Response to Referee #1:

Dear Dr. Max Oke Kluger,

We are grateful for your careful reviews and constructive comments, which is very useful for the improvement of our manuscript.

All the comments are addressed point by point, and the changes are tracked in the marked manuscript. It is worth noting some revisions requested by the other reviewer are also included in the revised manuscript. It is believed that all necessary changes are made to address every point of the concerns.

If any further information is needed, please don't hesitate to contact us.

Yours Sincerely

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CENERAL COMMENTS

In the paper under consideration, the authors present rainfall characteristics, soil moisture data, and landslide inventories collected in North Italy from 2006 to 2016. The commonly used thresholds based on antecedent precipitation index (API-threshold) and 3-day cumulated rainfall (3-day-threshold) are compared with two new thresholds. The hybrid threshold combines information from the established API- and 3-day thresholds, whereas the updated API threshold considers positive or negative trends in the API preceding the landslide event.

In general, I see some merit in the paper as it addresses important aspects of rainfall-triggered landslides and how to improve risk predictions in regions prone to strong rainfall events. However, I consider the present manuscript needs substantial improvements in order to be publishable. During my revision I focused on the following issues: (1) Is the study sufficiently motivated by literature? (2) Are the methods sufficiently described to allow others replicating their work? (3) Are the results presented in a comprehensive way? And (4) are the conclusions supported by the results of the paper?

SPECIFIC COMMENTS

(1) Is the study motivated by the literature?

Point 1.1:
[p.1 – p.3 | Introduction] The authors introduce the rainfall triggering of landslides and give examples. They introduce existing rainfall thresholds in detail and support their motivation for the paper with literature. In my opinion, there is some potential for shortening, though.

Conclusion 1: the paper is well motivated by literature and furthermore fits well within the framework of the journal.

Reply: Many thanks for this positive comment.

(2) Are the methods sufficiently described to allow others replicating their work?

Point 2.1:
[p.5 | L13-L19] The reference cited for equation 1 is a M.Sc. thesis and not an adequate reference, as it doesn't have any proper ISI citations. I wonder, if there is a better paper to cite here as the API is a well-known equation. The authors did not define how API itself is derived from rainfall data. This would be helpful for readers not working with API on a daily basis.

Reply: Many thanks for this suggestion. A better paper has been cited and more information about API has been added in the manuscript:

"A general formulation of API is written as (Gray, 1970):

$$API_t = \sum_{i=0}^{N} b_i P_{t-i} \quad (1)$$

where API_t is the API value at time t; N is the number of the preceding days; b_i and P_{t-i} are the weight and the daily rainfall, respectively. Though the index of API is based on a daily scale, it can be extended for time series with other temporal resolution. Assuming $b_i = k^i$, Equation (1) can be written as:

$$API_t = k\,API_{t-1} + P_t \quad (2)$$

where k is the recession coefficient, less than 1, used to reflect the rate of drainage and evapotranspiration process. As the initial value of API and the number of preceding days need to be estimated, we carried out various experiments which are based on different combinations of the initial value of API and the number of preceding days. It is found that the initial value no longer has an effect on the API value when the equation is run from the preceding 60th day. As a result, API_t is calculated from API_{t-60}, where API_{t-60} is assumed to be 30 mm. "

Point 2.2:

[p.6 | L14-L26] I had a hard time understanding this paragraph and am not sure I fully understood it in the end. The authors write 'The hybrid threshold is established to explicitly include the antecedent wetness condition and the recent rainfall. [. . .] antecedent wetness condition is indexed by the API value of the day prior to the recent 3 days. [. . .] Various combinations of these two variables are explored, where the API value and the recent 3-day cumulated rainfall is defined by their different percentiles.' What do the authors mean exactly with 'explicit'? Why do the authors use the API of the day prior to the recent 3 days? What do the authors mean with various combinations of both variables in respect to the percentiles? The authors proceed with 'The percentile rank considered in this study includes 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 20 and 50.' However, Figs. 3 and 4 display percentile ranks up to 100%. From the text it is unclear to me how the authors calculated the API curves (e.g. green and blue curve in Fig. 3a). The authors proceed with 'We firstly used the API threshold as a cutoff, under which no landslide is expected. When it is exceeded, the 3-day cumulated rainfall threshold is then compared. The landslide occurrence is predicted only when these two threshold values are exceeded.' What do the authors mean with 'cutoff' and 'landslide occurrence is predicted'? I advise the authors to improve this paragraph by adding more details and a schematic figure explaining how the threshold(s) work. I think a basic figure of rainfall characteristics and occurrence of landslides would also be beneficial to better understand the threshold.

Reply: When defining landslide thresholds, the variables that are related with landslide occurrences are calculated, such as the recent 3-day cumulated rainfall prior to landslides, API values prior to the 3 days or prior to the landslide occurrence. Based on these variables' distribution, their different percentiles are used as the critical value. Four types of landslide thresholds are designed by consisting of one variable or the combination of variables, where the critical value of the variables is used to determine the threshold level. A schematic figure explaining how the threshold(s) work has been added, as shown in Figure 3. In order to better illustrate the format of different landslide thresholds, Figure 4 has been added to present the example of these thresholds. The curves in Figure 6 are the distribution of landslides' variables for all landslide events, and 12 different percentiles of each variable are considered as the critical value, marked with triangles.

