General comments

The manuscript presents a Monte Carlo-based probabilistic framework that couples ground shaking, tsunami, liquefaction, lateral spreading, and landslides for cascading earthquake risk assessment, demonstrated on residential buildings in Napier, New Zealand, using a 100,000-year Hikurangi Subduction Zone catalogue. However, although the effort is highly appreciated, the work does not provide a meaningful innovation or a significant improvement over existing multi-hazard methodology.

We thank the reviewer for their time and thoughtful assessment of our work. While we acknowledge the reviewer's perspective, we respectfully believe that this study provides a valuable contribution by explicitly quantifying the role of cascading earthquake-induced hazards within a unified probabilistic framework. In particular, the work highlights how multiple interacting hazards can be consistently modelled and combined to assess their joint impact on risk.

Furthermore, to the best of our knowledge, this level of detail and integration has not yet been explored in the context of New Zealand. Given the relevance of cascading hazards in this region, the proposed framework contributes to improving risk quantification, supporting catastrophe preparedness, and enhancing understanding of regional hazard interactions.

Specific comments

1. The tsunami modelling relies on only 33 rupture scenarios, with 10 slip variations each, explicitly due to computational constraints. This small scenario set may under-represent the full epistemic and aleatory uncertainty in subduction tsunami generation.

    330 tsunami scenarios, all modelled on a fine resolution grid using the non-linear shallow wave equations, still amounts to a very large number of hydrodynamic tsunami models for a study such as this. So we would argue that the aleatory and epistemic uncertainty is taken in as much as is practical. We note that tsunami is not alone with this question. Being sure that you have fully incorporated these uncertainties is an issue for the other perils as well and for most hazard and risk studies in general. We would also note that the tsunami models are the only peril in this study where the physics of the process itself is taken into consideration. The other methods use empirically derived relations. So while they are less numerous, they have the advantage of being physics based. Whether a smaller number of physics based hazard models are better or worse for calculating risk than a much

larger number of simplified empirical ones is an interesting question, but beyond the scope of this paper. However, one of the main reasons for having both methods in the case study is simply to demonstrate that the framework is flexible enough to work with either approach and combine them together. We will add some comments to clarify this motivation to the revised paper.

2. Liquefaction and lateral spreading are modelled conditionally on shaking, yet the paper does not clearly state whether co-occurrence effects (e.g., lateral spreading exacerbating liquefaction damage) are captured or treated independently.

   Thank you for this comment. In the framework, liquefaction and lateral spreading are treated as separate hazards. While both are triggered by ground shaking and depend on geological (e.g., material type, age, cementation, and compaction) and geotechnical properties (e.g., soil strength and water saturation), lateral spreading additionally requires specific conditions such as ground slope or proximity to a free face.

   As a result, the two processes are modelled independently, although they share a common triggering mechanism through the same ground shaking field. The resulting damage states are then combined through the damage state harmonization procedure described above.

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3. The landslide damage model uses a rule-based approach with 3 damage states. Please comment more on the choice and on the damage model. No limitation are presented.

   Thank you for this comment. This damage model was adopted primarily due to the lack of more suitable models for New Zealand building typologies. Our intention was to avoid a purely binary representation of damage (i.e., no damage vs. complete damage) and instead include an intermediate damage state for buildings that are not fully covered by landslide runout. This limitation will be clearly acknowledged in the revised manuscript.

4. A justification for using HAZUS fragility functions in New Zealand should be given.
   Thank you for this comment. Due to the limited availability of fragility models for New Zealand residential buildings, we adopted HAZUS 2.1 functions, supported by similarities with local timber building typologies. We acknowledge that using US-

based models introduces uncertainty due to differences in construction practices and design standards. This limitation has been clarified in the manuscript, and we note that locally derived fragility functions would improve damage estimates in future work.

Revised text:
While HAZUS-based fragility functions provide a consistent and well-documented basis for damage estimation, their application to New Zealand building stock introduces uncertainty due to differences in construction practices, materials, and design standards. Although similarities exist for certain building typologies (e.g., timber structures), these models may not fully capture local vulnerability characteristics. The use of locally derived fragility functions, based on New Zealand-specific empirical or analytical data, would improve the representation of damage and reduce uncertainty in future applications.

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5. Residential building exposure is simply mentioned in the paper without a discussion of the structural typologies, and without any sensitivity or completeness analysis. Thank you for this comment. We will include a table summarizing the exposure classes and structural typologies of the residential building stock in Napier (see below).

   The methodology used to derive the exposure database, including data sources and underlying assumptions, is described in detail in Scheele et al. (2023). To avoid repetition and maintain a concise manuscript, these details are not reproduced here, and the reader is referred to the original study.

