Flume and field-based calibration of surrogate sensors for monitoring bedload transport

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Abstract

Bedload transport assessment is important for geomorphological, engineering, and ecological studies of gravel-bed rivers. Bedload can be monitored at experimental stations that require expensive maintenance, or using portable traps, which allows measuring instantaneous transport rates, but at a single point and at high costs and operational risks. The need of measuring continuously bedload intensity and dynamics has therefore increased the use and enhancement of surrogate methods. This paper reports on a set of flume experiments on which a Japanese acoustic pipe and an impact
plate have been tested using four well-sorted and three poorly-sorted sediment mixtures. Additional data were collected in a glacierized high-gradient Andean stream (Estero Morales) using a portable Bunte-type bedload sampler. Results show that the data provided by the acoustic pipe (which is amplified on 6 channels having different gains) can be calibrated for both the grain size and the intensity of transported sediments coarser than 9 mm ($R^2 = 0.93$ and 0.88, respectively). Even if the flume-based calibration is very robust, the upscale to the field is more challenging, and the bedload intensity could be predicted better than the grain-size of transported sediments ($R^2 = 0.61$ and 0.43, respectively). The inexpensive impact plate equipped with accelerometer could be calibrated for bedload intensity quite well in the flume but only poorly in the field ($R^2 = 0.16$), and could not provide information on the size of transported sediments.

**Keywords**: Transported grain-size, impact plate, acoustic pipe, Bunte-type sampler, mountain streams, Andes.

1. **Introduction**

Quantifying coarse sediment transport is of crucial importance for civil engineers, geomorphologists, river ecologists and managers (e.g. Rickenmann and Koschni, 2010), as bedload determines river morphodynamics, and type and persistence of riverine habitats. Equations for bedload prediction are usually derived from flume experiments, and tend to overestimate the actual sediment transport (e.g. Barry et al., 2004; Vazquez-Tarrio and Duarte, 2015), especially when applied to ordinary floods (D’Agostino and Lenzi, 1999) and under conditions of limited sediment supply (Recking, 2012). On the other hand, field bedload monitoring is notoriously difficult and expensive. Continuous measurements of bedload fluxes can be achieved in experimental stations using vortex-
type (Tacconi and Billi, 1987), Reid-type slot samplers (Lucia et al, 2013), or stations in which bedload and water fluxes can be separated (Bogen and Møen, 2003; Lenzi et al, 2004, Rickenmann et al., 2012), but are expensive to maintain and observations are limited to a single cross-section. Field samplings can be achieved using portable basket traps, mainly Helley-Smith (Emmett, 1980) and Bunte-type traps (Bunte et al., 2004, 2007) that can be handled from bridges, boats, or wading the channel bed. Although traps allow to monitor the size and intensity of sediment transport, there are issues related with the limited duration of bedload sampling (Bunte and Abt, 2005), size of traps, and disturbances on the bed produced by the same samplers (Vericat et al., 2006). Also, samples can be taken only occasionally, and sampling during flood events is challenging and dangerous. These limitations are especially evident in high-gradient mountain streams, where flood events tend to be short and unpredictable. More importantly, mountain streams feature coarse grain sizes, uneven bed surface, high temporal variability of bedload transport, and changes in sediment supply conditions (Comiti and Mao, 2012; Rickenmann et al., 2012), all of which makes continuous measurements with indirect methods very appealing.

Bedload can be monitored indirectly using morphological methods or methods based on virtual velocity of tracers (Liebault and Laronne, 2008), or with a variety of surrogate devices such as piezoelectric sensors (e.g. Rickenmann and McArdell, 2007), acoustic sensors (Rennie and Church, 2010), acousticpipe sensors (Mizuyama et al., 2003, 2010a,b), hydrophones (Geay, 2013), geophones (Rickenmann et al., 2014; Hilldale et al., 2014), and other sensors fixed beneath steel plates. Comprehensive reviews of the techniques and devices are provided for instance by Gray et al. (2010) and Rickenmann et al. (2012, 2014).
Even if uncalibrated, bedload sensors can provide precious indications on the beginning and end of bedload transport (Turowski et al., 2011), dynamics of bedload during flood events (Beylich and Laute, 2014; Mao et al., 2014), and sediment supply conditions (Beylich and Laute, 2014). However, there is a growing body of literature devoted at calibrating surrogate sensors versus actual bedload transport rates and size measured either in the laboratory or in the field. Rickenmann et al. (2014) calibrated Swiss plate geophones using field data collected using samplers or traps in five mountain streams, and reported that the number of collected impulses correlated with bedload mass of coarse grains, further observing that the number of impulses per bedload mass depends on the velocity of the flow, mode of sediment movements, and size of transported sediments. Beylich and Laute (2014) calibrated an impact sensor equipped with an accelerometer using data collected over a range of field sites and conditions and in a series of flume experiments, reporting that the raw data provided by the sensors could be calibrated for bedload intensities of sediments coarser than 11.3 mm. Working on the whole range of acoustic signals provided by a geophone, Tsakaris et al. (2014) were able to calibrate in a flume the transport intensities and to differentiate impacts produced by rolling and saltating sediments. More recently, Barriere et al. (2015) developed a sophisticated signal processing technique for analysing the amplitude and frequency of each impact registered by a piezoelectric hydrophone, which allowed predicting the median grain size of transported sediments. Using Bunte-type samples taken on a glacierized mountain river, Dell’Agnese et al. (2014) were able to calibrate the bedload transport rates analysing only raw data recorded with a Japanese acoustic pipe.

Overall, to date there have been only few attempts of calibrating surrogate devices in both field and flume conditions, and very little examples of calibration of more than one
sensor at a time. The main objective of this study is to calibrate a Japanese acoustic pipe and a simple impact plate encapsulating an accelerometer in order to obtain information on intensity and size of transported sediments. The study is based on a series of flume experiments using sediments ranging from 5 to 40 mm, and on Bunte-type samples taken in a high-gradient, boulder-bed stream of the Andes. We analysed the number of impulses exceeding a certain threshold as provided by the sensors, in order to develop a robust and practical way of deriving the grain size and the rate of coarse sediment transport.

