Response to Reviewer Comment on nhess-2022-154
Anonymous Referee #2

This paper investigated the uncertainty cascade in storylines of landslide susceptibility emerging from climate change and parametric landslide model uncertainty. In general, this paper is interesting and rich in content. However, there are many mistakes in the basic concept of landslide susceptibility, hazard and risk assessment. In terms of landslide susceptibility prediction modeling process, the writing of this paper is rather rough. In terms of organizational structure, the thesis is difficult to understand. Therefore, it is recommended to reject the paper.

Dear reviewer,

The coauthors and I are thankful for the review. We regret that the topic was difficult to understand and that the methods were not clear enough. We try to elucidate the methodological approach for the reader with specific adaptations and to clarify the misunderstandings regarding the definition of susceptibility. We would be grateful for your constructive comments on this manuscript regarding critical points, which are at the current state not clear for us. Furthermore, we would be very pleased if a revised version of the manuscript is still under consideration for publication. The referee's comments were taken into account in the revision, and we strongly believe that the comments and suggestions have largely increased the scientific value of the revised manuscript.

For our reply and revision of the manuscript we numbered the comments given by the referee. The comments by the reviewer are presented in black color, whereas our reply is in blue color. Additionally, we tracked changes using the latexdiff package in LaTeX in the revised manuscript.

– **Point 1:** Landslide susceptibility refers to the spatial probability of landslide occurrence affected by landslides themselves conditioning factors, without considering triggering factors such as heavy rainfall, earthquake, et al. Landslide hazard refers to the spatial and time probability of landslide occurrence under condition factors and trigger factors. Hence, this paper focus on landslide susceptibility affected by land cover change and heavy rainfall. I believe this paper has problems with the basic concepts of landslide susceptibility.

  Response 1: We agree with the reviewer that the term "landslide susceptibility" is still commonly understood as the likelihood of a certain area to be affected by landslide occurrence on the basis of local terrain conditions, which. are assumed to be purely spatial ("where") and time-invariant. The authors would like to emphasize that this is a purely terminological issue.

However, already, Meusburger and Alewell (2009, in NHESS) questioned the validity of static landslide susceptibility maps under changing environmental conditions. But recently, this issue gained more attention (e.g. Jones et al., 2021; Ozturk et al., 2021), with several authors showing that the concept of time invariance is often violated on the time scale of few to several decades (e.g., Reichenbach et al. (2014) analyzing anthropogenic land use changes, Samia et al. (2017) analyzing "follow-up" landslides). Therefore, we followed the recommendation of Gariano and Guzzetti (2016, 246), Reichenbach et al. (2018, 84) and other authors (Jones et al., 2021; Ozturk et al., 2021) to construct new models considering and investigating changes of environmental variables for landslide susceptibility.

In our approach, local terrain conditions (e.g., predisposing factors such as slope angle, slope aspect, etc.), which are assumed not to change substantially in the course of centuries, are still considered time-invariant, but are extended by time-varying predictor variables (e.g., preparatory and triggering factors such as soil moisture, precipitation or land-use and land-cover). Furthermore, in the entire manuscript the terms "hazard" and "risk" are only used in the context of damages or fatalities and in the broader context of management, which fits very well the in Brabb (1984) defined terminologies.

For clarification we enhanced the understanding of "landslide susceptibility" with additional information in the Landslide Susceptibility Model section.

Proposed change 1:

Lines 179-181: For the landslide susceptibility analysis, we linked predisposing and time-varying preparatory and triggering factors to landslide occurrences, by following recent recommendations for non-stationary landslide susceptibility models (Gariano and Guzzetti, 2016; Reichenbach et al., 2018; Jones et al., 2021; Ozturk et al., 2021).

Lines 514-516: Additionally, the time-varying modeling-perspective on landslide susceptibility as recommended by various authors (Gariano and Guzzetti, 2016; Reichenbach et al., 2018; Jones et al., 2021; Ozturk et al., 2021), allowed us to analyze the effects of LULC and climate change dynamics.