Construction Type	**Count**	**Count Percentage**
Brick Masonry	13,603	0.8%
Concrete Masonry	49,815	2.8%
Light Industrial	7,401	0.4%
Light Timber	1,635,250	91.7%
Reinforced Concrete Moment-Resisting Frame	7,156	0.4%
Reinforced Concrete Shear Wall	53,173	3.0%
Steel Braced Frame	12,836	0.7%
Steel Moment-Resisting Frame	253	0.0%
Tilt Up Panel	4,137	0.2%
Total	1,783,624	100%

6. The paper does not assess scalability or feasibility of the proposed methodology which is computationally cumbersome and may limit real-world applicability.

   Thank you for this comment. We will include a discussion on the scalability and feasibility of the proposed framework. In particular, we will highlight the data and computational requirements, as well as potential strategies for applying the approach in lower-resolution contexts and the associated uncertainties.

   The scalability of the proposed framework depends on the availability of high-resolution data and the computational demands of the hazard models. While this enables a detailed multi-hazard assessment, its application in other regions may be limited by data constraints.

   Simplified approaches using lower-resolution datasets could improve scalability but would introduce additional uncertainties. Among the hazards considered, tsunami modelling is the most computationally demanding, and reducing DEM resolution can lower computational cost at the expense of accuracy.

7. The combination of damage states from multiple hazards into a single harmonized DS lacks a rigorous and thorough approach.

   Thank you for this comment. The combination of damage states is handled through the damage state harmonization procedure, which maps damage from individual perils into a unified damage scale based on the fragility model definitions. This approach does not account for sequential weakening effects (e.g., earthquake damage increasing vulnerability to tsunami loads) except for structures which experience both significant liquefaction and ground shaking (as described in Section 3.2.7 in the main manuscript). We have clarified this limitation in the manuscript and added a reference to Petrone et al. (2020), which presents fragility functions for sequential earthquake–tsunami loading.

   Lines 364 to 369:
   In multi-hazard risk assessment, particularly when evaluating cascading impacts from cascading hazards, a key challenge arises from the need to integrate damage estimates derived from different fragility models, each with their own damage state definitions and granularity. This process, known as damage state harmonization, involves mapping and aligning the distinct damage classifications used for different perils into a unified

framework. While this approach enables the combination of damage from multiple hazards, it does not explicitly account for sequential weakening effects, where damage caused by one hazard (e.g., earthquake shaking) may increase vulnerability to subsequent hazards (e.g., tsunami loading). Such path-dependent damage processes are therefore not represented in the current implementation, although they have been explored in previous studies (e.g., Petrone et al., 2020).

Crescenzo Petrone, Tiziana Rossetto, Marco Baiguera, Camilo De la Barra Bustamante, Ioanna Ioannou, Fragility functions for a reinforced concrete structure subjected to earthquake and tsunami in sequence, Engineering Structures, Volume 205, 2020, 110120, ISSN 0141-0296, https://doi.org/10.1016/j.engstruct.2019.110120.

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8. Why is only the Hikurangi Subduction Zone (HSZ) taken into account? A seismic hazard disaggregation should be presented to justify the choice.
   We modelled the Hikurangi Subduction Zone as a separated seismic source to quantify the effect of the largest seismic source threatening New Zealand, in particular Napier. The model is based on the last version of the NZ NSHM, as detailed in Gerstenberger et al 2022. The NSHM reports include numerous disaggregations which show that HSZ is a significant contributor to seismic hazard, so we do not include them here to conserve space. We will ensure that there are appropriate references to them in the revised paper.

   We also note that the primary aim of the case study is to demonstrate the feasibility of the framework, rather than a comprehensive study of all the sources of cascading earthquake risk to Napier. The latter study would have to include other earthquake sources and probably other earthquake induced perils (e.g. subsidence loss or fire following earthquake). However, the framework has the potential to be used for such a study in future work.

9. How are the epistemic uncertainties from the fragility functions or hazard estimations taken into account?

   Uncertainty in fragility functions is quantified through random sampling of the damage state probability density function defined. Earthquake shaking includes this uncertainty in the stochastic event set generation, where every event footprint has an already sampled acceleration. Liquefaction uncertainty is included through grouping borehole information within an area where the geological conditions are expected to be similar (liquefaction susceptibility zones), LSN values were shown to be normally distributed within each zone. Lateral spreading follows the same phenomena as the liquefaction modelling, where the volumetric strain of the soil (where its uncertainty is gathered through the normal distribution of the volumetric strain values gathered in the boreholes of each zone), the slope and the distance from a free face are they key factors for determining the lateral displacement index, also normally distributed for each liquefaction susceptibility zone.