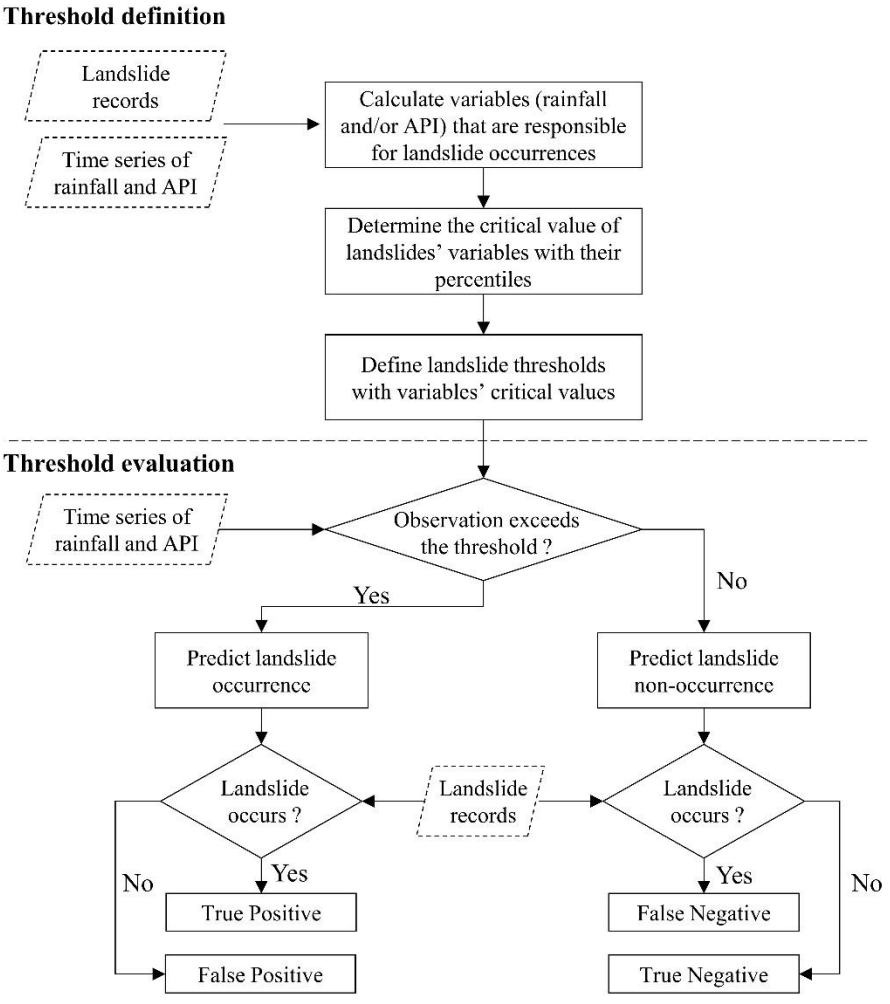

Figure 3. The procedure of threshold definition and threshold evaluation

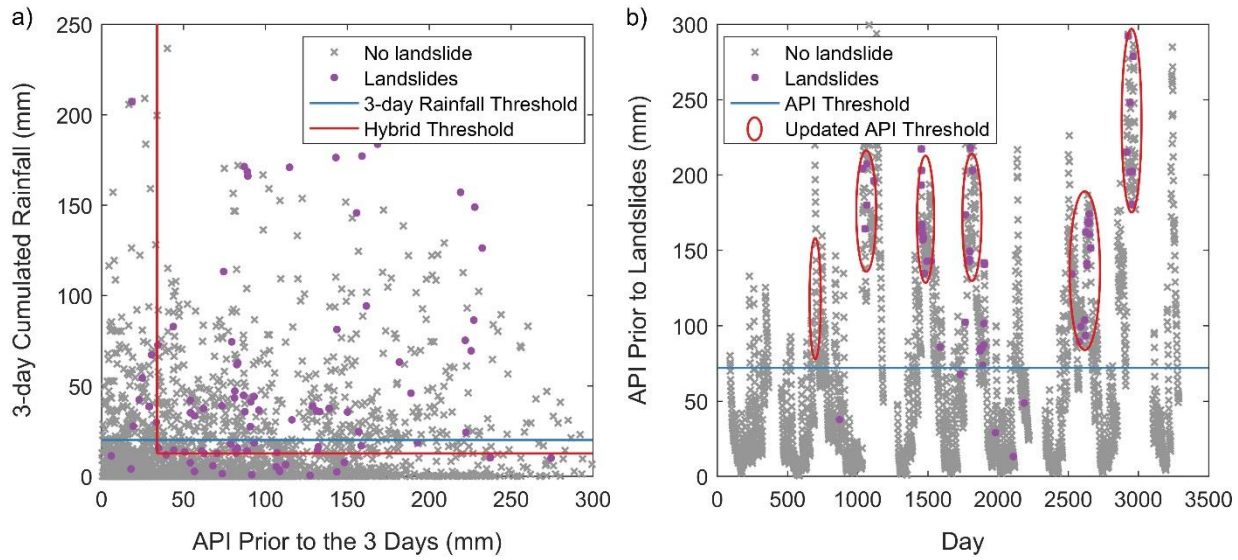

Figure 4. The example of landslide thresholds as well as the events with landslides and without landslide, a) for 3-day rainfall threshold and hybrid threshold, b) for API threshold and the updated API threshold