– **Point 2:** The writing ideas of this paper are very confused, and it is difficult for people to understand the specific steps and methods of the research. Especially in the introduction and methods section.

  Response 2: We are thankful for the referee pointing out sources of confusion and misunderstanding. Regarding the methods, we have added a flow chart in the appendix showing a general overview of methodical approach from the beginning - model fitting, to the end - uncertainty ratios. Regarding the introduction, we more specifically describe the term storyline and emphasize more clearly our objectives.

  Proposed change 2:

  Lines 31-33: Focusing on the rainfall event in 2009, Maraun et al. (2022) analysed the effect of projected future climate (2070–2100) and LULC changes on landslide occurrences using a storyline approach (i.e. physically self-consistent, plausible pathways, Shepherd et al. 2018) for the most-affected Feldbach region.

Lines 66-67: The focus was not on creating landslide susceptibility maps, but on the quantification of uncertainties.

Lines 169-171: The proposed approach to assessing landslide susceptibility uncertainty addresses model fitting accounting for spatial dependency (Sect. 3.1), predictions considering environmental change (Sect. 3.2), and their amount of uncertainty (Sect. 3.3). Please refer to Fig. A1 in the Appendix A for an overview.

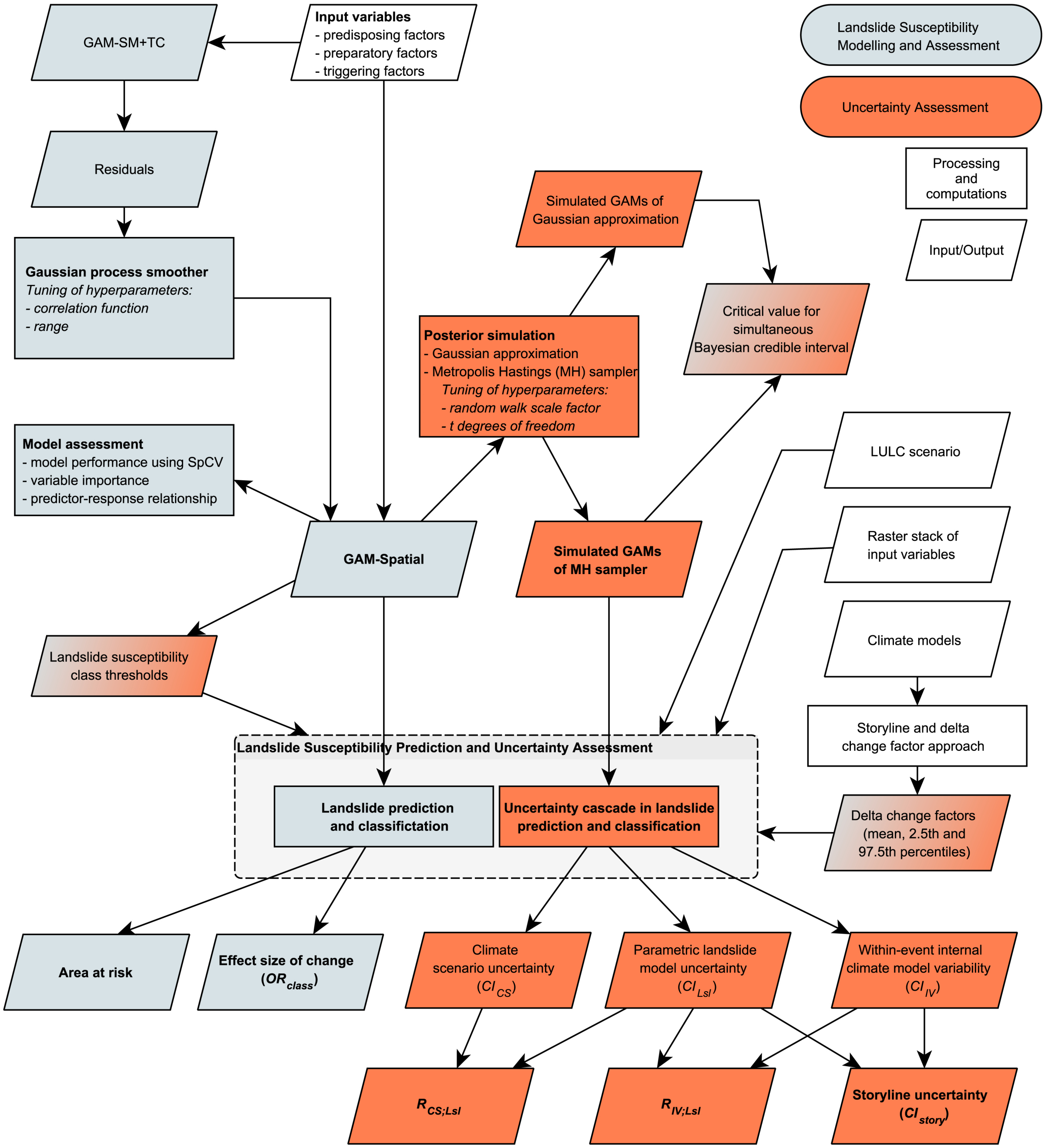

Figure 1. Overview of the proposed landslide susceptibility prediction and uncertainty assessment. (Note, the figure number does not match with the revised manuscript - Fig. A1 in the Appendix A)

– **Point 3:** Where are the input and output variables of landslide susceptibility prediction modeling described in this paper?

Response 3: The reviewer correctly pointed out a missing linkage to the Knevels et al. (2020) reference. The input variables were briefly mentioned at the second paragraph of the chapter in which the landslide model was introduced (3.1 Landslide Susceptibility Model, lines 173-177). In Knevels et al. (2020) further details are available on how these input variables were derived (software, hyperparameter settings etc.). As this paper is already quite extensive in pages, we shortened this description. In the revised manuscript we added the information that more details on the delineation can be found in Knevels et al. (2020).

