



An internally consistent framework for calculating cascading probabilistic earthquake risk and its application to a case study in New Zealand

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Abstract. Quantifying the combined effects of earthquakes and their cascading hazards is essential for realistic risk assessment, yet most existing multi-hazard frameworks either neglect the correlations between cascading perils or represent them using simplified assumptions. Dynamic frameworks that explicitly correlate hazard intensities and their uncertainties across cascading perils provide more consistent and physically plausible impact estimates, offering greater value for resilience planning and risk management.

This study introduces a probabilistic risk assessment framework that integrates ground shaking, tsunami inundation, liquefaction, landslides, and their combined impacts into a unified modelling approach. The key methodological innovation is a fully correlated Monte Carlo framework that propagates uncertainty from earthquake rupture through sequential hazard models (ground shaking, tsunami, liquefaction, and landslides) to asset damage, preserving the conditional dependence between primary and secondary hazards at every stage of the simulation. This enables physically consistent realization-by-realization estimates of cascading losses rather than combining independently simulated hazards.

The framework was tested in Napier, a city of 65 000 inhabitants situated directly above the Hikurangi Subduction Zone (HSZ), New Zealand's largest earthquake source with an estimated maximum credible moment magnitude (M_w) ~ 9.1 . A 100 000-year stochastic catalogue of ruptures was generated and applied to ~ 30 000 residential buildings, with ground shaking, tsunami inundation, liquefaction severity, and landslide runouts explicitly modelled.

Results include damage state and damage ratio metrics for individual and combined perils, allowing attribution of losses

across hazards. Ground shaking and liquefaction contribute approximately 60 % of the average annual building damage, with lateral spreading accounting for a further ~ 35 %, while tsunami contributes less than 3 % on average. However, for very rare events (return periods > 10 000 years), tsunami losses become comparable to those from ground shaking and liquefaction, demonstrating the importance of explicitly modelling cascading hazards. The framework provides decision makers, urban planners, and the (re)insurance sector with actionable metrics to guide resilience investments, refine underwriting, and minimize losses from cascading hazard events.

1 Introduction

Megathrust faults along the interface of subducting plates are responsible for the largest and most powerful earthquakes in the world, such as the 2004 M_w 9.3 Sumatra, 2010 M_w 8.8 Chile, 2011 M_w 9.1 Tohoku (Japan) and 2025 M_w 8.8 Kamchatka earthquakes. The Hikurangi Subduction Zone (HSZ), where the western Pacific Plate subducts under the Australian Plate off the east coast of the North Island of New Zealand, is thus potentially the most significant source of earthquake hazard and risk in New Zealand (Fig. 1). An earthquake on the Hikurangi margin could trigger a cascading sequence of hazards that would have a significant impact on New Zealand communities, assets, and the national economy. For example, a large earthquake could trigger widespread shaking, landslides, tsunami, fires, onshore ground subsidence, liquefac-

tion, and further large earthquakes via a prolonged sequence of aftershocks. These effects could then create their own cascading series of further potential impacts. An earthquake on the HSZ is one of the most likely sources of offshore tsunami hazard for the several major New Zealand cities on the North Island (Power et al., 2022) and it is also one of the largest single sources of seismic hazard to these cities, including New Zealand's capital city Wellington (Gerstenberger et al., 2022). To better prepare for, and mitigate, the effects of a large earthquake on the HSZ as many as possible of the combined perils that could be caused by the earthquake should therefore be considered.

Natural hazard risk assessments are traditionally carried out on individual hazards in isolation. This type of approach can be referred to as “single hazard” as opposed to a more holistic “multi-hazard” approach. Global scientific interest has been building over the last few years toward improving the quantification of risk by taking into account the potentially disastrous combination of multiple hazards, where the interactions between perils, or between cascading perils, are considered (e.g., Kappes et al., 2012; Zharikova et al., 2020). For example, the necessity for a “holistic and multi-hazard approach to disaster risk management” (United Nations ISDR, 2007) has been called for as part of the Hyogo Framework for Action. The 2011 M_w 9.1 Tohoku earthquake and subsequent tsunami precipitating the Fukushima nuclear disaster (Pescaroli and Alexander, 2015), the 2018 M_w 7.5 Palu earthquake (severe shaking and tsunamis with extensive landslides, liquefaction and mudflows; Goda et al., 2019, Yolsal-Çevikbilen and Taymaz, 2019) and the 2008 M_w 7.9 Wenchuan earthquake with seven episodes of extraordinary hazards impacting the Sichuan area (earthquake, multiple large landslides, dam-breaching floods, large-scale debris flows, severe sedimentation, change of river course, and flooding/scouring; Zhang et al., 2014; Fan et al., 2019) are three global examples highlighting the amplifying effect of cascading and multisource hazard systems. New Zealand has also experienced the disruptive effects of multi-hazard and cascading events. For example, the 2010–2012 Canterbury earthquake sequence resulted in widespread ground shaking, landslides, and liquefaction, while the 2016 Kaikōura earthquake triggered a cascade of hazards, including strong ground shaking, landslides, tsunami, landslide dam formation, and floodplain subsidence (Hughes et al., 2015; Robinson and Rosser, 2017). Cyclone Gabriel 2023 caused flood and rainfall induced landslides in New Zealand's North Island (Pelmar et al., 2026) – plus cascading impact to infrastructure. Interactions within and across possible event chains can be complex and can involve a range of both geological and meteorological perils.

For the purposes of this paper, we define “cascading hazard” to be a hazard which has a causal link to the triggering event, possible via other perils. We are not including in this study the potential impact from coincidental perils, such as a tsunami that coincidentally arrives at the same time as

equinox high tide or storm surge, or any changes to the risk due to long-term changes like, for example, the climate.

1.1 Multi-hazard Risk Assessments

Existing methods for multi-hazard risk assessment can be classified into qualitative, semi-quantitative and quantitative (Kappes et al., 2012; Zharikova et al., 2020). For qualitative methods the hazard intensity and recurrence interval limits are predefined and are then used to classify each of the perils into several classes. The value boundaries are usually determined by the location or objectives of the assessment. However, it is difficult to compare information from different sources in these types of assessments since most assessments have different criteria (Marzocchi et al., 2009).

Semi-quantitative methods typically use index-based approaches to represent risk on a standardized numerical scale (Kappes et al., 2012). With indices, the risk is given a score usually on a continuum. For example, this score could be calculated by multiplying the frequency of the peril per annum by the number of people (or the area) affected by it. If the index is needed for multiple perils combined, they are usually summed together from the individual perils. Both qualitative and semi-quantitative methods treat multiple perils as being independent. It is therefore difficult to consider the relationship between the perils within these frameworks.

In the context of risk reduction, quantitative methods offer advantage with the ability to quantify impact or risks and evaluate risk reduction measures thereby supporting decision making. Tilloy et al. (2019) did an extensive review of quantitative methods dealing with interconnected hazard and classified quantitative approaches into three techniques: stochastic, empirical, and mechanistic. Stochastic methods consider the statistical dependency between occurrence and intensity of hazards. For stochastic methods, the purpose is either to model the distribution of each individual hazard (Hao and Singh, 2016; Liu et al., 2018), or to model the joint probability between hazards (Sadegh et al., 2018). The empirical method uses existing datasets to fit probability distributions. The accuracy of the fit can be quantified using dependence measures like Pearson or Spearman (Czado, 2019), or regressions (Petroliagkis et al., 2016). The limitation of the empirical method is its dependency on data, and data is often limited in number due to rarity of mega events occurrence and damage information recorded. Mechanistic methods have been widely used by risk scientists for computing the potential impact of natural hazard events. However, the intensive nature of the computation makes them difficult to use for probabilistic risk assessment and hence there can be bias toward a particular set of outcomes (Geist et al., 2009). Tocchi et al. (2023) propose a multi-risk framework by integrating probabilistic hazard data (earthquakes and floods) with exposure and physical/social vulnerability indicators at the municipal level. A weighted, normalized aggregation produces a composite risk index to support disaster

