Estimating National-Scale Losses to Infrastructure from Natural Hazards

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CONTENTS

FIGURES

TABLES

EXECUTIVE SUMMARY

This project developed national-scale estimates of damage and loss to vertical and horizontal infrastructure sectors from natural hazards. The purpose of the study is to provide the New Zealand Infrastructure Commission Te Waihanga with a high-level national-scale estimate of losses that may occur from natural hazards in order to plan long-term investment needs for infrastructure.

Estimates of damage and loss were generated using RiskScape, an open-source multi-hazard risk-modelling tool developed by GNS Science and the National Institute of Water & Atmospheric Research (NIWA). To account for unknown infrastructure networks, simplified risk models using existing hazard data were developed to estimate national-level losses. The RiskScape model estimated average annual loss (AAL), the expected loss per year averaged over the long term, for each natural hazard and infrastructure sector as the primary risk metric.

Infrastructure sectors included were water (potable, waste and storm), electricity, telecommunications, road and rail and certain vertical infrastructure (i.e. buildings in education, health and government sectors). Natural hazards with available data that were considered were earthquakes (including landslide and liquefaction hazards), coastal flooding, fluvial-pluvial flooding, tsunami and volcanic ash.

Results show that the total expected AAL for all infrastructure sectors across all hazards considered is NZD$632M, which represents 0.26% of the infrastructure value. Road and Rail dominates the expected losses with $188M in AAL, followed by electricity ($142M), water ($139M) and vertical infrastructure ($133M). Telecommunications has the smallest estimated sector loss with an AAL of $2.8M.

Flooding is the hazard with the highest estimated AAL value for all infrastructure sectors of $281M, followed by earthquake ($169M) and coastal flooding ($166M). Tsunami ($8.9M) and volcanic ash ($7.6M) are estimated to be some two orders of magnitude smaller than the other hazards.

The results can be used to understand the potential losses expected at a national scale for the major infrastructure sectors and to prioritise and rank the risk to each sector. It is not intended to be used at a sub-national scale or for detailed sector-based decision-making.

Future work could prioritise certain natural hazards and sectors for more detailed investigations, such as developing scenarios to better understand the spatial distribution of losses or modelling the change in risk over time from resilience measures and changing hazards due to climate change. The RiskScape model is transparent and modular, so can be re-run with updated information such as infrastructure sector valuations or updated hazard data.

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1.0 Introduction

Natural hazards pose significant threats to the safety, economy and environment of New Zealand. As an island nation located in a seismically active region, New Zealand frequently experiences natural hazards, including earthquakes, storms, volcanic eruptions and tsunami. These events can lead to substantial losses, not only in terms of human life but also in economic and environmental impacts.

In recent years, New Zealand has faced a series of significant natural disasters that have led to considerable economic and social losses across different parts of the country. The impacts of these events have been felt across different infrastructure sectors, highlighting the vulnerability of the country to both geological and meteorological hazards. Among the most notable geological hazards were the 2010–2011 Canterbury earthquakes, which alone cost an estimated NZD$40B[1], with the losses spread across infrastructure, housing and public services. The 2016 Kaikōura earthquake resulted in widespread infrastructure damage, particularly to road and rail networks, and generated an estimated economic loss of around $3B. This event disrupted transportation networks, affecting communities and revealing the interconnectedness of infrastructure resilience and disaster preparedness.

More recently, severe weather events, including intense storms and flooding, caused extensive damage in various regions. For example, the flooding and landslides in Auckland during January 2023 led to significant residential property damage, estimated in the hundreds of millions. Shortly after the Auckland floods, Ex-Cyclone Gabrielle in February 2023 brought widespread destruction, particularly in the eastern North Island, severely impacting agriculture, horticulture, residential buildings and infrastructure with estimated losses in the range of NZD$9–14B.

These disasters underscore the urgent need for robust disaster risk-management strategies as New Zealand deals with the ongoing challenges posed by natural hazards. Investments in infrastructure resilience are essential to mitigate future losses. By understanding potential future losses, New Zealand can further enhance its strategies for and vulnerability reduction and resilience, ensuring that infrastructure sectors are better able to respond and recover from natural hazard events.

This study aims to estimate the potential long-term economic losses from natural hazards on New Zealand's infrastructure sectors. The results from the study are intended to be used by the New Zealand Infrastructure Commission Te Waihanga for long-term planning on investment and risk mitigation of infrastructure to minimise and manage future losses from natural hazards.

The study is intended to provide a high-level national-scale estimate of natural hazard losses for key infrastructure sectors. The infrastructure sectors included are:

- Three waters (potable water, wastewater, stormwater)
- Electricity
- Telecommunications
- Roads and rail
- Vertical infrastructure (i.e. buildings).

Natural hazards included in the study are:

- Earthquakes (including landslide and liquefaction)
- Fluvial-pluvial (riverine) flooding (referred to here as 'flooding')
- Coastal flooding
- Tsunami
- Volcanic ash.

1 https://www.icnz.org.nz/industry/cost-of-natural-disasters/

The study uses an established risk-modelling methodology applied in previous studies at global and national scales to estimate losses to infrastructure from natural hazard events. The primary risk metric estimated in the study is average annual loss (AAL), which is the estimated loss per year when averaged over the long term. The results are intended to be used for high-level national-scale planning and not at an individual sector level or in regional applications.

Due to scope and budget constraints, the study utilises existing hazard models, which results in varying levels of confidence in the models used across the different hazards and infrastructure sectors.

1.1 Report Outline

The report is divided into three main sections:

- The "*National-Scale Natural Hazard Risk Models for Infrastructure*" section provides an overview of the risk-modelling methodology, the hazard and vulnerability models used in the risk modelling and a summary of the confidence in the models.
- The "*Results*" section presents the risk results for each hazard-sector combination and discusses the findings.
- The "*Discussion*" section provides a discussion on the limitations of the risk modelling, areas for future improvement and suitability of using the results for various purposes.

1.2 Glossary of Terms

This glossary provides a definition and explanation of technical terms used in this report.

Annual Exceedance Probability (AEP) – The probability of a hazard of a certain intensity occurring in a single year. A 1% AEP hazard map shows the hazard intensity that has a 1% (or 1 in a 100) chance of being exceeded in a given year.

Asset – An element at risk that has certain attributes (e.g. location, value, characteristics). Also see *exposure*.

Average Annual Loss (AAL) – The expected loss that is estimated to occur each year, averaged over many years.

Damage Ratio – The ratio of the cost to repair an asset to the cost to replace it.

Exposure – An asset exposed to a hazard that has certain attributes (e.g. location, value, characteristics).

Footprint – A polygon that shows the physical extent of a building when viewed from above.

Hazard Intensity – The intensity of a given hazard expressed as defined units. For example, depth in metres for flood, or volcanic ash thickness in millimetres.

Hazard Map – A spatial map that shows the hazard intensity for a certain *AEP*.

Hazard Model – A mathematical and computational model that estimates the intensity of hazards across an area.

Hazard Curve – A curve that represents *Annual Exceedance Probability* against *hazard intensity*.

Line Segment – A geospatial representation of a linear exposure or *asset* (e.g. a road) that is split into lengths of equal or unequal length.

Loss – The magnitude of loss from a natural hazard, in this study it is economic loss.

Loss Curve – A curve that represents *AEP* against *loss*.

Probabilistic Hazard or Loss – A model that estimates both the likelihood (*AEP*) and *hazard intensity* or *loss* for a given hazard.

Return Period – The average return time for a *hazard intensity* or *loss* of a given level. A 1-in-100-year return period is equivalent to a 1% AEP.

Spatial Resolution – The horizontal distance between points in a dataset or map.

Vulnerability Curve – A curve that represents the *damage ratio* against *hazard intensity*.

2.0 National-Scale Natural Hazard Risk Models for Infrastructure

This section provides an overview of the risk-modelling methodology used to estimate national-scale losses for the infrastructure sectors from natural hazards, as well as the various hazard and vulnerability models used as inputs to the risk model.

Section 2.1 provides an overview of RiskScape, the multi-hazard risk-modelling tool used for the risk assessment. Section 2.2 gives a detailed description of the risk-model framework used to calculate the AAL. Sections 2.3 2.7 outline the hazard and vulnerability models that are used in the risk model for each natural hazard.

