

Response to Reviewer 2 by Milledge et al.

We thank the reviewer for their careful and helpful review which we feel has considerably improved the article. In our response below reviewer comments are in normal text, and our replies are in bold.

General Comment

Thank you for this interesting paper. Using six inventories of coseismic landslides, the authors test the significance of multiple topographical parameters to constrain a set of simple rules in order to minimise exposure to landslide hazard. The paper forms a significant added value to the landslide hazard scientific community as a first attempt in identifying simple rules which is essential for communication about complex hazards to a broad (lay) audience in creating awareness and minimizing landslide exposure. I appreciate the authors' balanced conclusion on the most effective parameters for hazard reduction ["We conclude that decisions on how to reduce landslide hazard most effectively need to be made on a case by case basis, and are best made using hazard area, skyline angle, and the local slope in conjunction with each other."], unfortunately this is not taken in the abstract and conclusion where the authors present without further nuances three simple rules. The discussion is focused on the authors' results with limited reflections with respect to related research (cf. introduction). I believe such a reflection would make the results more convincing.

Thank you for your careful reading of the paper and your many helpful comments and suggestions. We have worked hard to identify this set of simple rules and it is encouraging that this comes through in the manuscript. However, we will take on board your suggestion to temper our presentation of these rules. We have sought to clarify that we are suggesting such rules as a new tool to complement existing approaches rather than replace them. We highlight, though, that we are clear from the outset that the rules are designed to complement other approaches. For example, we say in the abstract: "Our simple rules complement, but do not replace, detailed site-specific investigation; they can be used for initial estimation of landslide hazard or guide decision-making in the absence of any other information."

Specific Comments

The first time I read through the paper I found the abstract and introduction confusing while the terms hazard, exposure, risk, hazard response, "anticipating" . . . are used without first clearly constraining them. Even though the audience from NHESS should be familiar with these terms I believe that these terms are still easily confused. I would therefore recommend to distinguish these terms in the introduction, or make reference to literature in which this is done.

Thank you for this useful feedback. We had been careful to define key terms such as hazard, exposure, risk and mitigation in the introduction and were even concerned that these definitions hampered the flow of the text, so it is helpful to know that they are important. We generally define terms in the introduction rather than the abstract given the limited space in the abstract. In all these cases we give the definition within five lines of introducing the term, though to retain the flow of the text our definitions are generally 'in-line' rather than taking the form of a separate sentence in the form 'x is defined as...'

However, following your comment we have sought to simplify our language, removing hazard response (and instead talking in terms of risk mitigation, which we introduce earlier).

The paper is well structured and the figures of high quality presenting very clearly the results, yet I would suggest to shorten the paper to bring forward the main messages even more clearly. Sections that I would suggest to reduce are section 4 ("Earthquake inventories") by providing a summary of the used inventories with the most important parameters necessary for the analysis; and section 5 ("Methods") could also be reduced, moreover this would allow the reader to more easily follow the workflow.

We are pleased that you found our presentation of the results clear. We have considerably shortened the "Earthquake inventories" section of the manuscript and slightly shortened the Methods section.

I wonder how easily the presented rules can be adopted without prior knowledge or skills, which seems to be the main purpose of the study yet lacking from the discussion. This is not easily answered and out of scope of the study to check the applicability of their rules by householders, local government, and NGOs, but I would recommend to be more cautious when claiming to present 'simple rules'.

We have chosen the term 'simple rules' to make the connection to an existing and active field of research around heuristic decision-making (e.g. Gigerenzer, 2008). This field explicitly refers to heuristics as 'simple rules' (e.g. Todd and Gigerenzer, 2000, Behavioral and brain sciences,

23(5):727-741). We would argue that the first two rules are simple and do not require prior knowledge or skills: 'minimize your maximum angle to the skyline' and 'avoid steep (>10°) channels with many steep (>40°) areas that are upslope'.

