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Bar dynamics and sediment transport pulses in gravel-bed channels

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Abstract. Mountain rivers exhibit sediment transport rate fluctuations that often cover more than two orders of magnitude. Bedform migration is often cited as the key process that causes giant fluctuations in the sediment transport rate. To quantify the effect of bedform migration on transport rate, we ran laboratory experiments in a 19-m long 60-cm wide flume with well-sorted gravel bed. At the flume inlet, the water discharge and the particle flux were kept constant. Experiments were conducted over long times (typically > 500 h). Sediment transport rate was monitored at the flume outlet using accelerometers. Bed topography was scanned at high spatial resolution using a laser sheet. Water depth was measured using ultrasonic probes mounted on an automated rolling carriage. We observed that, under steady state experimental conditions, bed morphology played a key part in the generation of bedload transport fluctuations. The bars migrated downstream intermittently, producing the most important pulses. When the bar position was stable for a few hours, additional pulses resulted from sediment transfer from pool to pool, in the form of sediment waves (bedload sheets). Thus, in our experiments, alternate bars formed a two-entity system (bar + pool) with two distinctive functions: the bars contributed to fix and stabilize the bed whereas the pools were the preferential zones of short-term storage and transfer of sediment.

1 Introduction

The unsteady nature of sediment transport in gravel-bed rivers is a complex issue [1], which has hindered the development of accurate models [2]. In the 1980s, spatial and temporal variability has been recognized as an inherent characteristic of bedload transport [e.g., 3, 4]. Bedload pulses have thus been observed in both single-thread and braided [5–8] channels. Moreover, they have been identified to originate, at the macro-scale and with steady boundary conditions, from migrating bars [6] and low-relief bedforms such as sediment waves [7], bed waves [8], and bedload sheets [4, 9].

However, the relationship between bed structures of different types is still poorly understood. More precisely, in the context of alternate bars which are typical of gravel-bed channels [10], available studies generally focus on bar structure when investigating the origin of

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bedload pulses [6] although smallest bedforms can also migrate [11–13]. In this experimental study, we investigate the different macro-scale mechanisms that can explain the pulsating nature of bedload transport in alternate bar configurations. We have therefore performed a particularly long experiment (> 500 h) at constant sediment feed rate and water discharge. The flume was equipped with up-to-date monitoring techniques in order to collect high-resolution measurements of the bedload transport rates and bed topography. The results obtained are presented below in two steps: we first characterize the pulsating regime of bedload transport observed in our experiment, and then we relate the bedload pulses recorded to the bar and pool dynamics.

2 Experimental Setup

We carried out the experiment in a 19 m long and 60 cm wide tilting flume with glass walls allowing lateral observations. The bed was made of well-sorted natural gravel having characteristic diameters of $d_{30} = 5.2$ mm, $d_{50} = 6.0$ mm, and $d_{90} = 7.7$ mm; the mean diameter was 5.5 mm, and standard deviation 1.2 mm. The flume was inclined with a slope of 1.6%. The bed thickness was therefore nearly uniform along the flume length during the experiment. The mobile bed was retained at the flume outlet by a perforated plate in order to limit disturbing effects induced by flow resurgence.

The experiment was conducted during 567.5 h under steady bulk conditions: the flow rate was 15 l/s and the sediment feed rate was 5.0 g/s. The experiment was interrupted every 8 to 24 h in order to refill the hopper with sediment. Special attention was paid to the beginning of each run when smoothly increasing the flow as to avoid any bed disturbance. Initially, the bed was flat and about 31.5 cm thick. Alternate bars quickly developed along the bed and the Shields number then remained close to 0.08.

The bedload transport rate was measured continuously during the experiment using six impact plates placed in-line and vertically 5 cm away from the flume outlet. The vibrations caused by the impacting grains flushed out from the channel were recorded using accelerometers (model MMA7361LC manufactured by Freescale Semiconductor$^{\text{TM}}$, Inc.) fixed on the plates and then post-processed using a peak-over-threshold method. The average transport rates over one minute were finally recovered using calibration curves (relating the mass transported to the number of impulsions in the signal). Further details about the calibration can be found in [14].