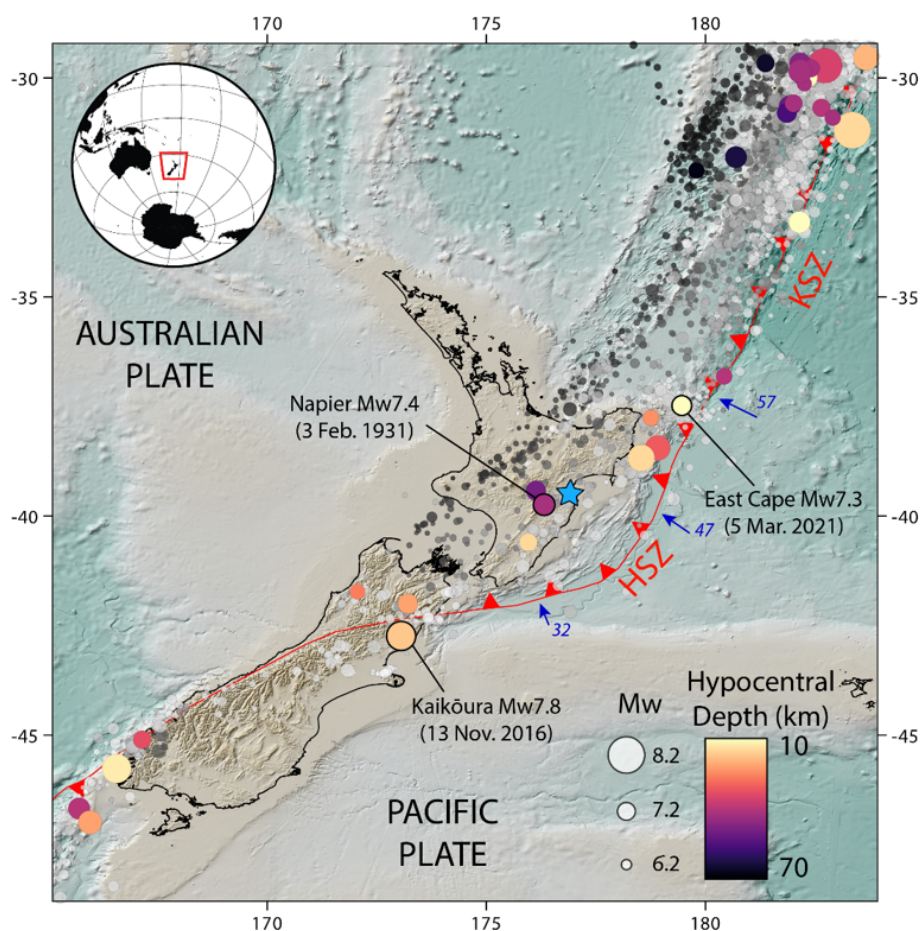


Figure 1. Seismotectonic setting of New Zealand, showing the subduction boundary between the Pacific and Australian plates. Grey circles indicate earthquakes with moment magnitudes of $5.0 \leq M_w < 7.0$ since 1970, whereas coloured circles indicate $M_w \geq 7.0$ earthquakes since 1900 (USGS catalogue). Blue arrows show the relative plate convergence rates (cm yr^{-1}), and red triangles indicate the orientation of the subduction zones. The blue star marks the location of Napier. Hikurangi Subduction Zone (HSZ) and Kermadec Subduction Zone (KSZ) denote the Hikurangi and Kermadec subduction zones, respectively. Convergence rates are adapted from Clark et al. (2019).

risk reduction prioritization. Recent reviews have also highlighted the need for probabilistic frameworks capable of representing cascading hazard interactions and propagating uncertainty consistently across hazard, vulnerability, and loss models (Goda and De Risi, 2023; Behrens et al., 2021).

Existing probabilistic earthquake multi-hazard studies have progressively expanded the range of hazards considered; however, they generally involve a trade-off between the number of cascading hazards represented, the treatment of uncertainty, and the ability to quantify long-term probabilistic risk.

1.2 Earthquake Hazard and Risk Assessment

Probabilistic earthquake risk assessments generally focus on one earthquake peril, typically seismic stochastic models with many of the parameters constrained through empirical methods and, sometimes, physical modelling. For probabilistic seismic hazard assessments, it is common practice to

model the expected level of ground shaking and its variability due to site effects and aleatory uncertainty using Ground Motion Prediction Equations (GMPEs) across a region. Examples of these types of models span local (e.g., Burbidge et al., 2019), national (e.g., Burbidge, 2012; Leonard et al., 2014; Gerstenberger et al., 2022) to global scale (e.g., Johnson et al., 2023).

It is much rarer for a probabilistic earthquake impact or risk assessment to consider a combination of earthquake induced perils. The most common method to incorporate the cascading effects of earthquakes is to focus on one or two earthquake scenarios and cascades (e.g., Power et al., 2018; Burbidge et al., 2019; Kianirad et al., 2019). These are often done for a particular cascade of secondary effects (e.g., Power et al., 2018) in a deterministic or expert judgment-based approach or are done probabilistically but without fully quantifying the uncertainty and variability in the final loss estimates (e.g., Kianirad et al., 2019). The paper by Iannacone

et al. (2024) introduces a simulation-based methodology to generate multi-hazard event sets over a system's life cycle, accounting for Level 1 (occurrence-based) interactions. Utilizing competing Poisson processes and sequential Monte Carlo sampling, the approach models concurrent, triggering, and altering interactions among hazards, producing realistic event sequences.

Two earthquake-induced perils that have been combined to calculate the combined probabilistic losses are those from strong ground shaking and tsunami (e.g., Goda 2020). In Goda (2020) the earthquake occurrence was represented by a set of multiple renewal models, implemented using a logic-tree approach, whereas earthquake rupture characterization is based on stochastic source models with variable fault geometry and heterogeneous slip distribution. By integrating these hazard components with seismic and tsunami fragility functions, the author calculated the time dependent multi-hazard loss potential from the combined impact of ground shaking and tsunami for some coastal communities in Japan. However, the framework was limited to the direct impacts of ground shaking and tsunami, and did not account for earthquake-induced ground failure processes such as liquefaction, lateral spreading, and landslides. Consequently, it did not capture the full cascade of earthquake-induced hazards that can substantially influence losses, particularly in regions such as New Zealand where these secondary hazards are common. More recently, Goda and De Risi (2023) reviewed the evolution of earthquake–tsunami catastrophe modelling and identified the explicit representation of cascading and compounding hazards as one of the key directions for future probabilistic risk assessment.

One probabilistic approach that captures the uncertainties in the ground motion modelling and its variability across the sites, the triggered cascading hazards, and the uncertainties in the asset's performance for a specific earthquake is presented by Moratalla and Uma (2023). In that study they first created an event tree of possible cascades from a M_w 8.4 earthquake offshore Napier and then used Monte Carlo Simulation to determine a range of possible series of disruption outcomes to the road network for that specific earthquake. The study included the combined effect of shaking, liquefaction, lateral spreading, landslides and building collapse on the road network, but did not include tsunamis or consider a range of possible earthquakes. It thus could not calculate impact metrics such as annualized probabilistic loss or risk exceedance curves from the combined effects of these earthquakes induced perils which require assessment of the risk across a range of earthquakes, rather than just one scenario.

Dunant et al. (2021) proposed a novel method for probabilistic cascading multi-hazard risk assessments using graph theory. The framework was tested in Franz Josef, New Zealand, and included impacts from earthquakes, landslides, and floods to housing and road infrastructure. One major advance provided by that study was the inclusion of non-dependent perils such as geological and meteorological haz-

ards in a multi-hazard approach capable of combining them. However, the emphasis of that framework was on representing interactions between different hazard types rather than preserving the realization-by-realization conditional dependence between earthquake source characteristics, cascading hazard intensities, and asset damage.

1.3 Objectives of this study

This study develops a probabilistic framework for quantifying the combined physical damage and loss ratios arising from earthquake-induced cascading hazards, including ground shaking, tsunami inundation, liquefaction, lateral spreading, and landslides. The framework propagates uncertainties consistently through the hazard and damage modelling chain using a fully correlated Monte Carlo simulation, enabling the estimation of physically consistent multi-hazard risk metrics from a stochastic earthquake catalogue.

The framework is demonstrated through a case study of residential buildings in Napier City, New Zealand, exposed to earthquakes generated by the Hikurangi Subduction Zone (Sect. 3). The resulting risk metrics support applications including land-use planning, emergency management, resilience assessment, mitigation prioritization, and insurance decision-making.

2 Methodology

2.1 A Monte-Carlo based approach for cascading hazards

In this study, we propose a Monte Carlo Simulation (MCS)-based framework to estimate the impact of earthquakes and their cascading hazards on the built environment. The framework is designed to model the effects of ground shaking, liquefaction, tsunami inundation, lateral spreading, and earthquake-induced landslides, using a synthetic catalogue of earthquakes. The results generated include Damage States (DS), which represent discrete levels of structural damage ranging from slight to complete. These are harmonized across all perils using a unified five-level classification developed in this study, based on existing fragility models such as those in FEMA (2013) and Suppasri et al. (2012). In addition, the framework estimates Mean Damage Ratios (MDRs) – representing the proportion of repair cost relative to full replacement – assigned to each harmonized DS using values derived from the HAZUS methodology.

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 haz-

ards 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.

