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Discussions

Interactive comment on "Sensitivity analysis and calibration of a dynamic physically-based slope stability model" *by* Thomas Zieher et al.

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We thank the referee for the positive evaluation of our manuscript and the provided feedback. Please find our responses below, with referee comments in italics, and the authors' responses in blue.

General comments

Although the English is generally very good, the manuscript would benefit from editing to make minor grammar corrections throughout.

The manuscript was proofread by a native speaker of the research field (see supplement for all changes made).

Throughout the manuscript, please change "effective cohesion" and "effective angle of internal friction" to "cohesion for effective stress" and "angle of internal friction for effective stress." The fact that these parameters are for effective stress is an important distinction that is glossed over in far too many recent papers about landslides

Changed as requested.

Given the requirement of high-performance computing to complete the modeling exercise described in this manuscript, the authors should be aware that an MPI version of TRIGRS is available (Alvioli & Baum, 2016).

Most of the simulations were run already a year ago and we were not aware of this version. We will definitely regard using it in future. A comment on this issue was added in the discussion.

Specific comments

P.2 line 5. What are 'settlement objects', houses, residential structures?

Changed as requested: the term 'settlement objects' was changed to residential structures.

Figure 2c. The legend to the geologic map lists the map unit names mostly in German. It would be helpful to list the main lithology for each unit in English.

Changed as requested. A table (new Table 1) listing the geological units shown in Fig. 2c and the respective lithology was added.

p.12, lines 2-3. What is the lithology of Leimernmergel and Dursbergschichten?

Leimernmergel are clayey marls and shales which formed in the upper Cretaceous. Drusbergschichten are marls with thin calcareous layers which formed in the lower

Cretaceous (Friebe, 2007; Oberhauser, 1958). The information is now provided in the new Table 1.

Table 2, Figure 2c and d., and p. 12 lines 2-3. Based on the information presented, it appears that landslides initiated in a number of map units that were not sampled. How do you know that the range of physical property values presented in table 2 represents the range parameter values to be expected throughout the map area? What effects do you think any sampling bias that might be present in your field and lab program had on your calibration results?

The geotechnical sampling focussed on the areas close to the settlements. Remote areas were indeed not sampled. However, the resulting parameters cover a broad range (e.g. the angle of internal friction: 24.8 – 38.1deg, cohesion 0 – 17600 Pa) which is considered representative for the materials encountered in the Laternser valley. This raises the question, if the laboratory tests were necessary at all. These ranges could have been derived from text books as well.
With respect to the answer to the following comment – it is possible that laboratory tests conducted on samples obtained in the southern part of the catchment could additionally extend the value ranges of the tested parameters (e.g. higher angles of internal friction for effective stress). However, the parameter values of the identified ensemble are within the tested ranges. In case of the angle of internal friction for effective stress the optimal value range of the ensemble touches the tested lower boundary (21deg). Therefore, even lower values for the angle of internal friction for effective stress (in combination with enhanced cohesion for effective stress) could yield fair results. However, such low values become physically unreasonable. This issue is now discussed in Section 5. Furthermore, the results of the laboratory tests were added in Fig. 12.

Figure 11. Landslide density is noticeably higher in the western part of the area than in the eastern half. Despite the favorable overall results for your model ensemble, the

high percentage of failures predicted along the southeast rim and northeast sector of the study area compared to the relatively low number of actual landslides seems to indicate that your model calibration is biased toward the western part of the study area. This might have to do either with the regolith depth model or cohesion and friction parameters. What additional insight can you share relative to the apparent east-west bias of your model results? Could the possible sampling bias noted previously have any bearing on this?

This observed bias may have to do with the lithology and the associated characteristics of the unconsolidated materials. The south-eastern part of the catchment is built up of nappes of the Penninicum (ca. 60% of the catchment area, Fig. 1a at the end of the document). These nappes include mostly sandstones whereas the nappes of the Helveticum and Ultrahelveticum in the western and northern part of the catchment mostly consist of marls and shales. However, large parts of the catchment are covered by till deposits, including material with a long travel distance (originating from the southern part of Vorarlberg with a completely different lithology). The extent of the till deposits in the southern part of the catchment is somewhat unclear because of the two geological map sheets prepared by different authors (rough linear delineation of the hatched area in Fig. 1a at the end of the document). We suspect, that the southern and eastern part of the catchment (Penninicum) above the till deposits feature higher angles of internal friction compared to the rest of the catchment (Helveticum, Ultrahelveticum). This may be particularly true for the unconsolidated material in the cirques which is mostly coarse-grained debris originating from debris flows and rock falls from source areas above (highlighted in Fig. 1b at the end of the document). The generally lower parameter values of the geotechnical parameters considered by the ensemble would hence lead to predicted slope failures where there are none in nature. This may explain the observed bias. These issues are now addressed in the discussion section.

