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- Large variability between discharge and sediment transport
- Assessment of nature and strength of memory in fractional transport rates
- Memory depends on sediment yield, grain size, and aggregation interval

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Temporal variability and memory in sediment transport in an experimental step-pool channel

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Abstract Temporal dynamics of sediment transport in steep channels using two experiments performed in a steep flume (8%) with natural sediment composed of 12 grain sizes are studied. High-resolution (1 s) time series of sediment transport were measured for individual grain-size classes at the outlet of the flume for different combinations of sediment input rates and flow discharges. Our aim in this paper is to quantify (a) the relation of discharge and sediment transport and (b) the nature and strength of memory in grain-size-dependent transport. None of the simple statistical descriptors of sediment transport (mean, extreme values, and quantiles) display a clear relation with water discharge, in fact a large variability between discharge and sediment transport is observed. Instantaneous transport rates have probability density functions with heavy tails. Bed load bursts have a coarser grain-size distribution than that of the entire experiment. We quantify the strength and nature of memory in sediment transport rates by estimating the Hurst exponent and the autocorrelation coefficient of the time series for different grain sizes. Our results show the presence of the Hurst phenomenon in transport rates, indicating long-term memory which is grain-size dependent. The short-term memory in coarse grain transport increases with temporal aggregation and this reveals the importance of the sampling duration of bed load transport rates in natural streams, especially for large fractions.

1. Introduction

Sediment transport is a fundamental process in fluvial systems, which has been the focus of extensive research for a wide range of purposes. Understanding and properly describing fluvial sediment transport dynamics has important implications in geomorphology and engineering; e.g., sediment erosion and deposition are the main drivers of landscape evolution [e.g., Dietrich *et al.*, 2003; Tucker and Hancock, 2010], and they can impact civil infrastructures and cause natural hazards [e.g., Totschnig *et al.*, 2011; Badoux *et al.*, 2014]. Sediment transport strongly influences river ecosystems and fish habitat [e.g., Lisle, 1989; Konrad, 2009] and determines the morphology of channels [e.g., Hassan *et al.*, 2005; Church, 2006]. Modeling sediment transport is a challenging task, especially in channels steeper than 4–5%, where the methods developed for lowland streams do not perform well [Rickenmann, 2001, 2012] because of complex boundary conditions in channel morphology (due, for example, to step-pool structures and to the wide range of particle sizes and shapes), turbulence of the flow (enhanced by roughness elements like boulders and log-jams), and the impossibility of defining uniform and steady conditions.

Step-pool morphology is very often found in such steep channels, when large boulders create channel-spanning structures called steps, with downstream pools maintained by the tumbling water flow [e.g., Montgomery and Buffington, 1997; Chin and Wohl, 2005; Church and Zimmermann, 2007]. Sediment transport in step-pool streams is particularly influenced by morphological changes within the channel [e.g., Grant *et al.*, 1990; Lenzi, 2001; Hassan *et al.*, 2005; Comiti and Mao, 2012], by the spatial and temporal variability of sediment supply [e.g., Recking *et al.*, 2012; Recking, 2012], by the geomorphic coupling with adjacent hillslopes [Molnar *et al.*, 2010], and extreme hydrologic events [Lenzi *et al.*, 2004; Turowski *et al.*, 2009].

Alluvial sediment in step-pool streams is poorly sorted and boulders constitute a distinctive feature of the bed morphology. They enhance channel stability, acting as keystones in the step formation process [Judd and Peterson, 1969; Hayward, 1980; Whittaker, 1987; Church and Zimmermann, 2007; Curran, 2007]. When

these large grains are dislodged, they mobilize significant quantities of sediment which propagate downstream. Step-pool channels have been studied extensively in recent decades, focusing mainly on channel and step geometry [Curran and Wilcock, 2005; Milzow et al., 2006; Chartrand et al., 2011], hydraulics [Comiti et al., 2009; Zimmermann, 2010; Wilcox et al., 2011], bed morphology [Zimmermann and Church, 2001; Weichert et al., 2008], step formation, and channel stability [Zimmermann et al., 2010; Waters and Curran, 2012].

