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Interactive comment on "On the nexus between landslide susceptibility and transport infrastructure – agent-based vulnerability assessment of rural road networks in the Eastern European Alps" *by* Matthias Schlögl et al.

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We would like to thank Elmar Schmaltz for the thorough evaluation of our manuscript, his feedback, and his suggestions for improvement.

Please find our responses below, with referee comments in italics, and authors' responses in standard format.

Please note that reviewer comments referring to syntax and typing errors are not answered explicitly, these will of course be corrected.

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Discussion paper

1 Introductory comment from the authors

To start off with we would like to state a general proposition which affects a majority of reviewer comments in this review.

The susceptibility map we used as a basis is the so-called "Gefahrenhinweiskarte Rutschungen 1:200 000 der Österreichischen Bundesländer" by Schindlmayr et al., 2016.[1] In this official data set, landslide susceptibility is derived from a very simple disposition map (based on lithology) and event data.

Therefore, the WoE approach was pursued by the authors in order to provide a more accurate, sophisticated susceptibility map. Due to the incompleteness of the underlying landslide inventory data this approach did not provide as much additional information as initially expected.

Hence, we propose to conduct a full landslide inventory for the whole federal state of Austria based on satellite images and DEM data by manually mapping the extent of previous landslides as polygons. Based on this additional information we will generate an updated susceptibility map.

2 General structure

The authors structured the manuscript very well. I believe the study area should be explained more in detail, either in the Introduction or in the Methods.

We will provide a more detailed description of the study area as suggested by the reviewer.

[1]The map can be accessed through the web-gis application eHORA (Natural Hazard Overview and Risk Assessment Austria) at http://www.hora.gv.at/. The corresponding documentation is available at http://www.hora.gv.at/assets/eHORA/pdf/2016-10-31_GHK-Rutschungen_Schlussbericht.pdf (in German).

3 Abstract

In my opinion, the introductory part of the abstract (P1 L1-5) is too long and could be shortened to a concise sentence that directs to the research gap and the aim of the paper (P1 L6-8). Furthermore, I believe that the results should be presented already in the abstract in a more quantitative and discussable way (P1 L17-19), leading to a closing sentence that states the key findings of the paper.

We will rework the abstract accordingly, including quantitative summary of the main results.

4 Introduction

The introduction embeds the research into a very broad methodological and ethical context about impacts of hazards on transport systems. I do not disagree with this, however, I suggest that the authors sharpen their scientific purposes on landslide hazards and do not divagate too much into rather remotely related hazard fields (hurricanes, terrorist attacks). A connection to these fields, e.g. as application of the presented techniques and methods on those different hazards, could be given in the outlook of the study. I believe the introduction would benefit from the following structure:

1. *Introduction to transport network systems and transport network vulnerability*
2. *Introduction to all kind of landslide hazards that can affect transport networks and how they can affects them in terms of topological and system-based vulnerability*
3. *Introduction to the situation in Austria with focus on Vorarlberg (why was particularly Vorarlberg chosen as study site?)*

4. *Statement of the research gap, the hypothesis and related (methodological) research questions*

It is up to the authors, where to present the geomorphic and infrastructural peculiarities of Vorarlberg (either in the Introduction or the Methods part). Although this paper can be considered as a methodological one, at its present form it lacks of information about the specific situations in Vorarlberg, regarding landslide dynamics and transport networks.

We would like to thank the reviewer for this constructive feedback. The introduction is rather broad indeed and does require a more precise description of the scientific purposes of the manuscript. We agree with the reviewer and will rework the introduction accordingly.

In addition, we will clarify the specific comments relating to the introduction section:

- *P2 L7: The authors mention 'a growing amount of studies' that deal with the impact of natural hazards on roads, however, only three studies are referenced, albeit there are certainly many more. I would suggest to provide more references, at least for landslide studies that underline the purposes of this paper.*
  We will add additional references as proposed by the reviewer.
- *P2 L11: From a geomorphological point of view, a 'complex landscape' does not necessarily have to be steep - just a minor comment...*
  Yes, the reviewer is right. We will adjust this accordingly.
- *P2 L14-15: What are 'reliable networks' in this context? In general, this sentence is relatively hard to understand from my point of view.*
  We agree, this sentence needs to be re-written.

