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Discussions

Interactive comment on "Landslide susceptibility near highways is increased by one order of magnitude in the Andes of southern Ecuador, Loja province" *by* A. Brenning et al.

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We thank the anonymous referees for providing thoughtful, constructive and detailed comments on our manuscript. We have improved out manuscript based on these comments and are pleased to present our point-by-point responses, which we hope will satisfy the referees and editor. In general terms, the main changes we made to the manuscript include the following:

- Quality of the landslide inventory is described in more detail, indicating that field-mapped and air photo based inventories are consistent with each other and not subject

to bias.

- The issue of land use versus highway effects is discussed in more detail. While we agree that this is a valid concern, we believe that we have good reasons to believe that land use does not distort our results.

- More detailed information on geology has been included.

Please find the detailed authors' responses (AR) to the comments of Referee #1 (RC) below.

RC: This manuscript on landslide susceptibility uses advanced statistical methods to analyze the landslide hazard along roadways. GLM and GAM models are fitted to the data to detect the environmental and anthropogenic variables that are strongly associated with the landslide occurrences. The authors strongly emphasize the increased landslide hazard after road building. Although this result is not particularly surprising or novel, the robustness of the statistical methods is certainly exemplary in this work. Before publication, I would suggest the authors to address the following issues:

AR: We would like to thank the referee for these observations. We would like to note that, while road construction is known in general as a risk factor especially in developing countries and in forest areas, little is known on the magnitude of its effect on landslide occurrence in absolute terms or relative to other preparatory factors in tropical regions. In our view, quantification of highway-related effects at the landscape scale allows for an improved resource allocation in infrastructure planning compared to more qualitative assessments.

RC: (1) The landslide database is now compiled with data from field observations (from 2010, landslide close to the roads) and airphoto interpretation (2000, for landslides far from the roads?). As far as I can understand from the text, these two datasets are then merged into one dataset for statistical analyses. It is not entirely clear if the two landslide inventories derived with completely different techniques (and with different spatial resolution?) are entirely compatible, and I would like to see a discussion on this.

AR: We thank the author for carefully considering data quality issues, and we agree that additional information is required in our manuscript, which has now been added. We have been taking this possible source of bias seriously since the beginning and re-assessed it for this discussion.

A careful re-examination of our data indicates that only 47 landslides that are not visible in the air photo are included in the final, combined inventory. Thus, there were only 47 'new' landslides (in addition of course to numerous landslides that were reactivated since 2000).

Since the air photos have a 1:5,000 scale (or 1 m x 1 m resolution as a digital orthoimage) and only landslides >100 m2 were considered for statistical analyses, we also consider that scale and resolution of field mapping and air photo analysis are consistent. Muenchow et al. (2012) suggested that the available imagery is suitable for practically complete mapping of landslides >100 m2

Overall, we are therefore confident that the combination of field-assisted mapping and additional air photo-based completion of the inventory within the 300 m buffer did not introduce a bias in our data set and analysis, and we hope that the referee is satisfied with our assessment. The additional information provided in this response has been added to the revised manuscript.

RC: How do you correct for the fact that there were major road works in the area during this time period (2000-2010)?

AR: Overall, there is always some construction work in some portion of the highways studied here due to heavy downpours, poor engineering design and oversteepened slopes. Hence, roads are constantly cleared from the latest landslide residues since their very existence (1960s). Since these efforts appear to be comparable throughout

the study area, we did not attempt to account for them. However, as pointed out by the referee, the Ecuadorian government has indeed set up a program to modernize the road network in Southern Ecuador. In 2010, the road renewal overlapped partly with our field research. Given that these modernization measures focused on already existing roads, there is little reason to believe they might have further increased landslide susceptibility. By contrast, the government tried to install preventive measures. Hence, our study provides even a baseline to assess the effectiveness of these measures in the future (see end of section 4.2).

RC: How do you map the spot of landslide initiation during fieldwork, given that most of the landslide affected areas are extremely steep and still unstable?

AR: We noticed that the previous version of the manuscript did not contain information on the extraction of landslide initiation points from the digitized landslide polygons. This information has been added to section 2.2. Landslide initiation points were selected manually in the central part of the uppermost portion of each digitized landslide polygon.

