

Article

A National-Scale Assessment of Population and Built-Environment Exposure in Tsunami Evacuation Zones

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Abstract: Evacuation zones are a critical tool for mitigating loss of life in tsunami events. In New Zealand, tsunami evacuation zones are implemented by emergency management agencies at regional or sub-regional scales, providing national coverage for populated coastlines at risk to tsunami inundation. In this study, we apply the exposure component of a risk model framework (RiskScape) to deliver a first national-scale assessment of New Zealand's population and built-environment exposure in tsunami evacuation zones. Usually-resident populations, buildings, land and transport network components are identified at an asset level and enumerated at national and regional scales. Evacuation zones are occupied by just under 10% of New Zealand's population, residing in 399,000 residential buildings. These are supported by a further 5400 critical buildings and 6300 km of road transport network. Approximately 40% of exposed populations and buildings occupy evacuation zones expected to be inundated once every 500 years. This includes over 150,000 people in highly vulnerable age groups, i.e., children and elderly. The complex arrangement of built environments highlights a need for disaster risk managers to proactively identify and prepare populations for evacuation based on their vulnerability to harm from tsunami and ability to access resources for recovery after the event.

Keywords: tsunami; evacuation; exposure; population; buildings; RiskScape

1. Introduction

Population evacuation from tsunami is essential for preventing loss of life [1]. Tsunami have caused over 250,000 deaths globally in the last 20 years, mostly from near-field events with short wave arrival times [2,3]. In response, disaster risk management agencies and researchers have mapped tsunami hazard threat areas [4] to establish evacuation zones [5]. Tsunami evacuation zones identify areas where a threat to human safety requires people to leave inundation areas rather than sheltering in place. The zones are now a critical risk-mitigation tool in tsunami-prone areas that educate coastal populations on tsunami inundation threats and identify locations and routes for evacuation to safe areas [1,5].

Evacuation zones are maps representing areas at risk to tsunami inundation. Delineating evacuation zones requires methodologies for mapping inundation at different spatial scales [6]. Inundation mapping methods range from simple attenuation rules based on maximum wave height at coast [7] to complex numerical modelling of tsunami wave propagation and inundation from tsunamigenic sources [8,9]. Tsunami inundation scenarios can be mapped as deterministic 'maximum credible' or single source events, or probabilistic events, representing numerous sources and tsunami

events. Evacuation zone boundaries are often defined from the inundation area expected from a maximum tsunami run-up height or temporal recurrence interval.

Comprehensive tsunami risk assessments apply models that analyze the exposure and vulnerability of elements at risk (e.g., populations and assets) to estimate impacts from inundation hazards [10]. Risk analysis in tsunami evacuation planning can characterize populations and built assets exposed to inundation, then apply vulnerability models to quantify their damage response [1,11,12]. This determines where vulnerable populations (e.g., children and elderly) may experience harm or evacuation difficulties, and impediments from secondary hazards such as building collapse, road damage and debris. Despite recent advancements in understanding the evacuation response of populations using methods such as agent based [13,14] or least-cost distance [15] models, few studies investigate population and built-asset exposure or impacts in evacuation or hazard zones at national or regional scales. This information is important for implementing a cohesive preparedness and response to tsunami events [11].

In New Zealand, tsunami evacuation zone implementation is prescribed by National Emergency Management Agency (NEMA) guidelines [16]. The guideline provides a consistent national approach for fifteen regional emergency management agencies (termed Civil Defence Groups) to map tsunami evacuation zones, create public information for evacuation response and align tsunami evacuation plans and processes with official tsunami warnings. In 2020, spatial maps of evacuation zones are implemented by all agencies at regional or sub-regional scales, providing national coverage for populated coastlines at risk to tsunami inundation. Publicly available evacuation zone maps and recent government provision of open spatial data for built assets now provide an opportunity to assess national- and regional-scale exposure of populations and built environments in tsunami evacuation zones.

This study presents a first national-scale assessment of New Zealand's population and built-environment exposure in tsunami evacuation zones. Here, we define exposure as the 'location of people, built assets and land that overlap with tsunami evacuation zones. We use the exposure component of an analytical risk model framework, RiskScape [17], to enumerate population, built-land and asset exposure in evacuation zones representing varying levels of tsunami threat. We present exposure information at national and regional authority scales and discuss its implications for future tsunami evacuation preparedness and response planning. This study contributes to the expansion of global data and knowledge of population and built-environment exposure to tsunami hazards.

2. Materials and Methods

2.1. Regional Setting

New Zealand's location on the edge of the "Pacific Ring of Fire" creates exposure to numerous tsunami sources. The country lies on the Australian and Pacific Plate boundary, with the Hikurangi subduction margin a near-field source capable of producing local tsunami waves from great ($M_W > 8.0$) subduction earthquakes [18] (Figure 1a). This subduction margin poses the greatest concern to New Zealand due to its potential for generating large waves and onshore flow depths (>5 m) with short arrival times (<30 min) along the North Island east coast [19]. The Hikurangi margin has not ruptured in the last 200 years. However, 10 possible subduction earthquakes have occurred over the past 7000 years, with the last earthquake at 520–470 years BP in the southern Hikurangi margin and evidence for a full margin rupture at 870–815 years BP [18]. New Zealand is also at risk to tsunami generated from regional sources [20,21]. The Tonga-Kermadec trench northeast of New Zealand, poses the greatest regional tsunami hazard threat, with waves heights up to 10 m generated from earthquakes $M_W > 8.0$ expected to reach coastlines of New Zealand's northern regions at least every 500 years [22]. Waves generated from this area could arrive within 4 h. In the last 150 years, three tsunami generated by earthquakes off the Peru–Chile trench have caused inundation along New

Zealand's eastern coastlines [23]. This source area poses the most frequent far-field tsunami hazard threat, with waves typically reaching coastlines 12 to 15 h after generation [24].

