Dear Editor and Reviewer,

Thank you very much for your useful comments and suggestions.

In this document, you will find a detailed explanation of the changes made to the original manuscript to meet your suggestions.

For the sake of clarity, we used the following text styles:

black, italics:	reviewer comment
blue, plain text:	our reply
blue, italics:	revised text

Best regards

Elena Ioriatti

Mauro Reguzzoni

Edoardo Reguzzoni

Andreas Schimmel

Luca Beretta

Massimo Ceriani

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1. The authors position the main innovation of this manuscript as an alternative method for defining rainfall thresholds that relies on monitoring data collected over a relatively short period and does not require extensive records of debris-flow events. This claim suggests the use of a physics-based approach, which typically does not demand large event datasets. However, the thresholds in this study appear to be derived empirically, which generally does require a substantial number of events for development and validation. Could the authors clarify why they believe their method circumvents the need for numerous debris-flow events? Further elaboration on this point would be helpful.

We regret the lack of clarity in our previous description and thank you for pointing this out. The thresholds were derived empirically with the aim of collecting as much empirical data as possible within a limited monitoring period. Since intense events are rare in such a short timeframe, we adopted two strategies:

1. We included all the recorded rainfall events, not only the triggering but also the non-triggering ones. To this end, we applied Linear Discriminant Analysis, which defines the threshold through the statistical separation of predefined classes.
2. We considered as triggering not only debris-flow events (C4) but also all events that produced a basin response, i.e. high flow (C2) and high flow with sediment transport (C3) and we calculated the lower threshold TH1. As the hydrological process is directly linked to discharge, different I–D combinations along the same threshold correspond to the same flow type. This allows us to rigidly shift TH1 upward, keeping the slope constant and adjusting the intercept, until identifying TH2, which only isolates the debris-flow events.

These clarifications have been included in the Introduction of the revised manuscript as follows:

In this study, we propose an alternative approach to define Intensity-Duration rainfall thresholds, which is based on the use of monitoring data collected over a relatively short period and does not require a large number of debris-flow events. The method relies on data acquired through relatively low-cost sensors and a lightweight, easy-to-install monitoring station. This station was located on the stream bank within an Alpine catchment. The monitoring data provided a good understanding of the catchment's hydrological response, allowing the identification of a lower threshold associated with increases in stream water level and sediment transport that may serve for pre-alert purposes.

To overcome the limitation posed by the small number of debris-flow events, we propose two complementary strategies. First, we consider not only triggering but also non-triggering rainfall events, applying statistical analysis to distinguish between the two classes. Second, we draw on the larger set of high-flow and sediment-transport events to establish a robust lower threshold, which then serves as a reference for isolating debris-flow conditions and defining the debris-flow threshold.

In addition, the study explores the uncertainty in threshold definition associated with two key factors: the spatial location of the rain gauge and the duration of the inter-event time used to separate rainfall events.

2. Another highlighted contribution is the incorporation of the catchment hydrological regime, with the classification of four regimes: C0, C1, C2, C3, and C4. However, the classification criteria seem somewhat arbitrary and based on expert judgment. To strengthen the robustness of this classification, it is recommended to incorporate quantitative hydrologic variables—such as water level or runoff—given that hydrological regimes are fundamentally governed by these factors. Since water level data are already monitored at stations H1 and H2, integrating these measurements into regime classification is advisable. Alternatively, employing a hydrological model to simulate runoff across different regimes could help elucidate the underlying mechanisms.

Thank you for this suggestion. We examined the water-level sensor data, but unfortunately they proved unreliable. For some events an increase is visible in the radar dataset, while for others it is not, and the dataset also contains negative values. The sensor is suspended high above the channel to avoid damage during debris flows, and its wide measurement cone is appropriate for capturing extreme events but not sensitive enough to reliably detect smaller flow increases. The attached image illustrates this issue: during a high-flow event (C2) recorded at the Hortus station, a small rivulet is visible below the radar but it flows along one bank of the channel rather than in the center, making accurate measurement difficult. For this reason, we could not integrate water-level measurements into the regime classification.

3.3 Classification of images and linking rainfall events to the observed channel response

[…]

Data from the water level sensor were examined but proved unreliable, as the dataset contained negative values and showed inconsistencies with the observed flow dynamics. The sensor was mounted high above the channel to avoid damage during debris flows, and its wide measurement cone is suitable for capturing extreme events but insufficiently sensitive to reliably detect smaller flow increases.

We thank you for the suggestion of using a hydrological model: in the revised manuscript we applied the SCS-CN and Unit Hydrograph approach to simulate runoff and compare the results with the empirical thresholds. This new analysis and discussion have been added in Sect. 5.3 and are described in detail in our response to the following comment.

