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Debris flow initiation characteristics and occurrence probability after extreme rainfalls: case study in the Chenyulan watershed, Taiwan

Jinn-Chyi Chen, Jiang- Guo Jiang, Wen-Shun Huang, Yuan-Fan Tsai

First Contact: Jinn-Chyi Chen, jinnchyi@cc.hfu.edu.tw

Response to Reviewer 2

I. General comments

The paper deals with an empirical/statistical analysis of debris flow occurrence base on a variable the authors introduce, the rainfall index RI, defined as the product between the maximum 24-h rainfall and the maximum hourly rainfall of a rainfall event. It has a specific focus on changes of debris flow probability due to the occurrence of previous events (landslide reactivation); so, this makes the MS innovative at some level. The manuscript certainly fits within the scope of the NHESS journal. The methods are overall valid, though the rationale underlying RI is not that clear and supported (see specific comments below). The MS requires an overall revision of the language, as too much of symbols and acronyms are used, which makes it very difficult to follow. Finally, I suggest major revisions for the manuscript.

Response:

We would like to thank the reviewer for their detailed comments and suggestions for the manuscript. We believe that the comments have identified important areas that required improvement. Major revisions have been implemented in the manuscript following the reviewer's suggestions.

(1) We have added sections (3-1~3-3) and Figures (2 a and b) to describe, analyze, and explain for the RI index, including the reason for using the index in this study and the rationale underlying RI.

(2) The overall language of the manuscript has been revised. The usage of symbols and acronyms have been reduced and a list of symbols and abbreviations has been added in the Appendix to ensure easy understanding.

(3) We have also responded to the specific comments and technical corrections suggested by the reviewer; point by point responses are as follows.

II. Specific comments

1. P2 L 3-5 These are quite strong statements on climate change impacts. Are the authors really sure that the cited papers allow to make these statements?

Response: This description in the original manuscript has been deleted.

2. P2 L 9 [": : : and increase the volume of loose debris within a watershed"] The paper analysis is based on the assumption that after an extreme event causing landslides, the probability of landslides increases as a feedback effect. I suppose that in other cases, the *opposite may be observed, as the occurrence of landslides can bring to a stabilization of affected slopes, and thus a lower probability of subsequent initiations. The authors should discuss better this issue.*

Response:

(1) This description in the original manuscript has been revised and the opposite feedback effect that may be caused by landslides has been added (Lines 7-9, Page 2).

(2) The supply of loose debris caused by landslides plays an important role in the occurrence of future debris flows and may change the critical rainfall threshold for the initiation of debris flows during subsequent rainfall events. The related phenomena are presented in Figure 3 and shown in the text, (blue text in Lines 13-28, Page 11).

3. P2 L 28 [": : :hydraulic design."] Authors should here add some literature on previous studies focused on the assessment of debris flow/landslide triggering return period. For instance:

M. Borga, G. Dalla Fontana, F. Cazorzi, Analysis of topographic and climatic control on rainfall-triggered shallow landsliding using a quasi-dynamic wetness index J. Hydrol., 268 (1–4) (2002), pp. 56-71.

D.J. Peres, A. Cancelliere, Estimating return period of landslide triggering by Monte Carlo simulation, Journal of Hydrology, Volume 541, 2016, Pages 256-271, ISSN 0022-1694.

P. D'Odorico, S. Fagherazzi, R. Rigon, Potential for landsliding: dependence on hyetograph characteristics J. Geophys. Res.: Earth Surf., 110 (F1) (2005).

L. Schilirò, C. Esposito, G. Scarascia Mugnozza, Evaluation of shallow landslide triggering scenarios through a physically based approach: an example of application in the southern Messina area (northeastern Sicily, Italy), Nat. Hazards Earth Syst. Sci., 15 (9) (2015), pp. 2091-2109.

Bogaard, T. and Greco, R.: Invited perspectives. A hydrological look to precipitation intensity duration thresholds for landslide initiation: proposing hydro-meteorological thresholds, Nat. Hazards Earth Syst. Sci. Discuss., in review, 2017.

Response: Thank you for the suggestion. We have added the suggested references (blue text in Lines 3-5, Page 3).

4. Section 2. The data section lacks of some essential information: what kind of rainfall data was available (a continuous series? Hourly? Sub-hourly?), how was the rain gauge selected to compute the RI (the "nearest" rain gauge?).

Response:

We apologize for the missing information. Essential information associated with rainfall estimation has been added in section 3.

There are only three meteorological stations (Sun Moon Lake, Yushan, and Alisan stations) near/within the Chenyulan stream watershed, as shown in Fig. 1(a), and these stations provide long-term (more than 43 y*r*) records of hourly rainfall data series. Thus, data from the three meteorological stations were used to estimate the regional rainfall characteristics for the whole Chenyulan watershed by the reciprocal-distance-squared method. The use of the reciprocal-distance-squared method and its limitation are presented and the estimation of the regional rainfall characteristics is expressed as Eq. (1).

