Informing the development of tsunami vertical evacuation strategies in New Zealand

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Stuart A. Fraser

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ABSTRACT

Tsunami education and evacuation planning promote evacuation to high ground in the event of tsunami. In some low-lying coastal areas, the distance to safety on high ground or inland of the hazard zone may exceed the travel distance possible in the time before wave arrival. This is a particular problem in local-source tsunami with arrival times of less than one hour. Vertical evacuation provides alternative refuge within the inundation zone. Buildings, towers or berms can provide refuge at elevations above the tsunami flow depth, but must be designed to be effective in the maximum credible tsunami. The potential benefits and costs of vertical evacuation buildings were demonstrated during the 2011 Great East Japan earthquake and tsunami, when thousands of people took refuge in such structures.

The aim of this thesis is to enhance the current theoretical and methodological basis for development of vertical evacuation strategies in New Zealand. To achieve this aim, numerical simulation of local-source tsunami is conducted at Napier, Hawke's Bay, New Zealand, to establish the maximum credible inundation extent, flow depth and arrival times. Interview data describe the use of vertical evacuation in the 2011 Great East Japan tsunami, and surveys are used to investigate intended evacuation behaviour in a local-source tsunami. Finally, an existing geo-spatial evacuation analysis method, augmented with temporally-variable exposure and distributed travel speeds, is used to assess pedestrian evacuation potential in local-source tsunami. The method is demonstrated in an assessment of the need for vertical evacuation in Napier.

The outputs of the four stages of research enhance the theoretical basis for planning evacuations in local-source tsunami, extends Geographic Information System-based evacuation modelling methods, and provides empirical advances in tsunami hazard and evacuation planning at Napier. The proposed methodology is applicable to other locations, thus contributes to tsunami risk reduction in New Zealand and internationally.

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I have been lucky during the course of this research to visit Japan and the US Pacific Northwest on a number of occasions. Thank you to John Schelling and his colleagues at the State of Washington Emergency Management Division; the emergency managers with whom I met at the very beginning of this research; Hitomi Murakami, Ichiro Matsuo and translator Joel Challender, with whom we collaborated in Japan in October 2011. Thank you to all of my colleagues on the IStructE Earthquake Engineering Field Investigation Team with whom I visited Japan in June 2011.

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LIST OF ACRONYMS

ABM Agent Based Model.

ADA Americans with Disabilities Act.

AEP Annual Exceedance Probability.

ANUGA Australian National University-Geoscience Australia.

API Application Programming Interface.

ASCE American Society of Civil Engineers.

BP Years before present.

CAPI Computer-Assisted Personal Interviewing.

CDEM Civil Defence Emergency Management.

COMCOT COrnell Multi-grid COupled Tsunami.

DART Deep-Ocean Assessment and Reporting of Tsunamis.

DEM Digital Elevation Model.

DRR Disaster Risk Reduction.

EEFIT Earthquake Engineering Field Investigation Team.

EQC New Zealand Earthquake Commission.

FEMA Federal Emergency Management Agency.

GIS Geographic Information System.

GPS Global Positioning System.

HFA The Hyogo Framework for Action 2005–2015.

IBC International Building Code.

IL Importance Levels.

ISO International Standards Office.

IStructE UK Institution of Structural Engineers.

JMA Japanese Meteorological Agency.

LCD Least-Cost Distance.

LiDAR Light Detection and Ranging.

MCDEM Ministry of Civil Defence and Emergency Management.

MHW Mean High Water.

MMI Modified Mercalli Intensity.

MOST Method of Splitting Tsunami.

MSL Mean Sea Level.

NIWA National Institute of Water and Atmospheric Research.

NOAA National Oceanic and Atmospheric Administration.

NPO-CeMI Crisis and Environment Management Policy Institute.

NSHM National Seismic Hazard Map.

NTHMP National Tsunami Hazard Mitigation Program.

NWS National Warning System.

NZCPS New Zealand Coastal Policy Statement.

NZTA New Zealand Transport Agency.

PEP Public Education Programme.

PTHA Probabilistic Tsunami Hazard Assessment.

PTWC Pacific Tsunami Warning Center.

PTWS Pacific Tsunami Warning System.

RC Reinforced Concrete.

RiCOM River and Coastal Ocean Model.

RMA Resource Management Act.

SMS short message service.

SRC Steel Reinforced Concrete.

SWE Shallow Water Equations.

TEP Tsunami Expert Panel.

TUNAMI Tohoku University's Numerical Analysis Model for Investigation of Near-field tsunamis.

TVEB Tsunami Vertical Evacuation Buildings.

URP Usually Resident Population.

US United States.

USD United States Dollars.

USGS United States Geological Survey.

VBA Visual Basic for Applications.

WREMO Wellington Regional Emergency Management Office.

WTPS 'What's The Plan Stan?'.

1. INTRODUCTION

Vertical evacuation is a strategy for risk reduction, which can enhance evacuation capacities in local-source tsunami, floods and storm surges. New Zealand science and emergency management communities have begun to consider the application of vertical evacuation strategies to provide additional evacuation capacity in the case of local-source tsunami due to Hikurangi subduction zone earthquakes. This thesis presents new inundation modelling of local-source tsunami in New Zealand and research on vertical evacuation in the 2011 Great East Japan tsunami. It contributes new data on evacuation behaviour and pedestrian evacuation potential in local-source tsunami. These distinct research components combine to provide recommendations for the application of vertical evacuation in New Zealand. This research is timely, commencing weeks before the 2011 Great East Japan tsunami, which demonstrated the potentially devastating impacts of large-magnitude local-source tsunami and provided a unique post-tsunami case study of vertical evacuation.

Tsunami have the potential to cause massive destruction and a high death toll when they inundate populated coastlines. Over 200,000 people died in the 2004 Indian Ocean tsunami, over 19,000 people died in the 2011 Great East Japan tsunami, and several other tsunami since the 1980s have each resulted in hundreds to thousands of deaths (Table 1.1). Past events have shown that evacuation of the hazard zone is important for maximising chances of personal survival. Evacuation is most-often recognised as the horizontal movement of people to safe locations outside the hazard zone, i.e., further inland or to areas of high ground outside the inland extent of the hazard.

In local-source tsunami there may only be minutes before tsunami arrival in proximal locations, precluding dissemination of official warnings to the public. For earthquake-generated local-source tsunami, ground shaking is likely to be felt in coastal areas proximal to the source. When this shaking is interpreted as a natural warning of tsunami, which often requires public education, it can trigger evacuation of the exposed population. In tsunami with particularly short arrival times or in areas with long distances to high ground, the exposed population may not have sufficient time to travel to safety, even if they evacuate immediately after the earthquake. Vertical evacuation has been proposed as a solution to enhance evacuation capacity in such situations (Cabinet Office Government of Japan, 2005; FEMA, 2008, 2009; Okada et al., 2005; Project Safe Haven, 2011a,b). In vertical evacuation, people seek safety *above the tsunami flow within the hazard zone* by moving into multi-storey tsunami-resistant buildings or towers, or to raised areas of natural/artificial high ground.

Tab. 1.1: The 10 most deadly tsunami since the 1980s, based on number of reported fatalities. Total number of deaths for some events differ in the literature, dependent on whether the number of missing people is included

Event	Date	No. of fatalities	Source
Indian Ocean	26 Dec 2004	226,898	United States Geological Survey (*Earthquakes with 50,000 or More Deaths*)
Great East Japan	11 Mar 2011	19,000	Suppasri et al. (2013b)
Papua New Guinea	17 July 1998	2,182	Kawata et al. (1999)
Flores, Indonesia	12 Dec 1992	1,712	Yeh et al. (1993)
Java	17 July 2006	802	National Geophysical Data Center/World Data Service (2014)
Mentawai, Sumatra	25 Oct 2010	431	National Geophysical Data Center/World Data Service (2014)
Java	3 June 1994	344	Tsuji et al. (1995)
Okushiri, Japan	12 July 1993	230	Satake and Tanioka (1995)
Samoa	29 Sep 2009	189	Okal et al. (2010)
Nicaragua	2 Sep 1992	168	Lander, Whiteside, and Lockridge (2003)
Maule, Chile	27 Feb 2010	124	Fritz et al. (2011)
Izmit, Turkey	17 Aug 1999	$\geq$150	Lander, Whiteside, and Lockridge (2003)
Irian Jaya, Indonesia	17 Feb 1996	110	Disaster Prevention Research Institute (2004)
Sea of Japan, Japan	26 Apr 1983	103	Lander, Whiteside, and Lockridge (2003)
Total	1983-2011	252,443	

Tsunami science effectively began in Japan following the 1896 Meiji Sanriku tsunami, which killed 22,000 people (Shuto and Fujima, 2009). Since then, the major advances in this field have been in response to major events, notably the development of forecasting and ‘comprehensive countermeasures’ following the 1933 Shōwa Sanriku tsunami (Shuto and Fujima, 2009). The distant-source 1960 Chile tsunami provided insight in Japan into the different onshore impacts that can occur in distant tsunami compared to previous local-source tsunami, for example longer wave period. This event was the catalyst for development of some of the founding theories of tsunami science (Kajiura, 1970), and development of structural tsunami defences, including tsunami breakwaters that were designed using the first instance of numerical modelling for tsunami (Shuto and Fujima, 2009). Elsewhere, the 1960 tsunami triggered the expansion of the Pacific Tsunami Warning System (PTWS) to become a Pacific-wide warning system, having been solely focussed on the United States (US) since its inception. Progression in numerical simulation developed from proposal of a method for simulating the initial tsunami surface deformation due to an earthquake (Mansinha and Smylie, 1971b), implementation of shallow water theory (Goto and Ogawa, 1982) and increasing computational capabilities. With the increased ability to assess tsunami hazard, risk reduction practices have been continuously developed and have become more widely applied around the World.

Tsunami are generated when a source event rapidly displaces a sufficiently large volume of water in a body of water. The most common cause is displacement of the sea bed during submarine earthquakes (1,811 events (72%) of 2,501 contained in the NOAA/NGDC tsunami event data catalogue; National Geophysical Data Center/World Data Service, 2014). Tsunami can also occur due to: coseismic (88, 4%) or aseismic (85, 3%) sub-marine or sub-aerial landslides; submarine or sub-aerial volcanic eruptions (146, 6%); meteorological conditions (91, 4%). Thirteen events (1%) are listed as ‘questionable earthquakes’, two are attributed to ‘astronomical tide’ and one is attributed to ‘explosion’. The remaining 11% (264 events) are listed as having an unknown source. The greatest tsunami hazard exists along coastlines that face subduction boundaries, in Indonesia, the Mediterranean Sea and around the Pacific ‘Ring of Fire’ (Fig 1.1). Global historic tsunami statistics show that 43% of all offshore earthquakes ($>M_W5.0$, a focal depth shallower than 200 km and a sea depth less than 7 km) in the years 1963-2011 have been tsunamigenic (Suppasri, Imamura, and Koshimura, 2012). The highest ratio of tsunamigenic earthquakes to all offshore earthquakes occurs in New Guinea-Solomon (62%), Alaska-Aleutians (59%) Japan (56%), Kurile-Kamchatka (56%), South America (54%) and New Zealand-Tonga (51%) (Suppasri, Imamura, and Koshimura, 2012).

Tsunami are commonly categorised in terms of their travel time from source to impact. *Local-source* tsunami (also *near-field tsunami*) are defined in New Zealand as having a source that is <1 hr of tsunami travel time to the location of interest. *Regional-source tsunami* have a travel time of 1–3 hr[1] and *distant-source tsunami*, >3 hr. The same tsunami source may be considered

[1] The Solomon Islands is regarded as a regional source, despite having travel time of 4-5 hours

local to one area and regional or distant to other areas, dependent on the location of interest. This classification is useful for tsunami research and response because: (a) the distance from source influences the impact of a tsunami, and (b) effective tsunami response is reliant on the time interval between event generation and arrival of waves at the location of interest. The primary impacts of tsunami are damage to coastal defences, buildings, infrastructure and lifelines. Tsunami pose a significant threat to life of anyone who comes into contact with inundation, due to the significant flow depths and velocities and the entrainment of debris, which can range in size from sand grains to large debris such as ships.

Historic tsunami (most notably Peru 1868, Gisborne 1947, and Chile 1960) have inundated coastal areas of New Zealand and demonstrate the potential for casualties and economic damage from local and distant source events. Additionally, palaeo-tsunami studies provide evidence of significant ($>M_W$ 7.0) tsunamigenic earthquakes at the Hikurangi subduction margin (Cochran et al., 2005, 2006). The first New Zealand national tsunami hazard and risk reviews were conducted in 2005 (Berryman, 2005; Webb, 2005). Since then, there has been an increased focus on tsunami hazard assessment and risk reduction through ongoing tsunami education, installation of warning sirens and evacuation route planning. Damage and life loss can be mitigated by land-use planning to minimise development within the tsunami hazard zone, by installing tsunami-resistant coastal defences, bridges and buildings, and by maximising people's ability to evacuate the hazard zone prior to wave arrival. A comprehensive disaster mitigation strategy should comprise all of these approaches, but implementation of each element is not always suitable or feasible.

While there has been much progress in tsunami risk reduction and readiness in New Zealand in the last decade, vertical evacuation could enhance tsunami evacuation capabilities in a number of locations around the country where the distance to high ground would present difficulties for evacuation during a local-source tsunami. Additionally, vertical evacuation could be used in regional-source tsunami. The distance of regional-source earthquake from land means that there may be no natural warning in the form of ground shaking or gentle swaying, but the time required to process and disseminate official warnings could result in minimal available evacuation time between a warning and wave arrival. This introductory chapter presents the research aim and objectives, contextualises the research within the framework of risk management in New Zealand, outlines the research methodology and describes the structure of the thesis.

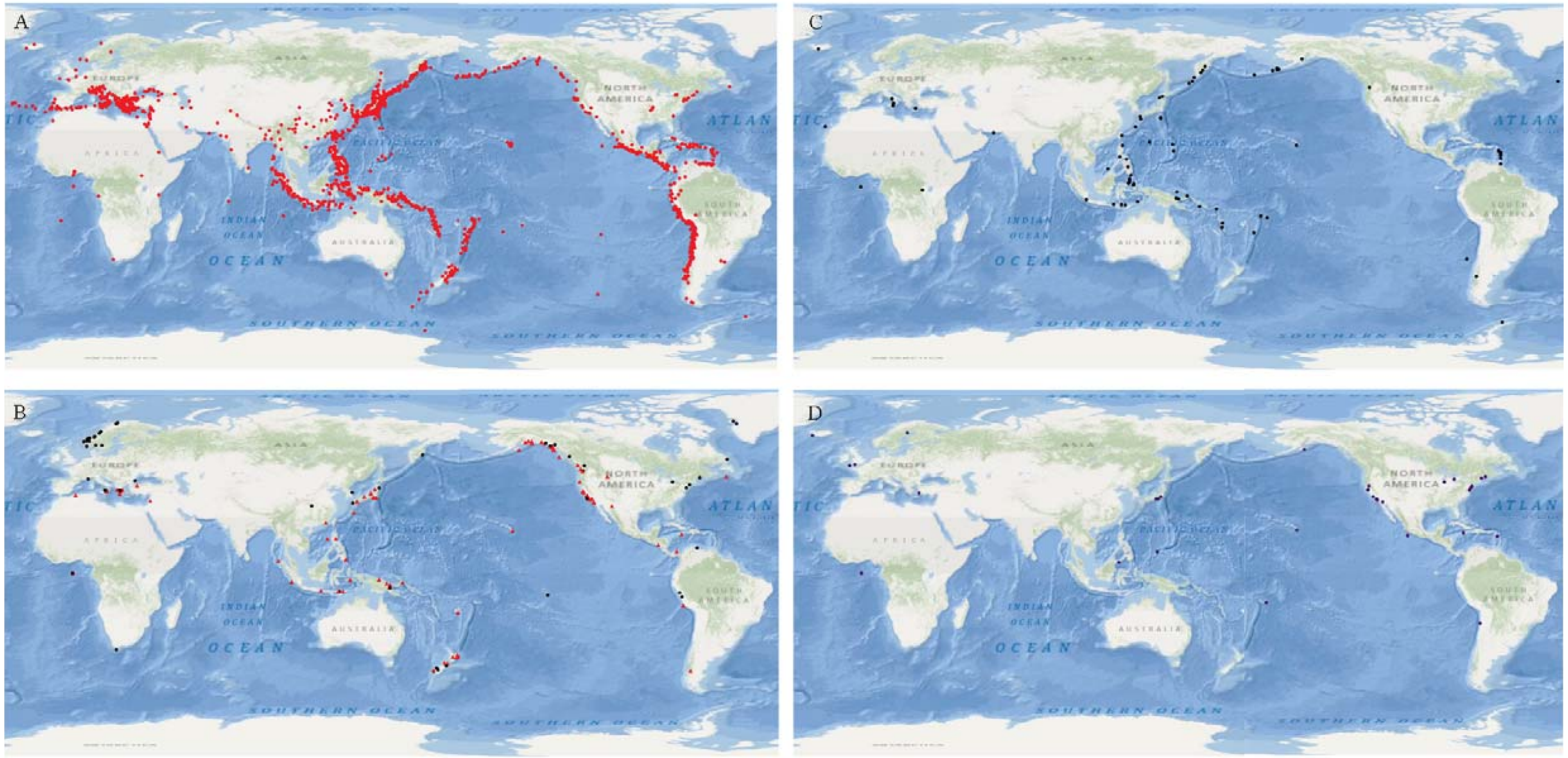


Fig. 1.1: Maps of tsunami source events, 2000 BC – 2013 AD. A: Earthquake sources, B: Coseismic (red triangle) and aseismic (black circle) landslide sources, C: Volcanic sources (with and without earthquake and/or landslide), D: Meteorological sources. Source of event data: National Geophysical Data Center/World Data Service (2014).

1.1 Research aim and objectives

Recognising the aforementioned New Zealand tsunami hazard, impacts of tsunami and importance of evacuation, there has been much progress in developing tsunami warnings, evacuation signs, maps and education around the country (Johnston et al., 2014). To address the potential for difficulty in evacuating certain areas in a local tsunami, New Zealand research and emergency management communities initiated a scoping study to review international examples of vertical evacuation and explore the potential for using Tsunami Vertical Evacuation Buildings (TVEB) in New Zealand (Leonard et al., 2011). The scoping study focussed on structural components of TVEB and how they would be incorporated into the New Zealand emergency management legislative framework, building standards and land-use planning. Importantly, the scoping study did not address the assessment of where vertical evacuation might be a suitable evacuation option, or how to determine optimal placement of refuges. This thesis seeks to address this knowledge gap and provide recommendations for the implementation of vertical evacuation in New Zealand. Internationally, engineers are currently applying the experience of structural damage in Tōhoku, Japan, in the development of new design guidelines for tsunami-resistant buildings (Chock, 2012). These will provide guidance for development of tsunami-resistant standards within the New Zealand national building codes, and this thesis does not seek to pre-empt or replicate this engineering work.

The overall aim of this thesis is to enhance the current theoretical and methodological basis for development of vertical evacuation strategies in New Zealand. The objectives set to achieve this aim are to:

1. Determine maximum credible inundation extent, flow depth and available evacuation time due to local-source subduction zone tsunami at a case study location in New Zealand (Chapter 4);

2. Elucidate experiences of vertical evacuation in the March 2011 Great East Japan tsunami to inform vertical evacuation planning in New Zealand (Chapter 5);

3. Explore intended evacuation behaviours in local-source tsunami in New Zealand, and gather preliminary research on public perception of vertical evacuation facilities (Chapter 6);

4. Develop a method to assess pedestrian evacuation potential of the exposed population to inform decision-making on evacuation planning, including vertical evacuation strategies (Chapter 7).

1.2 Conceptual framework

This research contributes to natural hazards management and risk reduction in New Zealand, which is conducted within the Civil Defence Emergency Management (CDEM) sector. The 2002 CDEM

Act promotes: sustainable management of hazards; encourages communities to reduce risk to acceptable levels; provides for planning and preparation for civil defence emergencies, and for response and recovery; requires local authorities to co-ordinate reduction, readiness, response and recovery activities through regional groups; provides a basis for the integration of national and local CDEM; and encourages coordination across a wide range of agencies, recognising that civil defence emergencies are multi-agency events (MCDEM, 2008b). The approach prescribed by the Act is described by four areas of activity: *Reduction*, *Readiness*, *Response*, and *Recovery*. By informing the development of evacuation plans, this thesis makes its primary contribution to *Readiness*, in that it develops capabilities for public response in advance of a civil defence emergency. CDEM in New Zealand is led by the Ministry of Civil Defence and Emergency Management (MCDEM) and the operational structure (Fig 1.2) is determined by the CDEM Act 2002, which requires local authorities to be part of a regional CDEM group. The 16 CDEM groups in New Zealand must each have a CDEM Group Plan, which states and provides for the arrangements necessary to manage hazards and risks affecting that region. The information presented in this thesis is intended to be of use by CDEM group members (i.e., local authorities) to ascertain the requirement for vertical evacuation in coastal communities within their jurisdiction. It is expected that the research would contribute to the development of a national standard on planning and design of vertical evacuation facilities.

Fig. 1.2: The New Zealand CDEM framework (MCDEM, 2008b).

