Temporal Evolution of Bedload in a Steep Channel over a Long Duration Experiment

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ABSTRACT: Bedload fluctuations over time in steep rivers with wide grain size distributions have been observed, even under constant sediment feeding and water discharge. Observed bedload pulses are periodical and a consequence of grain sorting. Along with bedload, flow velocity and bed morphology fluctuate in time as well. The presence of large relatively immobile boulders, such as erratic stones often present in mountain streams, have an impact on flow conditions. Their influence on these bedload fluctuations has not been studied yet, namely in what concerns the frequency and amplitude of bedload fluctuations. The influence of boulders on sediment transport and flow conditions is herein investigated by means of laboratory experiments carried out in a 8 m long and 0.25 m wide tilting flume. The detailed analysis of one set of measurements obtained during a 12.8 hours (774 minutes) test is presented in this paper. For this experiment 12 boulders of diameter D=0.075 m were randomly placed in the flume, corresponding to 3% of the flume surface initially occupied by boulders. The flume slope was set to 6.7%. Input sediment discharge was constant and equal to $q_{s,in}$=0.0563 x10^{-3} m^2/s and the liquid discharge was fixed at q=1.68 x10^{-2} m^2/s. Sediment transport and boulder protrusion are measured regularly during the experiment. Furthermore, bulk mean flow velocities are measured every 15 minutes. Periodical bedload pulses are clearly visible on this long duration experiment. Bulk velocity and boulder protrusion are linked with the fluctuations of the bedload transport as demonstrated by correlational analysis. The period and the phase of the fluctuations are similar for all the measured variables. Observations indicate that the detected periodical fluctuations correspond to different bed states. Grain size distribution through the channel, varying in time and space, is clearly influencing these bedload pulses. During low sediment discharges, coarse stable riffles are formed. On the other hand, in high sediment fluxes the destruction of riffles followed by bed fining is observed. A detailed description of the experimental observations and an analysis of amplitude and frequency of fluctuations for this long duration test are presented in this article.

KEY WORDS: Bedload fluctuations, Macro-roughness elements, Boulders, Steep channel, Wide grain size distribution.

1 INTRODUCTION

Flow conditions and sediment transport are widely studied for lowland rivers. On the contrary, only relatively few studies have been made on steep mountain channels, mainly during the last two decades. Alpine rivers are typically characterized as streams having longitudinal slopes ranging from 0.1% to almost 20% or more (Papanicolaou et al., 2004). These rivers, often called gravel or boulder bed streams, constitute an important part of the total channel length in mountainous regions because most sediment reaching floodplains are mobilized on hillslopes and transit through high-gradient torrents (Yager et al., 2007).

Gravel bed and boulder bed streams are characterized by a wide grain-size distribution that is composed of finer, mobile sediments and large, relatively immobile grains or boulders (Rickenmann, 2001; Papanicolaou et al., 2004; Yager et al., 2007). In these torrents, water depth is small compared to the roughness elements. Large relatively immobile boulders can thus be considered as macro-roughness elements. Boulders have rarely been taken into account in bedload transport experimental studies. Before Ghilardi et al. (2011, 2012), only Yager et al. (2007) carried out experiments on steep slopes in the presence of boulders (regularly spaced spheres and uniform GSD). Yager et al. (2007) suggested that only the part of the shear stress not acting on boulders will induce sediment transport. Hence, the presence of boulders decreases the sediment transport capacity. Boulder dimensionless distance λ/D (-), where λ (m) is the average distance between boulders of diameter D (m), and protrusion P_{av} (m) are good proxies for sediment transport in mountain streams (Yager et al., 2012).

The presence of a wide grain size distribution (GSD) in mountain rivers has a noticeable impact on bedload. In the last decades, several researchers studied this phenomenon in experimental flumes (Iseya et al., 1987; Frey et al., 2003; Recking, 2006; Bacchi et al., 2009). Iseya et al. (1987) showed that a longitudinal sediment sorting occurs when a wide GSD is constantly fed into a flume. This segregation produces rhythmic fluctuations in the bedload transport rate. Moreover, sediment particles availability, induced by longitudinal sediment sorting, determines the magnitude of sediment transport rate and its pulses. According to Iseya et al. (1987), two main factors cause sediment transport to fluctuate. Namely migrations of bedforms and segregation of the surface grain size distribution, with the formation of an armor layer. Recking et al. (2008, 2009) carried out tests with uniform and wide grain size distribution. They noticed that bedload fluctuations were not observed in setups with uniform grain size distributions, confirming that fluctuations are a consequence of grain sorting in mixed sediments.

