

Authors' Response to Reviewer Comments

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1 Response to Reviewer 1

We would like to thank the referee for the thorough evaluation of our manuscript and the provided feedback. All of the feedback provided will certainly contribute to improve the quality of the manuscript.

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

1.1 General comments

1. *In the title, the paper implies an "... agent-based vulnerability assessment of rural road networks...". Unfortunately, this is not delivered, i.e. at the end of the paper, the reader does not have a clear answer on the question "How vulnerable is the road network (in Vorarlberg) towards landslide hazards?" Instead, 10 (very specific) Scenarios were analyzed and compared, considering the detour length and the evasion time. Hence, the concept how to assess network vulnerability has to be better expressed, beginning with a clear definition how the authors define vulnerability in their paper, and the introduction of some vulnerability measures for quantification and justification (e.g. using indices, curves, tables, maps, etc.).*

The reviewer is right. We have adjusted the title to indicate that the focus of this work is on the application of an agent-based transport model rather than on a vulnerability assessment of the network. The goal of this manuscript is actually to assess the vulnerability of the **agents**, not the vulnerability of the road network. Thus, the purpose of this manuscript is to demonstrate this approach, thereby highlighting the benefits of obtaining in-depth conclusions using spatio-temporally disaggregated mobility behaviour. See response to (3) for a more detailed description on that aspect. We have indicated this more clearly in the manuscript, including a definition of vulnerability as used in this context. In addition, the introduction/motivation section has been completely reworked.

2. *Throughout the introduction, several times the importance of socio-economic impacts and the severe losses caused by the disrupting services are mentioned. Finally, only the prolongation of the travel is considered. Since the authors already implemented a very detailed agent-based model with many socio-demographic data (e.g. the agents are employed or unemployed), why not actually assessing the socio-economic impacts? This would also be a novel contribution of the paper, which is currently missing.*

The reviewer is right that this is an important issue in this context. We have added a more detailed analysis of select socio-demographic data (e.g. age, employment status) in the results section (including 2 new plots). Furthermore, we have reworked the introduction completely. However, we would like to point out that although the underlying mobility patterns of the modelled agents are available, the transfer from their individual socio-economic features to comprehensive socio-economic impact values and resulting costs entails an extensive analysis in itself, which is methodologically different from the interdisciplinary basis that was presented in this paper. The travel time costs nevertheless provide a quantifiable indication that can serve as the basis for further analyses. The novel contribution of this work was to demonstrate the applicability of using spatio-temporally disaggregated mobility behaviour data for assessing the impacts on the local population rather than providing monetary quantification of impacts. We have emphasized the benefits and novelty of the approach in the introduction, and including daily evasion time heatmap, illustrating spatio-temporally disaggregated conclusions.

3. *In the current version of the paper, the methodology can be summarized as: “Running a traffic model, thereby disabling a selected link”, which is not a novel concept, or method. What’s missing is a clear description of the novelty for the proposed methodology. i.e. What is new? How is it better than other approaches?*

As mentioned in (2), we have highlighted the novelty and the advantages of using an agent-based traffic model distinctively in the introduction section. While several studies on network effects caused by disabled links do exist (see citations in the paper), we are not aware of a similar analysis that has been performed using an agent-based traffic model. The drawbacks of classical aggregated (macroscopic) traffic models include:

- everything is just an indistinguishable flow → “gravity model ambiguities”
- modal re-decision can not be mapped w.r.t. each agent’s properties
- flows are usually zone-to-zone, as larger spatial aggregation areas are used
- models are just trip-based, considering single “hops” from activity to activity, not whole day-plans
- more time and space averaging, therefore less policy-sensitive

Other publications (such as e.g. Postance et al., 2017) do not consider whole-day travel plans, but only the peak traffic flow period on the investigated network. In

addition, OD route assignment is done by a conventional network loading algorithm to find the user equilibrium. As discussed above, the approach described in this manuscript alleviates such problems by employing an agent-based traffic simulation, which works on a disaggregated (finer) scale. We have clarified and emphasized these aspects in the manuscript.

4. *Concerning the landslide susceptibility map:*

- (a) *There is a conceptual flaw, using landslide susceptibility maps for assessing network-related processes. Contrary to building assets (e.g. houses, facilities, etc.), networks are used to describe dynamic processes (e.g. traffic flow), with the consequence that local events can have a severe impact on the whole network (as the authors showed in their example). The problem is that landslide susceptibility maps describe only the relative likelihood of future landslides, however, since the network is more than its components, there is a probability that a very unlikely landslide (low susceptibility), causes more harm than a very likely landslide. For example, there is a very low susceptibility that a landslide will be triggered and affecting a major connection, causing thousands of people to stay at home while incident 6 affects only 128 agents. At the current state of the paper, such network effects are completely neglected, however, this is the core concept (and challenge) of analysing network structures.*

The selected incidents are used as scenarios to illustrate the applicability of the traffic model. To assert the realism of our assumptions, blockage locations were chosen based on the landslide susceptibility map. The goal was not to assess the worst effects (i.e. focusing on extreme landslides events), but the most likely blockages representing realistic everyday risks in this area (often a result of highly variable but very local thunderstorms during summertime), which in consequence were used as basis for assessing the impact on agents. We have clarified this in the manuscript.

- (b) *Why did the authors develop a landslide susceptibility map although “The government of the province of Vorarlberg offers an official landslide susceptibility map...” (Page 5/ Line 26) and “The official hazard map already provides a reasonably accurate and consistent basis for the purpose of identifying vulnerable sections.” (11/30)? Additionally, the used Weight of Evidence Method (Bonham-Carter, 1994) is nothing new, and therefore worth to spent 4 pages of the paper, only to figure out that the official landslide susceptibility map is a good enough estimate.*

Against the background of publication bias, we feel it to be our responsibility as scientists not to hide negative results, but rather to discuss them openly. In this case, our assumption that the application of the Weight of Evidence method would clearly improve the susceptibility map (as implied by various publications on this well-known method), was not met in the first place. Instead, our efforts to improve the basic susceptibility map yielded

only slight improvements. We found this outcome (which is largely due to the data quality of observed landslide events) to be worth mentioning and discussing. However, our efforts during the revision to improve on the landslide inventory data by validating historic events and conducting a landslide mapping (polygons) based on the LIDAR DEM and satellite images for the whole study area did improve the quality of the map. Albeit there is still room for improvement (c.f. discussion section), the landslide susceptibility map contained in this revision is definitely more accurate than the rather simple and coarse government-provided map.

5. *Concerning the selection process of links to be blocked*

- (a) *It is absolutely not clear, how the 12 incident sides were selected. Please, give a detailed description how this was done (quantitative?, qualitative?), especially since the authors remove later on selected sides (“... 12 had to be removed due to its close proximity to Silvretta-Hochalpenstraße ...”(13/1).)*

We agree with the reviewer that this is unclear. We have clarified this in the text (subsection ‘incident sites’).

- (b) *Also, it would be of interest which landslide susceptibility is associated with each incident side. See point 5: If only areas with high susceptibility are considered, the question arises, if there is not a scenario where the road network is more vulnerable to landslides in less susceptible areas.*

We have included maximum and average landslide susceptibility values for each incident into Table 2, using 50 m buffers around all incidents.

- (c) *An important part missing is the interaction between landslides and road network. In the current version, it is assumed that a landslide occurs at the incident side and completely damage (block) the road section over a period of at least 24 hours (runtime for the MATSim model)? If so, these are very strict assumptions and is contradicted by the author’s statement “...due to the fact that landslides, which affected traffic routes or (agri-)cultural areas, are usually fixed quickly and efficiently.” (12/10). Also, how could such assumptions be made without the knowledge of the particular landslide type (initiation and run-out, volume, speed)? The likelihood of the occurrence of landslides is not a sufficient reason to assume a damaged infrastructure. Please, specify the assumptions made and give a detailed description how the (physical) damage of the infrastructure was derived from a landslide susceptibility map.*

The reviewer raises an interesting point in pointing out that the likelihood of the occurrence of landslides is not a sufficient reason to assume a damaged infrastructure - especially, if in-depth knowledge of the event is lacking. However, we would like to emphasize again that the focus of this study is on the application of an agent-based traffic model to model responses in case of capacity reductions of a regional scale road network. We argue that occurrence probability of landslides is a reasonable proxy for assuming likely

network interruptions that are representative of common, everyday risks in the study area. While the primary road network is indeed very resilient to landslide exposure, rural road networks are way more susceptible to landslide occurrences (since the high building standards for highways cannot be met on all rural roads). Complete interruptions caused by landslides are just one possible scenario to obtain blockage points. The described methodology also allows to specify capacity reductions (e.g. 50% capacity if only one lane is blocked). We would like to point out that we put the focus on assessing the whole federal state using several likely incident locations with a predefined (simple) interruption scenario instead of focusing on one or two locations with different varying blockage duration and capacity reduction patterns. Please note that the statement that roads are “usually fixed quickly and efficiently” does not mean that roads are fixed instantly. For safety reasons (and of course the FRC of the road), interruptions of at least 1-2 days are common for high level roads. Interruptions of several days are common on the rural road network in Austria. This is well within the assumptions made in this study. Finally, modelling physical damage is no focal topic of this manuscript. Landslides are merely considered as a scenario to obtain blockage points. We have added a clarification to subsection ‘incident sites’.

6. *Concerning the agent-based traffic model*

- (a) *The implementation of an agent-based model is very ambiguous, please clearly state why such an approach was used, especially since most of the results (affected persons, detour lengths, evasion times) could also be observed by a flow-based traffic assignment.*

While we can understand the confusion regarding the differences, we’d like to underline that the comment of the reviewer is not true as stated. The main benefit is in the temporal and spatial disaggregation of information on agents, which are lost in the flow of conventional transport models. See responses above for further detail. We have clarified this in the manuscript.

- (b) *In the current version of the paper, several assumptions made and several limitations of the traffic model are not clearly stated. e.g. the MATSim simulation considers only/maximum one day, an agent has perfect knowledge of the interrupted section, origin and destination do not change during and after extreme events, etc.*

This is only partly correct. The agents do not have perfect knowledge of the interrupted section initially. They only acquire this knowledge iteratively as a whole population after optimizing for best route user-equilibria. Most of the limitations are discussed in the manuscript (18/6ff in the initial manuscript). We have further clarified these aspects mentioned by the reviewer.

- (c) *A major shortcoming is that only trips of inhabitants of Vorarlberg are considered, which does not reflect reality and certainly leads to an underestimation of the socio-economic impacts in the region. The question is how can the*

vulnerability assess given this constraint? Additionally, how could the traffic model be calibrated and validated, neglecting a majority of the travellers on the network?

This may indeed be considered a shortcoming. However, it is also clearly stated as such in the manuscript. Conducting mobility surveys is extremely resource-intensive. In the said case study region, we would need similar mobility survey data for Germany (Bavaria), Switzerland (Cantons of St. Gallen and Grisons), Liechtenstein and the Austrian federal state of Tyrol to cover all adjacent countries or regions respectively. Given the resources at hand, and since the focus is on the impacts of network interruptions on the local population (user level), we consider this model to be useful despite certain restrictions (i.e. likely underestimation of the impacts). Also, the fidelity of any model is restricted toward the boundary areas. In addition, it can hardly be argued that “a majority of travellers on the network” are neglected. Only the two highways, A14 and S16, can be considered major transit routes in the area, a majority of commuter travel on rural roads is definitely captured by the underlying mobility survey data.

- (d) *Why was so much focus put on introducing and analyzing 10% scenarios, without any additional benefit for doing so? It could have been stated, that for computational reasons a pre-sampling with 10% of the agents has been done, but the evaluation has been done with a 30% scenario.*

The official MATSim guidelines state that 10% is a reasonable subset of the full population to model all relevant effects. However, results of the subsequently used 30% sample show different implications, as discussed in the manuscript. This is particularly the case for the variance of the results, which increases (!) with increasing sample size. We consider this to be an interesting discovery, since this questions the general recommendations. We will clarify this in the manuscript.

- (e) *It is not clear how many simulations (not iterations) have been done for each incident. In other words, how often was the traffic model run for one incident? Since the agent-based model tries to optimize the behaviour of multiple agents, the simulation results might change over time.*

For computational reasons, each simulation was only done once. The model could be re-run multiple times using different random seeds. While this might provide better insights with respect to analyses of specific incidents by reducing uncertainty of the results, this does not affect the applicability of the demonstrated approach. We have added this information to the manuscript.

- (f) *Using advanced modelling tools often suggests precise outcomes, however, since many unknown input parameters are necessary, the results might come with high uncertainties. These uncertainties have to be quantified in order to make meaningful statements. At least a more detailed (quantitative) description how accurate the traffic model compared to the actually measured traffic*

volumes should be given.

The core purpose of any traffic model tool is to provide predictive models (based on partially known real-world data) for scenario estimation, rather than precisely calculate exact values. Reliability based on comparisons with traffic count data is also limited, since these data are only valid for a very specific location and are likely to change at the next crossroads. In addition, traffic count data are also subject to high uncertainties (as they are often extrapolated from a measurement period of e.g. 2 weeks). Also, KPI values for assessing the quality of traffic models are not yet available, but currently still under development. The whole question can thus be broken down to “systematics vs. statistical uncertainties”. We argue that discussing systematics is more important in this context. The uncertainties of any traffic model are rather grounded in the quality of the input data rather than in the model itself. Therefore, classical uncertainty quantification (e.g. in terms of Monte Carlo simulation using multiple model runs to obtain a distribution of results) often does not provide substantial insights. In addition, this kind of uncertainty assessment would be computationally prohibitive for the present study when using a sufficiently large number of scenario runs for all incident scenarios. However, we consider this issue a valuable question which is intended to be answered in future work.

7. *As mentioned in the beginning, it is hard to interpret the results and conclude how vulnerable the road infrastructure is. For example for side incident 10, 4709 agents are affected by an average evasion time of 3:10 minutes over a whole day. Does this mean there is almost no vulnerability against landslides? How can road authorities derive conclusions from this results? Should they invest in some protection measures or not?*

The first order interpretation of this result is correct. Road blockage of incident 10 has only minor effects on the traffic displacement in this area.