Bed topography was monitored every 10 min using eight ultrasonic probes and a laser diode mounted on a moving cart. During each bed scan, the probes measured the water elevation. The bed topography was simultaneously measured by analysing the deformation of the laser-sheet projection on the bed surface (through the water). Bed elevation was subsequently corrected for refraction effects.

3 Bedload transport rates

The time series of the bedload transport rates measured at the flume outlet (see Fig. 1) is characterized by large fluctuations. This shows that intense transport events alternate with low transport phases during the experiment. Indeed, the transport rates vary within one order of magnitude about the mean value (4.8 g/s), and the corresponding coefficient of variation (i.e., the ratio of the standard deviation to the mean value) is larger than 100%. Our measurements are therefore consistent with other studies that have documented the fluctuating nature of bedload transport, including under steady flow conditions. The fluctuations we recorded are, however, larger than the ones usually reported (which are typically larger than the mean value by a factor < 10) in similar experiments [e.g., 3, 4, 6, 8]. The most likely explanation lies in the difference in the sampling time, which was much shorter in our experiment, and the run duration, which was much longer than the ones cited above (they last typically for a few tens of hours). Keep in mind that no damping of the fluctuations was observed, which supports the idea that fluctuations are an inherent characteristic of bedload transport in gravel-bed channels.

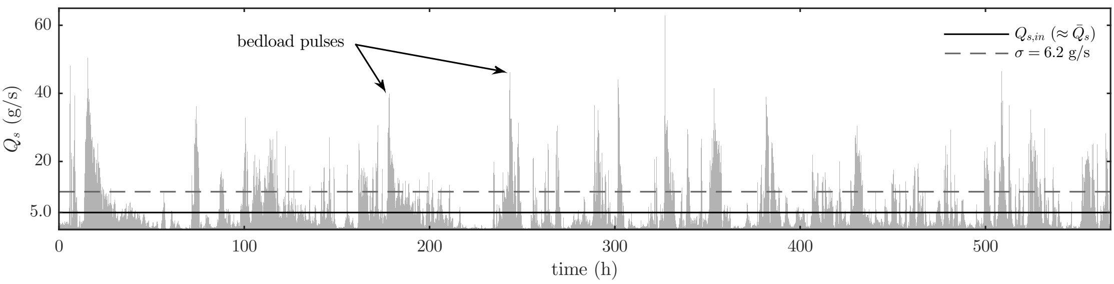

Figure 1. Time series of the bedload transport rates measured at the flume outlet and averaged over one minute. The black line represents the sediment feed rate and the grey line the standard deviation of the transport rates.

As shown by Figure 1, the fluctuations show varying peak magnitude, reflecting the intermittent nature of bedload transport. The peaks of bedload transport rate identifiable in Figure 1 are hereafter referred to as *bedload pulses* following the terminology used in [5]. They can be closely related to the notion of intense transport *events*, which are a hint of memory effects and intermittency in the time series [15].

Bedload pulses are characterized by their magnitude, duration, and frequency. We therefore define pulses in the following as any set of consecutive transport rate values in excess of the sediment feed rate and whose maximum value exceeds a given threshold. Compared to a simple peak-over-threshold approach, our method has the advantage of leaving the number of pulses independent of the threshold value that is used to define them. However, this ignores the fact that pulses with different characteristics (e.g., associated with different timescales) can overlap each other [6].

Bedload pulses in our experiment occurred over a wide range of timescales (from minutes to tens of hours). This is illustrated in Figure 2a, which shows that the transport rates are characterized by significant pulses even for sampling times as long as ten hours. The coexistence of fluctuations at different timescales has been observed in other studies [6, 16], and suggests that they are generated by distinct physical processes [8]. The power spectra of the bedload transport rates plotted in Figure 2b provide further information about the scales of fluctuations. The spectra saturate at low frequencies: it features white noise and stationarity [17]. The saturation timescale is about 45 h in Figure 2b, and gives the largest scale of fluctuations. At higher frequencies, the power spectral density decreases with increasing frequency. The log-log linearity observed indicates a scale dependence of fluctuation characteristics [16, 18]. Note that the decrease follows a power law with an exponent equal to $-3/2$. In this scaling range, some frequencies are more energetic, e.g., 1/27 h^{-1}, and indicate the dominant fluctuation periods.

