Reply on RC2

My **major concerns** concentrate around the method choices forming the foundation of the current study. I highlight the line number of a piece from the manuscript in quotation marks which is followed by my comments after the sign of -->.

Line 79: "spatially intersected with the German rail network" --> Is this intersection achieved considering purely spatial overlap, or are rainfall runoff conditions taken into account as well? For instance, rainfall upstream could potentially impact tracks downstream, even in the absence of local precipitation.
This intersection is achieved considering purely spatial overlap and does not take rainfall runoff conditions into account. We are aware that this is strong simplification and does not represent the real world. However, this aspect is not the central part of the study; our intention of this simple intersection is only to show that large parts of the German rail network can potentially be affected by heavy rainfall events and that it is therefore necessary to have a closer look on this natural hazard. In the revised version, we are happy to point out the limitations of the spatial intersection and point out that a detailed consideration is necessary for recommendations for action, etc.

Line 97: "one heavy rainfall event" --> Could the authors clarify if they are referring to hydrogeomorphological events, including mass-wasting process? I suspect that the tree falls might relate more to wind than rainfall. If the tree fall process is indeed related to wind, it might be beneficial to consider a term that encompasses all three phenomena. Perhaps including wind events as a factor, or alternatively, reconsidering the inclusion of tree fall cases, might provide a more concise, easy-to-explain analysis.
This paragraph refers only to the spatial intersection of the CatRaRE precipitation events with the rail network and does not take into account the effecs of heavy rainfall events such as mass movements or tree fall events. The topic that tree fall events are often caused by wind and that heavy rainfall events are often accompanied by wind gusts is already discussed at various points in the manuscript, e.g.: lines 416/17 and references therein, line 436.

Line 158: "e.g. shown for shallow landslides" --> While the observation may hold true for shallow landslides, it's important to note that gravitational mass movements also encompass deep-seated landslides, where the lag time could extend significantly, potentially reaching years. Even excluding these exceptional cases, a lag time of 10-15 days appears realistic, as evidenced by Dille et al. (2022; https://doi.org/10.1038/s41561-022-01073-3). Should the focus be on shallow landslides, it would be helpful if this distinction is made clear. The choice of a 2-day lag for considering landslides raises some concerns for me, and I kindly suggest revisiting this aspect for a more nuanced discussion. The term "gravitational mass movements" might cover more processes than the authors intended.
We are aware of the problem that the term „gravitational mass movements“ encompasses a broad range of different processes, all of which have very different triggering factors and recurrence times. However, no clear process assignement can be derived from the event data along the rail network, so that unfortunately no further differentiation or adapted models (e.g. longer lag times for deep seated landslides) are possible here. However, as the disturbance durations for the events in the database are very short in almost all cases, we assume that these are predominantly smaller events. The process diversity of gravitational mass movements and the restriction of the DB damage data base

are already addressed in the discussion in the manuscript (chapter 4.2), but we are happy to go into more detail in the revised version.

Lines 200–202: "The segment is considered to have been affected by a heavy rainfall event on a given day if a heavy rainfall event from the CatRaRE database has occurred on that day up to a maximum of two days previously." --> As I mentioned in my previous comment, I'm concerned that the proposed time-lag window might not adequately capture the lag time associated with landslides. Later on, in the results (comment below), the authors highlight that only a small fraction of gravitational mass movements were linked to certain rain events. Hence, as previously mentioned, extending this window could offer a more accurate representation of the impact of heavy rainfall on landslide occurrences.
See response and figure to comment from reviewer RC1, Methods, comment 2. The lag-time for all three processes (floods, tree falls and gravitationl mass movements) is rather short.

Line 275: "a total of 59 events (14 %)" --> I wonder if the correlation might become more pronounced if the lag time were extended to 15 days or more. This adjustment could potentially offer a more comprehensive analysis of the impact of heavy rainfall on these events.
See response to previous comment.

