# Flood-driven sediment dynamics on gravel bars mapped using UAV photogrammetry and machine learning: Sense River, Switzerland.

Nahin Rezwan[1], David Mair[2], Alexander C. Whittaker[1], Fritz Schlunegger[2], Ariel Henrique do Prado[2], Sadia Hossain Setu[3]

## Abstract

Gravel-bed rivers are shaped by complex interactions between hydrological forcing, sediment sorting, and channel morphology, yet fine-scale, spatially continuous observations of these processes remain rare. We combine UAV structure-from-motion photogrammetry with machine-learning grain segmentation to quantify flood-driven sediment redistribution in a minimally disturbed gravel-bed river (Sense River, Switzerland). Two surveys of four gravel bars (2021 and 2024) mapped individual clasts in images at centimetre resolution, allowing spatial and temporal analysis of grain-size patterns. We show clear intra-bar fining from crests to tails and a reach-scale morphology control on sorting: bend-associated bars are moderately to well sorted, while straight reaches are more poorly sorted. Grain-size distributions converge to self-similar forms across all bars, with analysis of ca. 1.86 million grains providing unprecedented empirical validation of scale-invariant sorting, an improvement by orders of magnitude over conventional pebble counts. To understand the detailed hydraulic controls during the moderately large flood captured between surveys (ca. 180 m³/s; ca. 2-10 years recurrence), we performed detailed hydraulic modelling for one bar, estimating spatial fields of shear stress, Shields parameter, and stability conditions during the flood. We also differentiated the topography between the two surveys to map the relative elevation change. The crest and margin armour remained largely stable, whereas the tail part was extensively reworked. A hydraulically driven mobilisation model reproduced observed mobility with ca. 65% overall accuracy (up to 82% in tails) but under-predicted movement on crests. We also show that where floods were large enough to mobilise the grains, coarse patches were rapidly buried or completely replaced, demonstrating that local hydraulic geometry can override patch stability. Overall, bar adjustment was deposition-dominated for that bar, consistent with the waning stage of the flood, during which reduced shear stresses promoted net deposition. Our data indicates that flows <200 m³/s can remobilise large bar areas, and analysis of gauging data for the Sense River since 1928 shows that such events are becoming more frequent. Our results highlight the important geomorphic role of moderate to moderately large floods in such

*rivers and demonstrate high-resolution, hydraulically informed grain mapping as a robust tool for predicting gravel-bed river response under changing flood regimes.*

## Response to Reviewer 2:  Main Comments

Reviewer comments are indicated in regular and black text, while our responses are formatted as blue text.

We thank Reviewer 2 for the careful and constructive assessment of our manuscript. We appreciate the positive evaluation of the dataset and methodological framework, as well as the insightful comments regarding terminology, hydraulic assumptions, grain-size validation, and the role of smaller flow events. The suggestions have helped us clarify several methodological aspects and refine the scope of interpretation. Below we restate each of the reviewer's main comments and describe how the revised manuscript addresses these.

(1) Validation of Grain Size Distributions (GSDs)

In addition to the uncertainty estimation via bootstrapping, the results would benefit from validation of the image segmentation approach. For example, were there any manual grain-size measurements that could confirm that the GSDs derived from the machine-learning approach are representative of reality?

We thank the reviewer for highlighting the importance of validation. Direct field-based grain-size measurements were not collected during the UAV surveys, which limits our ability to perform a traditional comparison with Wolman counts or manual measurements. However, the machine-learning segmentation model used in this study (ImageGrains) was originally trained and validated using datasets derived from similar gravel-bed environments, also along the River Sense, i.e., site S1 in Mair et al. (2024). For this site, a comparison of ImageGrains predictions with manually measured b-axis values, resulted general good agreement within errors with <20% difference for any percentile value of the entire GSDs (cf. section 3.2.2 and Fig. 9 in Mair et al., 2024). The present study therefore applies a segmentation workflow that has already been validated for gravel-bed environments in the Sense River catchment. To clarify this point, we explicitly note in Section 3.2 of the revised manuscript that the ImageGrains model and workflow have previously been validated for this river system and are here used to analyse spatially extensive, multi-temporal grain-size datasets.

