How fast or how many? Sources of intermittent sediment transport

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Abstract

Near the threshold of grain motion, sediment transport is "on-off" intermittent, characterized by large but rare bursts separated by long periods of low transport. Without models that can predict the presence of intermittency, measurements of average sediment flux can be in error by up to an order of magnitude. Despite its known presence and impact, it is not clear whether on-off intermittency arises from the grain activity (the number of moving grains) or grain velocities, which together determine the sediment flux. We use laboratory flume experiments to show that the on-off intermittency has its origins in the velocity distributions of grains that move by rolling along the bed, whereas grain activity is not on-off intermittent. Improved predictions of sediment flux require that the types of intermittency we identify be incorporated into stochastic models of sediment flux. Their recognition opens the door to physically based uncertainty estimates of time-averaged sediment flux.

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How fast or how many? Sources of intermittent sediment transport

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KEY POINTS

1. We use grain tracking data from laboratory experiments to separately study the statistics of grain velocities and grain activity.
2. We show that on-off intermittency has its origins in the velocity distributions of grains, not in the grain activity.
3. On-off intermittency comes from grains rolling on the bed, and disappears as more and more grains are lifted into the bulk of the flow.

PLAIN LANGUAGE SUMMARY

The transport of sediment by wind and water contributes substantially to the evolution of Earth's surface, as well as the surfaces of other planetary bodies. Predicting the time-averaged sediment flux is standard practice in the field and is crucial for modeling landscape evolution. Near the threshold of grain motion, sediment flux is highly intermittent, experiencing long periods of low flux punctuated by large, rare bursts of sediment transport. This creates difficulties when taking time averages, which must be done over longer periods of time the stronger the intermittency is. It has been demonstrated that the intermittency is of a particular kind, called on-off intermittency. Despite this, there is currently no understanding of its physical origin. We use a series of laboratory experiments to show that the on-off intermittent component of sediment flux comes from velocities of the grains rolling on the bed, and that the intermittency is reduced as more grains are lifted into the fluid. This understanding will help connect channel and flow properties to the theory of on-off intermittency, paving the way for better measurements and predictions of sediment flux.

ABSTRACT

Near the threshold of grain motion, sediment transport is “on-off” intermittent, characterized by large but rare bursts separated by long periods of low transport. Without models that can predict the presence of intermittency, measurements of average sediment flux can be in error by up to an order of magnitude. Despite its known presence and impact, it is not clear whether on-off intermittency arises from the grain activity (the number of moving grains) or grain velocities, which together determine the sediment flux. We use laboratory flume experiments to show that the on-off intermittency has its origins in the velocity distributions of grains that move by rolling along the bed, whereas grain activity is not on-off intermittent. Improved predictions of sediment flux require that the types of intermittency we identify be incorporated into stochastic models of sediment flux. Their recognition opens the door to physically based uncertainty estimates of time-averaged sediment flux.

INTRODUCTION

Sediment transport by wind and water drives the evolution of landscapes on Earth as well as on other planetary bodies. In bed load sediment transport, grains roll, skip, and collide in an irregular fashion (Parker et al., 2007), leading to fluctuations in sediment flux. Near the threshold of grain motion, these fluctuations are accompanied by occasional large bursts, making the sediment flux intermittent, a phenomenon that has been observed in gravel and sand transport by water (Gomez, 1991; Ancey et al., 2006, 2008; Singh et al., 2009) and in wind-blown sand (Stout and Zobeck, 1997; Wang et al., 2014; Carneiro et al., 2015). Statistically, this produces non-Gaussian probability distribution functions (PDFs) of sediment flux with long tails corresponding to the rare, large bursts. When taking averages of intermittent time-series, the number of large bursts observed can significantly alter the calculated mean, resulting in very long time windows being required for a properly converged average (Bunte and Abt, 2005; Singh et al., 2009; Ancey and Pascal, 2020). For example, Singh *et al.* (2009) found that increasing the averaging window from a few minutes to more than an hour changed the measured average flux by more than an order of magnitude (Singh et al., 2009), while other laboratory flume experiments have shown convergence times on the order of tens of hours (Ancey et al., 2015). Intermittency poses a challenge for quantitative predictions of sediment flux, which rely on empirical laws calibrated with time-averaged flux measurements in different flow conditions (Ancey, 2020a, 2020b). These sediment transport laws are applied in many engineering contexts, such as flood mitigation, dam construction, and coastline erosion, as well as in studies of landscape evolution (Jones et al., 1986; Bridge and Demicco, 2008; Alcantara and Goudie, 2010; Wilcock, 2012). A theory for predicting the time windows required for properly converged averages, given the flow conditions and channel characteristics, would aid field and experimental studies of sediment transport. Such a predictive theory requires a mechanistic understanding of the underlying cause of the intermittency.

