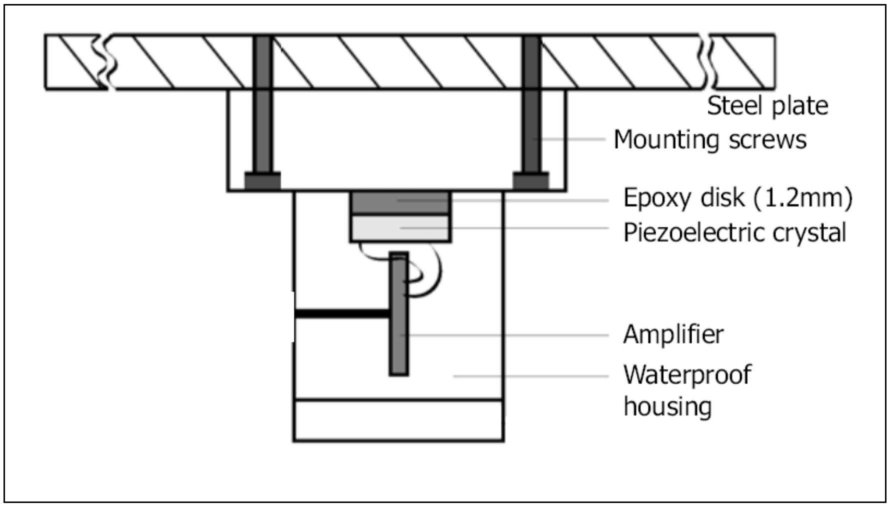

Figure 1. Schematic vertical section of a PBIS used for bedload transport measurements, showing how the sensor is fixed to the steel plate (modified from Etter, 1996).

Hitherto we have installed the stainless steel plates in a metal box, which in turn is mounted in a concrete structure in the channel (for example, on the surface of a check dam). We use a rubber membrane to isolate the plate from the box, and to avoid or minimize cross-transmission of vibrations from neighboring steel plates. The thickness of the steel plates (0.015 m) has been selected so that they can support a considerable vertical load without much deformation. A different thickness and/or size of the steel plates may change the sensor response due to the impact of bedload particles, a matter we have not investigated.

The piezoelectric sensors were fabricated in our workshop. To check the performance of the sensors among each other and with time, we dropped a rubber sphere with a steel core 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 ten years of operation in the Erlenbach, some of the piezoelectric sensors started to deteriorate and had to be replaced.

Since the year 2000 we replaced the piezoelectric sensors and changed to geophones, because they have a more standardized signal response and are commercially available (and therefore less expensive). The geophone sensors are probably more reliable and may also have a longer lifetime than the previously used piezoelectric sensors. We use the 20DX geophone from Geospace Technologies (Houston, Texas) in a PC801 LPC Land-case. Figure 2 shows how the geophone sensor is fixed in a cylindrical aluminum case mounted on the underside of the steel plate.

Figure 2. Geophone sensor in metal case fixed to the steel plate from underneath.

Calibration of PBIS system

To establish a relationship between the PBIS data and independently measured sediment loads it is necessary to account for sediments smaller than the minimum size resulting in a PBIS signal. Based on laboratory experiments using one PBIS and sediment from the Erlenbach (Etter, 1996) and on field tests in the Erlenbach during lower flows, we estimate that the critical size for registering an impulse must be larger than 1.4 g to 38 g, corresponding to a mean diameter of 10 mm to 30 mm for a perfect sphere of quartz material. For higher flow stages the limiting grain size may be somewhat larger since higher turbulence will increase the minimum grain size to be transported in suspension.

Even if all particles transported over a sensor are large enough to be detected by the measuring system, a calibration with an independent measurement on the transported bedload volume would be necessary. Our experience from laboratory experiments with the PBIS system (Etter, 1996) and from studies with similar systems (see the review in Rickenmann & McArdell, 2007) indicate that the signal response depends on a number of factors (e.g. type of movement, location of impact, hydraulic conditions), which are difficult to isolate and to quantify. Therefore, a calibration of the system is necessary. The catchment characteristics of the two main calibration sites, the Erlenbach and the Pitzbach stream, are summarized in Table 1.

Table 1. Characteristics of the Erlenbach and Pitzbach catchments.

Catchment parameter	Erlenbach	Pitzbach
Basin area (km^2)	0.7	26.8
Maximum elevation (m)	1655	3472
Minimum elevation (m)	1110	1811
Average gradient of main stream (%)	18	19
Channel gradient above measuring site (%)	10	6
Mean annual precipitation (mm)	2300	920
Forest cover (%)	40	-
Wetland + grassland (%)	60	-
Glacier cover (%)	-	60
Bedrock, moraines, grassland, alluvium (%)	-	40

As a first approximation for the conversion of data from number of impulses to sediment transport rates or volumes, we assume that the proportion of bedload and suspended material remains constant for different flood events in the Erlenbach and the Pitzbach streams. For bedload transport in the Erlenbach, we have estimated that about 50% by volume of the material has a grain size larger than 10 mm, and about 30% by volume of the material is larger than 30 mm (Rickenmann and Dupasquier, 1994). However, the ratio between bedload and suspended load may be variable in small mountain streams; for example the proportion of suspended sediment yield on the total sediment yield is 76% for the Rio Cordon in Northern Italy (Lenzi et al., 2003).