2.1 RiskScape

Risk modelling for this project was undertaken using the RiskScape multi-hazard loss-modelling tool (Paulik et al. 2023b). RiskScape is a software suite for multi-hazard risk analysis developed in partnership between GNS Science, the National Institute of Water & Atmospheric Research (NIWA), Catalyst IT, and the Natural Hazards Commission Toka Tū Ake. RiskScape is open-source software with a flexible modelling engine that processes user-customised risk-analysis workflows. RiskScape is one of few open-source software specifically designed for multi-hazard risk analysis that is globally available.

RiskScape implements a risk-model design centred on an established conceptual framework for risk quantification:

$$R = f_c(H_i, E, V_i) \quad \text{Equation 2.1}$$

where risk (*R*) is a function (f_c) of the consequences from a hazard event (*H*) impacting an exposure (*E*) (i.e., element at risk). Consequences are determined from the exposure vulnerability (*V*) to an impact type and magnitude in response to either single or multiple hazard events (*i*). Risk-quantification principles are often similar between modelling software; however, implementation of model workflows and functions may differ. Modelling software practised for single or multi-hazard risk quantification often operate standard model workflows or ‘calculators’ using prescribed data classifications or standards. RiskScape operates models and input data as independent entities, enabling risk quantification for any hazard and exposure type combination, including spatio-temporal interactions. This flexibility in the modelling system overcomes the major challenges of implementing highly variable methodologies for single or multi-hazard risk analysis in a software system.

A RiskScape model requires four key components:

- **Hazard data** in the form of geospatial files that represent the hazard intensity for a single scenario event or a probabilistic hazard map for a given AEP.
- **Exposure data**, which are geospatial data represented as a point, line or polygon that represent the asset at risk and any associated attributes relevant for the risk model (e.g. building construction type).
- **Risk function**, which is a mathematical expression of the vulnerability of the asset when exposed to the hazard. This is typically expressed as a vulnerability curve that relates the damage ratio (ratio of repair cost to replacement cost) to the hazard intensity, which may vary based on the attributes of an asset.
- **RiskScape pipeline**, which is a customised and flexible risk-analysis workflow that executes the RiskScape engine. A RiskScape pipeline allows the user to define steps to undertake in the risk-model workflow, such as geoprocessing input hazard or exposure data, geospatial sampling, consequence analysis steps and post-processing of risk results (Figure 2.1).

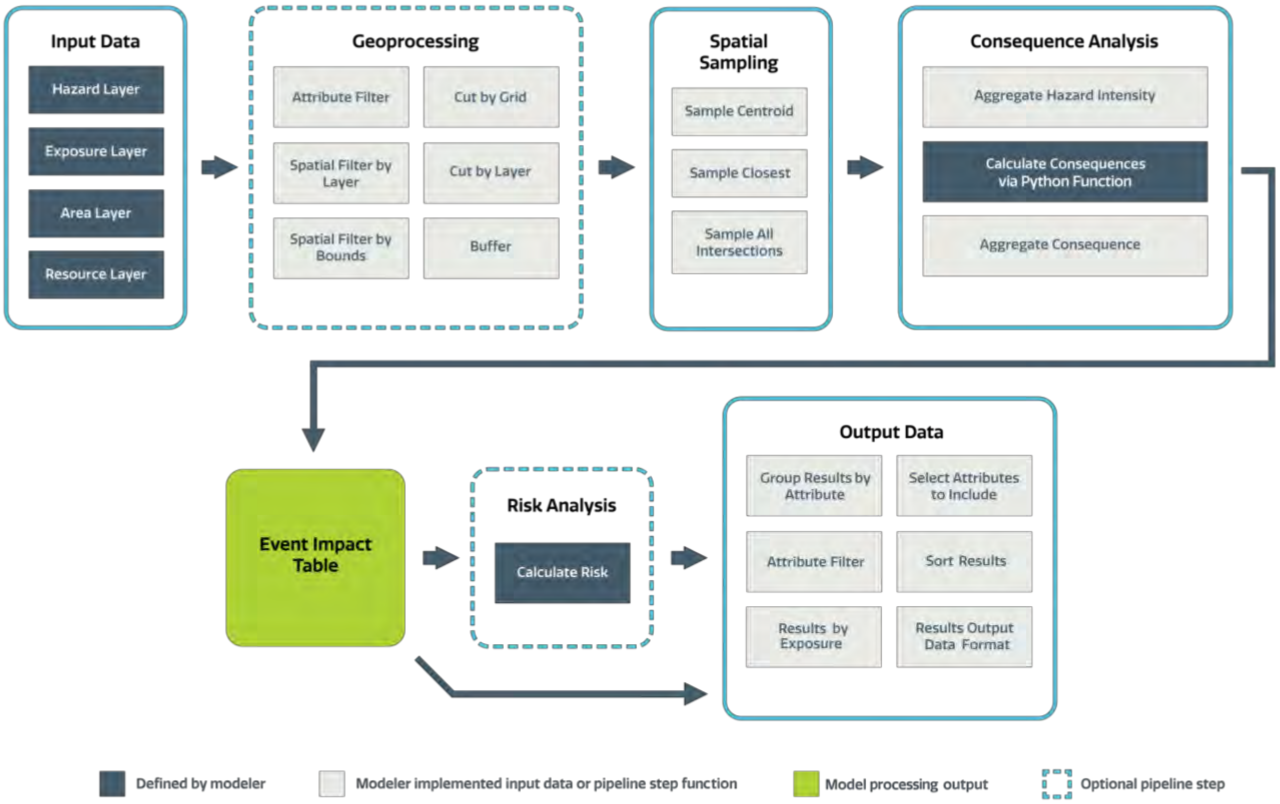

Figure 2.1 A schematic representation of the steps and functions of a RiskScape model pipeline.

The RiskScape software engine is distributed under AGPLv3 and is available for download.[2] Here, detailed information on the engine design, along with user guidance and tutorials, is available. A further description of the RiskScape engine design is presented by Paulik et al. (2022).

2.2 Risk-Modelling Methodology

The risk-model pipeline developed for this study estimates losses using a probabilistic methodology, in that a range of hazard events across the probability (AEP) and hazard-intensity spectrum are considered. This differs from scenario-based analysis where only a single scenario event is used. Probabilistic risk assessment allows estimates of annualised loss to be calculated considering all possible events that may occur for a given hazard.

To estimate AAL for this study, a risk model was developed based on the hazard-based probabilistic risk model framework.[3] In a hazard-based probabilistic risk model, the hazard data is in the form of probabilistic hazard maps that represent the hazard intensity for a range of AEPs. A minimum of five AEPs are recommended for this type of analysis, based on sensitivity testing, in order to represent the full spectrum of event probabilities and hazard intensities.

The hazard-based probabilistic risk analysis adopted for this study has been applied in other similar studies internationally. This includes estimates of seismic risk at a national scale by the Global Earthquake Model (Silva et al. 2020), a global multi-hazard risk assessment for road and rail assets (Koks et al. 2019) and a study on seismic risk to buildings in the United States of America (USA) based on their National Seismic Hazard Model (FEMA 2023).

The following steps are undertaken in the hazard-based probabilistic risk model:

1. For each infrastructure exposure element (e.g. grid cell, building footprint, line segment) the hazard value is sampled for each hazard map (corresponding to a given AEP) to create a hazard curve (Figure 2.2).

2 https://riskscape.org.nz/
3 https://riskscape.org.nz/docs/advanced/probabilistic/hazard-based.html

2. For each AEP in the hazard curve, use the hazard-intensity value is used to sample the vulnerability model for that sector to calculate the damage ratio that is defined as the ratio of repair cost to replacement cost. The damage ratio is multiplied by the replacement cost of the asset to estimate the loss (in NZD$) for that AEP.
3. This is repeated for each AEP to create a loss curve (Figure 2.3).
4. The area under the loss curve is integrated using numerical integration (Trapezoid function, shown in Figure 2.3) to estimate the average annual loss (AAL). The AAL is divided by the total value of that sector to calculate the AAL as percentage of total value (Figure 2.3).