2. Materials and Methods

A series of flume experiments using well- and poorly-sorted sediment mixture were carried out to test the performance of a Japanese acoustic pipe (Mizuyama et al., 2010a,b) and a bedload impact plate (Richardson et al., 2003), which were then installed in a high-gradient stream where Bunte-type bedload samplings were taken.

2.1. Tested devices

In this study we used a 0.5 m long acoustic pipe sensor (diameter 4.8 cm), manufactured by Hydrotech Company (Japan; Mizuyama et al., 2003, 2010a, 2010b). The Japanese acoustic pipe sensor is an empty steel pipe with a microphone inside which detects the acoustic vibrations induced by particles hitting the device. Acoustic pressure waves induced by moving particles hitting the pipe generate a signal amplified by a pre-amplifier and then transmitted to a converter. The converter generates a voltage which is processed through a 6-channel band-path filter (with channel 1 and channel 6 corresponding to the highest and lowest sensitivities, respectively). The band-path filters have lower (2.5 V) and upper (5 V) thresholds, hence an pulse is generated when the output of a channel exceeds 2.5 V. Each channel has a gain of 4 relative to the
previous, lesser voltage-output channel, e.g. the 6-channel voltage exiting the
converter's amplifier for a 10 mV signal is: channel 6 (×1) = 10 mV; channel 5 (×4)
=40 mV; channel 4 (×16) = 160 mV; channel 3 (×64) = 640 mV; channel 2 (×256) = 2.56 V;
channel 1 (×1024) = 10.16 V (for more details, see Mizuyama et al., 2010a; Dell’Agnese
et al., 2014; Mao et al., 2014). The converted signal is then processed by an 8-channel
interval timer attached to a datalogger, sampling the signal at a frequency of 5 Hz.

A simple bedload impact plate (Richardson et al., 2003) was tested along with the
acoustic pipe. The device is composed by a slightly convex stainless steel plate (130
mm x 150 mm x 6 mm) under which a 60 mm diameter steel cylinder encloses an
accelerometer. A count input data logger connected to the accelerometer allows to
register the cumulated number of impacts sensed at a certain time interval. The loggers
can record up to 255 impacts within a given time interval, up to 5 impacts per second.

2.2. Flume experiments

A series of experiments were carried out in a 10 m-long, 0.4 m-wide tilting flume at the
Department of Hydraulic and Environmental Engineering of the Pontificia Universidad
Católica de Chile. To reduce inlet and backwater effects, 1 m and 1.5 m-long artificially
roughened bed sections were placed at both the upstream and downstream ends of the
flume, respectively. The downstream adjustable weir was laid flat to allow the flow
depth to adjust naturally. Water level was measured at 8 locations along the flume every
30 minutes. Seven different sediment mixtures were used in the experiments (Figure 1).
Four mixtures were relatively well sorted (standard deviation of the grain size curves σ
always < 1.2), and the $D_{50}$ was of 5.6, 13.0, 24.6, and 35.9 mm, respectively. These well
sorted sediments were then mixed in order to produce poorly sorted distributions with
higher standard deviation and intermediate $D_{50}$. Thus, the two finer well sorted
sediments were combined to produce a mixture with $\sigma = 1.7$ and $D_{50} = 9.0$ mm, and the
two coarser well sorted sediments were combined to produce a mixture with $\sigma = 1.4$ and $D_{50} = 27.3$ mm. Also, the four well sorted sediments were combined to obtain a very poorly sorted grain size distribution curve with $\sigma = 2.5$ and $D_{50} = 15.2$ mm.

Bed load traps with 1 mm metal mesh were used to collect sediments at the downstream end of the flume. Sediment traps located at the downstream end of the flume were changed when approximately half full of sediments, and replaced by an empty one without stopping the pumps. Sediment collected with the trap was quickly weighted and recirculated manually into the fixed artificially roughened bed sections at the upstream end of the flume. Sediment was recirculated at intervals ranging from 1 to 40 min depending on the bed load transport rate. However, at least 200 g of sediment was collected prior to emptying the traps. Because the standard deviation of the well sorted sediments sediment mixtures was very small, it was assumed that the grain size of the transported material was equal to the grain size of the mixture in the flume. For the poorly sorted sediment mixture, a sample of the transported material collected on the trap was taken at each trap recirculating, and quickly dried and sieved in order to obtain the grain sizes of the transported sediments.

A series of runs were carried out for each grain size distribution curve, varying both discharge and channel slope in order to produce a wide range of sediment transport intensities (dimensionless shear stress ranging from approximately 0.06 to 0.1 for all grain mixtures). Transport rates were calculated in g m$^{-1}$ s$^{-1}$ using the dried weight of sediments collected at each trap changeover, the interval during which the trap collected sediments, and the width of the flume. Transport rates spanned four orders of magnitude, ranging from 0.08 to 453.44 g m$^{-1}$ s$^{-1}$. Overall, 400 and 540 measurements of sediment transport rates were taken using the well sorted and poorly sorted mixtures, respectively.
On the fixed bed sections at the downstream end of the flume, just 50 cm upstream from the sediment trap, the 0.5 m long acoustic pipe sensor was fixed transversally to the flume length (Figure 2a), with half of its diameter exposed to the flow as suggested by the manufacturer. The number of impulses for each channel was recorded at 10 seconds interval in the datalogger. In order to calibrate the device using the amount and size of sediments collected at each recirculation, the number of impulses registered for each channel was summed over the duration of each sediment collection. Also, two bedload impact plates were installed on the fixed bed section just 20 cm upstream from the acoustic pipe, 5 cm apart from one another along the flume (Figure 2a). Data was collected at 10 second interval in order to avoid data saturation on the datalogger (i.e. occurrence of more than 255 impacts in each registering interval) even at the highest transport rates.

