Revision notes on Manuscript No. NHESS-2023-180

First of all, the authors thank the Editors and the reviewers for considering our manuscript and providing constructive comments to help us improve the quality of our work. We have accordingly revised the manuscript by carefully addressing or answering the comments point-by-point, summarized as follows. Following the revision, we hope we have clarified all of the points summarized by the Editor and reviewers.

Responses to the Comments Raised by the Editor

Your manuscript underwent a thorough review by two experts, both of whom raised concerns about the novelty of your work. Upon examining your responses, the manuscripts, and your previous studies, it appears that you have assembled a modeling chain that integrates components previously addressed in some of your earlier papers.

1. While you have discussed the novelty arising from this approach, it seems necessary to enhance clarity in presenting the uniqueness of your analysis, particularly in the introduction and throughout the manuscript. Consequently, I would like to offer you the opportunity to submit a substantially revised version, addressing the comments provided by the referees and placing a stronger emphasis on explaining the novelty of your work.

Authors' reply:

Thanks for the comments. We have added a detailed and stronger emphasis on explaining the novelty of our work in the Introduction, and Discussion part as below:

In the Introduction part:

"Peak discharge has garnered widespread acceptance as a standard critical parameter for predicting debris flow occurrences (Wei et al., 2018). For instance, Li et al. (2021) established rainfall intensity-duration thresholds based on process-based critical runoff discharge. Bernard and Gregoretti (2021) proposed an approach to determine debris flow occurrence through coupling a hydrological model with a critical discharge relationship using rainfall and raw radar data. However, in these existing frameworks,

the peak discharge is usually predicted by a hydrological model; such an approach may predict the occurrence but not the scale of debris flow".

"Moreover, in comparison with the previous studies that solely used peak discharge as a critical parameter for predicting debris flow occurrence (Li et al., 2020; Bernard and Gregoretti, 2021; Wei et al., 2018), the current integrated hydrological and hydrodynamic modeling approach offers potentially a more detailed and reliable estimation by directly considering overland flow dynamics in susceptible debris flow areas. With grid-based hydrodynamic indices and through identifying the spatial distribution of triggering cells, the proposed framework facilitates the prediction of occurrence, and meanwhile, the magnitude and scale of debris flows".

In the Discussion part:

"Actually, several studies have been reported to establish Intensity-Duration (ID) rainfall thresholds through a numerical approach (Domènech et al., 2019). In the previous studies, runoff-induced erosion is considered to occur when the bed shear stress exceeds a critical value, and the volumetric concentration of solids in the debris flow is smaller than an equilibrium value. Furthermore, most of the previous studies adopt simplified hydrological simulations, e.g. calculating runoff using a basic lumped infiltration model that neglects the initial moisture content of the soil. Different from these existing attempts, the proposed approach focuses on predicting spatially varying hydrodynamic index (unit-width discharge) at each cell to indicate the occurrence of runoff-generated debris flows.

In the authors' previous works (Wei et al. 2018; Wei et al. 2017), the rainfall thresholds in the same study site were also calculated using a runoff prediction model. Wei et al. (2018) developed an approach solely based on a hydrological model, whilst Wei et al. (2017) presented a machine learning model for runoff prediction. These approaches are clearly different from the current integrated hydrological and hydrodynamic modeling framework which provides a more robust method to directly incorporate overland flow dynamics into debris flow occurrence estimation. Furthermore, our previous studies used peak discharge as the critical parameter to indicate debris flow occurrence; if the peak discharge predicted by the adopted hydrological model exceeds *the critical discharge, debris flow occurrence is confirmed. Whilst such peak discharge-based approaches can estimate debris flow occurrence, they cannot provide any insights related to the magnitude and scale of a debris flow. Our new framework includes the use of a hydrodynamic model to predict detailed overland flow dynamics to derive grid-based hydrodynamic indices in the areas susceptible to debris flows. This enables not only the prediction of debris flow occurrences but also provides insights into the magnitude and scale of a debris flow.*

"Furthermore, to evaluate debris flow occurrence at a catchment scale, we introduce a new concept as "zone threshold" to represent varying degree of conservatism or adventurousness in rainfall thresholds. By associating different zone thresholds with the corresponding level of warning, the framework facilitates decision-making and response actions based on identified rainfall thresholds, allowing implementation of risk management strategies tailored to the different level of caution or preparedness."