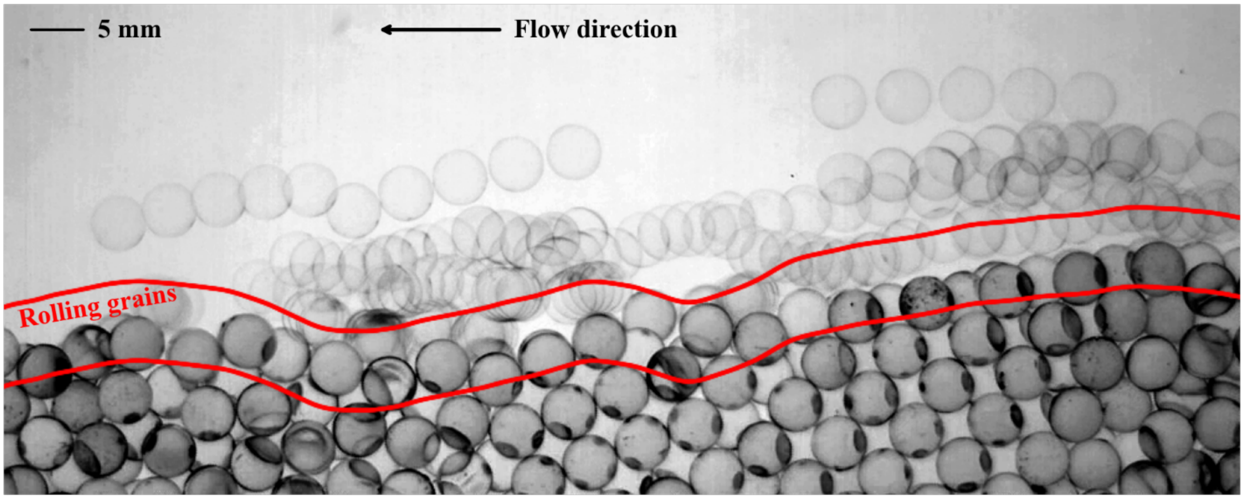

Figure 1. Strobed time-lapse image of grain motion in a laboratory flume demonstrating various coexisting modes of bed load transport, manifested by differences in grain velocity and height above the bed. The two red lines denote the population of rolling grains, defined as grains whose centers lie within three grain radii above the bed (defined in the text). The snapshot is composed of 5 frames taken 0.01 seconds apart.

A common approach in the study of bed load transport is to consider separately the two dynamical components that contribute to the flux: the velocity of the grains, and some measure of the number of grains moving, or grain activity (Ancey et al., 2008; Lajeunesse et al., 2010; Furbish et al., 2012; Roseberry et al., 2012; Ancey, 2020a). Since grain velocities are believed to have either exponential or Gaussian (non-intermittent) statistics (Charru et al., 2004; Lajeunesse et al., 2010; Roseberry et al., 2012; Martin et al., 2012; Furbish and Schmeeckle, 2013; Fan et al., 2014; Heyman et al., 2016), studies of intermittency tend to focus on the role of grain activity. For example, Ancey *et al.* (2008) showed the number of moving grains in an experimental viewing window to have a negative binomial distribution, resulting in large fluctuations being more likely than predicted by a Gaussian distribution with the same mean and variance – in other words, intermittency. They attributed the intermittency to the dependence of entrainment rate on the number of grains currently entrained, commonly referred to as collective entrainment.