RC: (2) The representation of the geological data in this analysis is rather weak, and should be improved to say something meaningful on geological hazards.

AR: We agree that the geological data available for this study is rather limited, and will reply to the individual specific comments point by point. However, we would also like to point out that the primary goal of this study is to examine the relationship between highways and landslide occurrence.

RC: First of all, lithological strength (internal cohesion, friction angle, etc.) affects slope stability and you would expect to see a reclassification of the raw geological data into 'lithological strength classes' or similar.

AR: We agree with the referee in that a re-classification of geological units according to geomechanical properties would be desirable. However, this would imply a further aggregation of the available five classes into more general categories. We do not think that this is necessary given the comfortable size of our data set, which allows us to investigate possible differences in landslide susceptibility among these geological classes without making prior assumptions.

RC: Second, the authors have used old geological maps (1975) of the area to characterize the bedrock geology. The geology of Southern Ecuador has been revised by the British Geological Survey in the 2000s, with a completely revised classification. Why is the new geological data not used in this work?

AR: While we have not been able to access more recent geological maps through a variety of library catalogs, maps included in the publication of Litherland et al. (1994) are 1:500,000, which would not provide sufficient geometric detail for our study. Also, since general information on rock types seems more relevant in the present context than a precise stratigraphic classification, the descriptive information provided by the Ecuadorian geological maps at a 1:100,000 scale seems to be adequate for our purposes. Since the mentioned BGS maps don't seem to be available or known to the DFG collaborative research project to which this research was connected, we would appreciate if the reviewers could provide additional bibliographic and/or access information for the post-2000 BGS maps in order to ensure that future research within the DFG network will benefit from these map products.

RC: Can you rather give the name of the Formation and the Period (instead of numbers which are not very instructive)?

AR: Where possible, we completed the geological information (period and formation). Moreover, we renamed the five geological classes as follows: - class 11: metamorphic rocks - class 12: plutonic rocks - class 13: volcanic rocks - class 1: sedimentary rocks - class 2: unconsolidated sediment

Please note also that we included more geological details on the main units in section 2.1 (strike, dip, and prevailing joint system). Figure 1 was also modified to show geological units along the highways, and numbers were replaced with unit names in figures 3 and 4.

RC: (3) The authors currently make abstraction of any potential impact of vegetation (land use, housing) on slope stability. It is well known that the land use pattern is strongly controlled by the road network, and that land use change can control landslide susceptibility. Areas close to the roads typically have agricultural fields, pastures, farmhouses, staples and irrigation canals; that can all enhance landslide susceptibility. So, it is not uncommon that part of the enhanced landslide susceptibility close to the road network is not directly caused by road construction but rather by land use change.

AR: We agree that highway-related effects may, in principle, include indirect effects, even though we made efforts to eliminate the most relevant confounding effects. The revised manuscript addresses this more explicitly (please refer to subsection 4.1). Nevertheless, we will try to explain why we are confident that our estimated highway-related effects have not been confounded with (other) land use effects, as suggested by the referee:

Urban areas were masked from the study area, thus avoiding any major influence of human-made structures other than the road. In particular, agricultural fields are located in our 'urban area' polygons and/or on gentle slopes and in the valleys, which are not subject to landsliding. The 300-m buffer around the road ensures that remote, inaccessible, natural areas are not included in the analysis. Two of the authors (J. Muenchow and M. Schwinn) have detailed knowledge of land use conditions throughout the study area, according to which there is no major (distance-related) land use gradient within the 300-m buffer, and in particular not within the 150 to 200 m within which the hazard susceptibility decrease is concentrated according to our analysis (see also Fig. 2a,b from different parts of the study area). Thus, while land use has indeed changed as a consequence of road construction, highway effects are estimated under roughly equal land use conditions near the road and more distant from the road.

RC: (4) There is some inconsistency in the number of landslide events that was used in the analyses. In the data section, the authors mention 2185 slides, while on p. 1953 they mention 2106 mapped slides. Please clarify.

AR: Thanks for pointing this out - this is due to the application of exclusion criteria. In addition to the removal of landslides <100 m2, which is already mentioned on P1953L1-2, we added: “and landslides located in urban areas or with missing data in one of the predictors were furthermore omitted.” The discrepancy is also made more visible by writing “2106 out of the 2185 mapped landslide initiation points.”