The Editor also could find the changes in Lines 93-99, Lines 105-113 and Lines 697-725 of the revised MS.

2. Furthermore, it would be beneficial to provide additional clarification regarding the hydrodynamic model's input. Specifically, could you elaborate on whether the hydrograph input is distributed, or if you have selected specific input points along the river network or elsewhere?

Authors' reply:

Thanks for the comments. The input hydrograph is applied at a particular input point/cell located at the outlet of the culvert beneath the road as the point-source boundary conditions to drive HiPIMS to simulate the subsequent flow dynamics. During an intense rainfall event that occurs in the headwater catchment area, the generated overland flow converges into the main channel, passes through the culvert beneath the road, reaches the triggering area, and erodes the available loose soil materials to initiate a debris flow.

The Editor also could find the changes in Lines 483-488 of the revised MS.

Responses to the Comments Raised by Reviewer #1

The authors present a method to obtain rainfall intensity-duration thresholds for runoff-generated debris flows. To obtain these thresholds the authors have used existing equations in the literature to compute the critical discharge that could lead to the destabilization of catchment slopes that have a fine granulometry and slopes that have large boulders. The presented rainfall intensity-duration thresholds have been established using the rainfall events that reach the critical discharge value over different percentages of pixels in the catchment. However, no recommendation on the critical area required for debris flow initiation is given.

1. My main concern is the novelty of the presented work. The hydrological simulations were conducted by Wei et al., (2018). The relationship between the intensity-duration of the rainfall event that triggered the 2013 debris flow and the discharge is also studied in Wei et al., (2018). Moreover, as the authors point out in line 630, Wei et al., (2017) already used the same method to establish an intensity-duration threshold for the studied catchment.

Authors' reply:

Thank you for your comments. The authors have explained the novelty and advantages of the newly proposed model in lines 630-645 of the initial manuscript. The framework presented in this study significantly diverges from our previous research. Firstly, in earlier studies led by Wei et al. (2018), the focus was solely on the hydrological model (NAM model), with the presentation of hydrological simulations. In Wei et al. (2017), a machine learning model was employed for runoff prediction. In contrast, our current study adopts an integrated hydrological and hydrodynamic modeling approach, providing a more robust estimation by directly incorporating overland flow dynamics in regions prone to debris flows.

The second key deviation lies in our approach to determining the occurrence of debris flow. In prior studies, such as Wei et al. (2018), peak discharge was used as the critical parameter. If the calculated peak discharge from the hydrological model exceeded the critical discharge, debris flow occurrence is confirmed; otherwise, it was deemed non-occurrence. However, in this study, we use hydrodynamic metrics as the critical parameter for predicting debris flow occurrences. This is in contrast to the common practice, such as our earlier works (Wei et al., 2018 and Wei et al., 2017), where peak discharge served as the critical parameter. Now peak discharge has become widely accepted as the standard critical parameter for predicting debris flow occurrences. For instance, Li et al. (2021) established rainfall intensity-duration thresholds based on process-based critical runoff discharge. Bernard and Gregoretti (2021) proposed determining debris flow occurrences through a hydrological model coupled with a critical discharge relationship using rainfall and raw radar data. However, it is important to note the limitations of the previous frameworks, which solely relied on peak discharge predicted only by a hydrological model. Such an approach could predict the occurrence of debris flow but lacked the capability to predict the scales of debris flow. In essence, our previous model could only forecast the likelihood of debris flow occurrence, without providing insights into the magnitude of the runoff-generated debris flow.