- *P2 L21-30: The aim of the paper is ''[...] to present how road infrastructure is vulnerable towards landslides [...]'. In this paragraph, however, the authors somehow begin to embed their research into prior assessments of transport network systems that were affected either by terrorist attacks or supra-regional or national effective natural hazards like hurricanes. Even though I see the slight connection here, I am strongly suggesting to focus on what was already proposed in the abstract, which is an assessment of the impact of landslide on transport networks in Vorarlberg.*

  The reviewer is right, the introduction is too broad. We will focus on the research aim as proposed in the abstract.

- *P3 L13-15: Which means it is related to (1) topological vulnerability analysis? If yes, it should be clarified explicitly.*

  A topological vulnerability approach comprises the assessment of all potential impact (i.e. caused by natural hazard events) paths at the current road network system. Topological vulnerability studies are usually based on graph theoretical concepts, including behavioural aspects, such as travel demand and supply models. Here the "real" road network is represented in an albeit accurate, but still abstracted network (graph).

5 Data and methods

The first subsection of section 2 (2.1 Modeling landslide susceptibility) should be restructured in a way that it follows a more logical order. The description of landslide inventories and the necessities of their compilation should be explained at first. The computation of susceptibility maps that emanate from the inventories, including the incorporation of DTM-derivatives as predictor variables within the modelling procedure, should then subsequently follow. Generally, some paragraphs appear to belong rather

in the introduction part than in the methods part (e.g. P5 L4 - P7 L16). The description of the derivatives may be read like a textbook. I suggest to specifically state why these derivatives were chosen as predictors to generate the susceptibility map, with a clear focus on their geomorphic reasonability for landslide initiation. Furthermore, please explain in detail which methods were applied to compute the landslide susceptibility and provide a short description of these methods. If solely the 'Gefahrenhinweiskarte' of the Federal State Vorarlberg was used, then the authors should explicitly state that in the methods part, otherwise it is not clear to the reader if a susceptibility map was generated or an existing one was used.

We will restructure section 2.1 as suggested. However, we would like to emphasize that the description of the predictors is quite detailed on purpose, due to the potential audience of readers with non-geomorphic background. We will clarify that the susceptibility map created by the authors was used as a basis.

- *Since the authors refer here to regional landslide inventories and landslide susceptibility analysis, I suggest to replace 'Schmaltz et al., 2016' with Schmaltz, E. M., Steger, S., Glade, T. The influence of forest cover on landslide occurrence explored with spatio-temporal information, Geomorphology, 290, 250-264, https://doi.org/10.1016/j.geomorph.2017.04.024, 2017. since a more complete landslide inventory was used.*

  Thanks for pointing this out. We will replace the reference.

- *P6 L8: (i) It is mentioned that the landslide inventory differentiates several process groups. Which are they? (ii) Are all kinds of landslides considered (soil creep, debris flows, rockfalls) or only those of the slide-type movement? (iii) The landslide process, which is considered in the inventory should be specified in order to understand the susceptibility map.*

  (i) The process groups are: Mass movement (general), creep, complex large mass movement, slide, and flow. (ii) As listed in the previous answer, only slide-

type landslides were considered (e.g. no falls). (iii) We will clarify this in the text and add a short description including the number of events per process group.

- *P6 L9: '1178 landslide were available': Are they equally distributed? Are there any (systematic) biases that the authors detected or expected within the dataset?*

  As we point out in the result section of the manuscript (p10, L8) the mapped landslides are not distributed equally. We will rework the section to make this fact more clear.

- *P6 L11-12: Please specify the classification of the different geological units. (i) Which of the units were considered as similar according to their lithological and geotechnical characteristics? (ii) Did the authors also distinguish between the landslide process that can be induced by different lithologies in Vorarlberg (e.g. rather steep walls in sand- or limestones in the Montafon, Rätikon, Walgau and Großwalsertal (etc.), prone to rockfalls; claystones, marls (Walgau, Bregenzer Wald, Pfänderstock) and Molasse (Doren), prone to slides; etc...)?*

  (i) The concept of the Gefahrenhinweiskarte Voraralberg is as follows:

  - Lithological disposition map (scale 1:200 000) on the basis of an engineering-geological classification in terms of sliding susceptibility with three classes.
  - Event-register of landslides

  Therefore, two types of information are available:

  A: Indication if surface is prone to landslides in terms of unfavorable process factors (general characterization).

  B: Indication if landslides did already occur

  (ii) See comment above. We distinguished between the main different lithologies causing sliding events.