2.2 Required Inputs

The implementation of the framework requires the 6 following components:

1. *Earthquake Catalogue.* A stochastic catalogue of earthquakes affecting the study area, including rupture geometries, magnitudes, and recurrence information. For example, in the case study presented in this study we use a 100 000-year synthetic catalogue of Hikurangi Subduction Zone (HSZ) earthquakes, developed using Event-Based Probabilistic Seismic Hazard Assessment (PSHA), the magnitude-frequency distribution (MFD) based on the 2022 New Zealand National Seismic Hazard Model (Gerstenberger et al., 2022) and implemented in OpenQuake (GEM, 2019).
2. *Ground Shaking Footprints.* Ground motion intensity fields (e.g., Peak Ground Acceleration, PGA) generated for each event in the earthquake catalogue using Ground Motion Prediction Equations (GMPEs).
3. *Tsunami Inundation Depths.* Inundation models triggered by each earthquake rupture capable of inundating the region of interest, providing water depth footprints.
4. *Cascading Ground Shaking Hazard Models.* These include models for earthquake-induced landslides, lateral spreading, and liquefaction, which compute hazard intensities conditionally based on ground shaking.
5. *Fragility Functions.* Harmonised peril-specific fragility models that relate hazard intensities to structural damage probabilities for different building types.
6. *Exposure Model.* A dataset of buildings including location and construction characteristics, used to assign appropriate fragility functions.

2.3 Framework Workflow

Each earthquake in the catalogue is analysed using an MCS-based approach, which simulates damage from each individual peril and the combined effects of cascading hazards. Across all modules, hazard intensities are derived consistently from the same simulated earthquake event. Ground shaking intensities (e.g., PGA) modelled act as inputs for ground-failure-related hazards such as liquefaction, lateral spreading, and landslides, while tsunami inundation is modelled directly from the earthquake source parameters. A detailed description of the hazard-specific models and their parameterisation is provided in the Supplement. The overall procedure, detailed in steps 1–9 and illustrated in Fig. 2, is as follows:

1. *Event Selection.* A single earthquake event is selected from the stochastic catalogue (see Sect. 3.1).
2. *Shaking Intensity Modeling.* GMPEs are used to generate a ground shaking footprint (e.g., PGA) for the event at all exposure locations.
3. *Tsunami Inundation Modeling.* The earthquake ruptures are used to model tsunami generation and inundation depths, which are mapped to exposed assets (Sect. 3.3).
4. *Liquefaction Severity Modeling.* Liquefaction Severity Number (LSN, Tonkin & Taylor Ltd., 2013) is calculated using local geotechnical conditions and PGA derived from the ground shaking modelling in Step 2. LSN is sampled from a Poisson distribution within predefined susceptibility zones (Sect. 3.2.3), for the modelled PGA and earthquake magnitude.
5. *Lateral Spreading Modeling.* Lateral Displacement Index (LDI; Zhang et al., 2004) is calculated per site using geotechnical data, slope angle, distance to a free face, and PGA derived from Step 2. The resulting displacements are assigned to exposed buildings (Sect. 3.2.4).
6. *Landslide Modeling.* Earthquake-Induced Landslide Probabilities (EILP) are calculated from an earthquake-induced landslide susceptibility model to identify potential landslide source areas (Massey et al., 2021b, 2022). This model uses PGA derived from the ground shaking field in Step 2 as input at each source location. Landslide runout modelling identifies potential debris-inundation areas should a landslide occur (Brideau et al., 2020, 2021; Massey et al., 2021a). The resulting probabilities are assigned to exposed buildings (Sect. 3.2.5).
7. *Damage Estimation.* For each peril, the corresponding hazard intensity at each building is passed to the assigned fragility function to compute DS probabilities. A uniform random number is used to sample the final DS from these probabilities.

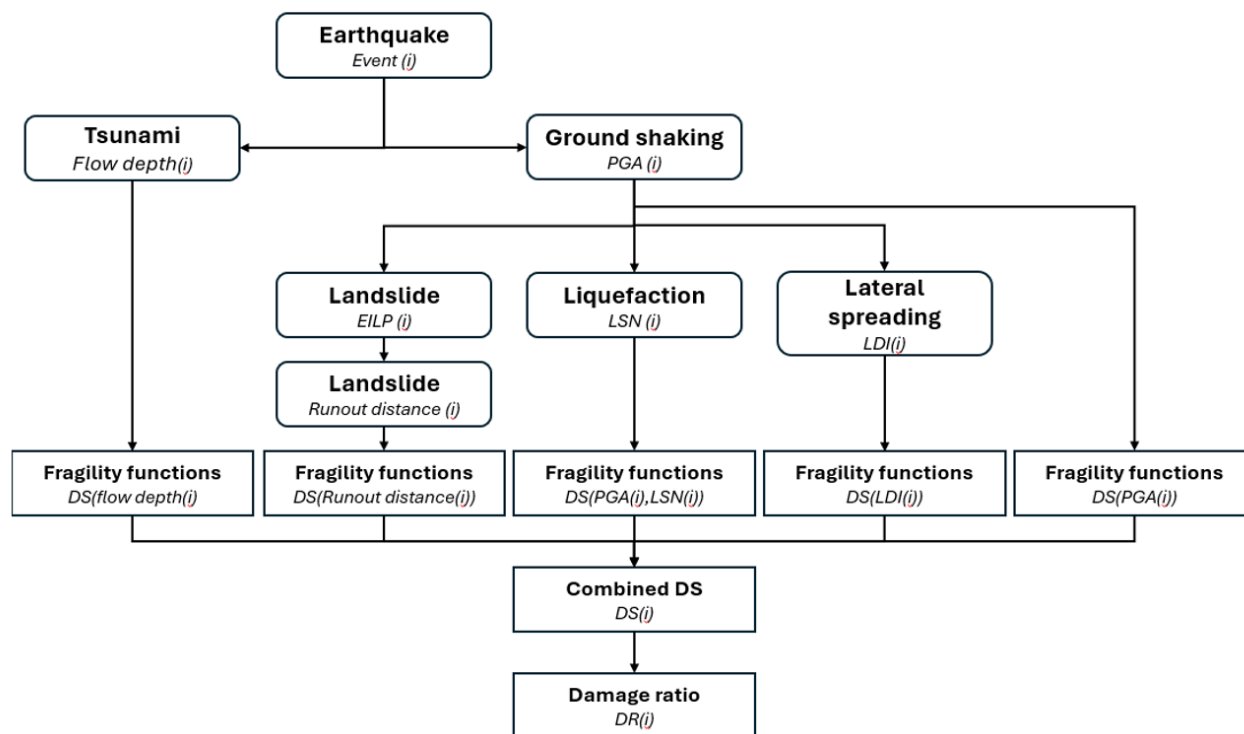


Figure 2. Damage state (DS) and damage ratio (DR) calculation diagram for each simulation (i) performed for every event in the stochastic catalogue. Monte Carlo sampling is performed between each stage of the workflow, while the hazard realizations remain conditioned on the same earthquake event, thereby preserving the correlations between cascading hazards.

8. **Damage State Harmonization.** DSs from all perils are combined into a single harmonized damage state for each asset, reflecting the aggregated effects of shaking, tsunami, and secondary seismic hazards (Sect. 3.2.7).
9. **Damage Ratio Assignment to Damage States.** Damage ratios (DRs) represent repair costs as a percentage of a building's replacement value. Once the harmonized DS is determined for each asset, a corresponding DR is assigned. This is done by mapping each DS to a pre-defined MDR, following established relationships such as those proposed in the HAZUS methodology (FEMA, 2020). The MDR values vary by building type and occupancy class, and are typically expressed as a fraction of total replacement cost (e.g., DS1 = 2 %, DS5 = 100 %). In this framework, DRs are sampled from a defined distribution (e.g., triangular or normal) centered on the mean, enabling further use in loss estimation or economic impact analysis if desired.

Across all modules, hazard intensities are derived consistently from the same simulated earthquake event. Ground shaking intensities (e.g., PGA) act as inputs for ground-failure-related hazards such as liquefaction, lateral spreading, and landslides, while tsunami inundation is modelled directly from the earthquake source parameters.

For each event in the catalogue, multiple MCSs are performed to sample hazard intensities from their respective uncertainty distributions. Damage states are then sampled from the corresponding damage state probabilities, resulting in a range of possible damage scenarios for each event. This probabilistic sampling approach enables the representation of uncertainty in both hazard and impact, generating multiple realisations of physically consistent damage outcomes. A detailed description of the hazard-specific models and their parameterization is provided in the Supplement.

The number of MCSs required to achieve stable mean damage estimates for each event in the catalogue can be determined via convergence analysis. Due to the inclusion of multiple hazards and uncertainty sources, the minimum number of scenarios (N) needed for convergence is typically higher than in single-peril models.

3 Case study: Napier City

3.1 Overview of the study area

Napier City was selected as a pilot study area to test the cascading hazards framework developed in this work. Situated on the eastern coast of New Zealand's North Island, the city lies directly above the Hikurangi Subduction Zone interface (Williams et al., 2013) and less than 200 km from the

subduction trench, making it highly exposed to seismic and tsunami hazards, as well as to cascading effects arising from intense ground shaking (as shown by the historical examples in Sect. S1 in the Supplement, Callaghan, 1933; Dowrick, 1998).