2.3. Field data collection

One acoustic pipe and one impact plate were installed in September 2014 in a high-gradient stream of the Chilean Andes called Estero Morales. The basin (27 km²) ranges from 1850 m a.s.l. to 3815 m a.s.l., and hosts various little glaciers, some uncovered and some covered by debris, with an overall current extent of 1.8 km² (Infante Fabres, 2009; Mao and Carrillo, submitted). Runoff is dominated by snowmelt in late spring (from late September to November) and glacier melt from December to March, providing a long season of daily fluctuations of discharge with coarse sediments being transported every day at different rates. In its lower part, just upstream of the confluence with the El Volcan River, the stream cuts into glacier deposits and it is confined and steep (0.14 m m⁻¹), featuring coarse sediments \((D_{16} = 20.2 \text{ mm}; D_{50} = 59.1 \text{ mm}; D_{84} = 317.5 \text{ mm}; D_{90} = 448.1 \text{ mm})\) and a cascade/step-pool morphology.
The Japanese acoustic pipe sensor used in the flume (0.5 m long; diameter of 4.8 cm) was mounted in a log installed transversally in the channel bed (Figure 2b), in a cross section approximately 7 m wide. A slot was previously carved into the log to host half the diameter of the steel pipe as done before (e.g. Dell’Agnese et al., 2014; Mao et al., 2014). The log created a step of approximately its diameter (0.5 m) downstream, and this prevented sediments to accumulate above the sensor. The datalogger and solar panel system to supply the battery were installed in a boulder in the channel bank. Impulses for the 6 amplification channels was registered at 1 minute interval. The impact plate was installed in a 500 mm x 500 mm x 300 mm concrete box placed flush with the bed surface 1 m upstream from the acoustic pipe. The sensor was set to record the number of pings in successive 1 minute intervals.

Bedload field data for calibrating the acoustic pipe and the impact plate were collected using a 30 cm wide Bunte-type trap (Bunte et al., 2004, 2007). Overall, 193 samples were taken at the same location where the pipe and plate were installed, at a range of discharge varying from 1 to 3 m$^3$s$^{-1}$. The trap was placed just downstream of the impact plate, but upstream of the Japanese pipe. Samples were taken from January to March 2015 for intervals ranging from 1 minute to 2 hours depending on the transport rate, which ranged between 0.001 and 1851.9 g m$^{-1}$s$^{-1}$. The sediment collected in the traps was dried and sieved in the laboratory. The grain size distribution of the bedload samples was then calculated to obtain the significant percentiles ($D_{16}$, $D_{50}$, and $D_{84}$) and the standard deviation of the mixture ($\sigma$) was derived as the root of the ratio between $D_{84}$ and $D_{16}$. Because the mesh of the Bunte traps was slightly larger than 3 mm we assume that the trap was able to capture sand with unclear efficiency, and then the grain size distribution curves were all truncated at 4 mm. As done with the data collected in the flume, the impulses generated by the acoustic pipe and the impact plate were
cumulated foreach sampling period, and then expressed as number of impulses per second.

3. Results

3.1. Relationships between impulses and bedload transport rates

The acoustic pipe sensor collects impulses due to sediment impacts in 6 channels (i.e. 1 to 6, from the most to the less sensitive, respectively). The relationships between the number of impulses (per minute and per meter of sensor length) registered by each channel and sediment transport rate are shown in Figure 3. It appears that the number of impulses increases with the intensity of sediment transport. Also, Figure 3 shows that for the most sensitive channels (e.g. channels 1 to 3), at a certain transport intensity a coarser mixture produces less impulses than a finer mixture. For example, at a transport intensity of 10 g m$^{-1}$ s$^{-1}$, channel 1 registered 0.3 and 10 impulses m$^{-1}$ s$^{-1}$ for mixtures with $D_{50}$ equal to 35.9 and 5.6 mm, respectively. Indeed, for each channel the coefficient of the power-law regressions between transport and impact intensities decrease consistently from the coarser to the finer mixture (Table 1). Also, for each mixture, the coefficient of the power law regressions decreases for the more sensitive channels, whereas the slope tends to increase (Table 1). It seems worth noting also that the regression’s coefficients change considerably among grain sizes, especially for the more sensitive channels (e.g. channels 1 to 4). In fact, the coefficient of the regressions derived using channel 2 for example are remarkably different if comparing the coarser (WS = 35.9 mm) and the finer (WS = 5.6 mm) mixtures, being equal to 90.811 and 0.107, respectively (Table 1). Instead, the coefficients are comparable if values derived from data collected in channel 5 are taken into account, being equal to 276.7 and 287.5, respectively. Due to this effect, the regression curves are more spaced for the more
sensitive channels (e.g. coefficients for channel 1 ranging from 50.9 to 0.031), than for less sensitive channels (e.g. coefficients for channel 6 ranging from 349.7 to 184.4).

Data collected in the Estero Morales is plotted in Figure 3 as well, showing that for channel 6 the intensity of impulses increases with sediment transport at a rate comparable with what observed in the laboratory. For instance, the coefficient is around 381.6, similar to what was obtained for the coarsest mixture in the flume (349.7 for WS = 35.9 mm). Instead, the slope of the regressions obtained with the Estero Morales data increases for the more sensitive channels, and for channel 1 is virtually negative, indicating that the number of data registered by the pipe sensor is insensitive to the actual intensity of sediment transport.

3.2. Relationships between impulses and the size of the transported sediment

Data plotted in Figure 3 indicates that the acoustic pipe registers more impulses at higher transport rates. However, the regressions can be substantially different depending on the grain size of the transported sediments. As a consequence, the grain size of the transported material needs to be known in order to apply the correct regression and relate impulses with transport rates. However, if the rates of impulses collected by the 6 different channels are plotted one versus the others, some interesting patterns appear. Figure 4 shows that if channels 1 and 3 are compared, data obtained for the coarsest mixture plots along the line of equality, whereas finer grain sizes plots above the line of equality suggesting that, as expected, more impulses are registered in the more sensitive channel. This pattern is similar if impulses collected by more insensitive channels are compared, and on each graph of Figure 4 it appears that different grain size mixture tends to plot differently. The slope of each regression obtained combining all available channels for all grain sizes have been analysed, and the pairs that allowed to better discriminate between grain sizes are those plotted on Figure 4. A non-linear, power-law
regression was fitted, in order to obtain the grain size of transported sediments (D_{16}, D_{50}, and D_{84}) from the relationships between intensities of impulses registered for channels of different sensitivity:

\[ D_{xx} = a \left( \frac{I_{s,c1}}{I_{s,c3}} \right)^b \left( \frac{I_{s,c2}}{I_{s,c4}} \right)^c \left( \frac{I_{s,c3}}{I_{s,c5}} \right)^d \left( \frac{I_{s,c4}}{I_{s,c6}} \right)^e \]  