Your point here and in detailed comments that the language of the third rule needs to be improved is helpful and we have simplified this rule to read: 'minimise the angle of the slope under your feet, especially on steep hillsides, but not at the expense of increasing skyline angle or hazard area'.

Examining the applicability of these rules is, as you suggest, beyond the scope of this study, but that doesn't prevent the development and testing of the rules themselves from being a useful exercise. We have had some experience of applying these rules with organisations involved in post-earthquake reconstruction in Nepal, and have some positive feedback so far, but it is too early for a more formal evaluation and we feel strongly that this would be the topic of another manuscript.

Detailed comments on "Simple rules to minimize exposure to coseismic landslide hazard"

L10 - The abstract misses information on the fact that the study is on coseismic landslide hazard.

Agreed, added 'coseismic' on line 15.

L15 - Do you present in the end primarily simple rules to identify hazard? Or rules to minimize exposure, of title? I understand they go hand in hand, but it would be good in my opinion to be aware that the terms Hazard, Exposure and Risk are easily confused by readers. Being consequent in using terminology in the abstract might avoid confusion.

Thank you for spotting this possible source of confusion. Although the metrics identify hazard, we have written the rules in such a way that they provide advice on action to take to minimize exposure. We have modified this sentence on line 15 the abstract to be consistent with the title.

L18 - Not sure what you mean with "as a proxy for hillslope location".

We added: "...location relative to rivers or ridge crests." (L18).

L20 - From reading only the abstract it is difficult to agree that defining "the upslope area with slope >39° that reaches a location without passing over a slope of <10°" does not require prior knowledge or skills and that it is easy understandable.

Agreed, but on line 26 we distil this into a simpler rule: 'avoid steep (>10°) channels with many steep (>40°) areas that are upslope'

L22 - Could you add the observation period covered by the inventories here between brackets to know what is 'recent' to you?

Added: "... earthquakes (occurring between 1993 and 2015)" (L23)

L23 - Show which other metrics were tested besides the two new metrics you introduce so this sentence ("most skilful") has more meaning.

We mention these on lines 16-17 and are conscious that we are short on space in the abstract. The text now reads: "We examine rules based on two common metrics of landslide hazard, local slope and upslope contributing area as a proxy for hillslope location relative to rivers or ridge crests. In addition, we introduce and test two new metrics..." (L17)

L25 - If the rules should be simple and applied by people without skills, why not round to 40°? What is the sensitivity of this rule to a change in the slope of one degree?

Agreed, we will round to 40 degrees, the impact on performance of a one degree change is negligible.

L26 - How does that work, "minimise local slope especially on steep slopes"?

It is particularly important to minimize local slope on steep slopes. This is explained in more detail in the results and discussion sections. We are not sure if you found the sentence difficult to interpret or were concerned about how robust the finding was. The latter will be addressed in the results and discussion section of the paper. We have added a comma between the clauses and altered the second 'slopes' to 'hillsides' to help to clarify the meaning of the phrase (e.g. L28).

L26-28 - This rule seems dubious when stating at the same time "even at the expense of increasing upslope contributing area" and "but not at the expense of [...] hazard area" with the latter also comprising upslope contributing area.

The hazard area is found within the upslope area but these two metrics are radically different from one another, as we show in the paper. Our results strongly support both parts of this rule that you identify above.

L38 - I would suggest to use the updated paper of Petley, 2012:

Froude, Melanie J., and D. Petley. "Global fatal landslide occurrence from 2004 to 2016." *Natural Hazards and Earth System Sciences* 18 (2018): 2161-2181. Given the very extensive reference list I think that 'e.g. Froude et al. 2018' would do while omitting the other references if not necessary in the rest of the paper.

Agreed. Added.

L46 - I think "respond to that hazard" is of lesser relevance here as you do not deal with hazard response in this paper.

We agree that response is not our focus, but information at a scale that enables decisions to be made on how to respond to the hazard is one of the key motivations for this work. Thus we think it is important to retain the response clause.

L55 - I would add to "site-specific information that may not be available" something like "such as..." to make it more informative.