3. The manuscript dedicates significant space to discussing the effects of spatial differences and minimum inter-event time on rainfall thresholds. While relevant, these aspects have been explored in previous studies. It is suggested to condense this section and instead expand the discussion on the influence of hydrological regimes on rainfall thresholds, which represents a more novel aspect of this work.

Thank you for this valuable suggestion. A new analysis has been performed to interpretate the thresholds in relation to hydrological regimes (new Sect. 5.3). This section now links the empirical thresholds to runoff generation modelled using the SCS-CN and Unit Hydrograph approach and discusses the physical basis for TH1 and TH2.

3.4 Rainfall threshold definition using the Linear Discriminant Analysis (LDA)

[…]

For the debris-flow threshold (TH2), events classified as debris flows (C4) were treated as "triggering" ("True"), while all other classes (C1, C2, C3) were treated as "non-triggering" ("False"). The LDA method *was not applied in this case because the limited number of debris flows made it difficult to reliably estimate within-class variance and class means for a stable discriminant axis. Moreover, the strong imbalance between classes biases the separation boundary, as the dominance of the majority class shifts the boundary toward the minority class, reducing classification accuracy. TH2 was derived by keeping the scaling exponent β (slope) of TH1 and iteratively increasing the coefficient α in steps of 0.1, which in the log–log form of* $I = \alpha \cdot D^{\beta}$ *corresponds to shifting the intercept* $\log_{10}\alpha$ *upward. The model performance was evaluated at each step by using the Area Under the Receiver Operating Characteristic Curve (AUC). The final threshold was selected as the value that maximized AUC, ensuring the best separation between debris flows and non-debris flows. The final threshold was selected as the value that maximized the AUC, ensuring the best separation between debris flows and non-debris flows. Although assuming parallelism between TH1 and TH2 is methodologically convenient, it can be questioned from a hydrological perspective, as the rainfall duration–intensity relationship may differ between flow-depth increases and debris-flow mobilization. However, for runoff-generated debris flows, studies have shown that the two thresholds display similar slopes, at least for the short-duration events that typically trigger debris flows (Berti and Simoni, 2005; Simoni et al., 2020; Berti et al., 2020). This similarity arises because runoff generation and the mobilization of channel debris are both expressions of the same hydraulic process: the concentration of overland flow within the catchment and its transformation into channelized flow.*

5.3 Hydrological interpretation of rainfall thresholds

A major strength of our method, which relies on monitoring data from many rainfall events, is the ability to identify thresholds not only for debris-flow initiation but also for earlier stages of hydrological response. The lower threshold, TH1, which separates events that do not change channel flow depth from those that cause a measurable increase, is particularly relevant from a hydrological standpoint. It marks the point at which rainfall surpasses the catchment's initial losses, producing overland flow on exposed rock surfaces and shallow runoff along talus-slope drainage lines, and ultimately supplying water to the main debris-flow channel. This empirical threshold can be further supported by a simple hydrological analysis that improves understanding of catchment response.

Figure 15 compares the UNIBO TH1 threshold with the theoretical runoff discharge computed at the UNIBO monitoring station using the SCS Curve Number (CN) rainfall–excess model combined with the SCS dimensionless Unit Hydrograph (CN–UH method; Soil Conservation Service, 1972). A similar approach was applied by Gregoretti et al. (2016) and Berti et al. (2020) to evaluate rainfall excess in debris-flow initiation zones of alpine catchments. Input data for the analysis are listed in Table 5. The key parameter of the method is the Curve Number, which defines the watershed's potential maximum retention and directly controls runoff generation. We derived a composite CN as the area-weighted average of three values assigned to exposed bedrock, old landslides, and debris deposits that characterize the basin upstream of the UNIBO station (Fig. 3). A sensitivity analysis was carried out using minimum and maximum CN values for each unit, derived from USDA-SCS lookup tables and from values back-calculated by Bernard et al. (2025) for three monitored basins in the Eastern Italian Alps. All analyses assumed normal antecedent moisture conditions (AMC II), and the time of concentration was estimated with Kirpich's formula (Kirpich, 1940).

The results show a fairly good agreement between empirical and theoretical thresholds. In particular, this agreement is clear for high CN values, which reflect low infiltration capacity. In these cases, the zero-discharge line marking the onset of channel runoff coincides with the lower boundary of the blue triangles, which indicate visible increases in flow depth recorded on video. Nevertheless, the theoretical TH1 threshold is steeper than the empirical one. This discrepancy arises from the simplified assumptions of the SCS-CN abstraction model. As highlighted by Berti et al. (2020), under the assumption of constant initial loss the model behaves like a simple "bucket," where the catchment begins to spill once its storage capacity is filled. In such conditions, the theoretical slope of the runoff-initiation threshold is –1, compared with –0.56 for the empirical threshold. The gentler empirical slope suggests that initial losses increase with rainfall duration, likely due to long-term infiltration into weathered rock or debris, an effect not represented in this simplified analysis.