Figure 3a shows the autocorrelation functions of the transport rates averaged over sampling times ranging from one minute to five hours. Large-scale pulses are characterised by a period of about 27 h, which is consistent with the period identified in Figure 2b. Moreover,

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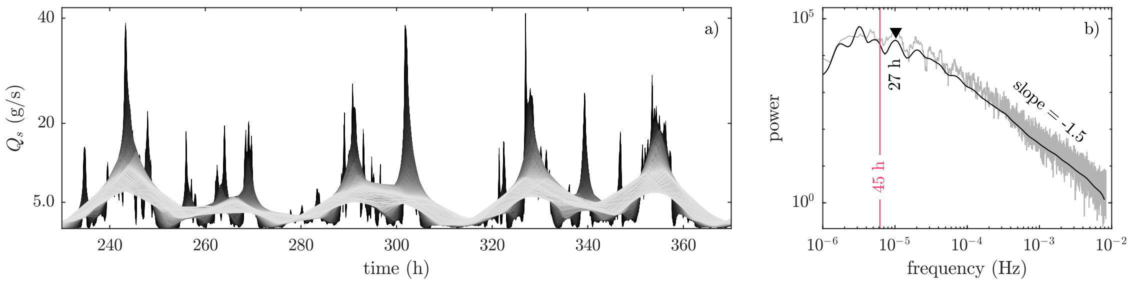

Figure 2. (a) Bedload transport rates averaged over sampling times ranging from 10 min to 10 h for a sample of the original time series. Each curve represents a different sampling time and light shades of grey stand for large values. (b) Multitaper spectrum (grey) and wavelet spectrum (black) of the bedload transport rates. The vertical line indicates the saturation timescale and the triangle marker one of the dominant frequencies.

the first time the autocorrelation functions drop to zero gives an estimation of the duration of large-scale pulses. Note that any periodicity in fluctuations at shorter timescales cannot be investigated in Figure 3a since they are "over-written" by the more energetic large-scales pulses. The pseudo-periodic character of the latter suggests that large-scale pulses originate from deterministic mechanisms occurring in the bed [19] rather than from stochastic processes [16].

From a morphological perspective, the occurrence of bedload pulses much larger than the sediment feed rate implies that, during the bursts, large sediment volumes are transported along the bed, which is therefore globally eroded. During low transport phases, the bed is aggraded because of sediment deposition. These fluctuations in the total bed volume, which can be computed based on the difference between the transport rates and the feed rate, are shown in Figure 3b. A striking feature of this time series is the two large-scale fluctuation regimes that can be identified: bed volume variations are slower and of greater amplitude during the first part of the experiment (230 h) than during the second part. Both regimes present, however, the same hysteretic behaviour, i.e. the bed volume decreases much faster than it increases. These sudden drops in bed volume and slow aggradation phases are consistent with the pulsating nature of bedload transport discussed above since the latter implies that large amounts of sediment are released over short time periods compared to sediment deposition phases. It is worth noticing that this behaviour seems independent of the timescale considered.

The fluctuations in the bed volume reflect the large-scale fluctuations in the transport rates. Among other things, the bed volume variations have the same pseudo-periodic behaviour as the transport rates (see Figure 3b). This underlying fluctuation pattern, which was not readily identifiable in Figure 1, suggests that the bed storage capacity controls large-scale fluctuations in the system. In this view, the bed behaves like an electric condenser storing incoming sediment until a certain critical point related to its storage capacity, and then releasing sediment over short time periods (this cause the pulses). In addition, the existence of two fluctuation regimes (Figure 3b) indicates that quasi-equilibrium conditions may be achieved under controlled conditions only after very long time periods compared to common experiment durations (typically less than 100 h). It also demonstrates that different fluctuation regimes may be observed during resilience periods, e.g., following a disturbance that flattened out the bed.