Agreed, changed to "...available (such as geological maps or landslide inventories)". (L56)

L62 – "hazard maps cannot resolve hazard at those scales" : I doubt that, with the current availability of high-resolution remote sensing data; yet I agree it could be time-consuming.

Agreed, although it is worth highlighting that we are talking about national and regional scale maps in this clause. We softened the statement by changing from "cannot" to "do not". (L64).

L97 - How does the "self-recovery" relate to the first part of the sentence? I don't see the relevance of it here.

We added an inline indication of what self-recovery means "...self-recovery after disasters (for example, via reconstruction programmes in which householders rebuild their own homes)". (L100).

L102 - Not only of "less use" but also inherently different; your rules aim to minimize landslide exposure, not to help in hazard response. Please modify.

We disagree with this point. Action to minimize your exposure to a hazard can occur both before and during an earthquake. Taking the earthquake example, this might be the difference between relocating away from an earthquake prone area and choosing to 'drop cover and hold on'. Given this, we think that 'less use' is the appropriate modifier here.

L107 - Could you site a reference at the end of this sentence, in order to make "our" refer to the scientific background.

Here, the use of 'our' was referring to the findings of this paper. To clarify this, we modified "Some of our results may be transferrable to landslides caused by more frequent triggers, such as storms, and we consider this point in the discussion." To "We consider the extent to which our results may be transferrable to landslides caused by more frequent triggers, such as storms, in the discussion." (L109).

L110 - Add respective countries between brackets.

Modified to: "Finisterre (Papua New Guinea), Northridge (USA), Chichi (Taiwan), Wenchuan (China), Haiti, and Gorkha (Nepal) earthquakes". (L114).

L112-116 - I don't see much difference between the two questions?

The first relates to absolute performance of the rule set, the second to relative performance of rules within the set. We have added this sentence on L121 to clarify this point.

L116 - What kind of patterns? Temporal/spatial... **modified to "spatial patterns". (L122).**

L118 - Which "combined datasets" you refer to? The landslide inventories or more specifically to the derived topographical parameters from the inventories? **Modified to "landslide datasets". (L124).**

L127 – This question is probably related to my lack of knowledge in the earthquake-triggered landslides, but to me it is not clear what you mean here with ‘local slope’, could you specify? Do you mean the slope at the landslide head ? What is the spatial extent of a "local" slope?

We have now clarified our definition of local slope, which although conventional may not be familiar to all readers: “Local slope, the gradient of the ground surface measured over some short distance (usually ~1-100 m)” (L133).

L129 - In Parker et al. 2017, who you cite, they find hillslope gradient as an important driver, which is different than local slope I would think? Parker et al. 2017: "We find that a simple model combining PGA and hillslope gradient provides the most numerically elegant and best fitting model. The use of topographic variables other than hillslope gradient were found to produce models with a lower fit,..."

In fact we use ‘local slope’ to refer to the same property that Parker et al. 2017 call hillslope gradient. We considered a switch to their nomenclature but feel that local slope is the best established and most appropriate term for the property that we refer to. One reason for this is that local slope indicates that a gradient is being calculated over a (relatively) short length scale rather than over the entire hillslope (from ridge to river). It is also more clearly contrasted with a non-local measure like skyline angle, which considers the topography over a larger window around a particular point of interest. We now clarify this by defining local slope within the sentence (on L133) as mentioned above.

L135 - Can you add a reference here, after “However, shaking for any future earthquake cannot be predicted due to lack of certainty on source location, magnitude, rupture style, and local site effects. **Added on L142.**

L194 - How is this "non-local" when accounting for local slope?

The hazard area is a non-local metric because the value of the metric at a given cell is a function of cells within a wider neighborhood than only its 8 connected (local) neighbors. In this case the property is the gradient (local slope in our terms) of the cells in this wider neighborhood (from all possible initiation points to the target cell).

L323 - "conditional probability for landslide occurrence" seems more informative to me.