Erlenbach

Sediment transporting flood events in the Erlenbach are typically of short duration with a rapid rise of discharge during summer thunderstorms. On average there are more than 20 bedload transport events per year. Near the confluence with the main valley river, there is a stream gauging station and a sediment retention basin with a capacity of about 2000 m^3. The total accumulated sediment load can be measured there at regular intervals as well as after extreme flood events. The topography of the deposited sediment has been surveyed using a sounding rod from a small boat. The PBIS system installed in 1986 was developed to continuously measure the intensity of bedload transport and study its relation to stream discharge. Nine of these sensors, termed hydrophones in earlier publications, were installed in the channel within 1 m of the upstream end of the sediment retention basin (Bänziger and Burch, 1990; Bänziger and Burch, 1991), flush with the concrete along the entire wetted perimeter of a large concrete check dam (Fig. 3).

Figure 3. The PBIS array for measuring bedload transport in the Erlenbach is mounted underneath steel plates at the crest of a large check dam. The red arrow points to the steel plate of sensor no. 3.

In our experience the impulses registered with sensor number 3, which is mounted near the centerline of the channel cross section (Fig. 3), can be used as a reliable indicator for the total bed load transport. During the period 1986 - 1993, sensor no. 3 registered 56.5% of all sensor impulses, and together with the two neighbouring sensors more than 80% of all sensor impulses. To develop a calibration relationship we used observations from 1986 to 1999, which included a total of 287 bedload transporting flow events and 25 survey periods. Only the records of sensor no. 3 were used because during the period 1994 to 1999 some of the other sensors malfunctioned and were replaced. A survey of the volume changes of deposited sediment in the retention basin includes on average 11.5 flood events. The measured deposit volumes ranged from 12 to 889 m3, each representing several events of different duration and peak discharge. As observed in other streams under similar conditions (Bathurst, 1997; Mao and Lenzi, 2007), we expect the grain size distribution of the transported sediment to become coarser with flood magnitude, and this effect may contribute to the scatter in the calibration relationship.

Characteristic grain sizes (Fig. 4) were determined by sieve analysis for samples from the sediment retention basin in the proximity of the inlet channel, and by transect-by-number analysis (Fehr, 1987) for the streambed material upstream of the sediment retention basin. Characteristic grain sizes of the transported sediment are: $d_{m,t}$ = 11.3 mm, $d_{90,t}$ = 125 mm, $d_{50,t}$ = 16 mm and $d_{30,t}$ = 4 mm. The corresponding surface bed material sizes are: $d_{m,s}$ = 51.2 mm, $d_{90,s}$ = 400 mm, $d_{50,s}$ = 80 mm and $d_{30,s}$ = 29 mm. Here d_m is the mean grain size, and d_{xx} refers to grain size for which xx percent of the material is finer. The subscript *t* refers to transported sediment and the subscript *s* to bed surface sediment. Based on grain size analysis of the deposits in the Erlenbach retention basin, about 50% by volume of the material is coarser than 10 mm. In comparison, the deposits of grains larger than 30 mm comprise about 30% by volume of the total sediment deposit (Rickenmann and Dupasquier, 1994).