Einstein's pioneering work [Einstein, 1937, 1950] pointed out almost 80 years ago that bed load transport should be treated as a stochastic process. Since then, many studies have adopted a probabilistic view, focusing on the microstructural description of bed load and its implication for macroscopic observations [e.g., Ancey et al., 2006; Ancey and Heymann, 2014] or on a probabilistic description of the bulk sediment flux [e.g., Furbish et al., 2012; Roseberry et al., 2012]. Effort has also been devoted to describe bed load with different statistical formalisms [e.g., Ganti et al., 2009; Singh et al., 2009; Turowski, 2010], as well as to characterize transport fluctuations at different temporal scales [e.g., Heyman et al., 2013; Ma et al., 2014].

Statistical analyses of transport rates, measured directly in the field or in laboratory experiments, could help to improve our understanding of sediment transport and its prediction. For example, by computing the Hurst exponent or similar parameters, as done extensively in hydrological studies [e.g., Hurst, 1951; Mandelbrot and Wallis, 1969; Koutsoyiannis and Montanari, 2007], the degree of memory (or persistence) in bed load transport could be assessed at different temporal scales as well as the clustering and burstiness in transport rates. Although the Hurst exponent has previously been calculated for suspended sediment concentration of the Yellow River by Shang and Kamae [2005], to our knowledge, the memory effect for bed load data collected for different grain sizes has not been investigated.

Our work provides new insight into the dynamics of bed load transport in step-pool streams, focusing on grain-size-dependent effects. Flume experiments allow observations of sediment transport at high resolution in channels where step formation is facilitated. We use part of a data set of experiments performed in a steep flume at The University of British Columbia [Zimmermann, 2009]. The novelty of these experiments lies in the combination of a realistic channel morphology (step-pool sequences with 12 different grain sizes) and long and high-frequency (1 Hz) sediment transport measurements for different grain sizes.

In this paper, we use the experimental data to address three objectives. (1) We explore temporal variability in sediment transport rates in relation to sediment supply, flow conditions, and channel adjustment in a step-pool morphology. (2) We estimate the probability distribution of instantaneous transport rates, focusing on the effect of intense bursts in sediment transport. (3) We detect and describe memory in sediment transport: first by estimating the Hurst exponent and its dependence on grain size, and second by an autocorrelation analysis to establish the short-term memory signals in sediment transport as a grain-size-dependent phenomenon that is affected by the aggregation interval.

2. Methods

2.1. Description of the Experiments

We use part of a data set of 32 experiments performed at The University of British Columbia in a 5 m long and 0.83 m wide flume, with slopes ranging between 3% and 23% (all details about the experiments can be found in Zimmermann et al. [2008], Zimmermann [2009], Zimmermann et al. [2010], and Zimmermann [2010]). The length of the flume was sufficient to observe the formation of at least five step-pool units in every run. In order to simulate natural gravel-bedded streams, gravel-sized sediment was employed and walls made rough by attaching plywood to the flume sides to enhance the sidewall roughness. The bed surface was scanned every hour with a red laser profiler after stopping the water flow in order to obtain a DEM of the entire channel bed; repeated measurements of the same bed revealed an average standard error of ± 1.9 mm (very good considering that the largest stones in the channel have a 128 mm diameter). Average flow velocity was measured every minute with an automated salt conductance method by injecting approximately 250 mL of dilute salt solution into the upstream end of the flume and monitoring the downstream concentration with two conductivity probes located 1 and 4 m from the top of the flume. Water discharge was measured with a Thermo Polysonics DCT 1088 Transit Time Flow Meter (the instrument error is 5%) at 10 Hz frequency and then averaged to obtain a 1 Hz times series.

Table 1. Summary of Experiments 5 and 6^a

	Exp. 5	Exp. 6
Duration (h)	20.1	21.4
Flume slope (%)	8	8
Mean channel width (m)	0.359	0.359
Feed pulses (number)	4	4
Total sediment fed (kg)	76	80
Adjustment phase: Q values		
DQ1 (L/s)	19	19
DQ2 (L/s)	23	23
DQ3 (L/s)	28	28
DQ4 (L/s)	34	34
DQ5 (L/s)	41	41
DQ6 (L/s)	50	50
DQ7 (L/s)		60

^aMore details can be found in Zimmermann [2009].

outlet of the flume [Zimmermann *et al.*, 2008]. In order to study the influence of different grain sizes, in this paper, we integrate the sediment classes into four grain sizes for which transport rates (TR) were analyzed: TR1 (2–5.6 mm), TR2 (5.6–16 mm), TR3 (16–45 mm), and TR4 (>45 mm).