Recking et al. (2009) suggested that solid peak discharges are caused by the formation and migration of bedload sheets. This phenomena is accentuated in low flow conditions (small discharge) and is associated with fluctuations of bed slopes, bed load and bed state. Bed aggradation is associated with a longitudinal and vertical grain sorting, resulting in a coarsening of the bed surface and fining of the subsurface. Local slope increases only to a maximum value, followed by an abrupt increase of gravel mobility. Coarse sediments are mobilized, and fine sediment previously hidden under surface layer are transported. Recking et al. (2009) measured bedload transport and bed slope for a long duration test but no measurement of flow velocity were done.

The objectives of this paper are to elucidate the relation between sediment transport pulses, and time varying boulder protrusion and average flow velocity. This is achieved through flume experiments where bedload, bed topography changes (protrusion fluctuations) and flow velocity are assessed. Results herein presented are based on the results of a long duration experiment with boulders. Following this introduction, the experimental methods are presented, then results are analyzed and discussed and finally main conclusions are drawn.

2 RESEARCH METHODS

The main goal of this research project is to analyze the impact that randomly distributed boulders have on sediment transport capacity in steep slope rivers. This is done by means of laboratory experiments, carried out on an 8 m long (7 m usable), 0.25 m wide, tilting flume.

Sediments are constantly fed into the system by a calibrated sediment feeder situated upstream. Water discharge is measured by an electromagnetic flow-meter (Figure 1). A filtering basket suspended to a balance recuperates the sediments at the outlet, where the weight is measured every minute. When the sediment feeder is empty or the basket is full, the latter is emptied into the first and sediments are recirculated. No sediment sorting is observed at the outlet of the feeder. The protrusion P_{av} of 4 boulders is measured with a point gauge during the experiment, with a time interval of approximately 10 minutes (2-3 minutes per boulder, in a loop). Average flow velocity is measured every 15 minutes by following a dye tracer and using video analysis. A new technique, based on the tracer dilution, allowing the measurement of mean bulk velocity through the channel reach has been developed. The passage of the cloud of colorant in the reach in analyzed based on the difference between images. The movement of mass center of the cloud defines the average flow velocity (Calkins et al., 1970). Five colorant injections are done in order to obtain an average velocity value. The advantage of this technique is the simple instrumentation needed (a camcorder with 24 fps and 576x480 pixels; a computer to analyze the data). Moreover, interesting data regarding bed morphology can be obtained from the captured video (not presented in this article).

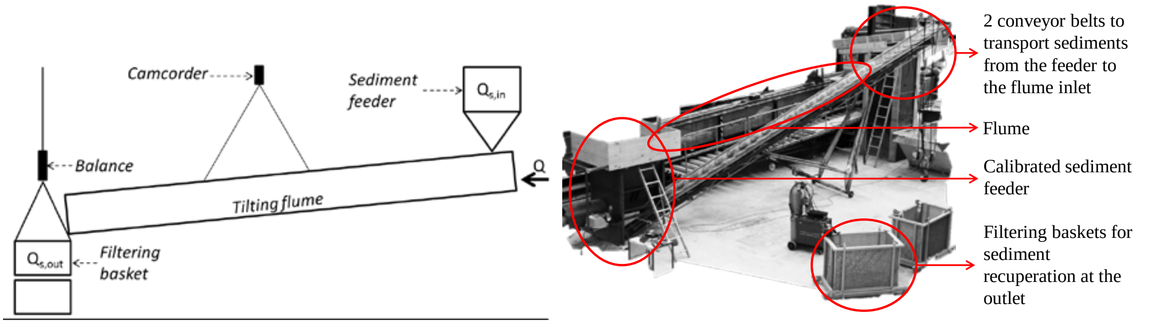


Figure 1 Sketch and picture of the experimental setup.

The grain size distribution of the supplied sediments is: $d_m=d_{65}=11.9$ mm / $d_{30}=7.1$ mm / $d_{90}=19$ mm, where d_x is the grain size diameter for which x% in weight of the amount of sediments have smaller diameters. Boulders are not taken into account in this calculation and are not supplied as mobile sediments; they are instead placed in the bed before the experiment. Boulders are relatively immobile, which means that they are not transported by the flow, although they may move up to some times their diameter during experiments, due to erosion effects around them. This is especially true for the smaller diameter of boulders (D=0.075 m), used in the present article.