For the purpose of the case study, the HSZ was modelled as the sole seismic source in order to isolate and quantify the contribution of subduction interface earthquakes to seismic and tsunami risk in Napier. The adopted parameters and recurrence characteristics follow the latest New Zealand National Seismic Hazard Model framework (Gerstenberger et al., 2022), in which the Hikurangi subduction interface is identified as a major contributor to seismic hazard in the Hawke's Bay region.

Liquefaction represents a major threat due to the prevalence of loose sedimentary deposits and a high groundwater table (Fairless and Berrill, 1984; Dellow et al., 1999), while the proximity of water channels to residential areas enhances the potential for lateral spreading. The city also exhibits potential for landslides triggered by seismic shaking, particularly on surrounding slopes. Furthermore, its coastal position facing the Hikurangi Subduction Zone increases vulnerability to earthquake-induced tsunamis, as well as to possible submarine landslide-generated tsunamis. The coexistence and interdependence of these hazards underscore Napier's pronounced susceptibility to cascading impacts, justifying its selection for the application and validation of the proposed framework. Sect. 3, along with the corresponding Supplement (Sects. S1 to S8), include the details of the hazards, exposure and fragility modelling for this case study.

3.2 Hazard modelling

3.2.1 Earthquake

For this case study we generated a 100 000-years stochastic earthquake catalogue using the Hikurangi Subduction Zone (HSZ) as the sole seismic source (Williams et al., 2013). The catalogue was produced with OpenQuake (GEM, 2019), using the Hikurangi Magnitude–Frequency Distribution (Gutenberg–Richter a and b values) based on the Distributed Seismicity Model of the New Zealand National Seismic Hazard Model (Rollins et al., 2022). The HSZ was assumed capable of hosting events up to M_w 9.1, and Ground Motion Prediction Equations (GMPEs) for subduction interface events were selected following the latest model recommendations (Gerstenberger et al., 2022), with site effects incorporated through the mean shear-wave velocity in the upper 30 m (V_{s30}). The subduction interface geometry, recurrence implementation, and ground-motion modelling details are described in more detail in Sect. S2.

3.2.2 Tsunami

To calculate the tsunami inundation, we first stochastically generate slip distributions for a set of earthquakes of different magnitudes at a set of points distributed along the HSZ. Simulating tsunami inundations with a hydrodynamic model at the resolution used in this study comes at a considerable computational cost. This meant that we had to limit the number of tsunami models in order for the project to be tractable. To help with this, the scenarios were carefully selected to include only those ruptures most likely to generate inundation in Napier, taking into consideration the city's unique topographic setting, notably which coast acts as a natural barrier against tsunamis of small to moderate heights (e.g., elevated topography and presence of large coastal gravel ridges). In the end, 33 scenarios were selected spaced with centroids spread along the HSZ. The scenarios ranged in moment magnitude from 7.5 to 9.1. For each of these 33 scenarios, 10 variations of non-uniform slip distribution were calculated, and the resulting 330 models were then run through to inundation using the tsunami hydrodynamic model COMCOT (Wang and Power, 2011) on a set of nested grids, including a 10 m spatial resolution grid covering Napier and its neighborhood. The flow depth at each building in the city was then extracted from each of these tsunami scenarios. During the MCS process, described below, the tsunami scenario for a particular earthquake realisation is randomly chosen from the 10 possible slip variations in the tsunami inundation model library which were closest to the epicentre and magnitude of the earthquake in the stochastic catalogue. For the purposes of this case study, each of the 10 possible slip variations is assumed to be equally likely. Further details of how the tsunami scenarios were created can be found in Sect. S3.

Although the number of tsunami simulations was constrained by the high computational cost of fine-resolution hydrodynamic modelling, the 330 considered scenarios still represent a substantial suite of physics-based inundation models. The selected scenarios were designed to capture the principal aleatory and epistemic uncertainties associated with tsunami generation and inundation within practical computational limits. Unlike many other hazard assessment approaches that rely on empirical relationships, the tsunami simulations explicitly resolve the physical processes governing tsunami propagation and inundation through the non-linear shallow water equations.

The current framework does not account for concurrent coastal processes (e.g., tides or storm surge) or long-term changes such as sea-level rise, tectonic uplift or subsidence. These factors may influence tsunami inundation patterns and associated damage, particularly in low-lying coastal areas. Incorporating sea-level rise scenarios could modify inundation extents and depths, potentially increasing exposure and losses. Extending the framework to include these effects would improve its applicability for long-term risk assessment and climate-informed urban planning.

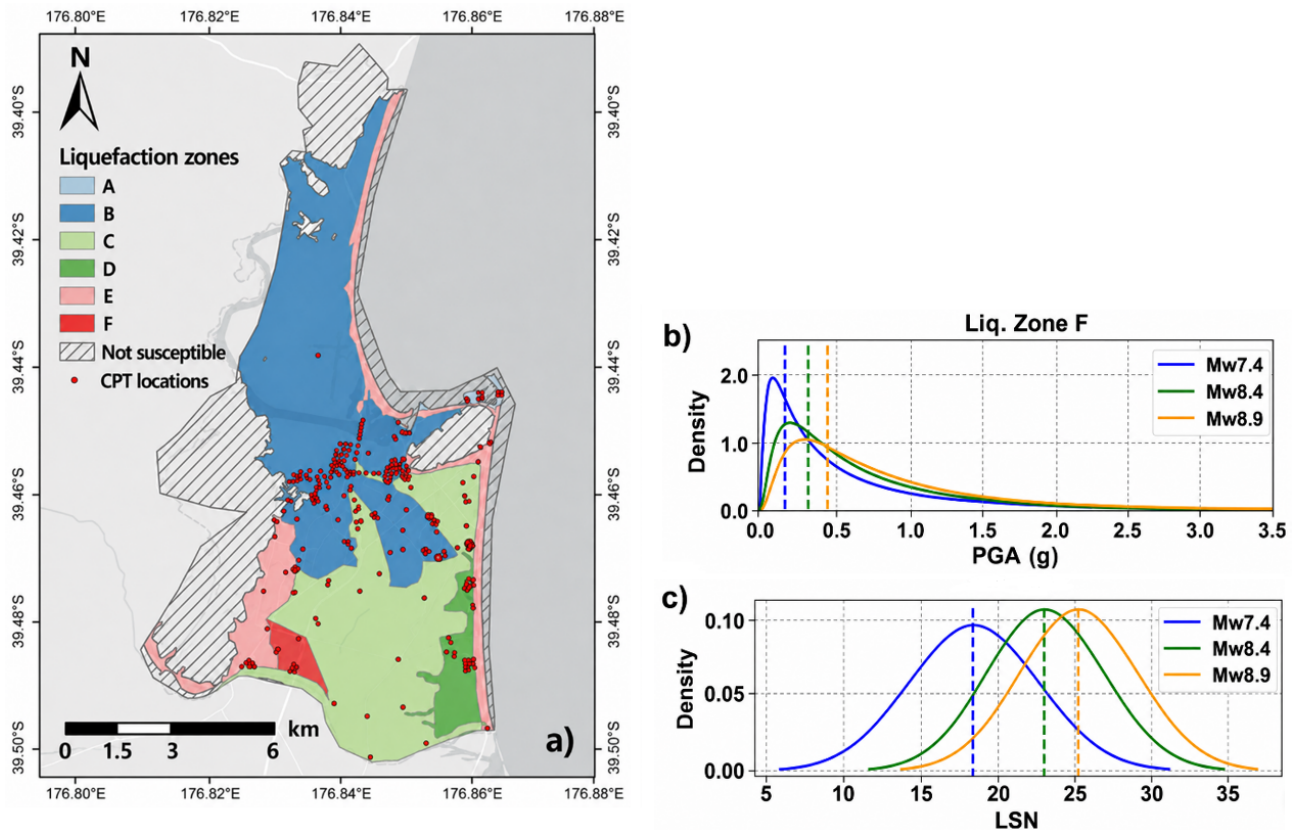


Figure 3. (a) The Liquefaction Zones in the study are and the CPT locations that were used to derive them. (b) Peak ground Acceleration (PGA), (c) LSN distributions for zone F, for three example earthquake scenarios. Results for the rest of the zones are shown in Fig. S7.

3.2.3 Liquefaction

Liquefaction susceptibility zones defined by Rosser and Dellow (2017) were adopted to represent the spatial variability of liquefaction potential across Napier City. These zones, derived from geomorphological and sedimentological mapping, were used to delineate six liquefaction susceptibility areas in this study (Fig. 3a). To enhance the confidence in the Rosser and Dellow (2017) maps, seventeen additional cone penetration tests (CPTs) were analyzed for liquefaction susceptibility, using the existing parameters from the 2017 work and new knowledge gained since then (Griffin, 2024).