In this study, the results of experiments 5 and 6 of the data set, characterized by the same channel slope and same experimental setup, are analyzed. A summary of the two experiments is provided in Table 1 and Figure 1. In these two experiments, a feed phase was followed by an adjustment phase. In the feed phase, a sequence of four periods with sediment input and slowly increasing flow rates lasting 1 h each (F1–F4) was applied with the purpose of developing a stable armored bed and a step-pool morphology. After every sediment feed pulse, a recovery phase (R1–R4) followed, during which the feed was shut off. In the adjustment phase, sediment input was turned off and water discharge was increased every hour (see Table 1) until either the sediment at the base of the flume at the channel outlet was completely scoured or the maximum permitted flow rate (85 L/s) was reached. When one of these two conditions was reached, the experiment was terminated. In the adjustment phase, we analyzed separately periods with different discharge values (DQ1–DQ7), in order to observe the relation between water discharge and sediment transport in a supply-limited condition.

2.2. Analysis of Instantaneous Transport Rates

We computed basic statistics for instantaneous (1 s) transport rates of fractional and total bed load transport, the former being the time series of the four grain-size classes chosen (TR1–TR4) and the latter being

Figure 1. Phases and periods of experiments (left) 5 and (right) 6. Different grain-size classes (TR1–TR4) are shown with different colors, and water discharge (Q) is represented by a light blue line. Different columns show average transport rate for different periods lasting 1 h each. During the feed phase, feed periods (F1–F4) alternate with recovery periods (R1–R4). During the adjustment phase, hourly periods (DQ1–DQ7) represent an increase in water discharge (see Table 1).

Figure 2. A 10 min time series for the four instantaneous fractional transport rates during the adjustment phase (experiment 5, DQ6). Finer fractions (TR1 and TR2) move continuously, with increasing and decreasing trends and Hurst exponents close to 1. Coarser fractions (TR3 and especially TR4) show an intermittent behavior with bed load bursts followed by periods of no movement, and also a smaller H .

their sum. An example of four time series of fractional transport rates is provided in Figure 2. It can be seen that fine grains (TR1 and TR2) move almost continuously with pulse-like features. In contrast, coarse grains (TR3 and especially TR4) move intermittently, i.e., bed load bursts are followed by long periods of no movement.

We analyzed the relation between total instantaneous transport rates and water discharge during the adjustment phase. We fitted different probability distributions to the total instantaneous transport rates, finding that the best fit is given by a three-parameter Generalized Extreme Value (GEV) distribution. The GEV model is a versatile distribution which is able to capture the heavy tail characterizing phases of intense sediment transport. Special attention

was devoted to bursts in transport rates (i.e., instantaneous values of intense transport rate) as these are responsible for most of the bulk transport, despite being infrequent. Moreover, we determined the grain-size distribution of extreme transport rates and compare it with that of the entire experiment.

2.3. Scaling Behavior, Memory, and Autocorrelation

We perform a scaling analysis of the time series of total and fractional transport rates, in order to estimate the Hurst exponent H . The Hurst exponent is a parameter which quantifies the degree of memory (or persistence) of a process, by analyzing the properties of its time series over different temporal aggregation scales.

We estimate H by calculating σ , the standard deviation of the time series aggregated at different temporal scales T [Koutsoyiannis, 2006; Koutsoyiannis and Montanari, 2007] ranging from 1 to 90 s. H is then defined by:

$$\sigma = \frac{\sigma_0}{T^{1-H}} \quad (1)$$

where σ_0 is the standard deviation of the original time series (with 1 s aggregation scale). In a log-log space, the slope of the straight line interpolating $\frac{\sigma}{\sigma_0} = \frac{\sigma}{\sigma_0}(T)$ is equal to $H - 1$.

