

Deep learning-based object detection on LiDAR-derived hillshade images: Insights into grain size distribution and longitudinal sorting of debris flows

Paul E. Schmid, Jacob Hirschberg, Raffaele Spielmann, and Jordan Aaron

Response to Referees

We thank Pierluigi Confuorto very much for reviewing our article and for the constructive feedback. Below we provide our point-by-point responses.

1. *It is my understanding that using hillshade representation, only 2 dimensions can be analyzed. Is there any possible improvement to obtain also the vertical dimension, which could be very important to be estimated?*

Yes, your assumption is correct: we report 2D velocities and ignore the vertical component. Since the channel inclination on the fan is low (3–4°), the vertical component can be neglected. Fig. 6 supports this assumption, as the PIV velocities are in fact 3D (Aaron et al., 2025) and match well with the 2D object velocities. We will address this limitation and provide reasoning in the discussion. Additionally, we will note that 3D velocities could be obtained by projecting the vectors onto the 3D point cloud.

2. *Would this methodology be implemented also to forecast trajectories of boulders and woods?*

This is a good question, which we do not yet address in the article. As mentioned in the Introduction, we aim to develop a framework to efficiently obtain object trajectories. On the one hand, this will allow us to analyze object dynamics to better explain debris-flow phenomena such as longitudinal sorting and levee formation. On the other hand, if the model operates in real time, it could be used for early-warning purposes.

The method could also be used to test new numerical models that explicitly simulate the motion of large particles in the flow. This is a promising venue for future work, and we will add a paragraph to discuss the potential future use cases of our method.

3. *Which are the error bounds of the different size materials in terms of velocities using Sort and Bot Sort?*

Thank you for this comment. We did not clearly explain how we calculate object velocities based on bounding-box tracks. In the revision, we will specify that velocities are computed from the temporal displacement of the bounding-box centroid (x_c , y_c). Since we use the centroid rather than the box extent, the estimate is independent of box size. We will also add a comparison between manually annotated tracks and detector-derived centroids to quantify image-plane jitter (σ_x , σ_y in pixels). The image-plane jitter represents the frame-to-frame variability in the detected bounding box position caused by minor localization noise.

4. *Can this method be extended to differentiate submerged vs. surface-level boulders?*

Thank you for this question. This is exactly why we differentiate between boulders and rolling boulders. According to our definition, rolling boulders are approximately the same size as the flow depth, meaning they have contact with the channel bed and are submerged. Boulders, on the other hand, are smaller and only visible because they are on the surface of the flow. We will clarify this distinction more effectively in the method section when defining the classes.

*As a mere suggestion on the arrangement of the paper, I would split section 2 into 2.1 Geological and geomorphological setting (providing more info about the catchment area) and 2.2 about the monitoring set up. I find it a little bit confusing as it is.
All the best*

Thank you for this suggestion. Since the geological and geomorphological context is not extensively described, we believe that a dedicated subsection is not necessary and could disrupt the flow of the text. However, we will merge Sections 2.1 and 2.2 and move the description of the monitoring setup to a new Section 2.2 in the revised manuscript.

References:

Aaron, J., Langham, J., Spielmann, R., Hirschberg, J., McArdell, B., Boss, S., Johnson, C. G., & Gray, J. M. N. T. (2025). Detailed observations reveal the genesis and dynamics of destructive debris-flow surges. *Communications Earth & Environment*, 6(1), 556. <https://doi.org/10.1038/s43247-025-02488-7>