Response to Referees comments:

Characteristics and causes of natural and human-induced landslides in a tropical mountainous region: the Rift flank west of Lake Kivu (DR Congo)

December 29, 2022

The authors thank the editor and the two reviewers for their proofreading of the manuscript. Reviewer #4, after the second reading, accepted the manuscript as is for publication. We have taken note of the comments of reviewer #6; not all of them being relevant. Indeed, key comments/ are on issues that were already well addressed in the manuscript. We however have tried to improve the manuscript wherever possible based on these. We have provided explanations to all the questions raised. In addition, we have spotted a few typos and made a few small changes here and there to improve the readability.

Our answers to the reviewers' comments are presented as follows: the reviewers' comments are shown in **black**; the answers are text in ***blue italics***. And the revised texts are in **green**. The lines of the final manuscript are shown in **purple**, while the lines of the manuscript with the tracked changes are in **orange**.

Contents

Reply to Referee #6

Dear Authors,

The papers present an interesting study to map and assess landslide susceptibility in an area where it is difficult to have detailed data both from the field and remote sensing.

The last version improved from the previous versions, and the question of the previous reviewer where addressed.

However, Some critical points, sometimes already evidenced by other reviewers, need to be clarified.

In particular, the description and the discussion of landslide classification and the effect of anthropic activity.

The authors thank reviewer's #6 for reading the manuscript and for reviewing the former replies. We have paid attention to all the comments and made a specific effort to address and clarify the classification issues. This has led to changes in the abstract, in the text (lines **21-24 / 21-24***) and in the conclusion (***729-737/ 741-749***) .*

We would like to recall that the goal of our research goes beyond the sole aspect of a landslide susceptibility assessment and that, in that sense, we do not fully agree with the first sentence of the review.

L21-24 / 21-24: … into five categories that are adapted to study the impact of human activities on slope stability: old (pre 1950's) and recent (post 1950's) deep-seated landslides, shallow landslides, mining landslides and road landslides. We analyze the landslides according to this classification protocol via frequency-area statistics, frequency ratio distribution and logistic regression susceptibility assessment.

729-737/ 741-749: On a more technical/methodological note, our study also demonstrates the importance of considering the timing and the depth of landslides as well as the differentiation between mining and road landslides. While several well-known landslide classification systems are used at the international level (Hungr et al., 2014; Sidle and Bogaard, 2016), these systems are not framed around the combination of the differentiation criteria that are used in this research. Our study does propose a unique effort at classifying landslide types in order to investigate them in the context of the Anthropocene. We believe that our mapping effort and classification protocol is the most adapted (based on strong field observation and comprehensive understanding of the landscape) in this case to address the problem of natural and human-induced landslides in the region. However, it certainly needs improvement to be used in a more universal way.

1.1 General comments

Q1: Do you have only hillshade from Tandem-X DTM or the full data? In the second case, why did not use Tandem-X DTM instead of SRTM, especially for the shallow landslides? In addition, a figure showing the Tandem-X hillside should be added, for instance, in some panels of figure 4.

- *In regard to the first part of your question; indeed, the TanDEM-X digital elevation model at 5 m resolution is unique for our study area. As pointed out on line 168 / 169, the TanDEM-X model does not cover our entire study area. In addition, the 5 m resolution DEM is associated with noise and artifact. TanDEM-X data cannot indeed be used at this resolution without such a caveat (Albino et al., 2015; Jacobs et al., 2018). As described by Dewitte et al. (2021), the production of this DEM was aimed at analyzing visually topographic features at an unprecedented resolution. The choice of the SRTM DEM at 30 m was further guided by the fact that it is commonly used in susceptibility analyses at regional scales (Reichenbach et al., 2018). In addition, in a specific landslide susceptibility analysis carried out in the Rwenzori Mountains, a neighbor region of Uganda, Jacobs et al. (2018) evidenced that the 30 m resolution DEM clearly outperforms higher resolution products (here at 10 m) arguing that there is always a trade-off between model complexity and data needs. This was already explained in lines on lines* **326-328** */* **335-337**. *We have improved this section to make the point clearer.*

L326-328 / **335-337:** Furthermore, in a region of Uganda located in a relative proximity, Jacobs et al. (2018) evidenced that the 1 arc second SRTM DEM clearly outperforms higher resolution products derived, in that specific case, from TanDEM-X.

- *For the second part of your question on visualizing hillshade information, we have made some attempts, but it does not show anything relevant at this scale of the photos. Therefore we have brought extra information directly in the text (lines* **165-167** */* **173-175***).*

L165-167 / **173-175:** Despite some artefacts present in the DEM (Albino et al., 2015), this resolution allows to visually identify geomorphological features relevant for characterizing landslide processes (Dewitte et al., 2021).