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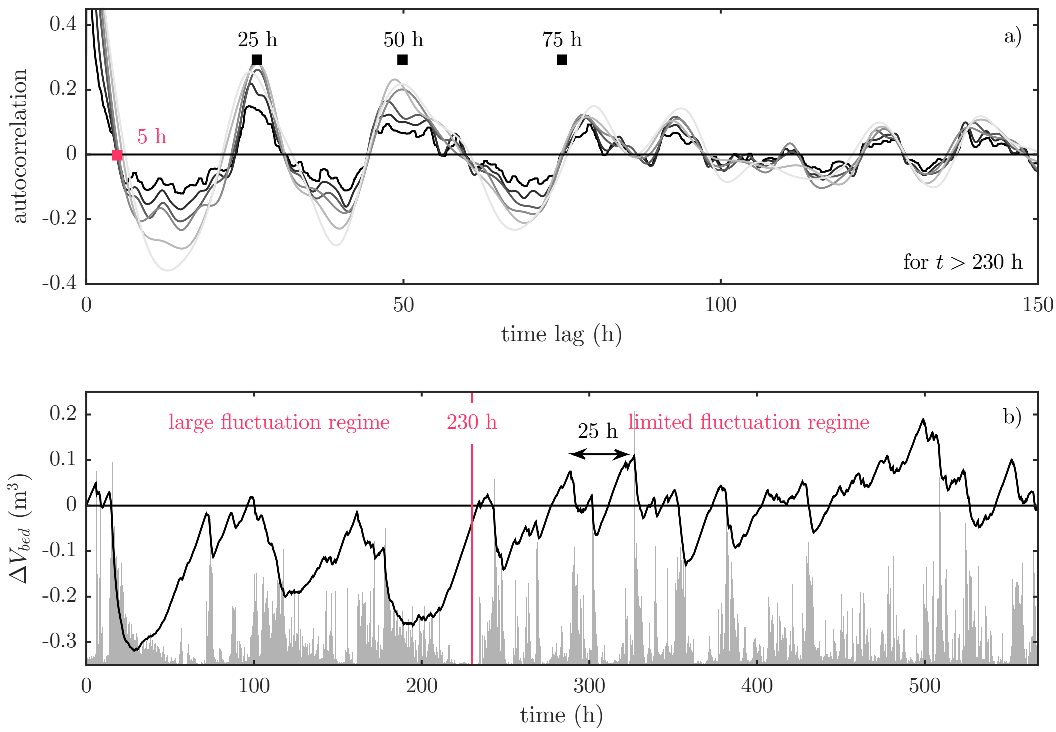

Figure 3. (a) Autocorrelation function of the bedload transport rates averaged over different sampling times. The black curve corresponds to a 1 min sampling time. The grey curves correspond to sampling times ranging from 1 h to 5 h (light shades stand for large values). The first 230 h of the experiment were ignored in order to stress the autoregressive behaviour observed. (b) Temporal evolution of the relative bed volume during the experiment (the dry bulk density of the bed material is 1490 kg/m^3). The plot in the background shows the bedload transport rates on an arbitrary scale.

4 Morphological Origins of Bedload Pulses

The bed topography in our experiment is typical of single-row alternate bars, with a succession of bars and pools on either flume side (see Figure 4). Note that the bars were mostly in flush with the water surface and their length scaled with the flume width by a factor of 4–6 times, in agreement with dimensionless diagrams presented by Yalin [20]. In addition, the pools were about 10 cm deep, the flow velocity was close to 1 m/s, and the flow regime was turbulent and transcritical, with a Froude number oscillating around 1. The average bed slope, computed by averaging the bed elevation in the downward direction and then by performing a linear regression, was 1.5%, which is close to the flume slope (1.6%).