Eq. 1

where intensities (I_s) for each channel (from channel 1 to channel 6) were used. The coefficient (a) and exponents (b, c, d, and e) of the regressions calculated for well sorted, poorly sorted, field data, and the whole database are reported on Table 2. The coefficients of determination obtained in the flume are very high, and are higher for the D_{50} than for finer or coarser fractions. Also, surprisingly, the coefficients of determination derived using poorly-sorted mixture are slightly higher than those obtained using well-sorted mixtures. As expected, the regressions calculated using data collected in the field are weaker (e.g. R^2 = 0.47 for the D_{50}). However, if the whole dataset is used, the R^2 of the regression needed to obtain the D_{50} is around 0.65, and all parameters are significant. As shown in Figure 5, the D_{50} of well-sorted mixtures can be predicted fairly well for mixture coarser than 10mm. In fact, for the finer mixture (D_{50} = 5.6 mm), Eq. 1 is not able to predict the median size of transported particles. This is due to the fact that grains are so small that less sensitive channels (e.g. 4 and 5) are rarely activated, as can be seen in Figure 3 and 4 as well. The regression derived for poorly-sorted mixture is also effective in predicting the D_{50} of transported sediments, for a size ranging from 10 to 40 mm. If only data collected in the field are used to derive the regression, the scatter becomes considerable (Figure 5), with a clear tendency of overestimating fine median grain sizes (< 10 mm), and underestimating the D_{50} of transported sediments coarser than 50 mm. Indeed, median grain sizes as coarse as 100 mm are underestimated by half (Figure 5). When all data are used to derive a regression
to estimate $D_{50}$ for a range of grains ranging from 5 to 110 mm, Figure 5 confirms that
sediments coarser than 40 mm tends to be strongly underestimated in size.

Apart from showing that the ratio between impulses registered by different channels
plots differently depending on the grain size, Figure 4 allows appreciating that well- and
poorly-sorted mixtures plot differently. Similarly to what is presented above, the slope
of each regression obtained combining all available channels for all grain sizes have
been analysed in order to obtain the standard deviation ($\sigma$) from the relationships
between intensities of impulses registered for channels of different sensitivity, and the
best non-linear regression was fitted, obtaining the following empirical power-law
regression equation:

$$\sigma = a \left( \frac{I_{5,52}}{I_{5,54}} \right)^b \left( \frac{I_{5,53}}{I_{5,55}} \right)^c \left( \frac{I_{5,54}}{I_{5,56}} \right)^d$$

Eq.2

The coefficient (a) and exponents (b, c, and d) of the regressions obtained for well
sorted, poorly sorted, field data, and the whole database are reported on Table 3. The $R^2$
of regressions obtained in the flume are fairly high, but its performance is low for the
data collected in the Estero Morales ($R^2 = 0.28$). If the whole dataset is used, the $R^2$ of
the regression needed to obtain $\sigma$ is around 0.42.

3.3. Predicting bedload transport rates using the Japanese acoustic pipe

Figure 3 and Table 1 suggest that the rate of bedload transport ($q_s$, in g m$^{-1}$ s$^{-1}$) could be
predicted fairly well from the intensity of impulses collected by the acoustic pipe,
provided that the grain size of the transported sediments is known. Because the grain
size of the transported material could be derived from exploring the ratio between
impacts registered for channels of different sensitivity, the best-fit non-linear equations
were fit for regressions including the grain size of transported sediments (Eq. 3) and also
the standard deviation of transported mixture (Eq. 4):

\[ q_s = a D_{50}^b I_{s,c3}^c \left( \frac{I_{s,c2}}{I_{s,c5}} \right)^d \]  
Eq. 3

\[ q_s = a D_{50}^b I_{s,c3}^c \left( \frac{I_{s,c2}}{I_{s,c5}} \right)^d \sigma^e \]  
Eq. 4

The coefficients and exponents of the regressions obtained for well sorted, poorly
sorted, field data, and the whole database are reported on Table 4. It appears that the
empirical equations have high coefficient of determination if derived using data
obtained in the flume, whereas if the dataset is expanded to include field data the
performance of the regressions reduces (Figure 6). As expected, regressions feature
higher coefficients of determination if the observed rather than the predicted values of
transported grain sizes (D_{50} and \sigma) are used. Of course, if no samples are taken in the
field, D_{50} and \sigma need to be calculated (using Eq. 1 and 2, respectively) in order to assess
the intensity of sediment transport. Table 4 and Figure 6 show that the quality of the
regression equations improves slightly if the standard deviation of the transported
sediments is included. For instance, using all flume data the R^2 increases from 0.89 to
0.92 if observed values of grain sizes are considered, and from 0.87 to 0.88 if the
predicted values of grain sizes are used in the regressions. If no direct field observation
of transported grain size is available (which is the usual situation), data provided by the
pipe acoustic sensor could be converted to actual bedload intensity using an empirical
regression with R^2 = 0.61. Figure 6 e and f show that the inclusion of \sigma in the equation
does not provide a better prediction of bedload rate, and that the actual transport rate is
likely to be underestimated at the lower rates, whereas better predictions are expected at
the highest bedload transport rates.
3.4. Relationships between impulses collected by the impact plate and bedload transport rates

The impact plate, which records vibrations due to impacts in a single channel, collects higher number of impulses at higher sediment transport rates. Figure 7 shows that the slope of this relationship is fairly similar and span from 1 to 2 approximately for the range of grain sizes explored in the flume experiments (Table 5). Instead, the coefficient of the power-law regressions increases for the coarser fractions, similarly to what is observed for the acoustic pipe. Even if higher impulses are registered at the higher bedload intensities, the regression obtained from the field data is quite weak ($R^2 = 0.16$, Table 5).