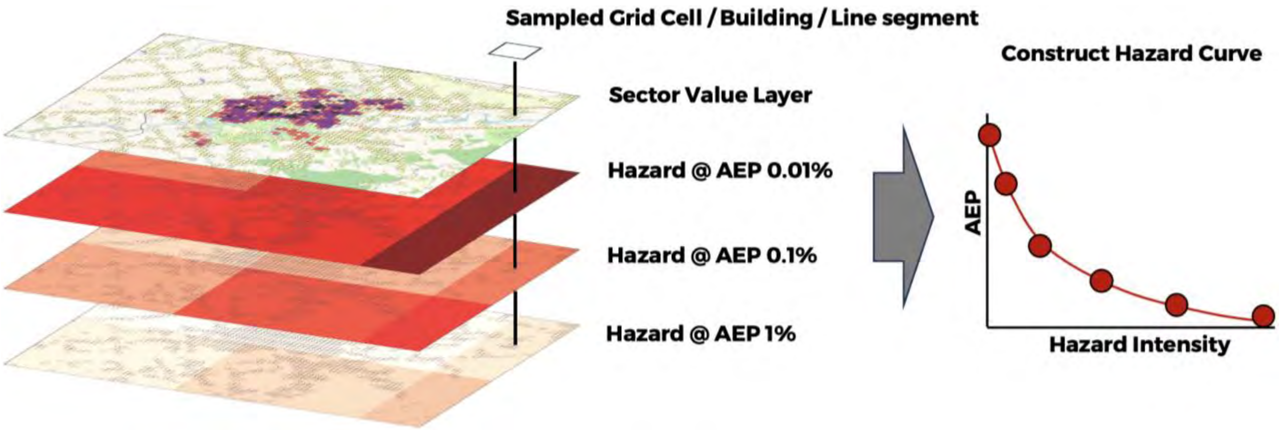

Figure 2.2 Schematic showing how a hazard curve is constructed for an exposure by sampling the hazard intensity at the geospatial location of the exposure for a set of probabilistic hazard maps.

While the risk-modelling workflow was the same for each infrastructure sector and hazard, the input data varied by hazard type and infrastructure sector. At present, there are no national consistent hazard data for all hazards in New Zealand. Hazard data that are available vary due to inconsistencies in the hazard models, such as different AEPs available 'off the shelf', varying spatial resolution of the hazard models (e.g. 5 km resolution for earthquakes versus 10 m for coastal flooding) and varying model coverage (e.g. national-scale models for earthquake, flood, volcanic ash and regional models for tsunami). Infrastructure asset information is even more variable than hazard data. Some infrastructure asset information required for risk modelling is available with national coverage via publicly accessible web services (e.g. national state highway networks, national rail networks), some is only available from regional networks (e.g. council-owned roads) and others are not available at all (e.g. privately owned electricity or telecommunications networks). In order to address these inconsistencies in the asset information available for each infrastructure sector, three different risk models were developed that were used for certain infrastructure sectors. The overall risk and loss calculation as described above is consistent across the three models but the way that the exposure data is processed varies.

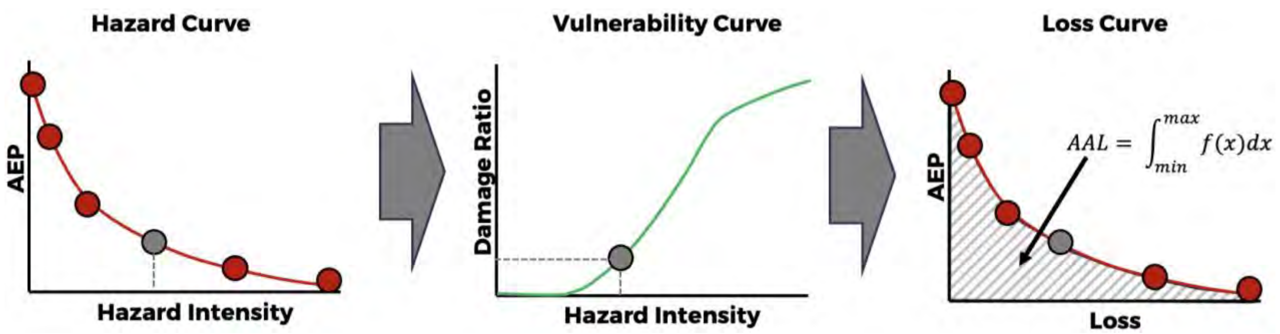

Figure 2.3 Processing steps to convert a hazard curve into a loss curve. For each AEP point that defines the hazard curve, a vulnerability curve that represents that infrastructure sector is used to calculate the damage ratio for that AEP. The damage ratio is multiplied by the exposure value to calculate the loss. When repeated for each AEP, the AEP-Loss points define the loss curve. The area under the curve is calculated through numerical integration to calculate the AAL.

2.2.1 Infrastructure Valuations

One of the key pieces of information for the risk model is the replacement cost of the infrastructure sectors. As noted above, this is required to estimate the loss when the damage ratio from the vulnerability function is multiplied by the replacement cost to estimate the loss. To maintain consistency with New Zealand Infrastructure Commission Te Waihanga reports, we used infrastructure-sector valuations from the *Build or Maintain* report published in 2022 (New Zealand Infrastructure Commission 2024). This report published national valuations for each of the infrastructure sectors analysed in this study. This means that the loss estimates are based on 2022 valuations.

2.2.2 Model 1: Horizontal Infrastructure

This model was used for infrastructure sectors where national-scale linear networks were available. This includes the state highway and rail networks. For this model, the data was sourced from the Toitū Te Whenua Land Information New Zealand (LINZ) geospatial data service.[4] Each network was represented as line geometry. The line network was separated (cut) into segments of length equal to the resolution of the hazard being analysed. For example, the coastal-flooding hazard model had a spatial resolution of 20 m, so the line segments of the state highway and rail network were cut into 20 m segments. The replacement cost of each segment was calculated by dividing the total infrastructure-sector valuation by the total length of the network to calculate the value per kilometres; this was then multiplied by the length (in kilometres) of each segment. This approach assumes equal valuation across the network (i.e. the Auckland Harbour bridge has a per kilometre valuation the same as a rural state highway), as no valuation information was available to assign these in a more detailed manner. This simplified approach results in a 'smearing' of valuations across the country. In areas of high replacement cost (e.g. bridges), the losses are likely to be lower than expected, while, in areas of low replacement cost (e.g. rural state highways), the losses are likely over-estimated. However, it is assumed that this will average out across the country.

The vulnerability model applied for roads and rail for each hazard are described below in Sections 2.3–2.7.

As described above, each line segment is iterated through the risk model to calculate the AAL for that segment. The AAL for each segment is then summed to calculate the national AAL for that network.

2.2.3 Model 2: Aggregated Infrastructure

Some infrastructure sectors have no national-scale information available and so a method was developed to address this. This includes the three waters, telecommunications, electricity and local roads sectors. This information is held by either individual councils or private operators and was not available. However, the total valuation of each sector is available in the New Zealand Infrastructure Commission (2024) report.

To distribute the replacement cost of each sector geospatially across the country, a proxy for infrastructure density (and therefore replacement cost) was adopted. This approach has been applied in global studies to estimate infrastructure distribution and value to develop exposure models for natural hazard risk assessments (Nirandjan et al. 2022, 2024). In this approach, a proxy available across the area of interest, in this case, New Zealand, is used to approximate the distribution of infrastructure. It is assumed that population density is a good approximation of where infrastructure is distributed, as has been used in the studies by Nirandjan et al. (2022, 2024). The Statistics New Zealand gridded population dataset is used as the proxy for infrastructure density across New Zealand. The population grid has a resolution of 250 m x 250 m and provides the resident population in each grid cell.[5] An example of the population grid is shown in Figure 2.4.