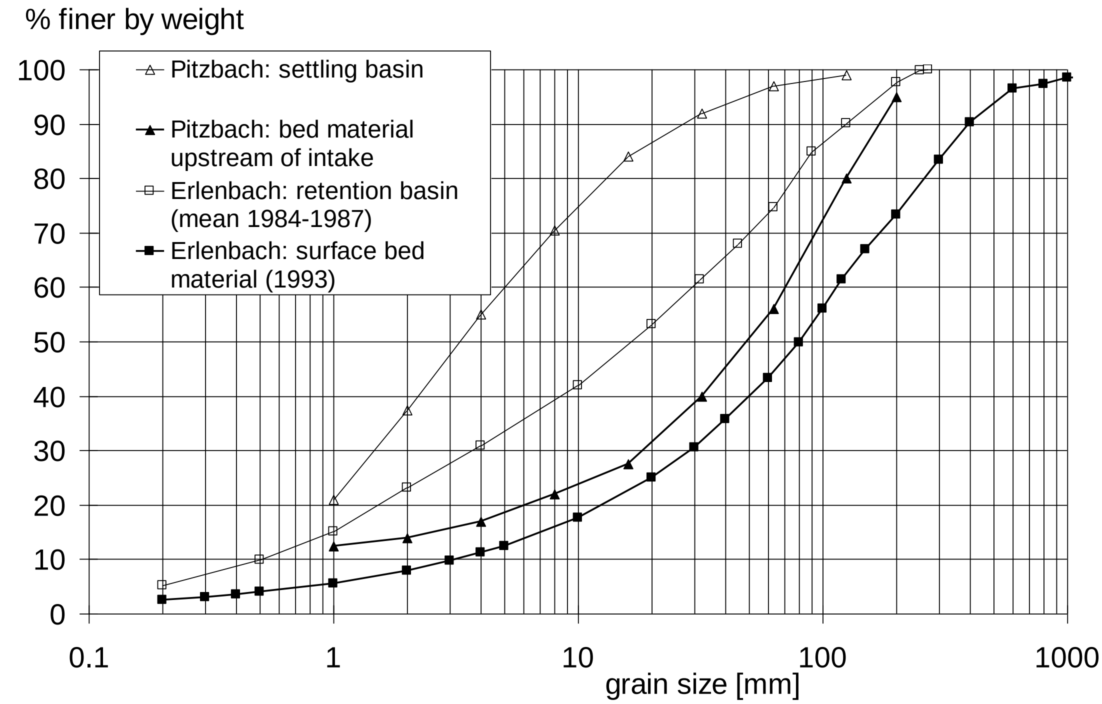

Figure 4. Grains size distributions of bed material and bedload for the Erlenbach and the Pitzbach streams. The maximum surface bed material grain size of the Erlenbach is 1500 mm.

Based on the 25 surveys of the sediment volume in the retention basin for the period 1986 to 1999, the following calibration relationship was derived (Rickenmann and McArdell, 2007):

$$F_E = 0.934\ SP3, \tag{1}$$

where F_E is the sediment volume expressed in m^3, and $SP3$ is the sum of the number of impulses recorded by sensor no. 3, divided by 1000. Note that for eq. (1) and for all the following linear calibration relationships, the coefficient was determined for the condition $\Sigma F_{predicted} = \Sigma F_{measured}$, where the summation symbol Σ refers to all sediment measurements for a given data set. By comparing calculated F_E values and measured values $F_{E,m}$ of deposited sediment volumes, the following statistical parameters are determined: correlation coefficient $r^2 = 0.872$ and relative standard error (normalized by the mean of the measured values) $s_e = 0.44$. Considering the ratio $R = F_{predicted}/F_{measured}$, for the 25 survey periods, 80% of the data points have a relative accuracy of R within a factor of 2.

For the field data from natural floods in the Erlenbach, we assume that 50% of the deposited volume includes particles coarse enough to have contributed to the PBIS recordings, i.e. with particle sizes larger than about 10 mm. In the following, all data referring to coarse sediment is labeled F_c. To estimate the total number impulses caused by all sensors, SP, the sensor impulses $SP3$ are multiplied by a factor (1/0.565). The calibration relation (1) for the Erlenbach may be alternatively expressed with the modified coefficient $k_c = (0.934)(0.5)(0.565) = 0.264$ as:

$$F_{E,c} = 0.264\ SP \tag{2}$$

To compare the observations from the retention basin with other calibration measurements, we assume an equivalent deposit bulk density of 1750 kg/ m^3, which is based on an analysis of deposit samples in 1986.

Pitzbach

The Tyrolean Water Power Company (TIWAG) in Austria measures sediment transport at several of their water intakes since the 1960s. The most detailed observations were made at the water intake of the Pitzbach stream (Hofer, 1985, 1987; Düster, 1991). The hydrologic regime of the Pitzbach is clearly seasonal, with maximum discharges typically occurring in July and August, during periods with most intense glacier and snow melt, when sediment transport occurs almost every day.

Calibration measurements with the PBIS system at the Pitzbach were made in the summers of 1994 and 1995 (Rickenmann et al., 1997). A PBIS array of 12 sensors was installed at the upstream end of the Tyrolean weir (Fig. 5). From the Tyrolean weir at the intake the water flows into the settling basin where the sediment is deposited, to have clear water for the hydropower generation in the turbines. When the deposited sediment exceeds a predefined volume, a flushing operation transports all sediments back into the Pitzbach stream downstream of the weir. For the entire observation period, sediment transport occurred on average during 16 hours per day, necessitating several flushing operations on the same day and sometimes up to several operations per hour during peak flows. Typical summer daily bedload transport volumes range from a few cubic meters to about 500 m^3.