In this study, we introduce a novel framework that employs an integrated hydrological and hydrodynamic modeling approach to enhance the accuracy of rainfall thresholds estimation for runoff-generated debris flows. The incorporation of a hydrodynamic model enables the prediction of detailed flow dynamics, providing grid-based information such as water depth and flow velocity in regions susceptible to debris flows. The flow information obtained is then employed to compute hydrodynamic metrics based on unit-width discharge. These metrics are compared with corresponding hydrodynamic thresholds, serving as indicators for the occurrence of runoff-generated debris flows. Given that the derived hydrodynamic indices are grid-based, the framework allows for determining the proportion of trigger cells within the triggering area or the total number of trigger cells. This leads to clear advantages of the current framework against existing approaches, enabling not only the prediction of debris flow occurrences but also providing insights into the magnitude and scales of debris flow. As a summary, in contrast to our previous study and similar works, such as Li et al. (2021), our approach represents a significant advancement in the prediction of runoff-generated debris flows.

Furthermore, to evaluate debris flow occurrences at the catchment scale, we have introduced a new concept as "zone threshold." The zone threshold is defined as the critical proportion of trigger cells within the triggering area. If the proportion of trigger cells surpasses the zone threshold, it signifies a debris flow occurrence; otherwise, it is categorized as a non-occurrence event. This concept integrates zone thresholds with hydrodynamic thresholds within the proposed framework. The advantage of incorporating zone thresholds lies in their ability to represent varying degrees of conservatism or adventurousness in rainfall thresholds. A smaller zone threshold corresponds to a lower rainfall threshold, reflecting a more conservative approach. Conversely, a larger value results in a higher rainfall threshold, indicating a more adventurous approach. By associating different zone thresholds with corresponding levels of warning, the framework facilitates decision-making and response actions based on identified rainfall thresholds. This approach allows for a spectrum of risk management strategies tailored to the desired level of caution or preparedness.

Overall, with the integration of the hydrodynamic model, the introduction of a critical parameter, and the incorporation of zone thresholds, we assert that our study makes a novel contribution to the prediction of runoff-generated debris flows.

The Reviewer also could find the changes in Lines 93-99, Lines 105-113 and Lines 697-725 of the revised MS.

References:

Wei, Z.L., Shang, Y.Q., Zhao, Y., Pan, P. and Jiang, Y.J., 2017. Rainfall threshold for initiation of channelized debris flows in a small catchment based on in-site measurement. Engineering Geology, 217:23-34.

Wei, Z.L., Xu, Y.P., Sun, H.Y., Xie, W., Wu, G., 2018. Predicting the occurrence of channelized debris flow by a cascading flood debris-flow model in a small debris flow-prone catchment. Geomorphology, 308 :78-90

Li, Y.J., Meng, X.M., Guo, P., Dijkstra, T., Zhao, Y., Chen, G., Yue, D.X., 2021. Constructing rainfall thresholds for debris flow initiation based on critical discharge and S-hydrograph. Engineering Geology, 280:105962.

Bernard, M. and Gregoretti, C. 2021. The use of rain gauge measurements and radar data for the model-based prediction of runoff-generated debris-flow occurrence in early warning systems. Water Resources Research, 57(3): e2020WR027893.

2. An additional major concern is that the thresholds presented in this manuscript have only been tested using one debris flow event. However, the authors employ rather strong language throughout the manuscript and claim that the proposed thresholds can effectively identify the triggering and non-triggering rainfall events. In my opinion, a larger inventory with more debris flow events and spanning a longer period is needed to provide a reliable calibration and verification of the proposed thresholds.

Authors' reply:

In response to the comments, it's important to note that the framework has been tested against one debris-flow event, but also four no-debris-flow events. The results demonstrated that the proposed framework has successfully predicted both the occurrence and non-occurrence of debris flow events. However, the authors acknowledge a significant limitation here application and testing of the framework were confined to a small catchment. This is related to the challenges associated with obtaining high-quality observed hydrological data in small and unstable channels. Additionally, the validation process relied on only one debris flow event, emphasizing a need for broader testing in similar catchments to enhance the framework's robustness. We have explicitly considered this limitation in the Discussion Section of the initial manuscript.

