Response to Reviewer Comment on nhess-2022-154
Anonymous Referee #1

The manuscript is a good piece of science addressing a relevant issue, i.e. the evaluation of the uncertainties in landslide susceptibility modeling, taking into account also climate and environmental changes. The manuscript is clear, written in fluent English, and well organized. The figures and tables are useful for presenting and discussing the results. The introduction is complete and useful for focusing on the topic. The method is well presented and the discussion is clear. However, I've found some issues that need to be addressed and explained before the manuscript can be reconsidered for publication.

Dear reviewer,

The coauthors and I are thankful for giving us the opportunity to submit a revised draft of our manuscript titled "Assessing uncertainties in landslide susceptibility predictions in a changing environment (Styrian Basin, Austria)" to Natural Hazards and Earth System Sciences. We are grateful for your encouraging, critical and constructive comments on this manuscript. The comments were taken fully 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:** Although earlier work by some of the authors is recalled in several places, the whole manuscript is rather long, so I would suggest trying to shorten it by at least 10% of the current length.

  Response 1: We are thankful for the suggestion to shorten the manuscript. We acknowledge that the manuscript exceeds the expected number of journal pages, but we find that the work is succinctly written. We gave as briefly as possible only relevant details for model construction and reproducibility of the analysis. At some points we refer the reader to the cited publications for further detail. However, following the suggestion, we will be in touch with the editor if a shortening of the manuscript is required.

- **Point 2:** You use the term "storyline approach". I can't grab what you mean with "storyline" and "storyline approach". It seems to me that this term is not common in landslide analyses. I would suggest adding some explanation.

  Response 2: Maraun et al. (2022) was to our knowledge the first who introduced "storylines" in the context of climate-change related landslide analysis. Even though the concept of storylines is not "new" (since 2018, Shepherd et al. 2018), the emphasizing of this approach was recently highly promoted by the IPCC (Doblas-Reyes et al., 2021). The definition of a "storyline" is given at the beginning of chapter 2.2.2, however, we agree that a short explanation in the introduction may improve the understanding of the terminology. In the revised manuscript, we added in brackets (i.e. physically self-consistent, plausible pathways, Shepherd et al. 2018).

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.

- **Point 3:** You defined the events that occurred in June 2009 and September 2014 as "extreme". How can you classify such events as "extreme"? Was a statistical analysis carried out?

  Response 3: The reviewer correctly pointed out a possible source of confusion. For the 2009 event, Haiden (2009, 4) analyzed the amount of rainfall in less than 24 h in Styria, and grouped that rainfall event into events with a 50-year return period. Such an analysis was, however, not conducted for the 2014 event (nevertheless, as consequence, flood events corresponding to HQ50 and HQ100 were recorded at some places, see http://app.hydrographie.steiermark.at/berichte/september2014.pdf). Therefore, in the revised manuscript, we used the word "extreme" only in the context of the 2009 event, and "heavy" when accounted for both events.

  Proposed change 3:

  Lines 23-24: In June 2009 and September 2014, weather phenomena developed through a cut-off low brought heavy rainfall into the Styrian Basin, Austria (e.g., over 100 mm in 24 h in 2009).

  Lines 26-27: The combined effect of premoisturing over the preceding winter and spring, and the actual triggering rainfall made these weather events into compound events [...].

  Line 76: Study Area and ~~Extreme~~ Rainfall Events

  Line 85: In June 2009 and September 2014, heavy rainfall events occurred in southeast Styria.

  Caption Figure 1: (b) Occurred landslides during ~~extreme~~ rainfall events.

  Line 114: As landslide data, we used landslides that occurred during the heavy rainfall events, which were initially mapped by [...].

- **Point 4:** You added in the susceptibility analysis the rainfall data on the landslide failure day, i.e. the triggering precipitation conditions. I think this is questionable and in contrast with the theoretical definition of susceptibility (see e.g. Reichenbach et al. (2018) [https://doi.org/10.1016/j.earscirev.2018.03.001]; van Westen et al. (2008) [https://doi.org/10.1016/j.enggeo.2008.03.010]). Landslide susceptibility is "the likelihood of a landslide occurring in an area on the basis of the local terrain and environmental conditions", therefore the triggering rainfall conditions should be removed from this analysis. You also wrote "For the landslide susceptibility analysis, we linked predisposing and triggering factors to landslide occurrences.". I think this can be considered a methodological issue.