Proposed change 3:

Lines 185-186: For more information on the delineation of the predictor variables and their maps, refer to Knevels et al. (2020) and Fig. S6 in the Supplementary Material, respectively.

– **Point 4:** How is the uncertainty problem concerned in this paper quantified?

Response 4: The authors thank the referee for the hint to a possible source of confusion. In last paragraph of the chapter "3.3 Uncertainty Cascade in Landslide Predictions" (lines 285 - 289), the authors described how the ratios are delineated: "Finally, to compare the different sources of uncertainty in the uncertainty cascade, we calculated the ratio of the uncertainty spread of within-event internal climate model variability and scenario uncertainty (i.e., spread of climate signals), respectively, to the parametric uncertainty spread of the landslide model. The joint uncertainty distribution of the landslide models' parametric uncertainty and within-event internal climate model variability is here referred to as the storyline uncertainty."

In the revised manuscript, we introduced a mathematical notation and changed the term "spread" to "width" to prevent the possibility of confusion. Furthermore, we hope that Change 2 (flow chart of methodological approach) improves the understanding of the analysis.

Proposed change 4:

Line 294-300: (Note, the equation numbers do not match with the revised manuscript)

Finally, to compare the different sources of uncertainty in the uncertainty cascade, we calculated the following ratios:

$$R_{IV;Lsl} = \frac{width\ of\ CI_{IV}}{width\ of\ CI_{Lsl}} \tag{1}$$

$$R_{CS;Lsl} = \frac{width\ of\ CI_{CS}}{width\ of\ CI_{Lsl}} \tag{2}$$

where $R_{IV;Lsl}$ and $R_{CS;Lsl}$ denote the ratio of the uncertainty width of within-event internal climate model variability (CI_{IV}) and scenario uncertainty (i.e., width of climate signals, CI_{CS}), respectively, to the parametric uncertainty width of the landslide model (CI_{Lsl}). The joint uncertainty distribution of the landslide models' parametric uncertainty and within-event internal climate model variability is here referred to as the storyline uncertainty (CI_{Story}).

