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How Fast or How Many? Sources of Intermittent Sediment Transport

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Key Points:

- We use grain tracking data from laboratory experiments to separately study the statistics of grain velocities and grain activity
- We show that on-off intermittency has its origins in the velocity distributions of grains, not in the grain activity
- 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

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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 account for the effects 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. Incorporating the types of intermittency we identify into stochastic models of sediment transport could yield improved predictions of sediment flux, including physically based estimates of the uncertainty in time-averaged sediment flux.

Plain Language Summary Sediment, such as sand and gravel, is transported across the surface of the Earth and other planets by wind and water. Predicting the amount of sediment that can be transported given a certain flow rate is crucial for predicting how a landscape will change over time. For low flow rates, little to no grain motion occurs. Just beyond the flow rate required for motion, sediment transport occurs mostly in rare bursts. This so-called "on-off" intermittency creates difficulties when trying to measure the average transport rate, which must be done over longer time periods as the bursts become larger but less frequent. While on-off intermittency has been identified in previous studies of sediment transport, there is currently no understanding of its physical origin. We use a series of experiments in a small laboratory river to show that the on-off intermittency is due to large fluctuations in the speed of the grains rolling on the bed, and that the sediment transport becomes less bursty as more grains are lifted off the river bed and into the fluid. Our results will pave the way for better measurements and predictions of sediment transport in rivers.

1. 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, bursts of sediment transport above background levels become more common, making the sediment flux intermittent, a phenomenon that has been observed in gravel and sand transport by water (Ancey et al., 2006, 2008; Gomez, 1991; Singh et al., 2009) and in wind-blown sand (Carneiro et al., 2015; Stout & Zobeck, 1997; Wang et al., 2014). Statistically, this produces non-Gaussian probability distribution functions (PDFs) of sediment flux with long tails corresponding to the rare, large bursts being more common than for a process following a Gaussian distribution. In this work, we define a time series to be intermittent if its PDF has larger-than-Gaussian values at small or large variable values. Different types of intermittency discussed in this work have different, non-Gaussian PDFs. 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 (Ancey & Pascal, 2020; Bunte & Abt, 2005; Singh et al., 2009). 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

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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 (Alcantara & Goudie, 2010; Bridge & Demicco, 2008; Jones et al., 1986; 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.

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, 2020a; Ancey et al., 2008; Furbish et al., 2012; Lajeunesse et al., 2010; Roseberry et al., 2012). Since grain velocities are believed to have either exponential or Gaussian (non-intermittent) statistics (Charru et al., 2004; Fan et al., 2014; Furbish & Schmeeckle, 2013; Heyman et al., 2016; Lajeunesse et al., 2010; Martin et al., 2012; Roseberry et al., 2012), 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. Therefore, Ancey et al. (2008) document a particular kind of intermittency in grain activity, associated with a negative binomial distribution. 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 subsequent studies on the origin of intermittency (Lee & Jerolmack, 2018), models based on grain activity and collective entrainment do not reproduce a change in intermittent behavior, and a corresponding change to the PDF of sediment flux, that occurs closer to the threshold of grain motion. This particular type of intermittency, called *on-off intermittency*, is characterized by long periods of low sediment flux ("off" phases) followed by rare bursts of larger flux ("on" phases) (Aumaître et al., 2005; Benavides et al., 2022; Fujisaka & Yamada, 1985; Ott & Sommerer, 1994; Platt et al., 1993). 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 (Benavides et al., 2022). 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 yielding 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 distribution of grains that are rolling along the bed.