While these insights have influenced future studies on the origin of intermittency (Lee and Jerolmack, 2018), models based on grain activity and collective entrainment do not reproduce a change in intermittent behavior observed closer to the threshold of grain motion. This different type of intermittency, called *on-off intermittency*, is characterized by long periods of inactivity followed by rare bursts of flux (Fujisaka and Yamada, 1985; Platt et al., 1993; Ott and Sommerer, 1994; Aumaître et al., 2005; Benavides et al., 2022). The resulting PDF of sediment flux has a power-law tail at small values, making the observation of low transport more likely than for either a Gaussian or negative binomial distribution with the same mean and variance. Among other things, on-off intermittency results in a power-law distribution of waiting times between flux events (Ancey et al., 2008; Carneiro et al., 2015; Liu et al., 2019) and is ultimately responsible for the very long averaging times required close to the threshold of motion. Although on-off intermittency is apparent at the lowest transport stages examined in some previous studies (e.g., Ancey et al., 2015), it has only recently been measured and studied. Benavides *et al.* (2022) compared experimental data with a statistical theory of on-off intermittency and linked a measure of shear stress variability to bed load fluctuations, yielding a new approach for estimating the critical shear stress for grain entrainment, and a function describing the divergence of waiting times as the entrainment threshold is approached (Benavides et al., 2022).

Despite this progress, the physical origin of on-off intermittency in bed load sediment transport remains unclear. The statistical theory used by Benavides *et al.* (2022) is partly empirical, relying on an approximation to an unknown dynamical equation for the sediment flux. A more mechanistic model of on-off intermittency, which would help connect bed and channel properties to important parameters, such as the shear stress variability, requires an understanding of what is causing the intermittency. In this work, we analyze particle tracking data from a series of flume experiments and show that the on-off intermittency has its origins in the velocity distributions of grains that are rolling along the bed.

FLUME EXPERIMENTS

Experimental procedure

We performed a series of experiments in which glass spheres 5 mm in diameter were transported as bed load through a 10.3-mm-wide flume. In each run we used the same water discharge but set a different sediment feed rate. After an initial period of bed adjustment, each experiment reached a steady state with a constant bed slope, at which point the moving grains were filmed from the side using a high-speed camera (Figure 1). Image frames from each experiment were then analyzed with a grain detection and tracking algorithm, yielding grain positions and velocities for each frame (Benavides et al., 2022).

For each experiment we measured the time-averaged non-dimensional shear stress, $\langle \tau^* \rangle$, also sometimes referred to as the Shields Number, where $\langle \cdot \rangle$ denotes a time average, $\tau^* \equiv \tau_b / ((\rho_s - \rho_w)\, D g)$, ρ_s is the grain density, ρ_w is the water density, g is the gravitational acceleration, and D is the grain diameter. The dimensional bed shear stress τ_b was calculated from the one-dimensional simplification of the momentum equation (depth-slope product), $\tau_b = \rho_w \mathrm{gR}$, with hydraulic radius R and streamwise slope . The shear stress quantifies the ability of the fluid to move sediment, with larger shear stress values corresponding to more transport. Below a critical average shear stress $\langle \tau^* \rangle_c$, little or no grain motion occurs.

Measurement of grain activity and velocities

Using the time series of location and velocity for individual grains obtained from the grain tracking, we decomposed the statistics of the sediment flux into that of grain velocity and grain activity. In Benavides *et al.* (2022), we measured the downstream sediment flux through a cross section of the channel perpendicular to the flow by summing the downstream component of velocity for each grain weighted by its cross-sectional area intersecting the cross-section. This resulted in a time-series of $q^* \equiv q_s/(D\sqrt{(\rho_s - \rho_w)\, gD/\rho_w})$, the dimensionless sediment flux, where q_s is the dimensional downstream sediment flux divided by channel width. Here we further analyze the sediment flux measurements by examining time series of (i) the average downstream component of velocity of the grains through the cross-section at one time, v (m/s), and (ii) the total grain area intersecting the cross-section at one time, n (dimensionless, normalized by a single grain cross-section, $\pi(D/2)^2$). In our measurements of n and v, we only count grains whose centers lie above the nearly static bed line (bottom red line in Figure 1). The bed line is found by averaging frames over 1.5 seconds and using an edge-detection algorithm to find the boundary between stationary grains and grains that moved during that interval (Benavides et al., 2022). Grains may creep below the bed line, but this motion is not distinguishable from stationary over our measurement periods. In this study, n serves as the measure of the grain activity by counting the number of mobile grains intersecting a vertical window perpendicular to the flow. This definition is analogous to other measures of grain activity in previous work, including the number of entrained grains per unit area of the bed ("particle activity") (Furbish et al., 2012) and the number of entrained grains in a vertical window parallel to the flow (Ancey et al., 2008).