5. P3 L18-20 the computation of the RI requires a criteria for identifying what is a "rainfall event". The authors should specify the criterion that they have adopted to single-out rainfall events from a rainfall sequence.

Response: The criteria for identifying rainfall event has been added in the section of 3-2, as shown in Lines 10-15, Page 6.

6. Figure 2. In this figure it seems that an "ad hoc" criterion has been used to plot the RI corresponding to events ("10 or more debris flows"). Since it does not seem that the RI has a physically-based/hydrological rationale, the authors should at least better prove if the RI works well in separating triggering and non triggering events. So: what happens if the "10 debris flow" threshold changes (e.g. to 5, or another number)? What happens if the RI index values for NON-triggering events are plotted?

Response:

We have added more descriptions is the revised manuscript describing the reasons for using the RI index (see Section 3).

(1) The use of other rainfall indexes is analyzed, as shown in Figure 2 (a) and (b), and the use of rainfall index is discussed. From the analysis of RI index, the index more suitably reflects the critical rainfall to trigger debris flows, especially for extreme rainfall that induced both high rainfall intensity and high accumulated rainfall in the study area.

(2) The five extreme rainfall events discussed in this paper have both characteristics of having high critical RI value and triggering a large number of debris flows (N>10). Most rainfall events, occupying 87%, caused four or less debris flows (N<4). The number of debris flows for the five extreme rainfall events varies significantly from other rainfall events. Thus, we used the rainfall index to separate the two groups of extreme rainfall events (N>10) and non-extreme rainfall events (exactly is N<4, not N<10 in the original manuscript). This description has also been added in the revised manuscript.

(3) It is important to understand how the non-triggering events affect the rainfall index. The analysis that only focused on non-triggering events using the RI index was not presented in this paper because the RI index is developed on the basis of the criteria of debris-flow occurrence, and there are too many non-triggering events, making it difficult to clearly present them. Perhaps the combination of the probability concept to discuss or analyze the effect of non-triggering events is more meaningful. Therefore, we developed the probability model of debris flow occurrence in this study.

7. Figure 3. It is unclear to which data points the curves are fitted (or where the curves come from).

Response: The section in the revised manuscript describing Figure 3 has been improved and rewritten, particularly for clarifying the fitting of data points and origin of the curves (Lines 16-27, Page 10, and Lines 1-2, Page 11).

8. Figure 4. It is unclear how this curve has been determined.

Response:

The section in the revised manuscript describing Figure 4 has been improved and rewritten.

There are four data sets, either for minimum r_{RI} or for recovery period, in Figure 4. Values of these data are obtained from the critical lines in Figure 3. The method of determining the critical lines has also been described in Lines 2-8, Page 12.

9. P1 L18-20; P 6 L4-8; P6 13-15 : (not exhaustive) list of sentences difficult to follow because an excessive use of symbols and acronyms. Write more in terms of "concepts" rather than in terms of "symbols". Perhaps the authors should rewrite the MS with the support of a native-english writer.

Response:

(1) The manuscript has been revised following the reviewer's suggestion and rewritten more in terms of concepts to explain the results of study. The usage of symbols has been reduced, such as t_0, r_{R0} and OCC.

An Appendix: List of symbols and abbreviations has also been added to ensure ease of understanding.

(2) We have revised the manuscript with the help of a native-English writer.

10. P 10 L 1: n is the number of years only if one value per year is in the sample (e.g. annual maxima data). From table 2 it seems that multiple values of RI can be present within a year. Please clarify.

Response:

The use of n was aimed to evaluate the return period T. In this study, the RI data of the annual maximum series are ranked and collected between 1960 and 2016. The data of the annual maximum RI were used to determine the return period T of rainfall. T responds the long-term hydrological characteristics of an area and is useful for hydrological or hydraulic design.

Table 2 lists numerous debris-flow events triggered by rainstorms and typhoons between 1996 and 2016, and shows the events of debris flow for their corresponding RI. Because many debris flow events occurred within a year, multiple values of RI can be presented within a year.

For hydrological design, a rainfall event or a value of RI, has a corresponding T in the Chenyulan watershed. The abovementioned explanations are emphasized in the revised manuscript.

III. Technical corrections

1. P2 L 28 warranted is not appropriate. Perhaps use "needed"

Response: "warranted" has been replaced with "needed" (Line 8, Page 3).

2. P3 L28 replace "it had" with "they had"

Response: "it had" has been replaced with "they had" (Line 16, Page 7).