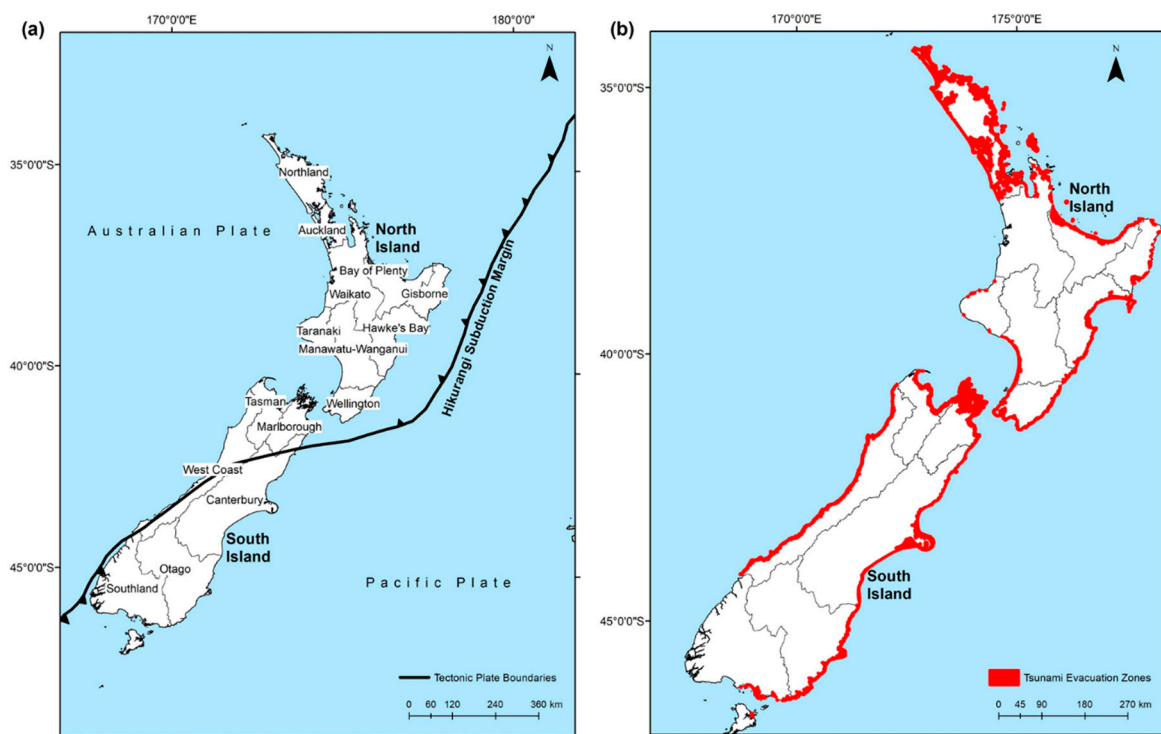


Figure 1. (a) New Zealand regional authority boundaries and (b) coastline coverage with mapped tsunami evacuation zones.

New Zealand's coastline is over 14,000 km in length and bordered by sixteen regional authorities (Figure 1a), administered by fifteen regional emergency management agencies (includes a joint agency for Nelson and Tasman regions). Eighteen coastal towns and cities, ranging in size from 10,000 to 1,675,000 people, represent approximately 70% of New Zealand's total population. Coastal populations and built assets are highly exposed to inundation hazards such as coastal flooding and sea-level rise. A resident population of 72,065 and more than 49,000 buildings could be exposed to coastal flooding from present-day 100 year annual recurrence interval (ARI) extreme sea levels (ESL₁₀₀) [25]. A mean sea-level rise of 1 m more than doubles this exposure to over 177,000 people and 125,000 buildings. These low-lying populations and buildings are connected by an extensive transport network with over 1400 km of roads, 86 km of railway and 13 international and domestic airports on land exposed to ESL₁₀₀ flooding. As present-day ESL₁₀₀ elevations range from 1.4 m to 4.2 m around the New Zealand coastline [25], many areas where there are populations and built assets exposed to coastal flooding will be susceptible to inundation from near-field, regional and far-field source tsunami.

2.2. Exposure Mapping Methodology

The exposure analysis presented in this study applies the RiskScape multi-hazard risk model framework [17]. RiskScape provides a modular framework configurable for analyzing tsunami exposure and impacts from deterministic or probabilistic inundation scenarios. The system combines hazard, exposure (i.e., elements at risk), and vulnerability datasets in a state-of-the-art software engine that quantifies risk of exposure or impact at national to local scales. RiskScape is configured here to enumerate populations, built assets and land, and their geometric quantities exposed within tsunami evacuation zones (Figure 2). Exposure model datasets are described in Section 2.3. and Section 2.4., and assessment process in Section 2.5.

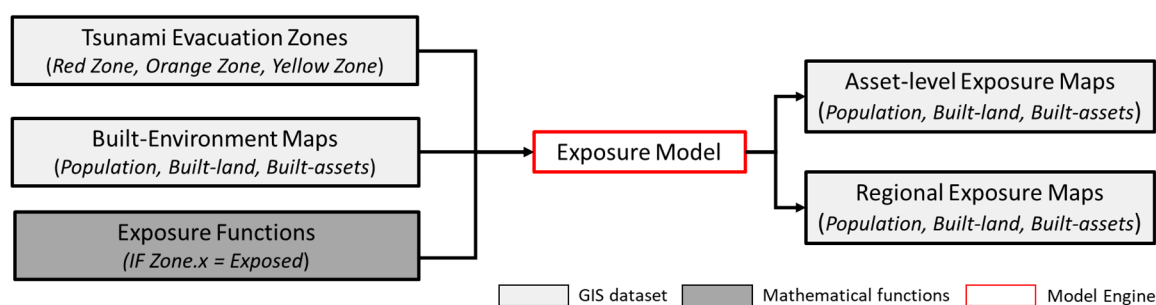


Figure 2. Schematic representation of the RiskScope exposure model framework and workflow applied in this study.

2.3. Tsunami Evacuation Zone Maps

New Zealand’s fifteen regional emergency management agencies have mapped tsunami evacuations zones for coastlines in their jurisdictional areas (Figure 1b). Tsunami evacuation zones are required to be consistent with NEMA guidelines, promoting a nationally consistent approach for mapping zones [16]. Constraints on technical capacity, data and tools for tsunami inundation modelling, however, mean that a range of inundation mapping methods are required to determine evacuation zones. These range from simple ‘bathtub’ models or attenuation rules through to complex numerical modelling of tsunamigenic sources, wave propagation and inundation. NEMA guidelines account for these methodological variations, providing a framework with four developmental levels that evaluate model complexity and reliability for tsunami evacuation zone mapping [16].