RC: (5) The statistical models were evaluated based on the AUROC and ROC curves. It is not entirely clear why the authors opted to use all the LS points for the calibration of the empirical models, and not a subset of 40 to 60% of the data. The latter would make an external validation possible.

AR: Cross-validation was used to assess the models’ predictive performance, or to “validate” these models. This approach is statistically superior to using (e.g.) 50% of the data for validation and 50% for calibration since the latter procedure (1) does not account for sampling variability and (2) unnecessarily reduces the size of the training sample. See e.g. Brenning (2012a in ISL/NASL proceedings) for additional motivation and manuscript section 2.3 for further details on cross-validation in this study.

RC: (6) At the end of section 4.2 (p. 1958, L. 3-19), the authors make some statements of the mechanical effects of road building on landslide susceptibility. A multitemporal analysis is needed to bring more insights. I would suggest to remove the two last paragraphs of this section, as they are not based on hard data nor statistical analyses.

AR: We consider this paragraph important as it discusses possible relationships between highways and landslides, which may further be modified by other human activities and known differences in vegetation response to such disturbances. The temporal evolution of landslides is, as far as vegetation is concerned, just a different aspect of vegetation succession as discussed by the cited studies of Muenchow et al. (2012) and

in particular Richter (2009) in the same general study region. These studies are indeed based on multitemporal landslide inventories and detailed field observations, although they are more local in scale. In this discussion, we consider it important to relate observations in the time domain (Richter, 2009) to our current findings in the spatial domain, which puts increased observation of landslide-affected terrain in proximity to highways into perspective.

We furthermore agree with the authors that additional – future – statistical analyses are needed in order to assess the effectiveness of specific road design features, as expressed on P1958L15-19, which does not contain specific claims regarding the effectiveness of current modernization efforts by the Ecuadorian government. We believe that the last short paragraph reflects the referee’s call for multitemporal analyses and would therefore prefer to keep it as is if the editor agrees.

RC: P. 1946, L21: Rephrase ‘technological denudation’

AR: Changed to “anthropogenic denudation”.

RC: P. 1947, L. 29: Rephrase. What do you mean with ‘empirical effect of highways’

AR: We understand that this wording is less common in the landslide literature than in other fields of empirical research and therefore appreciate the referee’s comment. “Empirical effect” refers to the empirical difference in the outcome of interest (landslide occurrence) between areas affected by highway construction and areas that are not affected by highways, under otherwise equal conditions. To avoid this wording while maintaining the emphasis on the empirical nature of our comparison, we rephrased the sentence as follows: “. . .in order to empirically estimate the effect of. . .”.

RC: P. 1948, L. 6: Delete ‘two’ before ‘paved’

AR: Changed as requested.

RC: P. 1948, L. 14: Can you really speak of the western escarpment here? Is this part not just draining to the InterAndean Valley, and not corresponding to the Western

Escarpment of the Andean chain?

AR: Changed to “west of the main divide”.

RC: P. 1948, L., 16: Rephrase. I would not consider 400mm of annual rainfall as something ‘extremely dry’

AR: Deleted “extremely”.

RC: P. 1948, L.20-24: A geological map is needed with clear delineations of lithological units. Also, I would suggest to add the names of the geological Formations to avoid confusion.

AR: We added a geological reference to Fig. 1. The names of geological formations were also added in section 2.2.

RC: P. 1948, L. 24: Rephrase, as land use is always the result of human activity

AR: Deleted “Human”.

RC: P. 1948, L. 25: Rephrase: ‘converted into pasture’

AR: Changed as requested.

RC: P. 1949, L. 1-3: The authors mention that the protected areas are not located in the study area. I can agree for the Podocarpus National Park, but what about the ‘ECSF’ (Estacion Cientifica de San Francisco’)? This is indicated on Fig. 1, but there is no reference at all in the text.

AR: We appreciate this comment and added one sentence to the text accordingly (section 2.1). The part of this reserve that overlaps with our study area is, however, not natural rainforest but mostly subject to deforestation and land use.