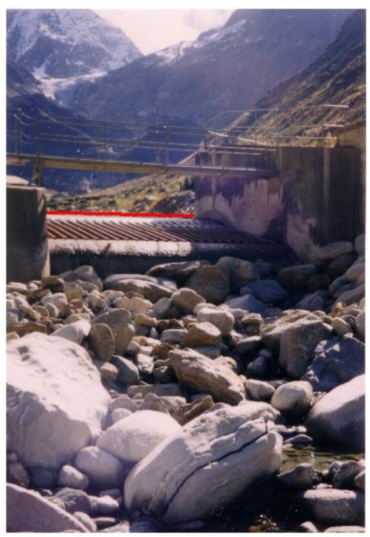

Figure 5. The water intake at the Tyrolean weir in the Pitzbach (photo courtesy of TIWAG). The PBIS sensors were mounted at the upstream end of the weir (location marked with red line).

The settling basin is 40 m long, 3 m wide, and has a trapezoidal cross-section at the bottom (bottom width 1.5 m). Sediment deposition conditions in the basin are monitored by five weighing cells located along the centerline of the basin floor and a water pressure sensor in the basin, with the data recorded every 15 min. Data from the weighing cells and water level sensor were converted to depositional volumes using several measurements of depositional geometry; the bulk density of the deposits typically varied in the range 1690 - 1510 kg/m3 (Hofer, 1985).

The grain size distribution was determined by sieve analysis of volumetric samples taken both from the settling basin and from the Pitzbach streambed (Fig. 4). In the settling basin, sediments of grain-size 0.1 - 150 mm are deposited; this sediment is finer than the streambed material upstream, with typical grain sizes in the settling basin of D50=3.4 mm, and D90=28 mm. Particles larger than 150 mm cannot enter the settling basin and partially remain on the rack; based on observations from 1975 to 1980, their proportion of the total sediment load is estimated to be 0.2 - 2% (Hofer, 1987).

The calibration of the PBIS array is based on the original data set (A), which includes sensor impulses summed over 15 minute intervals and sediment volumes deposited in the settling basin during the same intervals. On average over the entire measuring period, about 50% of all impulses were recorded by sensor no. 1 (out of 12 sensors), which is located on the orographic right side of the Tyrolean weir near the centre of the Pitzbach streambed. Only the total number of impulses registered by all 12 sensors, *SP* (given in units of 1000 impulses), are considered here. Sediment volumes, F_P, are expressed in m^3 and refer to bulk deposits including pore space. The following calibration relationship was derived (Rickenmann and McArdell, 2008):

$$F_P = 0.119\ SP \qquad \text{[data set A]} \tag{3}$$

By comparing calculated F_P values and measured values $F_{P,m}$ of deposited sediment, the following statistical parameters were determined: $r^2 = 0.503$ $s_e = 1.69$ for data set A.

The measurements from the original data set A were also integrated over one hour periods (data set B) and over daily periods (data set C). Longer observation periods are potentially useful at other sites with different conditions, and for comparison with data from the Erlenbach, where sediment volumes have been determined only for longer time intervals. For the integrated data sets, the following statistical parameters are determined when applying equation (3): r2 = 0.559 and se = 1.98 for data set B, and r2 = 0.689 and se = 1.29 for data set C.

The analysis of the Pitzbach data showed that the measured sediment load strongly depends on the maximum discharge Qmax for all time periods. The discharge conditions typically show a steady rise, peak, and recession both during individual days (Hofer, 1987) and during a season. For increasing discharges between about 2 m^3/s (threshold for beginning of transport) and about 6 m^3/s (maximum discharge entering the water intake), the ratio SP/F_P = increases by about one order of magnitude, asymptotically approaching a constant value. We hypothesize that there is an increasing proportion of coarser grains, which are large enough to produce sensor impulses, being transported in this discharge range (Rickenmann and McArdell, 2008). However, a given volume of larger particles appears to produce less impulses than the equivalent volume of smaller particles (if these are all larger than the threshold size), as is also illustrated by Fig. 6. For the Pitzbach observations, the first factor appears to outweigh the second factor.

For the integrated data sets B and C with hourly and daily values, respectively, this results in a bias towards the grouping of low and high transport intensity periods. Therefore, the best fit regressions derived directly from data sets B and C result in power law calibration equations: FP = 0.231 SP0.81 for data set B, with r2 = 0.624 and se = 1.08; and FP = 0.442 SP0.79 for data set C, with r2 = 0.759 and se = 0.69. The statistical parameters are improved for longer integration periods. However, the coefficient of the power law calibration relationships depends on the range of considered sediment volumes (Rickenmann and McArdell, 2008).