1.2 Specific comments/questions

1. *(1/10): “The focus of this case study is on resilience issues and support for decision making in the context of a large-scale sectoral approach.” this is clearly not the case in this paper. Either this will be added to the paper or this statement should be deleted.* The reviewer is right. We have removed this statement.
2. *(1/15) Here only single events are considered, however, in reality, we often have to deal with the occurrence multiple hazard events (e.g. heavy rainfall caused several landslides). How can the proposed methodology cope with such situations?*

From a methodological point of view, this is not different to what was done in the present study. Expanding the methodology accordingly is simple: instead of removing a single link from the routing graph, multiple links can be removed, and the model can be re-run on these modified graphs.

3. (7/23) “Road capacity was derived from the functional road class.” For personal interest, how was this done and in which range were those values per road class?

Road capacity was estimated from the FRC attribute of the OSM graph:

```
def get_capacity_per_lane(frc):  
    if frc == 0:  
        return 2000  
    if frc == 1:  
        return 1500  
    if frc == 2:  
        return 1200  
    if frc == 3:  
        return 1000  
    else:  
        return 500
```

4. (10/1) Figure 1. The different road classes should be indicated (e.g. highway, primary road, ...) in order to give the reader an overview how the network is structured and where the major links are located. Additionally, since the base scenario is already computed, a map with the traffic volume should be added, to indicate the traffic flow. Next, to such a figure, it would be interesting to see a figure for the traffic volumes of an interrupted network.

Different classes are already represented by different line width. In addition, minor roads are omitted in the right plot. We have added two interactive leaflet maps as additional supplementary material. These include various basemaps showing different functional road classes. Two additional plots have been included, showing home locations and time delay for a selected interruption scenario.

5. (14/3) “In some situations, the blockage of a non-redundant link can occur, meaning that no alternative routes are available, as is the case for incident 11. Here, it is of no benefit to run a traffic simulation on the modified road graph affected by the landslide event.” Actually, what would happen is that the overall travel time will decrease for the network since fewer people are on the roads. The issue of missed trips (people who are cut off from the network) is neglected in the current version of the paper, however, it is important problem and should also be treated. Especially since this could cause more socio-economic impacts than a trip prolongation of several minutes.

While this is theoretically correct we do argue that this is only of minor relevance. For a vast majority of links in the network alternative routes do exist, and the rare cases where complete blockages would result in a complete cut-off the agent-based traffic model does not offer much additional benefit over simpler traffic models. All other agents on the network might be marginally faster due to less traffic, but this is actually not the most important issue in case of total cut-off. The assessment scheme would be different than on the other scenarios.

6. (15/9) *How many agents were simulated? 30% of 260000 is 78000 and not 5518. Probably this sentence has to be clarified.*

The number of affected agents in the baseline scenario is listed in table 1. 5518 is the total number of agents affected by any incident, corresponding to approx. 30% of $565 + 1486 + 4794 + 586 + 858 + 128 + 572 + 1404 + 576 + 4709 + 5 = 15683$, which is the total number of agents affected by any interruption in the baseline scenario. We have clarified this sentence.

7. (16/1) *Figure 2. Why showing the 10% and the 30% example, is there any additional value in showing and discussing the 10% example?*

See response to (6d).

8. (19/4) *“In this paper, we have shown that agent-based traffic modelling allows gaining interesting insights into the impacts of road network interruptions on the mobility behaviour of affected communities by modelling their responses to network disturbances.” This might be true but is only slightly related to the topic of road network vulnerability which was promised in the title of the paper.*

This is correct. We have adjusted the title of the manuscript to avoid confusion with respect to network vulnerability versus agents’ vulnerability.

Again, we would like to thank the reviewer for the thorough review and the helpful feedback provided. These comments have certainly contributed to improve the quality of the manuscript.

We have put a a lot of effort into reworking the manuscript, including a completely reworked introduction/motivation section and extensive changes to other parts of the manuscript. With some exceptions, which would simply be beyond the scope of a single manuscript, we have implemented all suggestions provided by the reviewer, which resulted in a clearer structure of the manuscript. Since covering the whole methodological chain from detailed landslide process simulation, agent-based traffic modelling (including various combinations of single link and multiple link failures for different values of section vulnerability), network vulnerability assessment, socio-economic analysis of consequences and provision of decision support as well as recommendations for road authorities would simply break the mould, we have strived to specify the aim of this paper.

Our approach is based on certain assumptions and scenarios, which allow to illustrate the application of an agent-based traffic model to obtain the consequences of network interruptions (in terms of detour statistics) on the local population, by using actual mobility survey data. This manuscript is intended to serve as a methodological blueprint covering an interdisciplinary process chain from landslide susceptibility modelling via agent-based traffic modelling to an agent-specific vulnerability assessment. Thanks to the insightful reviewer comments we will add a more concise description of the process flow, including a more detailed assessment of a selection of socio-demographic variables to illustrate the advantages of an agent-based model.

We are fully aware of the fact that the approach can of course be extended, e.g. by including cross-border traffic, assessing capacity reductions instead of complete blockages or assessing multiple link failures at the same time. However, all these aspects are not in the focus of this study, as they are merely methodological extensions of the approach we present here.

2 Response to Reviewer 2

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.

2.1 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. While the creation of a full landslide inventory for the whole federal state of Austria based on satellite images and DEM data would go way beyond the scope of what can be achieved within this revision, we have worked on the landslide susceptibility map by manually mapping the extent of previous landslides as reported in the historic data sets as polygons. Based on this additional information, the susceptibility map was updated accordingly.

2.2 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 have provided a more detailed description of the study area in the introduction section.

¹The 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).

2.3 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 have reworked the abstract as proposed, including quantitative summary of the main results.

2.4 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 affect 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 was rather broad indeed and did require a more precise description of the scientific purposes of the manuscript. We agree with the reviewer and have reworked the introduction completely. In addition, we have 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 have added 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. However, the term ‘complex orography’ or ‘complex topography’ is commonly used in similar studies.

- *P2 L14-15: What are ‘reliable networks’ in this context? In general, this sentence is relatively hard to understand from my point of view.*

Has been clarified and 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 was too broad. It has been re-written almost completely.

- *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).

2.5 Data and Methods

- *The first subsection of section 2 (2.1 Modeling landslide susceptibility) should be re-structured 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 have restructured section 2.1, and partially shortened it 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 have added 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 have clarified this in the text.

- *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 have reworked 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 Vorarlberg 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:

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

- *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.*

A 10m grid size was used. We have clarified this in the text.

2.6 Results

- *P11 L10-11: How did the authors deal with the detected inventory incompleteness mentioned in the manuscript? The incompleteness of the official inventory had to be accepted due to practical reasons. Efforts were undertaken to map additional landslides using satellite data and a very high resolution DEM. Conducting an extensive creation of a landslide inventory (as e.g. in Schmaltz et al., 2017) for a whole federal state would require prohibitively large amounts of resources, even though the modelling procedure would benefit from the additional wealth of data.*

- *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. When mapping landslides in the whole study area, this turned out to be a quite reasonable buffer size.

- *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. New modelling results are more in line with our expectations.

- *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.*

We have included average WoE values for the affected incident links to table 2 (incident site overview) and removed this statement from the manuscript entirely.

2.7 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 have reworked the statement accordingly.

- *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.

While the reviewer is correct that the geological underground is to some extent related to the slope, the correlation between lithology class and slope is not as high as implied by the reviewer (c.f. Figure 1).

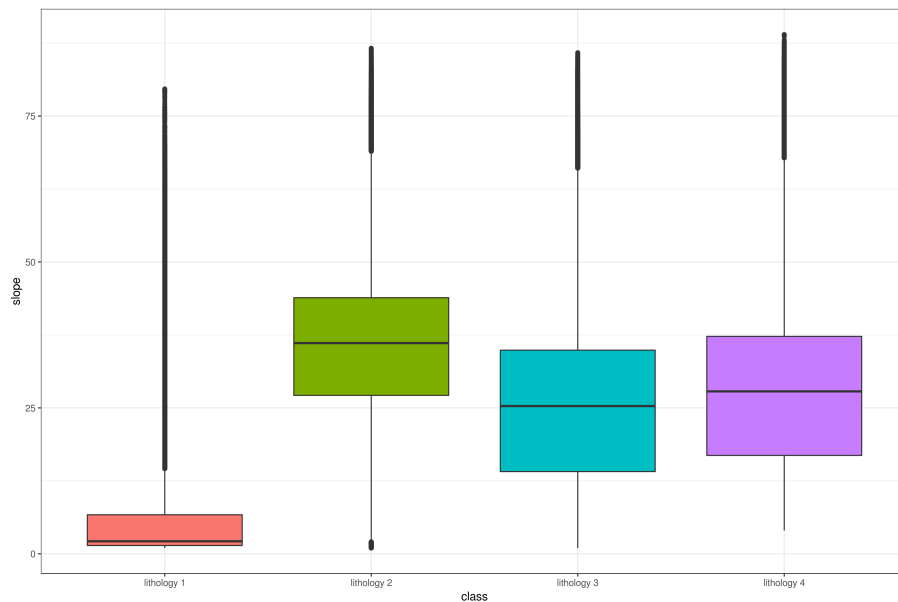


Figure 1: Slope by lithology class.

Therefore, both slope and lithology class are kept in the modelling process. Since the main focus of this paper is on the impacts of interruptions on the local population, and the selection of interruption points is not solely based on the geological map, which is only one of several predictors for the susceptibility map, the added value of including two different spatial resolutions of different geological maps would be only minor.

- *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 have clarified it accordingly.

2.8 Conclusion

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.

This is extremely complex and excessively prohibitive with respect to simulation efforts, as this would require to introduce in time-dependent disturbances (e.g. for each hour) and subsequent simulation of agent schedule optimization for all incidents. Daily traffic load curves are available, though.

2.9 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 have provided this map as Fig. 1.

On the nexus between landslide susceptibility and transport infrastructure – an agent-based vulnerability assessment of rural road networks in the Eastern European Alps ~~approach~~

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Abstract.

Road networks are complex interconnected systems. Any sudden disruption can result in debilitating impacts on human life or the economy. ~~Interruptions of the transport flow may lead to potentially severe consequences in terms of both direct and indirect losses.~~ In particular, road systems in ~~mountainous areas~~ mountain areas are highly vulnerable, because they often do not feature redundant elements at comparable ~~economic efficiency.~~ ~~Therefore, assessment of network vulnerability is of major importance for guaranteeing the smooth functioning of societies, especially in those regions.~~ efficiency.

~~Among various menacing hazards, landslides protrude as particularly destructive events jeopardizing the integrity of land transport systems by causing structural damage and network interruptions.~~ The aim of this paper is to present how road infrastructure is vulnerable towards landslides events, with emphasis on the consequences for the affected road users. This is addressed on the Austrian region Vorarlberg, which allows cross-learning and cross-comparison of, for example, rural and urban areas, also at different scales. The focus of this case study is on resilience issues and support for decision making in the context of a large scale sectoral approach. This paper addresses the impacts of network interruptions caused by landslide events on the (rural) road network system in Vorarlberg, Austria.

~~By taking into account derivatives of a high-resolution digital terrain model as well as geological properties,~~ Based on a landslide susceptibility map of the test region is derived by means of the weight of evidence method. This susceptibility map is concatenated with historic data of landslide inventories and a digital road graph in order to identify critical sections of the road network. Subsequently, effects of interruptions of the road network at these critical links are analyzed by applying a mesoscopic multi-agent transport simulation model. we demonstrate the performance of agent-based traffic modeling using disaggregated agent data. This allows gaining comprehensive insights into the impacts of road network interruptions on the mobility behavior of affected people. Choosing an agent-based activity-chain model enables us to integrate the individual

behavioral decision-making processes in the traffic flow model. The detailed representation of individual agents in the transport model allows for optimizing certain characteristics of agents and to include their social learning effects into the system.

~~Results show the merits~~ Depending on the location of the interruption, our findings reveal median deviation times ranging between several minutes and more than half an hour, with effects being more severe for employed people than for unemployed individuals.

Moreover, results show the benefits of using agent-based traffic modeling for assessing the impacts of road network interruptions on rural communities by providing insight into the characteristics of the population affected, as well as the effects on its daily routine daily routines in terms of detour costs. This allows hazard managers and policy makers to increase the resilience of rural road network systems in remote areas.

1 Introduction

~~Transport networks and its~~

Infrastructure networks and related assets support the delivery of essential goods and services to society (European Commission, 2017; Mejuto, 2017; Gutiérrez and Urbano, 1996). ~~The~~ In particular, the functionality of socio-economic systems in modern communities heavily depends on ~~the~~ extensive, interconnected ~~networks of critical infrastructures to such an~~ extent that ~~transport networks because~~ any disruption may cause rippling effects, eventually entailing instability of ~~the whole infrastructure network other critical infrastructure~~ – both domestically and beyond (Bíl et al., 2015; Jaiswal et al., 2010). ~~Main~~ challenges are negative socio-economic consequences (high direct and indirect losses) to societies as a result of hazard events (Bordoni et al., 2018; Rheinberger et al., 2017; Pfuertscheller and Vetter, 2015; Kellermann et al., 2015; Pachauri and Meyer, 2014; Schw

~~There is a growing amount of studies on roads being impassable and damaged by natural hazards such as flash floods~~ (Pregolato et al., 2017), landslides (Winter et al., 2016) or fallen trees (Bíl et al., 2017). Simultaneously, ~~media coverage on these incidents increased~~ (e.g. NZZ, 2018; ORF, 2018a, b; Tiroler Tageszeitung, 2018). The impacts caused by ~~such~~ severe weather events and associated hazards underline the importance of ~~climate resilient transportation infrastructure~~ resilient and reliable transportation infrastructure (Eidsvig et al., 2017), especially in complex landscapes such as the European Alps ~~where~~ the topography impedes redundancies and alternative routing. Failure and disruption of ~~infrastructure can affect the whole society and the~~ transport infrastructure can therefore affect a broader environment due to cascading effects which result from the dependence of economies, institutions and societies on ~~transport such~~ networks (Kellermann et al., 2015; Doll et al., 2014; Keller and Atzl, 2014; Pfuertscheller, 2014; Meyer et al., 2013; Kappes et al., 2012). This is especially true under severe weather conditions ~~,~~ triggering disasters, because reliable networks are crucial for ~~averting~~ emergency response to avert further damage, ~~saving lives and mitigating~~ save lives and mitigate economic losses. ~~Therefore, the~~ Network reliability in this context is defined to comprise network availability and network safety. ~~Non-reliable transportation networks and the associated~~ overall societal loss introduced by destructive incidents ~~considerably~~ exceeds the mere physical damage to ~~the infrastructure by far~~ such infrastructure. Apart from ~~an~~ impairment of roads – which results in maintenance and reconstruction efforts to be carried out by

road operators (c.f. Donnini et al., 2017) – secondary aspects-effects such as intangible and indirect costs of damage to infrastructure networks have to be considered in a broader economic context ~~-.Intangible and indirect costs, which are caused by e.g. detours or delays, may even surpass the mere infrastructural damage (Klose et al., 2015; Pfuertscheller and Thieken, 2013; Meyer et al., 201~~