Two extreme situations may occur. A process with $H = 0.5$ shows short-term persistence (or short-term dependence), typical of Markovian processes, having memory only of $t - 1$. On the other hand, a process with $H = 1$ is said to have long-term persistence (long-term dependence or long memory) because the past continuously influences the present. In such a process, there is a tendency toward clustering in time of similar events [Koutsoyiannis and Montanari, 2007]. In terms of sediment transport rates, this means a tendency of intense (or weak) instantaneous transport events to cluster into long periods of high (or low) transport [Koutsoyiannis, 2002; Shang and Kamae, 2005]. More details about the Hurst exponent and its relation to intermittency can be found in supporting information.

The tendency toward short-term or long-term persistence in sediment transport can be observed in our data (Figure 2). A process having $H \rightarrow 1$, such as TR1 and TR2, shows increasing and decreasing tendencies over a range of scales, while a process with $H \rightarrow 0.5$, such as TR3 and TR4, is more intermittent with very short memory of the past.

We compute the Hurst exponent for the 13 periods of the adjustment phase (DQ1–DQ6 in experiment 5 and DQ1–DQ7 in experiment 6), both for total and fractional transport rates in order to assess the properties of memory in sediment transport as a function of mean transport rate and grain size.

Figure 3. Box plots of instantaneous bulk sediment transport rates in the periods of the adjustment phase for experiments 5 and 6 as a function of increasing water discharge (DQ1–DQ7). The box includes the values between the first and the third quartile; the second quartile (i.e., the median) is represented by a horizontal red line; the whiskers delimit minimum and maximum values; when the minimum value is zero, the line is not shown. Transport rates are plotted on a log scale to show the large variability for the same value of discharge.

The strength of short-term memory can be determined from the temporal autocorrelation of the data. We estimate the autocorrelation coefficient ρ_τ as a function of the time lag τ :

$$\rho_\tau = \frac{c_\tau}{\sigma_0^2} = \frac{\frac{1}{N} \sum_{t=1}^{N-\tau} (Y_t - \bar{Y})(Y_{t+\tau} - \bar{Y})}{\frac{1}{N} \sum_{t=1}^N (Y_t - \bar{Y})^2} \quad (2)$$

where c_τ is the autocovariance with lag τ and σ_0^2 is the variance, $\bar{Y}$ is the mean of Y , Y_t , and $Y_{t+\tau}$ are, respectively, the values of the time series at time t and $t + \tau$, and N is the length of the time series Y . We calculated ρ for every time lag τ for every period DQ of the two experiments. Finally, we repeated the autocorrelation analysis for the time series aggregated at different temporal scales, in order to show the effect of sampling duration on autocorrelation for different grain sizes.

3. Results

3.1. Effect of Discharge on Bulk Sediment Transport

The evolution of the mean sediment transport rates in different phases and periods indicates that bulk sediment flux is poorly related to water discharge (Figure 1). When sediment is fed into the flume, the feed rate dictates the output: intense transport rates are recorded during feed pulses (F1–F4) while in the recovery periods (R1–R4) mean transport rates drop. When the feed is shut off in the adjustment phase (Figure 1) and discharge is gradually incremented, average sediment transport does not consistently increase with flow rate. There are periods of high transport rates during lower discharges (e.g., DQ1 in experiment 5 and DQ2 in experiment 6), related to morphological changes in the bed (e.g., the collapse of one or more steps) with release of sediment stored in steps and pools.

The lack of a relation between instantaneous sediment transport rates and discharge is shown by box plots in Figure 3. In both experiments, there is large variability in transport rates for the same value of flow discharge. Total instantaneous sediment transport rates range from 0 to more than 2000 g/s. Changes in the percentiles of transport rates are also not consistently associated with changes in discharge. Bursts in transport rates, such as values larger than 1000 g/s, happen both with small (e.g., DQ2 in experiment 6) and large discharges (e.g., DQ6 in experiment 5). Furthermore, there is a substantial difference between the sediment transport rates in the adjustment phases in experiments 5 and 6, despite identical discharge values. This

Figure 4. (top) Probability density function of total instantaneous transport rates and (bottom) grain-size distribution of sediment yield for different exceedence probability values. The probability density functions of instantaneous transport rates are estimated with a kernel smoothing function and fitted with a generalized extreme value distribution for the entire adjustment phase of both experiments. The percentage of the sediment yield belonging to the four grain-size classes as a function of the exceedence probability shows a consistent coarsening in bed load bursts of low exceedence probability.

shows the importance of random variations in sediment transport, conditioned by hydraulic fluctuations, incipient sediment motion conditions, sediment availability, and the formation of bed morphology.