For each susceptibility zone, borehole data were compiled and grouped, and their properties within the upper 10 m were analyzed to characterize material variability. The corresponding CPT-derived Liquefaction Severity Number (LSN: Tonkin & Taylor Ltd., 2013) values were fitted to normal distributions, enabling a probabilistic representation of LSN variability within each zone. This statistical approach captures the spatial variability in liquefaction response across Napier and is used in the subsequent hazard and risk analyses.

Further methodological details, including CPT processing, software implementation, and the derivation of LSN distributions under variable earthquake scenarios, are provided in Sect. S4.

butions under variable earthquake scenarios, are provided in Sect. S4.

3.2.4 Lateral spreading

Liquefaction induced lateral displacements were estimated based on the method proposed by Zhang et al. (2004) to first calculate the Lateral Displacement Index (LDI) and further include the influence of ground slope with and without a free face. This approach is recommended to be used for earthquake magnitudes between 6.4 and 9.2, and peak ground accelerations between 0.19 and 0.6 g. Areas with potential for lateral spreading were identified by mapping free faces and surface slope in areas with liquefaction potential and mapping their attributes to the building locations. Then, the Lateral Displacement Index (LDI) was estimated using the approach by Zhang et al. (2004). Further information about how this peril was calculated is also provided in Sect. S5.

3.2.5 Landslides

While most of the study area across Napier is flat, the areas in, or adjacent, to steep topography are potentially vulnerable to landslide impact. Although landslides may be triggered by multiple mechanisms, including hydrological pro-

cesses and progressive slope weakening, the present study considers only coseismic landslides triggered directly by earthquake ground shaking within the cascading earthquake hazard framework. The terrestrial risk from Earthquake-Induced Landslides (EIL) was estimated based on the methods proposed by Brideau et al. (2020, 2021) and Massey et al. (2021a). Underwater landslides, which could potentially cause a tsunami, are not considered in the present study.

Co-seismic landslide probabilities were modelled using the New Zealand Earthquake-Induced Landslide Forecast Tool (Version 2.0) (Massey et al., 2021b, 2022), which estimates regional landslide probability as a function of ground shaking intensity, topography and geology. The model was run for ten uniform PGA levels (0.2–3.0 *g*) to capture the range of shaking expected from the maximum event in the stochastic catalogue (M_w 9.1 HSZ scenario).

Slope units were delineated from the NZ 8 m digital elevation model (DEM), which were refined into source regions using empirical relationships between slope, local slope relief, and landslide occurrence derived from the Kaikōura Earthquake Inventory (Jones et al., 2024). For each source region, the maximum landslide volume class was defined, and the probability of each class was determined from the Kaikōura EIL frequency-area distribution.

Landslide runout extents were modelled using empirical landslide runout relationships, which use the Fahrböschung angle to estimate the runout distance for each volume class (Brideau et al., 2020, 2021; Massey et al., 2021a). Only open-slope dry rock and debris avalanches (OSD) were considered, as they are the most representative earthquake-triggered landslide type. Buildings intersecting either the landslide source regions or debris-inundation polygons were identified for subsequent risk simulations (Fig. 4). Further methodological details for each of these steps are presented in Sect. S6.

3.2.6 Exposure modelling

A national building inventory developed by Scheele et al. (2023) was used to represent the residential building stock in the study area. The dataset provides building locations and key structural attributes required for risk modelling. From this inventory, 38 344 residential buildings within the Napier City Territorial Authority were extracted for analysis.

Residential buildings are primarily exposed to earthquake ground shaking, with additional exposure to liquefaction, tsunami, lateral spreading, and landslide hazards. Due to the soil conditions across Napier City, liquefaction is expected to be the most significant secondary hazard (Table 1). Further details on the building inventory compilation and data matching procedures are provided in Sect. S7.

3.2.7 Fragility/vulnerability modelling

Building fragility functions express the probability of exceeding a given damage state (DS) for a specified inten-

Table 1. Number and percentage of buildings exposed to each hazard in the Napier case study, derived from the building exposure model described in Sects. 3.3 and S3.

	No. buildings	%
All	38 344	100 %
Earthquake shaking	38 344	100 %
Liquefaction	33 905	88 %
Tsunami	17 073	45 %
Lateral spreading	15 478	18 %
Landslide	6612	17 %

sity measure (e.g., PGA). DSs qualitatively describe structural damage, typically ranging from minor to complete, with two or three intermediate levels commonly defined (e.g., HAZUS 2.1). Fragility models are developed using either empirical data, based on observed post-event damage, or analytical methods, where structural response to hazard demand is modelled (Xin et al., 2020).

Earthquake damage was estimated using HAZUS 2.1 functions, which define four structural DSs (slight, moderate, extensive, complete) for major building types. Buildings in Napier were classified by material, height, and age. Each fragility curve follows a lognormal distribution, and DRs were assigned as: slight = 0.15, moderate = 0.3, extensive = 0.7, complete = 1.0.

Tsunami damage used empirically derived fragility functions from Suppasri et al. (2012), based on post-2011 Great East Japan Tsunami data. Six DSs were simplified into four representative DRs: minor = 0.1, moderate = 0.2, major = 0.7, and complete/collapse = 1.0.

Liquefaction effects were modelled as an aggravation factor (Δ) applied to earthquake fragility exceedance probabilities, using LSN as a proxy for severity: LSN (0–15] $\Delta = 1.1$; (15–25] $\Delta = 1.3$; > 25 $\Delta = 1.5$, capped at 100 %. The liquefaction aggravation factors adopted in this study were derived from Liquefaction Severity Modelling and observed building damage from the major Christchurch earthquakes as part of a confidential project undertaken for the New Zealand Earthquake Commission (Toka Tū Ake, Lin et al., 2024). The same confidential datasets and analyses were also used by Lin et al. (2023) to develop vulnerability functions for multi-storey residential buildings in New Zealand, although the liquefaction aggravation factors presented here represent a separate output from that project. Owing to the confidential nature of the underlying report and datasets, the detailed derivation and calibration of the aggravation factors cannot be presented. Accordingly, the factors are used here to demonstrate the proposed framework, and future work should focus on developing and validating publicly available liquefaction aggravation factors.

Lateral spreading damage was modelled using permanent ground displacement (PGD)–based fragility functions from

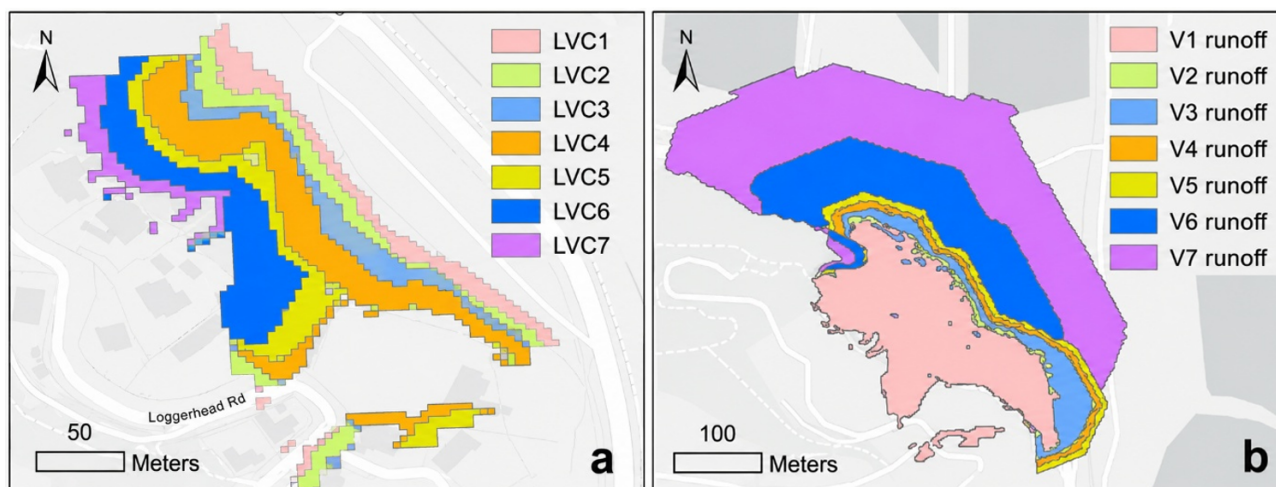


Figure 4. (a) Example of the seven landslide volume classes (LVC1–LVC7) within a single source region. As the volume of a future landslide is unknown, a range of landslide volume classes were modelled up to a credible maximum volume. (b) Example runout associated with each of the seven landslide volume classes (V1–V7).

HAZUS, with four DSs consistent with the ground-shaking model.

Landslide impacts were represented using a rule-based approach, classifying damage by the degree of overlap between the building footprint and the runout area: no overlap = no damage; partial overlap = moderate; full overlap = complete.