- **Point 5:** Where are the environmental factor maps of landslide susceptibility and landslide susceptibility outcome maps? These problems [Points 3-5] are not well reflected.

  Response 5: The reviewer pointed out a possible source of misunderstanding. This article is not about creating landslide maps, but to quantify uncertainties in predictions emerging from the landslide and climate models. However, we followed the reviewer and added two overview maps in the supplementary materials: a map showing all the input variables, and a map showing the landslide susceptibility classes of the event and selected climate model alongside with uncertainty graphs, which may be useful to communicate to local stakeholders.

  Please note that the estimated predictor-response relationship, which were of interest in our analysis, were already made available via the supplementary materials (Figure S4 and S5, https://nhess.copernicus.org/preprints/nhess-2022-154/nhess-2022-154-supplement.pdf).

  Proposed change 5:

  Lines 184-185: For more information on the delineation of the predictor variables and their maps, refer to Knevels et al. (2020) and Fig. S6 in the Supplementary Material, respectively.

  Lines 534-537: In the spatial context, recommendations for the construction of new settlement infrastructure may be derived based on a map, and zones of high landslide susceptibility along with uncertainty graphs (Fig. S7 in the Supplementary Material) can be communicated to local planners and environmental managers (cf. Petschko et al., 2014).

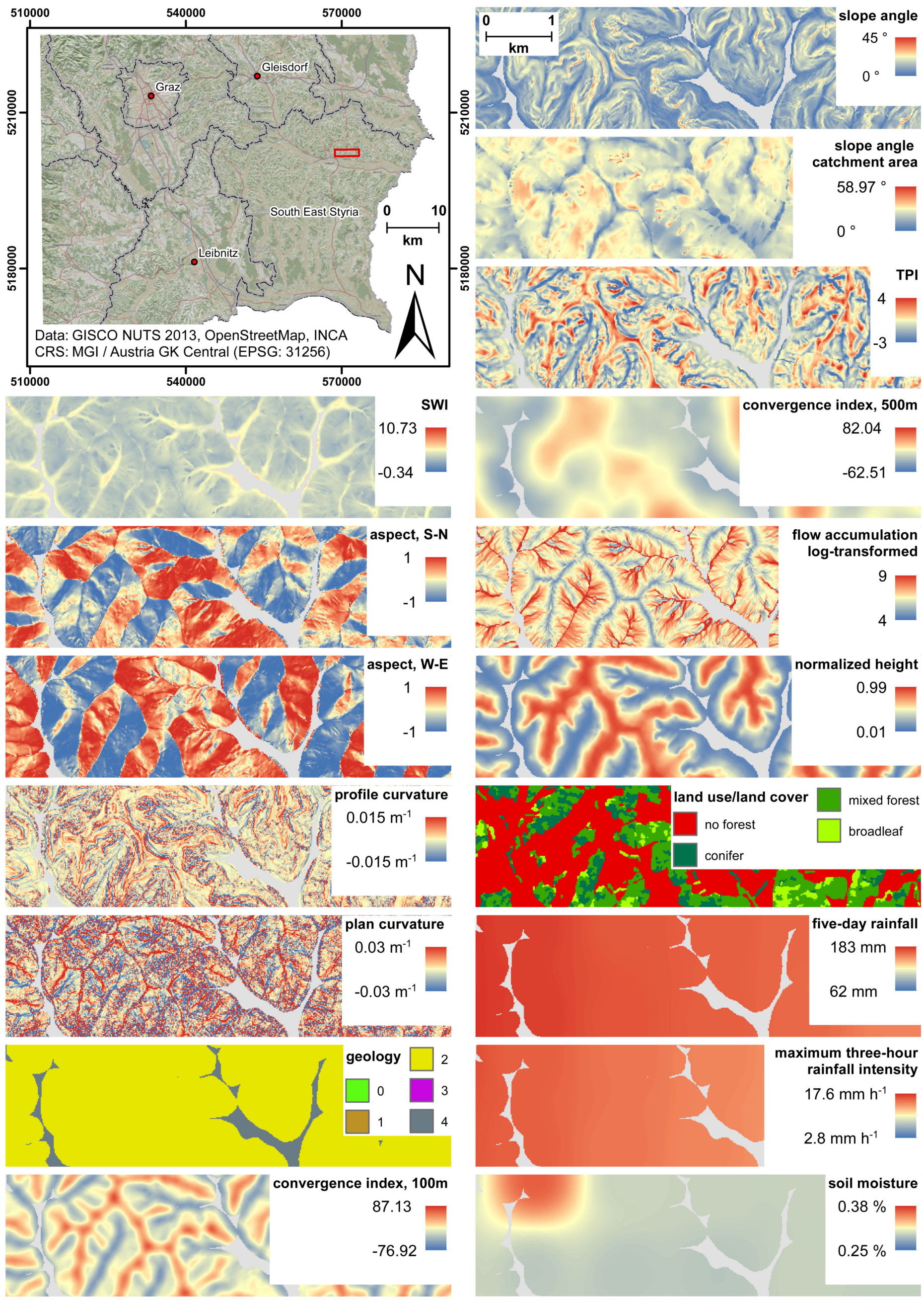

Figure 2. Overview of input variables for predicting landslide susceptibility of the 2009 event. Geology: 0: 'Others', 1: 'Neogene formations dominated by fine-grained sediments', 2: 'Neogene formations with coarse-grained layers', 3: 'pre-Würmian Pleistocene formations', 4: 'Würm and holocene sediments'. (Note, the figure number does not match with the revised manuscript - Fig. S6 in the Supplementary Material)