The CDEM Act 2002 'requires that a risk management approach be taken when dealing with hazards' (MCDEM, 2008b, p. 5). This is achieved by working to the New Zealand Standard risk management guidance, which requires anticipation and understanding of risk before evaluation of whether that risk warrants modification, when judged against risk criteria (Standards New Zealand, 2009, Fig 1.3). Leonard et al. (2008a), and later Johnston et al. (2014) presented the New Zealand

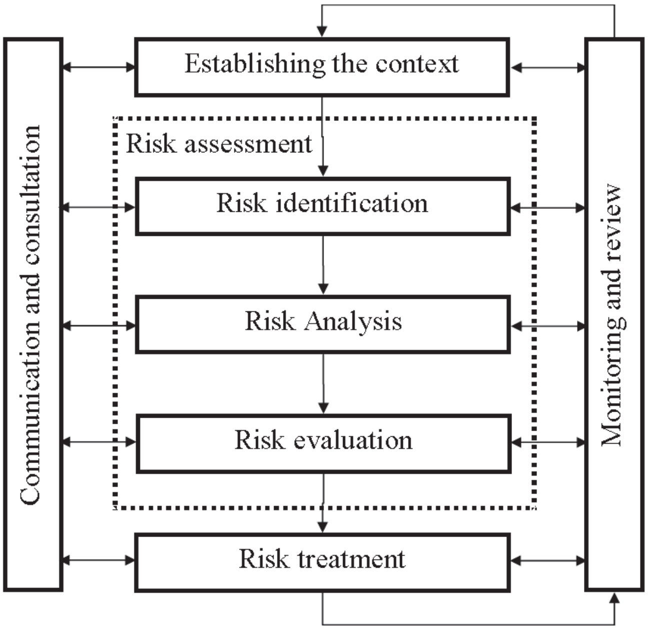


Fig. 1.3: Risk management process (Standards New Zealand, 2009).

Standard risk management process in a hazards context (Fig 1.4). *Risk* is commonly defined as the product of *hazard* and *vulnerability* (Blaikie et al., 1994). **Risk identification** is the first phase of **risk assessment** and requires that the sources and causes of risk are identified, in addition to potential areas of impact and consequences (Standards New Zealand, 2009). *Hazard* is '[a] dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage' (UNISDR, 2009, p.17). Hazard comprises the *probability* or *frequency* of an event occurring, the potential *intensity* of its damaging parameter (e.g., ground shaking, flow depth or wind speed), its onset speed and spatial extent (Wisner, Gaillard, and Kelman, 2012). Hazard frequency is described in terms of exceedance probability: the probability of exceeding a chosen intensity threshold in any given year. This can be converted into a *recurrence interval* or *return period* by taking the inverse of exceedance probability. Therefore, a 1% Annual Exceedance Probability (AEP) is the same as an average recurrence interval (or 'return period') of 100 yr and a 1 in 500 yr annual recurrence interval is equivalent to 0.2% AEP. *Vulnerability* refers to '[t]he characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard.' (UNISDR, 2009, p.30). The consequences of a hazard are influenced by vulnerability, which is a product of numerous interacting social, cultural and economic factors (Wisner, Gaillard, and Kelman, 2012). In engineering terms, vulnerability refers to the structural damage sustained at a given level of impact (e.g., earthquake magnitude or tsunami flow depth) in terms of vulnerability or fragility curves.

Risk analysis develops the understanding of the risk and its consequences (Standards New

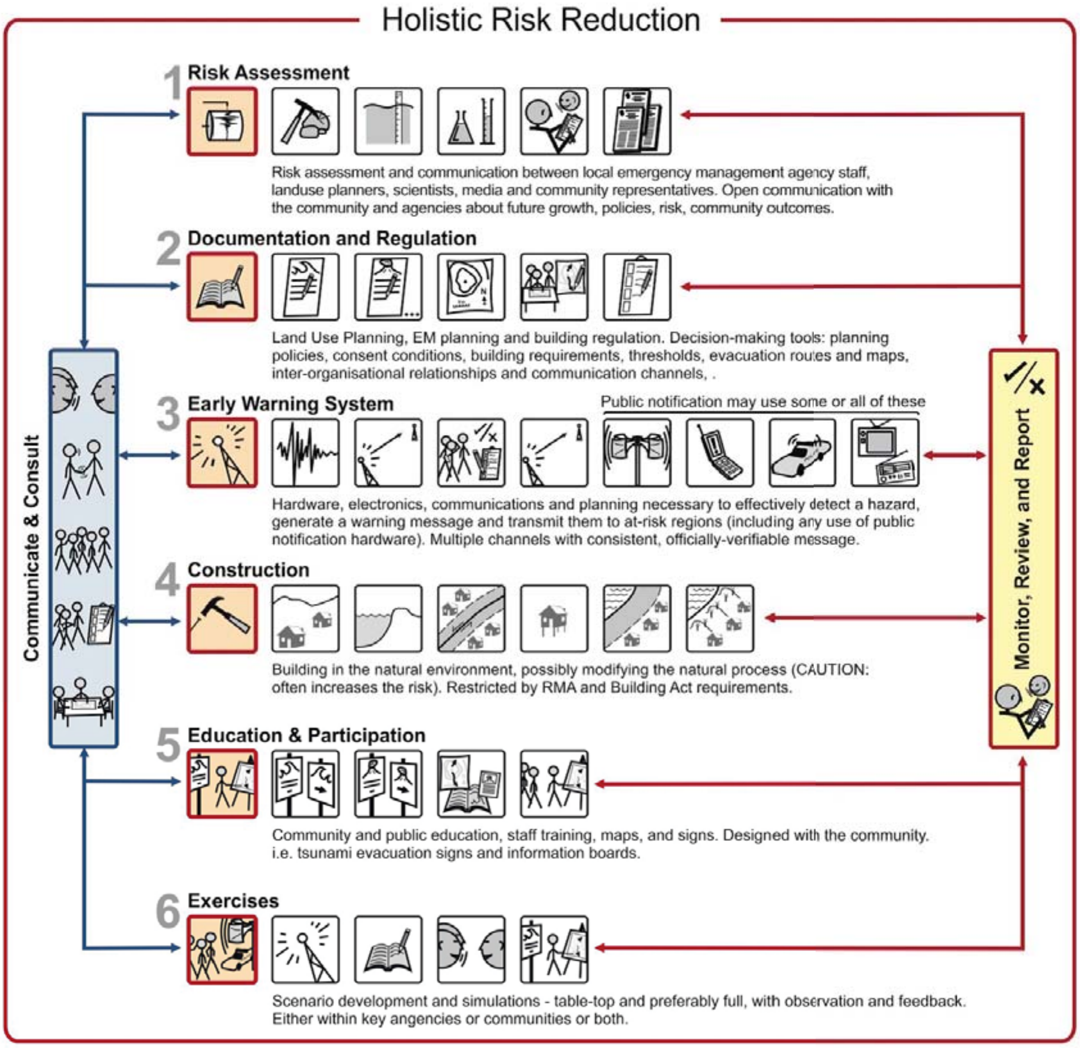


Fig. 1.4: An holistic disaster risk reduction framework (Johnston et al., 2014).

Zealand, 2009). Numerical modelling of past events or stochastic event sets, statistical analysis or experimental analysis is used to determine the spatio-temporal dimension of the hazard impact. Vulnerability models translate the impact into consequences, in terms of casualties (killed or injured), damage ratio or monetary loss. Insured loss assessment ('catastrophe modelling') is widely conducted in the reinsurance industry (Grossi and Kunreuther, 2005). Several loss models exist to assess economic loss and casualties to aid mitigation planning, including the Federal Emergency Management Agency (FEMA) *HAZUS*[2] model and the GNS/NIWA *RiskScape* model (Schmidt et al., 2011). **Risk evaluation** requires decision-makers to define a set of risk criteria that reflect their organisation's or community's risk appetite or level of acceptable risk. The results of risk analysis are compared against these criteria to determine what form, if any, of **risk treatment** is warranted to reduce the risk (Standards New Zealand, 2009).

Risk management forms an important component of *Disaster Risk Reduction (DRR)* — the over-arching 'concept and practice of reducing disaster risks through systematic efforts to analyse and reduce the causal factors of disasters' (UNISDR, 2005, 2009). DRR includes: reduction of hazard exposure and vulnerability of people and property; sustainable land and environment management; and improvements in preparedness and early warning capabilities[3]. *Mitigation* aims to reduce the likelihood of a hazardous event occurring, reduce the negative consequences if it does occur, avoid the risk altogether, or transfer/spread the risk. Risk transfer is primarily achieved through (re)insurance mechanisms that spread financial risk. It is currently impossible to reduce the likelihood of tsunami occurrence. Therefore, tsunami mitigation focusses on reduction of negative consequences by reducing or avoiding exposure to tsunami (through land-use planning and relocation of assets and population), and reducing vulnerability by improving warning systems and evacuation infrastructure, installing sea defences, and constructing/strengthening buildings to tsunami-resistant standards.

In the international DRR context, The Hyogo Framework for Action 2005–2015 (HFA) recognises evacuation in its 'Priority for Action' number 5: 'Strengthen disaster preparedness for effective response at all levels' (UNISDR, 2005, p.12):
'*losses can be substantially reduced if authorities, individuals and communities in hazard-prone areas are well prepared and ready to act and are equipped with the knowledge and capacities for effective disaster management.*'
Key activities under this priority are to:
'*Prepare or review and periodically update disaster preparedness and contingency plans and policies at all levels, with a particular focus on the most vulnerable areas and groups. Promote regular disaster preparedness exercises, including evacuation drills, with a view to ensuring rapid and effective disaster response and access to essential food and non-food relief supplies, as appropriate, to local needs.*'

[2] http://www.fema.gov/hazus
[3] http://www.unisdr.org/who-we-are/what-is-drr

Although this research demonstrates implementation of the developed methodology in New Zealand, and discussion focusses on how vertical evacuation strategies fit into the New Zealand CDEM framework, the publication of papers within this thesis contribute more widely to international DRR by developing knowledge of tsunami evacuation strategies and modelling.

1.3 Research methodology

This section summarises the research methodology applied in this thesis. Several distinct methods are implemented, reflecting the multi-disciplinary nature of research into tsunami evacuation. Because this thesis comprises several stand-alone papers (see section 1.5), the methodologies are also outlined in each relevant paper.

Fig 1.5 presents an overview of the research method. As a combined body of work the research contributes to the early stages of evacuation planning, specifically the first four points of Step 1 in the framework for tsunami evacuation planning (Scheer, Varela, and Eftychidis, 2012, Fig 1.6). The framework of Scheer, Varela, and Eftychidis, 2012 defines three stages of an evacuation plan: (1) risk and impact analysis to generate a valid first-iteration of an evacuation strategy; (2) implementation of the evacuation plan by placement of signage on routes and shelters, dissemination of the plan / training of the exposed population, and routines for maintaining public awareness and training; and (3) long-term monitoring and iterative improvements to the plan. This thesis satisfies the initial stages of evacuation planning, in that it determines the onshore impacts of the maximum credible local-source tsunami in the study area and assesses the requirement for evacuation facilities within the inundation zone. This thesis is not intended to develop a complete evacuation plan in isolation. As the risk management, holistic risk reduction and evacuation planning frameworks all state, effective evacuation planning requires ongoing collaboration, communication and/or consultation between local emergency management and stakeholders including the local community. The information presented in the thesis informs this collaborative discussion and later stages of evacuation planning.

Objectives 1, 3 and 4 were applied to a single case study area — Napier Territorial Authority, in the Hawke's Bay Region on the east coast of New Zealand's North Island (Fig 1.7). Napier was selected as the case study site due to its local subduction zone tsunami hazard and a potential requirement for vertical evacuation, which was reflected in the involvement of the regional CDEM group in the earlier TVEB scoping study (Appendix A). Much of Napier is <5 m above sea level, but there is one large area of high ground (>100 m elevation) close to the city centre and coast. The ability of the population to reach this high ground in the event of local-source tsunami is, as yet, untested.

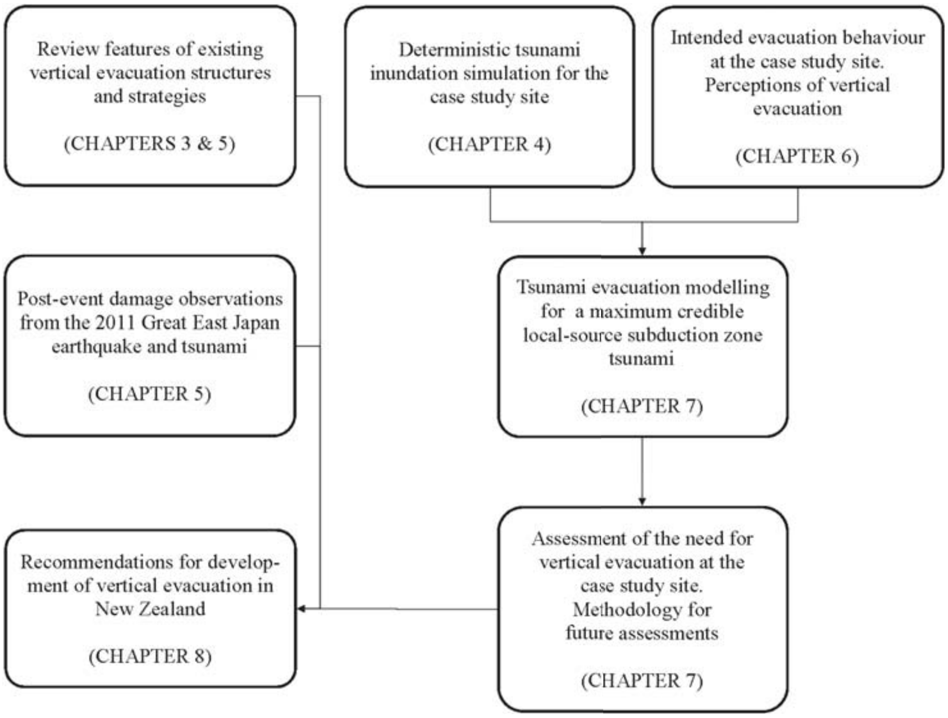


Fig. 1.5: The research method.

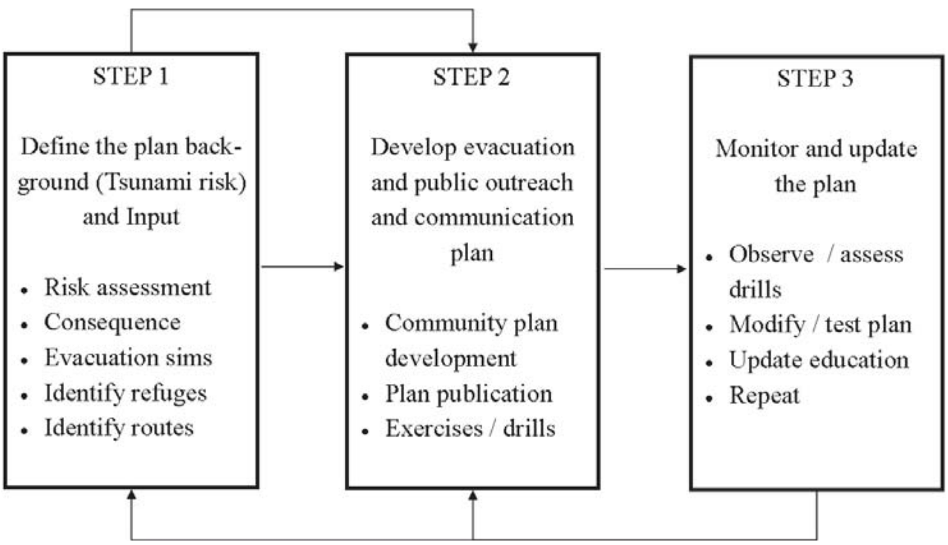


Fig. 1.6: A generic framework for the development of an evacuation plan, after Scheer, Varela, and Eftychidis (2012).

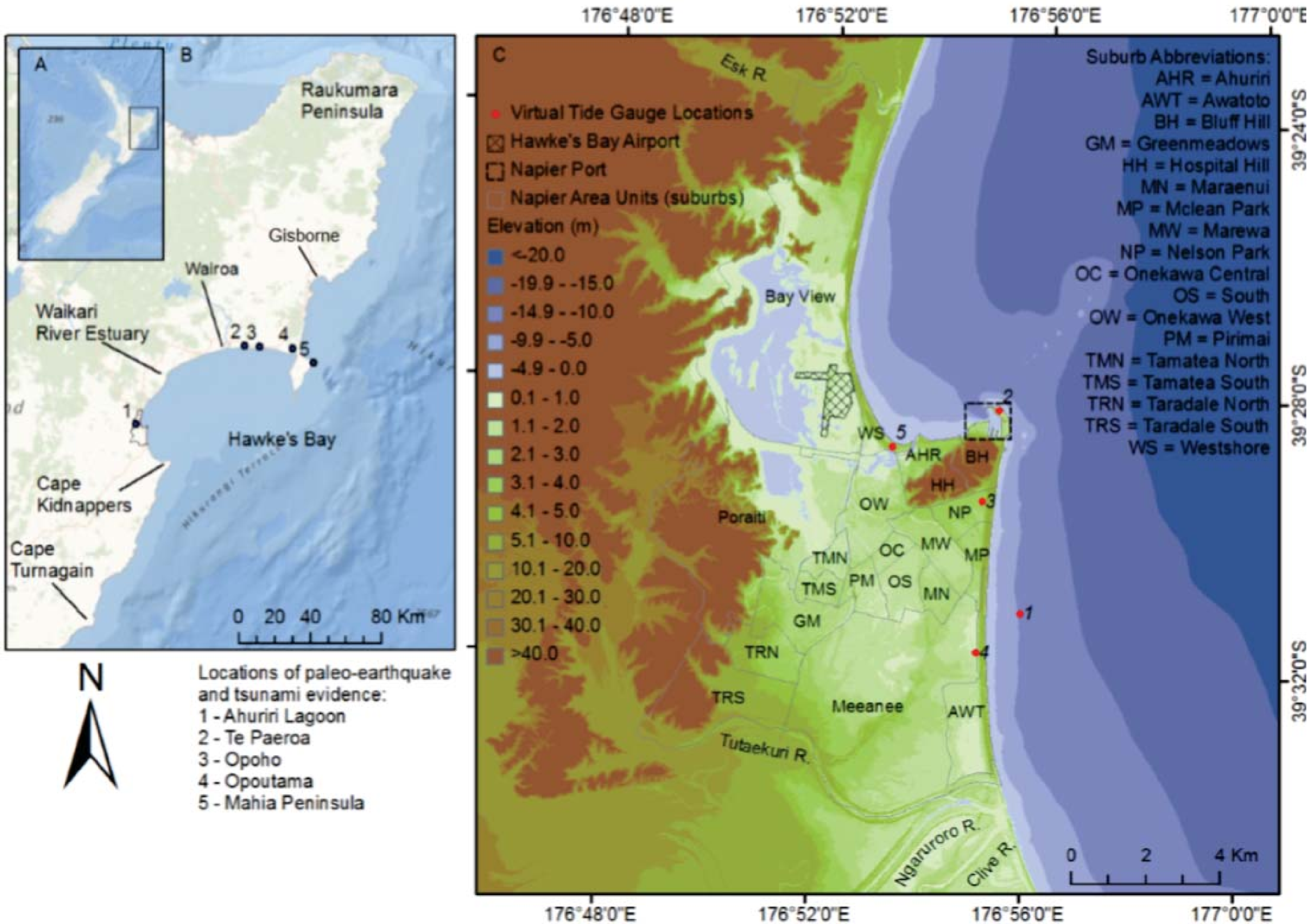


Fig. 1.7: A: Study area shown in the national context. B: Napier Territorial Authority in the Hawkes Bay regional context with numbered locations indicating palaeo-ecological analysis referred to in-text. The boundary of Napier Territorial Authority is shown and other locations referred to in-text are also indicated. C: Digital Elevation Model (DEM) of 10 m horizontal resolution showing topography of Napier Territorial Authority with labelled unit areas (suburbs), rivers, Napier Port and Hawkes Bay Airport.

1.3.1 Objective 1

Numerical modelling of tsunami is conducted to estimate inundation extent, flow depth and arrival time for local-source tsunami, to meet Objective 1. These data are required to improve tsunami hazard assessment for the study area and provide input for Objectives 3 and 4. Previous research had provided wave heights at coast (Power, Reyners, and Wallace, 2008), estimated the hazard zone using an initial waveform rather than source rupture so could not provide arrival time (Hawke's Bay Civil Defence And Emergency Management, 2011), or was conducted using low-resolution topography data.

The COrnell Multi-grid COupled Tsunami (COMCOT) numerical tsunami modelling code was employed to model tsunami generation, propagation and onshore inundation. The model has been validated against international standard analytical and physical modelling benchmark tests (Liu et al., 1995a,b; Wang and Liu, 2008) and has been used in previous studies of tsunami affecting New Zealand and several globally significant tsunami (Baptista et al., 2011; Power et al., 2012, 2013; Wang and Liu, 2006). It was also used in the latest national tsunami hazard review (Power, 2013). COMCOT was selected for use on this basis, and its ability to simulate the tsunami process from source through to inundation. With future application of the evacuation model in mind, it is beneficial to initially develop a workflow that is compatible with output from COMCOT, which is under continued development at GNS Science. A Python Application Programming Interface (API) is also under development for use with COMCOT, and it is anticipated that the subsequent evacuation modelling method (Objective 4) will become integrated into the API for coordination between COMCOT and the RiskScape asset and loss model.

Tsunami generation uses four distributed-slip fault planes located on the Hikurangi subduction zone. These have been adapted from previously-published source models (Cochran et al., 2005; Wallace et al., 2009) on the basis of their tsunamigenic potential. One fault plane represents the maximum credible earthquake, an M_W 9.0 whole margin rupture, in order to generate the maximum credible tsunami inundation zone. Limited source parameter testing (impact of tidal level, amount of slip) was conducted during the course of this work. Vertical deformation of each source was modelled using elastic fault dislocation theory (Okada, 1985) to generate the tsunami initial condition. A detailed DEM was constructed for the study area using Light Detection and Ranging (LiDAR) data and digital bathymetry data. Grid resolution, nested grid boundary location and time-step size were subject to sensitivity testing in order to optimise the model for boundary effects, accuracy and computational expense. The simulations provide estimates of wave arrival time relative to time of earthquake rupture, inundation extent and maximum flow depth for four local-source tsunami scenarios.