We are interested in exploring the statistical distributions of n and v and how they influence the statistics of the flux q^*. Since the time-averaged sediment flux is proportional to the average of the product of n and v, $\langle \mathrm{n\ v} \rangle$, looking at the statistics of n and v separately (and not the joint probability) is only justified if the two variables are uncorrelated (e.g. Furbish et al., 2012; Ancey and Heyman, 2014; Ancey, 2020a), implying that the time-averaged sediment flux is proportional to the product of their time averages, $\langle n\rangle\langle v\rangle$. Indeed, we find that $\langle n\rangle\ \langle v\rangle$ is proportional to $\langle q^*\rangle$, with a deviation of $\sim$25%, which decreases as the shear stress increases (Figure 2).

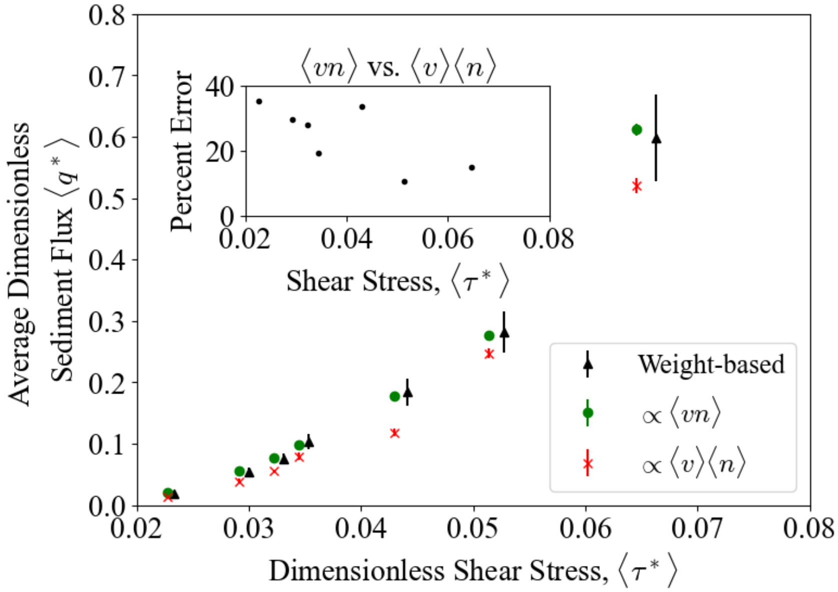

Figure 2. Comparison of the time-averaged dimensionless sediment flux calculated by 1) weighing bins of sediment collected as they exited the flume (black triangles), 2) measuring grains passing through a cross-section in high-speed video (green circles) and 3) multiplying the average time-averaged grain velocities and grain activities (red crosses). Inset: absolute percent error of the product of time-averaged velocity $\langle v \rangle$ and activity $\langle n \rangle$ relative to the time-averaged product $\langle vn \rangle$. Error bars are one standard deviation.

RESULTS AND DISCUSSION

We explore distributions of n and v for three example experiments of low, medium, and high transport stages (Figure 3A, B). Far above the threshold of motion, both PDFs are well approximated by a Gaussian distribution (Figure 3A, B), indicating less intermittency. Indeed, the farther above the threshold of motion, the less intermittent the statistics become. We quantify this for the grain activity by measuring the skewness of the PDF for each experiment, which decreases towards zero – the skewness of a Gaussian distribution – as the shear stress increases beyond the critical value (Figure 3C). A decrease in intermittency with increasing shear stress has been observed in previous experiments (Ancey et al., 2008; Singh et al., 2009; González et al., 2017; Lee and Jerolmack, 2018), although in some recent numerical simulations this was true only for the grain velocities, not for grain activity (González et al., 2017).

The most revealing statistics of velocity and grain activity occur close to the threshold of motion. We find that the PDFs of grain velocity are consistent with those expected for on-off intermittency (Aumaître et al., 2005), whereas the PDFs of grain activity are not. For small values of v, the PDF follows an approximate power law with an exponent that decreases linearly towards -1 as the critical shear stress is approached (Figure 3B), and this remains true when fitting the tail exponents for all 7 experiments (Figure 3D). This is in line with the predictions from on-off intermittency, namely a power law distribution with exponent $(\langle\tau^*\rangle - \langle\tau^*\rangle_c)/S - 1$, where S is the shear stress variability, and an exponential cutoff at larger q^*(*Aumatre et al.*, 2005). This goes against the current consensus that only grain activity is intermittent (Ancey, 2020a). On the other hand, the grain activity does not follow this pattern, and instead follows a gamma distribution (the continuous version of a negative binomial distribution) close to the threshold of motion (Figure 3A), in agreement with the theory of Ancey *et al.* (2008). In experiments close to the threshold of motion, large bursts of grain activity are more likely than for a process with a Gaussian PDF of the same mean and variance (Figure 3A), implying that the grain activity is intermittent, just not on-off intermittent (Aumaître et al., 2005).