RC: P. 1949, L. 27-28: What do you mean here with ‘catchment slope angle’ and ‘catchment area’? Is this the contributing area to a landslide initiation point? If so, clarify and rephrase.

AR: Changed to “(upslope) contributing area” and “catchment slope angle”, respectively, throughout the manuscript. This is now consistent with Wilson & Gallant (2001, Terrain Analysis, p. 7).

RC: P. 1950, L 1-5: The authors state that catchment area is a proxy for soil moisture and soil depth. I can see their point for soil moisture, but not really for soil depth. Can you clarify?

AR: We suggest that locations at the foot of a hillslope (especially one with a convergent cross-profile), which tend to be less affected by slope erosion and more likely present colluvium, may be expected to be associated with large upslope contributing areas. While these relationships may vary from one area to another, and local empirical evidence is not available for this study region, we believe that this expectation is consistent with general hillslope processes. No changes made.

RC: P. 1951, L 1-3: The authors mention that most of the area is not pristine land cover. I assume that land use conversion also has a major effect on landslide susceptibility. Why is this not analysed? In how far, can you make abstraction of the presence of ECSF being a pristine or semi-natural protected area in the mid of the study area?

AR: We agree with the referee that different types of land use might have major effects on landslide susceptibility. However, despite the drastic climatic gradient within our study area, land use is fairly homogeneous along the roads, i.e. pasture. The most abundant grasses are frequently the same on both sides of the climate divide (Melinis minutiflora, Setaria spe., Pennisetum spe.). As the difference in land use is pretty limited, we saw little reason to include land use in our analyses. The land use pattern holds also for the ECSF as the protected area only begins south of the Río San Francisco. North of the river, there are pastures and converted/degraded areas. Nevertheless, a small number of landslides (15) that were included in our analysis fall within the protected areas. Naturally, these <1% of the landslides included in our analysis do not have an influence on our analysis results.

RC: P. 1952, L. 20-23: Explain ‘bivariate loess smoother’ in one sentence.

AR: Added the following sentence: “These smoothers estimate, for any given combination of values of the two predictors involved, its contribution to the logit, while accounting for the other predictors in the model.”

RC: P. 1953, L. 9-12: The cluster analyses on the point coordinates is not clear to me. What is the meaning of this? What do you finally get as clusters?

AR: This is perhaps a misunderstanding. In this study, a clustering technique is only used in order to partition the study area into disjoint sub-regions that are used for spatial cross-validation, as explained in the manuscript. The intention is not to analyze the potential presence of clusters, nor to attribute any meaning to the clusters that we deliberately construct. We therefore tried to avoid the word “clustering” as much as possible, referring to the process as “partitioning” of the study region and data set. The partitions are more or less equally sized polygons (represented by the points that belong to these polygons) whose union equals the study region.

No changes made.

RC: P. 1954, L. 10: Give some more details on the landslide magnitude-area distribution of the landslide inventory. The big landslides seem to be more than 100m long (so with initiation point outside ‘high hazard zone’?)

AR: The majority of the landslides are smaller than 4267 m^2 (3rd quartile; additional size information given in section 3.1, Landslide characteristics). In Fig. 5 of the revised manuscript, there is one large landslide west of the ECSF whose initiation point would be outside of the most susceptible landslide zone. Given the large number of landslides and the probabilistic nature of these events it is of course possible that landslides – small ones as well as larger ones – occur in the low susceptibility areas.

The referee’s comment in parentheses seems to suggest a possible bias, or perhaps a model misfit, if we understand correctly. However, big landslides may equally be

located near the highway or distant from it, or have their initiation point outside the study area and reach inside it or vice versa. Based on this, we do not believe that the referee’s observation is reason to believe that the model is biased or misfit.

RC: P. 1954, l. 20 and following: Give the p-values and number of observations to see if these values are significant

AR: Our overall goal for the exploratory analysis section was to focus on the strength of association among predictors while avoiding much technical detail. Also, as suggested on page 1953, first paragraph, inferential statistics are not straightforward in the possible presence of spatial autocorrelation. We therefore used spatial bootstrapping to obtain confidence intervals where it mattered most (confidence intervals for odds ratios), while we refrained from reporting confidence limits or P-values in the exploratory analysis section. Sample size is 2106 + 4177 (page 1953 line 27-28 of original manuscript), which would almost inevitably lead to small P-values (if spatial autocorrelation is ignored). Rejecting null hypotheses of zero correlation would likely provide little additional insight.