3.2. Bed Load Bursts: Probability Distributions and Fractional Composition

We fit different probability distributions to the total instantaneous transport rates during the adjustment phase, finding a good fit, especially for the tails (i.e., large transport rates), given by a three-parameter Generalized Extreme Value distribution (Figure 4). We show the GEV model fits to data with a kernel smoothing function estimator applied in logarithmically spaced bins. In Figure 4 (top), we illustrate this comparison for the entire adjustment phase of both experiments.

It is very important to model accurately the tails of the transport rate distributions because they play an important role in the total mass of the bulk sediment transport. For example, in the adjustment phase of experiment 5 (lasting 6 h), there are only 216 single measurements with an instantaneous transport rate greater than 195 g/s (which corresponds to an exceedence probability of 1%) but they are responsible for 33% of the total sediment yield. Throughout 6 h, almost one third of the sediment was delivered in only 216 s. This analysis was conducted during the adjustment phase, when extreme transport rates are particularly interesting because they are likely to be associated with changes in bed morphology and sediment storage.

Figure 5. Relation between dimensionless standard deviation of total transport rates σ/σ_0 and aggregation scale T for different periods of experiments 5 and 6. Standard deviation displays a power law decrease with aggregation interval in log-log scale, with a slope equal to $H - 1$, where H is the Hurst exponent.

The fractional composition of bed load bursts during the adjustment phase indicates size-selective transport limited by the mobility of the coarsest grains (Figure 4, bottom). If only instantaneous transport rates with a low exceedence probability are considered, the grain-size distribution of the sediment yield is coarser than that of the whole experiment and the coarsening is inversely proportional to the selected exceedence probability. Visual observations during the experiments confirm that large transport rates during phases of no feed are directly linked to major channel adjustments. Movements of coarse grains and sometimes step collapses were unequivocally observed during periods with high average transport rates.

3.3. Memory and Autocorrelation in Sediment Transport

To detect memory and long-range dependence in sediment transport rates in the adjustment phase, we estimate the Hurst exponent H following equation (1). In Figure 5, we plot σ/σ_0 for the total transport rates. The values of H are listed in Table 2. The Hurst exponent is related to the total transport rate (see Table 2): periods characterized by a relatively intense transport (such as DQ1 and DQ6 in experiment 5 and DQ2 and DQ4 in experiment 6) display milder slopes in Figure 5, which means a larger Hurst exponent and thus long-term persistence.

We also find a grain-size dependence of the Hurst exponent (Table 2 and Figure 6). First, finer grain sizes have a tendency toward long memory with $H \rightarrow 1$, while coarser grains tend toward the short-term persistence regime with $H \rightarrow 0.5$ (Figure 6a). Second, the memory in total sediment transport is limited by the mobility of coarse grains. During periods in which coarse grains are showing short-range dependence

Table 2. Values of the Hurst Exponent for All the Periods in the Adjustment Phase and for the Four Grain-Size Classes

Experiment	Period	$\overline{TR}$ (g/s)	H_{TRtot}	H_{TR1}	H_{TR2}	H_{TR3}	H_{TR4}
5	DQ1	14.7	0.95	0.96	0.95	0.92	0.73
5	DQ2	5.3	0.78	0.95	0.94	0.66	0.57
5	DQ3	3.2	0.88	0.96	0.91	0.75	0.62
5	DQ4	2.7	0.77	0.93	0.87	0.61	0.50
5	DQ5	5.4	0.68	0.85	0.83	0.61	0.54
5	DQ6	31.2	0.95	0.97	0.96	0.91	0.75
6	DQ1	3.2	0.83	0.95	0.95	0.78	0.60
6	DQ2	20.3	0.91	0.96	0.96	0.90	0.69
6	DQ3	2.8	0.75	0.92	0.90	0.63	0.50
6	DQ4	20.4	0.93	0.96	0.95	0.84	0.66
6	DQ5	5.8	0.63	0.92	0.90	0.80	0.50
6	DQ6	2.8	0.67	0.91	0.77	0.56	0.52
6	DQ7	6.7	0.67	0.90	0.82	0.62	0.50

Figure 6. Dependence of the Hurst exponent on grain size. (a) Box plots of H for total and fractional transport rates for the 13 DQ periods of the adjustment phase. (b) H for the four grain-size classes plotted as a function of H of the total transport for the 13 DQ periods.