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). The harmonized damage states are summarized in Table 2. Detailed description of the harmonized DSs are included in Sect. S7.

Because DRs vary with construction characteristics, damage severity, and repair practices, they are modelled as random variables rather than fixed values.

DRs were assigned to each asset based on the harmonized DSs from the cascading hazard framework. Mean DR values were adopted from the Structural Repair Cost Ratios in HAZUS (FEMA, 2013), mapped to the five-level damage scale used in this study. Because HAZUS provides only mean values, uncertainty was represented using a triangular prob-

ability distribution with bounds of $\pm 30\%$ around the mean. During each Monte Carlo simulation, DRs were randomly sampled from this distribution to reflect variability in repair costs while maintaining consistency with standardized engineering assumptions.

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.

This study focuses exclusively on structural damage; potential losses to non-structural elements and building contents are not included in the damage or cost estimates. It is also recognized that HAZUS DRs are primarily calibrated for earthquake-induced losses, whereas other hazards may produce different damage mechanisms and cost relationships. Future work should therefore incorporate peril-specific DRs to enhance the accuracy of multi-hazard impact assessments.

3.3 Convergence analysis

A convergence analysis was conducted to assess the statistical stability of MDRs derived from the stochastic seismic simulations. Convergence refers to the point at which the cumulative mean MDR stabilizes with minimal variation as the number of simulations increases – a principle rooted in Monte Carlo-based uncertainty quantification (Burt and Garman, 1971; Ata, 2007). In the multi-hazard context, this anal-

Table 2. Unified five-level damage state framework developed to integrate disparate fragility model outputs for shaking liquefaction, lateral spreading, tsunami, and landslide hazards. The harmonization ensures consistency in structural damage interpretation across cascading hazard scenarios.

Harmonized DS	Label	Shaking	Liquefaction	Lateral Spreading	Tsunami	Landslide
DS1	Slight	Slight	Slight	Slight	Minor	No debris affects building
DS2	Moderate	Moderate	Moderate	Moderate	Moderate	No debris affects building
DS3	Severe	Extensive	Extensive	Extensive	Major	Debris affects part of the building footprint
DS4	Complete	Complete	Complete	Complete	Complete	Entire footprint covered by debris
DS5	Collapsed/ Washed away	– (implicit)	– (implicit)	– (implicit)	Collapsed/Washed away	– (implicit)

ysis is particularly important due to the concatenation of uncertainties across cascading perils, which generally require a larger number of simulations compared to single-hazard models. Two convergence tests were performed.

The first evaluated site–event level convergence, where a single building was repeatedly exposed to a given earthquake event to determine the number of realizations required for MDR stability. The mean MDR stabilized to within $\pm 2\%$ after approximately 120–180 simulations, indicating convergence (Fig. 5 shows an example for a M_w 7.5 earthquake). The $\pm 2\%$ value was used only as a representative indicator of convergence and not as a stopping criterion. Accordingly, 200 simulations per event were performed to provide an additional margin beyond the observed convergence point (Fig. 5 shows an example for a M_w 7.5 earthquake).

The second test assessed catalogue-level convergence, examining how many unique events were required for the cumulative MDR to stabilize across the stochastic earthquake catalogue. The results show that stability was achieved within $\pm 2\%$ after 20 000–30 000 events, with full convergence reached at 45 000 events (Fig. 6). These findings confirm that the 100 000-year event catalogue provides a statistically sufficient basis for robust risk estimation.

3.4 Results

The framework proposed in this work can provide damage state (DS) level results and DRs at each asset location. Results can then be processed to present area-wide outputs such as regional damage state vs. return period, MDRs from combined and disaggregated perils, or annual average MDRs. Results for the case study proposed – impacts from the Hikurangi Subduction Zone earthquakes and cascading hazards to Napier City’s residential building portfolio – are presented as follows:

1. *Regional damage states.* Return period DSs can be used to characterize urban resilience by quantifying the probabilities of structural damage over time. Results can be presented in the form of exceedance probability of DSs and the proportion of buildings under a certain damage state at different return periods. The DS exceedance probability per year (P) is calculated as follows:

$$P(\text{DS} \geq x) = \frac{N_{\text{buildings}}(\text{DS} \geq x)}{N_{\text{buildings}}} \quad (1)$$

Then, the return periods are obtained as:

$$\text{RP}_i = \frac{N_{\text{years}} + 1}{i} \quad (2)$$

Where i is the i th largest exceedance probability for damage state $\text{DS} \geq x$.

Figure 7 illustrates the distribution of exclusive damage states (DS0–DS4) in Napier City as a function of return period for earthquakes on the Hikurangi Subduction Zone. The estimated number of buildings in each damage state for each return period is provided in Table S2 of the Supplement. The results show a progressive shift towards higher damage states with increasing return period. Minor damage (DS1) becomes noticeable for return periods greater than approximately 100 years, whereas extensive damage (DS3) and complete damage (DS4) remain uncommon until return periods exceed approximately 500 years. Beyond approximately 2500 years, the proportion of undamaged buildings (DS0) falls below 20%, while the proportion of buildings in DS4 increases rapidly. At return periods between 5000 and 10 000 years, DS3 and DS4 become the dominant damage states, indicating that severe structural damage and collapse are expected for the largest

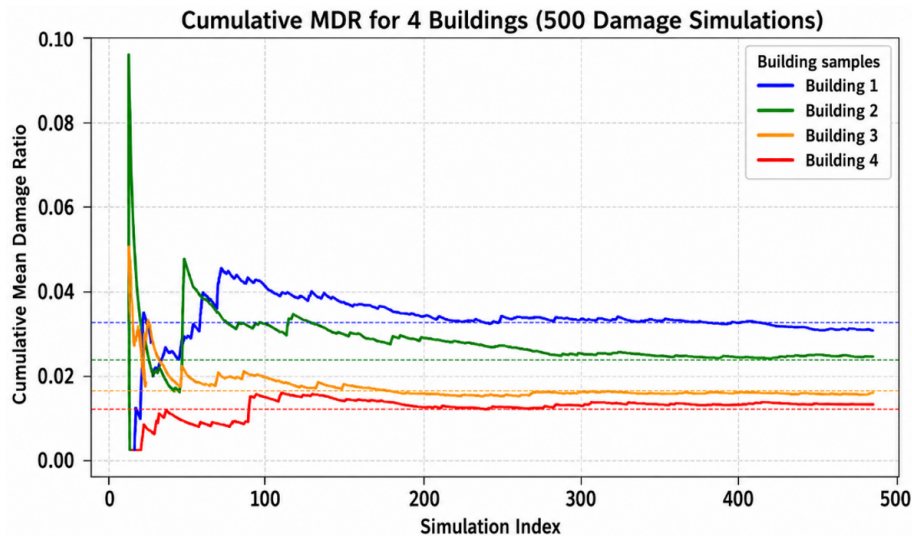


Figure 5. Cumulative mean damage ratio (MDR) for four representative buildings across 500 stochastic damage simulations of a single M_w 7.5 earthquake event. Each curve shows the progressive average MDR per building, with horizontal dashed lines indicating $\pm 2\%$ bounds around the final cumulative MDR value.

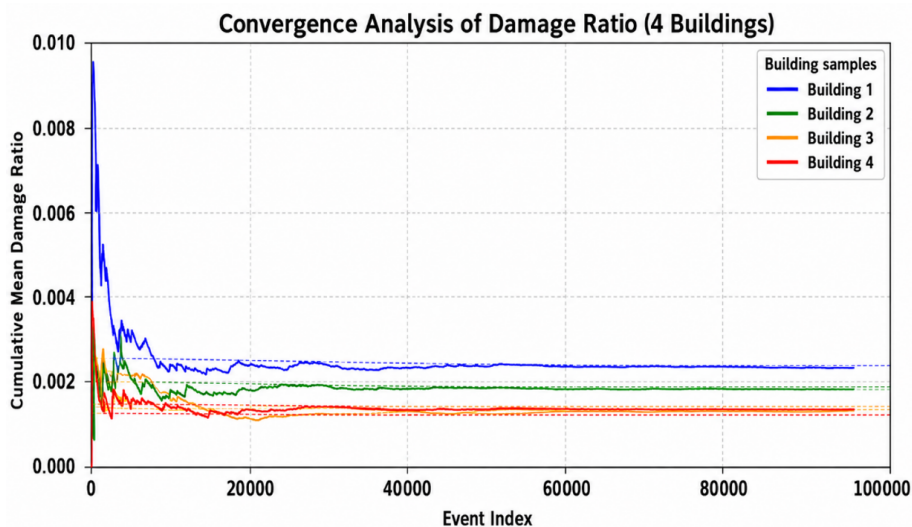


Figure 6. Cumulative Mean damage ratio (MDR) convergence for four representative buildings under the full stochastic earthquake catalogue. Each colored curve represents the evolving MDR as a function of the number of contributing events, while dashed lines indicate $\pm 2\%$ bounds from the final cumulative mean.

earthquake scenarios. At the longest return periods considered (10 000–100 000 years), the proportion of buildings in DS3 and DS4 approaches or exceeds 50 %.