On the flip side, when compared to traditional statistical Intensity-Duration (I-D) analysis approaches, the proposed framework in this study offers a distinct advantage. It excels in generating rainfall thresholds for areas with limited historical data on debris flow occurrences. This makes the proposed framework particularly well-suited for regions where data is scarce. It is essential to highlight that in cases where a more extensive dataset is available, encompassing multiple debris flow events over an extended period, the traditional statistical I-D rainfall threshold method is recommended. This is due to its straightforward calculation process and the availability of influencing factors that can contribute to a more comprehensive analysis.

3. Finally, the structure of the paper needs to be improved. The manuscript lacks clear objectives. The results, methods and discussion are mixed through section 4 and in the discussion (section 5). Some information appears repeated, and some relevant

information to understand parts of the paper comes late. This makes it difficult for the reader

Authors' reply:

Thanks for the comments. The authors have revised the structure of the paper in the revised MS.

4. Line 691: I do not agree. In my opinion, statistical methods used to obtain empirical rainfall intensity-duration thresholds are objective. In fact, such thresholds are calibrated and validated using large datasets containing multiple landslide events and no-events and, in some cases, even monitoring data. The thresholds you proposed have not been properly validated using debris flow data.

Authors' reply:

The authors acknowledge the common practice of calibrating and validating Intensity-Duration (ID) statistical thresholds using extensive datasets that include multiple landslide events and non-occurrence events. These ID statistical thresholds are often recommended due to their straightforward calculation process. However, the authors express concern about the objectivity of the ID statistical methods, primarily arising from the absence of a universally accepted definition for rainfall events. The definition of a rainfall event plays a crucial role in establishing ID thresholds.

In the revised manuscript, the authors will revisit this statement to ensure a more accurate expression of such perspective on the objectivity of ID statistical thresholds is provided.

The reviewer also could find the changes in Lines 683-685 of the revised MS.

5. Line 707: The approach was already presented in Wei et al., (2017).

Authors' reply:

Please see the response to Comment 1#.

Responses to the Comments Raised by Reviewer #2

1. Wei et al. explore the possibility of determining intensity-duration thresholds of runoff-induced debris flows through a combination of hydrological and hydrodynamic analysis. The authors present an alternative approach to deciphering the rainfall thresholds for debris flows instead of the traditional approach, which relies on statistical correlations of existing landslide information. I agree with the authors that this approach may be useful for areas having observational data on debris flow occurrences. The manuscript shows promising results. However, the authors have already presented similar works in two of their publications, i.e., Wei et al., 2017 and Wei et al., 2018, similarly on the same study area and using almost the same methods. Considering this, it is difficult to understand the original contribution of this study, the advancements, improvisation and improvements after the work of Wei et al., 2017 and Wei et al., 2018. Either the authors are not explaining it in detail, or I fail to understand where and how it is improved than the previous studies. In this regard, I recommend that the authors clearly present the advancements of this study compared to their previous publications.

Authors' reply:

Thank you for your comments. The framework presented in this study significantly diverges from our previous research. Firstly, in earlier studies led by Wei et al. (2018), the focus was solely on the hydrological model (NAM model), with the presentation of hydrological simulations. In Wei et al. (2017), a machine learning model was employed for runoff prediction. In contrast, our current study adopts an integrated hydrological and hydrodynamic modeling approach, providing a more robust estimation by directly incorporating overland flow dynamics in regions prone to debris flows.