5 and lead to considerable vulnerability of societies affected (Klose et al., 2015; Pfuertscheller and Thieken, 2013; Meyer et al., 2013; Fuchs
Consequently the assessment of transport network systems has gained relevance in academia as well as the policy agenda of
authorities across all scales ~~-.Some triggers were the influential terrorist attacks in recent years, maybe starting with the “9/11”
incidents in New York in 2001, and manifested later during the 2004 Madrid train bombings or the 2005 London attacks.
Moreover, natural hazard events such as hurricanes Katrina or Harvey in the United States, the 2007 UK Summer Floods or the~~
10 ~~2013 Danube floods in Central Europe also revealed the susceptibility of transport infrastructure. All these events affected larger
areas, considerably disrupting the traffic system (Bíl et al., 2017; Rupi et al., 2015; Jenelius, 2009; Taylor et al., 2006; D’Este and Taylor, 20~~
~~-.Their impacts created negative socio-economic consequences (high direct and indirect losses) to European societies (Rheinberger et al., 20~~
(Pant et al.; Unterrader et al., 2018; Bíl et al., 2017; Pregolato et al., 2017; Winter et al., 2016; Rupi et al., 2015; Jenelius, 2009; Taylor et
.
15 ~~Major losses were caused by disrupting services, the flow of crucial goods and supply chains (Pfuertscheller and Vetter, 2015; Taylor and S~~
~~-.Since no context-free definition of road network vulnerability exists, respective methodological approaches (even if highly so-~~
phisticated) remain fragmentary and repeatedly tailored to individual settings (Bagloee et al., 2017; Eidsvig et al., 2017; Mattsson and Jenelius
(Bagloee et al., 2017; Eidsvig et al., 2017; Mattsson and Jenelius, 2015; Rupi et al., 2015; Fuchs et al., 2013).

Berdica (2002, p.119), for example, ~~suggests-suggested~~ that network vulnerability should be understood as ‘susceptibil-
20 ity to incidents that can result in considerable reductions in road network serviceability’. This includes a focus of assess-
ment on the most critical hotspots (links or nodes) within a current network system, where the highest socio-economic im-
pact can be observed, which – according to other scholars – equals exposure ~~(?Khademi et al., 2015; Jenelius et al., 2006)~~
(Unterrader et al., 2018; Khademi et al., 2015; Jenelius et al., 2006). On the other hand, Taylor et al. (2006) understands-understood
network vulnerability as a close concept to network weakness and thus as the consequence of failure to provide sufficient ca-
25 pacity for the ‘original’ purpose of the system, being, to transfer people and goods from point A to point B. This already
shows the close connection of network vulnerability to other terms, such as accessibility, remoteness or robustness, which
is linked to the idea of network performance (Yin et al., 2016; Taylor et al., 2006; D’Este and Taylor, 2003). In sum, the
idea behind vulnerability is a decline in the ‘original’ capacity to handle the network flow based on disruption (Yin and Xu,
2010). Nevertheless, in the literature two main directions within network vulnerability assessment can be distinguished: (1)
30 topological vulnerability analysis, which includes the assessment of real transport network systems (represented in an abstract
network); and (2) system-based vulnerability analysis, which focuses on the structure of the network within demand/supply
models (Mattsson and Jenelius, 2015). In the context of the present study paper, we understand vulnerability as the assess-
ment of the disruptive impact based on a certain event (incident) which causes a malfunction or breakdown in the current
road network system (Postance et al., 2017; Pregolato et al., 2017; Klose et al., 2015; Mattsson and Jenelius, 2015). The po-
35 tential disruption may span from natural hazard events to terrorist attacks, infrastructure collapses or ordinary traffic accidents

(Bagloee et al., 2017; Vera Valero et al., 2016; Mattsson and Jenelius, 2015; Koetse and Rietveld, 2009; Zischg et al., 2005b; Margreth (Bagloee et al., 2017; Unterrader et al., 2018; Vera Valero et al., 2016; Mattsson and Jenelius, 2015; Koetse and Rietveld, 2009; Zischg et al., 2005b). Depending on the threat, the potential consequence can result in additional travel time from some minutes to total cut-offs of a community (Rupi et al., 2015; Taylor and Susilawati, 2012; Jenelius, 2009; Zischg et al., 2005b). Therefore, a central goal of vulnerability assessment is the identification of the critical links within the current network system that are highly susceptible to such disruptions (Bil et al., 2015; Jenelius et al., 2006; Berdica, 2002)(Gauthier et al., 2018; Jenelius et al., 2006; Berdica, 2002). In contrast to the ongoing vulnerability debates in natural hazard management, and risk management of buildings, (see for example Papathoma-Köhle et al. (2017); Fuchs et al. (2011) or Fuchs (2009)) however, network vulnerability usually does not account for any probability of disruption within the assessment (see for example Papathoma-Köhle et al. (2017); Fuchs et al. (2011) or Fuchs (2009)) (Rupi et al., 2015).

Two main methodological approaches on how to assess road vulnerability exist (Mattsson and Jenelius, 2015; Hackl et al., 2018). The first is a topological one which focuses on characteristics of the road network's links. It is based on graph theory which is widely used in various disciplines, such as computer science, physics, sociology and transportation (Heckmann et al., 2015; Phillips et al., 2015), with the aim to assess and understand networks and their individual properties (Slingerland, 1981). Using graph theory in vulnerability assessment of road networks generally means focussing on specific graph edges (links) and nodes, their criticality or redundancy, to reflect resilience and interdependencies between parts of the network, as well as potential cascading effects (Pant et al., 2016; Rupi et al., 2015; Tacnet et al., 2013; Jenelius et al., 2006; Meyer et al., 2013). This approach, however, is limited by the reduction to connectivity within a network, therefore not including the behavioural aspects of transport network users.

Among various causes, the A second group of models bridges this gap by considering link properties and traffic demands on the links of traffic networks. The network loads, together with appropriate traffic dynamics result in alterations of network properties, which gives rise to various stress response effects that can also be observed in real-world traffic. These models differ with respect to the chosen granularity, and can be divided in macro-, meso- and microscopic models (Treiber and Kesting, 2013; Hoogendoorn et al., 2001).

Macroscopic traffic models stem from the concept of flow theory, and consider aggregate continuous flow densities of anonymous users on the network. They can be applied to find equilibrium loading states within these networks, as well as to describe dynamic effects within the flow continuum. Their application usually requires solving systems of coupled equations. In contrast, the fine-grained *microscopic traffic models* consider each transportation network user as an individual entity ('agent' i.e. vehicle or pedestrian) with separate interaction details and decisions. These models are implemented as simulation frameworks, iterating over time steps the entire network evolution. Thus, individual entities (agents) retain their specific characteristics throughout the traversal of the network and therefore can react to different circumstances based on these characteristics. *Mesoscopic traffic models* are hybrids between macro- and microscopic models. They are less fine grained and borrow some characteristics from both approaches, offering a description that is less detailed in time or space, but also less demanding regarding the computational requirements. Depending on the implementation, micro- and mesoscopic models can be 'agent-based', thus retaining the individuality of their agents throughout the model evolution. A more detailed

conceptual distinction of agent based models regards the scheduling of mobility demands. Simpler approaches define individual (or multiple unrelated) trips between origin and destination pairs ('trip-based'), whereas more recent frameworks allow the expression of agent activity plans or chains ('activity-based') to be fulfilled by adaptively traversing the transportation networks of the simulation.

5 The change between levels of granularity in the description of model entities is referred to as (dis-)aggregation for in- or decreasing detail, respectively.

With the modeling discrimination provided above, the approaches of the second group of road vulnerability assessment methods allow to explore the effects of landslide events on a given population and its sub-groups with respect to their mobility requirements. The main drawbacks of aggregated (macroscopic) traffic models in that context include: (1) loss of population individuality, (2) therefore lack of behavioral alterations and co-dependent learning effects of individuals, (3) more time-averaging aspects, prohibiting re-decisions based on incidents, (4) more space-averaging aspects, prohibiting investigation of localized events without re-building the overall model (e.g. new zoning structure), (5) connected to unavailable consequences of precise socio-demographic measures, (6) macroscopic models are trip-based, considering individual journeys instead of whole day-plans and (7) macroscopic models are adaptable to the increasing level of detail available through continuously improving data by layering of multiple models. Choosing an agent-based activity chain model, which integrates the dynamic aspects of each agent, can overcome these limitations. The vulnerability assessment utilizing activity chain traffic modeling allows simulations to integrate multiple phenomena, to understand the dynamic interactions of human behavior and the environment in the sense of consequences for households or wider socio-economic systems.

The focus of this paper is on landslide hazards, which jeopardize repeatedly jeopardized the integrity of land-transport systems-road infrastructure by causing structural damage and interruptions (Postance et al., 2017; Klose et al., 2015; Bíl et al., 2014). This choice is justified by an estimation of the probability of occurrence based on relative event frequency, by hazard process type. For instance, within In the Austrian Alps, 1 444 damaging events to rural roads in the Austrian were recorded in the provinces of Salzburg (2007–2010) and Styria (2008–2011), and debris flows and landslides caused nearly 50 % of damage costs, thereby clearly exceeding damages resulting from other events such as windstorms, flooding, or snow avalanches the recorded damage costs (König et al., 2014b). The prevailing hazard potential caused by landslides is aggravated by the findings of several current other recent studies which have shown that landslide activity and thus related damage will most probably increase with progressing climate change (Postance et al., 2017; Bíl et al., 2015; Klose et al., 2015; Strauch et al., 2015; König et al., 2014a) . Recent regional hazard events occurring with increasing frequency and severity (at least as far as their impact on transport networks is concerned) seem to be in line with this prediction (Schlögl and Matulla, 2018; Gariano and Guzzetti, 2016; Bíl et al., 2015; Klose et al., 2014) . Similar results are available from other mountain regions (e.g. Postance et al., 2017; ?, Meyer et al., 2015; Fuchs et al., 2013) (e.g. Postance et al., 2017; Unterrader et al., 2018; Meyer et al., 2015; Fuchs et al., 2013).

So far, most studies have mainly focused on primary road networks (i.e. highways, (Postance et al., 2017; Taylor et al., 2006) (Postance et al., 2017; Taylor et al., 2006) and urban areas (Gauthier et al., 2018), while federal and local road networks have been largely neglected. Furthermore, mostly issues on technical realization and maintenance have been addressed rather than socio-economic impacts on communities or the society (Mattsson and Jenelius, 2015). Termed Mountain roads, in contrast

to lowland roads, are highly vulnerable due a higher probability of climate-driven hazard events and the inherent obstacles of implementing redundant systems (Schlöggl and Matulla, 2018; Matulla et al., 2017; Schlöggl and Laaha, 2017; Doll et al., 2014; Eisenack et al., 2015). Consequently, misleadingly termed as ‘forgotten road system’, ~~misleadingly, the latter in fact connects~~ local road networks in fact connect rural communities in various ways – from supply reliability over public health and tourism to all sorts of economy. Furthermore, mostly issues on technical realization of mitigation and road maintenance have been addressed, rather than socio-demographic impacts on communities or exposed societies (Mattsson and Jenelius, 2015). This paper partly closes this gap by assessing the road network vulnerability of alpine communities to landslide events in the context of rural road networks. Mountain roads, in contrast to lowland areas, are highly vulnerable due a higher probability of climate-driven hazard events and the inherent obstacles of implementing redundant systems (Matulla et al., 2017; ?; Schlöggl and Laaha, 2017; Doll et al., 2014; Eisenack et al., 2015). Nevertheless contributes to close the gap by including the full road network system. In particular, the relation between infrastructure and communal development in mountain areas is not one-directional, meaning that it is only the former that can impact the latter; instead, the influence is rather two-way (Jaafari et al., 2015).

Based on an updated landslide susceptibility map we show the merits of agent-based traffic modeling for gaining insights into the impacts of road network interruptions on the mobility behavior of affected communities. By modeling the responses of individuals to network disturbances the transport model allows for optimizing certain characteristics of agents (e.g. time of departure, route choice, activity list, etc.). Generalized costs of interruptions (i.e. monetary costs, time losses, etc.) are obtainable by employing a utility function to the agents’ resulting behavior. The presented approach is complementary to previous studies because of the consideration of whole-day travel plans (as opposed to a focus on peak traffic flow periods on the investigated network), with these plans stemming from the underlying agents’ activity chain model. This schedule of activities, which is far less dependent on fixed locations, allows for a more inclusive and flexible reassignment of mobility needs and resulting traffic demands. Therefore, integrating transport route finding and satisfaction of individual activity needs in one single simulation framework facilitates a more detailed and realistic representation of traffic loads on the network. We demonstrate an appropriate methodological response to foreseeable demands imposed by the increasing detail of available mobility data, which brings about particular relevance of this approach for future applications.

The applicability of the approach is demonstrated by the example of Vorarlberg, the westernmost province of Austria (Figure 1). While being the second-smallest federal state, the population density of Vorarlberg is only surpassed by Austria’s capital, Vienna, which indicates the need for a resilient transport network. The main traffic artery in this almost completely mountainous area is the connection from Germany to Western Austria, via Rhine valley, Walgau, Klostertal and the Arlberg massif. Apart from this link, which is realized as motorway (A14 and S16), rural roads prevail in the complexly structured topography of Vorarlberg. Because Vorarlberg is almost entirely surrounded by mountain areas and a considerable exposure to extremely high rainfall (with average annual precipitation totals exceeding 2000 mm), the transport system of Vorarlberg is highly exposed to landslides (maybe citation here on one of the landslide studies). The combination of (i) being characterized by high landslide susceptibility, (ii) exhibiting a high population density and (iii) lacking alternative routes on the rural network due to the mountain orography makes Vorarlberg a perfect case study.