To account for uncertainty, the complete stochastic event catalogue was simulated 200 times, with uncertainty sampled and propagated through the ground-motion, cascading-hazard, and damage-modelling chain during each realization. The results presented correspond to the median (50th percentile) damage-state distribution across the 200 stochastic catalogue realizations. The relative variability (coefficient of variation)

generally decreases with increasing return period, reflecting the more spatially consistent and severe damage associated with larger earthquake events.

2. *MDR by Return Period.* Resulting mean MDR can be presented as exceedance probability (EP) for a given time interval (e.g., 1 year), or return period, which represents the estimated period at which a given loss will be exceeded. Results can be disaggregated by hazard.

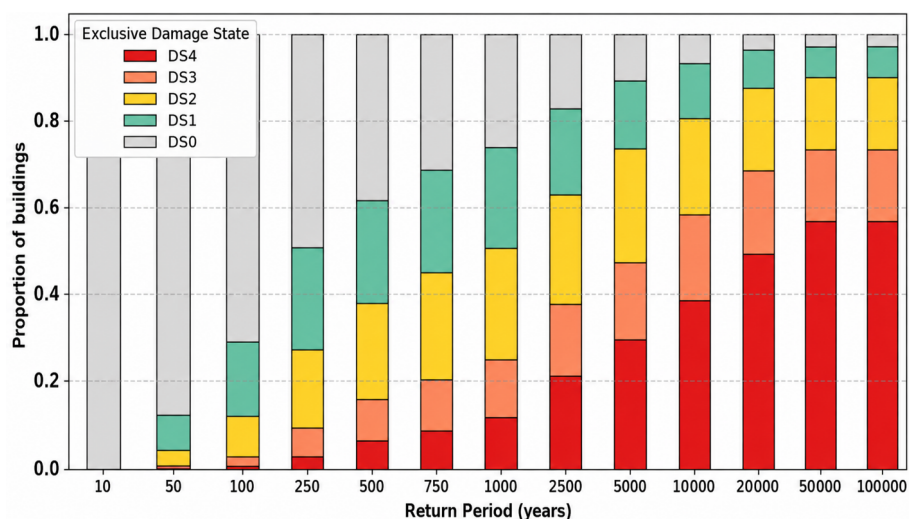


Figure 7. Proportion of buildings in the area of study at different damage states for different return periods. Damage states are defined as DS0 = no damage, DS1 = slight, DS2 = moderate, DS3 = severe/extensive, and DS4 = complete damage or collapse.

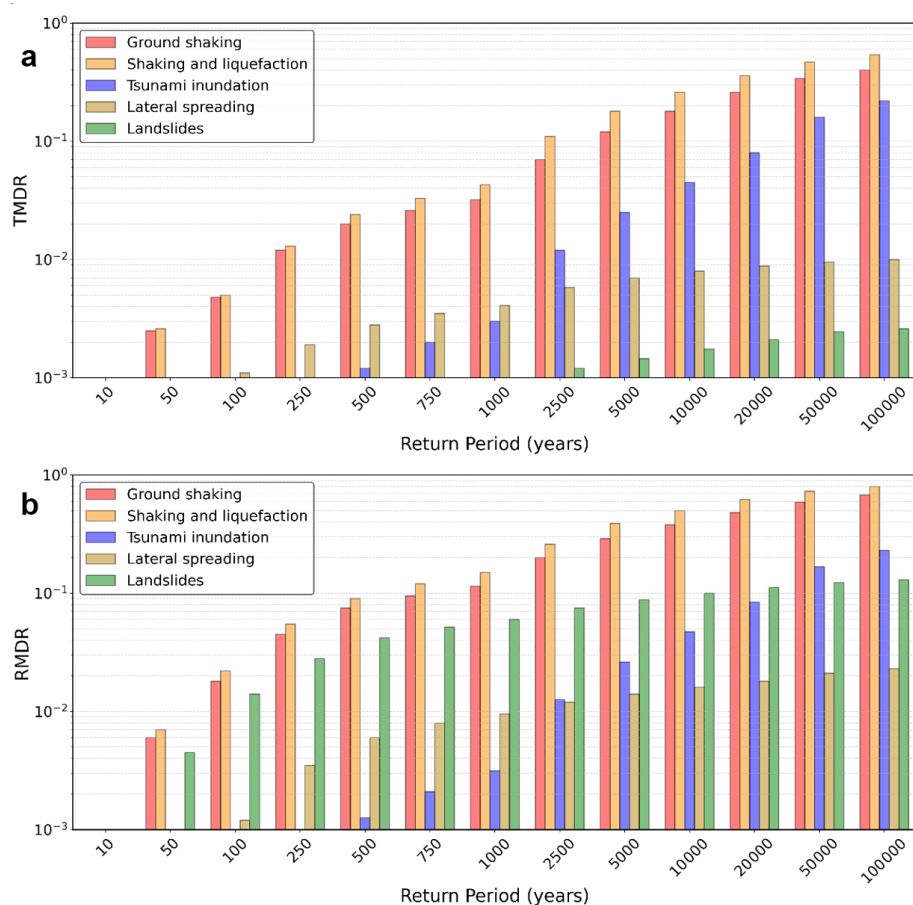


Figure 8. (a) Total mean damage ratios (TMDR) and (b) Relative mean damage ratios (RMDR) expected in Napier City disaggregated for earthquakes on the HSZ for each peril considered in this study. Damage states are defined as DS0 = no damage, DS1 = slight, DS2 = moderate, DS3 = severe/extensive, and DS4 = complete damage or collapse.

The MDR for an event j is calculated as:

$$\text{MDR}_j = \frac{1}{N_{\text{buildings}}} \sum_{i=1}^{N_{\text{buildings}}} \text{DR}_{ij} \quad (3)$$

Where DR_{ij} is the damage ratio for building i under the event j . Results per year can then be sorted by increasing MDR and RPs calculated as in Eq. (4).

When disaggregating the results for each peril, results can be expressed relative to the total exposure in the area considered (Total mean damage ratio, TMDR), or relative to the areas exposed to the different hazards (relative mean damage ratio, RMDR). Each result provides a different view of the risk, the first, TMDR, shows how each hazard contributes, separately, to the expected losses; the second, RMDR, presents how each hazard contributes to loss of its respective exposed buildings.

Figure 8 shows the TMDR and RMDR results for the Napier City case study. At the smaller return periods the losses are primarily from the ground shaking (red bars) and liquefaction (orange bars) as expected. At longer periods the losses from the other perils start to contribute to the total loss, with the losses from tsunami (blue bars) becoming comparable to ground shaking and liquefaction at very long return periods above about 10 000 years. The losses from EILs (green bars) are a relatively small proportion of the total loss, as shown by the TMDR figure, but this is mainly due to the relatively small amount of assets exposed to EILs in this case study region (Table 2). As shown by the RMDR plot, EILs start to impact buildings in their exposed area quite significantly for return periods above 50–100 years.

The relative contribution of each hazard reflects both the regional hazard characteristics and the spatial distribution of exposed assets in Napier City. Ground shaking contributes to losses across all return periods because the entire building stock is exposed to earthquake shaking, although local amplification varies according to site conditions. Liquefaction also contributes substantially owing to the geological characteristics of Napier, where a large proportion of the urban area is susceptible to liquefaction (Fig. S10a). Lateral spreading becomes increasingly important because the city is intersected by numerous rivers, streams, and drainage channels, resulting in many buildings being located within areas susceptible to lateral spreading. Although landslides contribute less to the total city-wide losses, they remain an important hazard because a significant proportion of the building stock is located within the hilly suburbs surrounding Napier. Tsunamis represent another key hazard given the city's proximity to the Hikurangi Subduction Zone, whose rupture mechanisms can generate large tsunamis. However, tsunami inundation in Napier is partially constrained by the local topography, as de-

scribed in Sects. 3.2.2 and S3, resulting in significant tsunami losses only for the largest earthquake scenarios.

Uncertainty differed among hazards, with the smallest variability observed for ground shaking and larger variability for the cascading hazards, reflecting the increasing influence of local site conditions and complex hazard interactions. Detailed percentile estimates are provided in Tables S3 and S4 in the Supplement.

3. *Annual average mean damage ratio (AAMDR)*. We have also calculated the average annual MDR for the 100 000-years stochastic catalogue. The length of the catalogue was selected based on a convergence analysis, which concluded that 100 000 years was of sufficient length. The AAMDR can be calculated as:

$$\text{AAMDR} = \sum_{j=1}^N P_j \cdot \text{MDR}_j \quad (4)$$

Where N is the total number of simulated hazard events, P_j is the annual probability of event j (typically $1/N$ years if all events are equiprobable) and MDR is the mean damage ratio for an event j .