Lines 278-279: "Of the 14461 tree fall events, a total of 312 (2 %) events can be spatially and temporally linked to a heavy rainfall event." --> This observation might suggest an indirect connection between rainfall and tree falls, potentially implicating other factors such as wind (as discussed by Gardiner et al.; http://dx.doi.org/10.2139/ssrn.4576016) or flooding (Lucia et al., 2018; https://doi.org/10.1016/j.scitotenv.2018.05.186). Further exploration of these factors could enrich the study.
Thank you for the literature references. The paper from Gardiner et al. is already mentioned in the discussion (line 416), but we can add more detailed information on the factors triggering tree fall events in the revised version.

My **minor concerns** primarily revolve around the use of terminology and the occasional absence of detailed explanatory statements that could further enhance the manuscript's readability and comprehension. Clarifying these aspects could improve the overall understandability for the readers. I list the minor comments in the attached file to keep my online comments concise.

Line 6: "associated natural hazards" --> Could you please specify which natural hazards are being referred to here?
See RC3, first minor comment

Line 8: "random-effects logistic models" --> At this juncture, I'm finding it challenging to grasp the specifics of this model. Could you possibly elaborate further for clarity?
A detailed description on the set up of the random-effects logistic model is given from line 207 onwards. For more clarity, we can include a definition of this model type in this chapter.

Line 8: "DB Netz AG" --> I'm concerned that this acronym might not be readily understood by a significant portion of the NHESS readership outside of Germany. Could a brief

explanation be provided for broader accessibility?
We decided to use mention the data sources already in the abstract, but we are aware that the abbreviations might not be understand by the whole readership. If the editors wish, we can replace the datasource by a more general term like „a damage database from a German railroad operator“.

Line 8: "CatRaRe" --> Similarly, this acronym might not resonate with the wider NHESS audience. A definition could greatly aid in understanding.
See previous comment.

Lines 10-11: "Twenty-three percent of the flood events, 14% of the gravitational mass movements and 2% of the tree fall events" --> I'm having a bit of difficulty following these percentages. To clarify, does this imply that 77% of the flood events are not attributed to heavy rainfall?
Yes, the percentages implies that 77% of the flood events, 86% of the gravitational mass movements and 98% of the tree fall events recorded in the damage database of DB Netz AG could not be attributed to a heavy rainfall event from the CatRaRE dataset.

Lines 12-13: "a heavy rainfall event significantly increases the probability of occurrence of a flood by a factor of 34.29." --> Am I correct in understanding that, according to the authors, there are floods that occur independently of heavy rainfall events?
Yes, this is correct.

Line 12: "Tree fall" --> I'm struggling to conceptualize how heavy rainfall directly leads to tree fall. Could you provide further insight into this connection?
To provide further insights into this connection is out of the scope of the abstracts. More detailed information on the relationship are given in line 161 and line 414 onwards.

Lines 13-14: "the 21-days antecedent precipitation index" --> I'm not entirely versed in the conventional determination of the 21-day threshold. If it's based on specific constraints, might I suggest clarifying or possibly reevaluating its presentation in the text?
The antecedent precipitation index (API) is an objectified measure of the soil water content based on the amount of precipitation that has fallen. The API is determined by the weighted sum of the previous daily precipitation values, whereby the weights decrease with the time elapsed decrease with time.
The DWD data catalogue used provides for both the 21-day and 30-day API. These are the most common models for modelling pre-moisture. As the natural hazards investigated in this study were examined in relation to heavy rainfall events occurring shortly before, the 21-day API is considered a useful parameter, as it reflects the medium-term conditions at the respective locations well and therefore an influence of this on the occurrence of sudden natural hazards was assumed (and proven in the analyses).

Line 15: "with no significant increase for gravitational mass movements" --> This finding seems to be at odds with existing literature. Could the authors confidently assert the robustness of their data in this regard? Further emphasis on this point might be warranted, especially given the indicated positive correlation between increasing rainfall and landslide occurrences in Figure 4.

The limitation of the study results are adressed in the discussion section, especially in chapter 4.2. The data quality and availability is a major restriction.

Line 15: "21 day threshold" --> Once again, the 21-day threshold's basis is not clear to me. If it's a discretionary choice, clarifying its rationale or considering its removal for a more straightforward explanation might be beneficial.
See response to comment line 13-14.