The present paper analyzes the fluctuations in sediment flux, bulk velocities and boulder protrusion observed throughout a long duration experiment (774 minutes). Velocities and boulder protrusion were measured only during the first 480 minutes of the test. However, sediment outflow has been recorded through the entire experiment. Average velocity U and boulder protrusion P_{av} are sub-sampled, by linear interpolation, in order to have a regular interval of 1 minute, the same measuring period used for sediment transport $q_{s,out,10'}$.

The water discharge was set to $q=1.68 \times 10^{-2}$ m^2/s and the sediment supply to $q_{s,in}=0.0563 \times 10^{-3}$ m^2/s, both kept constant. Twelve boulders of diameters D=0.075 m have been randomly placed in the flume, with an initial protrusion of 40%, this configuration corresponding to a dimensionless distance of $\lambda/D=5$ and where 3% of the bed surface is occupied by boulders. The flume slope S is 6.7%.

3 RESULTS AND DISCUSSION

For all experiments, cyclic fluctuations of bedload transport were observed. Both of the phenomena mentioned by Iseya et al. (1987) and Frey et al. (2003), namely bedforms migration and grain sorting, have been visually observed. Figure 2 shows the values obtained for the long duration experiment, for sediment transport $q_{s,out,10'}$, bulk velocities U and average boulder protrusion P^*(which is here given as a dimensionless value of measured averaged protrusion P_{av} in meters, scaled by the boulder diameter D (m): $P^*=P_{av}/D$).

Table 1 Minimum, maximum, mean values, standard deviation (σ) and ratio between standard deviation and mean values of sediment transport $q_{s,out,10'}$, velocity U and boulder protrusion $P^*=P_{av}/D$.

	Range (min-max)	*Mean*	*σ*	*σ/mean*
$q_{s,out,10'}$	0 - 0.240 x10^{-3} (m^2/s)	0.0570 x10^{-3} (m^2/s)	0.0517 x10^{-3} (m^2/s)	0.90
U	0.39 - 0.69 (m/s)	0.53 (m/s)	0.06 (m/s)	0.11
P^*	0 - 0.51 (-)	0.22 (-)	0.15 (-)	0.69

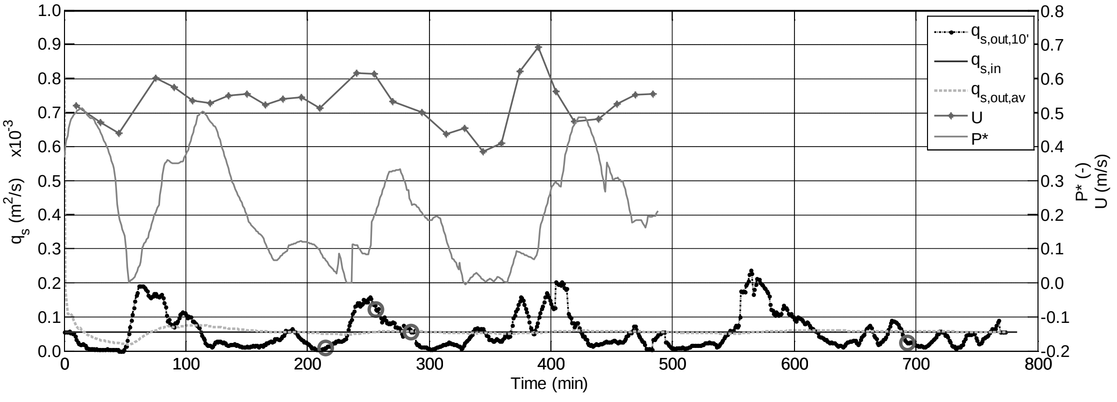


Figure 2 Measurements of bedload averaged over a 10 minutes window ($q_{s,out,10'}$), sediment supply ($q_{s,in}$) and global outlet ($q_{s,out,av}$) on the left axis. Measurement of mean velocity (U) and dimensionless average protrusion (P^*), calculated as mean protrusion (P_{av}) divided by mean boulder diameter (D), on the right axis. The dots in the velocity curve indicate the points actually measured. Long duration test (774 minutes), with 12 boulders of diameter D=0.075 m, λ/D=5 (-), $q_{s,in}$=0.0563 x10^{-3} m^2/s, q=1.68 x10^{-2} m^2/s, S=6.7%. Circles on the $q_{s,out,10'}$ curve present instants shown in Figure 3 (215, 256 and 282 minutes) and Figure 5 (693-694 minutes).