‘Level One’ inundation models apply a bathtub approach, where maximum wave amplitude heights are projected inland to derive a run-up height. Evacuation zone guidelines state that this is a least preferred approach as it does not consider tsunami behaviour such as attenuation as the wave moves inland. ‘Level Two’ models apply a rule-based attenuation method, whereby run-up limits and inundation areas are estimated from decreasing wave amplitude heights with distance inland. For instance, these models may apply a 1% attenuation rule to estimate inland run up that corresponds to wave height decrease by 1 m for every 100 m inland. ‘Level Two’ models intend to determine an interim inundation area while further resources and bathymetric and topographic details are gathered to allow for model refinement. These models are applied region-wide to delineate evacuation zones for Northland, Taranaki, Manawatu-Wanganui, Nelson, Marlborough, West Coast, Otago and coastline segments in the Waikato, Hawkes Bay and Wellington regions (Table S1). ‘Level Three’ modelling is applied in Auckland, Gisborne, Hawkes Bay, Wellington (harbour coastlines) and Canterbury, where deterministic tsunami inundation scenarios are simulated using complex physics-based models that combine seismic source, propagation and inundation models (Table S1). These models incorporate factors such as seismic trigger characteristics, land surface roughness and small-scale water flows to derive inundation areas and evacuation zone maps. ‘Level Four’ models apply probabilistic seismic, propagation and inundation models to derive an ‘envelope’ of tsunami inundation over an annual recurrence interval to represent evacuation zones. This level of modelling is rarely applied in New Zealand due to its complexity and financial resource requirements.

New Zealand tsunami evacuation zones correspond to tsunami inundation risk levels. Three zones are identified: the ‘red zone’—low-lying land up to two meters elevation above mean high water springs (MHWS); the ‘orange zone’—the expected inundation area from a 500 year annual recurrence interval (ARI) event with a travel time of greater than an hour; and the ‘yellow zone’—the expected area inundated in a 2500 year return period event with an 84% confidence level, or larger magnitude near-field event [16]. Zone boundaries may be adjusted to align with linear features, such as roads, before being communicated to the public (Figure 3a). Tsunami evacuation zone maps for New Zealand regions are openly accessible from emergency management agencies on request or through ArcGIS REST (Representational State Transfer) servers (Table S1).

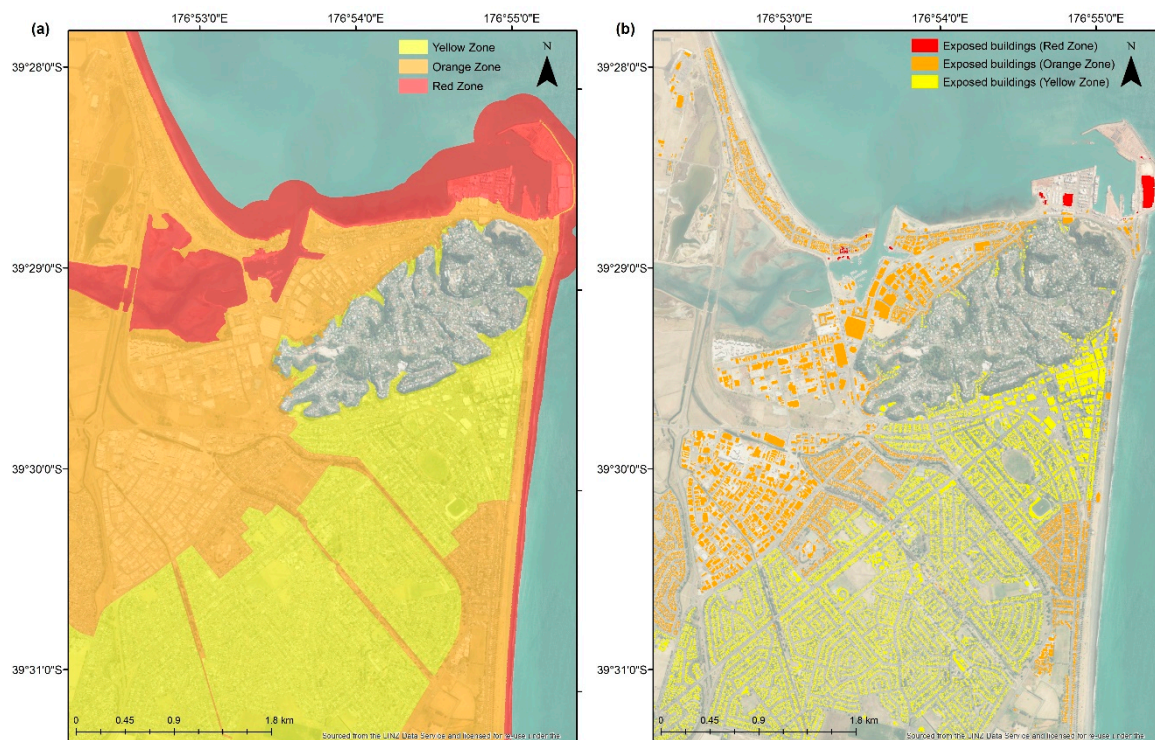


Figure 3. Tsunami evacuation zones and building exposure for Napier City (Hawke’s Bay, North Island, New Zealand), showing (a) red, orange and yellow zones; and (b) buildings exposed in each zone.

2.4. Built-Environment Maps

Built environments are considered here as land areas above MHWS used for human activities. Spatial maps representing built-environment elements in tsunami evacuation zones were obtained from government and open access data sources (Table S2). Elements representing ‘built assets’ were limited to buildings and transport network components (roads, railway, airports) (Table 1). These built assets were considered important for the congregation or movement of at-risk populations within evacuation zones. ‘Built land’ representing ‘built-up’ (i.e., settlements, infrastructure) and ‘primary production’ land areas identified in the 2018–2019 summer period is also included [26]. Built land and assets are geometrically represented as either vector polygons or lines with location and sizes approaching 1:10,000 scale. Buildings and transport network components are identified at the asset level; however, physical and non-physical information were limited to attributes with consistent information at this level (Table 1; Table S2). Inconsistent attribute information allowed only for reliable reporting of counts or linear extents for railways and airports.

Use category and usually-resident population attributes were included in the analysis as contextual information for buildings. Twelve categories representing residential and non-residential buildings were spatially joined to individual building outlines from available national datasets (Table S2) [27]. Residential building use categories informed attribution of usually-resident populations. Statistics New Zealand performs a national population census including the count, age and gender of people usually living in residences stated in the March 2013 census [28]. Usually-resident populations are aggregated to meshblock areas occupied by 0 to 1899 people, and divided into both age (<15 years, 15–65 years, >65 years) and basic gender (male, female) groups. Meshblock populations were used to calculate building population density rates by dividing the total meshblock population by the total meshblock residential building outline area (i.e., people/m²). Population densities were then multiplied by the outline area of each residential building object to estimate the usually-resident building population.