Lines 15-16: "The results underline the importance of gaining more precise knowledge about the impact of climate triggers on natural hazard-related disturbances" --> The connection to this conclusion in the abstract seems somewhat tenuous. A more detailed exposition in the text might help in directly leading the reader to this message. Alternatively, authors could consider revising the final message that summarizes their results.
We find this conclion locigal because, as the reviewer noted in the previous comments, it is surprising that only a small proportion of natural hazard processes on railroad lines can be linked to a heavy rainfall event. We would like to end the abstract with a more general sentence, but we can reword it if the editors wish.

Lines 19-26: "" --> This is a really nice start to the manuscript. It really caught my attention.
Thank you for the comment.

Line 28: "significant" --> I would advise against using 'significant' unless it is in a statistical context. Perhaps 'considerably' could serve as a suitable alternative.
We agree that „considerably“ is more appropriate in this context as „significant“ and will replace it in the revised version.

Line 39: "Within the framework of proactive natural hazard management" --> Is this framework well-documented in the literature, or is it an innovative concept proposed by the authors? A reference or a detailed explanation would be valuable for readers.
There are several publications on this topic and different elaborations of natural hazard frameworks (e.g. Mühlhofer et al. 2023 (doi: 10.5772/55538). Most procedures are very similar and show steps such as exposure (localising the hazard), vulnerability, risk and risk defence.

Line 98: "Starkregenindex SRI" --> Could the authors kindly provide a citation for this index? If it is a novel introduction, a detailed explanation within the manuscript would enhance understanding.
We will include a reference (Schmitt 2017 and/or Schmitt et al. 2018) in the revised version, as proposed by Katharina Lengfeld.

Line 100: "Lower Saxony" --> Given the frequent references to federal states, it may be helpful to include a reference map for those less familiar with Germany's geographical and political landscape.
If the editor wishs, we can add the names of the mentioned federal states in Figure 2.

Line 111: "with event-specific search terms" --> Could you specify which search terms were used?

We can add some examples of search terms in the revised version (e.g. branch, tree, landslide, flood), but a complete list is unfortunately not available as data was provided in several years and by different colleagues from Deutsche Bahn.

Line 128: "the period 1 January 2017-16 December 2020" --> I'm curious as to why data from earlier years and for 2021 were not included. This query also pertains to mass-wasting events. If they were absent in the data, do the authors know the reason behind.
We used all data for the anaylsis which was available for us. The recording system at DB changed and has been raised to a new level of quality in 2017, so data from earlier years is not available for external use and not suitable. The data set for 2021 for tree fall events was different from the recording accurancy for the years 2017-2020. In order to avoid misinterpretation due to data inhomogenity, we decided to exclude the report from 2021 for the tree fall data set.

Line 132: "Explanatory control variables" --> It would be immensely helpful to visualize these data. Is it possible to include them in one or more figures within the manuscript?
As proposed by reviewer RC1, comments on dataset, point 5 we will prepare a table of all used terms and variables. Additionally, we can add a graphical abstract in the revised version.

Lines 153-154: "Thus, there are event locations where more than 50 heavy rainfall events from 2011 to 2021 can be found." --> Could this indicate that a single event, such as gravitational mass movements, might be attributed to multiple heavy rain events? This clarification would greatly aid in understanding the methodology applied.
Yes, it is possible, that a single event might be attributed to multiple heavy rainfall events, but only if the rainfall events occur within three consecutive days. However, this is only the case in a low number of natural hazard events. There is only one tree fall event with two associated heavy rainfall events. There are also two landslides, each with two associated heavy rainfall events, one on the day oft he event and one the day before. There is no „double events" for floods.

Line 161: "for deep landslides" --> It may be more accurate to refer to these as "deep-seated landslides" to ensure clarity and precision in terminology.
We will add deep-seated landlides to ensure clarity.

Line 166: "the data set" --> It appears the term "dataset" is used inconsistently. Adopting a uniform usage could enhance the manuscript's readability.
We will replace „data set" by „dataset" in the whole manuscript.