4 https://data.linz.govt.nz/data/

5 https://datafinder.stats.govt.nz/layer/119709-new-zealand-estimated-resident-population-grid-250-metre/

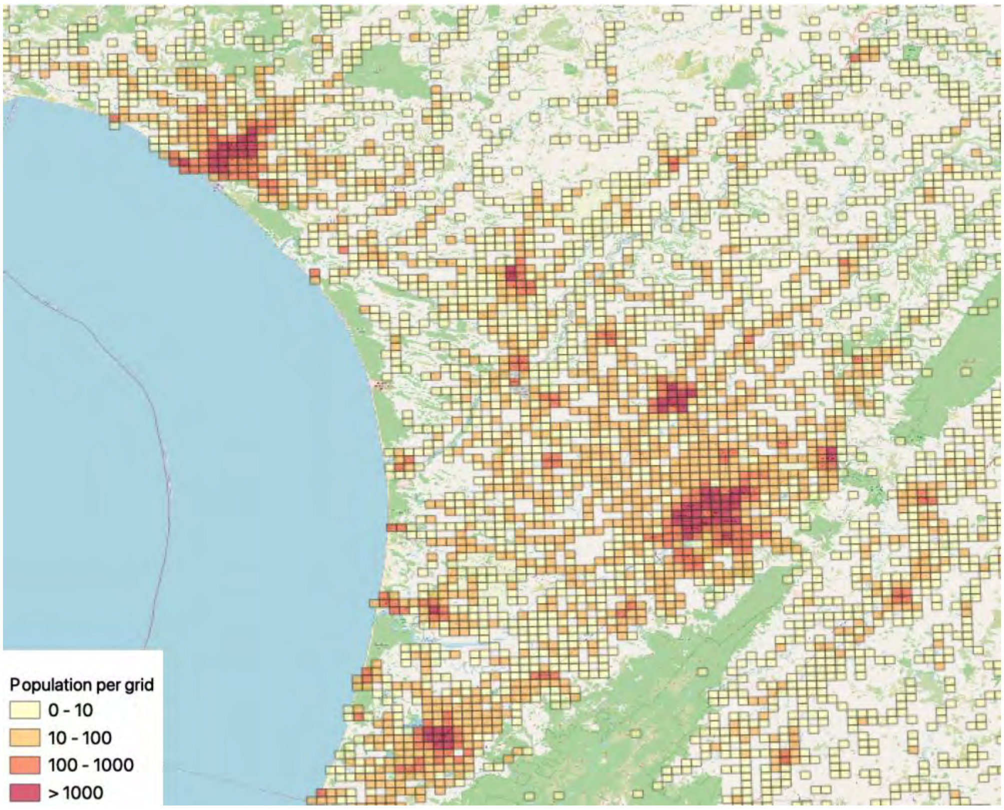

Figure 2.4 Example of the Statistics New Zealand population grid for the lower North Island.

To calculate the replacement value of each infrastructure sector per grid cell, the sector valuation per capita in New Zealand Infrastructure Commission (2024) is used and multiplied by the resident population per grid cell. This approach assumes that the infrastructure is located where people live. There are some cases where this is not the case, for example, an electricity transmission line that traverses over farmland or a local road in a remote region. However, for the majority of the infrastructure value, this is located in populated areas.

In addition to an unknown replacement value, the components of the infrastructure network required to assign vulnerability functions is also unknown. For example, with water networks, how much of the replacement value is from pump stations compared to pipes; and whether the water pipes are made of brittle or ductile material, which determines their vulnerability to ground-movement hazards such as earthquakes. To address this gap in information, regional infrastructure networks used for previous studies by GNS Science (that are not publicly available) were used to calculate the relative proportion of important components and their relative vulnerabilities. This information was used to create a single composite vulnerability curve that represents the entire network instead of multiple component-based vulnerability curves that are traditionally used for detailed infrastructure-network risk assessment.

Table 2.1 Example of how the average proportion of each component is calculated.

	Brittle Pipe Value Proportion	Ductile Pipe Value Proportion
Grid 1	0.4	0.6
Grid 2	0.5	0.5
Grid 3	0.3	0.7
Average Proportion	**0.4**	**0.6**

An example of how a single composite vulnerability curve is created for each hazard-sector combination is shown here using the example of the Auckland water network and earthquake vulnerability curves.

First the replacement value per grid cell of each of the key components was calculated. This is shown for Auckland in Figure 2.5 where the replacement value of ductile and brittle pipes is calculated for each grid cell from regional-scale infrastructure network data from previous studies. For each grid cell, the proportion of replacement value for brittle and ductile pipes is then calculated. The average value of this proportion is calculated for the region as a whole.

This average value of the proportions (per grid) provides the weight applied to each of the vulnerability functions for brittle and ductile pipes. Figure 2.5 shows how the vulnerability functions for brittle (red) and ductile (green) pipes are weighted by the average proportion to calculate a single composite vulnerability curve (black). The single composite vulnerability curve is used to represent that entire sector. The component vulnerability curves for each hazard-sector combination are described below in Sections 2.3–2.7.

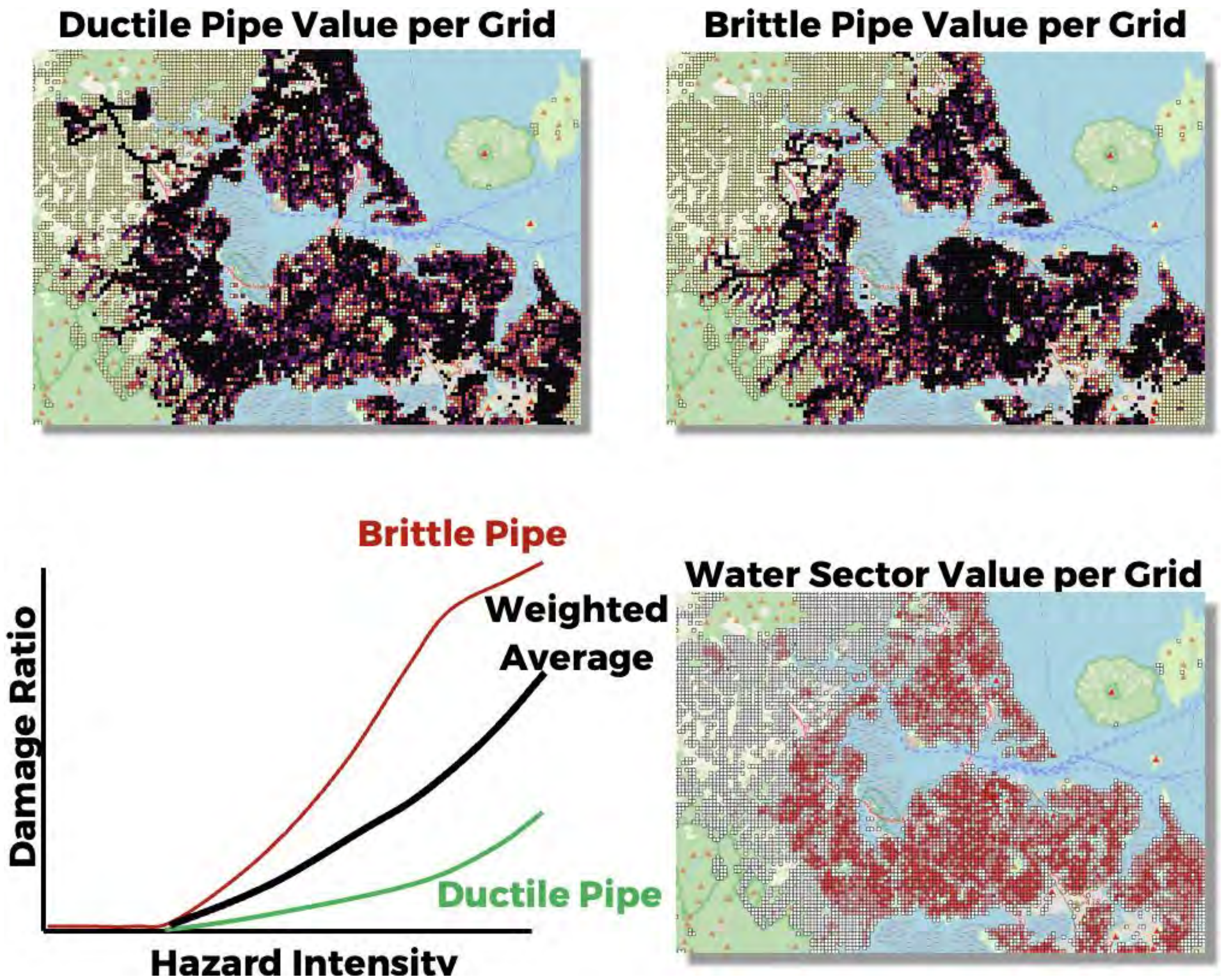

Figure 2.5 The value of each component (i.e. ductile pipes and brittle pipes) is calculated by summing the value of these assets per grid cell. The proportion of value per grid is then calculated. The average proportion of each component across the region is calculated to provide an average weighting of each component across the region. This is then used to calculate a weighted average vulnerability function that represents the vulnerability for the entire sector.

Once the composite vulnerability curve is developed for each infrastructure sector used in this model, it is applied through the common hazard-based probabilistic risk framework described above. This is done on a grid-by-grid basis where the AAL is estimated for each grid cell for a given hazard. This results in a dataset of AAL per grid for each sector and hazard. The AAL across all grid cells for a given sector-hazard combination are summed to calculate the AAL at a national scale.