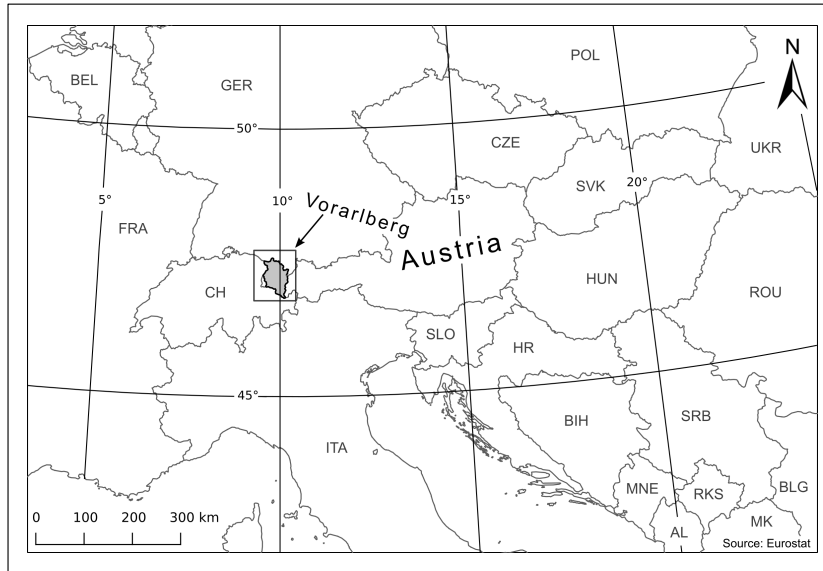


Figure 1. [Location of the study area in Europe.](#)

2 Data and methods

Methodologically the approach presented in this paper is divided into two modeling sections:

1. [creation-compilation](#) of a landslide susceptibility map in order to identify potential blockage sections in the rural road network, and
2. implementation of agent-based transport simulations [for deriving to derive](#) impacts of interruptions on local communities. [By modeling the responses of individuals to network disturbances the transport model allows for optimizing certain characteristics of agents \(e.g. time of departure, route choice, activity list, etc.\). Generalized costs of interruptions \(i.e. monetary costs, time losses, etc.\) are obtainable by employing a utility function to the agents' resulting behavior.](#)

2.1 Modeling landslide susceptibility

- ~~The impact assessment of landslide events on different aspects of society does still pose a great challenge for different groups of stakeholders. In order to evaluate the impacts of the process itself, numerous quantitative methods are in use. Goetz et al. (2015) give a comprehensive overview of different statistical prediction models for the assessment of landslide susceptibility. In this study we use the Weight of Evidence Method (WoE, first presented by Bonham-Carter (1994)) with early application to landslides by Lee et al. (2004). The main concept of WoE is based on the assumption that future landslides are very likely to occur in similar conditions as in the past (Varnes, 1984). This is an important aspect in answering possible effects regarding the occurrence of landslides under a changing climate (Gariano and Guzzetti, 2016). WoE is a data driven method representing a Bayesian approach in a log-linear form. WoE uses a prior and posterior probability for assessing the~~

~~relations between (i) the spatial distribution of the areas affected by landslides and (ii) the spatial distribution of the analyzed landslide susceptibility factors also named predictors (van Westen et al., 2008). Consequently, the degree of influence of of each predictor on past and future landslide events can be calculated.~~

The most decisive ~~database for the~~ data needed for a statistical modeling of landslide susceptibility is an accurate and representative landslide inventory (Zêzere et al., 2017). Different types of event landslide inventories exist: (i) Historical data from archives, (ii) field mapping results, (iii) information derived from remote sensing data, and (iv) combined inventories (Bell et al., 2012). In general, inventories which are based on archive data do only include ~~events which reported events. These often~~ caused some kind of ~~damage and were reported~~ loss were therefore recorded; landslides occurring in remote areas without significant ~~damages loss~~ are usually not documented. Event inventories give detailed information about the process type as well ~~as the date and the trigger of the event~~ location, the process type, the trigger (e.g. heavy rainfall), and sometimes additional data such as a precise event date. In terms of data acquisition inventories based on remote sensing data can be distinguished in two groups. ~~Inventories can be derived either:~~ Inventories can either be derived from passive optical sensors (~~products: i.e.~~ ortho-images ~~and~~ digital terrain models (DTMs) ~~from~~ obtained through photogrammetry) or from active sensors (e.g. laserscanning, radar: ~~product: DTMs~~). Data from passive systems, such as ortho-images, imply the big considerable disadvantage of only ~~sensing the surface from one point per image compared to e.g. laserscanning (constant sensing).~~ Therefore existing vegetation cover often prohibits an ~~area-wide, exact~~ area-wide, spatially explicit mapping of landslides, even in stereoscopic analysis (Petschko et al., 2015). In the last decade the availability of DTMs derived from airborne laserscanning (ALS) offers a new quality of high resolution terrain representation (spatial resolution of 1 m). Penetration of laser pulses ~~give exact results in~~ precise and accurate 3D-information of the surface – even in areas with high vegetation density – and have thus been used in many studies (Proske and Bauer, 2016; Petschko et al., 2015, 2013a). The most promising approach for the generation of representative event inventories in forested and unforested landscapes, as well as in landscapes which are characterized by intense human activity, proved to be a combination of the analysis of archive data with the visual interpretation of remote sensing data (ALS-data, orthophotos) followed by random field checks (Proske and Bauer, 2016; Guzzetti et al., 2012).

Goetz et al. (2015) provided a comprehensive overview of different statistical prediction models for the assessment of landslide susceptibility. In our study we used the Weight of Evidence Method (WoE, first presented by Bonham-Carter (1994) with early application to landslides by Lee et al. (2004)). The main concept of WoE is based on the assumption that future landslides are very likely to occur in similar conditions as in the past (Varnes, 1984). WoE is a data-driven method representing a Bayesian approach in a log-linear form. WoE uses a prior and posterior probability for assessing the relations between (i) the spatial distribution of areas affected by landslides and (ii) the spatial distribution of analyzed landslide susceptibility factors also named predictors (van Westen et al., 2008). As a result, the degree of influence of of each predictor on past and future landslide events can be calculated.

First efforts to delineate geomorphological landforms including mass movements in the study area of Vorarlberg date back to the 1950s (Matznetter, 1956). Further approaches include those of Seijmonsbergen (1992); Aulitzky et al. (1994) and van Asselen and Seijmonsbergen (2006). In terms of landslide assessment in the province of Vorarlberg, research activities comprise shallow landslide inventories ~~of elected test site~~ for selected large-scale test sites (Zieher et al., 2016) as well as land-

slide susceptibility analysis ~~of regional test sites (Schmaltz et al., 2016; Ruff and Czurda, 2008)~~ for regional-scale test sites (Schmaltz et al., 2017, 2016; Ruff and Czurda, 2008).

The government of the province of Vorarlberg ~~offers an official~~ published a small-scale landslide susceptibility map based on a classified geological map and the location of landslides events (details below). In order to generate ~~an enhanced~~ a larger-scale landslide susceptibility map ~~for Vorarlberg (including e.g. an enlarged landslides~~ (including an enlarged landslide inventory), we used a routine which was already successfully applied to two other ~~provinces~~ regions in Austria (Petschko et al., 2013b, 2014; Bell et al., 2013; Klingseisen and Leopold, 2006).

The only available area-wide geological map of Vorarlberg is based on information available at a scale of 1:100 000, therefore constituting a strongly generalized data basis. While geological information existing at a scale of 1:50 000 available in small parts of the province of Vorarlberg, this was not pursued further, as the different resolution of information would affect the consistency of modelling results. For instance, this rather coarse geological information does not accurately display alluvial depositions in the valley bottom, leading to inconsistencies with the DTM. In some cases, valley bottom sediments are even exceeding the limits of the foot of slopes. Consequently, the latter influences the information in the geomorphological input parameters such that e.g. the mean slope of the class valley bottom sediments is slightly biased.

Three major data sets ~~constitute~~ provided the main input for deriving model input parameters as well as for model training and evaluation purposes:

- ~~Historic landslide events (“Rutschungskataster Vorarlberg”, points) as model training points;~~
- ~~Official landslide susceptibility map—including geology—of Vorarlberg (“Gefahrenhinweiskarte”, polygons) as a model input parameter;~~
- ~~DTM of Vorarlberg (5 m grid).~~

The following list provides an explicit description of parameters used in this study:-

- ~~Inventory of historic landslide events: This~~ The inventory of landslide events (‘Rutschungskataster’) ~~is~~ was compiled from different data sources, such as archive data provided by the Austrian Geological Survey (‘Geologische Bundesanstalt’, GBA), the Austrian Service for Torrent and Avalanche Control (‘Forsttechnischer Dienst für Wildbach- und Lawinenverbauung’, WLW), the Federal Institute for Forests (‘~~Bundesamt Bundesforschungs- und Ausbildungszentrum für Wald, Naturgefahren und Landschaft~~’, BFW), different provincial staff units, and web data mining. Events ~~are~~ were represented by discrete points within a ~~shapefile~~ vector data set with one point for each database entry. The inventory of landslide events ~~includes information about~~ included information about the data source as well as ~~main and differentiated process group~~ the main hazard category and process subgroups (e.g. ~~slides; rock slides~~). ~~Within this inventory, information about~~ slide – translational slide). Information about some 2000 gravitational mass movement events dating back to the 1930s were available (with a small number of events even earlier). We considered only approximately 800 slide-type movements for our study. Based on this subset, efforts were undertaken to map each individual landslide extent as polygon using a

high-resolution LIDAR DTM with 1 meter spatial resolution in combination with natural color satellite images in order to avoid an underestimation of larger landslides. This thorough visual inspection revealed some uncertainties in the data set with respect to landslide localization, which are discussed further below. About one third of all slide events was identified and delineated this way. In addition, about 50 additional slides were discovered, delineated and included into the data set during the mapping process. For all other remaining landslides, a 50 m buffer was assumed around the point information taken from the landslide inventory based on the average extent of slide-type events in the study area. Finally, all overlapping polygons were united, thus creating a consistent landslide mask for the study area. Note that this step also included the removal of duplicated entries resulting from the use of different data sources. The final mask layer – consisting of both mapped slides and buffered point data – contained 728 distinct landslide areas in the study area.

– *Hazard index map*: The geological map of Vorarlberg (Friebe, 2007) (1:100 000; Friebe, 2007) shows 171 different geological units for the entire province area. To obtain suitable input parameters for landslide susceptibility modeling, these units were classified with respect to their lithological and geotechnical characteristics, generating a hazard index map (HIM). This map presents four classes representing different levels of geogenic risk roughly representing presented four classes which were almost identical to the main geological units. The polygon shape file was converted to a raster image for our modeling purpose. In order to avoid spurious precision, a raster cell size of 10 m raster image for our modeling purpose. This hazard map offers the only available data set covering geological information in a rather coarse and highly generalized scale of 1:100 000. was chosen when rasterizing the polygon data set. Being the least accurate data set, the hazard index map determined the spatial resolution during the entire investigation.

– *Digital terrain model*: The digital terrain model of Vorarlberg represents the data basis for many derivatives which build main input parameters for the modeling approach. The original DTM raster (derived from airborne laser scanning with a spatial resolution of 1 m) was already resampled to a 5 m grid and was then again used as a basis to derive several additional topographic input parameters needed, and was resampled to a 10 m grid in order to be consistent to the geogenic risk class layer mentioned above. This DTM was used as a basis to derive several additional input parameters, which are described immediately below available.

– *Slope*: The steepness of a hillside certainly is the most obvious factor for slope stability (SLO). The parameter is Slope: The parameter was derived by selecting as the maximum rate of change in elevation value from a grid cell with respect to its eight neighbors. It is thus a typical nearest-field parameter, which is expressed as a degree value of slope at the very cell location.

– *Aspect*: While slope gives no information about the geographical direction of the maximum rate of change in elevation, aspect (ASP) does provide this information with no information about the steepness. The value is Aspect: The value was calculated as the angle from north-North in degrees that features the maximum elevation gradient. Usually, the values are classified in and classified in eight steps of 45° according to the eight compass directions. A

ninth class ~~represents~~ represented flat areas, which ~~are typically~~ were defined to comprise steepness values smaller than 3°. These flat grid cells ~~are commonly~~ were excluded in the further modeling procedure. ~~It is obvious that—~~ ~~except for the definition of the last class—~~ ~~the values of slope and aspect are mathematically independent of each other, only conditioned by the characteristics of the landscape they describe.~~

- 5
- ~~Positive topographic openness:~~ Positive Topographic Openness (PTO) characterizes Positive topographic openness: PTO characterized the widest vicinity of a raster cell (usually radial limits of 10 000 raster cells are used) ~~and expresses the “dominance”~~ to express the ‘dominance’ of a landscape location, giving an index of the viewshed size above the horizon line. ~~Hence, higher values represent dominant hilltops, while low values places in narrow valleys.~~ For detailed information see (~~Yokoyama et al., 2002~~) Yokoyama et al. (2002).

10

 - ~~Topographic position index:~~ Topographic Position Index (TPI) compares Topographic position index: TPI was used to compare the elevation of a DTM raster cell to the mean elevation of its neighborhood in a radius of 100 grid cells, ~~that is in our model 1 km.~~ Positive TPI values represent locations that are higher than the average of their surroundings (ridges and hilltops), negative TPI values represent locations that are lower than their surroundings (valleys). ~~TPI values near zero are either flat areas (where the slope is near zero) or areas of constant slope (where the slope of the point is significantly greater than zero).~~ ~~Inherently, the TPI value is,~~ but are highly dependent on the given radius (Guisan et al., 1999).

15

 - ~~Terrain ruggedness index:~~ Terrain Ruggedness Index (TRI) was developed by (Riley et al., 1999) to Terrain ruggedness index: TRI express the amount of elevation difference between adjacent cells of a DTM. It ~~thus characterizes the “smoothness”~~ was thus used to characterize the ‘smoothness’ and the very local structural heterogeneity of a surface (Riley et al., 1999).

20

 - ~~Topographic wetness index:~~ Topographic Wetness Index (TWI) indicates Topographic wetness index: TWI was used to indicate the local water availability in a cell, based on a precipitation-run off calculation. ~~The size of upslope catchment areas of a cell and the steepness of the slopes are considered in its calculation. As heavy rainfalls~~ As heavy rainfall events are known to be a trigger for shallow landslide events, this parameter is also an important ~~evidence~~ predictor for modelling (Bogaard and Greco, 2018; Martinović et al., 2018; Gariano et al., 2017; Guzzetti et al., 2008; Sørensen et al., 2006).