1.3.2 Objective 2

The occurrence of the Great East Japan tsunami on 11 March 2011 provided a unique post-tsunami case study in which a major local-source tsunami affected a region with established vertical evacuation strategies. It was clear that this event would be valuable for informing mitigation strategies in New Zealand, so two periods of fieldwork were conducted in the affected areas.

The first field investigation was conducted as part of the UK Institution of Structural Engineers (IStructE) Earthquake Engineering Field Investigation Team (EEFIT), which travelled to Miyagi and Iwate Prefectures during 27 May – 4 June 2011. The field investigation had broad aims including surveys of flow depth, damage to structures, coastal defences and lifelines with respect to strong ground motion and tsunami (EEFIT, 2011, p. 2–3). The primary objective of the field investigation, with respect to this research, was to investigate the structural features of vertical evacuation buildings and the damage they sustained due to tsunami. A field survey methodology was adopted, following field investigation guidelines (Dominey-Howes et al., 2012; Hughes and Lubkowski, 2012). Survey locations were selected on the basis of previously-surveyed flow depths (Mori and Takahashi, 2012), reported damage levels and contrasting coastal environments. Multi-storey buildings within the inundated area, including those identified as designated vertical evacuation buildings, were surveyed to record building location, construction type, external features and damage level. Building location information comprised latitude/longitude coordinates, distance to coast, elevation, and surrounding land-use. Building construction information comprised: construction type, number of storeys, plan shape, ground floor type, construction age, occupancy (regular usage type), ground conditions, and orientation to coast. Building damage information comprised: a five-level damage scale (Appendix B; EEFIT, 2011); externally visible earthquake damage; number of storeys inundated; flow depth; and externally visible tsunami damage including debris strike and scour. An accompanying photograph record was generated for each building. The surveys were limited to external inspection only, and conducted during broader damage surveys in Minami-Sanriku Town, Ōfunato City, Natori City, Kamaishi City and Kesennuma Town (EEFIT, 2011). Further targetted surveys were conducted in Ishinomaki City and Kesennuma Town in order to visit areas that could not be visited with the wider EEFIT team. The observations were compiled and presented qualitatively to provide descriptors for required structural and non-structural features of TVEB (Chapter 5).

The second period of reconnaissance was conducted during 19–28 October 2011 in collaboration with two Japanese researchers (Mr Ichiro Matsuo, Director Secretary General and senior researcher, Crisis and Environment Management Policy Institute (NPO-CeMI); and Associate Professor Hitomi Murakami, Disaster Mitigation Planning, Yamaguchi University). The primary objective of this investigation was to conduct an exploratory analysis of the vertical evacuation strategy, evacuation process and planning of TVEB in Miyagi and Iwate Prefectures. Semi-structured interviews were used to gain insight into: official warning mechanisms; response to official, natural and informal warnings — including evacuation timing; style and origin of evacuation maps and education; and vertical evacuation buildings. The questions around vertical evacuation focussed on clarifying earlier data on their availability and locations, the local design and designation process, public awareness activities, the number of people using buildings for evacuation on 11 March 2011, and post-event review of the vertical evacuation strategy. Interview questions were translated into Japanese by our local collaborators and a professional translator. Semi-structured interviews are one of the most common methods used in social science research (Kitchin and Tate, 2000) and have been applied to a wide range of studies (Longhurst, 2003) to gain insight into complex behaviours, opinions and emotions. The semi-structured interview method was chosen due to the experiential nature of the data, in order to gather as much descriptive information as possible, and to provide the flexibility for interviewees to discuss issues, actions and concepts that had not been anticipated by the researchers, or had been observed in the field after development of the interview questions. This method also enabled interviewees to describe events in the context of their locality, without being limited by structured questioning. The interview comprised 21 questions, developed on the basis of the first field investigation and knowledge of previous research and literature on tsunami warnings and evacuation.

Seven case study locations (Tarō Town, Kamaishi City and Ōfunato City in Iwate Prefecture; Kesennuma City, Minami-Sanriku Town, Ishinomaki City and Natori City in Miyagi Prefecture) were identified based on identification of TVEB during the earlier EEFIT investigation. The case study locations comprise contrasting topography (rias and plains), and experienced a range of impacts and evacuation issues during the tsunami. Interviewees comprised civil protection, emergency management, fire department and police department staff). The relevant interviewees in each location were identified and recruited by our local collaborators, and were given the interview questions several days prior to the interview. The two primary interviewers (Fraser and Leonard) posed questions in English, with simultaneous translation into Japanese by the translator and/or Prof. Murakami. The translator was briefed in the required technical language prior to translating and conducting the interviews. Prof. Murakami is an expert in the field and has an excellent professional-level command of the English language. The interviewees provided responses in Japanese, with simultaneous or near-simultaneous translation into English. Notes were taken by Fraser and Leonard throughout the interviews, and the full interviews were audio-recorded. During the interview, any ambiguous or unclear statements or facts were checked with the interviewee.

Following each interview, notes were compared and discussed to collate themes for further analysis and exploration in any subsequent interviews. The two sets of notes were cross-checked and any ambiguities were clarified using the audio recordings. Factual statements and emergent themes from all interviews were collated to develop a descriptive account of warning and evacuation on 11 March 2011, and to form a summary of vertical evacuation in the municipalities investigated. Findings were published as a GNS Science report (Appendix D) and results pertaining to vertical evacuation were published as a journal paper, presented in Chapter 5.

1.3.3 Objective 3

To achieve Objective 3 ('Explore intended evacuation behaviours in local-source tsunami in New Zealand, and gather preliminary research on public perception of vertical evacuation facilities'), structured face-to-face interviews were conducted with residents and visitors in Napier. The interviews aimed to collect participants' intentions ('stated preferences') with respect to evacuation behaviour in local-source tsunami. Development of interview questions was informed by previous tsunami awareness surveys (Johnston et al., 2003, 2009; Leonard and Wright, 2011) and expectations of intended behaviour from the published literature. The interview items were structured in such a way to avoid problems such as fatigue bias and the use of leading questions (Parfitt, 2005). Questions were collated into sections to collect data on: participant type (resident/visitor); hazard awareness; behavioural intentions in two given tsunami scenarios (ground shaking occurring when at home or the survey location); opinions on the use of TVEB; and demographic information. Before explicitly addressing the use of TVEB, participants were given the opportunity to specify 'buildings' as a possible destination in order to explore awareness of TVEB as a concept.

Surveys were conducted by two researchers using a convenience sampling method at several locations in the city. The focus of the survey was to understand people's intended actions when in the city at the time of a local-source earthquake, so the study benefited from face-to-face interviewing at the location of interest, rather than providing scenarios in written form using a postal survey to residential addresses. Interviews were carried out throughout the day on a Friday, Saturday and Sunday at three locations: the city centre shopping area, Westshore beach during surf lifesaving training, and at Kennedy Road shopping precinct further inland. These locations were selected on the basis of being at risk and having high levels of day-time foot-traffic.

The interviews comprised closed-response and open-ended questions. Closed-response questions were used for hazard awareness, participant type and demographic data; Open-ended questions were employed to record intended behaviour and opinions on TVEB to ensure responses were not artificially constrained by set options. Questions were piloted by a group of GNS Science summer students (Currie et al., 2014) during tsunami awareness surveys in Wellington and tested with GNS Science staff prior to implementation. The interview questions were posed to participants as written on the interview sheet, with explicit instructions for interviewers to follow (Chapter 6, Appendix 1). Survey responses were coded and analysed using a semantic-level thematic analysis approach, reporting the explicit meaning of responses to develop knowledge of evacuation intentions, without interpreting social or psychological influences on those responses (Braun and Clarke, 2006). Frequency analysis determined the most-commonly reported behavioural intentions and cross-tabulation was used to assess awareness and actions in relation to participant type, location at the time of event, and demographic variables. Statistical analysis and correlation with demographics were conducted where the sample size was sufficient to do so.

1.3.4 Objective 4

To address the final objective ('Develop a method to assess pedestrian evacuation potential of the exposed population to inform decision-making on evacuation planning, including vertical evacuation strategies'), a Geographic Information System (GIS)-based Least-Cost Distance (LCD) evacuation modelling approach is used. An existing least-cost path distance model is augmented with newly-developed methods to enable modelling of temporally-variable exposure and variability in pedestrian travel speeds.

The exposure model is developed in Excel Visual Basic for Applications (VBA) using census data, school rolls and tourist accommodation data. Diurnal activity curves are developed to enable distribution of exposure to different locations according to time of day, day of week, and month. The distributed exposure is then used as the basis for evacuation modelling. The benefit of a temporally-variable exposure model is the potential to simulate evacuation potential for multiple exposure scenarios (e.g., rush-hour, weekday versus weekend and at different times of year), rather than the more-typical approach, which is restricted to day-time and night-time scenarios.

Travel speed distributions are developed from a review of travel speeds that have been previously-used in evacuation modelling. In the evacuation model, each person is assigned a randomly-sampled travel speed from a distribution based on their demographic group, derived in the exposure model. The application of travel speed distributions provides an improved representation of variability in travel speed compared to the typical approach of applying a fixed travel speed to each age or demographic group. Therefore, the proposed method enhances current assessment of pedestrian evacuation potential.

The LCD method is developed in Python programming code. The method is demonstrated in an assessment of pedestrian evacuation potential for the maximum credible tsunami at the case study location, Napier. Evacuation potential is used to inform the requirement for vertical evacuation in the city. An additional process is used to identify the optimal locations for vertical evacuation refuges, if a vertical evacuation strategy was to be developed. Hazard inputs (inundation extent, flow depth and wave arrival times) are required as input to the evacuation model; these are obtained from the numerical modelling conducted in Objective 1. The DEM generated to achieve Objective 1 is also applied in this stage.

1.4 Study area

Napier Territorial Authority, in the Hawke's Bay Region on the east coast of New Zealand's North Island has been chosen as the case study area for this research. Napier is a generally low-elevation coastal area of 106 km^2, comprising residential suburbs, commercial and industrial areas and agricultural land including orchards and vineyards. Bluff Hill provides an area of high ground immediately north of the city centre to maximum elevation over 100 m. Napier Port is the fourth largest in New Zealand, handling cargo including forestry products and container shipments, with storage of timber and containers on site (Port of Napier Limited, 2012). The estimated population of Napier in 2013 is 57,800 based on medium growth projections (Statistics New Zealand, 2013a) from the most recent census in 2006 (Statistics New Zealand, 2006). During peak tourist season (January to March), an average of 2,342 visitors stay in Napier accommodation every night (Statistics New Zealand, 2012c, 2006–2011 data). Numerous accommodation facilities, schools, one tertiary education campus, early childhood centres and care homes or retirement villages form concentrations of people who may be less able to evacuate effectively in a local earthquake and tsunami due to mobility issues or deficiency in local knowledge.

At the eastern shore of the city there is a steep gravel beach and berm stretching along the coastline from Bluff Hill in the north to the confluence of the Tutaekuri, Ngaruroro and Clive Rivers in the south (Fig 1.7). At its northern end, the berm elevation is 7 m above Mean Sea Level (MSL), reducing to 4 m above MSL at its southern end. Northwest of Bluff Hill the suburbs of Ahuriri and Westshore are separated by a tidal inlet and small marina. Westshore is situated on a peninsula elevated 4–6 m above MSL. Bay View is the most northern suburb of Napier, extending north around the bay. Much of the land around the present Ahuriri Lagoon was previously below sea level until uplift during the 1931 Hawke's Bay earthquake and due to artificial drainage in the years since (Hull, 1986).

The 1931 Hawke's Bay earthquake destroyed many of the buildings in Napier and triggered a rebuild in 1930s Art Deco style. The current building stock retains a large number of one- and two-storey 1930s structures, which are an important factor in the city's tourism activities. Ninety-five percent of the building stock in Napier is one or two storeys in height. Ninety-two percent of structures are of light timber construction, 3% are reinforced concrete shear wall and 3% are concrete masonry (Cousins, 2009; King and Bell, 2009; King et al., 2008). The remaining 2% are Brick Masonry, Light Industrial, Reinforced Concrete Moment Resisting Frame, Steel Braced Frame, Steel Moment Resisting Frame, or Tilt-up Panel construction. The small number of tall buildings in Napier has implications for tsunami evacuation. The suburban building stock primarily comprises single-storey family homes or small commercial premises and the only concentration of taller buildings occurs in the primary retail, tourist and civic area of Nelson Park.

Fig 1.8 shows Napier Territorial Authority from the air, with agricultural land in the south (foreground) and suburbs to the south of Bluff Hill. The strip of residential properties along the eastern shore of Napier is visible. Fig 1.9 shows the city from the north, overlooking Westshore, Ahuriri, the Marina and Ahuriri Lagoon, Napier Port and Bluff Hill. Fig 1.10 shows the Port of Napier, looking south-west. The moored cruise ship represents additional population exposure, and shipping containers and logs that provide potential large debris in a tsunami. Behind the Port are the cliffs and residential suburbs of Bluff Hill. Ahuriri Lagoon is visible behind the residences of Westshore along the shoreline coastline, and Hawke's Bay Airport is located at the right-hand edge (northern edge) of this image. Fig 1.11 shows the main traffic arteries between residential suburbs, and culverts with crossing locations.

Fig. 1.8: Oblique aerial photograph looking north towards Napier. The majority of the Territorial Authority is visible in this photograph. Photo credit: D Townsend/GNS Science

Fig. 1.9: Oblique aerial photograph looking south across Westshore, Napier Port and Bluff Hill/Hospital Hill. Photo credit: D Townsend/GNS Science

Fig. 1.10: Oblique aerial photograph looking south-west over Napier Port, Bluff Hill, Ahuriri and Westshore. Photograph taken in 2001. Source: Hawke's Bay Regional Council.

Fig. 1.11: Oblique aerial photograph looking southeast across the residential suburbs of Napier. Note the three large tree-lined culverts, crossed by major roads. Photo credit: D Townsend/GNS Science

1.5 Thesis structure

The structure of this thesis has been designed to provide logical progression through the research, placing the research in the context of tsunami processes, impacts, and mitigation. Chapter 1 has introduced the aims and objectives of the research, the risk management and CDEM frameworks in which this research sits and the research methodology. The case study location has also been introduced.

1.5.1 Literature review

The physical process and impacts of tsunami are described in Chapter 2. The tsunami hazard in New Zealand (Chapter 2.4) provides greater context to the need for tsunami risk management in New Zealand by describing the impact of previous tsunami in the historic and palaeo-tsunami records, and giving an overview of the recently-updated national tsunami hazard assessment (Power, 2013). Approaches to tsunami risk reduction are reviewed in Chapter 3 to place the role of vertical evacuation within in the wider framework of risk reduction.

1.5.2 Primary research and discussion

The subsequent four chapters present the primary research conducted during this research, in the form of published or submitted papers. Chapter 4 discusses in more detail the tsunami hazard from major earthquakes at the Hikurangi subduction zone and presents the results of deterministic local-source tsunami inundation simulation at Napier (Objective 1). The results of these simulations are pre-requisite for subsequent evacuation modelling and provide context to the subsequent discussion of tsunami risk reduction. The published work is preceded by an overview of tsunami numerical modelling (Section 4.1).

Chapter 5 focusses on vertical evacuation as a risk reduction strategy, presenting documentation of TVEB surveys in Tōhoku, and experiences of emergency managers in the 2011 Great East Japan tsunami (Objective 2). Chapter 6 is an investigation of residents' and visitors' intended evacuation behaviour in local-source tsunami scenarios at Napier. It includes preliminary research into people's views on vertical evacuation buildings (Objective 3). Chapter 7 then presents the development and demonstration of a time-variable exposure model in combination with a GIS-based model of pedestrian evacuation potential to assess the requirement of vertical evacuation for local-source tsunami (Objective 4). Detailed results on pedestrian evacuation potential in Napier, and the optimised selection of vertical evacuation locations is presented after the published work, in Section 7.8. It was decided that these results were too site-specific for publication in an international journal, and are intended for subsequent publication as a technical report. Discussion of the research findings with respect to the aim and objectives is presented in Chapter 8.

Chapters 4 and 5 have been published in international peer-reviewed journals, as Fraser et al.

(2014) and Fraser et al. (2012b), respectively. Chapter 6 has been published as a peer-reviewed GNS Science report (Fraser, Johnston, and Leonard, 2013). Chapter 7 has been submitted for publication as a journal paper. The manuscripts have been reformatted for consistent presentation in this thesis but are otherwise unchanged from the published and submitted versions. A preamble is presented at the start of each chapter to briefly elaborate on the context and methodology of the paper and give details of the published work. Each chapter concludes with a short paragraph introducing the subsequent chapter. Statements of author contribution for each submitted or published manuscript are compiled in Appendix H.

1.5.3 Appendices — Additional publications and developed code

Several additional publications have been co-authored during the course of this doctoral research. These are not included in the main body of the thesis because they do not form the core part of this research, or they are of wider scope to justify inclusion as a main chapter. However, they are referred to throughout the course of this thesis because they constitute research relevant to the overall thesis aim and have contributed significantly to development of the author's knowledge of this subject. They are included as appendices for ease of reference by the reader, and are summarised here. Appendix A is the original scoping study (Leonard et al., 2011), to which the thesis author contributed observations from his first field investigation in Japan. Appendices B and C provide field observations from the EEFIT field investigation (EEFIT, 2011; Fraser et al., 2013). Appendix D provides observations from the second field investigation, including evacuation and warning response in the 2011 Great East Japan tsunami (Fraser et al., 2012a). Appendix E demonstrates the validation of a standard New Zealand national evacuation mapping method, which has been applied to Napier for comparison against the numerically-modelled inundation zone (Fraser and Power, 2013). Appendix F gives indication of potential earthquake ground-shaking at Napier due to the whole margin scenario, and Appendix G provides flow charts and code used in the evacuation modelling process. Appendix I provides a full list of publications produced during the course of this doctoral research.

2. TSUNAMI PROCESSES AND HAZARD

2.1 Tsunami generation

2.1.1 Seismic sources

The primary cause of tsunami generation is sub-marine seismic sources. The potential for an earthquake to be tsunamigenic increases with increased seismic moment (Kanamori, 1972), shallower focal depth, and greater sea depth at the earthquake location (Suppasri, Imamura, and Koshimura, 2012). An earthquake must generally exceed M_W 5.0 to be tsunamigenic (National Geophysical Data Center/World Data Service, 2014) and although 90% of tsunami are due to the vertical motion of thrust earthquakes typical of subduction zones, they can also result from strike-slip or dip-slip mechanisms. Horizontal motion due to shallow-dipping thrust or strike-slip mechanisms can cause particularly large tsunami when they occur near steep sub-marine slopes (Tanioka and Satake, 1996b). Tsunamigenic earthquakes are generally $<$60 km deep (National Geophysical Data Center/World Data Service, 2014). In the shallowest 30 km, dip-slip events are ineffective (due to the surface integral of deformation becoming zero) while thrust events are most effective; there is little difference between the two at greater depths (Okal, 1988). Deep earthquakes can still cause tsunami despite the reduction in strong motion on the ocean floor, as the relative area affected by the displacement is increased, meaning a sufficiently large volume of water can be displaced by the relatively smaller ground motion (Okal, 1988).

Tsunami amplitude (Fig 2.1) is controlled primarily by earthquake magnitude and spatial variation of slip (Abe, 1979; Geist, 1998; Kajiura, 1981; Okal, 1988). Rupture velocity (Suppasri, Imamura, and Koshimura, 2010), energy directivity (Okal, 1988), occurrence of co-seismic landslides and rupture propagation across multiple rupture segments also affect amplitude. *Tsunami earthquakes* are earthquakes with relatively moderate magnitude and slow rupture speed, that cause tsunami disproportionately larger than their magnitude would suggest (Kanamori, 1972). Tsunami earthquakes pose problems for evacuation and education on response to natural warnings. Due to the relatively low magnitude, ground shaking may not be felt at the coastline, or may be dismissed as too weak to have caused a tsunami. Examples of tsunami earthquakes include the 1896 Meiji Sanriku (Shuto and Fujima, 2009), 1992 Nicaragua (Satake, 1994) and 2010 Mentawai Island tsunami (Newman et al., 2011).

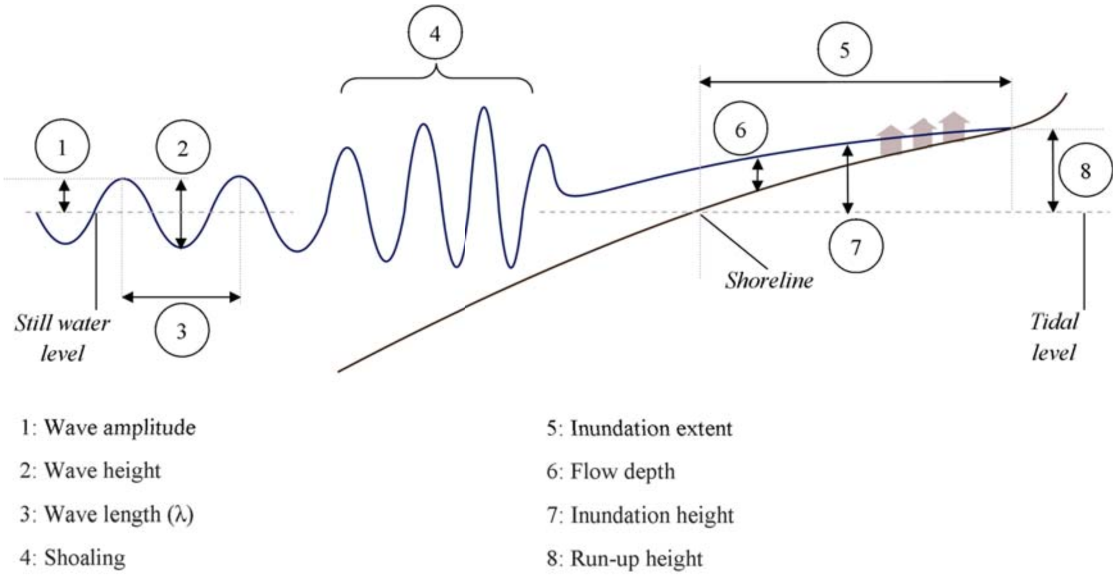


Fig. 2.1: Schematic diagram of tsunami wave terminology.