With regard to the empirical debris-flow threshold (TH2), the model indicates that debris mobilization corresponds to a peak runoff discharge of about 2–3 m³/s. These values appear much higher than the critical surface discharge values reported by Gregoretti and Dalla Fontana (2008) and Berti et al. (2020) in similar geological settings, which are typically below 0.2 m³/s. However, it should be emphasized that the runoff discharges in Fig. 15 are computed at the UNIBO station, not in the initiation area, where the contributing headwater catchment is considerably smaller. More relevant to our analysis is the fact that the empirical threshold TH2 is roughly parallel to a theoretical line of equal-runoff discharge, again supporting the physical basis of the threshold identified from monitoring data. Although the discharge contours do not exactly match the slope of the runoff-initiation line, the discrepancy is minor and difficult to detect in empirical datasets. Consequently, the simplified assumption of slope similarity between TH1 and TH2 remains theoretically founded.

Table 5. Parameters adopted for the SCS-CN and SCS Unit Hydrograph (SCS–UH) analysis at the UNIBO monitoring station. The table reports basin descriptors, land-cover/soil units with corresponding Curve Numbers (CN), and hydrological parameters used for runoff and hydrograph computation.

Parameter		Value
Basin characteristics	Basin area (m^2)	2052904
	Basin length (m)	2856
	Basin height (m)	1800
Land cover	Rock area (m^2)	1245455
	Landslide area (m^2)	328718
	Debris area (m^2)	478731
	Rock Curve Number [min–max]	85-95
	Landslide Curve Number [min–max]	60-70
	Debris Curve Number [min–max]	70-80
	Composite Curve Number [min-max]]	77-87
Hydrological parameters	Potential Maximum Retention, S (mm) [min-max]	38-76
	S=(25400/CN)-254	
	Initial Abstractions, Ia (mm) [min-max]	8-15
	Ia=0.2S	
	Time of Concentration, Tc (h)	0.18
	from Kirpich's formula	

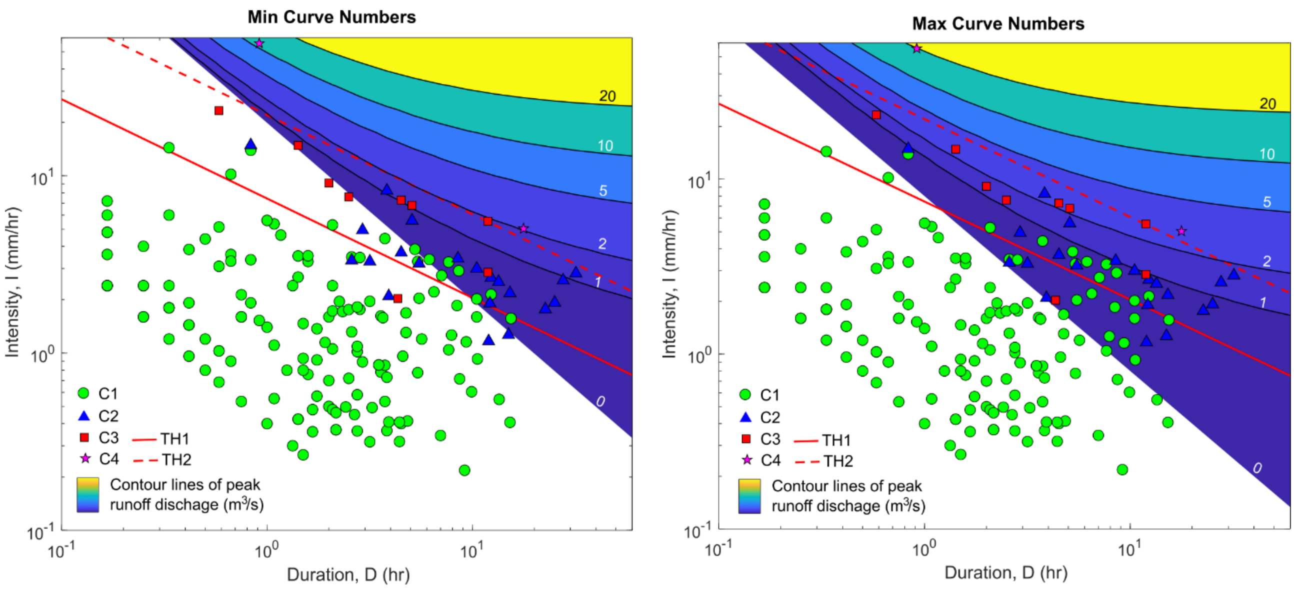
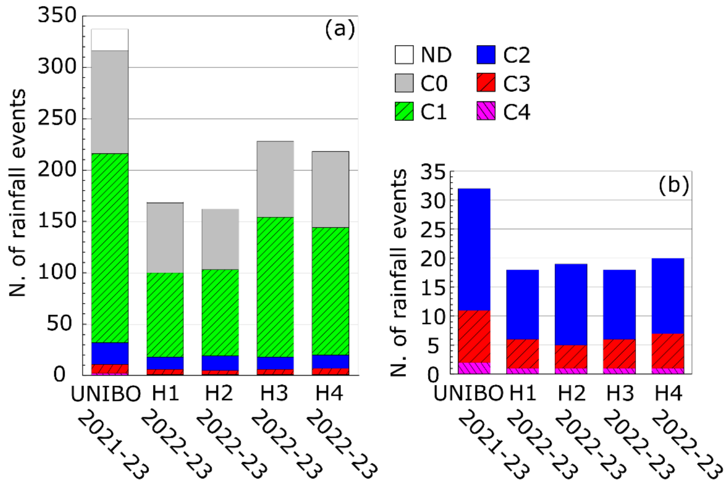