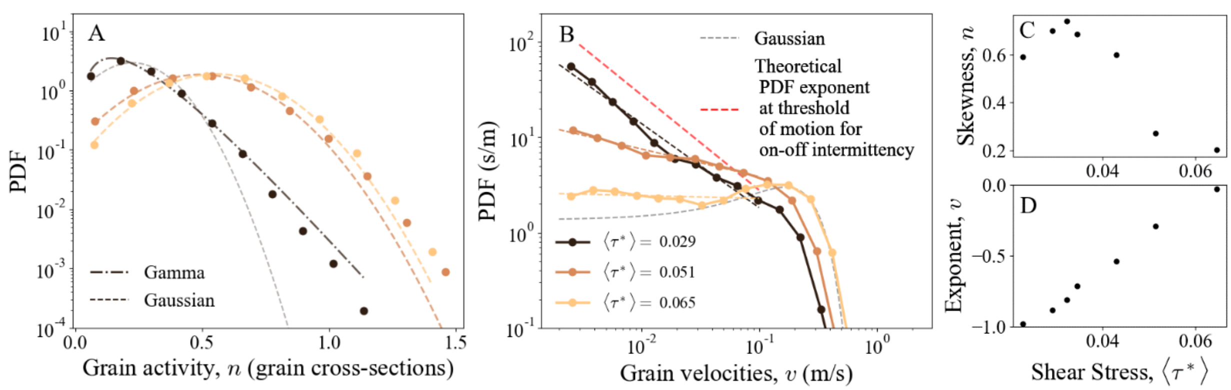

Figure 3. Probability density functions of (A) grain activity n and (B) grain velocity v for a subset of experiments with dimensionless shear stress ranging from a value just above the threshold of grain motion ($\langle\tau^*\rangle_c = 0.026$) to a value well above the threshold. (C) The skewness of the grain activity PDF for all experiments shows a decrease towards Gaussian statistics with increasing shear stress. Dashed line fits of a Gaussian PDF in panel A also confirm an increasingly better fit for higher shear stress values, whereas, for the lowest shear stress shown, a gamma distribution (dot-dashed line) gives a better fit to the data. (D) The power-law exponents of the PDF tails for v, based on least-squares power-law fits (color-matched dashed lines in B) show a linear approach to the theoretical exponent of -1 with decreasing shear stress, as predicted by the theory of on-off intermittency. We consider Gaussian statistics to be nonintermittent, and any distribution with the same mean and variance which has extreme values that are more likely than a Gaussian PDF to be intermittent. On-off intermittency, with its power-law tail PDF and maximum at small values, is a different kind of intermittency than that found in the gamma distribution.

To investigate the mechanisms responsible for on-off intermittency in the grain velocities, we explored how the statistics of the grain velocities varied with height above the bed. For the three example experiments in Figure 3 A and B we measured the joint probability distribution of v and the average y-location (in units of grain radii) of the grain centers intersecting the cross-section at one time (Figure 4). The bed line (bottom red line in Figure 1) corresponds to $y = 0$, and we define the rolling grain population as those grains whose centers lie within three grain radii above the bed line ($y = 3$, top red line in Figure 1). We find a clear difference between the velocity distribution of rolling grains and the velocity distribution of saltating grains that spend most of their time in contact with only fluid. The rolling grains experience velocities that range from 10^{-3} m/s to 10^{-1} m/s, with a PDF that peaks at the smallest values, suggesting on-off intermittency (compare with Figure 3B). The saltating grains, on the other hand, show a much smaller spread in velocities and follow a velocity profile that increases with height, like that of the fluid. This suggests that the on-off intermittency found in lower-shear stress experiments is due to the velocity distribution of rolling grains, which are known to contribute substantially to the sediment flux (Böhm et al., 2006; Schmeeckle, 2014). Indeed, at higher transport stages (Figure 4C), there are almost no rolling grains, resulting in a PDF of v and q^* with weak intermittency. This is consistent with Heyman *et al.* (2016) who showed that grains close to the bed followed exponential velocity PDFs peaking at low values, whereas those more than two grain diameters above the bed followed Gaussian PDFs. Although an exponential PDF could have made it appear that the velocities were not intermittent, it is possible that this study only captured the higher-velocity exponential tails of an on-off intermittent PDF, and would therefore be consistent with on-off intermittency when low velocities are accounted for (Figure 3B).

