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

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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.

Major comments

Reviewer 1

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

We sincerely thank Reviewer 1 for the careful, technically detailed, and constructive assessment of our manuscript. We appreciate the reviewer's recognition of the value of the dataset and the overall methodological framework. We are happy to have the opportunity to address the reviewer's questions regarding clarity of terminology, the simplifications involved in the hydraulic analysis, the attribution of geomorphic change to individual flood events, and the presentation of several figures.

In response to these comments, we revise the manuscript to clarify the conceptual framing of the study, improve the description of the hydraulic modelling assumptions, and refine the terminology used to describe sediment stability and surface textural adjustment. We also narrow the discussion of climate-related implications so that it is better aligned with the scope of the geomorphic analysis. In addition, we are revising the figures to improve readability and consistency. Below, we address each of the reviewer's major comments in detail.

Title: could be reworded to reflect the research finding rather than the topic.

We thank the reviewer for this suggestion. We revise the title to better reflect the geomorphic focus of the study while retaining the methodological context. The revised title reads: "Flood-driven sediment dynamics on gravel bars mapped using UAV photogrammetry and machine learning: Sense River, Switzerland.""

Previous work: the approach taken in this manuscript is similar to Reid et al. (2019). However, the approach here takes the next step from that research by using a more contemporary approach to mapping grain size and by acquiring a DEM of Difference. I recommend that the approach of Reid et al. is cited in the introduction (e.g. in L88-104) and potentially section 5.2.

Introduction: The first paragraph is pretty general in its discussion of gravel bed rivers. You could tighten the introduction by making this more concise and more quickly getting to the topic / focus of your investigation.

We revise this section to make it more concise and make it more focused on our work. In the revised manuscript, we cite Reid et al. (2019) in the Introduction when discussing previous work that combines high-resolution topographic data with hydraulic analysis to investigate flood-driven sediment redistribution.

Focus on climate change: I found the objective relating to projecting how dynamics may evolve in the future to be reliant on considerable postulation (L671-675). Whilst some hydrological analysis has been undertaken (figure 10) I do not consider that the geomorphological element of the analysis is conducted with as much rigour as the other sections of the manuscript. I recommend that the authors consider removing this part of their objective / analysis / discussion and, instead, presenting a much more tightly focused manuscript.

We appreciate this concern and agree that the climate-related discussion in the original manuscript extended beyond the strength of the geomorphic analysis presented. In the revised manuscript, we narrow the climate-change discussion. Specifically, we revise predictive language regarding future bar transformation. We also present the hydrological analysis strictly as contextual information regarding the frequency of moderately large floods.

Discussion of climate-related implications is framed cautiously as broader context rather than as a key objective of the study.

Grain segmentation approach: It is unclear how edge effects were mitigated between the 5x5 m tiles. Please clarify / explain.

We agree that this requires clarification. The image segmentation algorithm filters out grains for which the centre-points fall in the outermost 10% of each image tile. Thereby, grains with intersecting tile boundaries are in all likelihood excluded by default in our setup (only boulders larger than 1m could be still cut, theoretically). Statistical descriptors (D16, D50, D84) are derived only from grains that fall into the central 64% of each image tile, which are therefore very likely to be fully segmented grains. This clarification is being added to the Methods section. In addition we have updated the text in section 3.2 and figure 3e to communicate our approach clearly.

Correction of potential vertical offsets between DEMs: I was not previously familiar with the cited work of Minar et al. (2024) and Schwanghard & Scherler (2017) so I did a brief review of these articles to try to understand how the 75th percentile elevation value was selected to normalise each DEM (section 3.3). I was unable to understand the justification for this choice and/or why this approach would be preferred to explicitly accounting for survey noise (or other errors) following any systematic correction using an approach such as GCD (https://gcd.riverscapes.net/).

These studies were meant to illustrate the types of approach that have been used, but we did not wish to imply that we followed the entire workflow of the cited papers here. We employed a simple subtraction of the 75th percentile value here to normalise the DEM elevation to calculate the relative difference between the DSMs subsequently. The references were intended to provide further information on more complex workflows, and our approach is not intended as a probabilistic uncertainty model. In the revised manuscript, we clarify that the 75th-percentile approach was used solely to remove systematic vertical offsets and between independently reconstructed DSMs. We have revised 3.3 section to communicate this clearly.

Furthermore, we consider the survey noise (and referencing errors) by estimating the uncertainties in the sparse point cloud from the SfM model (details added in the supplementary material). Due to the online and in-flight RTK corrections, we could achieve high positioning accuracies during the surveys. This allowed us to obtain precise SfM models with average positioning errors < 2 cm for cameras in z direction (total 3D RMSE errors of < 3.5 cm), and an average sparse point cloud precision of < 3 cm (see supplementary material and response to the next comment below). These sparse cloud errors can be considered the main source of DSM noise (e.g., James et al., 2020), aside from external referencing errors. We add this information and discussion in sections 3.1.2 and 4.4, and we include references to more sophisticated uncertainty estimation methods, i.e., Wheaton et al. (2010) and Bailey et al. (2020).