Agreed, but we are talking about a broader class than simply occurrence. We have modified the title to: “Conditional probability and landslide hazard” (L268)

L324 – “Landslide hazard can be defined as...” should already have been clear from the introduction.

Agreed, but here we are building the case for a conditional probability based analysis, so we feel that the connection with the definition of landslide hazard needs to be retained here.

L342 - Make reference to preceding research using this approach, yet using rainfall characteristics (I,D) instead of landslide susceptibility (a). E.g., Berti, M., Martina, M. L. V., Franceschini, S., Pignone, S., Simoni, A., & Pizzuolo, M. (2012). Probabilistic rainfall thresholds for landslide occurrence using a Bayesian approach. *Journal of Geophysical Research: Earth Surface*, 117(F4).

Agreed, this is a useful reference and while many other studies apply similar approaches this has a stronger connection than most. We have added: “...landslide inventories. This type of approach has proved successful for a range of applications including identifying topographic controls on vegetation patterns [Milledge et al., 2012] and the rainfall conditions that trigger landslides [Berti et al., 2012]. If we grid...” (L289).

L383 - I would strongly reduce this section as readers of NHESS could be assumed to be acquainted with the concept of ROC curves. **We feel that a clear explanation of ROC curves is important in this paper because of the central role that these curves play in quantifying the performance of the metrics that we test.**

L396 – “the naïve (random)” : Necessary to repeat (L394) the two terms here again?

Agreed, removed ‘(random)’ on L356.

L402 - Why would you use NED elevation data? Since SRTM covers each of the inventory, it seems more logical to use consequently the same DEM source to avoid bias. Certainly because you emphasize on the

slope factor here, there should not be a biased introduced voluntarily (unless it would be used for an investigation of sensitivity to spatial resolution)

Our approach was to use the best freely-available data at each location, but to use a consistent resolution between sites. For all the locations but Northridge SRTM is the best quality available data. This can be problematic, as SRTM data can have gaps (as in Wenchuan) and can smooth highly dissected terrain (as in Northridge). While in Wenchuan we had to restrict our analysis to a subset of the terrain, in Northridge we were able to use better topographic data (the NED), though we downsampled to the same resolution. Our performance tests at Northridge, comparing SRTM and NED data, support this. We find a considerable performance reduction for SRTM relative to NED data, particularly for the hazard area metric. This is likely due to the highly dissected topography within the Northridge study area; the SRTM data do not capture this topography but the resampled NED data do.

L416 - Avoid repetition, cf. L181

Addressed by modifying and shortening sentence.

L420 - Could you clarify what you consider here as channel and channel spacing? How is channel spacing related to the skyline?

Channel spacing is related to the window size required to evaluate the skyline angle because the skyline is likely to be defined by local ridges and the distance to these ridges to be defined by channel spacing. However, the term was distracting and in retrospect unnecessary so we have removed it in our new explanation.

L421 - What is meant with 'characteristic hillslope length'?

Characteristic hillslope length can be interpreted as an estimate of the average hillslope length for the study area. It is calculated based on the upslope area at which there is a scaling break in the relationship between slope and upslope area following the approach of Roering et al. (2007). We have now replaced 'characteristic' with 'average' since this is a more straightforward term (L382).

L423 - What is the relation between the characteristic hillslope length and channel spacing?

Since channels are separated by ridges with hillslopes on each side, then the average channel spacing is twice the characteristic hillslope length. In answering this query we identified an alternative explanation for our choice of search radius that avoids the confusing connection to channels.

L422-423 - Since these are parameterized by the chosen inventories, do you estimate that your rules might change for other areas? Or do you argue that the conservative approach is general enough?

The size of this window should not have an impact on the rules. It will affect only on their implementation and testing within a GIS. The objective here is to ensure that the search radius is large enough to reproduce the same horizon angle in the GIS that would be measured in the field.