2. Flume Experiments

2.1. Experimental Procedure

We performed a series of experiments in which glass spheres 5 mm in diameter were transported as bed load through a flume that was 10.3 mm wide, 2.5 m long, and 45 cm tall, tilted at 3° from horizontal. Water was recirculated at a fixed discharge with a pump, with a bulk mean velocity of $u \approx 1$ m/s. The mean water depth was $H = 0.1$ m and the mean hydraulic radius was $R = 0.005$ m. This corresponds to a Reynolds number $Re = uR/\nu \approx 4800$ and a Froude number $Fr = u/\sqrt{gH} \approx 1$. 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

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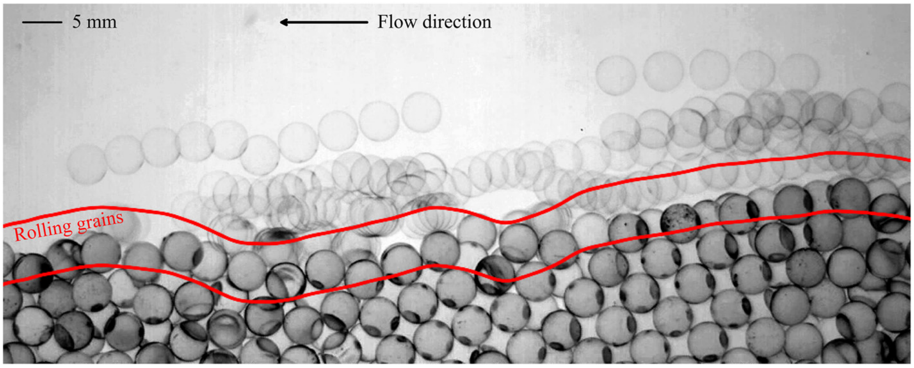

Figure 1. Strobed time-lapse image of grain motion in a laboratory flume demonstrating various coexisting modes of bed load transport, manifested by differences in grain velocity and height above the bed. The two red lines denote the population of rolling grains, defined as grains whose centers lie within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

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 (see Benavides et al., 2022 for more details on the experimental setup and procedures). The narrow flume, which was slightly wider than two grain diameters, was chosen to simplify the processes affecting grain motion by being narrow enough to eliminate cross-stream transport, lateral sorting, and bar formation, but wide enough to avoid jamming (Church & Zimmermann, 2007). An added benefit is the ability to perform side-on tracking of the grains in motion (Figure 1). However, it also resulted in a quasi-two-dimensional setup that restricted substantial spanwise variation. Such a setup may affect the characteristic size, strength, and frequency of flow structures (such as streaks and vortices) that interact with the grains, as well as restrict lateral grain motion and diffusion, and may therefore affect the spatial distribution of grain activity.

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, $\tau^* \equiv \tau_b/((\rho_s - \rho_w)Dg)$, 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 channel-scale average of the momentum equation, resulting in a one-dimensional momentum balance, $\tau_b = \rho_w g R \sigma$, with hydraulic radius R and streamwise slope σ. Although the hydraulic radius partially accounts for the effects of the flume walls in our narrow channel, we found in a previous study that the resulting values of τ_b are best interpreted as a “shear stress index” that likely underestimates the true bed shear stress, but nonetheless provides a reliable indicator of relative bed shear stress (Deal et al., 2023). For simplicity, and following the standard approach, we refer to the estimates based on the one-dimensional momentum balance as the bed shear stress.

2.2. 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 $q^* \equiv q_s / \left(D\sqrt{(\rho_s - \rho_w) g D/\rho_w} \right)$, 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 (a) the average downstream component of velocity of the grains through the cross-section at one time, v (m/s), and (b) the total grain area intersecting the cross-section at one time, n (dimensionless, normalized by a single grain cross-section, $\pi(D/2)^2$). The separation of v and n breaks down at zero velocity; however, this only happens exactly at $v = 0$. For any $v > 0$, n can take any value (and vice versa). 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 s and