Due to the simplification steps in both distributing the replacement value across grid cells and using a composite vulnerability model, the grid-cell results (an example if shown in Figure 2.6) are not recommended to be used at local scales. For local-scale studies, the damage and loss should be calculated using component-level analysis that is typically done for local authorities.

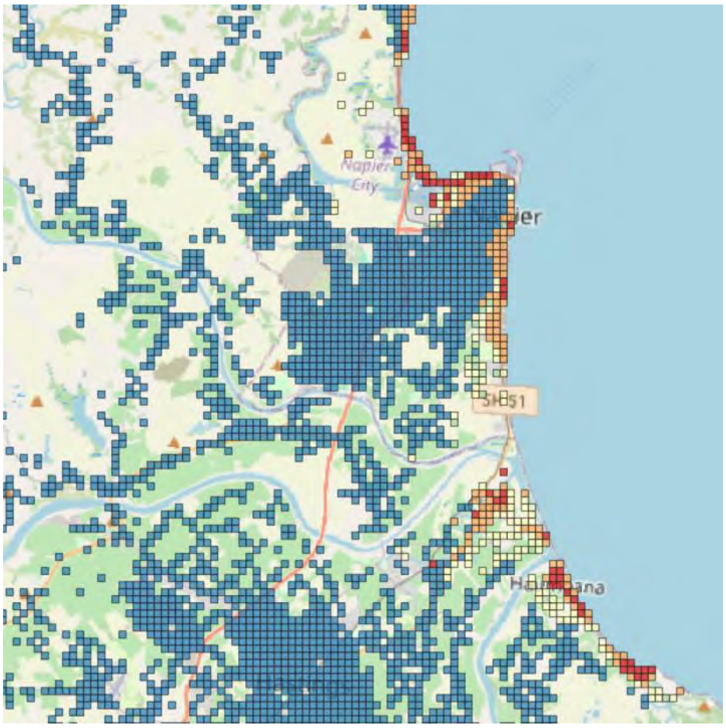

Figure 2.6 Example of estimated average annual loss (AAL) per grid cell for electricity sector from tsunami. Red colours are higher AAL and blue colours are lower AAL.

2.2.4 Model 3: Vertical Infrastructure

Modelling damage and losses to portfolios of vertical infrastructure (i.e. buildings) is common practise in New Zealand for insurance and re-insurance purposes. The risk models used for buildings are mature due to numerous events that have generated damage and loss, which vulnerability models can then be based on. Further, New Zealand has national-scale building-exposure data that represent each building in New Zealand in terms of its geospatial footprint and attributes (e.g. construction type, age, floor area), primarily based on the Core Logic dataset used for determining the capital valuation for rating purposes by local authorities.

GNS Science and NIWA have used the Core Logic dataset to develop a nationwide building-exposure dataset for risk-modelling purposes. This dataset contains every building in New Zealand and is updated every 2–3 years. The latest update occurred in 2022. The building-exposure dataset represents buildings geospatially by their footprint (polygon), sourced from the LINZ Building Footprint dataset. Attributes of the building are assigned based on either the Core Logic attribute information (e.g. floor area, use category) or by applying statistical distributions based on regional surveys by GNS Science and NIWA.

In this application, the NZ Building Exposure dataset is first filtered by use category to only include use categories that are within scope of the study as defined by the New Zealand Infrastructure Commission Te Waihanga. These are also the categories defined in New Zealand Infrastructure Commission (2024). This includes education, local and central government, and hospitals.

Once the target buildings are filtered, the replacement value from the building-exposure dataset is adjusted to ensure the sum of each use category is equal to that of the values in the New Zealand Infrastructure Commission (2024) report for that sector. This is achieved through normalisation, where a scale factor is calculated by dividing the value for a specific sector in the report by the total value of buildings in that sector (e.g. education) from the NZ Building Exposure dataset. This scale factor is then applied to each building replacement value in the dataset, ensuring that the total value of all buildings in that sector matches with the value reported in New Zealand Infrastructure Commission (2024).

The vulnerability model for each building is applied based on the building attributes such as age (related to building code), construction type, number of stories and, for flood-related hazards, the floor height. These vulnerability models are described below in Sections 2.3–2.7.

In this model, the AAL is estimated for each building following the hazard-based probabilistic risk framework described above. The results for each building are then aggregated up to the national scale for reporting.

2.3 Earthquake

Earthquakes can occur and impact any place in New Zealand. These are the leading cause of loss in recent New Zealand disasters. Earthquakes that generate damage and loss to infrastructure occur every few years; however, large earthquakes causing widespread loss have a low probability of occurring.

2.3.1 Hazard Data

National-scale maps of earthquake shaking expected over the next 100 years were sourced from the 2022 National Seismic Hazard Model (NSHM)[6] (Gerstenberger et al. 2022). Maps that contain the estimated ground shaking for average recurrence intervals of 2, 5, 10, 50, 100, 250, 500, 1000, 2500, 5000 and 10,000 years were used. The spatial resolution of the maps is 5 km x 5 km across New Zealand. Ground shaking was estimated on soil to incorporate shallow site-amplification effects. The V_{s30} (shear-wave velocity in upper 30 m) map used to represent the soil conditions was that of Foster et al. (2019). The Foster et al. (2019) model is available in 1 km resolution and the average V_{s30} value across each 5 km x 5 km grid was used in the calculations. The mean hazard estimate from the 2022 NSHM was used.

The earthquake model also includes the losses from earthquake-induced landslides and liquefaction. The earthquake-induced landslide model developed by GNS Science was used to estimate landslide probability conditional on ground shaking (Massey et al. 2021). The liquefaction model used estimates liquefaction susceptibility across New Zealand based on geologic and water table conditions.

2.3.2 Vulnerability Models

Different models available in the literature were reviewed and then used in this project for specific infrastructure sectors. For the electricity sector, a recent database of earthquake vulnerability curves for infrastructure components compiled by Nirandjan et al. (2024) was found to be appropriate for this project. It includes various models from earlier studies, including HAZUS models by FEMA (2020). For water, the vulnerability models from Nayyerloo and Buxton (2017) were used. For telecommunications, a study by Nayyerloo (2016) used most of the basic mean-damage ratios derived using estimates of New Zealand earthquakes, i.e. Hawke's Bay 1931, Wairarapa 1942, Inangahua 1968 and Edgecumbe 1987. Damage to the telecommunications components has been studied using the Edgecumbe and Wairarapa earthquakes (Dowrick and Rhoades 1993, 1997, 2002).

For road, the vulnerability functions from a study by Sadashiva (2018) were adopted. For rail, the vulnerability models from a rail systemic seismic vulnerability and risk assessment by Pitilakis et al. (2014) were selected.

2.4 Tsunami

All of the New Zealand coast is susceptible to tsunami. New Zealand has a history of small- to moderate-size tsunami impacting the coastline.[7] Tsunami events can impact many regions simultaneously and cause near-total loss to infrastructure that becomes inundated. However, tsunami events are very infrequent and are therefore considered low-probability, high-consequence events. The tsunami hazard and risk model is for earthquake-generated tsunami and does not account for tsunami generated by submarine landslides, volcanic eruption or those that occur within New Zealand lakes.

6 https://nshm.gns.cri.nz

7 https://www.gns.cri.nz/data-and-resources/new-zealand-tsunami-database-historical-and-modern-records/

2.4.1 Hazard Data

At present, there is no national tsunami hazard model for onshore inundation for New Zealand required for the risk modelling in this study. Previous estimates of tsunami loss at a national scale were developed using simplified models that used offshore wave height to approximate inundation extent (Horspool et al. 2015). The model is outdated now and not able to be used in this study. However, the Horspool et al. (2015) study calculated AAL and loss curves for building damage from tsunami.

Regionally, tsunami inundation models and inundation hazard maps are available. A recent example of this is for the Hawke's Bay region, where a probabilistic tsunami inundation model was developed (Burbidge et al. 2022). The model created inundation maps of tsunami flow depth for various AEP that were suitable for use in this study. Other regions where similar tsunami inundation maps are available are Wellington and Gisborne.

In order to address the gap in a national tsunami inundation hazard model, losses were calculated for regional models held by GNS Science. The losses were then extrapolated to the national scale by using the previous work by Horspool et al. (2015) as the basis for determining regional- to national-scale ratios. For example, the proportion of AAL from the Hawke's Bay region to the national scale in Horspool et al. (2015) was ~17%. Therefore, the AAL from the Hawke's Bay region in the current study was divided by 0.17 to extrapolate up to the national scale using the Horspool et al. (2015) study as a proxy. This was done for Hawke's Bay, Wellington and Gisborne and the average value taken as the final estimate for national-scale losses for tsunami.