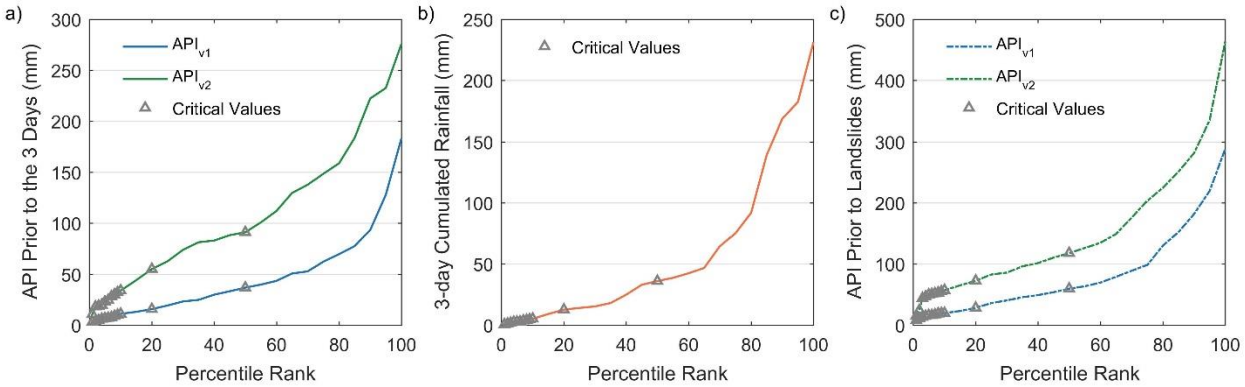

Figure 6. The distribution of landslides' variables as well as their different critical values (determined at the percentile rank of 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 20 and 50), a) for the API value of the day prior to the recent 3 days, b) for the recent 3-day cumulated rainfall prior to landslide occurrences, c) for the API value prior to landslide occurrences

In addition to the inclusion and modification of these figures, the text about the thresholds for landslides has been improved in Section 3.2 in the revised manuscript. As for other concerns, the 'explicit' used in the hybrid threshold is relative to the API threshold, where the antecedent wetness information and the recent rainfall information is integrated into one variable and there is no exact separation between these two types of information; however, in the hybrid threshold, these two types of information is described separately. The API of the day prior to the recent 3 days is used to index the antecedent wetness information in the hybrid threshold. How the hybrid threshold work is introduced more correctly in revised Section 3.2.

Point 2.3:

[p.6-p.7 | L28-L4] Maybe move these thresholds to the beginning as they are already established in the literature.

Reply: Agreed. The order of the thresholds has been modified, please see Section 3.2 in the manuscript.

Point 2.4:

[p.7 | L6-L12] Similar to the paragraph explaining the hybrid threshold, this paragraph lacks in detail and clarity. It is not clear how this 'added rule' works in practice. What do the authors mean with 'more explicitly consider the effect of the recent rainfall'? I wonder whether the hybrid or the updated API threshold is more explicit?

Reply: This paragraph has been improved:

"As the antecedent wetness information and the recent rainfall information is implicitly included in the API threshold, in order to explicitly consider the role of the recent rainfall, an updated API threshold is designed, which is based on the API threshold and updated with an added rule. The API critical value is firstly used as the criterion, if it is exceeded, whether there is rainfall in the recent 3 days is then evaluated. From Equation (2), it is clear that as the recession coefficient is less than 1, if there is no rainfall, the API value will decrease. Therefore, if the API value of the recent 3 days shows a decrease trend, it is considered there is no rainfall in the recent 3 days. In this case, even the API critical value is exceeded, it is assumed that landslides are unlikely to occur, and the landslide non-occurrence is predicted. In contrast, if the API critical value is exceeded and there is an increase trend of API value during the recent 3 days, the landslide occurrence is predicted. Examples of these cases are shown with red ellipses in Figure 4b, which could help illustrate the updated API threshold. "

The 'explicit' used to describe the hybrid threshold and the updated API threshold is relative to the API threshold. The antecedent wetness information and the recent rainfall information is described more separately or more explicitly in the hybrid threshold and the updated API threshold, compared with API threshold, where the antecedent wetness information and the recent rainfall information in integrated in one variable.

Point 2.5:

[p.7 | L14-L19] This paragraph describes how the thresholds are compared between each other. I wonder why the authors did not compare each combination but only three? At least, it would be helpful, if the authors would point out the reason for their choice.