2.1.2 Landslide sources

Landslide-induced tsunami present a risk to many coastlines and enclosed water bodies. Notable landslide generated tsunami events include 1958 Lituya Bay, and local landslide-induced tsunami triggered by the 1964 Prince William Sound earthquake, both in Alaska, United States (US). There have also been multiple events in Norwegian fjords (Lockridge, 1990) and the 1998 Papua New Guinea tsunami (Synolakis et al., 2002; Tappin, 2001) caused over 2,000 fatalities (Table 1.1). Slope failure may be triggered by: seismic activity; over-steepening of slopes, decomposition of gas hydrates or increased saturation; continuous sediment accumulation; or volcanic activity (Masson et al., 2006). Due to the source mechanism approximating a point source, the resulting tsunami is significantly more focussed and more dispersive than those generated by ocean floor displacement in a fault rupture (Glimsdal et al., 2013), therefore they are more restricted in travel distance and spatial extent of damage. The wave form of a landslide-induced tsunami is one of a low leading crest with followed by: a trough 2–3 times greater in amplitude than the crest; a large crest matching the preceding trough; and a series of higher frequency waves (Pelinovsky and Poplavsky, 1996). The exaggerated N-wave shape results in greater run-up values than in a comparable seismically-induced event but wave amplitude attenuates rapidly with distant from the source. Landslide sources are not considered further in this study.

2.1.3 Meteorological forcing, volcanic eruption, and bolide impact

Meteorological tsunami, or *meteo-tsunami* (Defant, 1961; Nomitsu, 1935) are large amplitude seiche oscillations, having similar temporal and spatial scales as typical seismically-forced tsunami, that are caused by meteorological forcing (Rabinovich and Monserrat, 1998). They are generated when strong atmospheric disturbances occur over a sea, bay or harbour that has specific resonance characteristics causing resonance between the atmospheric forcing and the resulting long wave, or where coastal orientation or configuration promotes amplification of long waves by resonance (Rabinovich and Monserrat, 1998). Because of the requirement for specific conditions, they are observed commonly in certain locations, sometimes with damaging wave heights of up to 4 m (Rabinovich and Monserrat, 1998; Tappin et al., 2013).

Volcanic eruptions present various mechanisms to induce tsunami: seismic tremors, pyroclastic flows, submarine explosions, caldera collapse, lateral blast, landslide, rock or debris avalanche, lahar, atmospheric pressure wave and lava (Latter, 1981). Among the most famous volcanically-generated tsunami are those from the eruption of Santorini (Thera), Crete, in the 2nd millenium BC (Cita et al., 1984) and Krakatau, Indonesia, in 1883 (Lowe and De Lange, 2000). Several studies have explored the potential for tsunami generated by flank collapse on volcanic islands in Europe (e.g., Ward and Day, 2001; Zaniboni et al., 2013).

Bolide impact has been discussed as having the potential to cause massive tsunami, due to the displacement of water if a bolide (meteorite) of larger than a few hundred metres diameter were to impact into a water body. This generation mechanism is often quoted in hazard assessments and general discussions of tsunami generation, however, there little evidence in the literature pointing to a specific bolide-generated tsunami event. Bryant, Walsh, and Abbott (2007) discuss the potential cosmogenic source of a mega-tsunami that affected 1500 km of Australian coastline in the 17th Century, as the dated deposit coincides with Aboriginal legends that appear to describe a comet strike and tsunami. Goff et al. (2010a) challenged the inferred causal mechanism due to an absence of evidence for a submarine impact crater and questioned the validity of the data pointing to the deposit being tsunami-derived. These generating mechanisms are outside the scope of the current research and are not discussed further in this research.

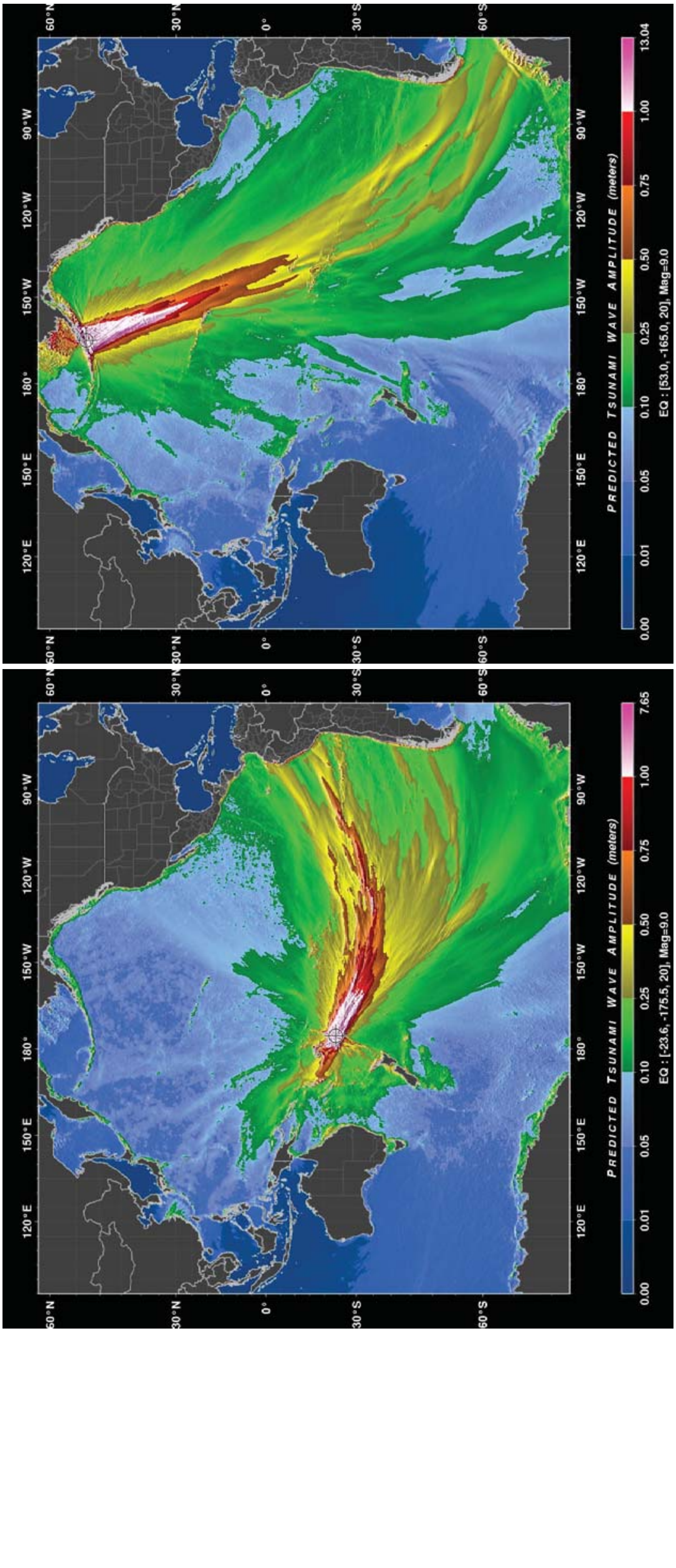
2.2 Propagation and inundation

The source event determines initial amplitude, directionality and wave-form of the resulting tsunami, which is then propagated across the body of water. A seismic thrust or normal faulting mechanism will commonly result in a tsunami wave that propagates in two directions, with most energy directed normal to the fault strike. Coastlines proximal to a subduction zone are generally positioned normal to the strike so receive most of the wave energy and experience the largest wave amplitude (Fig 2.2). Locations oblique to the strike receive less energy due to this directionality. The wave will take the form of an N-wave due to differential uplift of the seabed in the seismic event (Tadepalli and Synolakis, 1994, 1996). In one direction the wave will be a leading-depression N-wave and in the other, a leading-elevation N-wave (Tadepalli and Synolakis, 1994). Arrival of a leading-depression wave causes drawdown at the coast, preceding positive tsunami arrival; leading elevation waves arrive as a positive wave with no drawdown as warning. This important to address in tsunami education and understanding of natural warnings, to ensure that the public doesn't expect to see drawdown in all cases.

In the open ocean, tsunami typically have a wavelength (Fig 2.1) of hundreds of kilometres and amplitude of <1 m. The depth of the ocean (D; average of <4 km) limits the vertical dimension of the tsunami. Due to these dimensions, tsunami conform to the long wave theory, with implications for numerical modelling (Section 4.1). Wave celerity (propagation speed) of tsunami (c) is calculated using $c = \sqrt{gD}$, where g is the gravitational constant. Therefore, tsunami can travel at around 700 kmh^{-1} in the deep ocean and celerity reduces to tens of kmh^{-1} in shallow water on continental shelves, or over undersea ridges. The variation in velocity due to changing water depth results in wave refraction, which alters the path of wave travel. Waves become focussed over shallow bathymetry and spread in deep water (Satake, 1988; Woods and Okal, 1987, Fig 2.2). Divergence and convergence of the tsunami is also affected by the rotation (Coriolis Force) and curvature of the earth as they travel across the oceans, which influences the path of travel (Fig 2.2) and resulting wave height at coasts (Shuto, 1991).

Wave energy (and maximum amplitude) is attenuated with distance due to geometrical wave spreading and frequency dispersion. Dispersion occurs because waves with different frequencies propagate at slightly different speeds. The result is that tsunami in the far-field appear as multiple oscillations of different wave period, rather than the original single wave that was generated — hence the arrival of tsunami as a series of waves over several hours. The natural resonant periods of coastal topography determines the periods of distant tsunami that are observed at the location (Rabinovich, 1997, and references therein). Source fault plane dimensions are a key control on dispersion. Sources with smaller fault planes causing tsunami with greater dispersion effects (Glimsdal et al., 2013), thus greater attenuation of wave energy. Dao and Tkalich (2007) demonstrated that dispersion can significantly reduce maximum tsunami amplitude (by 40%–60%) in deep water where celerity is greatest.

As tsunami travel into shallower water close to the coast, celerity and wavelength reduce due to the decreasing water depth and amplitude increases to satisfy the conservation of wave energy ('shoaling'; Fig 2.1). The majority of tsunami occur onshore as non-breaking waves (Pelinovsky and Mazova, 1992). In some cases, however, a wave breaks offshore and forms a turbulent bore, which results in smaller run-up heights but retains its wave energy and destructive power (Yeh, 1991). The increased effect of bottom friction and turbulence causes energy dissipation and some energy is reflected off the coastline. Wave energy reflected off the coastline results in constructive and destructive interference as reflected waves interact with incoming waves. Despite this reduction in energy, the remaining wave energy and celerity is still significant and imparts huge



(*a*) Pacific Wave 2011 Tonga Trench scenario.

(*b*) Pacific Wave 2011 Aleutian Islands scenario.

Fig. 2.2: Predicted wave amplitude for two tsunami scenarios in the Pacific Ocean (UNESCO/IOC, 2011).

forces in the coastal zone and onshore. Tidal regime at the time of tsunami can be important in the coastal zone. Dao and Tkalich (2007) demonstrated that an increase of several metres in water depth (within a typical tidal range) can lead to an increase of up to 100% in maximum amplitude and earlier wave arrival time.

Local variations in wave height maxima are common due to interactions between the wave and coastal configuration and relief. Refraction and diffraction occur around coastal features due to variations in speed and wave height along the wave crest. These effects can result in the greatest wave amplitude occurring on the lee-side of islands, where waves can diffract around the coastline and meet on the lee-side, causing constructive interference and amplified run-up (Liu et al., 1995b). Within a semi-enclosed structure such as a bay or harbour, reflections, wave-focussing and resonance can amplify wave heights, leading to higher maximum run-up and greater damage. Wave focussing can occur due to the geometry of a bay constricting the volume of water as it flows towards the head of the bay (e.g., Pago Pago Harbour in Samoa 2009 — Didenkulova, 2013; Fritz et al., 2011; Okal et al., 2010).

2.3 Impacts of tsunami

The immediate impacts of tsunami are casualties and damage to structures, lifelines, infrastructure and the natural environment. Medium-term impacts include re-location of entire communities, loss of economic production and the need for extensive debris clearance before an area can be re-developed. Tsunami cause loss of economic production due to: disruption of agriculture (increased salinity of soils and sediment deposition); aquaculture and fisheries (loss of port infrastructure, vessels and ecosystem damage); commerce and industry (power outage, infrastructure damage, supply chain disruption, damage to retail or production facilities). In the longer-term, continued economic disruption and disconnection with family, community and culture can affect recovery (Rodriguez et al., 2006; Rofi, Doocy, and Robinson, 2006).

2.3.1 Structural damage

Tsunami damage to structures such as coastal defences, buildings and bridges have been well-studied during post-event field investigations since the 1990s and particularly post-2004 (Synolakis and Bernard, 2006). As a result, causes of damage and building failure modes have been well characterised. The main causes of damage to buildings are foundation scour, lateral bending failure of beams, failure of beam-column joints, out-of-plane failure of infill walls and windows, fire, debris impact (particularly on columns), and overturning (Fraser et al., 2013; Lukkunaprasit et al., 2008; Reese et al., 2007; Rossetto et al., 2006; Ruangrassamee et al., 2006; Shuto and Matsutomi, 1995; Suppasri et al., 2013b).

The development of tsunami fragility curves (Koshimura, Namegaya, and Yanagisawa, 2009) has provided further data on the vulnerability of structures to tsunami damage (Reese et al., 2011;

Suppasri, Koshimura, and Imamura, 2011; Suppasri et al., 2013a,c). Statistical analysis of damage data from >250,000 buildings surveyed after the 2011 Great East Japan tsunami show that timber frame buildings perform poorly in tsunami, Reinforced Concrete (RC) structures are most tsunami-resistant and buildings of more than two storeys are stronger than low-rise buildings (Suppasri et al., 2013a).

The 2011 Great East Japan tsunami was the first time that damage had been observed to coastal defences designed to withstand tsunami. Many coastal defences, such as the 10 m high wall at Tarō Town were designed for tsunami, but were overtopped. Concrete blocks that were insufficiently connected and comprised sand infill were toppled (Fraser et al., 2013). Over 8 km of breakwaters collapsed (Yagyu, 2011) and although the breakwater at Kamaishi may have reduced inundation in the town, scour between concrete blocks ultimately caused the breakwater to fail (Kazama, 2011). Concrete block revetments on the coastal plains were overtopped and heavily scoured on the lee-side, with concrete blocks transported up to 100 m inland (Fraser et al., 2013), showing the potential for damaged defences to develop into water-borne missiles. The coastal plains also exhibited buildings that had been damaged by uprooted trees from the coastal defence forest (Fraser et al., 2013). Appendices B and C present research on tsunami damage in the 2011 Great East Japan tsunami in more detail.

2.3.2 Tsunami casualties

Commonly reported injuries sustained in tsunami include fractures, crush injuries, abrasions and lacerations due to debris-strike (Guha-Sapir et al., 2006). Debris can range in size from abrasive particles of sand and gravel, to large debris such as buildings and marine vessels. The most common cause of death in tsunami is drowning, which is likely to be influenced by injuries sustained in the water. Mortality rate due to tsunami is highly variable and dependent on a variety of factors. Hazard factors influencing mortality are: flow depth and velocity; inundation extent; wave arrival time after the source event; time of tsunami occurrence; and presence of debris. Important human factors include: timing and efficacy of official or natural warnings; coastal population density; cultural, social, economic and demographic vulnerability; preparedness levels; and availability of evacuation routes and refuges. Activity and location at the time of the event, localised damage intensity, behaviour during the event, physical and mental condition and even types of clothing can all influence mortality rate (Nishikiori et al., 2006). Overall mortality rates reported from the 2004 Indian Ocean tsunami were 12.9% in Ampara, eastern Sri Lanka (Nishikiori et al., 2006), 13.9% in Aceh Barat and Nagan Raya districts, Aceh Province, Indonesia (Rofi, Doocy, and Robinson, 2006) and 5.3–23.6% depending on location in Aceh Jaya district (Doocy et al., 2007). Mortality rates for individual municipalities in the 2011 Great East Japan tsunami varied from 0.01% to 8.9% in Iwate Prefecture and 9.8% in Miyagi (National Police Agency of Japan, 2011). Cardiac arrest and near-drowning respiratory problems (due to inhalation of water) also contribute to post-tsunami deaths (Guha-Sapir et al., 2006).

Higher mortality among females than males occurred in the 2004 tsunami, despite their equal representation in terms of numbers of people affected (Frankenberg et al., 2011; MacDonald, 2005; Nishikiori et al., 2006). This gender difference was found to apply only to those of working age (Doocy et al., 2007; Guha-Sapir et al., 2006). Young children and the elderly also exhibited higher mortality rates than those in middle age groups in Sri Lanka in 2004 (Frankenberg et al., 2011; Nishikiori et al., 2006), but mortality was more equal between genders. The primary reasons for age-bias in mortality are mobility and strength. Socio-economic and cultural contexts, gender roles and daily activities influence a person's education level, location and likelihood of physical isolation at the time of tsunami, therefore influence mortality (Neumayer and Plümper, 2007). This was exemplified in 2004 when the higher female mortality rate was partially explained by women staying behind to look after children and elderly family, and by women having a lower likelihood of being able to swim (MacDonald, 2005). Conversely, in some areas male mortality was greater as males were commonly employed in the fishing industry, and were at sea when the tsunami struck (MacDonald, 2005).

Various formulae have been proposed for mortality as a function of flow depth, for coastal floods, river floods and tsunami (Jonkman, Vrijling, and Vrouwenvelder, 2008). Tests of human stability in flows suggest that 'people lose stability in relatively low depth-velocity products' (0.6–2.0 m^2s^{-1}; Jonkman, Vrijling, and Vrouwenvelder, 2008), not accounting for fatigue or the presence of debris. For flow velocity of 3–4 ms^{-1}, this equates to a depth of 0.2–0.7 m. Estimates of tsunami flow derived from videos of previous events suggest flow velocity at the water surface can exceed this. Velocity of 8 ms^{-1} has been recorded at the coast (Fraser et al., 2013; Rossetto et al., 2006) and up to 1 km inland (Hayashi and Koshimura, 2013). Fritz et al. (2006) recorded velocities up to 5 ms^{-1} more than 3 km inland which suggest instability could occur at even minor flow depths in much of the inundation zone. These estimates demonstrate the importance of early and efficient evacuation to avoid contact with tsunami flow.

2.4 Historic tsunami in New Zealand

New Zealand is situated in an active tectonic environment, on the boundary of the Australasian and Pacific tectonic plates. Offshore of the east coast of the North Island, the Pacific Plate is subducting beneath the Australasian Plate at the Hikurangi subduction margin (Fig 2.3). At the northern end of the South Island, plate motion transitions into a strike-slip motion along the Alpine Fault before reverting to subduction offshore of the South Island at the Puysegur Trench. The entire sub-aerial and sub-marine landmass of New Zealand is affected by active faulting and volcanic systems related to this plate boundary movement, which results in local seismic, volcanic and landslide-induced tsunami hazard. As a collection of islands, New Zealand is also exposed to tsunami originating at other major subduction zones in the Pacific Ocean, from the proximal Kermadec and Tonga subduction zones, to the distant Peru-Chile Trench. Fig 2.4 illustrates the direction of arrival and year of occurrence, of previous distant and local-source events. The NOAA-NGDC Tsunami Database (National Geophysical Data Center/World Data Service, 2014) lists 45 events that caused run-up in New Zealand between 1845 and 2013, while the New Zealand Historic Tsunami Database[1] contains 80 events (with variable reliability) since 1835, at a rate of approximately 4–5 per decade. The majority of these events caused maximum run-up <2 m, but several events have cause significant localised run-up >6 m. The most damaging events occurred due to local-source events in 1855, 1931 and 1947, and distant-source events in 1868, 1877 and 1960. These tsunami caused damage to coastal residences and coastal infrastructure but the only confirmed tsunami-related death to occur in New Zealand occurred during the 1868 Peru event (Richards, 1950).

2.4.1 Historic distant-source tsunami

The most significant distant tsunami to affect New Zealand in the historic record are those generated offshore of Peru and Chile in 1868, 1877 and 1960. The 1868 M_W 9.1 southern Peru earthquake caused 1–4 m run-up on the North and South Islands of New Zealand and in the Chatham Islands caused up to 10 m run-up (Hawke's Bay Herald 27 October 1868, in the New Zealand Historic Tsunami Database) and inundation extent >6 km (De Lange and Healy, 1986). The only fatality due to tsunami in New Zealand occurred during this event when the Māori settlement of Tupuangi, Chatham Island was destroyed (De Lange and Healy, 1986). Run-up of 18 m occurred locally in Peru during this event indicating that the source event was comparable the 2011 Great East Japan tsunami. In 1877 a M_W 9.0 earthquake in northern Chile caused run-up of 21 m locally and 3.5 m in New Zealand. In both events there was little damage in New Zealand because the largest waves arrived within a few hours of low tide. If these events were to occur today, there would likely be more damage due to the greater amount of coastal development in the worst-affected areas (Great Barrier Island, Bay of Plenty, Napier, Banks Peninsula and Oamaru).