- *P6 L17: Which ALS-DTM was used? 2004? If yes, why did the authors not consider the ALS-DTM of 2011, since there were remarkable changes of both landslide dynamics (e.g. triggering event of 2005) and infrastructural development on landslide-prone hillslopes.*

  The ALS-DTM of 2011 is used. Within the scope of the revision we suggest to use this ALS-DTM as a basis for mapping all landslides as training points on our own (like in Petschko et al., 2014, 2015).

- *P6 L18: The grid sizes are confusing me. Which one was used, 5 m or 10 m? If latter, then please correct on P6 L1, or further explain why the resampling procedure was performed as mentioned in the manuscript.*

  We will clarify this in the text.

6 Results

- *P11 L10-11: How did the authors deal with the detected inventory incompleteness mentioned in the manuscript?*

  The incompleteness of the official inventory was accepted due to practical reasons. To avoid further inconsistencies – as mentioned above – we intend to map the entire study area on our own.

- *P11 L12: A 50 m buffer around points that mark locations of landslide initiation introduces a large systematic error (that obviously already exists in the inventory) to the modelling procedure. The authors should justify i) why they chose such a large radius and ii) how they believe that they can still ensure geomorphic plausibility of their approach.*

A 50m radius was chosen to get a plausible “mean” area for modelling purposes. Slope are larger in alpine regions than in forelands, so a larger value was chosen as an assumption of slope areas in the first place. However, this will be changed by using the new training polygons obtained through mapping landslides in the whole study area.

- *P11 L26: What landslide susceptibility value did the authors expect?*

  Based on experience of our previous studies, overall occurrence probabilities are lower than expected. This is the case for both average and maximum landslide susceptibility values. For instance, much higher maximum landslide susceptibility values were expected (up to > 95% in certain cases).

- *P11 L29-31: I believe this statement should be justified quantitatively, since no quantitative measures or values were provided by the authors that indicate a reasonable accuracy.*

  Initially – due to the inconsistencies of the training points – we believed that discussing quantitative evidence is not as insightful an approach as to discuss the results qualitatively. As we were sure at the beginning that a susceptibility modeling would significantly enhance the quality of the Gefahrenhinweiskarte using the mentioned input data, we focused on the qualitative interpretation the consequences stemming from the usage of the available input data.

  As a next step – if the editor agrees – we propose to replace the WoE approach with a GAM or a tree-based classifier that will be applied to newly mapped landslides, which will feature significantly improved accuracy of landslide locations.

  We will then focus on presenting the results in a quantitative way.

7 Discussion

- *P16 L3-5: These are two crucial points for assessing the reliability of the susceptibility maps. Although the authors identified these drawbacks, I suggest to add information on how they cope with the resulting susceptibility maps and in which way their results have to be evaluated by the reader.*

  We will add a distinct description as suggested by the reviewer.

- *P16 L6-8: Even though the geological map might be too coarse for a reliable susceptibility analysis, the authors mentioned that they were able to detect incident points along the traffic network. If geology is believed to be of central importance for landslide susceptibility*, then incident points could be detected with the rough geological map and susceptibility could be re-computed using the more detailed maps for areas where they are available.*
  ** From my point of view, the lithological underground is a discussable predictor, since the lithological setting in Vorarlberg largely determines the topographical situation, meaning that for instance sandstone facies are responsible for steep terrains in the flysch zone, marly substrates for shallower slopes. Thus, the inclusion of slope steepness as a predictor variable might be already enough in order to avoid systematic biases in the modelling procedure. In my opinion, soil material plays a more important role and should be rather considered as predictor compared to geology. However, this is only my personal opinion that I thought be worth to mention here.*

  We agree with the reviewer and will consider this in the revision.

- *P17 L9-10: Is this always true for all rural areas throughout the year? I am thinking of locations for winter sports, which are frequent in Vorarlberg (Montafon, Bregenzerwald, etc.). Would not these areas might be also quite frequently accessed via roads and enhance an element at risk, particularly in early spring,*

where snowmelt occurs but winter sport tourism is still active?

The reviewer is right. Even though this does not affect the general validity of the statement in the manuscript, we will add this aspect to the text.

8 Conclusions

P19 L8-9: The authors should provide information, which of the analysed transport systems or roads (according to their applied classification) are mostly prone to landslides. Additionally, the temporal differences at which time each type of road is mostly vulnerable would be interesting.

We will add this information as proposed by the reviewer.

9 Figures and tables

Fig. 1: A small overview map of Austria with indication where Vorarlberg is located would be helpful for readers that are not familiar with the Alps.

We will provide this map as supplement.

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