The second key deviation lies in our approach to determining the occurrence of debris flow. In prior studies, such as Wei et al. (2018), peak discharge was used as the critical parameter. If the calculated peak discharge from the hydrological model exceeded the critical discharge, debris flow occurrence is confirmed; otherwise, it was deemed non-occurrence. However, in this study, we use hydrodynamic metrics as the critical parameter for predicting debris flow occurrences. This is in contrast to the common practice, such as our earlier works (Wei et al., 2018 and Wei et al., 2017), where peak discharge served as the critical parameter. Now peak discharge has become widely accepted as the standard critical parameter for predicting debris flow occurrences. For instance, Li et al. (2021) established rainfall intensity-duration thresholds based on process-based critical runoff discharge. Bernard and Gregoretti (2021) proposed determining debris flow occurrences through a hydrological model coupled with a critical discharge relationship using rainfall and raw radar data. However, it is important to note the limitations of the previous frameworks, which solely relied on peak discharge predicted only by a hydrological model. Such an approach could predict the occurrence of debris flow but lacked the capability to predict the scales of debris flow. In essence, our previous model could only forecast the likelihood of debris flow occurrence, without providing insights into the magnitude of the runoff-generated debris flow.

In this study, we introduce a novel framework that employs an integrated hydrological and hydrodynamic modeling approach to enhance the accuracy of rainfall thresholds estimation for runoff-generated debris flows. The incorporation of a hydrodynamic model enables the prediction of detailed flow dynamics, providing grid-based information such as water depth and flow velocity in regions susceptible to debris flows. The flow information obtained is then employed to compute hydrodynamic metrics based on unit-width discharge. These metrics are compared with corresponding hydrodynamic thresholds, serving as indicators for the occurrence of runoff-generated debris flows. Given that the derived hydrodynamic indices are grid-based, the framework allows for determining the proportion of trigger cells within the triggering area or the total number of trigger cells. This leads to clear advantages of the current framework against existing approaches, enabling not only the prediction of debris flow occurrences but also providing insights into the magnitude and scales of debris flow. As a summary, in contrast to our previous study and similar works, such as Li et al. (2021), our approach represents a significant advancement in the prediction of runoff-generated debris flows.

Furthermore, to evaluate debris flow occurrences at the catchment scale, we have introduced a new concept as "zone threshold." The zone threshold is defined as the critical proportion of trigger cells within the triggering area. If the proportion of trigger cells surpasses the zone threshold, it signifies a debris flow occurrence; otherwise, it is categorized as a non-occurrence event. This concept integrates zone thresholds with hydrodynamic thresholds within the proposed framework. The advantage of incorporating zone thresholds lies in their ability to represent varying degrees of conservatism or adventurousness in rainfall thresholds. A smaller zone threshold corresponds to a lower rainfall threshold, reflecting a more conservative approach. Conversely, a larger value results in a higher rainfall threshold, indicating a more adventurous approach. By associating different zone thresholds with corresponding levels of warning, the framework facilitates decision-making and response actions based on identified rainfall thresholds. This approach allows for a spectrum of risk management strategies tailored to the desired level of caution or preparedness.

Overall, with the integration of the hydrodynamic model, the introduction of a critical parameter, and the incorporation of zone thresholds, we assert that our study makes a novel contribution to the prediction of runoff-generated debris flows.

The Reviewer also could find the changes in Lines 93-99, Lines 105-113 and Lines 697-725 of the revised MS.

References:

Wei, Z.L., Shang, Y.Q., Zhao, Y., Pan, P. and Jiang, Y.J., 2017. Rainfall threshold for initiation of channelized debris flows in a small catchment based on in-site measurement. Engineering Geology, 217:23-34.

Wei, Z.L., Xu, Y.P., Sun, H.Y., Xie, W., Wu, G., 2018. Predicting the occurrence of channelized debris flow by a cascading flood debris-flow model in a small debris flow-prone catchment. Geomorphology, 308 :78-90

Li, Y.J., Meng, X.M., Guo, P., Dijkstra, T., Zhao, Y., Chen, G., Yue, D.X., 2021. Constructing rainfall thresholds for debris flow initiation based on critical discharge and S-hydrograph. Engineering Geology, 280:105962.