Reply: The three scenarios are designed to address two issues, one is what's the effect of incorporating antecedent wetness information to the landslide threshold, the other one is whether it is necessary to explicitly consider the antecedent wetness condition and the recent rainfall when defining thresholds for landslides. More detailed information has been added in the manuscript:

"With these four types of landslide thresholds, three scenarios are designed to address the concerns of this study. First, what's the effect of incorporating antecedent wetness information to the landslide threshold. The comparison of the hybrid threshold and the 3-day rainfall threshold is carried out to answer this question (referred as Scenario 1), because the only difference between these two types of threshold is the antecedent wetness information incorporated to the hybrid threshold. The second concern is whether it is necessary to explicitly consider the antecedent wetness condition and the recent rainfall when defining thresholds for landslides. To answer this question, Scenario 2 and Scenario 3 are designed. Scenario 2 compares the prediction performance of the hybrid threshold with that of the API threshold. In this scenario, the two components of the hybrid threshold could explicitly include the antecedent wetness information and the recent rainfall information, while these two types of information are implicitly included in the API threshold. As for Scenario 3, as the updated API threshold could explicitly considering the recent rainfall compared with the API threshold, the prediction performance of the updated API threshold is compared with that of the API threshold, which could help investigate the role of the recent rainfall in the threshold definition."

Point 2.6:
Conclusion 2: The methods could be much better explained by the authors. One may not be able to fully understand all steps required for data evaluation as well as the threshold definitions.

Reply: Agreed. The method of the threshold definition has been better explained in the revised manuscript, please see Section 3.2.

(3) Are the results presented in a comprehensive way?

Point 3.1:
[p.9 | L8-L20] The authors write 'The distribution of landslides' variables (as listed in Table 1) is shown in Figure 3 and Figure 4.' What do the authors mean with 'landslide variables'? The table only lists the types of rainfall thresholds used in the study. 'Variables' is ambiguous. The Figs. 3 and 4 show API and 3-day rainfall vs percentile rank and no landslide variables. The authors proceed with 'Figure 3a is for the API value of the day prior to the recent 3 days, Figure 3b is for the recent 3-day cumulated rainfall prior to landslide occurrences, and Figure 4 is for the API value prior to landslide occurrences.' As mentioned before, the plots confuse me because it was not well explained how the authors calculated API or 3-day rainfall for percentiles between 1 and

100% (lines in Figs. 3 and 4). For me it was hard to connect Figs. 3 and 4 to the four thresholds listed in Tab. 1. I therefore suggest to have four plots showing each of the four thresholds independently. The authors write ‘For rainfall - induced landslides, they mostly occur in the wet season, during which the temperature is low.’ One can hardly judge about this statement because the authors did not provide time scales of rainfall and landslide occurrences. Later the authors write ‘Taking the 3-day cumulated rainfall as an example, the amount of 0.4 mm is likely to trigger landslides, while the amount of 231.2 mm is also responsible for the landslide initiation.’ I cannot find these numbers in the plot. Why is 0.4 mm rainfall more ‘likely to trigger landslides’ than 232.2 mm, which is mentioned as only ‘responsible for the initiation of landslides’? Please revise the argumentation.

Reply: Agreed. All these concerns have been revised.

1) Landslides' variables are hydrological or meteorological variables that are related with landslide occurrence, such as the recent 3-day cumulated rainfall prior to landslides, API values prior to the 3 days or prior to the landslide occurrence. These variables are the component of different landslide thresholds, as shown in Table 1. We firstly calculate the value of these variables for all landslide events, then the distribution and percentiles of these variables are available, as shown in Figure 6. The percentiles are used as the variable's critical value to help determine the threshold level.

2) The monthly distribution of temperature, rainfall and landslide events has been added in Figure 2, and the corresponding text has been added at the end of Section 2.2:

"Figure 2 shows the monthly distribution of average temperature and rainfall for 50 weather stations as well as that of landslide events during the period 2006-2016. It can be seen from Figure 2a and Figure 2b, for months with higher temperature, their rainfall amount is smaller, such as the month from May to September. During this period, the difference of both temperature and rainfall is small among weather stations. As for other months, their temperature is relatively lower, and there is more rainfall. The temperature of these months shows small difference among weather stations, while rainfall varies a lot especially for months with high rainfall amounts. It is interesting to see that the landslide distribution is in line with that of rainfall. The majority of landslides occurred in months with higher amounts of rainfall, indicating the crucial role of rainfall in the landslide occurrence in the study area."