Note the difference in the bed configuration during the two large-scale fluctuation regimes discussed above (see Figure 3b): the bed is more sinuous (generally two pools instead of three) and the bars are more stretched in the longitudinal direction in the first regime. This result is interesting since it shows that the bed, under identical external conditions, can take different persistent configurations associated with different fluctuation regimes. In our experiment, the first configuration can be seen as a resilience state resulting from the initial flat bed configuration, which is unstable. Furthermore, the second state can be seen as an equilibrium configuration which is more stable and persistent over time.

We investigated the topography evolution during the experiment along the right and left longitudinal profiles of the bed (i.e., 5 cm away from either wall) since they captured the essential features of the bar and pool dynamics. Examining their evolution, an example of which is shown in Figure 4, shows that the bars were mostly stationary. However, they appeared to episodically migrate in the downstream direction, and modify the overall pattern of the alternate bars. Significant bar migration (i.e., over a distance larger than 50 cm) was observed 56 times over the experiment duration, and this corresponds on average to one migration event every ten hours. This low occurrence frequency confirms the quasi-stationary character of the bars in our study. The average duration and distance of these events were respectively 1.7 h and 1.4 m, which gives an order of magnitude of their temporal and spatial scales. Moreover, bar migration was identified to occur as a chain reaction propagating from upstream to downstream rather than in the form of a regular train of waves. This observation supports Crosato et al. [21], who suggested that the bar migration mechanism is akin to a domino effect.

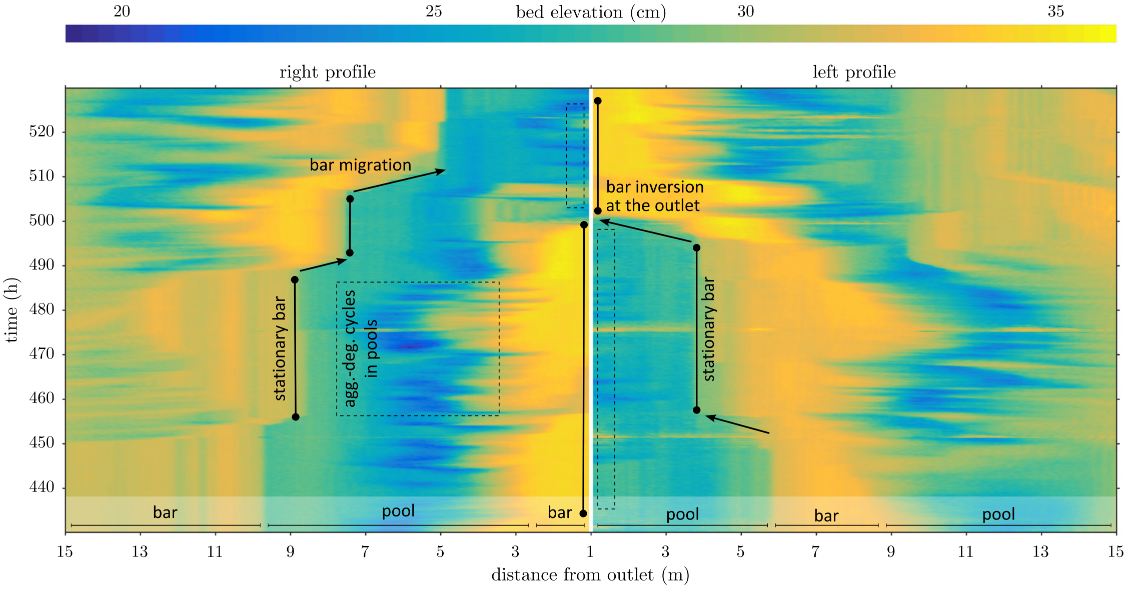

Figure 4. Evolution of the right and left profiles of the bed during 100 h. The two profiles are plotted symmetrically with respect to the flume outlet, which corresponds to the figure centerline. Bars migrate episodically downstream, while pools undergo cycles of aggradation-degradation as indicated by the continuous but limited fluctuations in their elevation.