Cyclic pulses in sediment transport $q_{s,out,10'}$ are observed throughout the experiment. Figure 2 shows that these fluctuations are clearly coupled with the other measured variables U and P^*. Table 1 shows that the measured sediment flux ranges from 0.000 to 0.240 x10^{-3} m^2/s, with an average value of $q_{s,in}$≈$q_{s,out,av}$=0.0570 x10^{-3} m^2/s and a standard deviation of 0.0517 x10^{-3} m^2/s, which corresponds to a considerable value of 90% of the average. The time between peaks, with small sediment transport, is longer than the duration of peak sediment discharges. Sediment output $q_{s,out,10'}$ is smaller than the inlet during 63% of the time.

Ample and rapid fluctuations are observed also for the other measured parameters. Boulder protrusion P^* ranges from 0% (boulders completely covered) to 51% (boulders completely exposed), with an average value of 22% and a standard deviation of 15%, which corresponds to 69% of the average. As visible in Figure 2, peak in protrusion arrives clearly after the peak in sediment transport. During experiments, rapid changes in bed morphology and especially erosion and deposition around boulders have been observed, as shown in Figure 3. These two pictures are taken at exactly one minute one from the other, at instant 693 min and 694 min from the beginning of the experiment. On Figure 2 we notice that this timing corresponds to the end of a small peak in sediment transport.

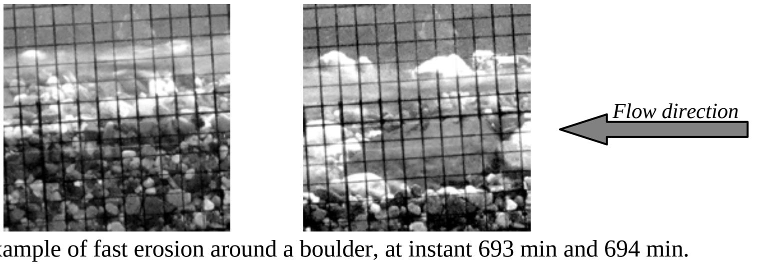


Figure 3 Example of fast erosion around a boulder, at instant 693 min and 694 min.

Variations in flow velocities U are less pronounced, they range from 0.39 m/s to 0.69 m/s, with an average of 0.53 m/s and a standard deviation of 0.06 m/s, corresponding to 11% of the average. The peak in velocity seems to take place almost simultaneously with the peak in sediment transport.

Figure 2 indicates that the average flow velocity is smaller when the protrusion is close to its maximum. This is seemingly linked to the additional flow drag induced by the boulders. Their presence disrupts the flow and dissipates energy namely through the presence of hydraulic jumps downstream of the boulders. After the peak in boulder protrusion, the latter slowly decreases. During this time sediment transport measured downstream is very low. Once the protrusion arrives at its minimum, sediment transport starts to increase again. This is a clear indication of the impact of boulders on sediment transport capacity, possibly due to decrease in shear stress available for sediment transport. Boulders do however not cause the fluctuations, since pulses seem to be even ampler and longer without them. Moreover, Yager et al. (2007) used a uniform grain size distribution for their tests, and thus didn't observe any bedload pulses.

For all the measured parameters, the increase from the lower value to the peak is faster than the decrease after the peak. This is especially visible in the sediment transport curve, which goes from close to zero to the maximum in 10 to 30 minutes and the decreases again in 50 to 70 minutes.