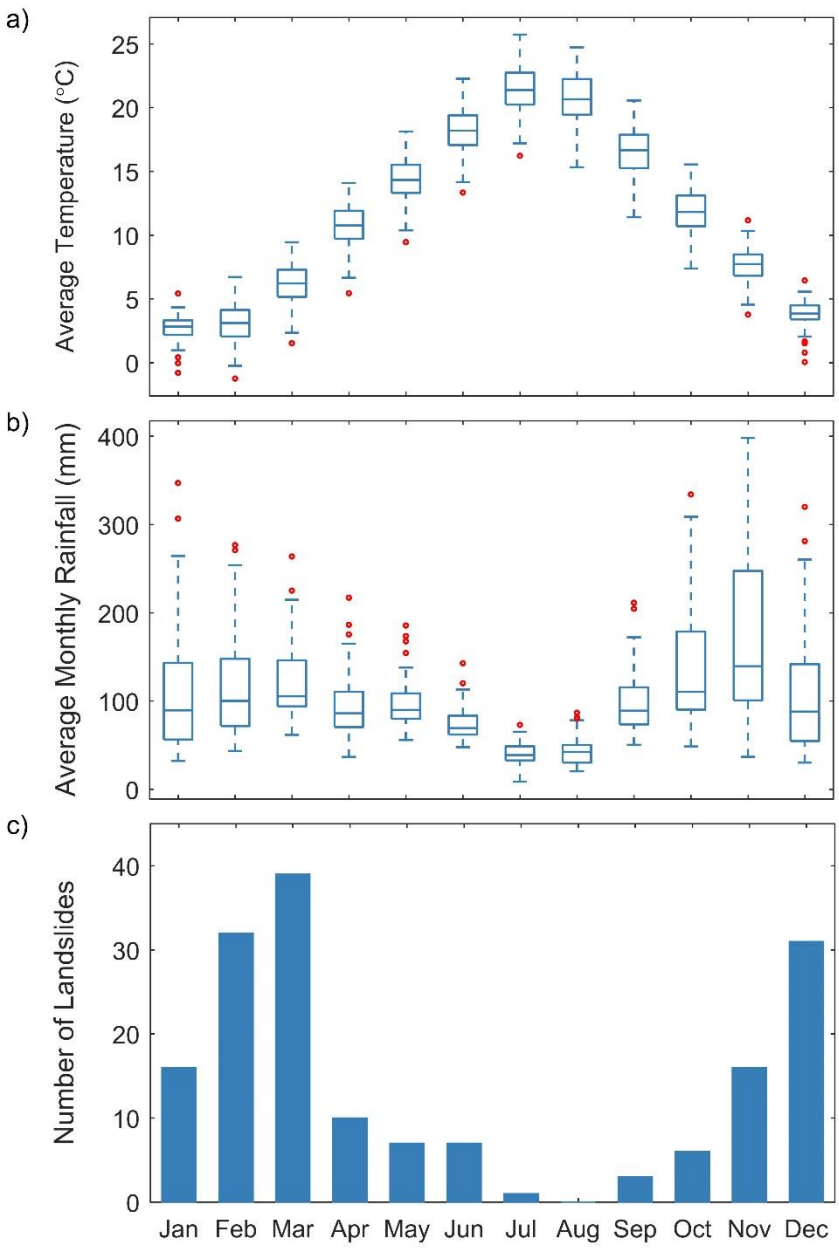

Figure 2. The monthly distribution of average temperature (a) and rainfall (b) for 50 weather stations as well as that of landslide events (c) during the period 2006-2016

3) Here 0.4 mm and 232.2 mm is the minimum and maximum value that are related with landslide occurrences, and 'likely to trigger landslides' and 'responsible for the initiation of landslides' both means 'related with landslide occurrence'. These expressions have been revised in the manuscript:

"The 3-day cumulated rainfall that are related with landslide occurrences ranges from the minimum value of 0.4 mm to the maximum value of 231.2 mm."