When bars remain stationary—this can last for tens of hours—, pools undergo continuous cycles of aggradation-degradation. This is reflected by the bounded variations in their elevation (i.e., of the order of few centimeters) appearing in Figure 4. Moreover, the cycles in the different pools were found to be correlated within a certain time window, which implies that they are the signature of low-height bedforms migrating in a step-like motion from pool to pool, as reported by [7]. In other words, *sediment waves* travel in the downstream direction and can be momentarily trapped in pools along their pathway. This mode of transport is a clear example of the intermittent nature of bedload transport in space and time. Note that the term *sediment waves* is used here in reference to a common process by which sediment is transported in alluvial channels (they are also sometimes referred to as *sediment translation waves* [22, 23]), inducing local variations in bed elevation [8]. We refer the reader to James' review paper [24] for clarification about this terminology and its usage in different contexts.

The migration of bars and sediment waves implies that large sediment amounts are transported in the downstream direction. In order to investigate the role played by these two mechanisms in the generation of bedload pulses (see Section 3), we investigated their dynamics close to the flume outlet. Bar migration ultimately resulted in bar inversion near the outlet (i.e., the most downstream bar and pool change side) as illustrated in Figure 4. By tracking these events during the experiment, we found that bar migration generated most large pulses recorded (e.g., 60% of the pulses exceeding $6Q_{s,in}$). However, the migration of these large structures only explained less than 20% of the pulses larger than $2Q_{s,in}$, which implies surprisingly that they were not the main cause of the pulsating behaviour observed. This finding motivated us to investigate the dynamics of the pool near the flume outlet when the adjacent bar was static. During these phases, the longest of which lasted 120 h, the fluctuations in the pool elevation and transport rates were found to be highly correlated to each other (the cross-correlation coefficients was about 0.7). This result led us to conclude that sediment waves were the primary mode of bedload transport in our experiment and generated most pulses recorded.

The considerations above highlight the role of sediment buffer played by the bed (as already suggested by the analogy with the electric condenser storing and releasing sediment). For the essential part, the bed intermittently transfers sediment volumes from one sediment reservoir to the other rather than acting like a sediment toboggan. This behaviour explains, to a large extent, why bedload transport appears as pulsating at the macro-scale. Pools seem thus to ensure the transport of sediment in a step-like manner while bars stabilise elements diverting the flow that and collapse at certain times. In our experiment, bar failures seem to be triggered by nonuniform sediment feed across the upstream cross-section (we used a Galton board to spread the sediment, so most of the sediment fell near the flume centerline, and little close to the walls).

5 Conclusion

Our experiment follow on the studies conducted since the late 1980s, which have investigated the link between the pulsating nature of bedload transport and migrating bedforms. The substantial improvement in measurement techniques over the last two decades has allowed us to collect a high-resolution dataset, which brings new insight into the origins of bedload pulses in gravel-bed channels with alternate bars.

Our results show that pulses in such channels can be caused by sediment waves migrating in a step-like motion. This finding sheds new light on the nature of bedload transport since, to our knowledge, large pulses in the context of alternate bars are generally attributed to migrating bars [6]. Such sediment waves seem to differ substantially from the ones reported in braiding channels [7, 8] as they result from the trapping of sediment in pools, which thus undergo continuous aggradation-degradation cycles. If so, the local sediment transport-storage relationship in alluvial channels is are of paramount importance to understanding pulse generation.

In addition, the especially long experiment duration allowed us to observe a pseudo-periodic behaviour of large-scale fluctuations, which seem ruled by the bed storage capacity. This highlights the role of sediment buffer played by the bed: the bed stores incoming bed material and releases it over short time periods. We also observed two fluctuation regimes

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associated to distinct bed configurations, which implies that any resilience state can be relatively persistent (230 h in this study) and that quasi-equilibrium can be reached after longer time periods than is usually assumed in similar experiments (typically in the order of hours).

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