For a comparison with the other calibration data, the sediment volumes F_P in the Pitzbach are reduced by a factor of 0.25 to represent the sediment volumes $F_{P,c}$ of particles coarser than 10 mm, the lower critical particle size to cause PBIS impulses. The calibration relationship for data set A becomes:

$$F_{P,c} = (0.119)\ (0.25)\ SP = 0.0298\ SP \tag{4}$$

Laboratory experiments

In experiments using a laboratory channel and particles from the Erlenbach (Etter, 1996), 240 tests were performed to investigate the effect of grain size and size mixtures on the PBIS signal. The apparatus consisted of an open channel, inclined at 20°, and connected to the PBIS steel plate. Individual particles of 0.1, 1, 2.9, and 5.9 kg mean weight, with corresponding b-axes of 35-45, 90-110, 130-160, and 180-200 mm, were tested. Both unisize mixtures and mixtures including 0.1, 1, and 2.9 kg grains were used. The original signal of the PBIS sensor was sampled at a maximum rate of 62.5 kHz, and frequency spectra were analyzed in the range 10 - 30 kHz. The following correlations with the total weight of transported particles were investigated: number of impulses above a threshold value of 0.2 V (as used in the Erlenbach and Pitzbach measuring systems), the area under the signal (integral of signal amplitude over time), and the maximum signal amplitude. An initial test series involved various sizes of metal spheres dropped vertically onto the steel plate at different locations. As expected, the signal pattern and strength depends on the location of impact; a similar result was obtained in flume tests with a pipe microphone by Mizuyama et al. (2008a, this volume). The peak amplitude positively correlates with the sphere weight.

Using single natural particles, the variability of the signal is greater for repeated tests with the same particle size than among different grain sizes due to different movement modes and impact locations. For several uniform particle size mixtures, a linear correlation is found between sum of impulses and mixture weight,, and the proportionality coefficient k depends on mean grain size. This calibration relation is of the form SuP = k Ws, where SuP is the sum of the sensor impulses and Ws is the weight of the sample (kg). Using mixtures consisting of three different grain size classes, there is a linear correlation between sum of impulses and mixture weight; using a mean correlation coefficient for all 63 mixture experiments, the maximum deviation between predicted and measured total weight is +/-50%. Considering all experiments, the number of impulses is better correlated with particle weight than is the area under the voltage signal correlated with the weight. A combined analysis using frequency information and area under the signal improves the overall correlations including all tests, but does not improve the correlations for “heterogeneous” mixtures. For these mixtures, no systematic variation of the proportionality coefficient k with mean particle size is observed. For mixtures of nearly unisize particles, a distinction between mean grain size is possible: the median frequency of the signal spectrum increases with decreasing mean grain size, similar to other studies (e.g. Thorne, 1986; A. Krein, written communication 2002; Møen et al. (2008, this volume).

For the comparison of all three calibration data sets (Fig. 6), we use a mean bulk deposit density of 1600 kg/m^3 for the Pitzbach settling basin. For the 240 laboratory experiments, the weight of the mixtures is converted into a deposit volume F_L using this bulk deposit density, resulting in the following calibration equation:

$$F_L = 0.0884\ SP \tag{5}$$

By comparing calculated F_L values and measured values $F_{L,m}$ of the mixtures (in the linear domain), the following statistical parameters were determined: $r^2 = 0.273$ and $s_e = 0.60$. For a comparison of the three calibration datasets, the sediment volumes of the Erlenbach are adjusted by a density ratio factor of (1750/1600) = 1.09, and (2) is transformed into:

$$F_{E,c} = (0.264)\ (1.09)\ SP = 0.289\ SP \tag{6}$$

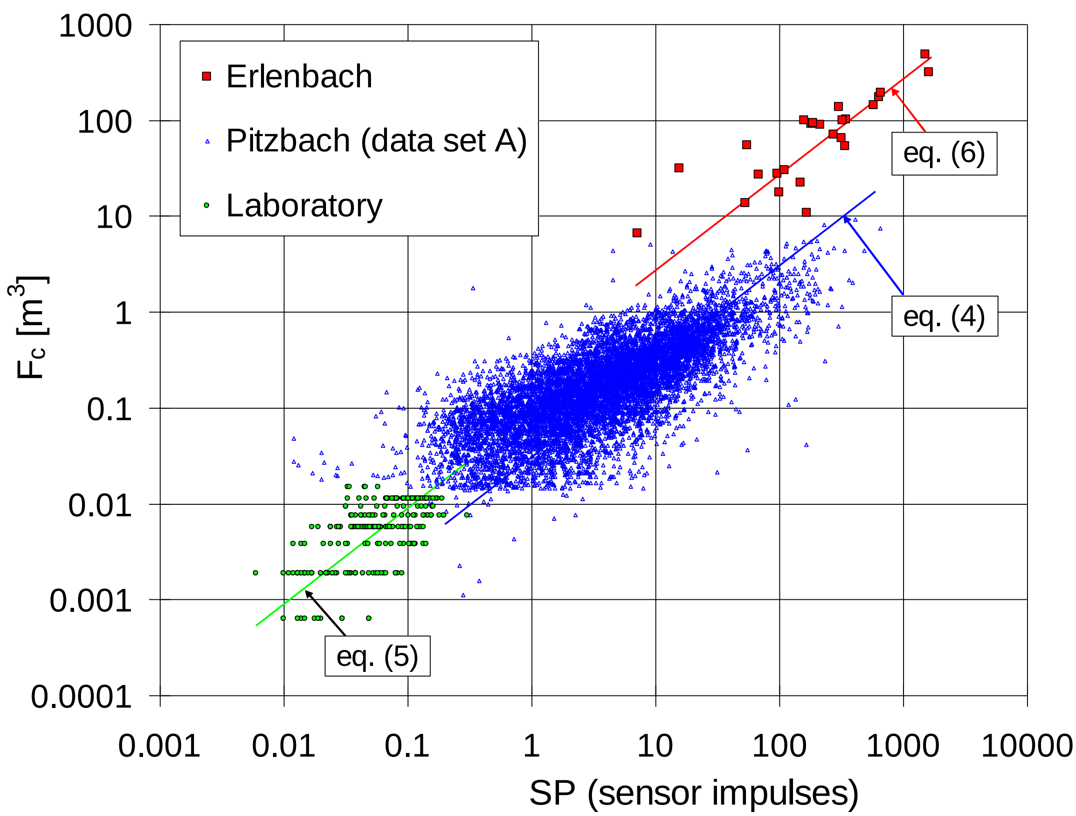

Figure 6. Measured sensor impulses (SP) vs coarse sediment volume (Fc) for the Erlenbach retention basin, from the Pitzbach settling basin (data set A), and from the laboratory experiments using particles from the Erlenbach streambed.

It is evident that the proportionality coefficient *k* for the linear calibration relationships differs for the three studied conditions. Some possible explanations are discussed in Rickenmann and McArdell (2007, 2008), but more investigations are clearly needed to better assess all the factors affecting the calibration.

Testing the PBIS system with two arrays in series

In the Erlenbach stream, there are three check dams in the vicinity of a road crossing the stream, to help stabilize the bridge foundation. This site is located some 500 m upstream of the retention basin. At two of these three check dams we installed PBIS arrays, each including 6 sensors (Fig. 7). The distance between these two check dams is 14 m, and the width of the streambed in this reach is 7.5 m. Assuming a maximum change in the bed level elevation of about 0.3 m, the sediment storage volume is estimated at about 32 m^3 between the upstream and downstream row of PBIS sensors. Using the calibration relation (2) from the Erlenbach retention basin, this storage volume corresponds to about 120 sensor impulses *SP*. However, observations indicate that normally much smaller changes in storage occur after flood events. Neglecting eroded or deposited sediment in the intervening reach, we should measure the same bedload rate over the upstream and the downstream PBIS rows. These measurements can therefore be used to assess the relative variability of the PBIS system.

Figure 7. A PBIS array mounted in the Erlenbach at a check dam ("upstream row") about 500 m upstream of the retention basin. A second array is installed at a check dam 14 m downstream of the check dam shown here.

From 11 July 1995 to 12 December 1997 we measured a total of 61 flood events with the two PBIS arrays. Here SP_u refers to the sensor impulses, divided by 1000, recorded at the upstream PBIS row, and SP_d to the respective sensor impulses at the downstream row during each of the 61 flood events (including all 6 sensors of a row). Figure 8 illustrates that there is a good correlation between the flood-based sensor impulses of the downstream and upstream PBIS row. The discrepancy between SP values at the two rows appears to be somewhat larger for SP values smaller than about 0.1 impulses at either station; according to (2) this roughly corresponds to a sediment volume of 0.026 m^3 or about 46 kg. Excluding 8 events with $SP < 0.1$, we plot the ratio of the sensor impulses measured at the two rows, $R = SP_d/SP_u$, as a function of the sensor impulses for the downstream row SP_d in Figure 9. More than 80% of the data points have a relative accuracy of R within a factor of 2. Summing SP_u and SP_d chronologically, R is around 0.67 to 0.70 for $\bullet SP_u$ up to about 1300 impulses and then R steadily increases to $R = 0.98$ for the entire observation period (with $\bullet SP_u \approx 2100$ impulses).