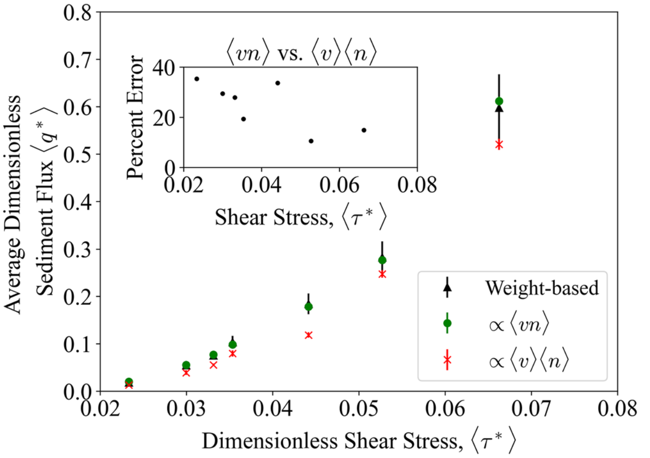

Figure 2. Comparison of the time-averaged dimensionless sediment flux calculated by (a) weighing bins of sediment collected as they exited the flume (black triangles), (b) measuring grains passing through a cross-section in high-speed video (green circles) and (c) multiplying the time-averaged grain velocities and grain activities (red crosses). Inset: 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.

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 quantifying 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, $\langle n\,v \rangle$, 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., Ancey, 2020a; Ancey & Heyman, 2014; Furbish et al., 2012), 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 ~25%, which decreases as the shear stress increases (Figure 2).

3. Results and Discussion

We explore distributions of n and v for three example experiments of low, medium, and high transport stages (Figures 3a and 3b). Far above the threshold of motion, both PDFs are well approximated by a Gaussian distribution (Figures 3a and 3b), 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 toward 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; González et al., 2017; Lee & Jerolmack, 2018; Singh et al., 2009), 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),

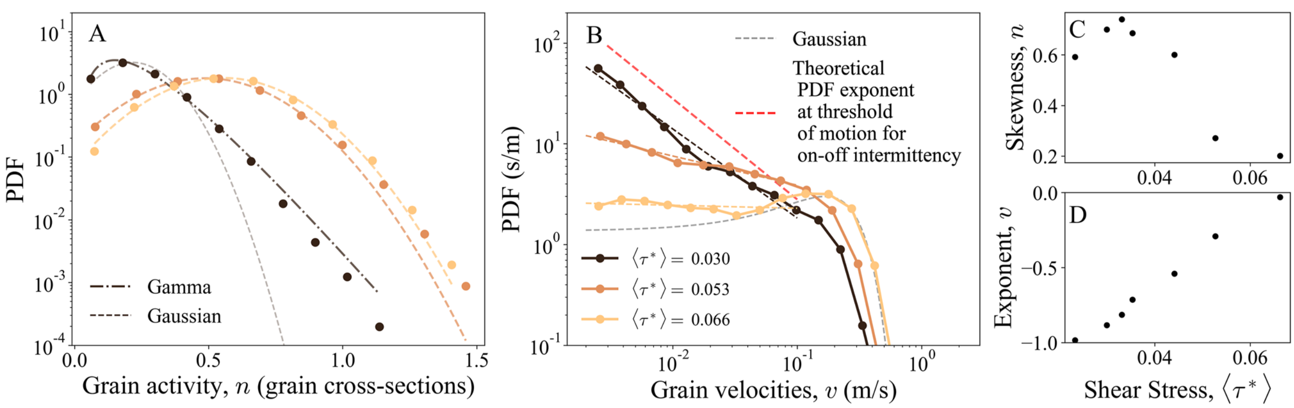

Figure 3. Probability density functions of (a) grain activity n and (b) grain velocity v for a subset of experiments with dimensionless shear stress ranging from a value just above the threshold of grain motion ($\langle \tau^* \rangle_c = 0.030$) to a value well above the threshold. The PDF of n in (a) is binned, meaning that the left-most value does not represent the probability of $n = 0$, but rather the probability that n is smaller than some finite value. (c) The skewness of the grain activity PDF for all experiments shows a decrease toward 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 (Aumaître et al., 2005)).