Bernard, M. and Gregoretti, C. 2021. The use of rain gauge measurements and radar data for the model-based prediction of runoff-generated debris-flow occurrence in early warning systems. Water Resources Research, 57(3): e2020WR027893.

The Reviewer also could find the changes in Lines 105-113 and Lines 697-725 of the revised MS.

2. On the other hand, the approach adopted by the author is also conceptualized by van Asch et al. 2014; Domènech et al., 2019; Siva Subramanian et al., 2023. It would be interesting for the readers to know the difference between the approaches of these studies and those of the current manuscript.

Authors' reply:

The authors acknowledge the similarity in conceptualization between this study and the mentioned research. Both studies aim to establish Intensity-Duration (ID) rainfall thresholds through a numerical approach. The mentioned studies build on the numerical framework proposed by van Asch et al. (2014). In those studies, erosion by runoff is considered to occur when the bed shear stress (τ, kPa) exceeds the critical erosive shear stress at the initiation of soil erosion (τc, kPa), and the volumetric concentration of solids in the debris flow (Cv) is smaller than an equilibrium value (Cv∞).

In contrast, our study diverges in its approach to determining debris flow occurrences. We focus more on the values of the hydrodynamic index (unit-width discharge) at each cell. When the calculated unit-width discharge exceeds the critical threshold, a debris flow is considered to happen. This establishes a distinct criterion/approach for determining debris flow occurrence compared to the mentioned studies.

The current study focuses on runoff-generated debris flows, where the most significant triggering factor is surface flow dynamics. The transition from clear water flow to debris flow hinges on hydrodynamic conditions, such as flow discharge, surpassing certain thresholds. Therefore, providing accurate spatially distributed hydrodynamic information, including water depth and velocity, is crucial for estimating the occurrence of runoff-generated debris flows. This differs significantly from the initiation of landslide-triggered debris flows, where infiltration plays a pivotal role. In the mentioned studies, the hydrological simulation is simplified, calculating runoff using a basic lumped infiltration model that neglects the initial moisture content of the soil. This underscores that the framework proposed in this study is tailored specifically for runoff-generated debris flows, given its primary focus on the hydrological processes associated with such events.

The Reviewer also could find the changes in Lines 697-705 of the revised MS.

3. I also request that the authors kindly use a considerate tone while referring to approaches that vary from the author's perspective i.e., statistical approaches.

Authors' reply:

Thanks for pointing this out. In the revised manuscript, we will use an appropriate tone to discuss and comment on other methodologies that differ from our perspective.

4. Line 123: Figure 1. Please revise this figure as a flow chart. The intensity-duration threshold curve looks unrealistic in shape. Please verify.

Authors' reply:

Thanks for the comments. Figure 1 serves as a conceptual illustration of the framework. Therefore, the I-D threshold curve depicted in the figure is not intended to be a realistic representation at this stage. We attempted to revise Figure 1 as a flow chart; however, the resulting height of the figure would be too large. Therefore, we have decided to maintain Figure 1 in its current form.

5. Line 356: Figure 5. Is this rainfall vs observed discharge from a debris flow event? Please explain whether the instrumentation and calibration using the NAM model will apply during an actual debris flow.

Authors' reply:

In Fig. 5, it's important to note that there are no debris flow events during the depicted rainfall events. The observed discharge in Fig. 5 corresponds to clear water flow.

The Reviewer also could find the changes in Lines 362-364 of the revised MS.

6. Line 421: How does this curve appear during an actual debris flow? The runoff values will be within the said range or higher? This question comes because it is unclear whether the approach actually simulates the erosion caused by runoff or only the runoff. Please explain.

Authors' reply:

The simulated discharge in Fig. 6 represents clear water flows. We anticipate that during an actual debris flow event, the discharge for this curve will significantly increase. This expectation aligns with the fact that the volume of a debris flow is typically several times larger than a clear water flow.

The Reviewer also could find the changes in Lines 419-420 of the revised MS.