4) This paragraph has been improved in the manuscript:

"With landslide records and time series of rainfall and API during the period 2006-2014, the variables that are responsible for landslide occurrences are calculated, such as the 3-day cumulated rainfall and the API values. The distribution of these variables as well as their critical values is shown in Figure 6. Figure 6a is for the antecedent API that are related with landslide occurrences, and Figure 6b for landslides' recent 3-day cumulated rainfall. These two variables are the component of the 3-day rainfall threshold and the hybrid threshold. As for the component of the API threshold and the updated API threshold, the distribution of the API value prior to landslide occurrences is shown in Figure 6c. The critical value of the variables is determined with different percentiles at 12 percentile ranks (including 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 20 and 50), which are marked with triangles in Figure 6 and listed in Table 2. The variables' critical values are then used to define different landslide thresholds. Taking the 3-day rainfall threshold as an example, as its component is the 3-day cumulated rainfall, the threshold value is determined using this variable's critical value, such as 5.14 mm at the 10th percentile rank. As for the hybrid threshold which has two components, the critical value of the API prior to the 3 days are combined with the critical value of the 3-day cumulated rainfall to determine various threshold levels.

From Figure 6a, the API value of the day prior to the recent 3 days is higher for APIv2 than APIv1. This is due to the variation of the recession coefficient in APIv2. The Emilia-Romagna region is characterized by the Mediterranean climate, with warm and dry summers and cool and wet winters. As shown in Figure 2c, the majority of landslides occurred in the wet season, during which the temperature is low. According to Equation (3), the recession coefficient in wet season is likely to be higher than 0.84, and the lower loss rate of the preceding rainfall leads to a higher API value. The similar result can be found in Figure 6c. It is found all these three variables have a wide variation range. Taking the 3-day cumulated rainfall as an example, as is shown in Figure 6b, the 3-day cumulated rainfall that are related with landslide occurrences ranges from the minimum value of 0.4 mm to the maximum value of 231.2 mm. This indicates in several cases with small rainfall amounts, the occurrence of landslides is not only attributed to the recent rainfall prior to landslides, but the antecedent wetness condition also plays a key role. The variables' wide variation range implies that the conditions responsible for landslides vary a lot, which is also the reason why different threshold levels are explored for each threshold approach."

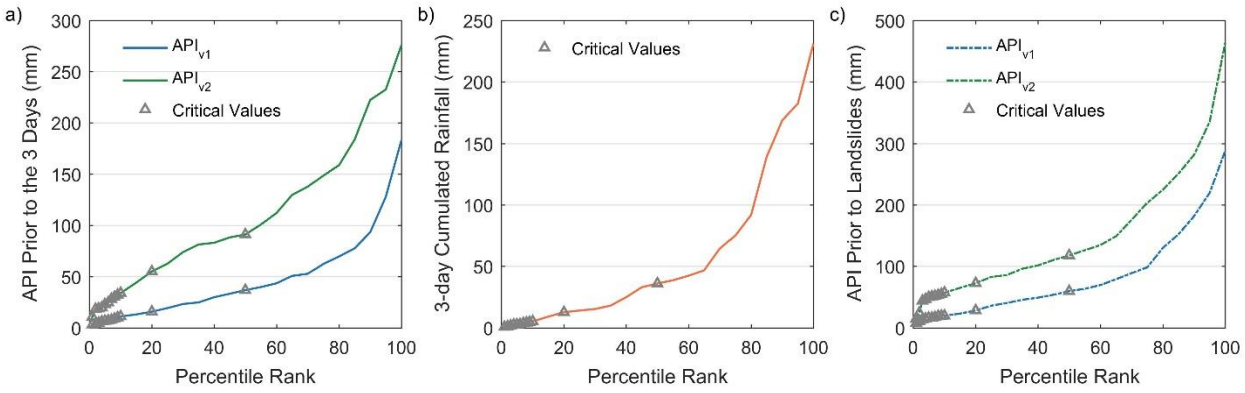

Figure 6. The distribution of landslides' variables as well as their different critical values (determined at the percentile rank of 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 20 and 50), a) for the API value of the day prior to the recent 3 days, b) for the recent 3-day cumulated rainfall prior to landslide occurrences, c) for the API value prior to landslide occurrences

Point 3.2:

[p.9 | L21-L25] This is redundant to methods and I advise to delete it.