A 1 km regular grid was generated across the study area, and the AAMDR for all buildings within each subdivision was computed to map its regional distribution (Fig. 9). Results show clear clustering of damage in areas with high building density (see Fig. S9 for reference on exposure distribution) and where multiple hazards occur simultaneously. The highest AAMDR values are concentrated in the central-eastern part of Napier, where relatively high exposure coincides with areas susceptible to liquefaction and lateral spreading. These hotspots are therefore controlled by the combination of high hazard intensity and high exposure, rather than by either factor alone.

Additionally, zones identified as landslide-prone display elevated AAMDR values, indicating the significant influence of local topographic effects on the spatial pattern of cascading hazard impacts. This spatial pattern is consistent with the hazard disaggregation results (Fig. 8), which show that ground shaking and liquefaction dominate the average annual damage, while landslides and lateral spreading produce localized increases in damage where buildings are exposed to these hazards. The estimated average annual damage ratios (AADR) for the buildings exposed to each hazard are 0.00568 for ground shaking, 0.00644 for shaking damage and induced liquefaction, 0.00107 for landslides, 0.00392 for lateral spreading, and 0.00029–0.00031 for tsunami inundation.

To provide an indication of the uncertainty associated with the Average Annual Mean Damage Ratio

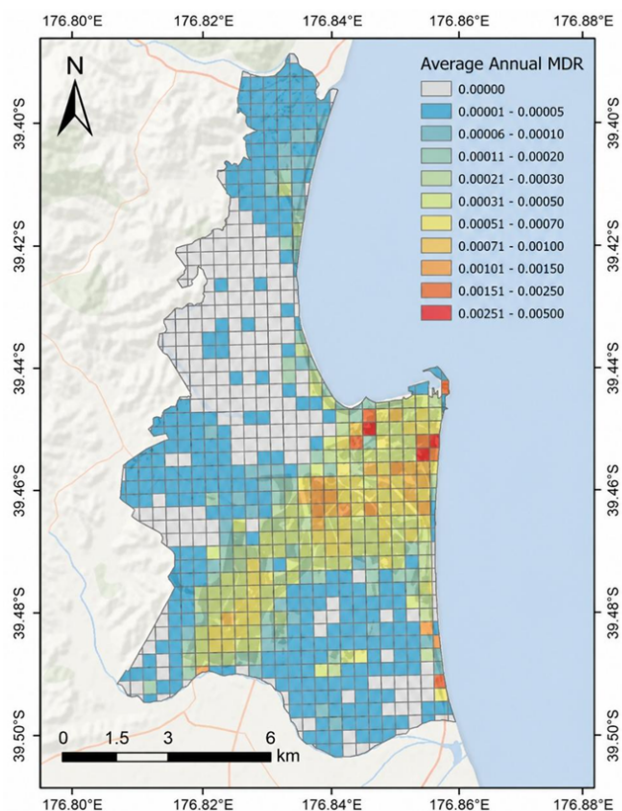


Figure 9. Regional distribution of the average annual mean damage ratio of combined effect of earthquakes on the HSZ and the cascading hazards considered in this study.

(AAMDR) estimates, the coefficient of variation (COV) was calculated for each grid cell across the study region. The resulting COV values are presented as a spatial map in Fig. S11, illustrating the relative uncertainty associated with the estimated AAMDR.

4 Discussion

In this study, we have described an internally consistent probabilistic framework for regional earthquake risk assessment that explicitly incorporates both primary and secondary hazards and demonstrated its application through a case study in Napier City, New Zealand. All hazard intensities and their associated damage states are sampled in a statistically coherent manner for each stochastic event, preserving the physical and causal relationships between ground shaking and the cascading hazards. This differs from the more common approach of modelling each hazard independently and combining the results afterwards, as it captures the inter-hazard correlations that arise naturally during a given earthquake realization and propagates their uncertainty consistently through the risk assessment.

The Napier case study demonstrates several advantages of this framework. First, it enables the combined effects of interacting hazards to be quantified within a single probabilistic assessment, rather than evaluating the contribution of each hazard in isolation. The progression in damage states shows that increases in earthquake losses are not solely driven by stronger ground shaking but also by the growing influence of liquefaction, lateral spreading, landslides, and tsunami inundation as earthquake magnitude and rupture extent increase. By preserving these hazard interactions, the framework provides a more realistic representation of the mechanisms leading to building damage during large subduction earthquakes.

Second, the framework allows earthquake losses to be disaggregated by hazard while maintaining consistency with the total regional risk. The TMDR and RMDR metrics provide complementary perspectives by distinguishing between the contribution of each hazard to city-wide losses and the severity of damage experienced by assets exposed to individual hazards. This enables hazards with limited spatial extent, such as landslides and lateral spreading, to be recognized as locally significant even when their contribution to regional losses is relatively small, thereby providing information that is directly relevant for risk reduction and land-use planning.

The Napier results further illustrate how the relative importance of different hazards evolves with earthquake magnitude. While ground shaking dominates losses associated with more frequent events, the contribution of liquefaction increases progressively with return period, consistent with the susceptibility of Napier's geological conditions and observations following the 1931 M_w 7.3 Hawke's Bay earthquake. Similarly, tsunami losses become significant only for the largest earthquake scenarios, reflecting the threshold behavior of coastal inundation, whereas lateral spreading and landslides primarily affect assets located within susceptible areas. These findings highlight the importance of considering hazard interactions when assessing regional earthquake risk.

Direct comparison of the results with previous earthquake risk studies or post-earthquake damage observations remains challenging because most existing studies either evaluate individual hazards independently or report aggregate earthquake damage without explicitly accounting for the interactions between ground shaking and cascading hazards. The objective of the proposed framework is therefore not only to estimate earthquake losses but also to represent the interdependence between multiple hazards within a physically consistent probabilistic framework. As additional observational data becomes available, future studies should seek to validate these coupled hazard interactions and further refine the representation of cascading hazard processes.

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.

Limitations

The proposed framework has limitations that should be acknowledged. Path-dependent damage is not represented, such that structural damage caused by earthquake shaking does not modify the vulnerability of buildings to subsequent hazards (e.g., tsunami), owing to the limited availability of fragility models describing sequential hazard interactions. The tsunami modelling does not account for debris impact, tidal stage, storm surge, or long-term sea-level rise. The earthquake-induced landslide model considers only co-seismic triggering and therefore does not account for antecedent rainfall, seasonal groundwater conditions, or other hydrological controls on slope stability. The liquefaction and lateral spreading assessments rely on empirical relationships, while the harmonization of damage states across hazards represents a necessary simplification to enable the integration of different fragility models within a unified probabilistic framework. The adopted harmonization procedure also introduces uncertainty into the estimated losses, and a systematic sensitivity analysis of alternative mapping approaches is recommended as future work. Validation of the integrated framework is inherently challenging owing to the scarcity of observational datasets documenting cascading earthquake hazards and their impacts, particularly in New Zealand. Owing to the modular structure of the framework, these components can be updated as improved hazard and fragility models become available.

5 Conclusion

This study presents an internally consistent probabilistic framework for assessing earthquake risk from cascading hazards by integrating ground shaking, tsunami inundation, liquefaction, landslides, and lateral spreading within a unified modelling approach. The framework preserves the conditional dependence between primary and secondary hazards through a fully correlated Monte Carlo simulation, enabling physically consistent estimates of damage and loss across multiple interacting perils.

By preserving the conditional dependence between cascading hazards throughout the modelling chain, the proposed framework provides a physically consistent basis for regional multi-hazard earthquake risk assessment. Its modular structure enables both empirical and physics-based hazard models to be integrated within a common probabilistic framework and facilitates the incorporation of improved hazard and vul-

nerability models as they become available. The resulting risk metrics can support resilience planning, emergency management, infrastructure prioritization, and (re)insurance applications by quantifying the relative contributions of individual hazards to overall earthquake risk.

Application of the framework to Napier, New Zealand, demonstrates the importance of explicitly modelling cascading hazards in regional earthquake risk assessments. While ground shaking and liquefaction dominate average annual losses, tsunami becomes increasingly significant for very rare events. Landslides have a more localized influence but can produce substantial impacts in affected areas, making their relative contribution important at the local scale. Together, these findings highlight the value of considering multiple interacting hazards when assessing earthquake risk.

Future work will focus on incorporating additional earthquake-induced hazards, improving fragility modelling to better represent sequential hazard interactions and path-dependent damage, and further validating the integrated framework as observational data from cascading hazard events become available.

Code availability. The code used to perform the analyses and generate the figures in this study is available from the authors upon reasonable request, with access provided through a private GitHub repository.

Data availability. The data used and/or generated during the study are also available from the authors upon reasonable request.

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