Table 1. Built-environment elements at risk and contextual information.

| Element Category | Object Type | Attributes | Units | Geometry | Data Owner |
|------------------|-------------|--|-----------------|----------|---|
| Land | Land Cover | Use Category, Area | km ² | Polygon | Government Research Institute |
| Buildings | Building | Population (age, gender), Use Category | - | Polygon | Government Research Institute, Central Government, Local Government, Private Sector |
| Transport | Roads | Length, Use Category, Traffic Volume | km | Line | Central Government |
| | Railway | Length | km | Line | Central Government |
| | Airports | Area | km ² | Polygon | Central Government |

2.5. Exposure Assessment

Tsunami evacuation zones were combined with built-environment population, built-land and asset maps in RiskScape [17] to enumerate exposure metrics at the asset level. RiskScape applies geoprocessing functions to intersect vector geometries representing evacuation zones, built-land and assets, and regional authority jurisdictional boundary locations, then recalculate geometric units for built-land and assets located within each evacuation zone and regional authority boundary. In this study, population, built-land and asset exposure in evacuation zones is aggregated from asset level to national and regional authority scale, and reported for vector polygon counts (#), polygon area (km²) and line length (km).

3. Results

In this section, we present information on regional-scale population (Section 3.1.) and built-environment (Section 3.2.) land (Section 3.2.1.), and asset (Section 3.2.2.) exposure in tsunami evacuation zones. Exposure information is reported for ‘red’, ‘orange’ and ‘yellow’ zones, as prescribed by national guidelines [16]. National-scale exposure for evacuation zones are presented in Table 2, and raw data for regional-scale exposure provided in Table S3.

3.1. Population

Over 430,000 people, nine percent of New Zealand’s population, reside in tsunami evacuation zones (Table 2). Of these, nearly 40% (>170,000 people) occupy ‘red’ and ‘orange’ zones, expected to be exposed to tsunami inundation within a 500 year ARI. Population exposure in these zones is highest in Auckland (34,693), Canterbury (30,943) and Bay of Plenty (25,681). Larger urban coastal populations in these regions are exposed to tsunami from regional (i.e., Tonga-Kermadec trench and Hikurangi subduction margin) and far-field (i.e., Peru–Chile trench) sources. Wave arrival times for regional source events may provide populations in these regions with less than 4 h for evacuation. Hawke’s Bay has the highest regional population (12,800) in ‘red’ and ‘orange’ zones. The region is also at risk to near-field tsunami preceded by an earthquake on the Hikurangi subduction margin may provide <30 min evacuation time before wave arrival in the region [18].

Several studies indicate people in children and elderly age groups experience difficulties evacuating from tsunami, leading to a higher likelihood of mortality [29]. Auckland has the highest exposure of people representing these age groups, where 17,600 under 15-year-olds and 15,498 over 65-year-olds are exposed (Figure 4a). Exposure of under 15-year-olds exceeds 10,000 people in Canterbury (13,469), and Bay of Plenty for the over 65 group (13,469). Approximately 15% of New Zealand’s ‘red’ zone population is under 15-years-old and 26% over 65. ‘Red’ zone populations are highest for these groups in Waikato (482 people <15 years, 861 people >65 years) (Table S3).

New Zealand has approximately 209,000 people who self-identified as male and 224,000 people self-identified as female residing in tsunami evacuation zones. The largest variance in gender exposure occurs in Auckland, where 3500 more females are exposed in evacuation zones (Figure 4b). In addition, the Bay of Plenty, Hawke’s Bay and Wellington regions each have over 2000 more women than men exposed.

3.2. Built Environments

3.2.1. Land

New Zealand tsunami evacuation zones cover a built-land area of 2709 km². This area consists of 354 km² ‘built-up’ land (i.e., settlements, infrastructure) and 2355 km² ‘primary production’ land (Table 2). More than half of exposed land is located within ‘red’ or ‘orange’ zones.

Most built-up land in evacuation zones occurs in New Zealand’s most populous regions (Figure 3a). North Island east coast regions including, Auckland (18%), Bay of Plenty (11%) and Hawke’s Bay (10%) account for nearly 40% of built-up land exposure, covering 116 km² (Figure 5a). Built land within Hawke’s Bay evacuation zones is vulnerable to tsunami inundation from near-field sources with short wave-arrival times (<30 min). On the South Island, built land on eastern coastlines is most highly exposed in Canterbury (20 km²) a region vulnerable to tsunami inundation from far-field sources with longer arrival times (12 to 15 h).

Table 2. National exposure estimates for population, built land and assets in tsunami evacuation zones.

| Element | Attributes | | Exposure Metric | Evacuation Zone | | | Total |
|------------|---------------------------|-------------------------|-----------------|-----------------|---------|---------|---------|
| | | | | Yellow | Orange | Red | |
| Population | Age | <15 years old | Count (#) | 53,796 | 29,887 | 617 | 84,300 |
| | | 15–65 years old | | 163,101 | 107,310 | 2278 | 272,689 |
| | | >65 years old | | 44,274 | 30,866 | 1007 | 76,147 |
| | Gender | Male | 125,260 | 81,544 | 1929 | 208,733 | |
| Female | | 135,754 | 86,323 | 1987 | 224,064 | | |
| Land | Built-Up | Area (km ²) | 177 | 158 | 17 | 353 | |
| | Production | | 1128 | 1126 | 100 | 2354 | |
| Buildings | Residential | Residential | Count (#) | 230,702 | 160,626 | 7774 | 399,102 |
| | | Retirement Home | | 373 | 139 | 0 | 512 |
| | Commercial and Industrial | Commercial | | 5151 | 5514 | 300 | 10,965 |
| | | Industrial | | 13,262 | 15,687 | 495 | 29,444 |
| | Critical | Hospital and Medical | | 275 | 186 | 9 | 470 |
| | | Emergency Management | | 368 | 228 | 1 | 597 |
| | | Government | | 1680 | 1647 | 202 | 3529 |
| | | Infrastructure | | 204 | 453 | 53 | 710 |
| | Utility | 2523 | 1092 | 28 | 3643 | | |
| | Education | | | | | | |
| Other | - | 19,823 | 18,454 | 2834 | 41,111 | | |
| Roads | High Traffic Volume | National | 122 | 173 | 4.7 | 300 | |
| | | Regional | 91 | 88 | 6.7 | 186 | |
| | Medium Traffic Volume | Arterial | 266 | 330 | 5.7 | 602 | |
| | | Primary Collector | 408 | 426 | 20 | 855 | |
| | Low Traffic Volume | Secondary Collector | 676 | 736 | 31 | 1444 | |
| | | Access | 1285 | 1423 | 101 | 2809 | |
| | Not Defined | - | 88 | 79 | 4.6 | 171 | |
| Railway | - | Length (km) | 137 | 228 | 46 | 411 | |
| Airports | - | Count (#) | 18 | 5 | 0 | 23 | |