Indeed, the statement in the results that a threshold of 0.06 m was used adds further uncertainty to the assumptions here. A more thorough explanation / justification / comparison is needed.

We now clarify that vertical SfM model precision is on average < 0.035 m, and the camera position errors are < 3.5 cm on average (see response to previous comment and added support information). Therefore, the ±0.06 m detection threshold corresponds to twice the estimated vertical uncertainty. We add clarifications on the approach in section 3.3, we report SfM uncertainty estimations in a new table in the supplementary material, and we discuss this now in section 4.4.

Calculation of hydraulically required grain size to control stability (L292): Confirm exactly how you calculated this. Overall, this is a simplified approach since parameters such as h and S are based on coarse scale assumptions (i.e from bankfull mapping) rather than a hydrodynamic model (e.g. as used by Reid et al., 2019). In the discussion, I recommend discussing the limitations of this approach and the relative uncertainties that may be associated with the maps of relative mobility arising from these assumptions. Treating the hydraulic models as uncertain may also help the authors to explain some of the results (e.g. L508) with more rigour.

We thank the reviewer for this important comment. The hydraulically required grain size for stability is calculated by rearranging the Shields relation to estimate the minimum grain size that would remain stable under the modelled flood conditions. In the revised manuscript we clarify this calculation and standardise the terminology by referring to the modelled dimensionless shear stress as τ^* and to the assumed critical shield threshold as τ^*c.

We also clarify that the adopted value of $\tau^*c = 0.06$ lies at the upper end of commonly reported thresholds for gravel-bed rivers (e.g., Paola and Mohrig, 1996; Buffington and Montgomery, 1997). Furthermore, 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 τ^*c around 0.05-0.06 are commonly adopted for gravel-bed rivers (Paola and Mohrig, 1996; Buffington and Montgomery, 1997). 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. Because the Shields threshold acts as a scaling parameter in the transport calculation, variations in the assumed value of τ^*c primarily affect the magnitude of predicted transport, whereas the spatial pattern of relative mobility across the bar surface 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 mobility across the bar surface, rather than to derive precise absolute estimates of bedload transport. We therefore acknowledge uncertainties associated with hydraulic parameters but note that these do not affect the primary objective of the analysis, which is to compare predicted spatial patterns of hydraulic competence with the observed distribution of morphological change across the bar.

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Conclusion: L744-752 – Can you really discount the effect of smaller flows in reworking sediment and only attribute change to one event during the period? Is this conjecture? L753-758 – as noted above, is this element sufficiently rigorous relative to other parts of the manuscript?
We agree that complete attribution of the observed changes to a single event is not possible, we clarify this point in the revised manuscript. However, several lines of evidence suggest that the November 2023 flood was the dominant geomorphic disturbance during the observation period. This event was the only discharge exceeding 180 m³ s⁻¹ between the two surveys and the only one that reached bankfull conditions, whereas all other events during this period were at least ca. 50% smaller in peak discharge.

In addition, our hydraulic competence analysis indicates that flow conditions associated with this flood were sufficient to mobilise large portions of the bar surface. The spatial patterns predicted by this analysis broadly correspond with the areas of elevation change identified in the DoD analysis, suggesting that the observed morphological adjustments were primarily associated with this event.

We therefore revise the manuscript to clarify that the changes observed between the surveys represent the cumulative response of the bar over the survey interval, while the November 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.

Finally, we emphasise in the discussion that despite the magnitude of the November flood, the bar was not completely reworked. Instead, the observed adjustments were spatially heterogeneous and strongly conditioned by the pre-existing bar morphology and slope distribution.

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Figure text size: The legends / axes labels etc on many of the figures are very small. Revisit for all figures.

The reviewer is correct. For the revised manuscript, we:
- Increase font sizes across all figures,
- Standardise tile scaling and colour bars,
- Add flow-direction arrows,
- Delineate crest/middle/tail boundaries explicitly

We recognise that figure clarity is essential for interpretation and address this comprehensively.

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., & 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

Phlip Bailey, Joseph Wheaton, Matt Reimer, & James Brasington. (2020). Geomorphic Change Detection Software (7.5.0). Zenodo. https://doi.org/10.5281/zenodo.7248344

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

Wheaton, J.M., Brasington, J., Darby, S.E. and Sear, D.A. (2010), Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets. Earth Surf. Process. Landforms, 35: 136-156. https://doi.org/10.1002/esp.1886