4. Discussion

The results presented in this paper show that the Japanese acoustic pipe has the potential of being calibrated for grain size and transport intensity if all the 6 channels of different sensitivity at which it collects data are used. Because the size of transported material can strongly influence the relationship between impulses and transport rates, inferring the grain size from the same collected signal is critical for a successful calibration. Results from the flume experiments reveals that the grain size of transported material can be assessed by relating impulses registered on different channels. Previous flume calibrations of the same sensors showed that the number of pulses recorded by the pipe depends on the length of the pipe, the location on which the grain impacts on the pipe, the sensitivity of the microphone, and the size of grains (Mizuyama et al. 2010a). In the present study, the same pipe (0.5 m long) has been used in the flume and the field application. Mizuyama et al. (2010a) also found that impacts of particles as small as 4
mm could not be well detected by the sensor, and suggest a lower threshold of 8 mm for bedload estimation using this device. Our results support this evidence in the way that, not registering impulses on less sensitive channels, it was not possible to calculate reasonably well the grain size of the finer mixture used in the flume runs (5.6 mm). Therefore, even if less sensitive channels could still detect impacts produced by the transport of this fine gravel particles (as in Mizuyama et al. 2010b), our calibration results are applicable only for particles coarser than 9 mm.

Evidence from the field bedload sampling suggests a lower threshold of around 6 mm, which coincides with what was reported by Dell’Agnese et al., (2014) from Bunte-type bedload sampling in the Saldur River, a stream comparable to the Estero Morales in terms of slope (0.05 and 0.1 mm\(^{-1}\), respectively), grain size (D\(_{84}\) = 304 and 317 mm, respectively), and basin area (18.6 and 27 km\(^2\), respectively). As to the estimation of the size of transported sediments from the collected impulses data, evidences from the flume experiments are encouraging, as the D\(_{50}\) can be accurately predicted. However, field calibration is rather poor and this could be due to the transport of particles of different sizes and shapes, mode of transport (rolling vs. saltation), but probably mostly to the saturation of signals of the higher sensitivity channels (1 and 2), which does not allow to calibrate well a regression like Eq. 1. Indeed, the saturation of high sensitive channels of Japanese acoustic pipe even during low transport rates has been also previously reported by Mizuyama et al. (2010b) and Dell’Agnese et al. (2014). This issue could probably be overcome by processing directly the raw data (similarly to what was done by Barrière et al., 2015), which were not available for this study.

In the flume experiments, the number of impulses recorded by each channel is strongly correlated with sediment transport intensity for a wide degree of bedload transport rates. Also, the lack of a decreasing trend in the number of impacts per second at the highest
transport rate seems to suggest that virtually all transported grains impacted on the sensor even at the highest rates. During the flume experiments, grains were observed to slide and roll over the pipe sensor, but also to jump over it. Indeed, the range of bedload rate explored in the flume extends up to 453 g m\(^{-1}\) s\(^{-1}\), which would correspond to high transport rates during ordinary events, where both rolling and saltation of grains would occur. For example, in the high-gradient Rio Cordon stream in the Eastern Italian Alps, bedload transport during ordinary events reached 600 g m\(^{-1}\) s\(^{-1}\), and only over short periods during the extraordinary 1994 event raised up to 25000 g m\(^{-1}\) s\(^{-1}\) (Lenzi et al., 2004). No sign of lower impacts registered at the highest transport rates is evident even in the field, where the highest bedload intensity reached 1851 g m\(^{-1}\) s\(^{-1}\). This would suggest that, by protruding for few centimetres from the bed, the sensor is able to capture sediments transported under different type of particle motion, even if flow velocity and local flow field conditions could greatly influence the number of registered impulses (i.e. Rickenmann et al., 2014).

Overall, the procedure for calibrating transport rates and grain size using the 6 available channels of the Japanese acoustic pipe seems robust and practical in flume experiments. The method is based on the evidence that the intensities of impulses decrease consistently from finer to coarser particles on each channel. This is comparable with what obtained with the Swiss plate geophone system for particles coarser than about 30 to 40 mm (Rickenmann et al., 2014), for which less impulses per bedload mass are recorded with increasing particle size. This is likely due to the fact that, for a given bedload flux or bedload mass, there are fewer coarser than finer particles which may potentially hit the plate or pipe. However, including field data into the calibration of transport rates and grain size obtained using the 6 available channels proved challenging, as the grain size of transported sediments is poorly predicted by the tested
empirical approaches. This is likely due to the fact that the grain size of transported sediments is not strongly correlated with the transport rate \( R = 0.42; \) Mao and Carrillo, submitted). Similar trends are commonly observed in high-gradient stream and have been related to equalmobility transport conditions for a wide range of particles sizes (e.g. Marion and Weirich, 2003; Mao and Lenzi, 2007). The lack of a very strong relationship between transport rates and transported sizes has been reported also by Dell’Agnese et al. (2014), who incidentally found a good regression between the transport rate and the number of impulses registered for the less sensitive channels of a Japanese acoustic pipe. Indeed, by expressing their power-law regression between transport rates and number of impulses registered for channel 6 as in Table 1, the coefficient and exponent derived from the Saldur River are remarkably similar to what we obtained for the Estero Morales, being for example the exponent 1.79 in the former and 1.29 in the latter, respectively. In fact, Figure 8 shows that Dell’Agnese et al. (2014) empirical regression using channel 6 would predict fairly well the bedload transport rates of the Estero Morales, especially at the highest transport rates. This suggests that only a few field observations with a new bedload monitoring station on a high-gradient boulder stream could provide a good approximation for assessing bedload transport rates simply using channel 5 or 6 of the acoustic pipe. On the other hand, a deeper analysis using all channels as provided by an empirical equation like Eq. 1, could provide insights on the size of transported sediments, which is a relevant information river scientists and practitioners.