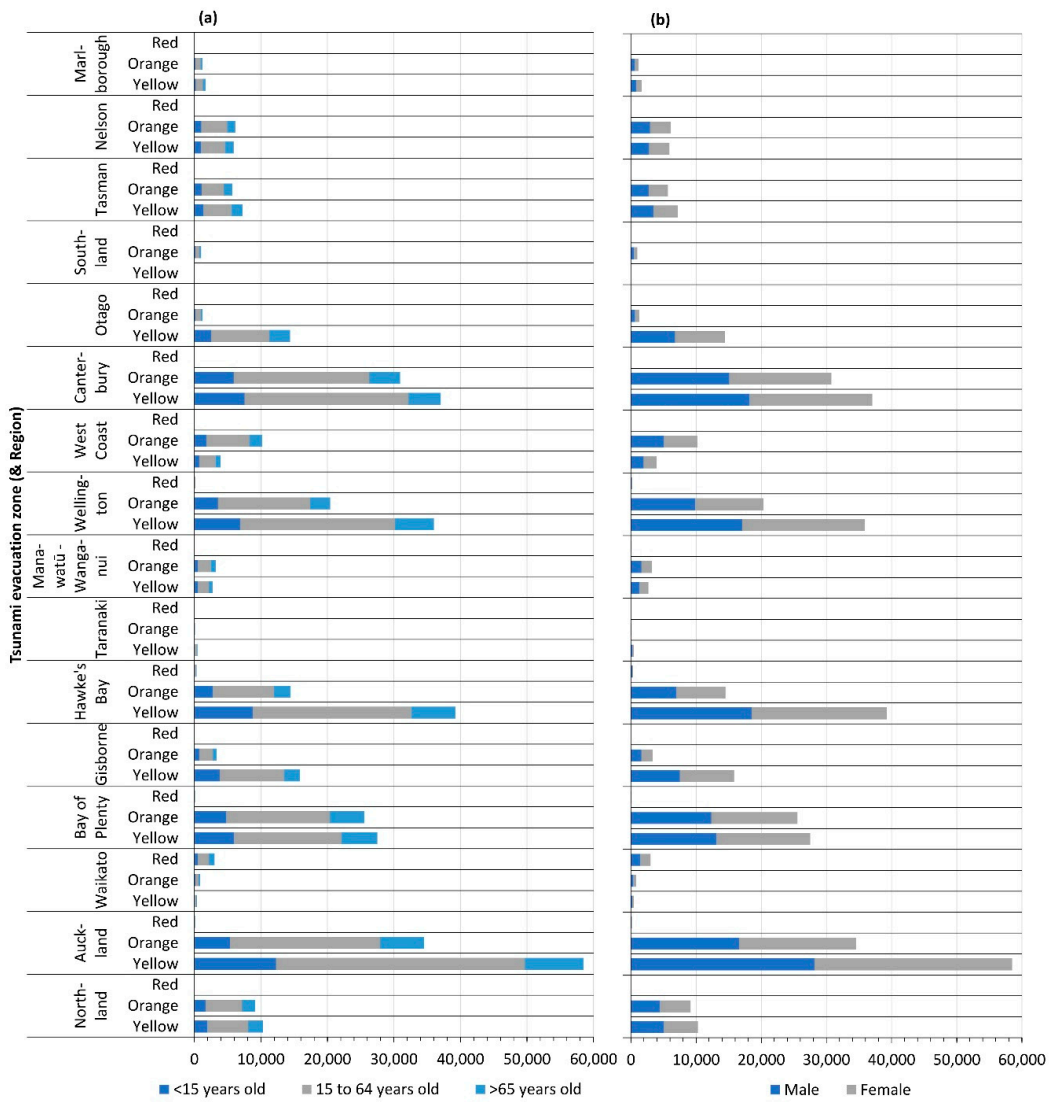


Figure 4. Regional population exposure by (a) age; and (b) gender in 'red', 'orange' and 'yellow' tsunami evacuation zones.

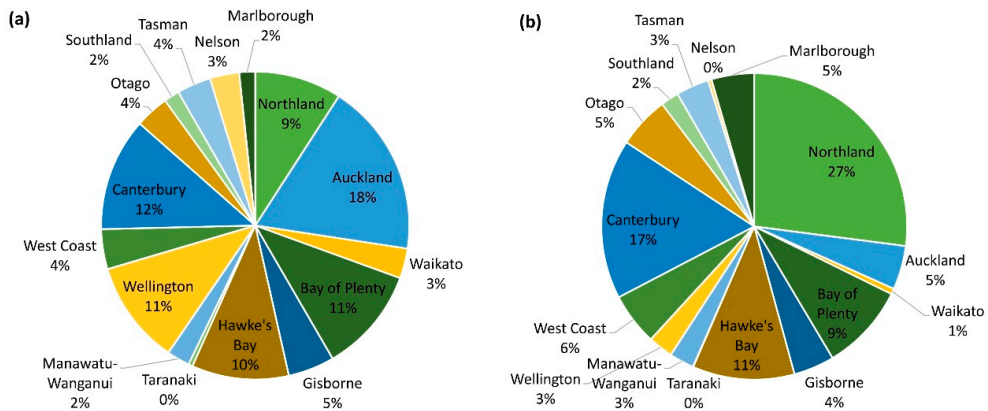


Figure 5. Proportional distribution by region for (a) built-up and (b) primary production land exposure in tsunami evacuation zones.