25

2.2 Traffic modeling

In order to assess the effects of road network interruptions, an agent-based traffic model was employed in the study area. The underlying data required for setting up a suitable traffic model stems from various sources. In terms of traffic services, open data provided by OpenStreetMap (OpenStreetMap Contributors, 2018), by the official road graph of Austria (GIP, 2018) and by the geodata service of the province of Vorarlberg (VoGIS, 2018) were used. The underlying road graph used for the traffic model is based on an OpenStreetMap extract, which was converted into a routeable road graph. Road capacity was derived from the functional road class. In (rare) cases of missing speed data, this information was also derived from the functional

road class. Fundamental data concerning traffic demand and agent characterization are based on data provided by Statistics Austria, by the province of Vorarlberg and land use data. This includes data about e.g. traffic behavior of the local population derived from mobility surveys, socio-demographic data such as population numbers, employment statistics, or commuting flows. All of these properties can be used to model and analyze the effects of transport network interruptions on the population in the test region. The agent-based transport model which was set up on these input data was implemented in the multi-agent transport simulation framework MATSim (Horni et al., 2016). This activity-based implementation of the transport model does not only allow for large-scale agent-based transport simulations in the test area, but also retains detailed socio-demographic information on single agents represented in the model runs. The model setup implemented using aforementioned data sources constitutes the representation of traffic flow on a generic, average weekday under normal (i.e. undisturbed) network conditions. This corresponds approximately to the annual average daily traffic (AADT) for ~~on~~ weekdays between Tuesday and Thursday. Regarding the demographic variable of employment it has to be noted that non-employment is not equivalent to unemployment. Rather, it also includes persons such as pensioners, students and home-makers.

The most significant mode of transport for the predominantly rural areas under investigation is motorized private transport, which mainly consists of cars. As such it is the mode that can be derived best from the available data and therefore is modeled in high detail on the road network. For the other modes with little available data (such as walking or bike), an origin and destination are determined, but no actual tracing of the modeled agents on the network is performed. Instead the agents simply change their position after some time (~~“teleportation”~~ “teleportation”). For the mode public transport, a trip duration is calculated, again with no explicit simulation of mapping trips onto a transportation network. Due to reasons of relative demand coverage mentioned above, modeling car traffic can be expected to provide a good first-order approximation of the effects of circumstantial changes within the transport network for the investigated area (see section ~~??~~3.3).

The full mobility simulation comprises several steps, which are facilitated by several software components. There are three main steps in conducting a full model run (Horni et al., 2016):

1. *Definition of the initial demand:* The initial demand arises from the daily activity chains of the population in the test area. It is based on the digital (routeable) road graph, points of interest along the graph and defined sequences of activities of all single agents. These *activity chains* were derived by means of population synthesis (using iterative proportional fitting) based on a mobility survey (Herry et al., 2014), socio-demographic data and land-use information. All activities of each agent are assigned to certain locations and time slots.
2. *Mobility simulation:* The actual mobility simulation is an iterative process carried out by running MATSim with a set of configuration parameters and data. It comprises the three steps of (i) *process simulation*, (ii) *scoring* and (iii) *re-planning*. Each agent features a set of plans with each plan describing the daily activity chain in the form of a desired schedule. Simulating each plan's execution allows determining associated scores, which can be interpreted as econometric utilities. The scoring function used in the simulation is the Charypar-Nagel utility function (Charypar and Nagel, 2005). ~~It~~ This function evaluates an executed plan by considering late or early arrivals and departures (with opening hours) at facilities, costs of defined and executed activities (e.g. working, shopping, leisure time, education and habitation) and the costs of

travel time¹. Each iteration step an agent selects one plan from its set as the active one to be carried out in simulation. A fraction of all agents are allowed to optimize their score by modifying a plan of their set (e.g. in terms of trip/activity time limits 20 %, route choice 40 %, score improvement 60 %) during the re-planning step. This iterative process is repeated until the average population score stabilizes sufficiently to assume a near-optimal equilibrium.

- 5 3. *Output aggregation and analysis*: This final step comprises the aggregation of model results, which are available at a temporal resolution of 1 second in the form of event logs describing the resulting executed plans.

Following the establishment of ~~a~~an user equilibrium in an undisturbed traffic network state as a *baseline-scenario*, the model is re-run on the modified routing graphs for each of the landslide-scenarios considered. For each of these *incident-scenarios*, the affected network links are removed from the graph in order to indicate a network interruption caused by a landslide, and the altered behaviors of the agents – as displayed by new equilibrium states – are recorded. Consequently, the impact of network disturbances is derived by comparing the new equilibrium state behaviors on the network for any given *incident-scenarios* with the *baseline-scenario*. Generalized costs of interruptions can be obtained from this comparison in terms of e.g. affected agents, travel time or ~~evasion~~diversion lengths.

For simulation models, a trade-off between accuracy and efficiency has to be considered. Using the full population for all defined incident simulations would result in substantially longer computing times, while yielding only limited benefits in terms of explanatory power. Reduction of the sample sizes in simulation runs is a common workaround, which allows to obtain plausible estimates at reasonable computing times, while the variance of the derived results only slightly increases. Therefore, three different population samples were used for the purposes of this study. ~~These comprise:~~

1. The total modeled population with roughly 2.6×10^5 persons (*baseline-100*). This population was optimized for 300 iterations to attain a solid equilibrium. It is used as a reference to determine basic properties of the population affected by the landslide incidents. The resulting activity chains were used as the basis for the following two samples.
2. A 10 % random sample drawn from all persons represented in the abovementioned baseline-scenario. It was optimized for 100 additional iterations to ascertain stability after random sampling (*baseline-10*). This sample was mainly used to establish the landslide incidents consequences' evaluation process in a less time-consuming manner, regarding that a percentage of 10 % constitutes the lower threshold recommended for MATSim to obtain consistent results (Balmer et al., 2009).
3. A 30 % random sample drawn from the baseline-scenario, sampled in the same way as the 10 % sample, again with 100 additional stabilizing post-sampling iterations (*baseline-30*). This sample is used to determine the actual consequences of the landslide incidents in a more robust manner, statistically speaking.

30 To mitigate an underrepresentation of traffic congestion effects, ~~it has to be noted that, with~~ a fractional reduction in the number of agents ~~, the network's~~entails that the network attributes in terms of traffic flow and storage capacity have to

¹See Charypar and Nagel (2005) and Horni et al. (2016) for detailed information on the formulation of the Charypar-Nagel scoring function.

be reduced accordingly. For rural roads, however, with traffic volumes mostly well below maximum capacity, this is not considered to be a major issue.

3 Results

The results section is organized as a description of a dependent process chain presenting (i) the area-wide landslide susceptibility map, (ii) blockage points and critical sections in the rural road network, (iii) agent-based transport modeling and (iv) the impacts on the rural network.

3.1 Landslide susceptibility

~~Visualization of modeling results in terms of a landslide susceptibility map~~

Visualization of landslide susceptibility derived via WoE gives a comprehensive picture of potential blockages and potentially critical sections of the rural road network in the province of Vorarlberg (Figure ??). ~~Unfortunately, insufficient quality of input data hampers the generation of an advanced 2). The input data basis of events (to some extent characterized by underreporting and uncertainties regarding event localization and size) calls for careful interpretation of the resulting map. The obtained landslide susceptibility map~~ While results do not meet our initial expectations, valuable insights can be gained—particularly with respect to subsequent work depicts a reasonable estimate which can serve as a valuable proxy providing indications for potential road network interruptions.

~~Basic verification by means of visual interpretation of DTMs and ortho-images rarely shows clear evidence of landslides (Petschko et al., 2015). In the present study, information on landslide localization is given with the differentiation in “exact” and “inexact” without any additional explanation. The description of data acquisition cites literature research (488 events) and archive data available from the Geological Survey of Austria (114 events) as main sources. However sources for several events (116 events) are missing. Acquisition and reporting of events do not seem to be performed in a systematical way; information rather appears to be collected and added to the data set at a certain date. In terms of spatial consistency—which is reflected by conspicuous disparities in data density, which is in turn attributable to different local perception and documentation—landslide events were mapped area-wide (e.g. Blons, St. Gerold), in spatial clusters (e.g. Laterns, Fontanella), or even underestimated due to a lack of sensitization. Hence, districts within the same geological sub-units show significantly different results in landslide reports. The resulting landslide susceptibility maps show a consistent pattern. Valley bottoms in the Rhine Valley and the Walgau exhibit low susceptibility values, while areas characterized by Flysch rock layers (e.g. within the Bregenz Forest Mountains) are correctly identified as being particularly prone to landslides. Approximately 60 % of all landslide events show an occurrence probability of less than 40 % (Figure 3) which is considered to be moderate hazard (Neuhaeuser and Terhorst, 2007). Yet, these results are perfectly in line with our expectations, given the likely underreporting of occurred events. Therefore, it can be expected that the effective landslide risk is slightly underestimated.~~

~~The inventory contains point information about the location of a landslide event with inconsistent information about the position truth. Each landslide event represents a discrete point with no further information about size (cp. polygon delineation).~~

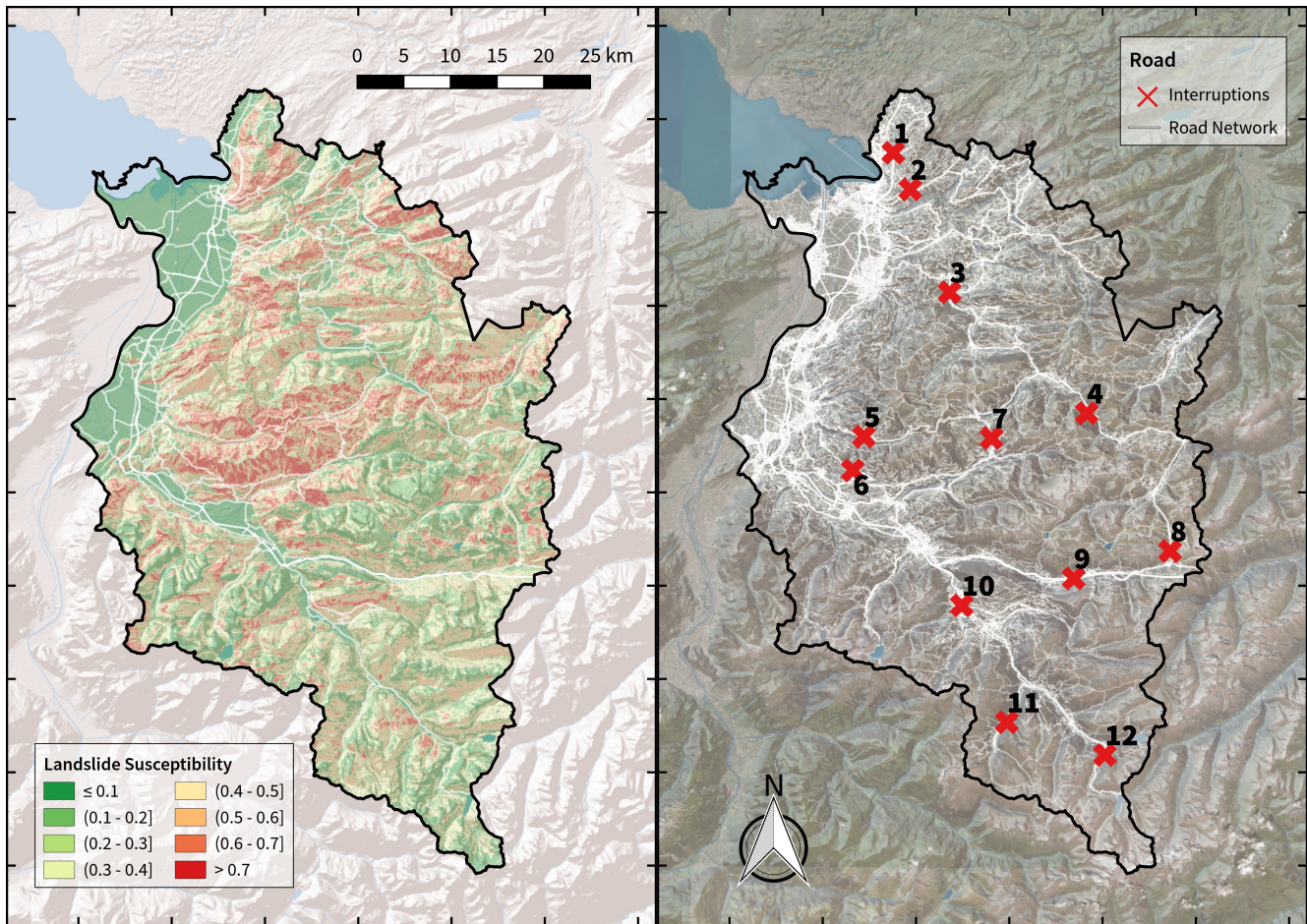


Figure 2. Overview of the study area featuring (a) the updated landslide susceptibility map as well as (b) the road network and the identified critical sections (incident sites).

Consequently, larger landslides cover larger areas and landslide areas and are therefore underestimated in the modeling results. An evaluation of the input parameter *position of landslide events* by visually checking the position of landslide points unearthed that in some cases singular landslides are referenced in the inventory through multiple points. Therefore, this overrepresentation of certain events was corrected by filtering this multiple-point representation of single landslide to only one point per landslide.

5 Regarding the quality of the localization of landslides-

Evidence from precise landslide localization and delineation proved that only about one third of all events included in the inventory , several points could not be verified by means of random check using could be identified unambiguously from high-resolution orthophotos and a satellite images and a very high resolution DTM. This is not solely To some extent, this is caused by imprecise localization, but also due to the fact that landslides, which affected traffic routes or (agri-)cultural areas, are

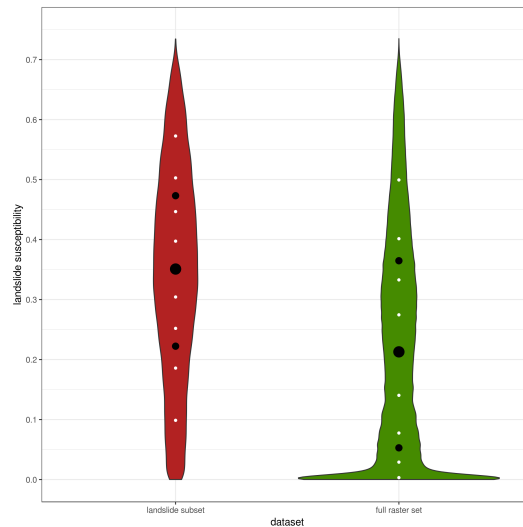


Figure 3. Density of landslide susceptibility values in landslide areas as well as across the whole study area. White dots indicate percentiles of the distribution (in steps of 0.1), and black dots indicate the quartiles of the distribution. Note that densities for both violin plots are displayed independently (as opposed to the conditional probability in the case of landslides) for visualization purposes. Consequently, sizes of the susceptibility density are not in the same scale and thus not directly comparable.

usually fixed quickly and efficiently. The modeling routine used needs landslide polygons as input, so we generated a simple 50-m-buffer around the inventory points to fulfill this requirement.