How might grain embeddedness or orientation affect GSD uncertainty? Could changes in median grain size partly reflect changes in grain arrangement or partial burial?

This is an important point, and we appreciate the reviewer raising it. Grain embeddedness, partial burial, and grain orientation can indeed influence apparent grain dimensions in image-based measurements (e.g., Buscombe, 2013; Mair et al., 2022; Garefalakis et al., 2023). The grain-size statistics used in this study are calculated from large numbers of grains within each tile (often several hundred measurements), which reduces the influence of individual partially occluded grains on the overall relative grain-size distribution.

We therefore acknowledge in section 4.3 of the revised manuscript that grain arrangement and partial burial may introduce some uncertainty in image-based grain-size estimates. However, given the large number of grains measured and the consistent segmentation workflow applied to both surveys, such effects are expected to have only a minor influence on the reported relative grain-size distributions.

(2) Sediment Mobility: Terminology and Assumptions

Clarification of hydraulic terminology would be beneficial. The reviewer recommends referring to the modelled dimensionless shear stress as $\tau^*$ and the critical entrainment threshold as $\tau^*c$ to avoid confusion.

We are happy to do this. In the revised manuscript we standardise the terminology throughout the text by referring to the modelled dimensionless shear stress as $\tau^*$.

To improve clarity, we will also explicitly define $\tau^*c$ in the manuscript as the dimensionless critical shear stress required for grain entrainment. This quantity is commonly referred to in the literature as the critical Shields stress for sediment mobilisation (Shields, 1936; Buffington and Montgomery, 1997).

We will avoid using the term "Shields parameter" ambiguously and instead clearly distinguish between the modelled hydraulic forcing ($\tau^*$) and the entrainment threshold ($\tau^*c$). This revision should improve clarity in the interpretation of the mobility analysis.

The assumption of $\tau^*c = 0.06$ requires further justification and discussion, particularly given potential variability due to hiding effects, sorting, and bed armouring.

We clarify that the adopted value of $\tau^*c = 0.06$ lies at the upper end of commonly reported thresholds for gravel-bed rivers, which is appropriate given the relatively high gradient of the Sense River. Using this value provides a conservative estimate of sediment mobility meaning that the inferred hydraulic competence and associated bedload transport should be interpreted as minimum estimates.

We acknowledge in the section 3.3 of the revised manuscript that grain protrusion and hiding effects can influence entrainment thresholds. Previous studies have shown that highly protruding clasts may experience lower mobility thresholds (e.g. Buffington et al., 1992), potentially reducing critical Shields stresses to values near 0.03 in poorly packed or weakly structured beds. However, field observations of the Sense River bars indicate relatively well-packed gravel surfaces with significant interlocking and partial embedding of larger clasts, conditions that tend to increase entrainment thresholds (Buffington and Montgomery, 1997). Under such conditions, values of $\tau^*c$ around 0.05-0.06 are commonly adopted for gravel-bed rivers (Paola and Mohrig, 1996; Buffington and Montgomery, 1997).

Most importantly, because the Shields threshold acts as a scaling parameter in the transport calculation, variations in the assumed value of $\tau^*c$ mainly affect the magnitude of predicted transport, whereas the spatial pattern of relative mobility remains robust.

Finally, we emphasise in the revised discussion that the purpose of this simplified hydraulic analysis is to evaluate spatial patterns of potential sediment instability across the bar surface, rather than to derive precise absolute estimates of bedload transport. Uncertainties in water depth, slope, and entrainment threshold are therefore acknowledged, but they do not affect the primary objective of the analysis, which is to compare the predicted spatial distribution of hydraulic competence with the observed patterns of morphological change across the bar.