The 23 May 1960 Chilean tsunami was generated by a M_W 9.5 earthquake offshore southern Chile. Maximum observed run-up was 3–4 m at Banks Peninsula, Gisborne, Chatham Islands and Napier (New Zealand Historic Tsunami Database). Maximum run-up in Wellington Harbour was 0.75 m (Heath, 1976). The tsunami caused damage to wharves, jetties, boats and houses, primarily in Napier and Banks Peninsula, resulting in $193,000 of insured damage (2006 values; De Lange and Healy, 1986; Johnston et al., 2008). Fortunately, the largest waves arrived within a few hours of low tide, which mitigated further damage and casualties.

The Chile 1960 event was noted for wave energy focussing, which occurred along the East Pacific Rise onto the east coast of the North Island (Okal, 1988), and by the Chatham Rise onto Banks Peninsula in the South Island (De Lange and Healy, 2001). This is a prominent feature of tsunami propagation from South America towards New Zealand, and is a factor in Chile and Peru

[1] New Zealand Tsunami Database: Historical and Modern records. Available at http://data.gns.cri.nz/tsunami/

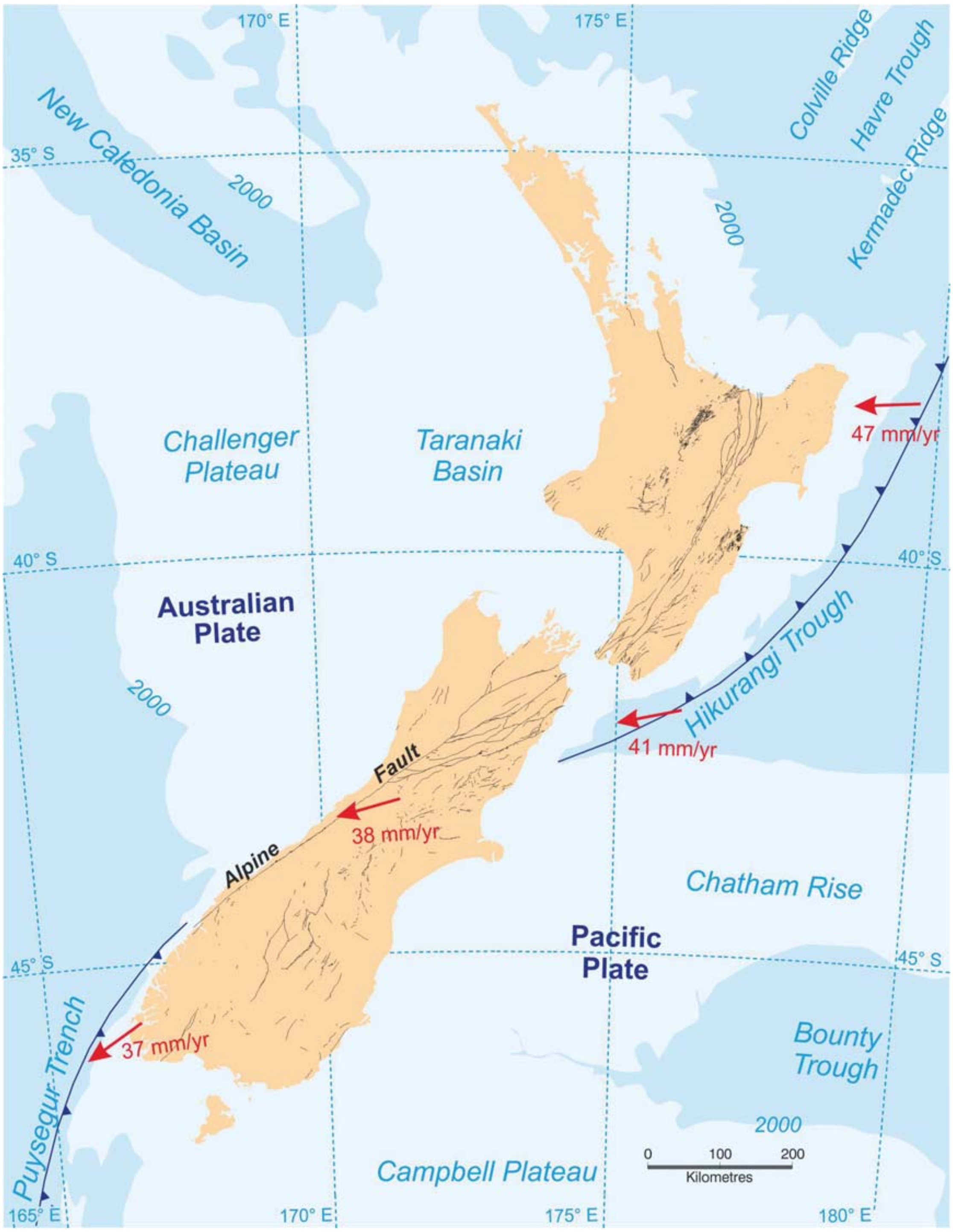


Fig. 2.3: The tectonic setting of New Zealand, showing the major subduction and strike-slip faults at the boundary of the Pacific and Australasian Plates. Slip rates are shown in red for each of the Hikurangi subduction margin, Alpine Fault and Puysegur Trench. Source: GNS Science Geological Map of New Zealand, http://data.gns.cri.nz/geoatlas/text.jsp?Page=1.

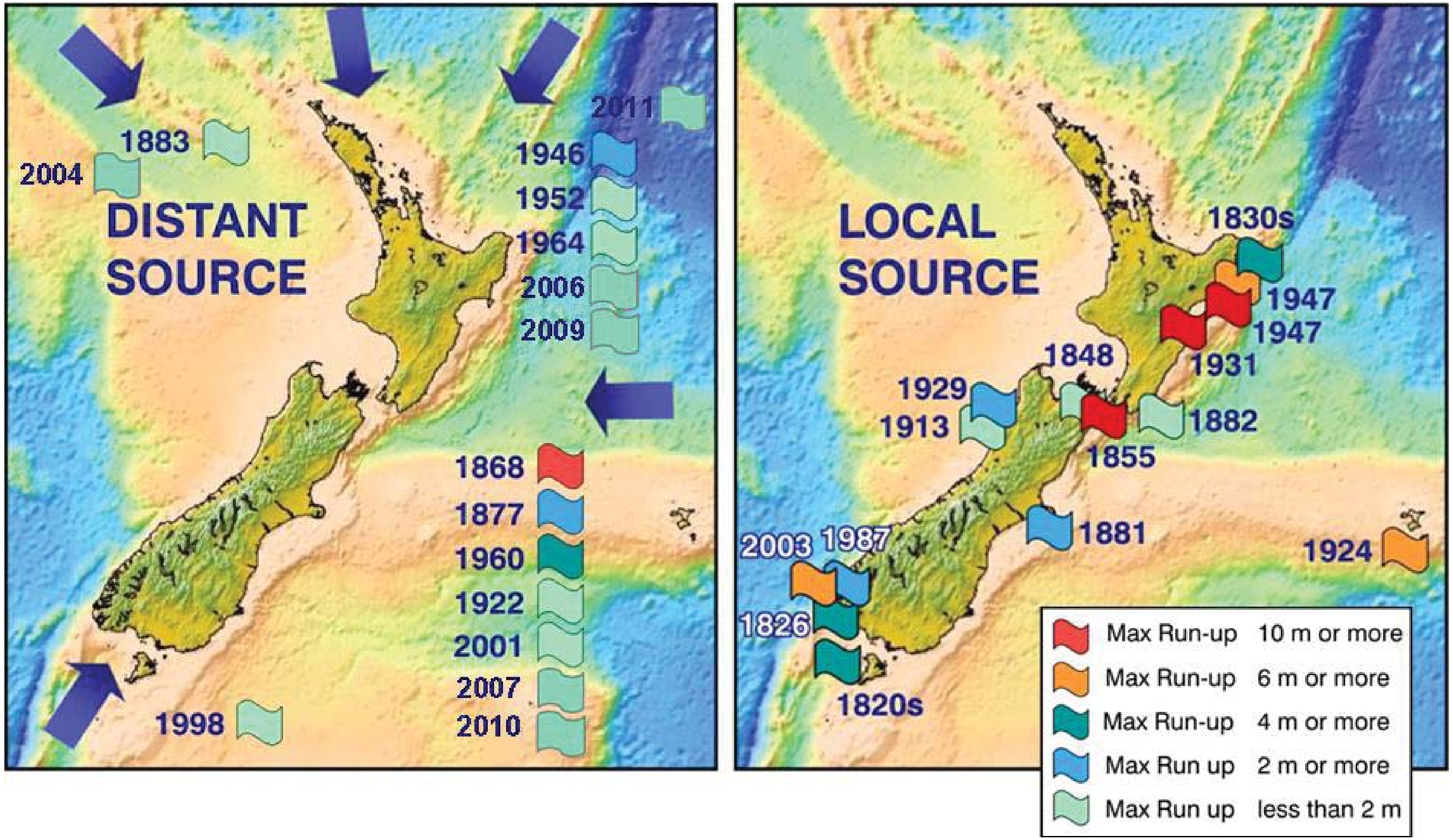


Fig. 2.4: Run-up height from distant and local-source tsunami in the New Zealand historic record, 1820s to 2013. Flags indicate source location for local-source events, and general direction of origin for distant-source events. Source: GNS Science, the original image has been updated to include recent events.

being the most hazardous distant-sources for New Zealand. Events generated offshore of Peru or northern Chile (e.g., 1868) direct wave energy toward New Zealand much more effectively than events in central or southern Chile (e.g., 1960). For this reason, run-up due to the 1960 tsunami was much lower in New Zealand than that from the 1868 event, despite the 1960 earthquake having a higher magnitude. No tsunami warning was issued on 23 May 1960, as there was no Pacific-wide tsunami warning system in existence at that time, although in some areas evacuations were initiated by local police (Johnston et al., 2008). The event triggered substantial debate around national and local tsunami warning arrangements in New Zealand and resulted in rapid arrangements to receive future warnings, which were issued for a M_W 7.5 aftershock four days later (Johnston et al., 2008). This event was the catalyst for extending the Pacific Tsunami Warning System (PTWS) to cover all nations around the Pacific Ocean.

More recently, tsunami from Peru in 2001 and 2007 resulted in $<$0.3 m run-up in New Zealand (Goring, 2002). Maximum wave amplitude at tide gauges was $<$1 m following the 2010 M_W 8.8 Maule, Chile earthquake (Borrero and Greer, 2013). Tide gauge analysis showed that although wave arrival was approximately 13 h after the earthquake, maximum water levels due to this event occurred between 10 and 37 h after arrival (Borrero and Greer, 2013). Such delays between arrival and maximum wave height have important implications for emergency management response and tsunami risk reduction, in terms promoting awareness of strong coastal currents and the possibility of damage for many hours after wave arrival.

Previous tsunami that originated in the northern Pacific have affected the New Zealand coast with moderate wave heights. The 1946 M_W 7.4 tsunami earthquake in the Aleutian Islands caused wave heights up to 1.2 m north of Whangerei, at Great Barrier Island, Tolaga Bay and Stewart Island (New Zealand Historic Tsunami Database). In 1952, a M_W 9.0 earthquake off the Kamchatka Peninsula resulted in wave height $>$1 m at Gisborne. Earthquakes in 1957 (Aleutian Islands) and 1964 (Alaska) also caused run-up up to 2 m in New Zealand (Berryman, 2005).

Orientation of the M_W 9.0 2011 Great East Japan rupture favoured lower tsunami heights in New Zealand. Due to the high level of instrumentation around the New Zealand coast, the water levels and current in this event were well-recorded, in addition to numerous eyewitness accounts from around the country (Borrero et al., 2013). Maximum amplitude recordings at tide gauges were 0.78 m at Whitianga and 0.86 m at Chatham Island approximately 12–14 h after the earthquake (Borrero and Greer, 2013). At Port Charles, north of Whitianga in the Northland Region, maximum amplitude was c. 1.5 m, with surges occurring approximately eery 20-40 minutes (Borrero et al., 2013). Surges travelled up to 600 m inland up streams and eight houses submitted New Zealand Earthquake Commission (EQC) insurance claims for tsunami damage. Spectral analysis of tide gauge data from the 2010 Chile and 2011 Japan tsunami reveals the fluctuations in wave energy throughout a tsunami and the potential for peak energy to occur as long as 30–40 h after wave arrival (Borrero and Greer, 2013). This delayed peak was observed at Gisborne, and is inferred to be due to reflections off Antarctica and South America. The data also show the variable regional susceptibility to distant-source tsunami in New Zealand, with Whitianga, Gisborne and Lyttleton/Sumner subject to enhanced tsunami response in both 2010 Chile and 2011 Japan tsunami (Borrero and Greer, 2013). Flow currents were recorded at Tauranga Port, where peak tsunami current speeds reached 2 knots (1.03 ms^{-1}), which is greater than the safe level for large tankers to manoeuvre through the harbour mouth (Borrero et al., 2013). Maximum flow velocities were estimated to be 0.5-1 ms^{-1} at Port Charles (Borrero et al., 2013).

2.4.2 Historic regional-source tsunami

Recent regional tsunami affecting New Zealand include: 1997 M_W 7.2 Tonga; 1998 M_W 7.0 Papua New Guinea; 1999 M_W 7.5 Vanuatu; 2006 M_W 8.0 Tonga; 2007 M_W 8.1 Solomon Islands; 2009 M_W 8.0 South Pacific; and 2009 M_W 7.6 Tonga tsunami (National Geophysical Data Center/World Data Service, 2014). The most significant of these in New Zealand was the 2009 South Pacific tsunami, although no onshore damage occurred. Wave arrival occurred after 4 h in the North Island and 8 h in the South Island, with maximum amplitude of 0.89 m recorded at Chatham Island (Power, 2013). Maximum amplitude at gauges around the North and South Islands were <0.6 m, occurring as late as 19 h after the earthquake (Power, 2013). Subduction earthquakes on the Kermadec Trench produced tsunami in 1917, 1976 and 1986.

Regional earthquake sources to the south of New Zealand comprise the Macquarie Ridge and Hjort Trench, southwest of New Zealand. Strike-slip earthquakes of M_W 8.1 occurred at the Macquarie Ridge in 1989 and 1998 (Berryman, 2005) resulting in tsunami of <0.5 m in New Zealand. Run-up of 0.3 m tsunami also occurred due to an earthquake at this source in 1981 (De Lange and Fraser, 1999) .

2.4.3 Historic local-source tsunami

Local-source tsunami have resulted in the largest run-up values in New Zealand recorded history. The most significant occurred on 23 January 1855, when the Wairarapa Fault ruptured, generating a tsunami with run-up of 3–5 m in Wellington Harbour and >9 m in Palliser Bay to the east of Wellington (Downes, McSaveney, and Heron, 2000). Wave amplification in Evans Bay resulted in 5 m waves heights, compared to 2–3 m in the more-sheltered Lambton Harbour (Grapes and Downes, 1997). The tsunami passed over the Rongotai isthmus several times at a depth of about 1 m, flooding what is now largely residential and commercial development, and the site of Wellington Airport. The Marlborough coast on the South Island also experienced wave heights of up to 5 m with a total of 300–500 km of coastline affected with run-up >1 m (Berryman, 2005). The primary cause of the tsunami is believed to be 6 m of vertical uplift at the south Wellington coast, although the contribution of earthquake-triggered submarine landslides has not been ruled out (Berryman, 2005). With the earthquake fault located so close to the mainland, initial waves arrived within minutes at Wellington. Further afield at Otaki and Marlborough arrival time was closer to an hour.

Despite the significant wave heights, damage was apparently limited to flooding of waterfront shops in Lambton Harbour, a few houses at Palliser Bay were washed away and a bridge and houses were damaged along the Hutt River.

The March 1947 M_W7.0–7.1 tsunami earthquake, located 50 km east of Gisborne, resulted in tsunami that affected 120 km of the East Cape coastline. Maximum run-up of 10 m occurred north of Gisborne at Tatapouri and maximum inundation extent was 800 m (Downes et al., 2000) with damage to a main road bridge and several houses and the hotel. Wave arrival time was approximately 30 min after the earthquake. In May 1947 another tsunami earthquake (M_W 6.9–7.1 Doser and Webb, 2003) caused 6 m run-up north of Gisborne and 5 m at Tolaga Bay. These are believed to have been tsunami earthquakes due to the low maximum Modified Mercalli Intensity (MMI) 4, and small magnitude relative to the tsunami they caused (Downes, McSaveney, and Heron, 2000). Bell et al. (2009) and Wang et al. (2009) showed that a rupture at or near a subducting seamount could have produced a shallow and slow rupture, which in combination with focussing effects of the seamount bathymetry, could have resulted in the significant run-up. The low intensity felt onshore poses a particular problem for local tsunami education and evacuation, because the weak earthquake shaking may be less-likely to be perceived as a natural warning of tsunami (Section 3.3.3).

The 2009 M_W 7.8 Dusky Sound, Fiordland earthquake generated a tsunami recorded with maximum run-up of 2.3 m (Clark et al., 2011), wave arrival of 15–20 min and strong currents that lasted for 2 h (Prasetya et al., 2011a). Due to the remoteness of the source area, further run-up observations are limited and there are no records of tsunami damage.

2.5 Palaeo-tsunami in New Zealand

Geological investigations of coastal sediments can identify deposits that may have been emplaced by tsunami. The location, distribution and dates of palaeo-tsunami deposits can enable the inference of inundation extent and run-up heights, augmenting relatively short historic records and extending our window of tsunami experience to several thousand years before present. Palaeo-tsunami research has led to the discovery of previously-unrecognised significant trans-oceanic events, resulting in significant extensions of regional tsunami catalogues and recognition of the potential impacts of extreme events (e.g., Atwater, 1987; Atwater et al., 2005b; Minoura et al., 2001).

Although there have been many recent advances in palaeo-tsunami research, a high degree of uncertainty exists around the provenance, dating and even correct identification of deposits as being emplaced by tsunami. Tsunami deposits have been characterised in numerous palaeo-tsunami studies and immediately after observed tsunami (Chagué-Goff, 2010; Chagué-Goff et al., 2000; Dominey-Howes, Humphreys, and Hesse, 2006; Goff, Chagué-Goff, and Nichol, 2001; Goff et al., 2011; Minoura et al., 2001; Sugawara and Goto, 2012; Sugawara et al., 2013):

- continuous or discontinuous sheet of silts, sands, clay, gravel or boulders, possibly containing shell material; sediments fining inland and/or upwards
- marine diatoms, foraminifera or other microscopic marine material
- diluted pollen content
- distinct geochemistry, for example increased concentrations of sodium, sulphur, chlorine, calcium and magnesium
- occurrence of shells, wood, or other organic material at the top of the deposit
- the stratigraphic position of the deposit overlying organic-rich muds, soils or plant material (the pre-tsunami surface)

These signatures can be used to distinguish high-energy marine deposits from terrestrially-derived floodwaters, or sediments that were deposited in low-energy (e.g., estuarine) environments (Cochran et al., 2005). Deposits are unlikely to display all of the above characteristics and the potential for mis-identification remains even for deposits that meet several of the characteristics. Other high-energy processes such as storm waves or storm surge can deposit marine sediments on land, therefore inland distance of the deposit and its elevation above maximum storm-wave height are important for distinguishing the magnitude of emplacement event. However, determining coastal elevation at the time of emplacement is difficult in active tectonic environments that undergo periodic uplift and subsidence, and inter-seismic sediment compaction. It is unlikely that complete geographic distribution of a deposit from a single event would be found because there is high potential for erosion and re-working of deposits in active coastal environments and many areas of coastline are unsuited to preservation of deposits. Palaeo-tsunami records are biased towards recording large events because the deposited sediment must be of a sufficient volume, height above sea level, and/or distance inland to be preserved.

The New Zealand palaeo-tsunami database contains 35–40 events (Goff, 2008a; Goff et al., 2010b). At present, many of the records are equivocal, of variable quality and have only been very tentatively linked to potential sources. The on-going discovery of new deposits, improved dating and refinement of the links between deposit and potential sources should enhance this record in the future. Despite the uncertainty, the more-reliable records in the database provide compelling evidence of repeated large tsunami prior to short historic and instrumental records in New Zealand. The publication of such evidence has greatly increased the recognition of the potential for large tsunami in New Zealand and in particular demonstrate the significant potential for local-source tsunami on the east coast (Cochran et al., 2005, 2006).

Dating palaeo-tsunami deposits can inform our knowledge on frequency of major tsunami. Deposits have been dated by ‘bracketing’ radiocarbon dates of organic material above and below the tsunami sediment (Goff, Chagué-Goff, and Nichol, 2001; Nichol et al., 2007) or through use of geochemical signatures and sediment accretion rates (Goff and Chagué-Goff, 1999). Some of the published date ranges are well-constrained to tens of years, while the date ranges of other events are hundreds to thousands of years, representing significant uncertainty in the age. Where possible, deposition has been correlated with geological events identified from other geomorphological evidence, cultural information such as oral records (Goff, Nichol, and Kennedy, 2009; King, Goff, and Skipper, 2007) or geo-archeological data (McFadgen and Goff, 2007). Where geographically-distributed contemporaneous deposits are have been identified, potential tsunamigenic sources have been inferred (e.g., Goff et al., 2010b,c) using known historic sources or numerically simulated events.

The oldest event in the database has been inferred to be 2.15 Ma. There are 186 deposit records from 250–1685 A.D., and 51 records dated between 1750 Years before present (BP) and 46 ka. The majority ($\sim$160) of the records pertain to an event or events dated to 1300–1600 A.D. with widespread geographic distribution and inferred sources (Goff, 2008a). The majority of these deposits are identified pebbles or sand overlaying occupation layers; dune re-mobilisation; or erosion features (Goff, 2008a). Relatively few deposits are identified as tsunami on the basis of marine diatoms or geochemical signatures. Depending on the location of the deposits, suggested sources include earthquakes in South/Central America, Tonga-Kermadec earthquakes, and multiple local faults, most notably on the Hikurangi subduction margin, Cook Strait and Puysegur subduction zone.