($H \rightarrow 0.5$), regardless of the H of finer grains, the Hurst exponent for total transport is low (Figure 6b). This can be seen also in Table 2, where H is compared to the average transport rate $\overline{TR}$. In periods with low $\overline{TR}$, memory is determined by H of coarse grains, while for periods with high $\overline{TR}$, memory associated with the mobility of finer grains starts to play a major role.

The strength in memory of grain-size-dependent transport rates can be assessed by the autocorrelation coefficient ρ_τ in equation (2). For the instantaneous ($T = 1$ s) transport rates, ρ_τ is shown in Figure 7 for the entire adjustment phase for the four grain-size classes in experiments 5 and 6. Finer fractions (TR1 and TR2) have a stronger autocorrelation, while for coarser grains (TR3) autocorrelation strength and decorrelation time (i.e., time at which the autocorrelation coefficient drops close to zero) become smaller and vanish for the largest grains (TR4). Here the intermittency of the signal, due to the infrequent mobility of these grains, is responsible for the absence of correlation.

The final question is how the strength of memory relates to the temporal aggregation scales in sediment transport data. To address this, we analyze ρ_τ from equation (2) for $\tau = 1$ lag as a function of the aggregation interval T for the studied grain-size classes (we plot an example for period DQ6 in experiment 5 in Figure 8). For this analysis, we selected periods with large sediment transport so that movements of coarse grains were present. The analysis shows that ρ_1 increases with aggregation scale T for the largest fractions (TR3 and TR4), while it slightly decreases for finer fractions. This has implications for bed load transport sampling, because it shows that the intermittent nature of size-dependent grain transport can be observed only at high sampling resolutions. Already at a sampling resolution of $T = 40$ s, we practically lose any meaningful grain-size-dependent difference in autocorrelation. Long sampling may be important for total transport rates, but it dilutes meaningful grain-size effects on memory.

4. Discussion

4.1. Discharge and Sediment Transport

The first outcome of our analysis is the absence of a consistent relation between water discharge and sediment transport in the experimental data set. The same Q can produce a large spectrum of possible responses in terms of bed load transport and sediment yield, as shown in Figure 3. Transport rates in the absence of sediment feed show variability at three different levels: (1) for the same value of Q , instantaneous values of transport rates span 3–5 orders of magnitude; (2) within the same experiment, progressive increments in discharge do not necessarily lead to larger values in sediment transport; (3) phases of equal Q in distinct experiments yield consistently different transport rates. These observations may have several causes.

Figure 7. Autocorrelation coefficient ρ_τ as a function of time lag τ for different grain sizes in the adjustment phase of experiments (left) 5 and (right) 6. Finer grain sizes (TR1 and TR2) have larger values of ρ_τ , while coarse grains show weaker autocorrelation (TR3) or even no autocorrelation at all (TR4). The horizontal dotted lines represent the 5% confidence bound on serially uncorrelated data.

As already pointed out in previous studies [Dietrich et al., 1989; Hassan et al., 2008; Recking et al., 2012; Recking, 2012], sediment supply may dominate sediment transport: periods of intense transport are those during which sediment is fed into the flume, even if the values of water discharge are smaller compared to the adjustment phase (Figure 1). When the feed is turned off, other mechanisms must be responsible for episodic displacements of large volumes of sediment. The use of a grain-size mixture instead of uniform sediment can partially explain the presence of bed load transport fluctuations [Recking et al., 2009]. Moreover, sediment storage strongly influences sediment transport [Hassan et al., 2008; Pryor et al., 2011]: step-pools are natural sediment storage units and they can act to inhibit the effect of flow conditions in mobilizing grains from the river bed. As directly observed during our experiments, some of the bursts in transport rates are due to the displacement of large grains (e.g., a step collapse) and as a consequence to the increased availability of sediment. A similar mechanism has been observed by Ghilardi et al. [2014a, 2014b] in an