Land used for primary production activities such as pastoral farming and horticulture has higher exposure in North Island evacuation zones (1408 km²). Over one-third of this land exposure occurs in Northland (616 km²) and exceeds 200 km² in both Hawke's Bay (245 km²) and Bay of Plenty (209 km²) (Figure 5b). In Hawke Bay, over 35 km² is located the 'red' zone. South Island production land is most highly exposed in Canterbury (385 km²). Canterbury (13 km²) and Otago (12 km²) regions, bordering the South Island east coast, observe similar levels of 'red' zone exposure for primary production land.

3.2.2. Building and Infrastructure Assets

In New Zealand, over 490,000 buildings are constructed in tsunami evacuation zones, with 215,722 (43%) in 'red' or 'orange' zones (Table 2; Table S3). Residential uses represent 81% of total building exposure. These buildings also represent the location of most people considered as New Zealand's usually-resident population in this study. Residential building exposure is higher east coast regions on both islands, and exceeds 50,000 in Auckland and Canterbury, New Zealand's two most populous regions. Waikato region (5983) has the highest residential exposure in 'red' zones, followed by Hawke's Bay (547) (Figure 6a). Red-zone buildings in these regions are susceptible to tsunami generated from regional or near-field sources with typical wave arrival times between 30 min and 3 h. Although no retirement home buildings are exposed in 'red' zones, 139 are exposed in 'orange' zones. 'Orange' zone retirement buildings are mostly located in Auckland (81) and Hawke Bay (36). These facilities are usually occupied by persons >65 years old and therefore, represent a higher potential risk for human harm during tsunami events.

Most evacuation zone buildings used for commercial (10,965) or industrial (29,444) purposes are in New Zealand's most populous regions: Auckland, Wellington, and Christchurch (Figure 6b). In the South Island, most commercial and industrial buildings in Canterbury (>90%) are located in 'orange' zones. In the North Island, lower levels of building exposure 'orange' zones are observed though several regions (i.e., Auckland, Bay of Plenty, Hawke Bay, Wellington) exceed 2000 buildings across all zones.

Critical buildings, such as hospitals, emergency management and government buildings often designated for emergency response and recovery activities from tsunami events total 8949 in evacuation zones for New Zealand (Table 2). Hospital and medical building exposure totals 195 in 'red' and 'orange' zones, with a further 229 emergency management buildings. Auckland (1485) has considerably higher critical building exposure than other North Island regions, including 136 buildings in the 'red' zone (Figure 6c; Table S3). In the South Island, Canterbury (410) has the highest critical building exposure in 'red' (15) and 'orange' (395) zones. Over 1000 educational buildings are exposed in these zones across New Zealand. Many educational buildings will be occupied by people <15-years-old during daytime hours and used as welfare centers for post-tsunami recovery activities.

Horizontal road (6370 km) and railway (411 km) infrastructure in tsunami evacuation zones, respectively, exceed seven and ten percent of New Zealand's national network (Table S3). Most road exposure occurs in 'orange' zones (3257 km), predominately access and secondary collector roads (2159 km) with 'low' daily traffic volumes (<3000 vehicles/day) in urban areas. Low-volume road exposure is highest in 'orange' zones for North Island east coast regions from Northland (206 km) to Bay of Plenty (189 km) (Figure 7). High traffic-volume roads representing national (>15,000 vehicles/day) and regional (>10,000 vehicles/day) highway networks are most extensively exposed in Auckland (91 km) and Canterbury (93 km). A little more than 11 km of high-volume roads are exposed in 'red' zones (Table 2), with 8.4 km located in the Auckland region. On the South Islands east coast, Canterbury has more than 80 km of high-volume national highway road exposure in 'orange' zones (Figure 7). Daily traffic volumes on national highways respectively exceed 25,000 and 15,000 vehicles per day in urban and rural areas.

Most international and domestic airports in New Zealand are located on flat, low-lying land close to coastlines. Twenty-three airports are built in evacuation zones, mostly located in 'yellow' zones (18) (Table S3). Five airports in 'orange' zones are used for domestic purposes with commercial services

for business and tourism (Hawke’s Bay, Southland, West Coast) or recreational and charter flights (Canterbury and West Coast). Dual international and domestic airports in Auckland and Wellington are located in ‘yellow’ zones. ‘Yellow’ zones in the Wellington region represent areas potentially at risk to tsunami inundation from near-field sources with short (<30 min) wave arrival times. Airports are complex facilities with people often distributed over a broad area, posing considerable logistical issues for organizing a safe evacuation, especially in response to short wave arrival times from a near-field tsunami event.