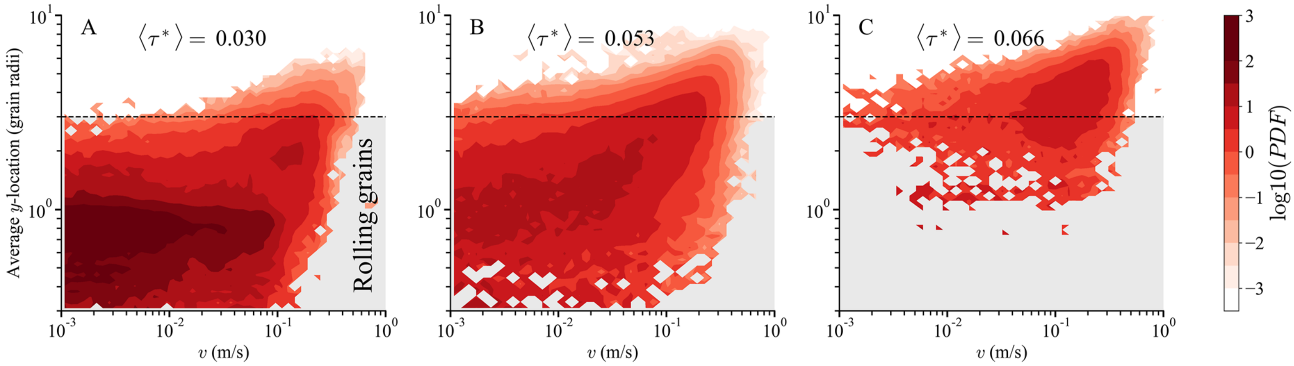

Figure 4. Joint probability distribution of the grain velocities v and their average height above the bed for the three sample experiments shown in Figures 3a and 3b. The rolling grain population is defined as the grains whose centers lie less than three grain radii above the bed (gray area below the black dashed line, see Figure 1). Rolling grains are found to have a large range of possible velocities, with the maximum likelihood occurring at low values of velocity (a), pointing to its on-off intermittent nature. On the other hand, saltating grains, whose centers lie three grain radii or more above the bed, tend to follow a velocity profile similar to that of the fluid, with a larger mean velocity and a smaller range of observed fluctuations around it (c).

whereas the PDFs of grain activity, although also non-Gaussian, are not. For small values of v the velocity PDFs follow an approximate power law, whereas an exponential cutoff is seen for large values of v. The power law exponent depends on the shear stress of the experiment, and decreases linearly toward -1 as the critical shear stress is approached (Figure 3b). This remains true when fitting the tail exponents for all seven experiments (Figure 3d). These findings are in line with the predictions from on-off intermittency: a PDF with an exponential cutoff at large v, and a power law tail at small values of v whose exponent is $\left(\langle\tau^*\rangle - \langle\tau^*\rangle_c\right)/S - 1$, where S is the shear stress variability (Aumaître et al., 2005; Benavides et al., 2022). These findings go 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).

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 Figures 3a and 3b 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} 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 on-off 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).

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 resistive 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.

Although spherical particles are more prone to sliding and rolling than irregularly shaped gravel, the observation of on-off intermittency in sediment flux time series of both spherical and natural grains (Benavides et al., 2022) suggests that the result from the current work also holds for natural grains. Similarly, it would be valuable to investigate the effects of flume width on the intermittent nature of the sediment flux, grain velocities, and grain activities. We know from Ancey et al. (2015) that on-off intermittent sediment flux is present in natural grain experiments with flume widths many times the width of a grain (Ancey et al., 2015), but the velocity and grain activity statistics in such configurations are not known. Our narrow flume restricts lateral motion of the grains and may affect the formation of lateral spatial structures in the flow and grain activity, resulting in a weakened intermittency for the grain activity, so it would be informative to study the grain activity PDF in a wider channel in future studies.

4. 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.

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Data Availability Statement

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

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