10. Extensive geotechnical investigations are mentioned in the paper, yet no clear presentation is shown.
    Thank you for this comment. The manuscript refers to two main studies in which the geotechnical investigations are described in detail (Dellow et al., 2003; Griffin, 2024). These studies present both the underlying investigations and the associated liquefaction analyses. To avoid unnecessary repetition and limit the length of the manuscript, these details are not reproduced here, and the manuscript focuses in the implementation of these investigations into the cascading hazards model.

11. The study stops at damage states and ratios without translating them into annualized losses, repair costs, downtime, or social impacts:

    Thank you for this comment. We intentionally limited the scope of the study to damage states and damage ratios to avoid presenting loss estimates in monetary terms, which can be sensitive and may quickly become outdated due to economic factors such as inflation and currency fluctuations.

    We acknowledge that extending the analysis to include annualized losses, repair costs, downtime, or social impacts would provide additional valuable insights. While these aspects were of interest, they were beyond the scope of the current study, particularly given the length of the manuscript. We consider this a relevant direction for future work.

12. The authors should explicitly address non-structural damage due to ground shaking. -
    Thank you for this comment. Non-structural damage due to ground shaking is accounted for within Damage States 1 and 2, which include effects such as broken windows and cladding damage. This is described in the Appendix (Section A7), and we will ensure that this is more clearly referenced in the main text.

13. Since less than 20% are exposed to lateral spreading or landslide, it is obvious that the most important hazards are ground shaking and liquefaction.

    Thank you for this comment. We respectfully note that this interpretation is not entirely accurate. While it is true that a smaller proportion of buildings is exposed to lateral spreading or landslides, their contribution to overall risk is not solely determined by exposure extent.

Lateral spreading and liquefaction, as modelled in this study, are cascading hazards triggered by earthquake shaking, but their occurrence and impact are also strongly controlled by local geotechnical conditions. For example, denser, more cemented, and more compacted soils are less susceptible to liquefaction.

In the case of Napier, the combination of shaking intensity and local soil characteristics leads to liquefaction being a dominant hazard. However, this may not be the case in other regions, where similar exposure exists but shaking levels or soil conditions differ, potentially leading to other hazards (e.g., landslides) dominating the damage.

14. Landslide hazard modelling consists only on open-slope dry rock and debris avalanches. Is this appropriate for Napier? For other sites, can the modelling be extended?

    We acknowledge that the landslide hazard modelling implemented in this study focuses on open slope dry rock and debris avalanche runout mechanisms. For the Napier study area, we consider this appropriate and defensible given the earthquake induced cascading hazard context and available data at the time of the analysis. Empirical 'dry' runout relationships provide a reasonable approximation of landslide mobility during rapid, seismically triggered failures where excess pore pressures may not fully develop at initiation. We agree that landslides under partially or fully saturated conditions may also be relevant for Napier and other regions – however we did not have the empirical runout data for 'wet' earthquake induced landslides at the time of this study. As the modelling approach adopted in this study is framework-based rather than method-specific, the landslide hazard workflow can be readily modified to incorporate alternative runout models or triggering assumptions (e.g. wet or fully saturated conditions) as appropriate empirical or physically based relationships become available.

15. What does "Internally consistent framework" actually mean? Could the authors extend the definition?

    We were referring to consistency across the different cascading earthquake perils caused by the triggering event. We propose to make this clearer in the revised paper by adding the following lines to Section 1.3:

> *The key advantage, and novelty, of the proposed framework lies in the generation of hazard intensities that are internally consistent across all perils within each simulated earthquake event. Here, internal consistency refers to the conditional dependence of all cascading hazards on a common set of event-specific ground motion parameters and spatial footprint, ensuring coherence across perils and locations for a given realisation. In contrast to approaches that sample hazards independently, this framework derives secondary perils (e.g., liquefaction, landslides, lateral spreading) directly from the primary hazard fields (ground shaking and tsunami), which serve as inputs to both hazard-specific models and subsequent fragility assessments.*
> *As a result, all sampled hazard intensities and damage states follow a correlated cascade, where dependencies are preserved throughout the modelling chain. For example, damage arising from landslides and lateral spreading is jointly conditioned on the same underlying ground motion intensity (e.g., PGA), rather than being treated as independent realisations. This approach reduces artificial variability introduced by independent sampling and produces more physically consistent event scenarios. The process is repeated across all stochastic event sets (SES), enabling the construction of long-term, statistically robust hazard and damage distributions that capture both frequency and interdependence among hazards.*

In my opinion, before the work can be considered for publication, the authors should substantially strengthen the methodological justification, expand the modelling components, clarify assumptions, and demonstrate the added value and scalability of the proposed framework. Addressing the specific points listed above would greatly improve the scientific contribution and reliability of the study.

Thank you for your thorough review and constructive suggestions. We believe that the revisions outlined above address these points by strengthening the methodological justification, clarifying key assumptions, and further demonstrating the value and applicability of the proposed framework.