Line 270: "events" --> Could you specify which events are being referred to here? Are these meant to be natural hazards?
„Events" refer to „flooding events". We can specify this in the text.

Lines 322-323: "After two days, the probability of a gravitational mass movement is no longer different from a situation with no heavy rainfall."
-> Unfortunately, there is no comment on this line. If there are any comments on this statement, we would be happy to discuss them.

Lines 325-326: "In contrast, one day after a heavy rainfall event, a tree fall event is 2.4 times

more likely to occur than in days with no heavy rainfall." --> The linkage of tree falls to heavy rainfall events, as highlighted here, is quite intriguing, especially considering that 98% of tree fall events were not directly linked to rainfall in the previous sections. Further clarification on this discrepancy would be beneficial.
That's right. It is interesting that heavy rainfalls, although they only directly affect 2% of tree falls, can increase the probability of their occurrence. However, it must be said that - as written - it is only a relative increase to the case without an associated heavy rainfall event. Also, both events (heavy rainfall and tree falls) are very rare events in relation to the route network and the time period in days. This means that the probability of an event occurring is still low.

Lines 352–353: "In the case of b) and e), the distance becomes greater at higher values, i.e., the higher the amount of accumulated precipitation, the more a heavy rainfall event increases the probability of occurrence of a flood or gravitational mass movement." --> It might be worthwhile for the authors to explore the findings of Saito et al. (2014; https://doi.org/10.1130/G35680.1), which suggest that increasing rainfall totals enhance landslide activity up to a certain threshold beyond which the effect does not apply. This could provide valuable insights into the study's analysis.
Thank you for the reference to the paper by Saito et al. (2014). We will be happy to include it in the discussion in the revised version.

Line 398: "susceptible" --> The use of "susceptible" might be slightly misleading, potentially being confused with the term 'landslide susceptibility.' Perhaps "prone" could be a more precise alternative, avoiding any ambiguity.
We will replace „susceptible“ by „prone“ in the revised version as proposed.

Lines 414-415: "for gravitational mass movements it was as much as 17 % (Figure 1)" --> The low percentage of gravitational mass movements attributed to heavy rainfall seems somewhat unexpected, given that rainfall or related floods are the main triggers for landslides in Germany. This observation suggests the 2-day threshold might be too restrictive. Extending this threshold could potentially reveal a more nuanced impact of rainfall on landslide occurrence. It's commonly suggested that lag times of 10 to 15 days are realistic, with some extreme cases even longer, which could be an important consideration for the study.
See response to reviewer RC1, comments on Methods, point 2.

Figures:
Figure 1 --> The resemblance between subplot d and f is quite notable. This observation raises an interesting question: might the authors consider the possibility that landslides along tracks are more influenced by flood processes than by rainfall alone? This could potentially be attributed to processes such as slope undercutting or toe removal by floodwaters. In times these floods might be caused by a rain event upstream that is spatially not overlapping with the landslide location. Further exploration of this hypothesis could provide valuable insights.
The good resemblance between subplot d and f is due to the years 2013 and 2016 where very rainy days/weeks occurred in May/June leading to a high number of heavy rainfall events and recorded

natural hazards along the German railway network. However, a spatial and temporal intersection of two processes could only observed for a few cases in the datasets.

Figure 2 --> It would be beneficial if the authors could provide a more detailed explanation of how the intersection depicted in this figure was calculated. This aspect seems crucial and might be more appropriately discussed in the results section to enhance the reader's understanding of the methodology. If it is discussed later than the figure's location, it might be an option to add a sentence summary in the caption.
See response to reviewer RC1, comments on Datasets, point 1. We will include a description on how the intersection was done in the revised version prior to the figure's location.

Figure 3 --> Currently, I find this figure somewhat challenging to interpret. Might the authors consider revising it to enhance its clarity and accessibility? Providing additional context or simplifying the presentation could improve its comprehensibility and overall impact on the reader's understanding.
In fact, we would like to leave the illustration as it is, as we cannot find a simpler representation for this complex issue. The figure actually only shows the occurrence of all three natural hazards in total (left bar), with (middle bar) and without (right bar) associated heavy rainfall events by season (colours).