The official hazard map of Vorarlberg is based on information available at a scale of 1:100 000, therefore constituting a strongly generalized data basis. Valley bottom sediments are indicated but not consistent with the DTM, and the valley bottom sediments exceed the limits of the foot of slopes. Consequently, the latter influences the information in the geomorphological input parameters such that e.g. the mean slope of the class *valley bottom sediments* is biased.

In order to evaluate the quality of the different input parameters, conditional landslide frequencies within the different categories were assessed. The variables *slope*, *topographic position index* and *terrain ruggedness index* show a nearly normal distribution, whereas the parameters *topographic wetness index* and *positive topographic openness* exhibit a right skewed distribution. Frequencies within the susceptibility classes of the official hazard index map exhibit high count values within the two highest classes ‘moderate’ (307; 43 %) and ‘high’ (384; 53 %) – which in fact supports the quality of the official landslide susceptibility hazard classification.

Overview of the weight of evidence models derived for the study area. Maximum landslide susceptibility (WoE_{max}) reflects the occurrence probability of landslides within range 0-1. Input parameters are described in the methods section above. The column ‘events’ reflects the data sources from the landslide inventory that were used as event data, with ‘subset’ indicating a reviewed, narrowed and hence more consistent data set information on landslide location in the landslide inventory. In some cases, evidence of landslides visible in the DTM did not coincide exactly with data points from the inventory. Rather, horizontal

~~shifts of several dozen meters were noticeable, indicating inaccuracies in location information in the landslide events HIM ASP SLO PTO TPI TRI TWI A 0.50 all 4 — 5 5 5 5 5 B 0.53 subset 4 — 5 5 5 5 5 C 0.64 subset 4 — 10 10 10 10 10 D 0.62 subset 4 9 10 10 10 10 E 0.49 subset — 9 10 10 10 10 10~~

Modeling the weights of evidence yields unexpected results. Approximately 80 % of all landslide events show an occurrence probability of less than 40 % which is considered to be moderate hazard (Neuhaeuser and Terhorst, 2007). These results imply a lower landslide susceptibility than initially expected, eventually effectively underestimating the actual landslide risk. Based on a synthesis of all results, we therefore decided to use both the information from the official hazard map of Vorarlberg and the updated landslide susceptibility map for identifying critical blockage points.

As a side note, it has to be noted that the twelve interruption sections identified in the study area Vorarlberg are unlikely to change considerably with new modeling approaches. The official hazard map already provides a reasonably accurate and consistent basis for the purpose of identifying vulnerable sections inventory. In many other cases, no evidence of any landslides could be found in the vicinity of inventory data points. This may be attributable to the fact that small landslides affecting (agri-)cultural areas or traffic routes might be fixed efficiently, leaving no distinctly identifiable evidence.

3.2 Incident sites

~~By concatenating~~

By merging the results of the landslide susceptibility map with a digital road graph and historic data of landslide inventories, critical sections of the road network were identified (Figure ??-2). The selection of incident links is based on a qualitative analysis taking into account (i) landslide susceptibility, (ii) road network structure, (iii) commuting flows, (iv) extent of historic events and (v) spatial distribution of incident links within the study area. In total, twelve incident sites located in different regions of the case study area have been selected for further analysis of the impacts of landslide events on the road network (Table 21). Each incident comprises one or multiple links, which were flagged to indicate total blockage in case of a landslide event. This is based on the underlying assumption that occurrence probability of landslides and extent of historic events are a reasonable proxy for assuming likely network interruptions that are representative of common, everyday risks in the study area.

A closer look at the transport simulation model revealed that incident 12 had to be removed due to its close proximity to Silvretta-Hochalpenstraße, a high alpine toll road across the Bielerhöhe pass which connects the federal states of Vorarlberg and Tyrol. The combination of an adjacent toll road, complete road-closure during winter months and the incident's proximity to the state-border constitute a rather special traffic pattern, which is difficult to reproduce adequately in a simulation of a much larger area with significantly differing traffic patterns.

3.3 ~~Transport network vulnerability~~ Traffic impact assessment

Transport network model simulations were conducted for the remaining eleven incident sites. For deriving insights from the agent-based transport modelling approach, we focus on the following three main aspects.

Table 1. Overview of the twelve selected incident sites located in landslide-prone areas. The table includes the names of the affected roads, of the geographic region and the toponyms of the affected villages. The average traffic volume is displayed in terms of annual average daily traffic (AADT) and the average daily number of heavy goods vehicles (HGV) on weekdays between Tuesday and Thursday in 2016 [vehicles/day]. In addition, the peak flow per hour (Q_{\max}) displays the maximum number of vehicles within one hour in 2016. Please note that no traffic counters are available in immediate vicinity for incidents 1 and 11 (Source: VoGIS (2018)). [The last two columns contain the average and maximum landslide susceptibility value within 50 meters around the selected incident links.](#)

Incident	Roads	Region	Toponym	ADT ₂₀₁₆	HGV ₂₀₁₆	Q_{\max}	WoE_{mean}	WoE_{max}
1	L11	Pfänder	Eichenberg	–	–	–	0.45	0.71
2	L2, L12	Rheintal	Bregenz-Fluh	5171	222	623	0.35	0.64
3	L48	Bregenzerwald	Andelsbuch	4147	243	973	0.03	0.14
4	B200	Bregenzerwald	Schopperrau	4331	255	909	0.17	0.71
5	L51	Latensertal	Latens	1472	82	566	0.35	0.72
6	L73	Walgau	Dünserberg	1693	287	263	0.56	0.72
7	B193	Großes Walsertal	Fontanella	872	61	428	0.34	0.65
8	B198	Lechtal	Zürs	3218	346	1048	0.14	0.54
9	L97, S16	Klostertal	Wald am Arlberg	11702	1716	–	0.10	0.66
10	B188, L94	Montafon	Bartholomäberg	14860	648	1845	0.24	0.70
11	L192	Montafon	Gargellen	–	–	–	0.14	0.44
12	B188	Montafon	Partenen	3217	236	546	0.17	0.48

First we are interested in the transferability of the traffic model to real world traffic conditions. As the model represents traffic flow on a generic, average weekday with undisturbed network conditions it is reasonable to compare against obtainable measurement data of traffic volumes, where available (VoGIS, 2018). Utilizing the baseline-scenario allows to identify the agents crossing the incident-affected links under normal conditions, as well as their properties. A direct comparison of the annual average daily traffic on weekdays between Tuesday and Thursday (Table 21) with the simulated number of affected car trips (Table 32) shows considerable variability depending on the [incidents' location and road class location of incidents and the affected road class](#) (e.g. highway, secondary road). While most of the incidents are located in rural areas or at roads with low daily traffic, some of them are very close to (semi-)urban regions or along main roads. Incident 10 is on the main road at the entrance to the Montafon region and therefore an essential part of the road network. This is reflected by the huge number of affected agents and car trips, which are modeled rather fittingly. Incident 11, on the other hand, is at a road segment of a valley's head with few affected agents (Table 32). All incident links providing access to skiing-resorts (e.g. sites 8, 9) can be expected to deviate strongly, as there was no data on tourism-induced traffic available in the mobility survey that served as basis for the traffic model. In some cases the simulation will choose to guide traffic flows on alternate routes (e.g. shift from site 6 to 5 and 7) which are similar with respect to functional road class and travel time. Additional considerations are explored in the discussion below (e.f. see section 4.2).

Table 2. Summary of car trip characteristics for agents in the traffic model of the undisturbed baseline scenario, to be affected by incident scenarios. Affected agents refer to those crossing the incident site at least once, within their regular daily plans. Employment rate is the share of working people within this group. Affected car trips designate the number of incident site traversals by those agents in that transport mode. The share of mode car gives the proportion of site traversals by car relative to all traversals mentioned before (in any mode). Site traversals of incident links by car undertaken by employed people are shown as percentage in column six. Medians of daily travel time and distance are displayed for employed and not employed people, respectively, which again refer to all affected agents and their trips crossing the respective site.

Incident	affected agents	employment rate	affected car trips	share of mode car	car trips by employed	median daily travel time [h:m:s]		median daily travel distance [km]	
	[]	[%]	[]	≐ [%]	[%]	employed	not employed	employed	not employed
1	565	83.54	1363	93.81	82.17	00:46:58	00:51:13	46.4	54.9
2	1486	64.20	3968	91.66	63.38	01:01:02	01:12:18	62.5	76.4
3	4794	64.15	13856	93.15	62.12	01:31:14	01:43:30	91.5	106.3
4	586	58.42	4285	93.33	56.24	02:07:49	02:22:19	118.2	143.5
5	858	67.53	3032	95.74	63.36	01:18:40	01:47:11	79.3	110.9
6	128	73.19	355	89.65	71.27	00:53:31	01:06:54	58.3	68.9
7	572	63.68	3200	93.73	60.81	01:52:53	01:59:40	103.2	118.8
8	1404	49.68	6305	92.93	49.72	02:13:48	02:18:50	159.4	166.8
9	576	52.06	7815	92.07	51.63	02:01:21	02:12:20	149.1	160.6
10	4709	52.16	16372	91.87	51.62	01:24:32	01:32:02	104.4	122.1
11	5	74.00	118	87.41	75.42	01:14:50	02:08:56	75.2	156.5

Second we outline the major features of the population affected by each ~~landslide incident's~~ road network obstruction caused by landslides. This also is information gained from analyzing the ~~model's baseline scenario itself. As stated before,~~ Table 3 baseline scenario of the model. Table 2 shows selected incident sites with a broad variability in terms of average daily crossings, ranging from as little as 118 up to more than 16 000 daily car trips. Considering the results of the baseline scenario, both median duration and median distance of daily car trips as well as the share of mode car indicate a strong reliance on this transport mode. Depending on the location of the incident blockage points, about 50 – 80 % of all trips are were attributable to working persons. A consistently similar percentage can be was found for the employment rate of affected agents, allowing the conclusion of similar stratification regarding the variable of employment, which barely influences the modal share of car-use. The ratio of affected agents to car trips is was mostly around 3.5. Cases 9 and 11 ~~, which are difficult to model appropriately due to reasons mentioned before,~~ show strong deviations. According to the medians of baseline results, which are were used as robust indicators for comparing distributions, non-employed persons complete longer daily trips with respect to both distance and time.

As ~~a third aspect, we are interested in the~~ exemplary properties, age and employment status of agents within the total synthesized population affected by each incident are shown in Figure 4. The age range tails are trimmed to the data range. The

widths of the distributions are scaled to the absolute agent counts, therefore displaying relative numbers of affected individuals (see Table 1). Employment status was distinctly related to a specific age range.

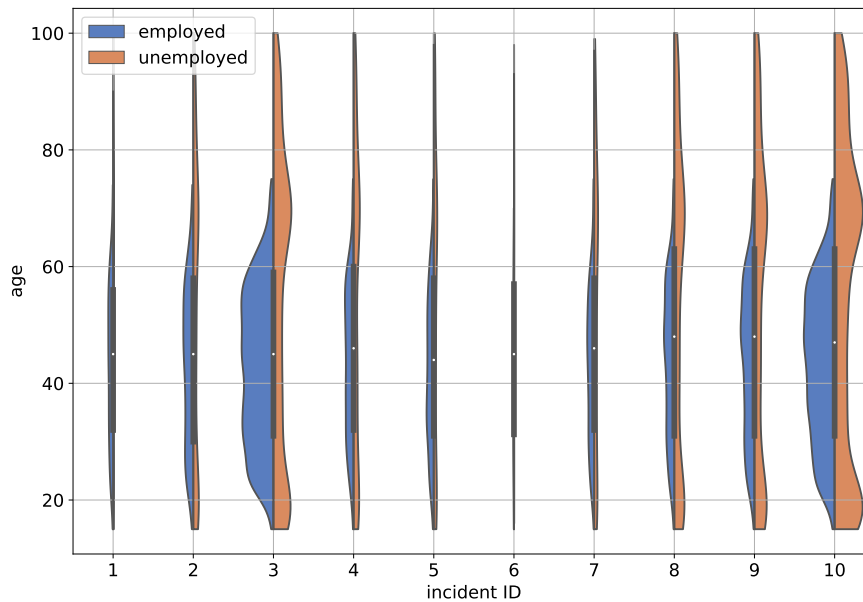


Figure 4. Kernel density estimates of the number of agents by age and employment status of agents affected by each incident.

As a third aspect, differential changes in travel patterns within the model were assessed. They can be analyzed by comparing the newly established traffic equilibria, which result from the interruptions occurring at the defined incident sites, against the baseline situation. In some situations the blockage of a non-redundant link can occur, meaning that no alternative routes are available, as is the case for incident 11. Here, it is of no benefit to run a traffic simulation on the modified road graph affected by the landslide event. All agents striving to cross the incident site would simply be marooned in a valley or be unable to reach it by car from the outside, respectively. In addition, there would be minor gains for all other road users due to slightly less traffic on the network. Results for all other incidents show a broad range of possible scenarios (see Table ??3) that might occur in case of network interruptions. The *detour length*, being the shortest alternate route length between the ends of the road links that were severed by the landslide, ranges from around 3 km up to 108 km. This distance is not necessarily reflected in the *evasion-diversion lengths* of actual car trips made in the simulation, because agents learn to give these interruptions an adequately wide berth, still striving to optimize their score. While optimized circumnavigation results in an increase of travel time across the board (*evasion-diversion time* > 0), our findings show that travel distance might actually decrease in some cases (*evasion-diversion length* < 0). This is attributable to the choice of lower priority alternate routes with smaller effective capacities (due to road-class road class and/or congestion) resulting in lower traveling speeds, yet shorter lengths. The quartiles were chosen to convey an impression of the distributions underlying the aggregated *evasion-diversion* quantities. Given the geographic situation in Vorarlberg, which is characterized by narrow valleys and mountains that serve as natural barriersthe

Table 3. Summary statistics of differences between each interruption scenario and the undisturbed baseline scenario, for both (10% and 30%) population samples. They are expressed in terms of quartiles of (additional) evasion-diversion lengths and times. For incident site 10, two individual stretches of road are affected (NE/SW), therefore two different detour lengths are indicated.