Figure 8. Autocorrelation coefficient for the first lag $\rho_{\tau=1}$ as a function of the aggregation scale T for different grain-size fractions. The largest fraction (TR3 and TR4) shows a general increase in autocorrelation when increasing the aggregation interval. Finer fractions (TR1 and TR2) exhibit a small decrease with increasing aggregation intervals.

experimental channel with a cascade morphology, where a geotechnical failure caused the breaking of the armor layer, therefore causing bed load bursts. Especially, in channels having well-structured and stable beds, flow-dependent parameters alone cannot explain patterns of sediment transport without considering channel stability and sediment storage dynamics [Hassan and Zimmermann, 2012].

Finally, in our experiments, channels having the same slope, same grain size, and same discharge responded quite differently because they experienced different bed-forming conditions in the past. The observed variability in sediment transport can

be explained as a consequence of the stochastic nature of bed stability [Zimmermann *et al.*, 2010], meaning that sudden channel instabilities, such as a step collapse, may cause the measured bursts in transport rates. It has been previously emphasized [Buffington and Montgomery, 1999; Hassan and Zimmermann, 2012] that in most streams flows characterized by the same duration and magnitude can produce largely different channel morphologies, and we have shown here how this applies also to sediment transport.

4.2. Stochastic Sediment Transport

The observed variability in transport rates highlights the stochastic nature of sediment transport [Einstein, 1937] and strengthens the need for its statistical description [e.g., Furbish *et al.*, 2012; Ancey and Heymann, 2014]. That instantaneous transport rates are well fitted by a heavy-tailed distribution is in agreement with previous work [e.g., Gomez *et al.*, 1989; Singh *et al.*, 2009] and identifies a process in which high-magnitude rates play an important role in bulk sediment transport. This might be also the case when looking at single particle dynamics (e.g., in tracer studies), where both particles travel distances and resting times can show heavy-tailed probability density functions, identifying a so-called anomalous diffusion behavior [e.g., Schumer *et al.*, 2009; Bradley *et al.*, 2010; Ganti *et al.*, 2010; Martin *et al.*, 2012].

Incipient motion itself can be treated as a stochastic phenomenon [e.g., Papanicolaou *et al.*, 2002], for example, in the context of an impulse formulation criterion [see Valyrakis *et al.*, 2011, and references therein]. Given the power law relation between magnitude and frequency, Valyrakis *et al.* [2011] used a GEV distribution to model impulses leading to particle entrainment. Our results are consistent with this outcome: the condition of incipient motion is directly linked to particle transport, so it is not surprising that impulses related to entrainment follow the same family of statistical distributions as instantaneous transport rates.

4.3. Hurst Phenomenon and Memory in Sediment Transport

In this work, we described the nature and strength of memory in bed load transport. As summarized in Table 2 and Figures 5 and 6, the tendency toward long memory in transport rates increases with sediment transport intensity and decreases with grain size.

We propose that, in the absence of sediment feed, stages with increased transport rates are due to changes in bed storage, when grains that were stored in steps and pools and other formerly stable structures are released and transported downstream, and this large sediment delivery is responsible for long-range dependence ($H \rightarrow 1$). On the contrary, during stages of low transport ($H \rightarrow 0.5$), we see mostly random fluctuations due to the stochastic nature of bed load transport.

The values of the Hurst exponent and the autocorrelation analysis reveal that memory is grain-size dependent and this highlights the importance of fractional transport data for an accurate description of bed load dynamics. Most notably, it is important to understand the contribution of coarse grains that are transported with high intermittency, especially because in natural steep streams their displacement can have major consequences as a natural hazard.

The Hurst exponent and the autocorrelation structure found in our data are similar to those found in a previous study of Shang and Kamae [2005]. By analyzing daily records of suspended sediment in the Yellow River, the authors proved the presence of long-range dependence both in the slow decay of the autocorrelation function and in the value of H . Despite using the same framework, our work provides a complementary analysis, proving the existence of long memory in bed load transport and its strong dependence on grain size.