The spatial resolution of the tsunami inundation data was 10 m x 10 m, and the models were run at mean high spring water level.

2.4.2 Vulnerability Models

Available tsunami vulnerability models for infrastructure were reviewed, such as Williams et al. (2019, 2020a, 2020b), Horspool and Fraser (2016), and Arup (2023). Most of these models are derived from post-event impact assessment from recent events in Indonesia, Chile and Japan. For road, the vulnerability models from Williams et al. (2020a, 2020b) were used. For power and water assets, vulnerability models proposed and discussed in Horspool and Fraser (2016) were used and expert judgement made by the project team when asset types were missing.

2.5 Volcanic Ash

All of New Zealand's volcanoes can produce volcanic ash during explosive volcanic eruptions. The impact can affect multiple regions and continue for days to years. The volcanic ash hazard and risk model estimates the ash depth and damage from New Zealand volcanoes. The model does not account for other volcanic hazards such as lava, ballistics or debris flows.

2.5.1 Hazard Data

The probabilistic volcanic ash data used in this study was provided by Christina Magill (GNS Science) and recently used in the National (New Zealand Lifelines Council 2023). The dataset was produced using the Tephra2 volcanic ash dispersal model to simulate 40,000 individual ashfall events for New Zealand volcanoes. Frequency-magnitude estimates were underpinned by Bebbington et al. (2018). Eruptive parameters such as eruption-column height were assumed from published studies of New Zealand volcanoes. Re-analysis meteorological data from the USA NOAA (National Oceanic and Atmospheric Administration) Earth System Research Laboratory was used to simulate wind fields. The 40,000 ashfall events were used to derive expected ashfall depths (in millimetres) at several return periods (50, 100, 500, 1000, 2500, 10,000 years) on a 5 km x 5 km grid across New Zealand.

2.5.2 Vulnerability Models

Tephra fall can impact infrastructure elements, causing both physical damage and disruption to the services that they provide (Wilson et al. 2014, 2017; Jenkins et al. 2014). Some assets (e.g. power lines) are more vulnerable than others (e.g. bridges) to ash loading. As tephra is hard and abrasive, corrosive (if moist and especially if bearing aerosols) and conductive (if moist), even small quantities of it can affect functionality of certain elements (e.g. plant and equipment components, especially those uncovered or with sensitive parts). Roads are typically affected by ashfall: obscured road markings, reduced visibility and skid resistance (traction) are common, and damage to road pavement is possible as a result of direct ashfall or indirectly from failure of structures (e.g. retaining walls) or other road elements (e.g. traffic light assembly) under heavy ash loading. Ash clean-up and disposal operations may be required to remove ash fallen over long lengths of roads, potentially resulting in significant costs.

Electrical networks are vulnerable to a number of impacts from ashfall, such as ash contamination at station and line insulators can lead to flashover (Wardman et al. 2012), damage to power lines and light structures from ash loading (a more pronounced effect when ash is wet). Ash accumulation can directly damage power poles (severity ranging from tilting to collapse of poles under heavy loading) and any element mounted on the poles (e.g. transformers getting clogged by ash or dislodged from or collapsing with the pole). Damage can also occur because of impact from tree-branch failures from ash loading. Abrasion damage to exposed electrical and mechanical equipment at substations and to solar panels, as well as ash-clogged transformers and control systems, can also be expected. Water-supply pipe networks commonly run underground, so these are less vulnerable to damage from ashfall. However, some exposed sections can get clogged (e.g. pipe carrying water from source infilled with ashfall) that may require ash removal. Some cost may also be involved in removal of ash near valves and hydrants. Damage to other water assets, such as storage tanks, is possible (generally in the form of roof collapse under moderate ash loading).

For all infrastructure assets in scope, no loss models were found to be readily available for use in this project, so all models applied here are based on judgement guided by the impact data (largely qualitative) found in the literature.

2.6 Coastal Flooding

Coastal flooding is a high-frequency event that impacts New Zealand infrastructure on an annual basis. The impacts are often localised but, due to the frequent events, the annualised loss can accumulate to become significant.

2.6.1 Hazard Data

Spatio-temporal maps of episodic flooding from extreme sea levels (ESLs) for present-day were obtained from Paulik et al. (2023a). ESL flooding maps represent 10, 20, 50, 100, 200, 500 and 1000 annual recurrence intervals (ARI). The mapping process involved extracting digital elevation model (DEM) raster cells situated below ESL and elevations using a static inundation mapping technique (Stephens et al. 2021). A comprehensive national DEM for coastal regions (Paulik et al. 2020, 2021), up to an elevation of 20 m above present-day mean sea levels, was established by amalgamating LiDAR (Light Detecting and Ranging) DEMs re-sampled to 10 m resolution and employing a fully convolutional neural network (FCN) model to rectify vertical biases in the Shuttle Radar Topography Mission (SRTM) data (Meadows and Wilson 2021).

Flood-depth calculations were performed by computing the disparity between ESL water-surface heights and land elevations for DEM grid cells. Only grid cells with a hydrologic connection to coastlines were considered, thereby minimising the risk of over-estimating inundation extents. Additionally, topographic protection structures such as levees were identified from aerial imagery and incorporated into the analysis, albeit without detailed design-level information. Consequently, land protection was assumed up to ESLs corresponding to a 100-year recurrence interval at present-day mean sea level (MSL). This was consistent with statutory flood hazard risk management directed by the New Zealand Coastal Policy Statement (Department of Conservation 2010), which requires regional and local authorities to avoid increasing the risk of social, environmental and economic harm from coastal hazards over at least a future 100-year timeframe.

2.6.2 Vulnerability Models

A consistent suite of infrastructure network component damage models was applied to assess both coastal and fluvial-pluvial flooding hazards. This approach is widely used globally due to the limited availability of empirical data on network component damage for either flood type. Direct physical damage to components is commonly represented using ‘depth-damage curves’, which quantify the relative damage response to increasing water depth. These damage curves express damage as a non-dimensional parameter, such as a percentage or ratio (e.g. ‘cost to repair’ divided by ‘cost to replace’), providing a standardised measure of the component’s vulnerability to flooding.

Judgement-based flood-damage curves developed for New Zealand infrastructure network components were used for this study. Component-specific relative damage curves were developed with network experts through a series of semi-structured workshops (Williams et al., in prep.). In each workshop, experts estimated minimum and maximum damage expected at 0.5, 1, 2 and 3 m water depths. Forty-six (46) expert responses were received and weighted by participant expertise level to aggregate minimum (5th percentile) and maximum (95th percentile) component damage curves. Thirty-four (34) component-specific damage curves were developed for transportation, energy, water and telecommunications networks. In this study, network-aggregated median (50th percentile) component damage curves were produced for water, road, rail, electricity and telecommunications network components.

Similar to infrastructure network components, relative depth-damage curves were used to represent building damage in response to increasing water depth. These damage curves were derived from empirical building damage data collected from eight New Zealand flood events, including the 2023 Ex-Cyclone Gabrielle in the Hawke's Bay and Gisborne regions. For this study, the damage data were aggregated into residential and non-residential building typologies and a square root regression function applied to fit continuous damage curves to each dataset (Paulik et al. 2024). The resulting aggregated damage curves provide estimates of the median (50th percentile) expected building damage corresponding to various water depths.

2.7 Fluvial-Pluvial Flooding

Fluvial-pluvial flooding has become prominent following recent events over the past decade. Much of New Zealand's communities and infrastructure are located in floodplains. Flood events that cause loss are an annual occurrence across New Zealand and can impact multiple regions depending on the nature of the rainfall event.