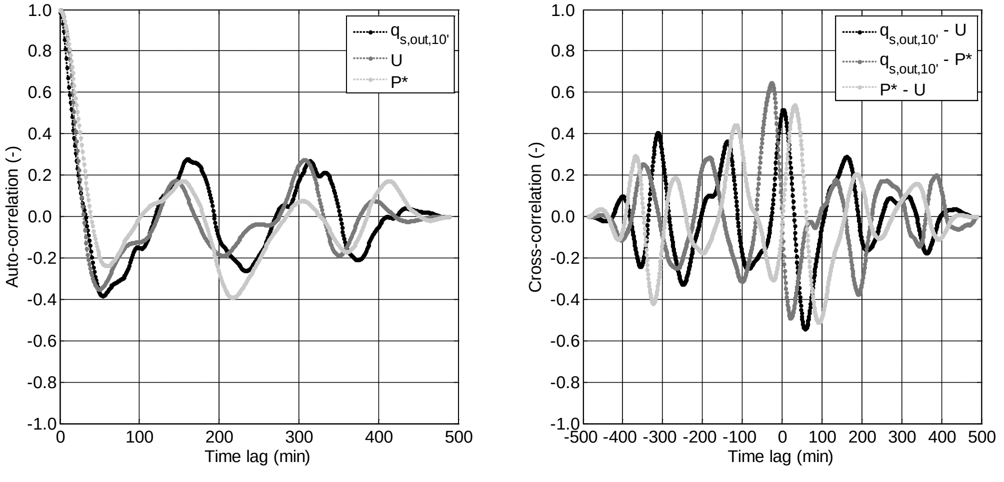
Figure 4a shows the normalized auto-correlation of the fluctuations of variables presented in Figure 2. It is clear that the duration of the periodic oscillation is the same for bedload transport, mean velocity and average boulder protrusion, roughly 155 minutes. Two peaks with statistically significant correlation values (about 0.20) are seen, namely at time lags of about 155 minutes and 310 minutes. Significant negative peaks happen at about one third of the time lag cycle indicating that the de-phasing is faster than the phasing, which is clearly confirmed by observing Figure 2 and in accordance to the previous arguments.

Figure 4b presents the normalized cross-correlation functions between the fluctuations of the three variables presented in Figure 2. Cross-correlation functions contain several statistically significant positive peaks (above and about 0.20), separated by a time lag of about 155 minutes. This indicates thus that the above identified cycle for each variable are correlated. Furthermore, distance between positive and negative peaks follow the same trend described for the auto-correlation fluctuations.

First peak of cross-correlation fluctuations show however short time delays, indicating that cycles of sediment transport, mean velocity and average boulder protrusion are not completely in phase. Cross-correlation between sediment transport and bulk velocities ($q_{s,out,10'}$-U) peaks for a small time lag of 3 minutes forward in time (cf. Figure 2). On the other hand, the cross-correlation between sediment transport and boulder protrusion ($q_{s,out,10'}$- P^*) peaks for a time lag of 27 minutes backward. This timing is similar to the one that can be observed on Figure 4a for a zero correlation after a peak in sediment transport series, which means that the peak in boulder protrusion generally occurs close to the end of a sediment transport peak, when the value in sediment transport is close to the average transport (cf. Figure 2).

The time delay between protrusion and average velocity is hence larger than the delay between these parameters and sediment transport. The delay P^*-U is 31 minutes, which corresponds to the sum of the two above mentioned delays for $q_{s,out,10'}$-U and $q_{s,out,10'}$-P^*cross-correlational function.

The period in cross-correlation remains approximately 155 minutes. Well-behaved cyclic oscillations in auto-correlation (Figure 4a) and cross-correlation (Figure 4b) confirm what can be observed in Figure 2 by looking at the measured values.



(a) (b)

Figure 4 Normalized auto-correlation (a) and cross-correlation (b) for bedload averaged over a 10 minutes window ($q_{s,out,10'}$), mean velocity (U) and dimensionless average protrusion (P^*).

The observed sediment transport fluctuations correspond to different bed states, as shown in pictures in Figure 5. A grid of 1x1 cm^2, placed on the channel wall, is visible. Picture in Figure 5a was taken at 215 minutes, during a low bedload event (cf. Figure 2). Clearly vertical grain sorting is observed, with fine sediments in the subsurface and a layer of 1 to 2 very coarse grains on the surface. According to visual observations, the diameter of the surface grains is close to or larger than d_{90} (19 mm). The bed is almost horizontal in the upstream part and steeper in the downstream part of the picture. At the downstream part of an almost horizontal coarse reach there is always a steep and coarse riffle. When few boulders are present, like in this long duration experiment, riffles can easily develop during low sediment transport event. As observed in other experiments, the fluctuations cycles are longer and with larger amplitude than when more boulders are present, due to the creation of riffle structures. The slope of the downstream part slowly increases with time, as more gravels are deposited upstream. Flow accelerates and eventually the structures fail, the breakdown propagating from downstream to upstream. Fine sediments trapped under the armor-layer are washed away and enhance the bedload transport measured downstream and breaking all existing structures in their passage. This phenomenon can happen in the downstream and central part of the flume and produce small peaks on the sediment transport measured downstream. Otherwise it can start from the upper part of the flume and, in this case, an important peak in sediment transport is observed, because the coarse structures in the entire channel are washed and allow fine sediment from the subsurface layer to move.