Q2: The classification of landside should be made in different ways, in fact, there are at least three types of classification:

1. One based on landslide depth: shallow/deep-seated

2 The second one is related to natural/anthropic (mining or road) causes

3 The third is based on landslide occurrence time recent/historical (pre-1955)

4 The landslides type (e.g., Cruden and Varnes), as shown in figure 4, should be another classification parameter at least for deep-seated landslide

Thus, the five categories of landslides presented in this way, in my opinion, it is not the best solution for analysing the results and also for the discussion sections (5.4 should be removed and some parts included in the previous section).

A flow chart, table or multiple figures with of landslides classifications will also help the work on inventory.

Our study does propose a unique effort at classifying landslide types in order to make an analysis between the natural and human induced processes. We have better formulated this in lines **156-159** */* **164-167** *and lines* **729-737** */* **741-749** *in order to better highlight this specificity. We believe that our mapping effort and classification protocol is the most adapted (based on strong field observation and comprehensive understanding of the landscape) in this case to address the problem of natural and human-induced landslides in the region. We therefore do not change this part of our research which is also strongly supported by the international literature (see section 3.1) and has not been questioned by the other reviewers.*

To our knowledge, we are the first ones to really address the problem of mining landslides at such a scale. We therefore believe that section 5.4 is a key text that must be kept in the manuscript.

We paid attention to better highlight the originality of our work in order to clarify our methodological choices.

Q3: The papers should focus more on distinguishing 1) shallow landslides related to rainfall events from 2) deep landslides, because the two categories have pretty different suscetiblity models.

Then, you can consider the road, the land-use change (deforestation) and mining activity as predisposing factors (when necessary) for landslides and their weight in susceptibility models, as shown in Tables 4 and 5.

The impact of human activity should be also shown with some more specific figures or plot, showing for instance, the comparison of shallow landslides trigger points density for different land-use conditions.

We are not sure to really understand what the reviewer is asking. With respect to the first point, we clearly say that shallow landslides are rainfall-triggered. This is clearly expressed for instance in lines **398-400** */* **407-409***. In addition, we clearly make a distinction between shallow landslides and deep-seated landslides. That point is the key of the whole susceptibility analysis (see Figure 7 for example).*

With respect to the use of predisposing factors, we explicitly use distance to roads and forest cover dynamics in the models. This is clearly justified in the text (see lines **310-323** */* **319-333***) and presented in Table 4. Here also what the reviewer is suggesting is already clearly done. With respect to the mining activities, one key predisposing factor that can be identified is clearly the altered topography. However, we clearly explain in lines* **310-323** */* **319-333** *that there is no topographic dataset that exists at a spatial resolution that can capture these tiny changes in the landscapes. This is one of the reasons why we do not perform a susceptibility analysis of the mining landslides.*

Q4: The deep-seated landslides should be classified in pre- 1955 and post- 1955 rather than recent/ancient.

We have explained in lines **172-176** / **181-184** *that old deep-seated landslides are pre-1955 and recent deep-seated landslides are post-1955. We think that to simplify the understanding of the terminology the terms old and recent deep-seated landslides should be maintained.*

Lines **172-176** / **181-184**: *The historical aerial photographs allowed to differentiate between old deep-seated landslides (i.e. landslides with an unknown time of origin and already present on the photographs) and recent deep-seated landslides that have occurred during the last 60 years (i.e. after the acquisition of the photographs).*

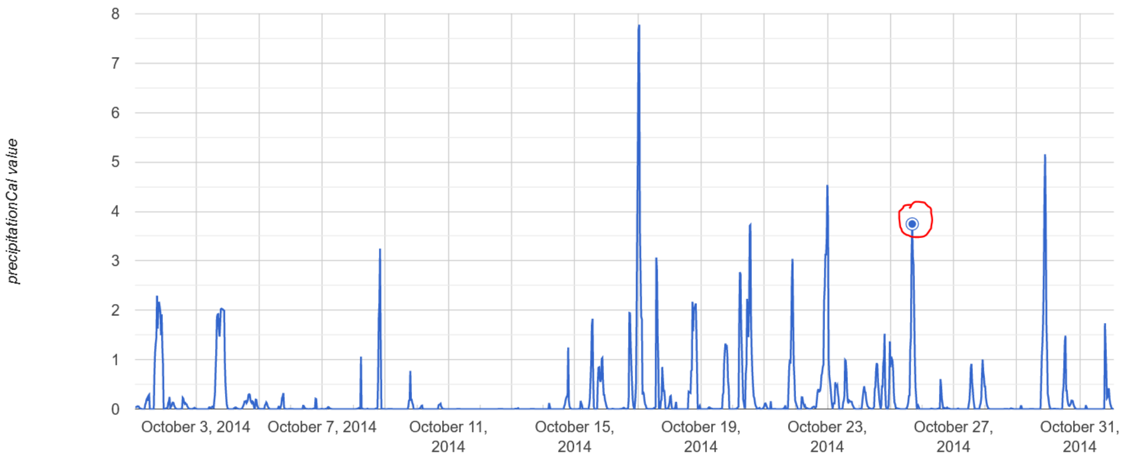
Q5: Lines 615-625 consider that several recent deep-seated landslides are, probably, in several cases, close to a shallow landside depth and were easily detected on hillsahde and Google Earth images. While the pre- 1955 landslides detection is based on low-resolution aerial photos, which could have introduced a bias in their different characteristics (the area)?