2.7.1 Hazard Data

The Endeavour project 'Mā te haumaru ō nga puna wai ō Rākaihautū ka ora mo ake tonu: Increasing flood resilience across Aotearoa' has developed a prototype system to generate consistent fluvial-pluvial flood maps for all of New Zealand in a semi-automated manner (Harang et al. 2024). The modelling system is based on flood plains and their feeder catchments. Nationwide fluvial-pluvial flood map coverage is achieved using 248 domains (i.e. catchments), each with LiDAR topography converted to a hydraulically conditioned DEM (Pearson et al. 2023) and a design rainstorm for a given duration and AEP. This rainfall flows through a hydrological model of the upper catchments and is modelled using the BGFlood two-dimensional hydrodynamic model (Bosserelle et al. 2022) in the floodplain. These modelling domains range in size from 5 km^2 for small coastal catchments in the Northland region to tens of thousands of square kilometres and thousands of river or stream inflow points for the largest domains in Southland region. Water depth above ground level for 10-, 20-, 50-, 100-, 200-, 500- and 1000-year ARI fluvial-pluvial flooding were simulated using an 8 m grid resolution, sufficient for estimating the exposure and impacts of vertical and horizon infrastructure network components.

2.7.2 Vulnerability Models

As noted in Section 2.6.2, the vulnerability models for coastal and fluvial-pluvial flooding are the same for this study.

2.8 Model Confidence

Each of the hazard-sector risk models has varying levels of confidence due to the various model components that make up that model (e.g. the hazard model, vulnerability model and exposure model). In order to communicate the confidence in the results, each hazard-sector model has been evaluated and categorised into having low, moderate or high confidence (Table 2.2). The level of confidence is related to the suitability of the model for the study purposes. The confidence-level categorisation is explained below:

- **Low Confidence:** Regional hazard models and/or vulnerability models based on international studies with no validation to New Zealand data. Models have been simplified or upscaled and there are significant assumptions for this study. This also includes vulnerability models based on expert judgement.
- **Moderate Confidence:** Regional hazard models and/or vulnerability models based on international events and validated in New Zealand. Moderate levels of model simplification, or assumptions.

- **High Confidence:** Nationally consistent hazard models at suitable spatial resolution and/or vulnerability models based on damage and loss data from New Zealand events. Models have been used for a variety of New-Zealand-based projects and have been improved over time.

Table 2.2 Overall confidence in hazard-sector models in this study.

	Water	Electricity	Telecommunications	Road and Rail	Vertical
Earthquake	High	High	Moderate	Moderate	High
Coastal Flooding	Moderate	Moderate	Low	High	High
Flood	Moderate	Moderate	Low	High	High
Tsunami	Low	Moderate	Low	Moderate	Moderate
Volcanic Ash	Moderate	High	Low	High	High

Of the hazard models, earthquake has the highest confidence due to it being developed at a national scale, updated recently in 2022 (Gerstenberger et al. 2022), and the vulnerability functions being based off New Zealand data. Flooding (coastal and fluvial-pluvial) and volcanic ash have moderate to high levels of confidence from national-scale hazard models and vulnerability models based mostly from New Zealand or similar international data. Tsunami has the lowest confidence due to the simplified models used, and the extrapolation from regional models to national estimates of risk.

For infrastructure sectors, vertical infrastructure has the highest confidence due to the maturity of the vulnerability functions that are based on New Zealand damage and loss data. Further, modelling losses to buildings is common for insurance and re-insurance purposes in New Zealand, which has led to development of high-quality models. The road and rail, electricity and water sectors have similar levels of moderate confidence as many of these sectors studied following New Zealand hazard events, and New-Zealand-based vulnerability models have been developed. Telecommunications is the sector with the lowest confidence, which is due to the closed nature of this sector in sharing information with researchers. This has resulted in few studies investigating the vulnerability of the sector, therefore resulting in risk models based mostly from international studies.

3.0 Results

The results from the risk assessment are presented as summary for New Zealand. The estimated AAL is presented for each hazard-sector combination, as well as hazard totals and sector totals. The estimated AAL are shown in Table 3.1, and the AALs as a percentage of the total value of that sector are shown in Table 3.2.

Table 3.1 Average annual loss (AAL) for each hazard-sector combination in NZD$ (million). For example, earthquakes are estimated to generate an average annual loss of NZD$14.02M for the water sector.

	Water	Electricity	Tele-communications	Central Govt Roads	Local Govt Roads	Rail	Vertical			Total
							Government	Hospitals	Education	
Earthquake	14.02	8.80	0.19	9.49	7.02	22.47	52.33	7.04	47.19	168.55
Coastal Flooding	54.72	40.26	0.68	19.84	34.11	2.95	9.49	0.52	3.00	165.58
Flood	68.42	90.1	1.15	25.29	46.85	14.6	17.37	3.62	13.71	281.11
Tsunami	1.71	2.63	0.55	0.08	0.24	0.03	3.36	0.001	0.30	8.90
Volcano	0.31	0.43	0.19	3.91	1.44	0.37	0.45	0.08	0.36	7.54
Total	139.18	142.22	2.76	58.61	89.66	40.42	83.00	11.261	64.57	631.70

The AAL per hazard was dominated by fluvial-pluvial flooding at $281M, followed by earthquake and coastal flooding on $169M and $166M, respectively (see Table 3.1). Tsunami and volcanic hazards were two orders of magnitude smaller than other hazards, with estimated losses of $8.9M and $7.6M, respectively.

In terms of infrastructure sectors, road and rail have the highest absolute AAL at NZD$189M, followed by electricity at $142M, water at $139M and vertical infrastructure at $133M. Telecommunications has the smallest estimated AAL at $3M (see Table 3.1). The sectors with the highest AAL as a percentage of the total value of the sector were water at 0.43% and telecommunications at 0.42%. These were followed by electricity at 0.31% and road and rail at 0.26%. Vertical infrastructure had the smallest AAL as a percentage of total value at 0.15% (see Table 3.2).

Table 3.2 Average annual loss (AAL) for each hazard-sector combination as a percentage of the total value of the sector. For example, earthquakes are estimated to cause an AAL of 0.043% of the total value of the water sector.

	Water	Electricity	Tele-communications	Central Govt Roads	Local Govt Roads	Rail	Vertical			Total
							Government	Hospitals	Education	
Earthquake	0.04	0.02	0.03	0.03	0.02	0.48	0.16	0.05	0.11	0.07
Coastal Flooding	0.17	0.09	0.10	0.05	0.12	0.06	0.03	0.004	0.01	0.07
Flood	0.21	0.19	0.18	0.07	0.16	0.31	0.05	0.03	0.03	0.12
Tsunami	0.01	0.01	0.08	0.0002	0.001	0.001	0.01	0.0000	0.001	0.004
Volcano	0.001	0.001	0.03	0.01	0.005	0.01	0.001	0.001	0.001	0.003
Total	0.43	0.31	0.42	0.16	0.31	0.87	0.26	0.08	0.15	0.26

There are very few published estimates of AAL at a national scale for New Zealand infrastructure available to compare with the results from this study.

The Natural Hazards Commission Toka Tū Ake (NHC Toka Tū Ake), which provides 'first loss' cover for residential buildings in New Zealand up to a cap of $300,000, recently provided estimates to Treasury for a Cabinet paper on their Funding and

Risk Management Statement, which was publicly released, in which NHC Toka Tū Ake estimated that its AAL for 2024 was $980M[8] for all hazards covered by its policy (earthquake, tsunami, landslip, volcanic eruption).

A recent study by McAneney et al. (2022) used a claims database from NHC Toka Tū Ake and the Insurance Council of New Zealand (ICNZ) to estimate that the observed AAL for insurable buildings over the past 55 years is $657M (standard deviation of $2,982M) per year. The large standard deviation is attributed to the low-probability, high-consequence nature of earthquake events.

The Lloyds of London Insurance Risk Index report from 2018, which estimates potential infrastructure losses from natural hazards globally, calculated that New Zealand's AAL for all infrastructure (e.g. horizontal and vertical) from all natural hazards was 0.66% of GDP, which equates to ~NZD$1,600M.

These previous estimates of AAL for buildings by NHC Toka Tū Ake and McAneney et al. (2022) are in the same order of magnitude as that estimated for this study. From recent events (e.g. Canterbury earthquakes, Ex-Cyclone Gabrielle), the infrastructure-related losses have been around one third to half of the total losses. The fact that the estimates from this study are in a similar order of magnitude to the NHC Toka Tū Ake and McAneney et al. (2022) estimates, and are lower than the total value for all infrastructure (both private and publicly owned) from the Lloyds of London report, provides some confidence that the model results from this study are in the right range.

8 https://www.treasury.govt.nz/sites/default/files/2024-08/funding-risk-management-statement-natural-hazards-commission.pdf

4.0 DISCUSSION

This section presents a broader discussion on some of the key topics and limitations from this study. It also suggests further work to improve the understanding of losses from natural hazards.