Figure 15. Contour maps of peak runoff discharge obtained with the SCS–UH method for (left) minimum CN values and (right) maximum CN values. Empirical observations of rainfall events are superimposed, with symbols indicating event classification. The comparison illustrates the sensitivity of theoretical runoff estimates to Curve Number selection.

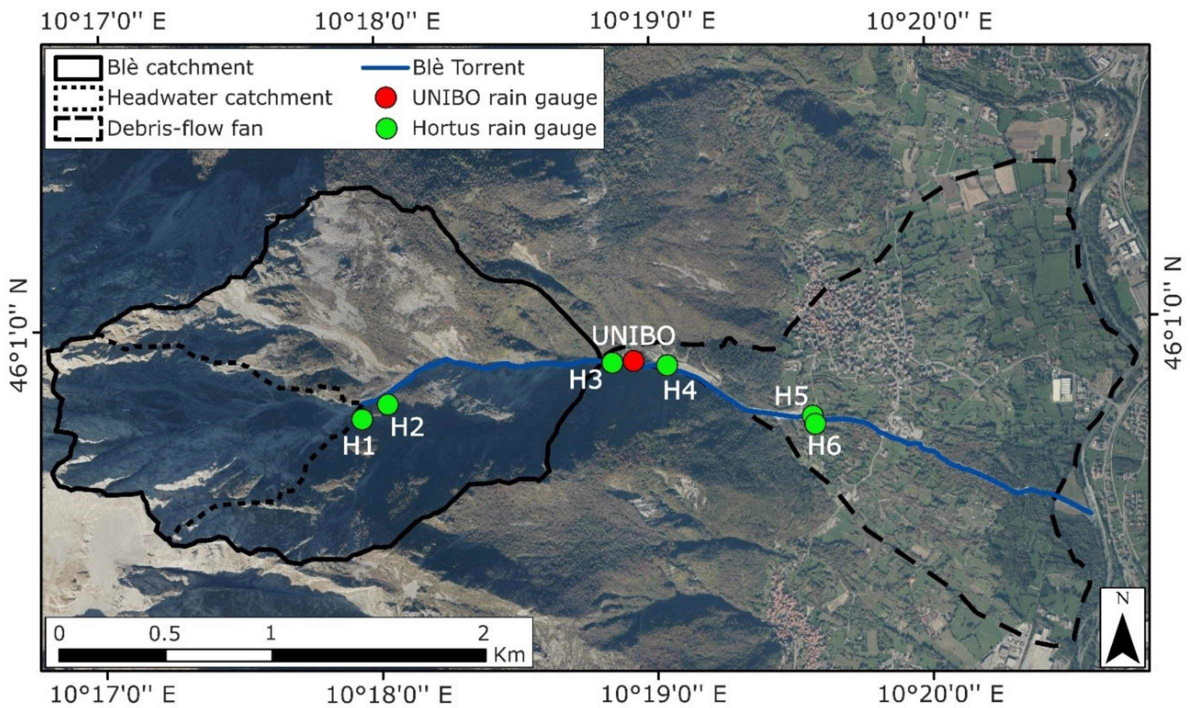
4. In Fig. 8, should the legend indicate the hydrological regimes C0, C1, C2, C3, and C4? Please verify and revise as necessary.

Thank you for noticing the error in the legend. The figure has been corrected.



5. For Fig. 3, please add a legend identifying the monitoring stations H1, H2, H3, etc.

Thank you for the suggestion. The icons for the stations have been added to the legend.



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