P 22, lines 1-2 and Figure 12a. The compensation between angle of internal friction and cohesion should be expected based on the structure of equations 2 and 3.

A reference to Eq. 2 and Eq. 3 was added: This can be expected from Eq. 2 and Eq. 3.

p. 23, lines 12-14. Based on available data (Fig. 5), what other predictors might be worth considering?

The tested morphometric parameters must be seen as proxies for a multitude of influencing factors such as material characteristics, geomorphological processes, climate, land cover, etc. (the parameters may be related to the competence of the rocks, to the landform as a result of the related geomorphological processes as well as the varying degree of weathering and erosion depending on the interplay of land cover and climate conditions). The contribution of these factors to the local morphometry may vary throughout the catchment. However, in the applied statistical model, the spatially varying effects of the parameters are not considered. We think that the introduction of expert knowledge (like geomorphological maps, Catani et al., 2010) may further improve the regolith depth model. Also land cover may be an important parameter to consider (Tesfa et al. 2009). Another issue remains the uncertainty of the area-wide regolith depth maps. For the assessment of slope stability, deviations in the order of decimetres can be crucial. The respective sentenced was revised: However, its spatial distribution may be better reproduced with techniques including further predictors like geomorphology or land cover (e.g. Catani et al., 2010; Tesfa et al., 2009).

p. 23, line 16, Please clarify, which parameter values are conservative, the geotechnical or vegetation parameters?

Changed as requested: However, this can be attributed to the conservative set of parameter values assumed for the three vegetation parameters.

P. 24, lines 1-5, As noted previously, the calibrated model appears to be strongly biased to the west half of the area. Table 2 indicates a wide range of lateral variation in model

input parameters. Property zones need not be as detailed as individual lithologic units. In the case studied here, the area might be divided into two or three zones, with division at major drainages or drainage divides. Then calibration of the separate zones could proceed without a need to deal with potential runoff interactions identified here.

In principle, the idea of using sub-catchments for the calibration procedure is good. However, we think that applying the proposed procedure to hydrologically defined sub-catchments would only be appropriate if they would coincide with units of common material characteristics. In case of the Laternser valley the material characteristics are to some extent predefined by the tectonic units except for the till deposits (Fig. 1 at the end of the document). The potential two or three sub-catchments would therefore still include a mixture of material characteristics. We expect that the results would therefore still show a bias within these units while the bias throughout the catchment may be reduced.

P. 24, lines 6-15. The difficulty identified here could easily be overcome with slightly more work. After completing the 10,000 model runs and converging on the 25 best models, it would be a fairly simple matter to rerun those 25, or a subset of them, with hourly precipitation inputs to see whether the outputs change significantly. Experience has shown that averaging precipitation into longer time steps can effectively reduce the total number of rainfall inputs needed (Baum et al. 2011; Alvioli & Baum, 2016). Testing to find the most effective combination(s) of time steps to represent a particular rainfall sequence can be done fairly quickly using single-grid cell models.

Hourly precipitation maps were used as model input, but to reduce the necessary disk space outputs were generated only for time intervals of 9h. As suggested, the ensemble was re-run to produce hourly FOS-maps (Fig. 2 at the end of the document). The results show that in some cases slightly more landslides are predicted in the time intervals between the original time steps. Theoretically, the issue remains whether more landslides are predicted within the time intervals of one hour. Also, the selection procedure would probably yield a different ensemble based on the hourly output. The part of the discussion addressing the effect of hourly output maps was revised and extended.

Discussion section: Please compare and contrast the relative advantages and disadvantages of the approach used here and a probabilistic approach to initializing the input parameters for TRIGRS (Raia et al. 2014).

A short comparison of the two approaches was added to the discussion:
Four parameters with a high impact on the model outcome were systematically sampled from a uniform distribution with defined increments and ranges. Hence, the subsequent calibration procedure which considers each parameter value combination remains deterministic. However, the combination of the results of the identified model ensemble must not be confused with a probability of failure, since the sampling of the parameter values is systematic and not based on probability distributions. Probabilistic approaches (e.g. Hammond et al., 1992; Raia et al., 2014), including a randomized parameter sampling strategy could overcome this limitation while considering the uncertainty of the input parameters. If the probability distributions of the parameters throughout the study area are known, probabilistic approaches can be applied to derive the probability of failure. Theoretically, the resulting parameter value combinations of the identified model ensemble could give insight into the area-wide probability distribution of the tested parameters. However, further investigations including an enhanced sampling strategy are necessary. Improved and optimized models (e.g. Alvioli & Baum, 2016) will facilitate this objective.