With future studies, raw data could be potentially used to assess the size of transported particles in a more sophisticated way. For instance, Wyss et al. (2014) recently proved that the amplitude of the signals captured by a Swiss geophone plate could be successfully used to extract grain size information from a geophone system. Wyss et al.
(in press) further extended this calibration demonstrating that the raw signal of Swiss plate geophones can be used to calculate impulse-based and packets-based (single particle impacts) amplitude histograms that can be related with good confidence to grain size classes and fractional bedload mass transport of particles coarser than 9.5 mm. In the present study, with the Japanese acoustic pipe we used different channels which can be considered amplification factors as pulses are generated using band-path filter with predefined thresholds, thus are analogous to the packet counts for different amplitude classes with the Swiss plate geophone system. Indeed, the calibration of a Japanese acoustic pipe could be further improved by analysing the number and magnitude of raw signals registered by the sensor. For example, Tsakaris et al. (2014) accounted for the number and magnitude of the signal spikes produced by the particle impacts on a plate geophone in order to discriminate rolling or saltation mode of transported particles. Their results point out that discriminating the grain size from signals provided by a geophone could be hampered by the fact that rolling and saltating particles may generate responses at multiple acoustic frequencies over a wider spectrum. Unfortunately, we could not record the raw data from the Japanese acoustic pipe and could not perform similar analyses. However, Rickenmann et al. (2014) found a strong correlation between the number of impulses registered by a Swiss plate geophone and a series of other parameters derived from the raw signal of the geophone, suggesting that the number of impacts is thus a good estimator of bedload transport rates of particles with a minimum grain size of about 20 mm.

The impact plate used in this study registers the impacts in a single channel, and thus does not allow to infer the grain size of the transported sediments. However, its use seems very promising, as for each grain size used in the laboratory the transport rates and impulses are strongly correlated. Also, the field-based regressions feature an
exponent remarkably similar to what obtained using the Japanese acoustic pipe. However, the regression obtained in the Estero Morales is poor ($R^2 = 0.16$) and this could be due to the fact that the plate is smaller than the pipe (150 vs. 500 mm) and does not protrude into the flow, thus limiting the chance of monitoring saltating particles. On the other hand, being longer than the diameter of the pipe (130 mm vs. 80 mm) the plates allow capturing the impacts of saltating particles with longer hop lengths than for the pipe. Overall, it seems that the Japanese acoustic pipe and the impact plates, especially the Swiss geophone plates which have been successfully calibrated in the field (e.g. Rickenmann et al., 2014), provide different but complementary data that have not been directly compared as yet, even if current efforts of producing devices with both sensors are underway (John Laronne, personal communication). Indeed, an attempt of comparing different indirect measuring systems is still lacking in literature, and this reduces the chances of using calibration formulas in streams different than those on which they have been tested.

5. Conclusions

The Japanese acoustic pipe proved to be an inexpensive and robust device for monitoring both the intensity and the grain size of coarse bedload transport in flume experiments, as the six channels at which raw data are pre-processed could be used to calibrate these two variables. The flume calibration appears to predict well the transport of grains coarser than 9 mm, and could be confidently used on flume experiments when detailed and continuous measurements of transported grain size is needed, for example during unsteady-flow experiments, which are challenging but are becoming more common practice recently (e.g. Waters and Curran, 2015). The impact plate with accelerometer can also be calibrated to obtain reliable assessment of sediment transport
intensity. However, the grain size of the transported particles could not be calibrated in this study, so that the device would work well on flume experiments using homogeneous mixtures. Nonetheless, using row data provided by an advanced acoustic version of the impact plate, Wyss et al. (in press) were able to calibrate for bedload mass fluxes and grain sizes. When installed in a high-gradient mountain stream, the acoustic pipe could not be calibrated well for the grain size of transported material, mainly due to the fact that the transport conditions approached the equal mobility conditions for the range of explored discharges. However, despite of that the bedload intensity could be calibrated reasonably well. As previously reported by Dell’Agnese et al. (2014), Bunte-type nets proved to be reliable and flexible samplers for collecting bedload data to calibrate surrogate sensors. The impact plate could not be calibrated as well as the acoustic pipe in the field, but nonetheless allowed to detect the start and end, and the temporal dynamics of bedload transport. Further investigations using the raw data of these surrogate devices could allow enhanced and more detailed calibrations, as recently proved by Wyss et al. (in press) and Barrière et al. (2015) who could also extend the calibration of a wider range of grain sizes. This could provide reliable systems for river management agencies, looking for relatively cheap and reliable ways of monitoring continuously sediment transport in rivers.

Acknowledgments

The research was supported by the project FONDECYT 1130378. We are grateful to the Corporación Nacional Forestal (CONAF) for the interest and support in this study. We thank Joaquin Lobato, Fernanda Gordo, Riccardo Rainato, and Matteo Toro for their help in the laboratory and in the field.
References


### TABLES

**Table 1.** Coefficients, exponents, coefficients of determination, standard errors and p-values for the power law regressions relating sediment transport intensity \(q_s, \text{g m}^{-1} \text{s}^{-1}\)
and number of impulses (impulses m$^{-1}$ s$^{-1}$) for each channel of the acoustic pipe and for each sediment mixtures used in the laboratory and the data collected in the field.

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Ch.</th>
<th>a</th>
<th>b</th>
<th>Se</th>
<th>Se</th>
<th>R$^2$</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>WS</td>
<td>1</td>
<td>50.901</td>
<td>1.247</td>
<td>2.860</td>
<td>0.033</td>
<td>35.984</td>
<td>0.113</td>
</tr>
<tr>
<td>35.9mm</td>
<td>2</td>
<td>90.811</td>
<td>1.121</td>
<td>2.860</td>
<td>0.033</td>
<td>35.984</td>
<td>0.113</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>143.852</td>
<td>1.032</td>
<td>3.609</td>
<td>0.032</td>
<td>31.973</td>
<td>0.014</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>208.687</td>
<td>1.025</td>
<td>4.964</td>
<td>0.032</td>
<td>31.973</td>
<td>0.014</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>276.729</td>
<td>0.999</td>
<td>7.840</td>
<td>0.034</td>
<td>31.973</td>
<td>0.014</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>349.742</td>
<td>1.009</td>
<td>10.216</td>
<td>0.030</td>
<td>31.973</td>
<td>0.014</td>
</tr>
</tbody>
</table>

**Table 2.** Summary of coefficients, exponents, coefficient of determination, and p-values for the Eq. 1 fitted to obtain the $D_{50}$ and $D_{84}$ using all well-sorted (WS) and poorly-sorted (PS) mixtures, all flume data, data obtained in the Estero Morales (EM), and the whole dataset. Numbers in bold are significant at $p < 0.01$. 