We are aware that there is always an uncertainty associated with the depth characterization of the landsides. However, our extensive field investigation shows that our inventory is reliable (Table 3), especially with respect to the hundreds of deep-seated landslides that are considered in this analysis. We can therefore assume that gteh outputs of our regional analysis are not biased by a few outliers. At a more general level, that justifies our methodological strategy to work with data-driven models; these models being perfectly adapted to datasets that will always contain uncertainties.

In lines **160-171** / **168-179** *and* **549-561** / **558-571**, *we discuss this issue of resolution of the photographs (1 m² resolution vs 0.5 m² for the satellite images). However, as quantified in Table 3, such a small issue of detection cannot explain the fact that on average old deep-seated landslides are 4 times larger than recent deep-seated landslides (Table 2).*

Q8: As most of the shallow landslides were triggered by 2014 event, is it possible to have a more detailed description of the event? Such as rainfall data and distribution (from satellite data such as GPM)?

In the region, detailed description of the rainfall characteristics of specific landslide events is difficult and associated with lots of uncertainties (Monsieurs et al., 2018a; Monsieurs et al., 2018b; Monsieurs et al., 2019a; Monsieurs et al., 2019b). Indeed, the only products we can rely on are satellite measurements (there is no rain gauge in the site or in the very close vicinity of the event that was operational at the time of the event). For example, IMERG (10 km resolution, available every 3 hours), is certainly one of the most adapted satellite-based sources of information (Nakulopa et al., 2022). However, km-scale resolution products are not valid for a spatial characterization of the rainfall over such a small area. In addition, such products may miss the extremes locally (Monsieurs et al., 2018a). *In addition, in the region, studies on precipitation thresholds triggering landslides show that the triggering event does not necessarily depend on the daily precipitation (of the day of the event) but may be associated with antecedent conditions of several days (Monsieurs et al., 2019a; Monsieurs et al.,* *2019b). According to the daily GPM satellite data, the event did not occur on the day of maximum precipitation (see circled in red). We have presented the October 25, 2014 event extensively in the manuscript (lines* **416-422** */* **425-431***); we do not believe further details are necessary, as our study is not interested in investigating precipitation thresholds triggering landslides.*



Q7: Conclusion should be rewritten based on previous points with the most significant numerical results

We believe that the conclusion should not be rewritten as most of the comments raised by the reviewer were not very appropriate. In addition, we do not really understand what the reviewer measn by "most significant numerical results; some insights would have been welcome. Nevertheless, based on the comments raised on the landslide classification system used in this research, we have added a last paragraph which we believe increases the international dimension of this work (lines **729-737***/* **741-749***)* .

729-737/ **741-749:** On a more technical/methodological note, our study also demonstrates the importance of considering the timing and the depth of landslides as well as the differentiation between mining and road landslides. While several well-known landslide classification systems are used at the international level (Hungr et al., 2014; Sidle and Bogaard, 2016), these systems are not framed around the combination of the differentiation criteria that are used in this research. Our study does propose a unique effort at classifying landslide types in order to investigate them in the context of the Anthropocene. We believe that our mapping effort and classification protocol is the most adapted (based on strong field observation and comprehensive understanding of the landscape) in this case to address the problem of natural and human-induced landslides in the region. However, it certainly needs improvement to be used in a more universal way.

1.2 Specific comments

Figure 2 and Figure 3: These figures should be mixed: the forest cover is not necessary in figure 3. At the same time, it should be better to show a map that compares forest cover change overlapped with landslide distribution.

Figure 2 was put in the methodology section on request of previous reviewers. By mixing the two figures, we will have a map overloaded with information. In addition, some of the information in two figures may disappear (such as Figure 2a).

Note that we here provide an improved version of figure 2, the layout of the coordinate system of figure 2b being made more readable (and visually lighter). For Figure 3, we have corrected a typo in the legend, "Shallow landslides clustered event" is replace by "Shallow landslide clustered events".

Figure 8: In the caption, better details the contents of each sub-figures

We have added extra details in the caption **530-531** / **539-540**.

L530-531 / **539-540**: Figure 8: Frequency distribution for shallow and deep-seated landslides in function of key predictor variables. Figures c, d, and e allow a multivariate comparison of the predictors.

1.3 References

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