4.1 Suitability of Results

As outlined in Section 2, where the risk-model framework is presented, there are a number of assumptions and simplifications that have been adopted in order to be able to undertake this study. These necessary steps mean that the results are not suitable to be used at a local scale, nor should they replace any more detailed studies for specific infrastructure sectors that have been conducted at a national scale.

The results are intended to be used to help the New Zealand Infrastructure Commission Te Waihanga to understand average annual loss at a national scale for the purposes of strategic planning of resilience measures. These can be used as input into financial calculations for planning or ranking and prioritising sectors or hazards for future work.

4.2 Simplified Model Limitations

Two of the simplifications used in the 'aggregated risk model (Model 2)' to represent the infrastructure exposure are worthy of further discussion. These include the way that replacement costs are distributed by population density and how infrastructure exposure are assumed to be located within population grid cells. Both of these steps were necessary due to the limitation of having no knowledge on the infrastructure networks at a national scale.

By using population as a proxy for infrastructure locations, the model will be missing locations where infrastructure is located outside of populated areas. In this case, any infrastructure located further than ~250 m from a residential property will not be modelled at its correct location. It is thought that this simplification will have negligible effect on the estimated losses. This is due to a very small proportion of infrastructure value lying outside of populated areas; the exception for this is dams, power-generation facilities, water-treatment facilities and large substations. From a calculation of known network exposure data, these facilities typically make up less than 1% of the total network value, so not modelling their correct location is likely to have no material effect at the national scale.

Using population density as a proxy for distributing the replacement cost of each infrastructure sector is also a simplifying and averaging effect. This means that high-value assets are 'smeared' across the rest of the country and low-value assets may have their replacement value increased in the model. The New Zealand Infrastructure Commission Te Waihanga found that urban areas have less infrastructure per person and rural areas have more infrastructure per person[9]. This means that the infrastructure cost may be overestimated in urban areas and underestimated in rural areas.

Combined these two limitations are thought to only change the national-scale AAL by only a few percent compared to using a precise geospatial model of replacement value apportionment, due to the averaging effect of the over-and-under estimation of both asset locations and asset valuations.

4.3 Dynamic Risk and Climate Change

This study estimates AAL for infrastructure replacement costs as of 2022, and for hazard model forecasts for the short term (i.e. next few years). However, risk and forecast losses change over time due to a number of factors.

First, hazards change over time due to climate change. Climate change leads to rising sea levels that can increase coastal hazards such as coastal flooding and tsunami. Climate change can also change rainfall patterns, resulting in changing flood hazards. Earthquake hazards also change in time due to aftershock sequences that may raise the seismic hazard and risk for short periods (months to a few years). Some of these can be modelled, such as climate-change effects on floodings and

[9] https://tewaihanga.govt.nz/our-work/research-insights/auckland-s-infrastructure-the-cost-to-serve-a-city-that-s-growing-upwards

sea-level rise, but were not the focus of this study. However, the models have been built so that future work on exploring the change in risk over time from changing hazards such as climate change could occur.

The effect of climate change on infrastructure losses has been investigated in some recent regional studies. A study by GNS Science and NIWA that investigated climate change risk in Orewa (north Auckland) showed that the AAL for buildings in Orewa exposed to coastal flooding hazards could increase by 50% - 100% over the next 30 years (Bretherton et al, 2023) with the range bounded by lower and higher emission forecast models. Paulik et al (2020) investigated infrastructure exposure to coastal inundation under various climate scenarios and found similar increases in infrastructure exposure (not loss) over the next 30 years. These studies indicate that the AAL for coastal flooding estimated in this study could increase by 50% - 100% over the next 30 years due to climate change.

Risk also changes over time due to changes in exposure, both of the location and the replacement cost. Some models are available to simulate urban and rural growth that could be used in future work to explore the effect of this on future risk. Calculating future risk from changes in replacement cost could be used with the results of this study. Because the losses are calculated from a damage ratio (repair cost as a ratio of replacement cost), the AAL results can be scaled by the change in replacement cost into the future to adjust for changing replacement values.

Finally, risk can change over time due to changes in vulnerability. As infrastructure assets are renewed or upgraded, their vulnerability generally decreases and resilience increases. An example of this is the renewal of water pipes where older fragile pipes made of materials such as ceramics are replaced with less vulnerable PVC materials. The model can be re-run with different assumptions on component vulnerabilities but was out of scope for this study.

4.4 Uncertainty

Due to the scope of this project, uncertainty is not propagated through the risk model to provide uncertainty in AAL. Uncertainty is present in the risk model in all components, including the hazard models, vulnerability models, exposure models and replacement cost models. It was out of scope to propagate uncertainty through the model and include uncertainty in the final estimates but, in general, estimates in AAL have large uncertainties from both these modelled uncertainties as well as the variability in year-by-year losses, which leads to a large standard deviation in the average value of annual losses.

Based on other probabilistic loss studies on infrastructure by GNS Science, the average coefficient of variation (COV) of AAL (standard deviation of AAL divided by mean AAL) is ~15. This COV could be used to provide a rough approximation of what the standard deviation could be for some of the AAL estimates presented in this study.

4.5 Average Annual Loss versus Annual Exceedance Probability Losses

The losses presented in this study are the AAL that represents the estimated annual loss averaged over the long term. Another risk metric commonly used in risk management is the losses for various AEP, also referred to as a loss curve. The AAL is related to the loss curve, as when the area under the loss curve is integrated the result is the AAL. However, the shape of the loss curve is useful in understanding the probability of losses of a given level over a forecast time period. For example, two hazards may have the same AAL where one has more frequent small-level losses (e.g. floods) and the other has less frequent small-level losses but more frequent large-level losses (e.g. earthquakes). The approach used in this study calculated loss curves for each asset (building, grid cell or road/rail line segment); however, these loss curves cannot be aggregated at a regional or national level as this would disregard the correlation of losses from specific events. To generate a loss curve at a national scale, an event-based approach to the loss estimation must be used, which requires modelling a range of scenarios and their hazard footprint to develop event-based losses. This differs from the hazard-based probabilistic method used here, where hazard maps can be used as input into the risk calculation. The event-based approach is currently only available for earthquake hazards at a national scale.

4.6 Nationally Consistent Hazard and Risk Models

Many of the limitations outlined above are due to having inconsistent natural hazard and risk models. These hazard and risk models are developed by different organisations through various funding schemes (or no funding at all) and motivated by different end uses. For example, the NSHM is primarily developed for the purpose of the Building Code and has only undergone a major update every 20 years following funding by MBIE; meanwhile, a national-scale flood model has only in the past year been developed (through Endeavour Funding), and no national-scale hazard models exist for tsunami inundation or rainfall-induced landslides (although funded projects may achieve this in the next five years). This leads to challenges when trying to undertake multi-hazard risk assessments for national-scale studies such as this.

A key recommendation is to move toward a consistent suite of national-scale natural hazard and risk models that would enable studies such as this to be undertaken with less effort and in a more regular, consistent manner.

5.0 Conclusion

This study has developed a national-scale estimate of average annual loss (AAL) for New Zealand's infrastructure from natural hazards using high-level risk modelling.

Results show that the total expected AAL for all infrastructure sectors across all hazards considered is NZD$632M, which represents 0.26% of the infrastructure value. Road and rail dominates the expected losses with $188M in AAL, followed by electricity ($142M), water ($139M) and vertical infrastructure ($133M). Telecommunications has the smallest estimated sector loss with an AAL of $2.8M. Fluvial-pluvial flooding is the hazard with the highest estimated AAL with an estimated value for all infrastructure sectors of $281M, followed by earthquake ($169M) and coastal flooding ($166M). Tsunami ($8.9M) and volcanic ash ($7.6M) are estimated to be some two orders of magnitude smaller than the other hazards.

The results are intended to be used to understand the potential losses expected at a national-scale for the major infrastructure sectors and not for detailed sector-based decision-making.

Future work could prioritise certain natural hazards and sectors for more detailed investigations, such as developing scenarios to better understand the spatial distribution of losses or modelling the change in risk over time from resilience measures and changing hazards due to climate change. The RiskScape model is transparent and modular and so can be re-run with updated information such as infrastructure sector valuations or updated hazard data such as with different climate scenarios.

The results for studies such as this could be greatly improved and made more useful for other government agencies by developing nationally consistent hazard and risk models for loss-modelling purposes instead of pulling together ad-hoc variable information.

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