(3) Bar Adjustment During Lower-Magnitude Flow Events

The manuscript attributes changes primarily to the November 2023 flood, but smaller flows between surveys may also have contributed to sediment reworking. Including information on bar inundation and discussing the influence of smaller flows would improve interpretation.

We agree that complete attribution of the observed changes to a single event is not possible, and we clarify this point in the revised manuscript. However, several independent lines of

evidence indicate that the November 2023 flood was the dominant geomorphic disturbance during the observation period.

First, hydrological records show that the November event was the only discharge exceeding 180 $m^3s^{-1}$ between the two surveys and reached bankfull conditions. It corresponds to an event with an approximate 5-year recurrence interval, whereas all other flows during this interval were substantially smaller, with peak discharges at least ca. 50% lower. The November flood therefore represents the only event during the survey period capable of producing widespread bar inundation and strong hydraulic forcing.

Second, our hydraulic competence analysis indicates that the flow conditions associated with this flood were sufficient to mobilise large portions of the bar surface. The spatial distribution of predicted mobility broadly corresponds with the patterns of elevation change identified in the DoD analysis, suggesting that the recorded morphological adjustments are primarily consistent with forcing during this event.

We therefore revise the section 4.3 of the manuscript to clarify that the measured changes represent the cumulative response of the bar over the survey interval, while the November 2023 flood likely provided the dominant disturbance. Smaller flows may have contributed incrementally to sediment reworking, but in the absence of higher-frequency surveys their individual contributions cannot be resolved. We also emphasise that the observed response was spatially heterogeneous and strongly conditioned by the pre-existing bar morphology and slope distribution.

(4) Within-Bar Trends in Grain Sorting

It would be useful to examine patterns of grain sorting within the bar by mapping sorting parameters for each grid cell.

In the present study, our analysis focuses primarily on spatial variations in median and coarse-percentile grain sizes (e.g., D50 and D84) and their relationship to hydraulic forcing and elevation change.

While mapping sorting parameters within each grid cell would indeed be valuable, implementing this analysis would require substantial additional data processing and interpretation beyond the current scope of the manuscript. For the revised version, we will expand the discussion to acknowledge the potential importance of within-bar sorting patterns and highlight this as a promising direction for future work using similarly high-resolution datasets. However, a full study of grain size sorting and patchiness will need to wait for a follow up paper.

(5) Figure Size and Readability

Figure text, particularly legends and axis labels, should be made larger. Some figures could be presented at a larger scale.

We agree with the reviewer's assessment. In the revised manuscript, we increase font sizes across all figures, improve legend clarity, and adjust panel layouts where necessary to improve readability. Where possible, key figures are enlarged to occupy greater page space so that spatial patterns can be interpreted more easily.

We thank Reviewer 2 again for the constructive comments, which have helped to improve the clarity of the terminology, strengthen the discussion of methodological assumptions, and refine the interpretation of the geomorphic processes represented in the dataset.

We thank the reviewer for the additional minor and line-by-line comments. These have been carefully addressed throughout the revised manuscript, and the text has been edited accordingly to improve clarity and consistency.

References:

Buffington, J. M., Dietrich, W. E., & Kirchner, J. W. (1992). Friction angle measurements on a naturally formed gravel streambed: Implications for critical boundary shear stress. Water Resources Research, 28(2), 411–425. https://doi.org/10.1029/91WR02529

Buffington, J. M., & Montgomery, D. R. (1997). A systematic analysis of eight decades of incipient motion studies, with special reference to gravel-bedded rivers. Water Resources Research, 33(8), 1993–2029. https://doi.org/10.1029/96WR03190

Paola, C., & Mohrig, D. (1996). Palaeohydraulics revisited: Palaeoslope estimation in coarse-grained braided rivers. Basin Research, 8(3), 243–254. https://doi.org/10.1046/j.1365-2117.1996.00253.x