<table>
<thead>
<tr>
<th>Mixture</th>
<th>D$_{50}$</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
<th>R$^2$</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>WS</td>
<td>16</td>
<td>22.692</td>
<td>0.607</td>
<td>-0.460</td>
<td>0.317</td>
<td>-0.463</td>
<td>0.89</td>
<td>0.000</td>
</tr>
<tr>
<td>PS</td>
<td>16</td>
<td>28.362</td>
<td>0.097</td>
<td>-0.002</td>
<td>-0.297</td>
<td>-0.290</td>
<td>0.97</td>
<td>0.969</td>
</tr>
<tr>
<td>All flume</td>
<td>16</td>
<td>28.893</td>
<td>0.357</td>
<td>-0.420</td>
<td>0.109</td>
<td>-0.471</td>
<td>0.89</td>
<td>0.076</td>
</tr>
<tr>
<td>EM</td>
<td>16</td>
<td>41.193</td>
<td>0.006</td>
<td>0.606</td>
<td>-0.430</td>
<td>-0.364</td>
<td>0.74</td>
<td>0.146</td>
</tr>
<tr>
<td>All flume and EM</td>
<td>16</td>
<td>26.659</td>
<td>0.356</td>
<td>-0.456</td>
<td>0.119</td>
<td>-0.472</td>
<td>0.84</td>
<td>0.099</td>
</tr>
<tr>
<td>WS</td>
<td>50</td>
<td>29.259</td>
<td>0.492</td>
<td>-0.391</td>
<td>0.256</td>
<td>-0.418</td>
<td>0.91</td>
<td>0.000</td>
</tr>
<tr>
<td>PS</td>
<td>50</td>
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<td>0.108</td>
<td>-0.088</td>
<td>-0.325</td>
<td>0.96</td>
<td>0.395</td>
</tr>
<tr>
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<td>50</td>
<td>33.762</td>
<td>0.215</td>
<td>-0.187</td>
<td>0.108</td>
<td>-0.396</td>
<td>0.93</td>
<td>0.006</td>
</tr>
<tr>
<td>EM</td>
<td>50</td>
<td>164.707</td>
<td>-1.480</td>
<td>1.413</td>
<td>-0.695</td>
<td>-0.476</td>
<td>0.47</td>
<td>0.158</td>
</tr>
<tr>
<td>All flume and EM</td>
<td>50</td>
<td>38.100</td>
<td>0.159</td>
<td>-0.401</td>
<td>0.366</td>
<td>-0.475</td>
<td>0.65</td>
<td>0.006</td>
</tr>
<tr>
<td>WS</td>
<td>84</td>
<td>34.773</td>
<td>0.464</td>
<td>-0.373</td>
<td>0.242</td>
<td>-0.402</td>
<td>0.91</td>
<td>0.000</td>
</tr>
<tr>
<td>PS</td>
<td>84</td>
<td>44.954</td>
<td>0.089</td>
<td>0.166</td>
<td>0.006</td>
<td>-0.357</td>
<td>0.94</td>
<td>0.093</td>
</tr>
<tr>
<td>All flume</td>
<td>84</td>
<td>39.604</td>
<td>0.185</td>
<td>-0.110</td>
<td>0.104</td>
<td>-0.359</td>
<td>0.92</td>
<td>0.013</td>
</tr>
<tr>
<td>EM</td>
<td>84</td>
<td>159.115</td>
<td>-0.334</td>
<td>0.404</td>
<td>-0.566</td>
<td>-0.059</td>
<td>0.45</td>
<td>0.785</td>
</tr>
<tr>
<td>All flume and EM</td>
<td>84</td>
<td>47.149</td>
<td>0.115</td>
<td>-0.463</td>
<td>0.518</td>
<td>-0.453</td>
<td>0.43</td>
<td>0.111</td>
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</table>

**Table 3.** Summary of coefficients, exponents, coefficient of determination, and p-values for the Eq. 2 fitted to obtain the standard deviation of the transported sediment samples using all well-sorted (WS) and poorly-sorted (PS) mixtures, all flume data, data obtained in the Estero Morales (EM), and the whole dataset. Numbers in bold are significant at $p < 0.01$. 

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Table 4. Summary of coefficients, exponents, coefficient of determination, and p-values for the Eq. 3 and Eq. 4 fitted to obtain the transport intensities using all well-sorted (WS) and poorly-sorted (PS) mixtures, all flume data, data obtained in the Estero Morales (EM), and the whole dataset. Equations are derived using both the observed (O) or the predicted (P) $D_{50}$ and σ from Eq. 1 and 2, respectively. Numbers in bold are significant at $p < 0.01$. Equations identified with a star are those shown in Figure 6.