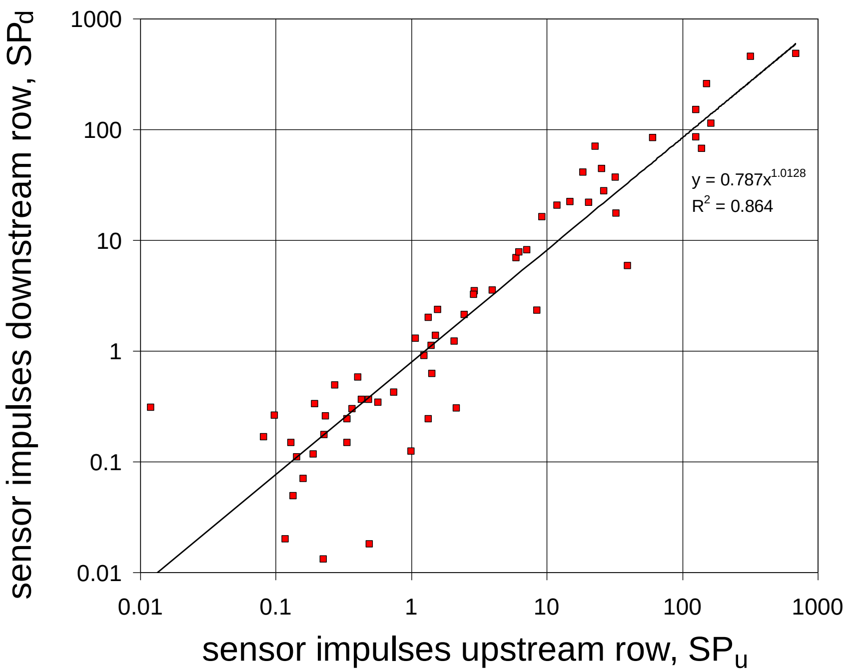

Figure 8. Correlation of sensor impulses measured at two PBIS arrays mounted in the Erlenbach at two consecutive check dams located 14 m apart.

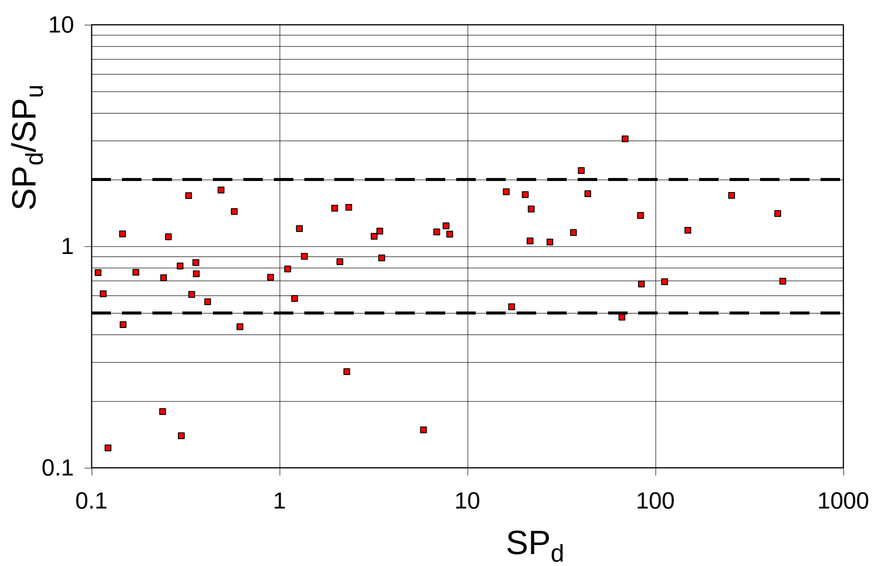

Figure 9. Comparison between consecutive rows of PBIS in the Erlenbach: the ratio SPd/SPu plotted versus the sensor impulses recorded at the downstream row, SPd. Eight events having either SPu or SPd < 100 were excluded. The data points within the two dashed line have a maximum deviation from perfect agreement by a factor of 2.

Advantages and disadvantages of the measuring system

The PBIS system has been in place in a relatively harsh Alpine environment in the Erlenbach for more than 15 years, and in some other streams for several years. The main advantages of the measuring system are:

- - continuous estimation of bedload transport intensities;
- - detection of the begin and end of bedload motion;
- - robust technique requiring very little maintenance;
- - relatively low costs for instruments and installation; and
- - for longer observation periods and larger bedload volumes a reasonable accuracy is obtained for the calibration relationships, in view of the natural variability of bedload transport in mountain streams and torrents (e.g. Rickenmann, 2001)

The disadvantages can be summarized as follows:

- - a calibration of the system is necessary;
- - no information on particle sizes in transport could be obtained in the past;
- - there is a lower limit for the particle size which can be detected (which may also depend on signal to noise ratio);
- - the influence of hydraulic conditions and sediment properties on calibration are almost unknown at present; and
- - changing flow intensities are likely to change the size distribution of transported bedload particles, resulting in non-linear calibration relations, if such effects are not averaged out

It is of particular interest to have more information on the influence of the hydraulic conditions and the sediment properties on the calibration of the system. Based on the laboratory experiments with particles from the Erlenbach, Etter (1996) found that the number of impulses depends mainly on: (i) size and shape of the particles, (ii) impact location, and (iii) type of motion (e.g. saltating, rolling or sliding). Some of these factors are averaged over longer observation periods, and may be a reason for clearly improved correlation coefficients and generally smaller standard errors for increasing integration periods when considering the Pitzbach data. However, the laboratory measurements resulted in systematically decreasing ratios SP/F with increasing (mean) particle size only for mixtures of nearly unisize particles but not for mixtures (although only two different sample volumes were investigated for multisize mixtures). Therefore, more detailed investigations are necessary to better understand the influence of particle size distribution on the calibration relations. In the Pitzbach, changing flow conditions were found to influence the calibration relationship when considering larger time intervals. Higher flow intensities result, on average, in more sensor impulses for a given sediment volume; this effect may be associated with a higher proportion of particles large enough to produce substantial sensor impulses, and may outweigh the decrease of the number impulses for larger particles observed in the laboratory for a given sediment volume.