In the Canterbury region, there is evidence of up to seven palaeo-tsunami between 6500 BP and 1604 A.D.. In each case the source was inferred to be an earthquake known to have occurred in South/Central America around the same time (Goff and Chagué-Goff, 2012). Deposits at Cape Pattison on the Chatham Islands that pre-date the 1868 Peru tsunami have been inferred to be due to a Chilean tsunami that occurred in 1604 A.D. (Goff et al., 2010c). Several deposits are inferred to be due to a Tonga-Kermadec source, including gravel deposits dated to c. 3000 yr BP on Great Barrier Island, which suggest run-up of $>$15 m (Nichol, Lian, and Carter, 2003) and sand layers dated to 2800 yr BP and 6500 yr BP at Kaituna Bay (Goff et al., 2010b). Deposits located in Abel Tasman National Park and dated to c. 250 A.D. have been inferred to be due to the Taupo volcanic eruption (Lowe and De Lange, 2000).

The strongest evidence for local-source palaeo-tsunami occurs in Hawke's Bay, where high-energy marine deposits have identified (Chagué-Goff et al., 2002; Cochran et al., 2005, 2006). The deposits are contemporaneous with evidence of significant subsidence at c. 7100 yr BP and 5550 yr BP, inferred to be caused by earthquakes on the Hikurangi subduction margin. Additional sand deposits located in Hawke's Bay have been dated to 3200 yr BP and 6500 yr BP and are also inferred as local-source events. Other investigations in this area support the occurrence of several major subsidence events, therefore large-magnitude local earthquakes, in this region (Hayward et al., 2006; Hull, 1986, refer to Section 4.5.2). Additional evidence of four possible local palaeo-tsunami between 260 A.D. and 1670 A.D. occur on the east coast of the North Island in the form of anomalously young deposits overlaying uplifted marine terraces (Berryman, Ota, and Hull, 1989; Berryman et al., 2011; Clark et al., 2010). Several sand deposits and submerged vegetation in the Bay of Plenty have been dated to c. 2,500 yr BP (Bell et al., 2004). No deposits outside the Bay of Plenty have been dated to the same age, so these are tentatively inferred to be caused by an earthquake in the Bay of Plenty but revised dating may place them as contemporaneous with other deposits and suggest a Tonga-Kermadec origin. Further discussion of palaeo-tsunami and the Hikurangi subduction margin are presented in Section 4.5.2.

2.6 Tsunami hazard assessment

Hazard assessment and its products — primarily inundation and evacuation maps — are fundamental to tsunami hazard planning (González et al., 2005) and risk reduction. Tsunami hazard assessment requires a knowledge of potential tsunamigenic sources and simulation of resultant onshore flow parameters (Fig 2.1): wave height, run-up height, flow depth, inundation extent, flow velocity, arrival time, tsunami duration, and resonance effects. Maps of tsunami inundation are the usual product for communication of tsunami hazard, delineating an area of certain flow depth on land, the area inundated at a certain event or threshold, or a combination of both. Following definition of the hazard, risk management strategies can focus on the areas that require mitigation of the impacts.

The simplest assessment of tsunami hazard where previous events have occurred, is to map previous maximum run-up and inundation extent, and define the area known to have been affected as the hazard zone. If additional events occur with impacts at that coastline, an improved picture of likely inundation can be collated, albeit limited to the historic record. The significant flaws in this approach were highlighted in the 2011 Great East Japan tsunami. Even in Japan, with a long history of tsunami observation, inundation due to historic events provides an incomplete catalogue of possible events and their impacts. The events used to delineate the tsunami hazard zone in Tarō (1896 Meiji and 1933 Shōwa tsunami), were believed to be the largest events that could affect this region. Additionally, the 1960 Chile tsunami had been used to demonstrate maximum flow depth in Ōfunato City. However, the 2011 Great East Japan tsunami exceeded flow depth and inundated a much larger area than the hazard zones, particularly in the Sendai Plains. Many evacuation centres that had been located outside of the perceived hazard zone were inundated (Fraser et al., 2012a). The observed events had not captured the largest possible tsunami after all.

Deterministic (scenario-based) or probabilistic tsunami simulation are used to assess tsunami hazard. In both approaches, ocean displacement at the source and subsequent propagation of tsunami waves to the coastline are numerically simulated to produce onshore flow parameters. Deterministic assessments generally use one or more source scenarios as the basis for simulation. The focus may be on simulating major historic tsunamigenic events, a characteristic earthquake or the maximum credible earthquake to elucidate subsequent tsunami impacts (e.g., Baptista et al., 2003;

Roger and Hébert, 2008; Satake, Namegaya, and Yamaki, 2008; Wang and Liu, 2007). The source event may be determined from wave inversion of instrumental wave records in previous tsunami (Satake, 1987) or from geological data that describes the source characteristics (e.g., slip deficit, fault dimensions). If historic events are used as a basis for maximum credible tsunami, then the potential for under-estimation remains. This is particularly true w

Advances in computing have facilitated the increased use of Probabilistic Tsunami Hazard Assessment (PTHA) using statistical approaches such as Monte-Carlo simulation (Geist and Parsons, 2006; Power et al., 2013), logic-trees (Annaka et al., 2007; Burbidge et al., 2008) and Bayesian statistics (Grezio et al., 2009) to sample uncertain source parameters and create a catalogue of t-housands of possible source scenarios. Uncertainties are classified as epistemic (knowledge-based, can be reduced by increasing knowledge) and aleatory (natural variability, cannot be reduced). Epistemic uncertainty includes quality of bathymetry data, accuracy of computation (Geist and Parsons, 2006), and overall rate of event occurrence. The primary sources of aleatory uncertainty are natural variability in seismic slip distribution (Geist and Parsons, 2006) and tidal level at the time of tsunami arrival (Mofjeld, Foreman, and Ruffman, 1997). At present, PTHA is generally used to output wave amplitude at shore, or offshore at a certain isobath (e.g., 50 m). Based on the event frequency and amplitude, selected tsunami can then be simulated through to inundation to assess onshore impacts. Probabilistic approaches form the basis of reinsurance loss modelling because they can be effective in simulating low-frequency high-impact events, even though may not been previously experienced, or are represented by very few events in the relatively short recorded historical data. This approach allows mapping of probabilistic inundation zones – for example, delineation of zones with certain maximum wave heights that are assigned a probability of occurrence. Probabilistic analysis is therefore required to estimate hazard frequency for structural design and land-use planning, which require building codes or zoning regulation related to a certain level of hazard based on a standard probability of occurrence.

Tsunami hazard assessments have been carried out for different regions of New Zealand. Regional and distant-source hazard to Auckland, Waikato and Bay of Plenty have been studied by Bell et al. (2004), Power et al. (2013) and Lane et al. (2013). The east coast of the North Island has been studied in relation to local, regional and distant-source tsunami (Power, Downes, and Stirling, 2007; Power, Reyners, and Wallace, 2008; Power et al., 2012; Wang et al., 2009). Canterbury has been the subject of landslide studies (Walters, Goff, and Wang, 2006) in addition to local and distant-source earthquakes (Lane et al., 2012; Walters, Barnes, and Goff, 2006). Local-source tsunami impact at Wellington has been studied by Cousins et al. (2007) and Power, Reyners, and Wallace (2008). Southland has been studied in relation to local tsunami hazard (Downes et al., 2005), while hazard mapping has been conducted in several locations in Northland (Arnold, Gillibrand, and Sykes, 2011; Arnold et al., 2009; Gillibrand, Lane, and Arnold, 2008; Lane et al., 2007)

The first New Zealand national tsunami hazard review (Berryman, 2005) made probabilistic estimates of wave height and casualties at 19 key urban centres due to distant, regional and local-source hazard. The 2013 updated national review (Power, 2013) used an updated probabilistic methodology to provide hazard estimates for every 20 km section of the New Zealand coastline from local, regional and distant subduction zone and local crustal fault sources. Monte-Carlo simulation was used to account for uncertainty in source magnitude, the modelling process, and slip variability. Hazard curves provide maximum tsunami amplitude at the coast (median, 16th percentile and 84th percentile curves) at return periods up to 1 in 2,500 years. The hazard at each section was de-aggregated to determine the contribution of sources to the hazard curve.

The 2013 review suggests that there is a 1.0% Annual Exceedance Probability (AEP) (1 in 100 yr average recurrence interval) of 4–6 m amplitude on much of the east coast of the North Island, Banks Peninsula, Northland and Chatham Islands. There are localised areas which have a 1.0% AEP of 6–8 m amplitude. The west coast of the North Island and most of the South Island has 1.0% AEP of tsunami with maximum amplitude of 0–4 m. At the 1 in 500 yr average recurrence interval (0.2% AEP), maximum amplitude is 6–10 m on the east coast of the North Island, Banks Peninsula, Northland and Chatham Islands. At the 84th percentile of 1 in 500 yr average recurrence interval, an increased number of coastal sections show maximum amplitude of 10–12 m and Great Barrier Island, Chatham Island and parts of Northland show maximum amplitude >12 m. There is 0.2% AEP of 2–6 m amplitude on the west coast, and 6–12 m in Fiordland. At the 1 in 2,500 yr average recurrence interval (0.04% AEP), maximum amplitude is >10 m for Northland, the east coast of the North Island, Fiordland and Chatham Islands. Elsewhere, maximum amplitude is in the range 4–12 m. Earthquakes in Peru or northern and central Chile, and on the Hikurangi subduction margin are the primary source for the 1 in 500 and 1 in 2,500 yr average recurrence interval hazard on the east coast. The primary hazard contribution for Wellington and the west coast of North Island are the Hikurangi subduction margin and Wairarapa Fault.

2.7 Summary and link to next chapter

This chapter has given an overview of tsunami processes and impacts, and summarised previous tsunami that have affected New Zealand in recorded history and earlier. Whilst there has been relatively little damage and very few casualties due to tsunami in New Zealand, run-up of several metres has been recorded and recent hazard assessments demonstrate the potential for wave heights much higher than those experienced in recent history. The short return periods at which damaging wave heights can occur, as demonstrated by the recent national hazard review (Power, 2013), puts tsunami risk reduction high on the agenda for coastal communities. The next chapter discusses tsunami risk reduction activities internationally and in New Zealand, providing context to the subsequent focus on vertical evacuation.

3. TSUNAMI RISK REDUCTION AND PREPAREDNESS

The previous chapter presented the processes and impacts of tsunami, and established the need for tsunami risk reduction in New Zealand. This chapter reviews international literature on tsunami risk reduction strategies and the current approach to risk reduction in New Zealand. While the focus of this thesis is vertical evacuation, the wider body of risk reduction tools and strategies are reviewed because, in order to be effective, vertical evacuation must co-exist with and complement these other tools within an holistic risk reduction framework. Two examples of holistic risk reduction frameworks are given by Johnston et al. (2014, Fig 1.4) and the United States (US) National Tsunami Hazard Mitigation Program (NTHMP) 2001 (Textbox 3.1). These frameworks are common in their consideration of risk assessment, land-use planning, appropriate construction, warning, education, and evacuation planning. However, the NTHMP framework places most emphasis on land-use planning and structural mitigation of risk, with five of the *Seven Principles for Planning and Designing for Tsunami Hazards* focussed on coastal development issues. In contrast, Johnston et al. (2014) explicitly states early warning systems, education and participation, and exercises as distinct components of the framework. These components are included under the seventh principle 'Plan for evacuation' (NTHMP, 2001). The following sections review the application of land-use planning and structural mitigation for tsunami risk reduction, before outlining the key concepts of warning, preparedness, education, and evacuation.

3.1 Land-use planning

Land-use planning is a policy-based approach to sustainable development of land for human use. Plans must address conflicting development interests, such as: consumption versus preservation of natural resources; balanced benefit of property development for private and public use; and economic development versus preservation of the environmental benefits of an area (Campbell, 1996; Godschalk, 2004). Barriers to effective land-use planning include conflict between different levels of legislation, prioritisation of issues perceived to be more immediately pertinent than land-use, and collaboration / coordination between stakeholders and authorities (Glavovic, Saunders, and Becker, 2010). The high economic and amenity value placed on coastal land for private and public development (Eisner, 2005), can give rise to the planning conflicts described above, and are now occurring during the reconstruction process in Tōhoku, Japan (EEFIT, 2013; Shibayama et al., 2013). Disaster losses have been increasing for many years, largely due to increases in wealth and population growth, but also because of encroachment in hazard-prone areas (Changnon et al., 2000). This is true of many hazards, for example development of floodplains was recognised many years ago as an issue for flood hazard management (White, 1937). As a result, land-use planning is now considered an essential tool in sustainable hazard management (Mileti, 1999).

Textbox 3.1 (Principles for Planning & Designing for Tsunami Hazards) *NTHMP Principles for Planning and Designing for Tsunami Hazards*

- *Know your community's tsunami risk: hazard, vulnerability, and exposure*
- *Avoid new development in tsunami run-up areas to minimize future tsunami losses*
- *Locate and configure new development that occurs in tsunami run-up areas to minimize future tsunami losses*
- *Design and construct new buildings to minimize tsunami damage*
- *Protect existing development from tsunami losses through redevelopment, retrofit, and land reuse plans and projects*
- *Take special precautions in locating and designing infrastructure and critical facilities to minimize tsunami damage*
- *Plan for evacuation*

NTHMP (2001)

In the natural hazards and Disaster Risk Reduction (DRR) context, land-use planning can help foster development without creating or exacerbating risk beyond an acceptable level. The rationale for land-use planning in terms of hazard management is that avoidance of the hazard is better (and can incur lower costs) than mitigation of the effects through engineered solutions or 'softer' means (Bolton et al., 1986). The four principles of land-use planning are defined by Hopkins and Saunders (2008) as: accurate information gathering; avoidance of natural hazards prior to development; applying a risk-based approach to natural hazards in areas at risk and already developed; and communication of natural hazards risk in areas at risk and already developed. Methods of implementing planning controls to avoid or mitigate the effect of hazards are various and can be regulatory or non-regulatory (Saunders, Prasetya, and Leonard, 2011), should be collaborative between authorities of different levels (i.e., national, regional, local) and geographic extent (i.e., neighbouring councils), and should consider inter-related hazards. Land-use planning tools include zoning ordinances and development regulations to influence the density, pattern and occupancy usage of new developments, with the aim to keep the risk below a defined acceptable level (Eisner, 2005). For example, the zones of highest risk might be designated as open space, or low-occupancy building functions to minimise the number of people who are placed at highest risk. High density residential developments would be restricted to low-risk zones.

The literature discussing land-use planning for tsunami is, to date, relatively sparse with many discussions of tsunami risk reduction mention land-use planning as a required tool, but not elaborating on how land-use planning can be implemented for tsunami. Tang et al. (2008) found that few counties on the US Pacific coast had adequately incorporated tsunami risk into hazard management planning, of which land-use is an important component. The Mitigation and Education Subcommittee of the NTHMP is tasked with promoting 'the integration of the tsunami hazard and risk into building codes and land use policy and planning efforts' (NTHMP, 2013). Glavovic, Saunders, and Becker (2010) highlighted that the emphasis of New Zealand emergency management has traditionally been on readiness and response and that as a result, hazards (especially tsunami) are poorly incorporated into land-use planning in New Zealand. Another possible reason that land-use planning and regulatory tools have traditionally had limited use in tsunami risk mitigation in New Zealand is the high level of public desire to develop the coastal environment (Garside et al., 2009). Saunders, Prasetya, and Leonard (2011) addressed this deficiency by proposing a risk-based method to incorporate tsunami risk into land-use planning. Many areas of tsunami-prone coastlines have already been developed, so a large part of tsunami land-use planning focusses on reducing risk or not exacerbating the risk, rather than outright risk avoidance. One of the primary challenges of land-use planning for tsunami risk reduction are that uncertainties in source parameters and simulation of the earthquake and tsunami propagate through to any mapped hazard zone. In order to provide a hazard zone suitable for use in land-use planning, Saunders, Prasetya, and Leonard (2011) demonstrated a map comprising three zones, representing zones of certain, uncertain, and no tsunami hazard. Alternatively, maps derived from Probabilistic Tsunami Hazard Assessment (PTHA) can be presented to show inundation extent for different event probabilities.

Councils in New Zealand are required to consider tsunami in their land-use planning, due to the inclusion of tsunami in the New Zealand Coastal Policy Statement (NZCPS), under the Resource Management Act (RMA) (New Zealand Government, 2010). NZCPS Policy 24 requires the identification of '*areas in the coastal environment that are potentially affected by coastal hazards (including tsunami), giving priority to the identification of areas at high risk of being affected*', including '*the potential for inundation of the coastal environment, taking into account potential sources, inundation pathways and overland extent*'. With regard to identified hazard areas, NZCPS Policy 25 requires that any redevelopment or land-use changes that increase the '*risk of social, environmental and economic harm*' from coastal hazards should be avoided and, furthermore, that such actions that reduce risk or potential harm should be encouraged. Methods cited include '*managed retreat by relocation or removal of existing structures*', '*designing for relocatability or recoverability from hazard events*', encouraging '*the location of infrastructure away from areas of hazard risk*', discouraging engineered defences with a preference for natural defences, and considering '*the potential effects of tsunami and how to avoid or mitigate them*'. The methods cited by NZCPS are echoed in the NTHMP planning principles (Text Box 3.1). Tsunami evacuation planning has featured in the proposed development of coastal areas in the Bay of Plenty (Beban et al., 2012), but earlier development strategies on the east coast (Hastings District Council, 2010) failed to consider tsunami evacuation, as did proposed land-use regulation changes to allow greater residential use of what is currently an industrial-use zone in Petone, Lower Hutt (Hutt City Council, 2013).

Specific planning strategies for avoiding new development are given by NTHMP as:

- Designate/acquire tsunami hazard areas for open-space uses
- Restrict development through land-use regulation
- Use infrastructure planning to support land-use planning, by encouraging/discouraging development in certain areas
- Adapt other plans/regulations for tsunami use where they have concurrent aims

In areas that have been developed already, site-planning strategies can be applied to new developments. These include: avoiding inundation areas, slowing water current by increasing friction in the development parcel, steering tsunami flow away from buildings, and blocking tsunami flow (NTHMP, 2001). Site planning regulation then becomes closely related to structural design to achieve tsunami resistance, in terms of open storeys and achieving sufficient height and structural strength. These methods are now being enacted in the reconstruction of coastal urban areas in Tōhoku, Japan, where planners are advocating the relocation of all residential housing to higher ground and allowing only industrial facilities close to the coastline, behind seawalls (Government of Japan Reconstruction Agency, 2013). Between the industrial zone and residential zone, there are plans to use coastal forests, open-space and infrastructure (road, rail) on raised berms to help slow or block inundation (e.g., Toyoshima et al., 2012). Critical infrastructure and schools would be located further inland. In some areas of the Sendai Plains, large areas of ground are being artificially raised by 5 m (EEFIT, 2013). In terms of site-planning, public housing structures are to be at least 5–6 storeys in height, with no dwelling space on the ground floor and be designated as Tsunami Vertical Evacuation Buildings (TVEB) (EEFIT, 2013). Post-event decision-making such as this can benefit from pre-event land-use planning (Becker et al., 2008), which aims to plan and agree potential post-disaster land-use changes to enable improvements in community resilience through appropriate repair, relocation or reconstruction. In post-disaster situations, Glavovic, Saunders, and Becker (2010) highlighted insurance incentives as a means to influence land-use during re-development.

With regard to vertical evacuation, land-use planning legislation could be used to oblige developers to design and construct refuges and designate TVEB in areas of high tsunami hazard (Leonard et al., 2011). Application of such an approach would be consistent with the site-planning guidance of the NTHMP. There is a legal precedent in New Zealand that ‘applicants seeking resource consents for the establishment and operation of public facilities in areas susceptible to natural hazards should not overlook evacuation planning in their application.’ (Garside et al., 2009). This was the Environment Court ruling on an application to develop a Marine Education Centre on the foreshore at Lyall Bay, Wellington. In this particular case, the tsunami hazard was not deemed sufficient to directly decline the application to develop a public facility, but in failing to consider appropriate evacuation measures, i.e., plan for access to nearby available high ground above the maximum elevation at risk from tsunami, the applicants had not reduced the tsunami risk to an acceptable level. Evacuation is therefore deemed to be a ‘necessary consideration for public safety’ (Garside et al., 2009) in addition to being a statutory obligation of the New Zealand Health and Safety in Employment Act 1992 (section 6(e)).