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Please also note the supplement to this comment:
http://www.nat-hazards-earth-syst-sci-discuss.net/nhess-2017-73/nhess-2017-73-AC2-supplement.pdf

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03r1_laterns_tectonics.pdf

Fig. 1. Tectonic units with mapped extent of till deposits (a) and geological units (b) of the

04r1_2005_1999_hourly.pdf

C11

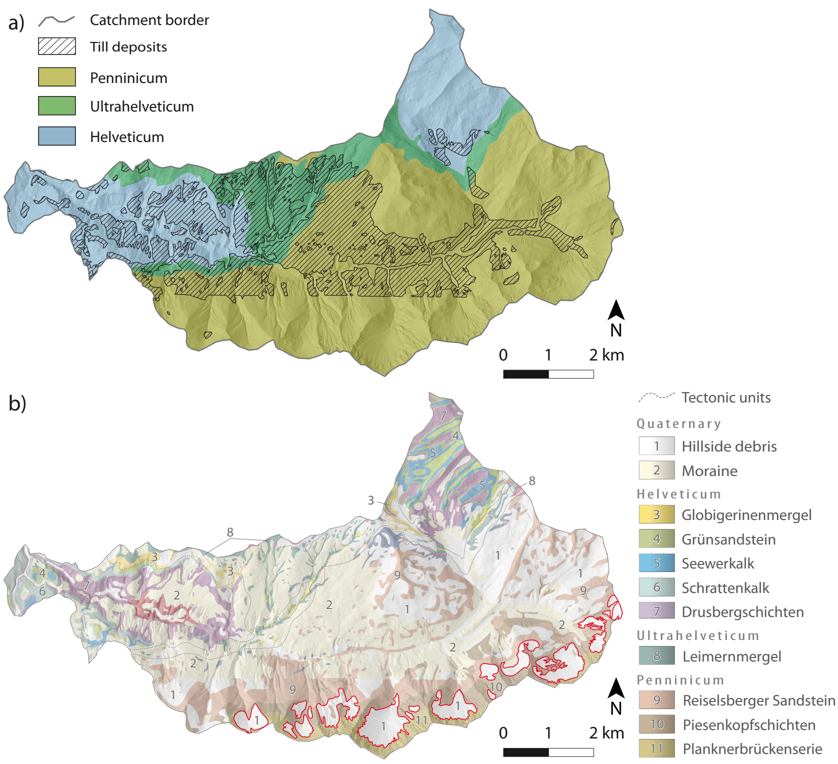

Fig. 3. Tectonic units with mapped extent of till deposits (a) and geological units (b) of the Laternser valley (Heissel et al. 1967, Oberhauser 1982).

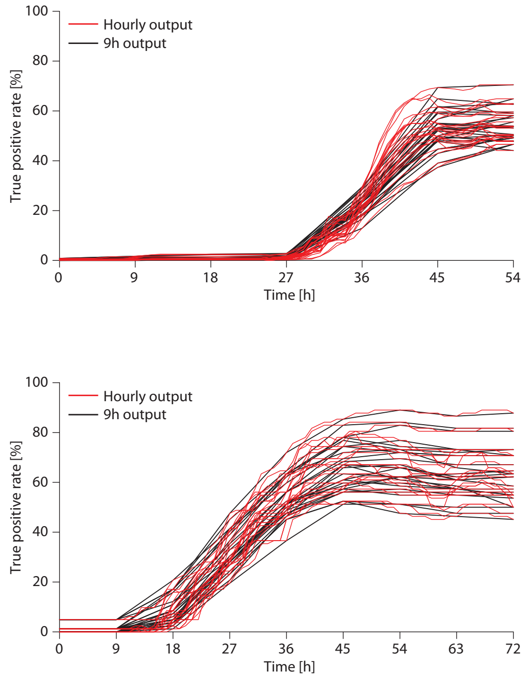

Fig. 4. Comparison of the ensemble prediction rates with 9h and hourly output time steps for the landslide-triggering rainfall events in August 2005 (a) and May 1999 (b).