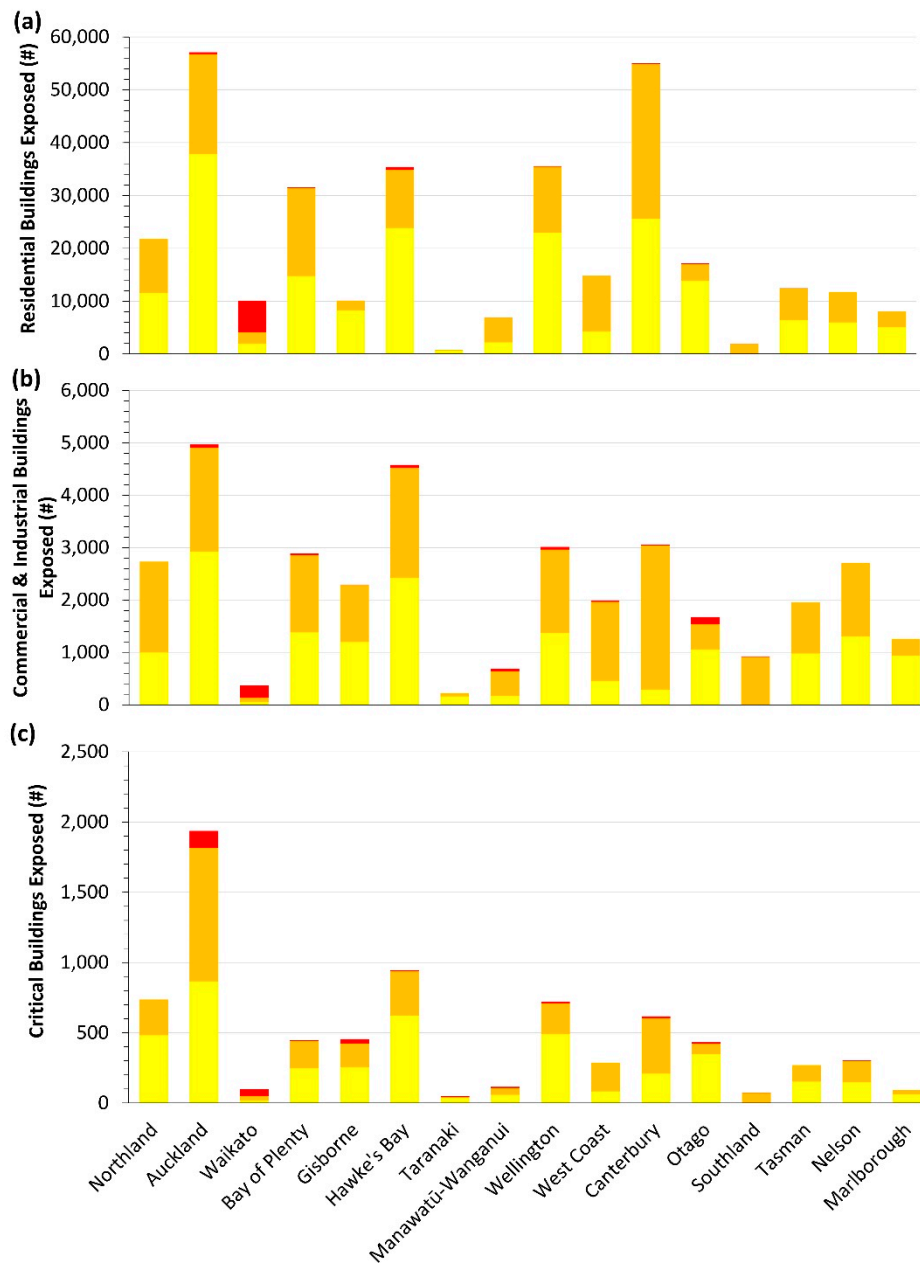


Figure 6. Regional building exposure within ‘red’, ‘orange’ and ‘yellow’ tsunami evacuation zones for (a) residential, (b) commercial and industrial, and (c) critical buildings.

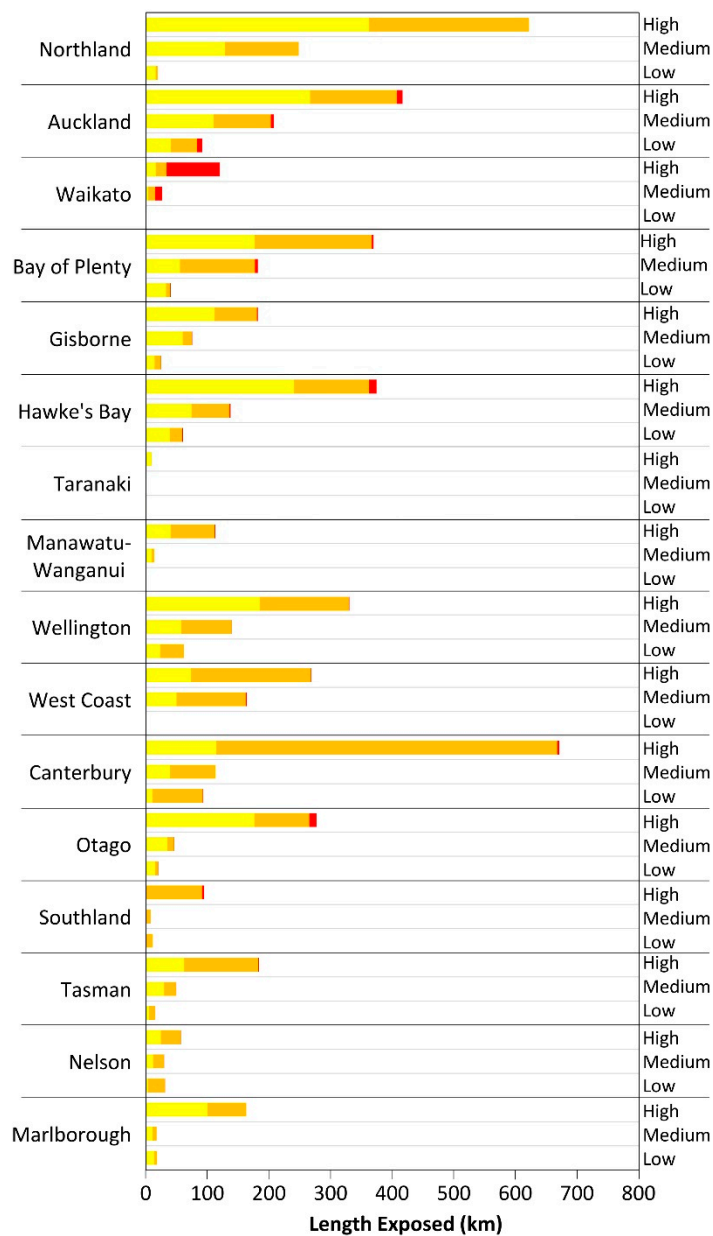


Figure 7. Regional road exposure within ‘red’, ‘orange’ and ‘yellow’ tsunami evacuation zones for ‘high’ (>10,000 vehicles/day), ‘medium’ (>3000 vehicles/day) and ‘low’ (<3000 vehicles/day) traffic volume, as defined in Table S2.

4. Discussion

Tsunami are low-frequency, high-impact events that threaten many coastlines around the world. Despite their recent and devastating impacts on human life and built environments [2], coastal populations continue to increase as towns and cities expand on land at risk to tsunami inundation. To protect human life during a tsunami, it is necessary to evacuate people to safe areas during an event. Evacuation zones perform an important role to educate coastal populations on tsunami inundation threats and identify locations and routes for evacuation to safe areas. Zone alignment with evacuation plans and processes can also create a consistent public evacuation response to tsunami from national to local scales.