The sensors are quite inexpensive. The main expense is a data logger or a (micro-) computer and related hardware to process the signals. Typically somewhat more expensive are the costs for the stainless steel plates and the metal construction to ensure a stable structure flush with the riverbed. For example, the cost for 6 geophone sensors is about US$1,000. The cost of the 6 steel plates, the aluminum case and the steel construction to fix the sensor plates is about US$9,000 for the measuring installation realized downstream of a check dam in the Erlenbach in 1995. The cost of a computer or data logger is US$2500.

Perspectives and further development of the measuring system

Since the year 2000 we have replaced the piezoelectric crystal with a geophone enclosed in aluminum housing. This potentially provides a more durable sensor and less variability among the individual sensors as compared to the previously used piezoelectric sensors. Although we have not yet analyzed the new measurements in detail, it appears that they behave qualitatively in a similar way as the piezoelectric sensors. A first comparison of the measurements in the Erlenbach for the period 2000 - 2002 showed that the absolute signal level of the geophones is on average lower than for the piezoelectric sensors. Therefore, the geophone signal has been amplified electronically (by a factor of 2) before the sensor impulses are counted and stored on a data logger at the Erlenbach installation since the end of 2002.

In some of the more recent geophone measuring installations a computer is used instead of a data logger. This typically requires an external electric power supply. With a computer it is possible to sample the complete geophone signal, after conversion from analog to digital, at a high frequency of several kHz. It is thereby also possible to introduce a signal amplification and set a threshold voltage level for the impulse counting in the course of data processing.

We are exploring the use of analyzing the complete PBIS signal to recover more information about the energetics of bedload transport. To do so, we plan to record the full geophone signal at a frequency of 10 kHz for some sensors, and to obtain physical samples of all grains transported over the steel plates at regular intervals. In the Erlenbach, for example, we plan to install metal baskets on the downstream wall of the large check dam above the retention basin, which can be moved laterally into the flow to sample bedload within a defined time interval. 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 ten meters, and special constructions are provided to either sample the bedload or to continuously record the weight of bedload particles deposited in a trap immediately downstream of a sensor plate (Habersack, 2008, this volume). To improve the calibration of the PBIS system and thus potentially also its range of application, we consider it essential to further investigate the effect of particle properties (grain size, distribution and shape) and flow conditions on the PBIS signal.

Conclusions

The PBIS technique provides a robust, low-maintenance method to continuously measure the intensity of bedload transport with a minimum of disturbance to the flow, if a suitable hydraulic control section can be used for their installation.

We find that transported bedload volumes are proportional to the number of impacts on the sensor per unit time. The data of numbers of impulses versus unit bedload volume display considerable scatter for small bedload volumes or short time intervals, similar to results from other methods such as vortex samplers and hand-held samplers and in conformity with the Japanese pipe geophone (Mizuyama et al., 2008b, this volume). Although the measuring system should be calibrated, the quality of the calibration increases as the duration of the averaging period increases, supporting the use of this technology particularly for long-term sediment monitoring (as shown also by Mizuyama et al., 2008b).

After calibration of the PBIS system, the error between predicted and measured sediment volumes is of the order of a factor of 1.5 to 2, both for sediment loads transported during individual flood events at the Erlenbach and for daily sediment volumes observed at the water intake of the Pitzbach (Rickenmann and McArdell, 2007, 2008). A similar relative accuracy is obtained by comparing PBIS measurements at two successive rows separated by a short channel distance in the Erlenbach. The comparison of calibration measurements from three complementary experimental investigations suggests that a linear calibration relationship may be a reasonable approximation in different bedload transporting environments. However, the proportionality coefficient depends on site specific conditions. Changing flow intensity and sediment properties are also likely to influence the calibration of the measuring system.

Acknowledgements

We are grateful to many colleagues at WSL who supported the bedload transport measurements at the Erlenbach stream. We thank the Tyrolean Water Power Company (TIWAG) for the cooperation and support at the Pitzbach measuring site. The review comments of Francesco Comiti and Takahisha Mizuyama helped to improve the manuscript, as well as comments of Brian McArdell on an earlier version of the manuscript.

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