Incident	detour length [km]	incident scenarios: 10% sample						incident scenarios: 30% sample					
		diversion time [h:m:s]			diversion length [km]			diversion time [h:m:s]			diversion length [km]		
		q ₂₅	q ₅₀	q ₇₅	q ₂₅	q ₅₀	q ₇₅	q ₂₅	q ₅₀	q ₇₅	q ₂₅	q ₅₀	q ₇₅
1	16.4	00:05:41	00:12:10	00:22:34	5.04	8.18	13.01	00:08:07	00:12:02	00:23:34	6.27	8.94	17.01
2	50.2	00:14:47	00:31:48	00:52:06	14.71	21.80	46.10	00:15:53	00:25:14	00:44:55	12.00	20.92	38.81
3	11.9	00:04:05	00:07:02	00:10:21	7.28	9.79	17.06	00:03:20	00:06:15	00:08:53/	7.19	9.57	17.30
4	106.9	00:06:32	00:16:11	00:44:30	37.85	61.17	72.97	00:09:23	00:19:43	00:52:20	39.47	66.26	86.44
5	65.7	00:12:51	00:16:10	00:49:54	7.63	19.88	34.52	00:10:58	00:24:44	00:51:10	11.09	22.90	45.14
6	27.2	00:07:56	00:10:36	00:11:25	11.90	15.17	15.89	00:04:20	00:05:43	00:11:20	7.11	8.28	15.21
7	65.7	00:06:24	00:13:22	00:21:22	18.32	27.39	46.30	00:06:52	00:11:52	00:21:32	18.61	32.58	48.13
8	107.9	00:10:42	00:21:18	00:34:51	-30.52	-15.82	8.61	00:13:09	00:27:58	00:42:52	-22.90	-5.38	16.51
9	107.7	00:15:05	00:31:50	01:14:09	-21.62	-0.71	31.43	00:17:15	00:35:56	01:15:42	-17.98	3.64	37.22
10	9.6 / 2.6	00:02:38	00:04:01	00:05:31	0.79	1.42	1.79	00:02:30	00:03:10	00:04:16	0.84	1.68	1.77

study area, the closing of specific road segments often results in a dramatic-considerable increase of travel distances. This is illustrated by the examples of incidents 4, 8 and 9 where detour length exceeds 100 km as there are no parallel routes traversable at comparable utility score in the used-obstructed road network model.

Figure 5 shows relative evasion-diversion quantities, which are-were obtained by comparing the daily aggregates of every agent's trips for each incident scenario against their counterparts in the baseline scenario. A summary over all affected agents across all incident scenarios and both travel time and distance shows the median of relative quantities to increase by approximately 7%. Results show that up to two times the amount of initial travel time and distance is required for evading a majority of the modeled incidents. In some outlier cases, up to the sevenfold time and distance is spent making the agents' daily journeys by car. However, on exceptionally rare occasions (i.e. 3 out of 5 518 agents affected by incidents in the 30% sample) it can also be observed that daily travel time and distance decrease marginally ($\approx -0.2\%$) relative to the baseline scenario. This seemingly paradoxical phenomenon is explored further in the discussion. An obvious feature when comparing the employment status are the wider tails in the distributions of evasion-diversion costs for employed drivers, as indicated by taller boxes and longer whiskers. This attributable-to-is attributable peak traffic conditions due to occupational time constraints resulting in wider detour variations.

Utilizing the disaggregated population information retained in the data, we can investigate the spatial distribution of distinct consequences on the agents. In Figure 6 the agents' home locations are used as spatial references. The residences of affected persons are distributed differently for the various incidents, naturally. However, due to the mountainous landscape with habitation predominantly located in the valleys, incidents can have far reaching impacts for commuters who usually traverse the main traffic axes along those valleys. While the home location was chosen as a spatial reference in the shown visualization,

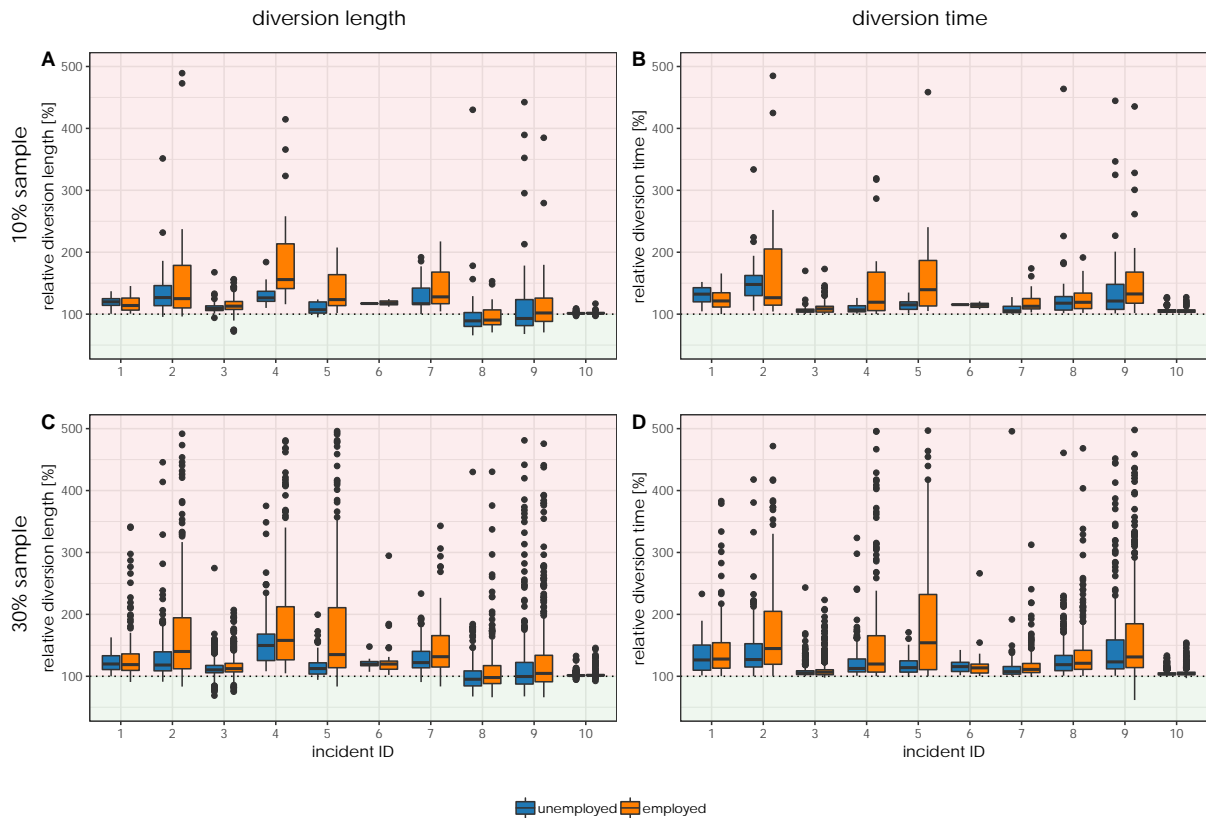


Figure 5. Relative changes of evasion-diversion length and evasion-diversion time with respect to the baseline scenario, resulting from landslide-induced network impairment. Boxplots in the upper / lower row show results for the 10 / 30 % sample, respectively. A discrimination of evasion-diversion costs between employed and non-employed agents is color-coded. Note that the y-axis has been limited at 500 % for better readability. Occasional outliers exist up to 700 % however do occur.

diversion times and distances can be spatially related to any other location connected to an agent's activity chain (e.g. main activity location, workplace location).

4 Discussion and conclusion

5 This study examined the different impacts of landslide-induced road network interruptions on communities in a rural area in the European Alps. In general, road network systems are highly complex – most notably regarding their socio-economic effects on communities. Alpine areas are particularly vulnerable to such interruptions and changes. Firstly, this is based on their topography. Mountain regions are usually prone towards natural hazards events, often lacking the feasibility to build a redundant transport system. Secondly, because of their socio-economic properties, mountain regions are strongly dependent on

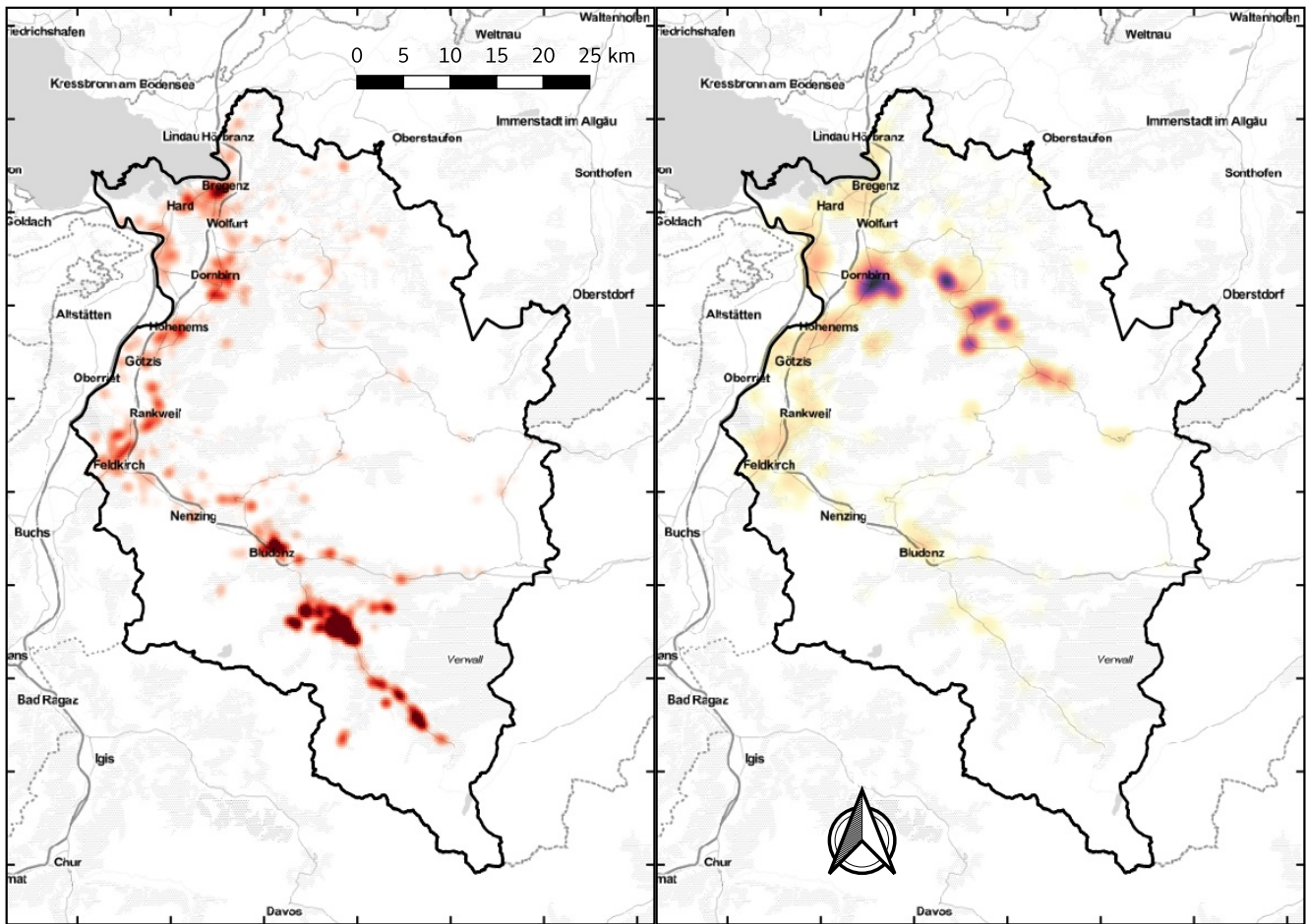


Figure 6. Spatial distributions of home locations of persons affected by incidents (based on the 30 % sample). Left: Home location density of affected persons for incident 10. Right: Relative diversion times for incident 3 (delay over total daily travel time – c.f. Figure 5) inscribed at each person’s home location (darker means greater accumulated diversion times).

the established road network (i.e. dependency on tourism and high numbers of commuters). This implicates a political debate on the question of how to manage mountain road network systems.

4.1 Landslide modeling

~~Our efforts to refine the official~~

- 5 A WoE approach relying on occurred events and various geophysical properties as input data was applied in order to obtain a refined landslide susceptibility map of Vorarlberg by using additional input data in a WoE approach revealed some substantial for the study area.

Results of the landslide susceptibility assessment showed a clear quality improvement over preceding efforts, which was mainly based on geological data. The inclusion of additional input parameters as well as an increased spatial resolution provided added value in comparison to the currently available governmental landslide susceptibility map ('Gefahrenhinweiskarte') of Vorarlberg. However, efforts undertaken within the modelling procedure revealed some shortcomings in the data basis. The quality of the distribution of the recorded events in the landslide inventory appears to be a major impediment for obtaining an enhanced susceptibility map. In order to achieve a satisfying result, an-

Both an accurate landslide inventory and precise geological information at a high spatial resolution substantially supported the modeling approach, as already successfully shown for other provinces of Austria, such as Lower Austria (Petschko et al., 2014), Styria (Proske and Bauer, 2016) and Burgenland (Leopold et al., 2017).

In terms of spatial consistency of the landslide inventory data, events were not equally distributed across the study area. This is reflected by obvious disparities in data density, which are attributable to different perception and documentation in different municipalities. Landslide events were either mapped spatially distributed (e.g. Blons, St. Gerold) or aggregated to spatial event clusters (e.g. Laterns, Fontanella). In some municipalities, significant underreporting of events (compared to neighboring municipalities) was evident. Hence, municipalities within the same geological sub-units showed substantially different results in the quality of landslide reporting.