Tsunami evacuation zones represent considerable scientific investigation of tsunamigenic sources, wave propagation and inundation from tsunami events. This study extends their utility in New Zealand by using the exposure component of a risk model framework [17] to enumerate zone populations, built

land and assets at national and regional scales. Population and built-asset exposure mostly occurs on land expected to be at risk to tsunami inundation from either a 500 year ARI event with a travel time of greater than an hour (i.e., 'orange' zone), or a 2500 year return period event with an 84% confidence level, or larger magnitude near-field event (i.e., 'Yellow' Zone). Our analysis shows that just under 10% of New Zealand's usually-resident population reside in evacuation zones, with over 150,000 people representing children and elderly age groups. These groups are acutely vulnerable to harm, observing high mortality rates in global tsunami events [29]. Vulnerable populations also occupy the 165,000 residential buildings in zones potentially at risk from inundation within a 500 year ARI, i.e., 'orange' zones. New Zealand's residential buildings are predominantly low rise (i.e., <2 storeys) with timber construction frames [28], a building typology highly susceptible to complete damage when tsunami depths exceed 2 m [30,31]. Critical buildings (3899) located in 'orange' zones, include 186 hospital or medical facilities and more than 90 used for emergency management. Their function for administering emergency response and recovery activities in a tsunami event could be implicated by both the requirement to evacuate occupants and damage resulting in loss of building function. These complexities highlight a need for disaster risk managers to proactively prepare populations for evacuation based on their vulnerability to harm from tsunami and ability to access resources for recovery after the event.

National tsunami mitigation strategies need to consider subnational-scale profiles of tsunami hazard exposure. Here, we investigated regional population, built-asset and land exposure to inform a national-scale assessment. The exposure analysis observes interregional differences and differences between the regional and national analyses. Residential populations and buildings in 'red zones', with tsunami inundation expected in a human lifetime, represent 1–2% of their national exposure for all zones. Coastal populations on low-lying land close to mean high water springs (MHWS) in regions such as Waikato (70%) may observe a higher proportional exposure overall in 'red' zones where a potential frequent tsunami inundation threat is present. The relative exposure of population age groups also shows regional variations. Total population exposure for highly vulnerable age groups (e.g., children and elderly) in 'orange zones', expected to be inundated within a 500 year ARI, is higher (>5000) for regions with major urban areas (>50,000 people) located on eastern coastlines including, Auckland, Bay of Plenty, Hawkes Bay and Canterbury. These age groups are proportionately highest for North Island east coast regions such as Waikato, Bay of Plenty, Gisborne and Hawkes Bay, where coastal settlements attract residents of retirement age (>65 years). In these regions, evacuations could be further complicated from a higher likelihood of tsunami from near-field or regional source events, with wave arrival times (<1 h to 4 h) affecting coastlines [20,22]. The capacity of exposure and risk models to identify the location and vulnerability of populations to harm in tsunami evacuation zones supports the assertion from [1] that detailed plans to prepare and evacuate populations need to identify spatio-temporal impacts on people and assets and attempt to alleviate impediments for movement of people to safe areas.

A risk model framework extends information on tsunami hazard characteristics (e.g., inundation) to include elements at risk and their vulnerability to impact from tsunami exposure. Risk model application in national and regional tsunami evacuation preparedness and response activities can further inform evacuation zone delineation from combined inundation and impacts to populations and built assets and prioritize resources to meet the evacuation requirements of vulnerable people and critical or (e.g., hospitals) complex (e.g., airports) facilities. Models are dependent, however, on high-resolution datasets that are often resource intensive to produce with limited small spatial coverage. In New Zealand, tsunami evacuation zones defined using 'Level Three' and 'Level Four' inundation modeling methods [16] are limited to few regions and at sub-regional scales (Table S1). Quantitative impact assessment for tsunami scenarios representing evacuation zones are limited to these locations. The exposure component of a risk model provides an approach to analyze at-risk populations and assets in evacuation zones using large scale albeit, lower resolution inundation data. Nevertheless, exposure assessments provide a useful tool to inform national and regional priorities for tsunami

evacuation planning including, requirements for detailed investigations to delineate evacuation zones based on hazard and risk.

While this study delivers a first national-scale assessment of population and built-environment exposure in New Zealand tsunami evacuation zones, information on human and built-asset impacts and criticality of the latter is not provided. Several local- to regional-scale assessments have been performed using vulnerability models (i.e., fragility functions) with high-resolution inundation maps and built-asset spatial data to quantify tsunami impacts including physical building damage [10,12,32,33]. This information is critical for identifying threats to evacuation zone populations by secondary hazards such as building collapse. The asset-level analysis presented here enabled exposure to be quantified for evacuation zones and reported at scales consistent with emergency management decision making. However, incomplete or inconsistent asset-level attribute information across multiple built-asset types would have limited a subsequent analysis of impacts for built-environment assets. A focus on developing tsunami risk model frameworks that comprise reliable asset-level datasets, high-resolution inundation maps and standardized human and built-asset vulnerability models will improve national- and regional-scale evacuation zone impact assessments that inform measures to evacuate people from future tsunami events.

5. Conclusions

This study presents a first national-scale assessment of New Zealand's population and built-environment exposure in tsunami evacuation zones. We applied the exposure component of a risk model framework (RiskScope) to enumerate populations, built-land and asset exposure in evacuation zones. New Zealand has national-scale coverage for populated coastlines at risk to tsunami inundation. Most zones are delineated using simple rule-based attenuation methods to map inundation threats. The multi-zone maps representing tsunami evacuation zones were suitable for regional-scale exposure analysis to inform a national-scale assessment.

New Zealand has considerable population, built-land and asset exposure in tsunami evacuation zones. Our analysis shows that just under 10% of New Zealand's population residing in 399,000 residential buildings are in evacuation zones. These are supported by a further 5400 critical buildings and 6300 km of road transport network. Approximately 40% of exposed populations and buildings occupy evacuation zones expected to be inundated within a 500 year recurrence interval. This includes over 150,000 people representing highly vulnerable age groups, i.e., children and elderly. These age groups are proportionately higher in North Island east coast regions, with a higher likelihood of tsunami from near-field or regional source events producing wave arrival times (<1 h to 1 to 4 h) affecting coastlines. The regional population and built-asset exposure variations observed emphasize that national-scale tsunami mitigation strategies require flexibility to consider regional and local exposure when facilitating evacuation preparedness and response plans.

Risk models extend tsunami hazard information to determine the exposure and impacts to people and built assets in tsunami evacuation zones. A limitation of risk models is their dependency on high-resolution data, often limited to a few tsunami-exposed coastlines. Future investment in numerical modelling to identify inundation areas, asset-level population and built-asset exposure data and vulnerability models will support risk model applications to delineate tsunami evacuation zones and inform preparedness and response strategies based on hazard and risk.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2076-3263/10/8/291/s1>, Table S1: Tsunami Evacuation Zone Map Metadata; Table S2: Population and Built-Environment Metadata; Table S3: New Zealand Population and Built-Environment Exposure in Tsunami Evacuation Zones.

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