3.2 Structural mitigation

3.2.1 Coastal defences

Structural (engineered) defences are commonly constructed for storm waves as part of coastal management strategies, but are rarely built specifically for tsunami defence. Japan is the only place in the world to have constructed defences designed to resist tsunami, and the first test of these under extreme wave conditions was in the 2011 Great East Japan tsunami. Depending on location, tsunami defences in Japan had been constructed to resist a design wave height equal to that experienced in the 1896 Meiji or 1933 Showa Sanriku tsunami (Suppasri et al., 2013b). The 2011 tsunami was significantly larger in many areas, thus the tsunami defences were overtopped and severely damaged or destroyed. Tsunami breakwaters at Kamaishi City and Ōfunato City (Fig 3.1), were subject to scour and significant hydrostatic pressure which caused separation of their individual concrete blocks and collapse of the breakwater (Kazama, 2011; Port and Airport Research Institute, 2011). The Kamaishi breakwater was somewhat effective before its collapse, reducing run-up from >20 m to 10 m, and provided an additional 6 min for evacuation before inundation of the city (Takahashi et al., 2011). Video footage from Ryoishi (Bombaadi, 2011) also displays a delay in inundation while the tsunami flow builds up on the seaward side of a substantial wall; the wall was eventually overtopped and the town destroyed (EEFIT, 2011). Most sea walls on the coast of the Tōhoku region were designed for storm waves, and 190 km (>60%) of these were damaged or destroyed in the tsunami. The 10 m-high sea walls at Tarō Town were designed against the height of the 1933 Shōwa Sanriku tsunami, and originally had a convex shape in the seaward-facing direction, to deflect tsunami around the town. Subsequent development in front of the walls led to construction of two new walls, forming an ‘X’-shape in plan, and a concave seaward wall (Fraser et al., 2012a). The concave shape led to focussing of the tsunami wave at the centre of the wall, which was overtopped and scoured, leading to the movement of poorly connected, poorly anchored concrete blocks (EEFIT, 2011; Suppasri et al., 2013b). Concrete-armoured revetments

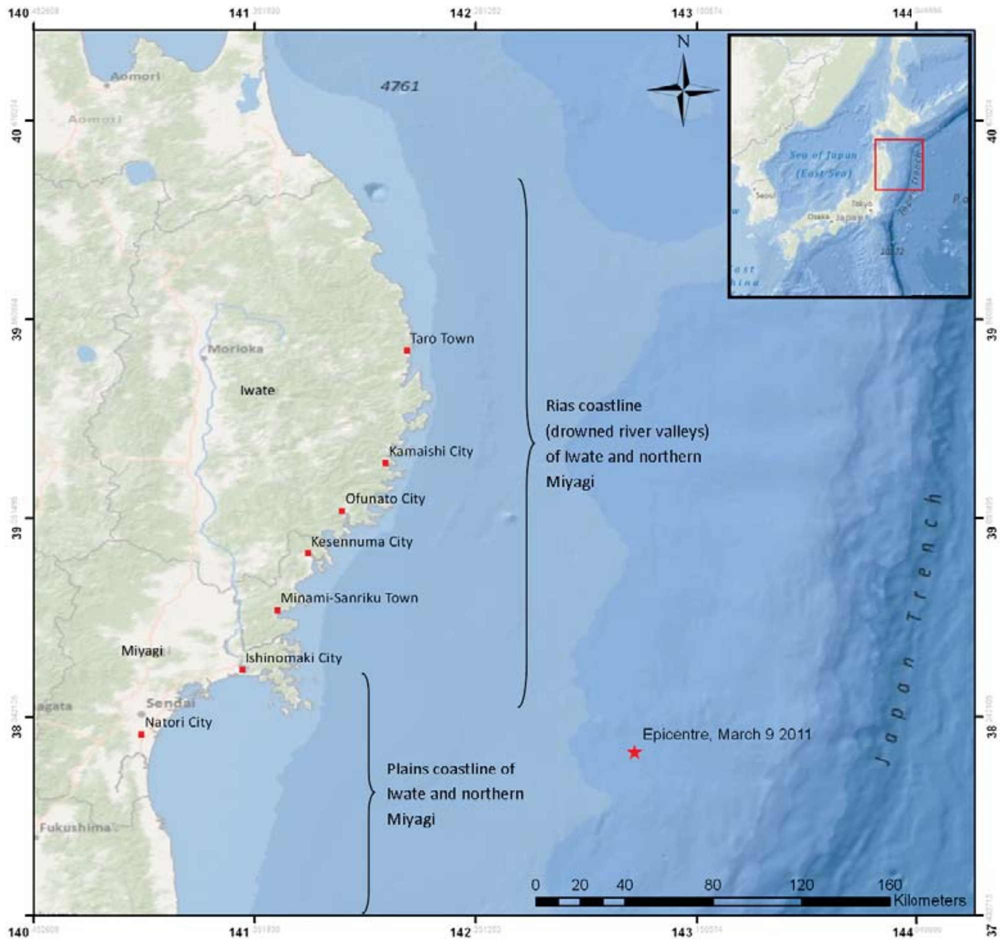


Fig. 3.1: Map of locations at which field investigation was conducted. The ria and plains coastal environments are also highlighted.

with sand infill along the beaches of the Sendai Plains were also overtopped, leading to severe scour and out-washing of infill on the lee-side of the defence (EEFIT, 2011).

Due to the failure of the substantial tsunami defences, Japanese coastal engineers' faith in structural defences to protect developed areas in all tsunami has been re-assessed (Shibayama et al., 2013). The view now is that defences are considered effective for lower magnitude, higher frequency events, but that evacuation is vital in the case of the less frequent extreme events. It has been proposed to have structural defences for protection of property in 'Level 1' tsunami, which are up to 10 m wave height, and soft (non-engineered) measures for life safety, in 'Level 2' events – those above 10 m wave height (Shibayama et al., 2013). In both cases, residents would be expected to evacuate to evacuation areas, in case of defence failure.

Engineered coastal defences can reduce access to the coast for livelihoods and recreation, and decrease the aesthetic appeal of a coastline. Shibayama et al. (2013, p.370) postulates that in Japan, 'aesthetic considerations are probably secondary to the preservation of not only their lives and livelihoods, but also their way of life'. This viewpoint is contradicted by anecdotal evidence that there is opposition of some coastal communities to the (re)placement of defences in response to the Great East Japan tsunami. While substantial defences may also have delayed inundation and reduced run-up in areas other than Kamaishi City and Ryoishi, these protective defences (importantly, in combination with warnings that underestimated expected tsunami height) provided a false sense of security and delayed evacuation (Ando et al., 2012; Fraser et al., 2012a; Yun and Hamada, 2012). They also prevented early visual cues or visual confirmation of tsunami arrival because the walls often blocked views out to sea; in fact, some witnesses believed that the spray hitting the seaward side of the wall was fire, not tsunami waves (Fraser et al., 2012a).

3.2.2 Tsunami loading and structural guidelines

Tsunami loading has been the subject of numerical and physical investigation in recent years (e.g., Lloyd and Rossetto, 2010; Lukkunaprasit et al., 2008; Palermo and Nistor, 2008; Palermo et al., 2009; Yeh, 2007). The wealth of structural damage data collected from the 2011 Great East Japan tsunami are being used by the American Society of Civil Engineers (ASCE) 7 Tsunami Loads and Effects Subcommittee to generate new tsunami loading guidelines for structures, which would be implemented in the International Building Code (IBC) post-2020 (Chock, 2012). In the proposed ASCE 7 code, TVEB would be required to provide immediate occupancy for the maximum credible tsunami (1 in 2,500 y). Other buildings would be assigned a performance requirement based on their risk category and height (Chock, 2012).

A review of the Japanese guidelines (Okada et al., 2005) is also underway, with a proposed reduction in tsunami loading factors. For example, the horizontal tsunami force calculated in Cabinet Office Government of Japan (2005) was derived using a co-efficient of 3.0 * water depth, based on earlier physical modelling. Analysis of structural damage compared to flow depth in Tōhoku showed that this is very conservative, and that the co-efficient could be closer to 1.0 (Nishiyama et al., 2011). As a conservative procedure, in temporary guidelines, the coefficient was relaxed to 2.0 for buildings that are sheltered by other buildings, and 1.5 for buildings $>$500 m inland. Further relaxation of the Japanese guidelines is expected when accurate methodologies for estimating other tsunami loads have been established (Nishiyama et al., 2011). There is a movement in the Japanese coastal management community away from reliance on structural mitigation measures in favour of combined approach with non-structural measures for life safety (Section 3.2.1). Shibayama et al. (2013) proposed a three-tier classification of evacuation structures (Table 3.1).

Presently, two non-mandatory international structural guidelines for TVEB exist. Federal Emergency Management Agency (FEMA) P646 presents the most complete set of guidance in terms of formulation of forces, and the companion report P646A (FEMA, 2009) presents guidance for community officials on building planning, design and construction capacity, maintenance, operation, and funding. FEMA (2008) prescribes methods for calculating multiple tsunami loads (Table

3.2) but all loading calculations are based on those included in previous design codes that were developed for storm surge and riverine flooding (American Society of Civil Engineers, 2006a,b; City and County of Honolulu, 2000; FEMA, 2005; International Code Council, 2006). As the best available information, these were used in the development of FEMA (2008) but the guidelines recognise that tsunami flow characteristics include extreme amplitude fluctuations, flow velocity and mass of flow than riverine flow. Additionally, tsunami loads are likely to sustain high velocities and flow depth over longer timescales than riverine or storm surge flood waters, due to their long wavelength. Loading time histories are not considered in the guidelines, which base design guidance on maximum loads rather than the entire flow time history. Therefore, progressive weakening may be inadequately accounted for. Although potential combinations of loads are recommended in the guideline, as is the consideration of the impact of earthquake and subsequent tsunami loading in a local-source, these are not adequately addressed without reproduction of the full loading time-history accounting for multiple cycles of flow and loading (Park et al., 2012b).

The FEMA (2008) loading guidelines rely on derivation of maximum momentum flux (flow depth * velocity) at a site, which can be derived from numerical models. Numerical simulation requires topography data of sufficiently high vertical and horizontal resolution, and resolution of complex velocity structures onshore, which generally requires simulation to be conducted using a high-order non-linear model Boussinesq model (Section 4.1). With regards to vertical evacuation, safe elevation must be defined. Due to uncertainties in numerical modelling, a factor of safety (1.3 * maximum run-up at the site + 3 m splash-up) is used, but FEMA (2008) also states that this should never be taken as less than 80% of the values generated using the provided analytical approximations for maximum momentum flux and maximum flow velocity.

The Japanese government guidelines for designation of building for vertical evacuation are that they meet adequate construction standards and minimum heights (Cabinet Office Government of Japan, 2005). The proposed *Structural Design Method of Buildings for Tsunami Resistance* (Okada et al., 2005) requires buildings to be designed for seismic resistance according to the standard building code. Subsequently, tsunami loads are estimated and pressure-exposed surfaces and structural frame are designed accordingly for hydrostatic, hydrodynamic and buoyancy forces based on maximum flow depth at the site (Okada et al., 2005). Overturning and sliding failure are also cited in the guidelines as a required analysis. The seismic safety requirement of TVEB in Japan was achieved by designating buildings constructed to post-1981 seismic standards (Textbox 3.2).

Based on tsunami load analyses, design guidelines and damage observations, several design concepts have been proposed for tsunami-resistant buildings. The principles defined by FEMA (2008) are: strong systems with reserve capacity to resist extreme forces; open systems that allow water to pass through with minimal resistance; ductile systems that resist extreme forces without failure; and redundant systems that can experience partial failure without progressive collapse. These include Reinforced Concrete (RC)/steel moment frame and RC shear wall systems. Particular concepts outlined in FEMA (2008) are: the use of round columns to reduce hydrodynamic force

Tab. 3.1: Proposed classification of evacuation areas (Shibayama et al., 2013).

Category	Description
A	Hills (higher terrain) that are adjacent to the coast but continue to increase in elevation for a long distance. Not be isolated low hills, include those that form part of larger geographical features and have a large hinterland region.
B	Robust buildings that have ≥7 storeys, or small hills that are more than 20 m in height. Such buildings would generally ensure the safety of anybody taking shelter in them and could be considered 'critical lifeline' structures. This category would have the inherent risk of being isolated during the worst tsunami, but would likely be safe for most events. All new Evacuation Buildings should be at least Category B.
C	Robust buildings that are >4 storeys high. This category, however, would have the risk of being overtopped during the worst tsunami events, as described earlier. The use of such a category is not recommended, but in areas where Category B or A do not exist they could be used while better evacuation points are not available. No new Evacuation Buildings should be built in this category.

compared to square columns; fixing of columns to every storey; orienting shear walls parallel to flow to minimise hydrostatic loads; designing floor systems for upward forces (uplift, buoyancy), as well as downward forces (gravity loads); piles that are designed to withstand scour of foundation around the pile cap; and use of breakaway non-structural walls, designed to fail under loading, thus reducing hydrostatic loading on the building.

Textbox 3.2 (Key criteria for TVEB in Japan) *The key criteria from the 2005 guideline for official designation of buildings as tsunami evacuation buildings (Cabinet Office Government of Japan, 2005):*

- *Are of a minimum height according to estimated maximum inundation depth*

  <1 m depth = 2-storeys or higher required

  2 m depth = 3-storeys or higher required

  3 m depth = 4-storeys or higher required

- *Are RC or steel reinforced concrete composite Steel Reinforced Concrete (SRC) construction*
- *Were constructed after 1981 (the latest significant update of building codes in Japan)*

Tab. 3.2: Description of tsunami loads considered by FEMA (2008).

Load	Description
Hydrostatic	Acts on a wall when the water surface is different levels on either side. This force will likely be reduced when the ground floor contains door and window openings that reduce unequal water level inside and outside the building.
Buoyant forces	The vertical (upward) equivalent of hydrostatic forces, acting on a water tight structure.
Hydrodynamic (drag) forces	Lateral force acting on structural components and the whole structure, comprising friction forces and pressure forces from the mass of water flowing through and around the building.
Impulsive forces	Caused by the leading edge of the water surge (i.e., before drag forces begin to act). Calculated by FEMA (2008) as a factor of the drag forces.
Debris impact forces	Vital in the assessment of critical infrastructure, and have been shown to be important in influencing the level of damage sustained by any structure in previous events. FEMA (2008) presents several formulations, indicating the current levels of uncertainty around debris forces.
Debris damming forces	Caused by the accumulation of waterborne debris, which can enhance the hydrodynamic force by effectively widening the wall surface.
Uplift forces	Vertical upward force acting on a floor level which is below the water level but where the building exterior displaces water above that floor level. It is a combinations of vertical hydrodynamic forces and some buoyant forces.
Additional gravity loads	Apply when tsunami water is retained in a building during and after drawdown, and is dependant on inundation exceeding the elevation of each floor.
Combination of loads	Several combinations of loads provided for the whole structure and individual components. Multiple combinations are provided as not all loads will act at the same time on the same part of the building.

The New Zealand Building Code, under the Building Act (New Zealand Government, 2004), requires that all loads likely to be experienced within a building's lifetime are taken into account in the design and construction of that building. However, there are currently no New Zealand structural design standards that account for tsunami loads. The Building Code is a performance-based code, which prescribes the required performance of buildings under static loads and imposed loads (wind, snow and ice, and earthquake) at different return period events, for their design lifetime, usually 50 years (King and Shelton, 2004). Buildings are classified as having one of five Importance Levels (IL), based on their function and occupancy; this determines the required performance for that building. At present, the international tsunami loading guidelines discussed above represent the best options for incorporation of tsunami loads into the Building Code (Leonard et al., 2011). A TVEB would have to be appropriately designed for tsunami loads so that it could maintain its critical life-safety function and post-disaster function in the case of the maximum credible tsunami (the 1 in 2,500 y return period event). As a structure with post-disaster function, TVEBs could be classed as IL 4. Currently, buildings of IL 4 would be not be required to maintain structural integrity following a 1 in 2,500 y earthquake, meaning that support and stability for significant parts and functional continuity may be extensively affected (Uma, 2012). This is clearly insufficient for buildings in which immediate occupancy is required. Therefore, TVEB would likely have to be classified as IL 5, which are beyond the scope of the building code and are required to be designed by special study (King and Shelton, 2004). Additionally, where TVEB were intended for local-source tsunami, they would be required to withstand the maximum credible earthquake and retain sufficient capacity to resist failure in subsequent tsunami loading. Leonard et al. (2011) recommended that a protocol be developed for design of new buildings and assessment of existing buildings for use as TVEB, and amendments be made to the Building Act to account for design against tsunami loadings.

3.3 Tsunami warnings

Hazard warnings may be classified as *official*, *informal* or *natural*. All three types play important and inter-linked roles in ensuring a warning reaches as large a proportion of the exposed population as possible. Official warnings are those that are disseminated through official, authoritative channels, typically through an organised, coordinated technological warning system with prescribed protocols in place before an event; these are important for distant-source tsunami where no natural warning is available and there is time to detect a tsunami, proceed through the decision-making process and disseminate the warning. Informal warnings are those passed on through unofficial channels, including word of mouth, short message service (SMS), email and social media by anyone who is not in a position of authority to do so. Natural warnings are environmental cues or natural phenomena that can be recognised as precursory events to the main event; they are most important for near-field tsunami, when there is little time to activate official warning procedures before wave arrival (Darienzo et al., 2005). There is no linearity to warning dissemination across the three types, particularly with the ever-increasing sophistication of modern communications and media. The hazard dynamics, social context and circumstances of the event determine how these warning types operate together, the extent to which informal warnings play a role, and the media used in those informal warnings.

3.3.1 Official warnings

Official tsunami warnings alert exposed populations who are too distant from the tsunami source to feel ground shaking. Such warnings provide official confirmation of received informal warnings or observed natural warnings. They are generated through a technological (hardware-based) hazard warning system, defined as '*a network of interrelated sensors and processes that detect signals of a possible or imminent dangerous event and provide information* [via public notification systems] *that people can use to make protective action decisions before the moment of impact.*' (Leonard, Johnston, and Gregg, 2013). Tsunami technological warning systems rely on seismometer networks to assess earthquake location, magnitude, depth and focal mechanism. The tsunamigenic potential of the earthquake is assessed by comparing the event parameters against pre-determined criteria or thresholds to determine the appropriate level of warning, if any, to be issued. This is often done rapidly with uncertain earthquake parameters, and revised when more data becomes available to improve accuracy of the assessment. In addition to the seismometer network, networks of ocean buoys such as the National Oceanic and Atmospheric Administration (NOAA) Deep-Ocean Assessment and Reporting of Tsunamis (DART) system (González et al., 2005) are used to provide water pressure and sea-surface time-series data, which can confirm whether a tsunami was generated or not. Sea-surface time-series data from such buoys facilitate wave inversion (Satake, 1987) to determine the characteristics of the source earthquake and provide site-specific inundation forecasts (Gica et al., 2008). Coastal sea-level gauges local to the earthquake source are also used to confirm the occurrence or absence of a tsunami, providing additional warning information for more distant coastlines.

The initial detection, data validation and decision-making phases of the official warning process have time-costs associated with them. Wei et al. (2008) gives an example timeline for Pacific Tsunami Warning Center (PTWC)/NOAA tsunami forecasts: an information bulletin was given 12 min after the earthquake, based on preliminary magnitude estimates. Thirty-eight min after the earthquake, the magnitude was revised and warnings/watches issued. Tsunami energy forecasts, with maps of maximum forecast amplitude became available 46 min after the earthquake. Verification of an event is necessary to minimise false alarms and maximise accuracy of subsequent warning messages. Japanese Meteorological Agency (JMA) uses a network of seismometers and Global Positioning System (GPS) sensors spread across the Japan Trench to rapidly collect more information on earthquakes that occur there. JMA can produce tsunami warnings only 3 min after an earthquake using their established earthquake early warning system with similar pre-computed tsunami scenarios to estimate wave heights and provide a warning based on tsunami height thresholds (Japan Meteorological Agency, 2006).

JMA issue a 'tsunami advisory' when expecting tsunami height up to 1 m, 'tsunami warning' when expected height is 1–3 m, and 'major tsunami warning' when height is >3 m (Japan Meteorological Agency, 2013). These thresholds were revised in 2011, following the Great East Japan tsunami. The previous threshold were 0.5 m, up to 2 m, and >3 m, respectively. In the 'major' category additional quantification of tsunami of heights may still be given (5 m, 10 m and >10 m). However, issuing height thresholds to the public is problematic. In the 2011 Great East Japan tsunami, inaccurate tsunami wave heights were provided to the public via sirens. These were gradually upgraded in three stages, by which time the tsunami was arriving at shore. Despite the changes in thresholds the aim of the warning systems remains the same, and still has the potential to under-estimate tsunami heights and provide incorrect information to the public.

Ministry of Civil Defence and Emergency Management (MCDEM) aims to assess the tsunami threat to New Zealand and if appropriate disseminate a national tsunami advisory or warning within 15–30 minutes following receipt of a Pacific Tsunami Warning Center information bulletin, watch or warning, or a GNS Science earthquake report (MCDEM, 2010a). With advice from GNS Science and a Tsunami Expert Panel (TEP) (comprising New Zealand experts from various agencies), response indicators based on earthquake parameters are used to make a decision on what action should be taken. This could be: i) no action, ii) an advisory or warning issued through the National Warning System (NWS), and / or iii) a request for media outlets to broadcast of the advisory or warning. Following an advisory or warning being issued, further threat assessment is conducted to provide information on expected arrival times and wave heights. Tsunami source modelling is carried out by GNS Science and TEP members to provide the earliest possible time of arrival of the leading wave at 22 pre-designated coastal points. Expected wave amplitude at shore is given for 43 pre-designated coastal zones. Wave amplitude is assigned to a level of threat: 'No threat', 'Threat to beach, harbours, estuaries and small boats', 'Minor land threat', 'Moderate land threat', 'High land threat', 'Severe land threat'. These are communicated by map or table format according to the warnings categories (Advisory or Warning informing of no threat or a potential threat, and cancellation messages) set out by MCDEM (2010a).

Tsunami travel time to New Zealand from Chile or Japan is c. 12–15 h and c. 15 h from Alaska. However, in local-source tsunami there is insufficient time to detect and assess the tsunami threat then disseminate the warning to the public. There is currently uncertainty around the performance of the tsunami warning system in regional events that have arrival times of 1–3 h. The MCDEM response to the 2009 South Pacific tsunami showed that the national tsunami warning was put into effect 47 min after the earthquake, so there should be sufficient time to issue a warning, but depending on the source location, there could be little subsequent time for widespread dissemination and evacuation. This issue presents the potential for a 'tsunami warning blindspot', in that there is insufficient time to effectively disseminate a warning and trigger an evacuation, but the possibility exists that there will be no strong ground shaking at the coast to provide natural warnings.