The four comments above suggest that our explanation of our choice of search radius for the skyline angle was a source of confusion. We have now rephrased the entire section as follows (removing reference to channel spacing which was a distraction):

“For each cell in a study area, we estimate the skyline angle by calculating vertical angles between the target cell and every other cell within a 4.5 km radius. This search radius is chosen to greatly exceed the average hillslope lengths in all study areas and thus to fully capture the local skyline. The longest average hillslope length out of our study areas is ~500 m for Wenchuan, estimated following the method of Roering et al. (2007). We choose a search radius nine times larger than this hillslope length to ensure redundancy in capturing the local skyline and because the only disadvantage of a larger radius is increased computational cost.” L380-386.

L423 – The sentence “We choose larger window size because skyline angle estimates become asymptotically insensitive to window size” is not clear to me, larger than what?

This sentence has been removed from the modified manuscript.

L437 - Seems to be projected from point P?

Agreed, altered.

L443 - With "non-local" you mean not at the landslide initiation location?

This point has been addressed in our earlier discussion of 'non-local'.

L464 - Avoid repetition with L453.

Modified to remove repetition.

L547-548 - "on which people generally choose to live" : This statement is too vague to me without a reference, does this statement reflect to your inventories solely?

We can be confident of this for our specific inventories but would argue that it is true in general. However, we do not have a reference to support it, so we have adjusted the sentence to refer to our inventories in particular (L509).

L567 - I do not see a significant difference in the point density (~number of observations) for observations with Upslope contributing area > 1000m./m.

Our point here was that the number of observations per bin was very small for upslope contributing area >100 m²/m. However, we have adopted a new approach (as suggested by reviewer 1) that enables us to identify the point at which sample sizes per bin are too small to confidently interpret.

L631- Make reference to the respective equations in the Methodology section for the parameters mentioned here.

Agreed, equation references added (L615).

L673- None, capital N. **The typo was the full stop, which should have been a comma. This is now fixed.**

L677 - Table 1 and Fig. 6 are redundant, you could add Fig. 6 in supplementary material?

We disagree, and feel that Fig.6 shows the data that are synthesized in Table 1. It is important for readers to see these curves rather than the AUC values only, both because they illustrate the point more clearly than a table of values and because they provide richer information. As a result, we feel that it is important to include this in the text rather than leaving it for the supplementary info.

L753-756 – I think it is very valuable that the authors take a step back from their rules while summarizing the main parameters to take into account for hazard assessment, being "hazard area, skyline angle, and the local slope in conjunction with each other". Yet this idea that is stated as a conclusion "We conclude that decisions on how to reduce landslide hazard most effectively need to be made on a case by case basis, ..." is not repeated in the abstract or conclusion, which to me is confusing. It is even in contrast with the conclusion stating (L858-859) "suggesting that the average parameters can be applied to other inventories. These findings can be distilled into three simple rules:".

The 'case by case basis' on L754 refers to application of the rules on a case by case rather than simply resolving to always move upslope or downslope for example. This does not conflict with our later conclusions. However, we have modified the sentence on L753 (now L742) to remove the word conclusion and thus avoid confusion.

L764-L766 I am not sure what your message is here, helping in decision-making before an earthquake is the same to me as decision making after an earthquake which is in turn also before a future earthquake. What is the differentiation that I am missing here?

The point we are trying to make here is that these rules could be used not only for long-term decision making, where the time that it takes to move a certain distance is not the limiting factor in whether you can locate yourself or your assets, but also for short-term decision making during or in the immediate aftermath of an earthquake when one may only be able to move short distances. We clarify this in our revised manuscript (L752-755).

L770 - This statement is largely depending on which spatial extent you perform your analysis and therefore I don't think it is relevant, or should be said in a different way.

Agreed. The sentence order has now been adjusted so that this statement (L759) follows the sentence on the granularity of landslide hazard and is supported by examples in two subsequent sentences.

L849 - In "the highest area at a given slope" it is not clear what you mean with "highest area".

Agreed, and this has been rephrased to “largest upslope contributing area” (L735).