4.4. Temporal Scales and Sampling Duration

Our results stress the importance of sampling duration, especially for an intrinsically intermittent process such as bed load transport. As pointed out by Bunte and Abt [2005], sampling time impacts the mean measured transport rates. We showed in Figure 8 that by aggregating the signal at different temporal scales the effect on grain-size-dependent correlation is significant. Coarse grain transport is uncorrelated at short sampling durations due to intermittency (see for example, the bottom plot for TR4 in Figure 2), but becomes correlated at larger aggregation scales. Only by increasing the sampling time it is possible to capture the time scales of sediment pulses connected to the release of large grains. This has important practical consequences: by studying the autocorrelation structure of sediment transport signals at different scales, it is

possible to determine the time scale characterizing the movements of different fractions and define a minimum sampling duration necessary to properly estimate them.

4.5. Statistical Framework for Sediment Transport

The statistical methods applied in our study are similar to those used by *Singh et al.* [2009] in analyzing instantaneous transport rates in laboratory experiments. Some differences in procedure and outcomes should be noted. First, we restricted our analysis to the monoscaling case, because our records are not long enough to perform a multiscaling analysis. For the same reason, we could not study the effect of the changing scale on the shape of the pdf function, even though this can be done with longer records, as shown by *Singh et al.* [2009]. Second, even if both studies deal with sediment transport rates, they cannot be directly compared: in our case, grain size, the absence of feed, and bed morphology play a fundamental role in dictating the results. We were able to show the importance of the coarsest fractions in bed load bursts and the strength of memory in different grain sizes captured by the Hurst exponent.

Moreover, we provided a complementary evidence for the observed trend of increasing mean transport rate with increasing sampling duration for large water discharge. We showed in Figure 8 that, in periods of intense transport, coarse fractions (which are responsible for bed load bursts) are uncorrelated at low sampling duration, i.e., the sampling duration is too short to capture the time scales characterizing their movement. It is only at sufficiently long sampling durations that they become correlated: at this point, as showed by *Bunte and Abt* [2005] and *Singh et al.* [2009], bed load bursts start to be measured and contribute to the mean flux.

Finally, we did not observe a decrease in intermittency with increasing discharge as in the experiments of *Singh et al.* [2009]. Again, this can be explained by the strong connections between bed load transport and changes in bed morphology in the experiments. As previously discussed, in well-armored channels in supply-limited conditions, the main factor dictating sediment transport response is the stability of the bed, thus masking the effect of the changing flow conditions.

5. Conclusions

By means of experiments performed in a steep flume with natural sediment, we have analyzed time series of fractional sediment transport rates measured at high frequency (1 Hz) in a step-pool channel. None of the simple statistical descriptors of sediment transport display a clear relation with water discharge. On the contrary, we observed a large variability between discharge and sediment transport, due to the stochastic nature of bed load transport and the influence of bed morphology, sediment supply and storage, and individual channel histories. Further research is needed to explain this variability and its causes; this will help to improve both sediment transport predictions and bed load modeling in general.

We analyzed instantaneous transport rates, whose pdfs are heavy tailed. The fractional composition of sediment yield reveals that the coarse fractions, which constitute a small part of the sediment yield of the entire experiment, become the dominant part during most intense sediment transport. This highlights the importance of large-grain dynamics, both in terms of channel stability and sediment budget estimates.

We performed scaling and autocorrelation analyses on transport rates to assess the nature and strength of memory in the data. We showed the presence of long-term memory in sediment transport by the Hurst exponent H . Factors affecting the tendency toward a long-range dependence regime are mainly (1) the magnitude of sediment transport, (2) the grain size of the transported material, and (3) the aggregation interval. We have shown that H is a function of grain size and that the long-term memory regime (H approaching 1) is limited by the displacement of the coarsest fractions. This effect can only be detected at sufficiently high sampling frequency and tends to disappear by aggregating the data. To our knowledge, this is the first time that the Hurst phenomenon has been quantified in bed load transport data together with other factors affecting the memory. Our work shows that fractional transport rates represent a key element for a better understanding of sediment transport and related changes in channel morphology, especially in step-pool streams, where sediment transport is supply limited and strongly modulated by the collapse of step structures and subsequent bed adjustment.

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