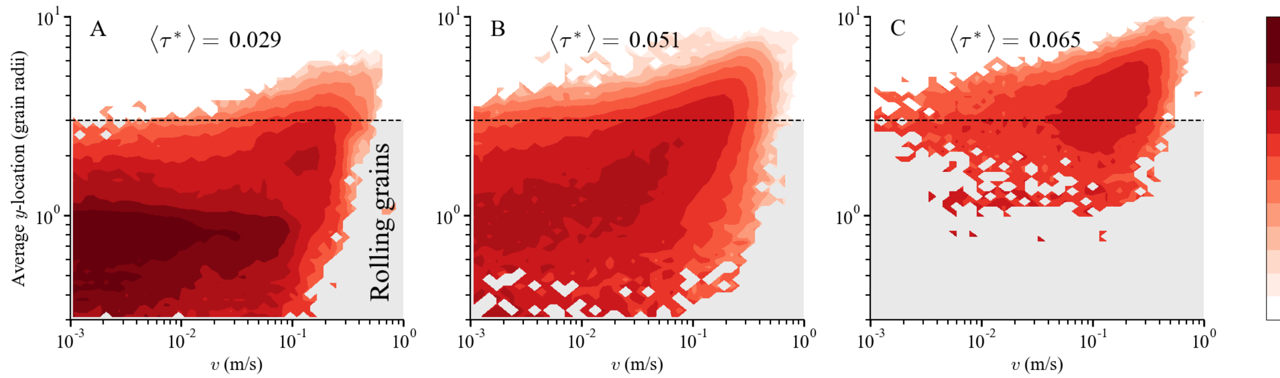

Figure 4. Joint probability distribution of the grain velocities v and their average height above the bed for the three sample experiments shown in Figure 3A,B. The rolling grain population is defined as the grains whose centers lie less than three grain radii above the bed (grey area below the black dashed line, see Figure 1).

We hypothesize that rolling grains experience on-off intermittency because fluid lift and drag forces and fluid-grain torques fluctuate below and above critical values for entrainment, causing sudden decay or growth in the velocity of the grains. Recent numerical work has revealed that, near the threshold of motion, the larger resistance torque (rotational stress) the grains experience, the smaller the average sediment flux is at a fixed $\langle \tau^* \rangle$, demonstrating a sensitivity of the rolling grain motion to the details of the forces and torques near the bed (Zhang et al., 2022). The time-averaged fluid forces and torques at the bed surface are, by definition, at the threshold of being capable of moving grains downstream. Forces on the rolling grains fluctuate because the fluid is turbulent (with a mean flow much smaller than the size of the fluctuations), neighboring grains are impacting each other, and the surrounding bed surface is irregular. Consequently, the force experienced by grains on the bed are at times below the threshold of motion, causing them to stand still or roll very slowly, and at other times above the threshold, resulting in abrupt motion and possible lifting into the faster flow above the bed. This allows for a very large range of possible grain velocities. On the other hand, once the grain is in the flow above the bed, the turbulent fluctuations are smaller than the mean flow, which results in less variation in grain velocities.

CONCLUSIONS

Our experimental observations indicate that there are two types of intermittency that coexist in the grain activity and grain velocity, which together determine the sediment flux. Whereas it was previously accepted that the intermittency lies entirely in the grain activity, we have shown that the grain velocities contribute substantially to the intermittency and additionally introduce on-off intermittency. On-off intermittency leads to the problem that accurate measurements of average sediment flux require long averaging times. We have also shown that the intermittent grain velocities come from the population of rolling grains near the bed, and that the amount of on-off intermittency observed in an experiment therefore depends on the fraction of rolling grains present. Our results suggest that simplified statistical models of sediment transport must consider the distributions of grain velocities, and in particular rolling grains, in order to capture the correct statistical behavior of sediment flux near the threshold of motion. This approach will provide a framework for connecting sediment flux intermittency to channel and flow properties, ultimately enabling better predictions of sediment flux fluctuations and averaging times.

OPEN RESEARCH

The time series data used in this work is available at https://doi.org/10.6084/m9.figshare.21431901.v1.

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