Reply: Agreed and deleted.

Point 3.3:

[p.9 – p.11 | Threshold comparison] I had a hard time understanding the Figs. 5 and 6 and the text corresponding to these figures. In my opinion, the text is too technical and requires more details when explaining the principle of the plots. For example, I did not understand why plotting the FAR in Fig. 5b, whereas in Fig. 5a the curves lie more closely to the Hit Rate axis. In addition, what do the authors mean with ‘threshold level of 3-day cumulated rainfall’ in Fig. 5b? The bars reflect the percentiles not only for 3-day rainfall threshold but also for the hybrid threshold.

Reply: The Section of Threshold comparison has been improved in the manuscript, please see Section 4.2.

As for the bar plot in Figure 7, it aims to illustrate the improvement of false positives that are caused by the added antecedent wetness information, as a result, we could see the direct contribution of the incorporation of antecedent wetness information to landslide thresholds, which is one of the objectives of our study. The label of x-axis has been modified to 'critical value of the 3-day cumulated rainfall'. The 3-day cumulated rainfall is the common component of the hybrid threshold and the 3-day rainfall threshold, by remaining the critical value of this variable the same, the difference caused by the added wetness information in the hybrid threshold could be investigated.

Point 3.4:

Conclusion 3: The presentation of results could be improved.

Reply: Agreed. The presentation of results has been improved in the manuscript, please see Section 4.

(4) Are the conclusions supported by the results of the paper?

Point 4.1:

[p.12-.14 | Discussion] In my opinion, the discussion needs to be improved. The authors did not critically reflect their results and compared them with other results from the literature. Generally, the discussion section requires more references.

Reply: Agreed. The discussion been improved by more critically reflecting the results and comparing with published works. Please see Discussion Section (Section 5) in the revised manuscript.

Point 4.2:

[p.14 | L10-L24] In my opinion conclusions 1 and 2 are more or less identical. The only real conclusion the authors make here is '[. . .] could improve the threshold's prediction performance in terms of reducing false alarms.' Just stating that the antecedent wetness is important is not enough because this has been shown by numerous researchers in the past. The third conclusion is fine.

Reply: Many thanks for this suggestion. We have rephrased the conclusions of this study:

"We presented a framework to explore the role of the antecedent wetness and recent rainfall information in the thresholds for landslides. The comparative study is carried out among four types of landslide thresholds. By including different variables that are responsible for landslide occurrences, these thresholds could represent different cases, like whether to include the antecedent wetness condition or whether to consider the recent rainfall explicitly. The important role of the antecedent wetness information in landslide thresholds is further reinforced. The false positives could be reduced by incorporating the antecedent wetness information in the threshold definition, where the proportion of reduced false positives could reach as high as 50%. It is beneficial for the threshold's predictive capability to include the antecedent wetness information and the recent rainfall condition more explicitly. It is also found the reliability of the soil moisture measurement is a key factor affecting the threshold's predictive capability. The proposed results provide a timely complement to the exploration on hydro-meteorological landslide thresholds. It is the empirical approach that we used to investigate the relative impact of different information in landslide thresholds, a physics-based approach is also expected to explore this issue, which

would benefit the development of the hydro-meteorological thresholds in landslide early warnings."

Point 4.3:

Conclusion 4: The conclusions are supported by the results, but need to be more specific and unique.

Reply: Agreed and improved.

TECHNICAL CORRECTIONS

Point 1:

[p.7 | L26] Should read as ‘true positive’.

Reply: Agreed and revised.