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Eq.</th>
<th>$D_{50}$ and/or σ</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>$R^2$</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>WS</td>
<td>3</td>
<td>O</td>
<td>0.007</td>
<td>2.672</td>
<td>0.871</td>
<td>0.343</td>
<td>-</td>
<td>0.85</td>
</tr>
<tr>
<td>PS</td>
<td>3</td>
<td>O</td>
<td>68.261</td>
<td>0.269</td>
<td>0.793</td>
<td>-0.960</td>
<td>-</td>
<td>0.94</td>
</tr>
<tr>
<td>All flume*</td>
<td>3</td>
<td>O</td>
<td>1.264</td>
<td>1.445</td>
<td>0.872</td>
<td>-0.763</td>
<td>-</td>
<td>0.89</td>
</tr>
<tr>
<td>EM</td>
<td>3</td>
<td>O</td>
<td>0.455</td>
<td>0.879</td>
<td>1.704</td>
<td>-0.232</td>
<td>-</td>
<td>0.68</td>
</tr>
<tr>
<td>All flume and EM*</td>
<td>3</td>
<td>O</td>
<td>5.358</td>
<td>0.927</td>
<td>0.771</td>
<td>-0.562</td>
<td>-</td>
<td>0.73</td>
</tr>
<tr>
<td>WS</td>
<td>3</td>
<td>P</td>
<td>0.0003</td>
<td>3.741</td>
<td>1.305</td>
<td>0.088</td>
<td>-</td>
<td>0.94</td>
</tr>
<tr>
<td>PS</td>
<td>3</td>
<td>P</td>
<td>68.32</td>
<td>0.282</td>
<td>0.797</td>
<td>-0.989</td>
<td>-</td>
<td>0.94</td>
</tr>
<tr>
<td>All flume*</td>
<td>3</td>
<td>P</td>
<td>0.535</td>
<td>1.643</td>
<td>0.919</td>
<td>-0.617</td>
<td>-</td>
<td>0.87</td>
</tr>
<tr>
<td>EM</td>
<td>3</td>
<td>P</td>
<td>1.5 E-4</td>
<td>1.681</td>
<td>3.760</td>
<td>-0.142</td>
<td>-</td>
<td>0.56</td>
</tr>
<tr>
<td>All flume and EM*</td>
<td>3</td>
<td>P</td>
<td>1.669</td>
<td>1.312</td>
<td>1.323</td>
<td>-1.104</td>
<td>-</td>
<td>0.61</td>
</tr>
<tr>
<td>WS</td>
<td>4</td>
<td>O</td>
<td>3.5 E-8</td>
<td>5.092</td>
<td>1.079</td>
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<td>20.335</td>
<td>0.92</td>
</tr>
<tr>
<td>PS</td>
<td>4</td>
<td>O</td>
<td>52.361</td>
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<td>All flume*</td>
<td>4</td>
<td>O</td>
<td>0.334</td>
<td>1.861</td>
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<td>-1.873</td>
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<tr>
<td>EM</td>
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<td>O</td>
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<td>0.912</td>
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<td>0.73</td>
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<td>O</td>
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<tr>
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<td>4</td>
<td>P</td>
<td>1.8 E-5</td>
<td>4.172</td>
<td>1.323</td>
<td>0.168</td>
<td>6.708</td>
<td>0.94</td>
</tr>
<tr>
<td>PS</td>
<td>4</td>
<td>P</td>
<td>98.532</td>
<td>0.513</td>
<td>0.952</td>
<td>-0.421</td>
<td>-6.144</td>
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<tr>
<td>All flume*</td>
<td>4</td>
<td>P</td>
<td>15.249</td>
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<td>EM</td>
<td>4</td>
<td>P</td>
<td>4.2 E-13</td>
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<td>1.570</td>
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<td>P</td>
<td>236.61</td>
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<td>1.791</td>
<td>0.379</td>
<td>-15.716</td>
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Table 5. Coefficients, exponents, coefficients of determination, standard errors and p-values for the power law regressions relating sediment transport intensity ($q_s$, g m$^{-1}$ s$^{-1}$) and number of impulses (impulses m$^{-1}$ s$^{-1}$) registered by the impact plate and for each sediment mixtures used in the laboratory and the data collected in the field.

<table>
<thead>
<tr>
<th>Mixture</th>
<th>a</th>
<th>b</th>
<th>Se (a)</th>
<th>Se (b)</th>
<th>$R^2$</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>WS 35.9mm</td>
<td>30.829</td>
<td>1.097</td>
<td>2.044</td>
<td>0.037</td>
<td>0.893</td>
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<td>WS 24.6mm</td>
<td>11.315</td>
<td>1.249</td>
<td>1.076</td>
<td>0.043</td>
<td>0.922</td>
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<tr>
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<td>1.305</td>
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<td>0.543</td>
<td>0.164</td>
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<tr>
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<td>0.036</td>
<td>0.871</td>
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</tr>
<tr>
<td></td>
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<td>PS 9.04mm</td>
<td>EM</td>
<td></td>
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<tr>
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<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&gt;0.01</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

**FIGURE CAPTION**

**Figure 1.** Grain size distribution of the well sorted (WS) and poorly sorted (PS) sediment mixtures used in the experiments. The names of the series on the legend correspond to the $D_{50}$ of the mixtures.

**Figure 2.** Picture of the impact plates and the acoustic pipe installed in the flume (on the left), and the monitored cross section where bedload sampling were collected in the Estero Morales using Bunte-traps (on the right).

**Figure 3.** Relationship between transport intensity and number of impulses registered by the Japanese acoustic pipe on each channel for each sediment mixtures used in the laboratory and the data collected in the Estero Morales.

**Figure 4.** Relationships between intensities of impulses registered by channels of different sensitivity by the Japanese acoustic pipe. The dotted line represents the identity line.

**Figure 5.** Prediction of median grain size of transported sediments using data acquired in the flume using well-sorted sediments (a) and poorly-sorted sediments (b), data collected in the field (c), and the whole dataset (d) using the Japanese acoustic pipe. The dotted line represents the identity line.

**Figure 6.** Observed vs. predicted values of bedload transport rates obtained using Eq. 3 (graphs on the left) or Eq. 4 (graphs on the right), and using observed (a and b) or predicted (c and d) values of grain size using the Japanese acoustic pipe. Graphs e and f refer to equations derived using the whole of data collected in the field and in the flume. The dotted line represents the identity line.

**Figure 7.** Relationship between transport intensity and number of impulses registered by the impact plate for each sediment mixture used in the laboratory and the data collected in the Estero Morales.

**Figure 8.** Observed vs. predicted values of bedload transport rates obtained using Eq. 4 (as in Figure 6f) and power-law regression proposed by Dell’Agnese et al. (2014) based on field calibration of a Japanese acoustic pipe. The dotted line represents the identity line.
**Observed $q_s$ (g s$^{-1}$ m$^{-1}$)**

- Predicted $q_s$ (g s$^{-1}$ m$^{-1}$)

- a) WS 35.9mm
- b) WS 24.6mm
- c) WS 13.0mm
- d) WS 5.6mm
- e) PS 27.03mm
- f) PS 15.01mm
- g) Estero Morales