In addition, landslide events were only represented as point data inventory, including only an additional tag referring to location accuracy ('exact' vs 'inexact') without any consistent additional information on landslide localization or extent. Literature research and archive data were cited as main data sources for data acquisition, while sources for several events (approx. 15%) were entirely missing in the dataset. Hence, acquisition and reporting of events did not seem to be performed in a consistent way across the whole province.

An area-wide mapping of landslides (points and/or polygons of i.e. delineating polygons of landslide extent based on ALS very high resolution DTMs and optical satellite images) is considered to be a crucial data base for modeling purposes (Zieher et al., 2016; Petschko et al., 2013b). Furthermore, Even though we established such a dataset, leading to a quality improvement of the landslide susceptibility map, there is a demand for (i) an area-wide objective assessment and mapping as well as reporting of landslide events, still room for progress. Landslide verification by means of visual interpretation of DTMs and ortho-images rarely shows clear evidence of landslides (Petschko et al., 2015). Main issues identified during the modeling procedure were related to inventory incompleteness (e.g. underreporting, especially of smaller events which may be fixed quickly by local authorities or farmers), biases (spatial distribution of events, including a subsequent addition of these events into the landslide inventory, and (ii) consistent information about meta-data-

The quality of the geological map—which is another major input factor for modeling landslide susceptibility—forms another obstacle. The area-wide map used in has a scale of 1:100 000 and is thus highly generalized, therefore providing rather coarse information. Geological maps in a scale of 1:50 000 are only available in small parts of e.g. across administrative boundaries) and inaccurate localization (including the extent). In order to address these issues, a substantial amount of resources (for the reconstruction of historic events using multiple archive data and a subsequent mapping of all events using high-resolution geo-data) would be required. The extent of these efforts has recently been illustrated by Schmaltz et al. (2017), who built up a

~~comprehensive inventory of events for a comparably small area within~~ the province of Vorarlberg. ~~Moreover the official hazard map is mainly oriented on the main geological units, e.g. alluvial depositions in the valley bottom are not depicted exactly, therefore the geohazard information shows some uncertainties. Both an accurate landslide inventory and precise geological information at a high spatial resolution will substantially support the modeling approach, whose applicability and added value over coarse susceptibility maps was already successfully shown for other provinces of Austria, such as Lower Austria (Petschko et al., 2014), Styria (Proske and Bauer, 2016) and Burgenland (Leopold et al., 2017)~~

At the same time, the landslide mapping process revealed the importance of an accurate polygon delineation when working on large scales. Our findings showed that landslide events recorded in the inventory are not located in the centroid of landslide areas, but rather at the specific location where damage was reported (e.g. at landslide scarp or toe).

10 4.2 Traffic impact assessment

Regarding the application of an agent-based traffic model for assessing the impacts of landslide-triggered road network interruptions in a rural alpine area, our findings ~~comprise several notable aspects. highlighted several issues:~~

Generally speaking, medians of total daily car travel times and distances ~~appear appeared~~ to be rather long (Table 2). ~~Considering the background of spatial planning and topographical structure in the area shows that this is nothing out of the ordinary. Agglomerations and activity centers 1), which is a result of the topography in the study area and the related limitations in spatial planning alternatives. Agglomerations~~ are mainly located either in the Rhine valley or its tributary valley, the Walgau, which ~~entails results in~~ long driving routes for commuters ~~in inhabiting~~ remote areas. ~~Furthermore, winter sports centers were found to be slightly underrepresented n the results for two reasons: Firstly, only data about the local population was available from mobility surveys. Secondly, a generic average weekday was modelled, thus seasonal effects were levelled out.~~

It also can be observed that total daily trips of employed agents ~~are were~~ shorter than those of the non-employed – as far as both daily travel time and daily travel distance are concerned (Table 21). This ~~is can be~~ explained by the daily schedules of the non-employed agents who fulfill various chores which shows in the consistently smaller percentage of car trips by employed agents compared to the employment rate. The occasional extra car-trip by non-employed agents ~~eovers the resulted in~~ daily travel differences of ~~≈ 5 — 10 approximately 5 – 10~~ %.

Concerning ~~evasion diversion~~ effects as shown in Table 3, ~~it is interesting to note that evasion times are 2, diversion times were~~ sometimes surprising when paired with the corresponding quartile of ~~evasion length. Here it has to be noted that a diversion length. A~~ small increase in travel time can still be accompanied by a ~~longer larger~~ increase in travel distance, given the choice of an appropriate high speed (and capacity) road. For incidents with shorter detour length (Table 32) the inter-quartile range ($q_{75} - q_{25}$) of ~~evasion diversion~~ times tends to be reduced in the 30 % sample when compared to the 10 % sample, while for the incidents with long detours (i.e. incident 4, 8 and 9) there is an opposite tendency. The source of these small effects is yet to be explored in detail, but it ~~most likely is is most likely~~ due to the ~~greater higher~~ number of agents required to spread out over a wider area of the network, thus causing network loading effects in the simulation which are not fully compensated by the population-equivalent scaling of road capacities.

Our results indicate that employed agents in general ~~are-were~~ more affected by network interruptions, for the medians of relative ~~evasion-diversion~~ costs being mostly higher (Figure 5). As it is the case with the ~~mentioned~~-wider-tailed distributions of ~~evasion-diversion~~ cost for employed agents, this ~~most likely stems from is due to~~ stricter time constraints in terms of working hours, entailing that the employed agents are more prone to congestion effects caused by rush hour traffic peaks.

A somewhat paradoxical situation ~~emerges-emerged~~ at incidents 8 and 9, where results show negative ~~evasion-diversion~~ lengths compared to the baseline scenario. Such effects ~~likely occur when it becomes necessary occurred when agents were forced~~ to use roads featuring a lower functional road class (~~which feature due to~~ lower speed limits, or at least lower effective speeds) than in the baseline scenario, thus entailing shorter travel distances but longer travel times. For instance, instead of using the highway S16 to cross incident link 9, agents ~~have-had~~ to use rural roads between the two corresponding highway junctions, which ~~can lead led~~ to a decrease in travel distance at the expense of a corresponding increase in travel time.

Even though ~~evasion-diversion~~ times show consistent overall increases, there ~~are-were~~ sporadic cases where both travel time and distance ~~decrease when contrasted decreased in comparison~~ to the baseline scenario. ~~It has to be noted These cases,~~ however, ~~that these cases are extremely rare and well within a realistic scenario were extremely rare~~. The establishment of a new user-equilibrium on the road network can – for very few agents – sometimes result in better individual outcomes under ~~worse overall circumstances worsened overall conditions~~.

~~It can be observed that the~~ ~~The~~ models for the disturbed situations ~~show-showed~~ shifts in agent trip start and end time. This indicates that agents naturally learn to e.g. adjust their departure time to reach their offices in time. However, no general patterns can be derived from these observations, as these adjustments vary strongly between ~~single-individual~~ agents.

However, results have to be interpreted under consideration of several limitations. ~~It has to be noted that Because~~ the points of interest within the daily plans of agents ~~are static- Consequently were static~~, the re-planning procedure so far ~~does-did~~ not include re-assignment to substitute facilities. This may not appropriately reflect reality since it is very likely that – in case of activities where alternative facilities exist – people would adjust their ~~evasion routes accordingly. They would diversion routes accordingly, such, as,~~ for example, ~~do their grocery shopping at a different and more accessible supermarket locations shifting shopping activities to better accessible locations~~.

~~Despite the quantitative similarity of the traffic simulation to actual traffic measurements of an investigated area might always be improved upon (which often is the case for comparable mathematically ill-defined problems), its informative value can still be derived from a comparative analysis as demonstrated in this work.~~

~~In the case of For~~ the employed traffic model, the reasons for deviations from traffic measurement data ~~are the following- were the following~~: Firstly, our model only considers trips by inhabitants of ~~Vorarlberg the study area~~. Consequentially, cross-border traffic from both people commuting from outside (e.g. Tyrol, Germany, Switzerland) to Vorarlberg as well as transit through Austria are not taken into consideration. While this restriction has less effects in rural areas ~~in the alpine region~~ (where many of the considered incidents ~~are-were~~ located), effects will get more pronounced in areas next to a (~~national~~) border or on highways with high volumes of transit ~~traffic~~ (see Table 21). Secondly, distortions may arise due to an unavoidable temporal

mis-alignment of utilized data sources. While the underlying mobility household survey that serves as basis for the MATsim model was conducted in 2013 (Herry et al., 2014), the available traffic counts refer to the year 2016.

~~This study examined the different impacts of landslide-induced road network interruptions on communities in a rural area in the European Alps. In general, road network systems are highly complex — most notably regarding their socio-economic effects on communities. Alpine areas are particularly vulnerable to such interruptions and changes. Firstly, this is based on their topography. Mountain regions are usually prone towards natural hazards events, often lacking the feasibility to build a redundant transport system. Secondly, because of their socio-economic properties, mountain regions are strongly dependent on the established road network (i.e. dependency on tourism and high numbers of commuters). This implicates a political debate on the question of how to manage mountain road network systems.~~

~~Despite several limitations, the efforts undertaken in this study can offer valuable guidance for decision makers, by providing a sound estimation of likely implications of landslide-triggered road network interruptions on local communities. In particular, information on the number of affected people, their employment status as well as their associated costs (in terms of both time loss and evasion length) can serve as a basis for gauging possible adaptation and protection measures in a broader context. Additionally, such findings can contribute to decision making by prioritizing such measures in line with budgetary constraints. Supplying decision support on where and how to efficiently and effectively allocate limited resources is beneficial for the whole society. It enables tackling the impacts of adverse weather events and natural hazards by means of appropriate measures.~~

In this paper we have shown that agent-based traffic modeling allows to gain interesting insights into the impacts of road network interruptions on the mobility behavior of affected communities by modeling their responses to network disturbances. The detailed representation of single agents in the transport model allows for optimizing certain characteristics of agents (e.g. time of departure, route choice, activity list, etc.). Generalized costs of interruptions (i.e. monetary costs, time losses, etc.) can be obtained by employing a utility function to the agents' resulting behavior.

Choosing a feature-enriched description of the basic population within the area of interest – as it becomes possible by use of increasingly fine-grained data over the recent years – allows to derive a very detailed picture of changes effected by systemic disturbances. These details can be any combination of socio-demographic or spatio-temporal characteristics which pave the way for more precise decision making and implementation of guiding measures. Therefore, the MATSim implementation is considered to be ~~particularly~~ suitable for providing ~~a~~an agent-based analysis of expected impacts on changes in the traffic system.

Our findings ~~are meant to~~ may also provide a basis for future work in this area, which should expand the limits of the present study by incorporating transit and cross-border traffic and might shed more light on traffic displacement effects. Moreover, further work could be devoted to the economic analysis of interruption costs.

While this study has explored road network vulnerability against the background of landslide susceptibility, the presented methodology is easily transferable to other (natural) hazards that might cause network interruptions, such as e.g. avalanches, floods, or terrorist attacks.

Despite some limitations, the efforts undertaken in this study can offer valuable guidance for hazard managers and decision makers by providing a sound estimation of likely implications of landslide-triggered road network interruptions on local

communities. In particular, information on the number of affected people, their employment status as well as their associated costs (in terms of both time loss and diversion length) can serve as a basis for gauging possible adaptation and protection measures in a broader context. Additionally, such findings can contribute to decision making by prioritizing such measures in line with budgetary constraints. Supplying decision support on where and how to efficiently and effectively allocate limited resources is beneficial, and it enables tackling the impacts of adverse weather events and natural hazards by means of appropriate measures.

Data availability. Special emphasis was put on using open data and open source software wherever possible. All openly accessible data sets used are listed in the following: The official road graph of Austria is available via the Austrian Graph Integration Platform GIP at <http://gip.gv.at/> (GIP, 2018). Additional geodata can be found at the geographic information system of the federal government of Vorarlberg, accessible via <http://vogis.cnv.at/> (VoGIS, 2018). The governmental landslide susceptibility map as well as historic event data can be accessed through the HORA (Natural Hazard Overview and Risk Assessment Austria) platform at <http://www.hora.gv.at/> (eHORA, 2018). The routing graph is based on an OSM data extract from <https://download.geofabrik.de/europe.html> (OpenStreetMap Contributors, 2018). The landslide susceptibility map is available as a supplement to this paper.

Apart from the traffic simulation, which was implemented in MATSim (Horni et al., 2016), all data preparation, processing and visualization has been done in **R** (R Core Team, 2018) using the tidyverse framework (Wickham et al., 2018), in Python (Python Core Developers, 2018) with its scientific tool stack SciPy (Jones et al., 2018), and in QGIS (QGIS Development Team, 2018).

Competing interests. Sven Fuchs is a member of the Editorial Board of Natural Hazards and Earth System Sciences. Otherwise, the authors declare that they have no conflict of interest.

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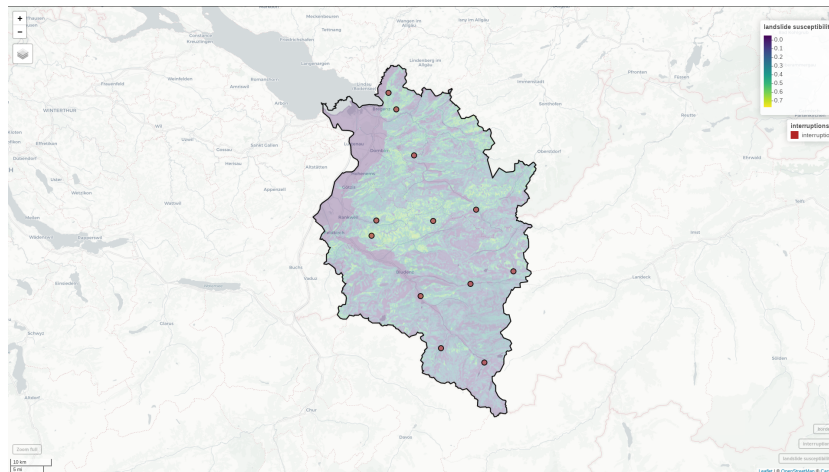
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Supplement 1: Interactive map 1

Interactive map (Leaflet) of the study area, including the calculated landslide susceptibility and the location of the incident sites over several different basemaps.



Supplement 2: Interactive map 2

- 5 Interactive map (Leaflet) of the study area, showing the home locations of all agents affected by any incident (based on the 30 % sample) over several different basemaps.