Response 4: 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. Already, Meusburger and Alewell (2009) 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) and Reichenbach et al. (2018) to construct new models considering and investigating changes of environmental variables for landslide susceptibility (Gariano and Guzzetti 2016, 246: “We recommend to construct new slope stability models capable of cope with nonstationary climate and landslide records, and of considering the time dependence of the events.”, Reichenbach et al. 2018, 84 “We recommend that studies should include climate-related variables in landslide susceptibility models.”).

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 precipitation or land-use and land-cover). For clarification we enhanced the understanding of “landslide susceptibility” with additional information in the Landslide Susceptibility Model section.

Proposed change 4:

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 5:** Regarding the environmental change simulation, you wrote (line 153) that "Adopting active forest management in the developed future LULC scenario, coniferous forest was replaced by climate resilient mixed forest".

Response 5: The authors agree with the referee that an in-depth analysis of effects of all possible kinds of land-use and land-cover changes on landslide occurrences is highly desirable. Actually, Maraun et al. (2022) analyzed a negative, “idealized” scenario representing extreme deforestation, i.e. one where all forest is removed (note: there was also a scenario with extreme afforestation). However, as the focus of the study is the assessment of uncertainties and not primarily the effect of LULC changes, we decided to include only the “realistic” instead of the “idealized” scenario (“realistic” scenario was developed in close cooperation with the Regional Forestry Directorate and the District Forestry Authority). Furthermore, the LULC data used to fit our landslide model do not allow for further discrimination between different types of non-forested areas.

We added some explanations to refer the interested reader to Maraun et al. (2022) for these “idealized” scenarios.

Proposed change 5:

Lines 157-158: The developed, idealized scenarios of Maraun et al. (2022) were not in the scope of this analysis (i.e. extreme de- and afforestation).

- **Point 6:** Furthermore, you wrote (line 161) "Specifically, for each grid cell we determined the maximum three-hour rainfall intensity, and we took the maximum five-day rainfall." In my opinion, also this is questionable, given that it is not always the most severe rainfall condition during a meteorological event that can trigger landslides. An explanation is needed.

  Response 6: We agree with the reviewer that there may be rainfall-triggering landslide events for which other precipitation aggregation schemes are more appropriate. Generally-spoken, there are many possibilities how to aggregate meteorological data, ranging from indices (e.g., landslide-rainfall index (Shou and Yang, 2015), antecedent rainfall index (Kirschbaum and Stanley, 2018)) to fixed moving sizes or number of days exceeding a certain amount of rainfall (e.g., in Gassner et al. 2015; Kim et al. 2015), and there is no general agreement on an optimal aggregation scheme. However, in Knevels et al. (2020, 9), we compared the two meteorological variables to “rainfall events responsible for landslides” extracted using the approach of Melillo et al. (2015). Specifically, for our landslides, we discovered a correlation of 0.95 between five-day rainfall and total amount during rainfall event, and of 0.58 between maximum three-hour rainfall intensity and amounts of rainfall sub-events; confirming the applicability of the presented aggregation scheme. To inform the interested reader where the rainfall aggregation comes from, we have now added an explanation in an appropriate place.

  Proposed change 6:

  Lines 105-107: Furthermore, precipitation was aggregated to obtain accumulated five-day rainfall (in mm) and maximum three-hour rainfall intensity (in mm h-1) on the landslide failure day, respectively (for the precipitation aggregation scheme, please refer to Knevels et al. 2020).

- **Point 7:** Finally, I suggest using round brackets for units of measurement. Please check all over the text.

  Response 7: We are thankful for this hint. Regarding the submission-guideline for Mathematical notation and terminology (https://www.natural-hazards-and-earth-system-sciences.net/submission.html#math), it seems that there are no brackets around units in the fluid text. However, we replaced square-brackets with round brackets in the figures

  Proposed change 7:

Figure 1: (mm); Figure 3: (mm), (mm h^{-1}), (%) + caption; Figure 4: (%); Figure 5a: (%); Figure A1: (mm); Figure A2: (%); Figure S1: (m); Figure S3: (mm), (mm h^{-1}), (%) + caption

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