At the peak of bedload transport (Figure 5b, at 256 minutes) the surface sediments in the bed are very fine. Visually, the grain size is close to d_{30} (7.1 mm), or slightly larger. All of the grain sizes are transported and neither longitudinal nor vertical segregation is visible. Practically no bedforms are visible. The bed is often plane and water occupies the whole width, which is not the case in most parts of the flume during low bedload events. During bedload peaks, boulders start to get visible again.

At the end of the peak in bedload transport (Figure 5c, at 282 minutes), the grain size distribution of the surface layer is visually close to supplied mobile grain size distribution, where fine and coarse gravels are present. Boulders have a high protrusion. They may even be totally exposed, and it is often at this moment that they may be moved, due to the scouring holes that can form downstream or laterally by local erosion processes.

Due to the presence of boulders, the drag is increased. Moreover, macro-roughness elements disrupt the flow. Boulder exposure decrease the shear stress available for sediment transport since the larger the macro-roughness cross-section, the smaller the shear stress available for sediment entrainment.

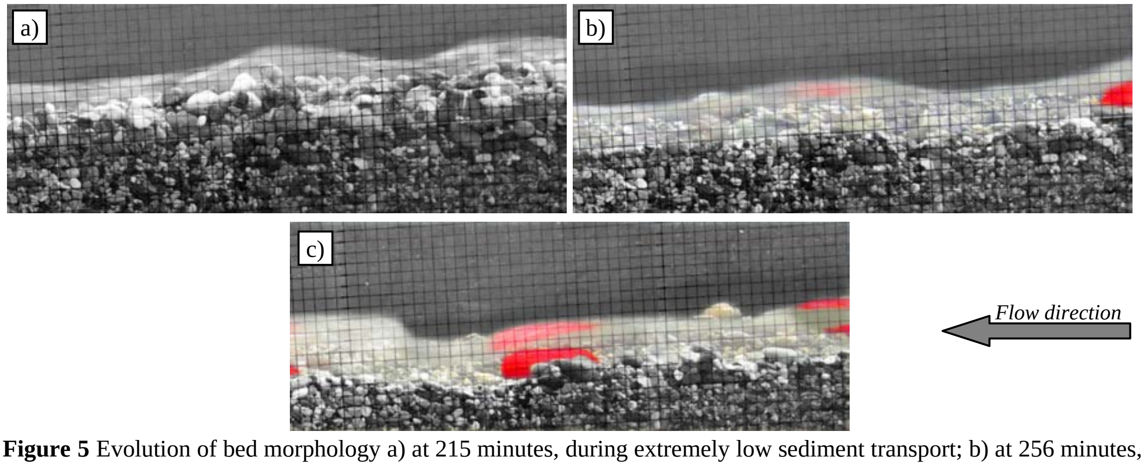


Figure 5 Evolution of bed morphology a) at 215 minutes, during extremely low sediment transport; b) at 256 minutes, at the peak of sediment transport; c) at 282 minutes, after the peak of bedload, when $q_{s,out,10'}$ is equal to $q_{s,in}$. The pictures are taken in the central part of the flume.

4 CONCLUSION

On steep slopes with wide grain size distributions and in the presence of large relatively immobile boulders, pulses of sediment transport have been observed. Empirical results from laboratory experiments, allowed analysis of bedload, mean channel velocity and average boulder protrusion in time. Correlational analysis showed the influence of oscillations on the measured variable as well as their eventual dependence in time.

One long duration experiment clearly showed that boulder protrusion and average velocity fluctuate concomitantly with bedload. The period of the fluctuations is the same for every parameter. However, feedback between the measured parameters, presents delay in time. At first, flow velocities increase due to the formation of riffles in the channel, characterized by upstream gentle slopes and downstream steep slopes. At this moment, these bed structures break down, causing the sediment transport to increase abruptly. Boulder protrusion starts then to increase due to intense sediment transport. While the protrusion increase, the bedload decreases until the boulders are mostly buried in the sediments again and a new cycle begins. However, boulders are not the cause of fluctuations; observations suggest that they have an impact on the amplitude (decrease) and frequency (increase) of the pulses.

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