No changes made.

RC: P. 1955, L. 1-3: What is the physical meaning of having higher susceptibility for steeper catchments and higher elevations?

AR: Possible causal mechanism – physical as well as anthropogenic ones – are discussed in the Discussion section in order to focus the Results section on the presentation of empirical analysis and modeling results. One possible interpretation of the importance of catchment slope is related to mechanical destabilization due to overloading (P1959L8-9 of original manuscript), while the importance of elevation is discussed on P1960L7-12 of the original manuscript. It should, however, be noted that the focus of this study was on determining the empirical effect of highways, and therefore these additional predictor variables are included in the model mainly to avoid confounding.

No changes made.

RC: P. 1957, L 1-20: There exists more work on the effect of roads, paths and human infrastructure on landslide hazards and sediment mobilization rates. It would be good to see a broader discussion.

AR: We conducted additional literature searches and added relevant information to the discussion section 4.1. However, much of the published literature on landslides and roads is related to landslide hazard assessment for highway planning, or on road protection and landslide risk (e.g., Winter et al., 2013; Jaedicke et al., 2014). Literature quantifying the effects of roads (including some of the literature cited in our work) is often limited to forest roads (presumably unimproved service roads) in humid temperate climates, which is quite different from provincial highways in tropical mountains in a developing country. We decided not to discuss road-related erosion rates in this study since we did not produce comparable data. Please refer to Muenchow et al. (2012) for estimates of material mobilization by landslides in climatically contrasting parts of this study region. Finally, much of the literature presenting empirical assessments uses descriptive data summaries or bivariate techniques such as weights of evidence or frequency ratios, which do not provide estimates of effect size that would account for confounding with other environmental conditions, or distance to road is modeled linearly despite the expected nonlinear relationship (e.g., Devkota et al., 2013).

Overall, we added further information and two references to section 4.1 in response to the referee's request (Das et al., 2012; Miller and Burnett, 2007).

Devkota, K. C., Regmi, A. D., and Pourghasemi, H. R., et al.: Landslide susceptibility mapping using certainty factor, index of entropy and logistic regression models in GIS and their comparison at Mugling–Narayanghat road section in Nepal Himalaya, Natural Hazards, 65, 135-165, 2013.

Jaedicke, C., van den Eeckhaut, M., and Nadim, F., et al.: Identification of landslide hazard and risk 'hotspots' in Europe, Bulletin of Engineering Geology and the Environment, 72, 325-339, 2014.

Winter, M. G., Harrison, M., Macgregor, F., and Shackman, L.: Landslide hazard and risk assessment on the Scottish road network, Geotechnical Engineering, 166, 522-539, 2013.

RC: P. 1958, L. 24 and following: This section on the geological control of landslide susceptibility is not clear, and even a bit confusing. It would certainly help if the authors would rather use lithological strength and reclassify the geological maps.

AR: The paragraph was edited for improved clarity. Reference to regression dilution bias was removed. Reclassification according to geomechanical material properties seems difficult and would lead to further aggregation into more general geological units (see response to comment (2) above).

RC: P. 1960, L 1-5: It is suggested that the rainfall amount is not a good proxy for rainfall-triggered landslides, as rainfall intensities can be high in semiarid climates. Some hard data are needed to back up these statements, with some reference data on rainfall intensities.

AR: We agree with the referee and would like to point out that this is what we discuss on P1959L24 – P1960L1, referring the reader also to Muenchow et al. (2012), who analyze the very limited available rainfall data from the study region. Unfortunately, not only are precipitation time series too short, but meteorological stations are also too scattered in this region with extreme climatic differences in order to represent spatial variation in high-intensity rainfall patterns in a more meaningful way.

While better rainfall data is not going to be available anytime soon, our study design, however, ensures that this poorly observed triggering factor does not bias the estimation of highway-related effects. This is because (obviously) highway distances from 0 to 300 m are achieved throughout the entire study area and therefore independently of the frequency of high-intensity rainfall events.

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