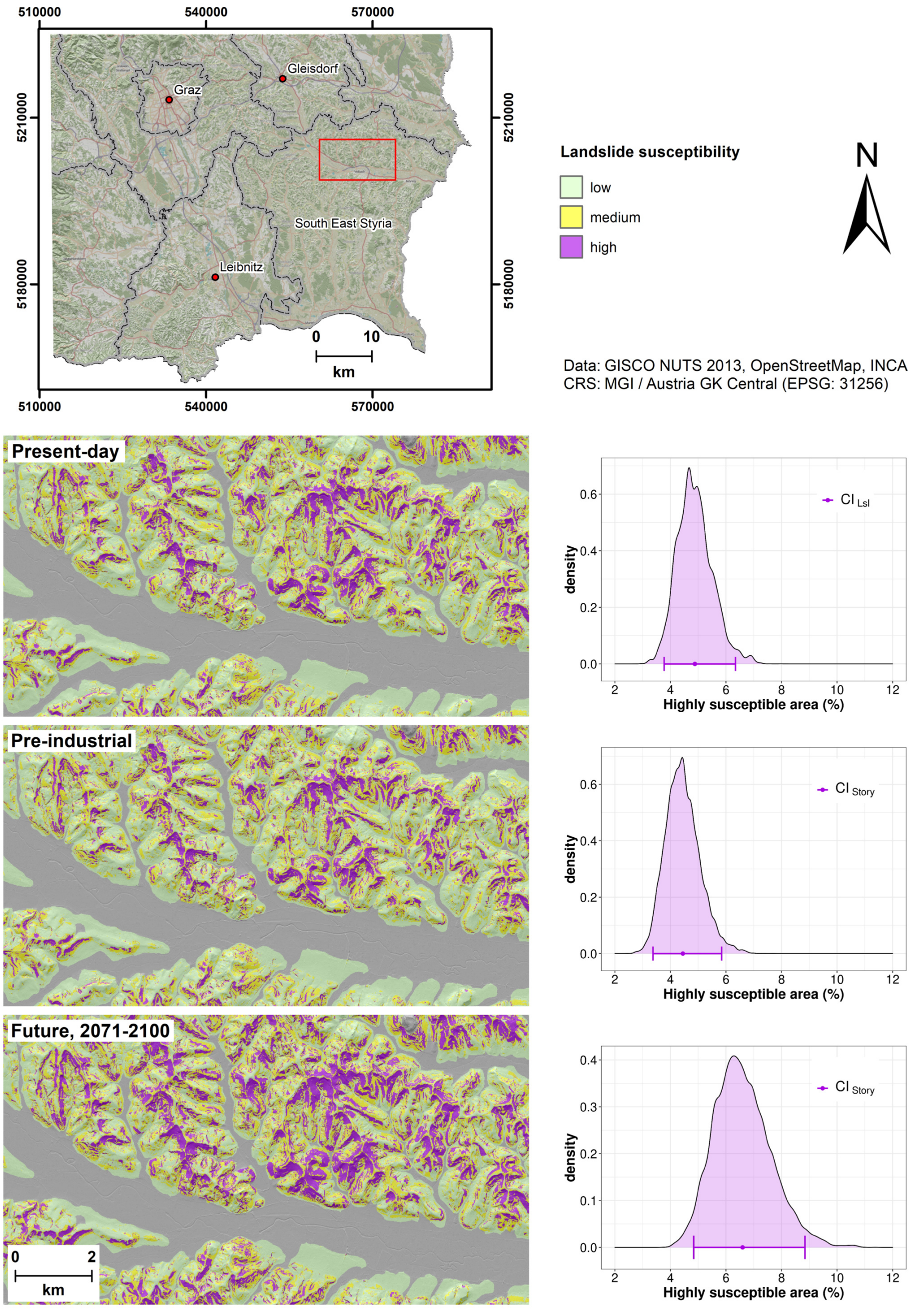

Figure 3. Example of landslide susceptibility maps of the 2009 event and associated uncertainties in highly susceptible areas. Pre-industrial and future storylines are based on the HadGEM climate model in the 4 K warming scenario. Note: Uncertainty graphs are based on the entire study area. (Note, the figure number does not match with the revised manuscript - Fig. S7 in the Supplementary Material)

– **Point 6:** The figures are not clear enough.

Response 6: The authors collectively went through all figures individually, and agreed that, except for Figure 5, all figures are clear. The authors modified Figure 5 by adding the mathematical notations introduced with Proposed Change 4, and thus improved its understanding.

Proposed change 6: see Figure 5 in the revised manuscript.

– **Point 7:** The references are not new enough and are not representative enough.

Response 7: The authors are wondering on what basis this statement was made. Nevertheless, the authors checked all references again on redundancy or the possibility for "updating", and modified them when it suited.

Proposed change 7:

Removed: Hastie and Tibshirani 1986; Nychka 1988; Oberkampf et al. 2004; Refsgaard et al. 2007; Brenning 2012; Fressard et al. 2014; Hussin et al. 2016

Added: Brock et al. 2020; Ozturk et al. 2021; Jones et al. 2021

– **Point 8:** The uncertainty characteristics are assessed by which indexes? These description are not clear.

Response 8: Please refer to **Point 4**.

Proposed change 8: see **Proposed Change 4**.

– **Point 9:** There is insufficient analysis of feasible solutions to the problems in this paper.

Response 9: The problem addressed in this paper is the assessment of uncertainties - not the reduction of uncertainties. Nevertheless, the authors even gave some ideas, how these analyzed uncertainties might be reduced (e.g. Lines 440, 450-453 for the climate uncertainties or Lines 482-485, 515-516 for the landslide model uncertainties). The authors have shown that the chosen approach to uncertainty assessment is valid and (evidently) feasible. We are therefore confident that in reviewing these text sections, the referee will appreciate our contributions mainly to the assessment of uncertainties.

Proposed change 9: No change made

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