Dissemination of official warnings requires the use of multiple communication channels to ensure system redundancy, and to reach as many locations and sections of the population as possible. Notification technologies include dedicated systems such as alert radios and sirens, and third party systems such as television and radio broadcasts, SMS messages, email, websites, social media, power line and telephone messaging (Leonard, Johnston, and Gregg, 2013). Due to the many channels through which messages can now be disseminated (Textbox 3.3; MCDEM, 2009b), informal warnings are often distributed through a population simultaneously or prior to official warnings (Gregg et al., 2007). The key features of an effective warning message are that they: are from an authoritative source; are specific and certain regarding the event, location and timing; give clear, accurate instructions; are consistent across messages and notification channels; provide a time-frame for subsequent messages; and are provided frequently (Lindell and Perry, 1992; Mileti et al., 2004; Sorensen, 2000).

Tsunami warnings for New Zealand are issued by MCDEM and disseminated through the NWS. On receipt of notifications via the NWS, local Civil Defence Emergency Management (C-DEM) groups are responsible for local threat assessment and local public alerting, in accordance with their response systems. Media are responsible for broadcasting official advisories and warnings if requested through a MCDEM ‘Request for the broadcast of an emergency announcement’. Official warning dissemination may be carried out using mechanisms that are reliant on third party hardware or staff, and mechanisms that require dedicated hardware but are controlled by warning centre staff (MCDEM, 2009b, Textbox 3.3). Additional options that are not yet available in New Zealand are: Break-in broadcasting; GPS receivers; Mobile-device Broadcasting. Tone-activated alert radio is currently used in the US (NOAA Weather Radio) and in Japan in limited areas (Fraser et al., 2012a). All of these alerting options have different monetary costs, effective time-frame, suitability regarding local terrain, population density and target population, and vulnerabilities to the hazard event. Multiple alerting systems are required to maximise population coverage and redundancy.

Textbox 3.3 (Tsunami warning public alerting options) *Mechanisms reliant on third party hardware or staff:*
Aircraft banners, loudspeakers or sirens; billboards; call-in telephone line; e-mail; marine Radio; mobile PA announcements – NZ Police or Fire Service; pagers; power mains messaging; radio and TV broadcasts; route alert (door-to-door); Short Message Service – Point to Point; landline telephone auto-dialling; telephone trees; tourist advisory radio; websites and website banners.

Mechanisms that require dedicated hardware but are controlled by warning centre staff:
Fixed or mobile PA loudspeakers; Flares, explosives; Radio data systems; and Radio (UHF, VHF and HF); Sirens (tone, no voice capability); and Tone-activated alert radio (not currently available in New Zealand). MCDEM (2009b)

Of all the options in Textbox 3.3, the most high-profile mechanism is sirens. Tsunami sirens are now present in many coastal communities across the World. Most major urban centres in New Zealand have some form of siren coverage, but in some locations these act as warning for any hazard. Previous surveys (Currie et al., 2014; Fraser, Johnston, and Leonard, 2013; Johnston et al., 2003; Pishief, 2007, GNS unpublished data)[1] and media coverage (Worthy, 2013) report public expectation of and preference for sirens as a tsunami warning in New Zealand.

Sirens are a valuable tool for distant-source tsunami, which allow time for source-event detection, confirmation of tsunami generation, for warning messages to be formulated and sirens to be activated. They are less effective in local-source events due to time constrains, and may hinder evacuation with catastrophic consequences if the public waits for sirens to sound as a signal to evacuate. In Wellington, almost 90% of respondents believed that a tsunami would follow a siren warning in <1 h (Currie et al., 2014). This suggests low levels of understanding about the types of tsunami for which sirens can be effective, and a misplaced reliance on sirens for warning in local-source tsunami.

Siren technology does not guarantee audibility when they are sounded, particularly for people indoors and in poor weather conditions such as high wind or heavy rain. This is a point of concern among the Wellington public respondents (Currie et al., 2014), but many members of the public still request sirens. Several recent tests of new siren systems have seen mixed success in terms of operational capability and response from residents in terms of audibility (e.g., Fuatai, 2012; Staff Reporter, 2012; Twentyman, 2012). There is also a lack of clarity among the public about the meaning of siren tones, which can be attributed in part to the variety of tones and meanings in use in different locations (MCDEM, 2013). Data about warnings of past distant-source tsunami raise

[1] These unpublished data refers to survey data which, at the time of writing is under analysis. These data will be published as a GNS Science report in due course. The data can be obtained from g.leonard@gns.cri.nz or d.johnston@gns.cri.nz. Unless otherwise indicated by a footnote, further references to unpublished data in this chapter refer to the same data.

questions about the efficacy of sirens compared to the other available mechanisms. Following the 2010 Maule, Chile tsunami surveys indicated that very few (0.4%) of people first learned of the tsunami via sirens. Most people receiving the warning via telephone call (29.7%), face-to-face (12.3%), or by radio (10.7%) (GNS Science unpublished data). First receipt of the official warning was dominated by radio (51.7%) and television (21.9%), with sirens cited as the official source by only 1.2% of respondents.

In Wellington the protocol for warning of a distant tsunami is to use multiple media channels and mobile sirens, rather than a fixed siren system. Maintenance of tsunami sirens is an ongoing cost, and in New Zealand this has not been addressed fully. In Tillamook County, Oregon, US, the low distant-source tsunami hazard, cost of siren maintenance and the non-specific message provided by sirens have led to the removal of tsunami sirens in favour of specific, targeted messaging (Tobias, 2012). Several false alarms have occurred with newly installed siren systems due to manual error or technological failure (Couling, 2014; Cuming, 2012; Staff Reporter, 2013; Twentyman, 2012). If fully explained, a false alarm that occurs when a tsunami threat has been detected but does not materialise (i.e., there is a scientific rationale for the false alarm) can potentially enhance awareness and understanding of risk information, but technological false alarms are likely to be detrimental to public response (Mileti and Sorensen, 1990).

3.3.2 Informal warnings

Informal warnings are those disseminated via family, friends, members of the public, general media or independent self-maintained networks of community members (MCDEM, 2009b). Developments in social media have enhanced the efficacy of informal warnings. Authorities should now recognise the potential for informal warnings to be highly effective in terms of speeding up warning dissemination and reaching some members of the population who may not receive official warnings (MCDEM, 2009b), although in the 2010 Chile tsunami the most-common method of warning receipt was television or radio (see above). Likewise, in Mauritius, television and radio media dominated warning of the 2004 Indian Ocean tsunami, with $<20\%$ of people disseminating warnings face-to-face or via telephone (Perry, 2007). ‘New technologies’, such as email, social media and SMS were not used, despite the common use of SMS at the time. The time that people received warning information, showed that informal warnings only began to be disseminated after media reports become widely received (Perry, 2007). Social media (Twitter) was used by officials in Kesennuma (Japan, 2011) to warn of the tsunami (Acar and Muraki, 2011). Although informal warnings via Twitter were not specifically mentioned in the study by Acar and Muraki (2011), it was noted that most of the tweets related to warnings, help requests, or reports about environment and self, suggesting that informal warnings were disseminated via this media. Analysis of Twitter use in Indonesia as warning of the Great East Japan tsunami reveals dissemination of official warning to a potential 4 million Twitter users within 10 min of the first official warning being tweeted, peaking at 9 million users after 2 h (Chatfield and Brajawidagda, 2012). Clearly, social media is a valuable new tool in warning dissemination, but Perry (2007) notes the concerning potential for false information.

3.3.3 Natural warnings

Natural warnings include audible cues such as a‘continuous sound like a locomotive’ and ‘thunder-like’ sounds (Shuto, 1997), tactile cues (ground shaking) and/or visible cues. Visible clues include drawdown of the water at the coast, exposing the seabed or reefs prior to wave arrival, and other unusual wave activity such as a wall of water, a rapidly rising tide, large eddies, and frothing or ‘boiling’ of the sea surface (Gregg et al., 2006). While observation of natural phenomena is commonly reported after the event (e.g., Borrero et al., 2009; Dengler and Preuss, 2003; Gregg et al., 2006; Reese et al., 2007), fewer people heed those warnings and evacuate.

In some areas of the world, tsunami have been recognised for generations through experience and local history, and a culture of hazard awareness and preparedness has developed. Recognition and understanding of natural warnings of tsunami saved many lives in the Solomon Islands in 2009, despite the tsunami arriving only 3 min after ground shaking ceased (McAdoo, Moore, and Baumwoll, 2009). A disproportionate number of the immigrant population died compared to the indigenous population because they did not recognise the tsunami warning (McAdoo, Moore, and Baumwoll, 2009). A similar cultural knowledge exists in Indonesia, where indigenous knowledge on the Simeulue Islands helped to save many lives in December 2004 (McAdoo et al., 2006). Gaillard et al. (2008) demonstrated a) a higher recognition of sea withdrawal and ground shaking as natural warnings, and b) much higher proportion of evacuation uphill by indigenous Simeulue people than immigrant Acehnese or Minangkabau people. These events demonstrated the benefits of immediate evacuation in the context of indigenous knowledge, but the same actions can be encouraged by public education. In Vanuatu in 1999, timely tsunami education augmented local knowledge and resulted in evacuation (Walshe and Nunn, 2013).

Where indigenous knowledge is less-pervasive, for example where there has been little or no experience of tsunami, public education is often the only means of encouraging appropriate actions such as immediate evacuation. Tsunami evacuation messaging internationally emphasises the importance of recognising natural warnings of tsunami and evacuating coastal areas immediately (e.g., Textbox 3.4).

Textbox 3.4 (New Zealand message: Local-source tsunami evacuation actions) *A tsunami generated in conjunction with a nearby large earthquake or undersea landslide may not provide sufficient time to implement official warning procedures. Persons in coastal areas who:*

- *experience strong earthquakes (hard to stand up);*
- *experience weak earthquakes lasting for a minute or more; or*
- *observe strange sea behaviour such as the sea level suddenly rising and falling, or hear the sea making loud and unusual noises or roaring like a jet engine*

should not wait for an official warning. Instead, let the natural signs be the warning. They must take immediate action to evacuate predetermined evacuation zones, or in the absence of predetermined evacuation zones, go to high ground or go inland.
(MCDEM, 2010a, p.9)

There is significant public confusion around the interpretation of this message, in terms of what constitutes sufficient strength to cause a tsunami, and data suggest that people have difficulty accurately perceiving the duration of earthquakes (Dorfstaetter, 2012). Only 37% of respondents to a tsunami awareness survey in Wellington, New Zealand, recognised that a strong earthquake could be a precursor to tsunami and only 7% noted that an earthquake would have to be too strong to stand up in (Currie et al., 2014). Only 8% cited a long earthquake as warning of tsunami. MCDEM and regional CDEM groups continue to emphasise the important differences in their ability to warn of local, regional and distant tsunami, and recommend education and self-evacuation as a greater priority than installation of sirens.

3.4 Preparedness

Preparedness refers to '[t]he knowledge and capacities developed by governments, professional response and recovery organizations, communities and individuals to effectively anticipate, respond to, and recover from, the impacts of likely, imminent or current hazard events or conditions' (UNISDR, 2009, p.21). Activities to enhance preparedness encompass: emergency planning; tests and exercises; communicating plans; and training for organisations and individuals in how to prepare for and respond to disasters (Tierney, 1993). Being prepared also requires having resources in place to respond to and recover from a disaster, and knowing how to use those resources (Sutton and Tierney, 2006). Evacuation is an important component of preparedness at the organisational level in terms of co-ordinating evacuation plans and activities, and at the individual level for having members of the community participate in evacuation planning and being aware of appropriate evacuation actions in a tsunami.

Emergency planning at the organisational level has been defined by a series of principles developed by Dynes, Quarantelli, and Kreps (1972) and Quarantelli (1982), and further developed by Quarantelli (1988), Perry and Lindell (2003) and others. These are summarised briefly here. Emergency planning is a continuous process (Quarantelli, 1982): written plans must be updated with changing hazard knowledge, land-use changes and development, and available response resources. Part of the continuous process is testing the plan through exercises and drills, which provide educational and network-building functions as well as an opportunity to monitor, critically assess and enhance the plan (Perry and Lindell, 2003). Emergency disaster plans should be distinct from 'everyday plans', due to increased uncertainty, increased magnitude of impacts and required response, and greater required communication among agencies (Drabek, 1986; Perry and Lindell, 2003; Quarantelli, 1988). Emergency plans should be generic, allowing greater accessibility and flexibility in their application and enabling application across multiple hazards (Dynes, 1970; Quarantelli, 1982). Plans should be based on sound knowledge of the hazard, human behaviour in disasters, and of available resources, to enable planners to make reliable assumptions of likely events and behaviour in disasters (Quarantelli, 1982). Knowledge of human behaviour enables planners to accommodate likely behaviours, increasing the efficacy of a plan. Authorities planning for emergencies should recognise the resilience and resourcefulness of communities and society and harness that in collaborative planning, rather than a military-style 'command-and-control' approach to managing disasters (Tierney, 1993). This approach should be reflected in preparedness activities, by engaging communities to take leadership roles in hazard management with support from authorities to enhance their capabilities.

The New Zealand National CDEM Strategy stresses an all-hazards approach to: increase community awareness, understanding, and participation in civil defence emergency management; reduce the risks from hazards to New Zealand; enhance New Zealand's capability to manage emergencies and recover from disasters (MCDEM, 2007). A specific goal is to increase community awareness, understanding, preparedness and participation in CDEM activities, encouraging personal responsibility for preparedness, and community-based resilience building. With regards to tsunami, several initiatives have been put in place: public education strategies (MCDEM, 2007, 2012); consistent messaging (MCDEM, 2010b); evacuation planning guidance (MCDEM, 2008d); signage standards (MCDEM, 2008c); and communication/warning systems (MCDEM, 2009b, 2010a). The subsequent sections elaborate on these initiatives after a discussion of individual preparedness.

Individual preparedness actions comprise such things as collating survival items, structural strengthening of property, securing contents in the home or business, developing a household emergency plan, gaining survival skills or participating in wider social preparedness actions (Becker et al., 2012; Sutton and Tierney, 2006). *Hazard awareness* is 'the foundation for developing strategies to mitigate a hazard. Without awareness, there is no push to assess the hazard, ascertain risk, or develop meaningful response or mitigation plans' (Dengler, 2006, p.53). Awareness refers not only to having knowledge that a hazard exists, but also knowing the factors that lead to the realisation of that hazard, its impacts and dynamics and actions required to mitigate resulting detrimental consequences (Coppola, 2011; UNISDR, 2009). Levels of awareness can be raised by education or media coverage of events (Connor, 2005; Dengler, 2006). However, high levels of hazard awareness do not necessarily lead to high levels of individual preparedness (Duval and Mulilis, 1999; Finnis, 2004; Johnston et al., 2005; Lindell and Whitney, 2000; Paton, 2003; Paton et al., 2008). For example, surveys on the coast of Washington State, US, found that placement of evacuation/warning signs and maps, and distribution of information including via brochures, posters and school resources reached the majority of the usually-resident population but this did not enhance respondents' low to moderate preparedness (Johnston et al., 2005). Low levels of preparedness persist even in areas of high hazard such as California, US (Turner, Nigg, and Helfer Paz., 1986). A similarly high hazard in Wellington, New Zealand, and several years of sustained education around hazard awareness and preparedness has had only minor impacts on household preparedness levels, with around one-quarter to one-third of the population fully prepared (Johnston et al., 2013).

Paton (2003) presented a social-cognitive model of preparedness, which treated preparedness as a three-phase process comprising motivating factors, intention formation, and transition of intentions into preparedness actions. Risk perception, hazard anxiety and critical awareness are important motivators of individual preparedness (Paton, 2003) and are linked to risk personalisation. When personalisation of the risk is low, there is generally a low willingness to prepare; more frequent experience of disaster can lead to greater personalisation and greater levels of preparedness (Drabek, 1986). However, when previous experience resulted in minor impacts, it can lead to normalisation bias (Mileti and O'Brien, 1992) or unrealistic optimism bias (Paton, 2003). The second stage in the social-cognitive model of preparedness is the stage at which individuals form intentions to prepare. Intentions are more likely to be formed if an individual recognises that preparedness can lead benefit them or mitigate impacts in an emergency (outcome expectancy), that they believe they have the competence or capability to prepare (self-efficacy) and that they have the resources to prepare (response efficacy) (Duval and Mulilis, 1999; Lindell and Whitney, 2000; Paton, 2003; Turner, Nigg, and Helfer Paz., 1986). When an intention to prepare has been formed, the realisation of preparedness actions is affected by: a person's perceived responsibility to look after other people; their levels of empowerment to take action; their levels of trust in, or perceived responsibility of authorities; and their sense of community (Paton, 2003). Societal norms can also encourage or discourage preparedness depending on the predominant hazard culture, with people more likely to prepare where such actions are widely encouraged and seen as positive in society. Paton et al. (2008) also identified community participation, collective efficacy, trust, and empowerment as important predictors of tsunami preparedness.

These models inform the content and format of community preparedness and education strategies, which seek to enhance preparedness behaviour by countering negative influences in the social-cognitive model. To be most effective, strategies must address the issues in the above models to encourage personalisation of the risk, improve levels of outcome expectancy and self-efficacy by demonstrating the benefits and ease of individual actions (Paton, 2003), and promote community engagement, trust and empowerment (Paton et al., 2008). Becker et al. (2012) highlighted the differences in types of hazard information and their relative impact on preparedness. *Passive* information (e.g., leaflets) was found to have the least impact, while *interactive* information was good for promoting discussion, enhancing understanding and preparedness. *Experiential* information was found to be the strongest type of information in terms of enhancing hazard beliefs and understanding of consequences.

For tsunami evacuation, the primary preparedness factors are being able to recognise natural warning signs of tsunami and an understanding of official warnings, having an emergency kit for immediate evacuation, preparing and discussing a household plan for evacuation from the home, work or school (including appropriate routes and rendez-vous points), and practicing evacuation. Community-based evacuation planning, such as the Blue Line Project in Wellington (Section 3.6.2) seeks to enhance preparedness by encouraging community participation, self- and collective-efficacy, trust and levels of critical awareness in the community. Similarly community-focussed processes have been conducted on the US Pacific Northwest coast in the *TsunamiReady*[2] community program and Project Safe Haven (Section 3.6).

3.5 Education

The infrequent nature of most hazards precludes widespread experiential learning, and reliance on media coverage of natural hazards does not guarantee realistic or proportional representation of hazards processes or impacts. Therefore, education is necessary for the public to develop accurate perceptions of hazards (Vitek and Berta, 1982), understand warnings, and learn the appropriate actions to take (Mileti et al., 2004). Experience from previous tsunami shows that behavioural response is complicated, with problems such as non-response to official warnings (Johnston et al., 2008), failure to act on natural warnings (Section 3.3.3), road congestion during evacuation, failure of warning systems, and returning to evacuated zones too early (Fraser et al., 2012a). Tsunami hazard education is important for assimilating these lessons into public knowledge and encouraging appropriate response behaviour.

Media coverage of international tsunami can be important for raising awareness and relaying key education messages, although Becker et al., 2012 notes that media coverage of overseas disasters can encourage personalisation of risk but can also contribute to fatalism. This can be particularly true when the media consistently focusses on the worst-affected areas. The 1998 Papua New Guinea tsunami received unprecedented international coverage and promoted discussions of the tsunami hazard, especially in the US, Australia, New Zealand and Japan (Dengler and Preuss, 2003). National-scale hazard events can also increase levels of awareness and preparedness can

[2] http://www.tsunamiready.noaa.gov/

also be significant. In response to the 2010/2011 Canterbury earthquakes, levels of preparedness among people rose significantly but levels of preparedness in other cities also increased (Colmar Brunton, 2011; McClure, Johnston, and Henrich, 2011). This can be a short-term effect so ongoing education remains a key component of risk mitigation (Suganuma, 2006).

Education programmes should be ongoing, with repeated consistent messages in multiple formats to reach different sectors of the population (Mileti et al., 2004). The education message should provide simple information on the impacts of a hazard, the chance of it occurring and what to do to reduce the impacts, presented such that the audience can personalise the risk and make their own conclusion that they need to and are able to prepare (Mileti et al., 2004). There should be support of further information-seeking and it is important to have subject experts and trusted organisations involved in the education (Mileti et al., 2004). Education can take many forms, including: media campaigns; public presentations, workshops, attendance at public events, educational videos, newsletters brochures, fact sheets, resource guides, guidebooks, childrens' cartoon books, trivia sheets, games, and evacuation maps (Dengler, 2005; Jonientz-Trisler et al., 2005). Evacuation maps and signage are considered essential education tools, which raise awareness through their visibility and can trigger media attention and hazard discussion in the community (Dengler, 2005).

Hazards education in schools is extremely valuable as it can raise awareness and preparedness not only in the schoolchildren, but also in teachers, parents and the wider community (Johnson, 2011). NTHMP developed tsunami hazard curricula in three US States, and it is now a legal requirement for schools in the inundation zone in Oregon, US to teach tsunami hazard education and conduct tsunami evacuation drills (Dengler, 2005). Tsunami-specific professional development courses are offered to teachers and student teachers at Humboldt State University to aid education in schools (Dengler, 2005). In New Zealand, a national hazards education schools programme 'What's The Plan Stan?' (WTPS)[3] is available to schools. Currently, use of WTPS remains regionally variable, due to a lack of awareness of the resource and absence of an strategy based on required outcomes, and there remains no official requirement for schools to include disaster preparedness education in the curriculum and hold disaster training exercises, such as 'Drop, Cover and Hold' (Johnson, 2011). Tsunami drills are also rare among coastal schools (Johnson, 2011). Evacuation exercises are particularly important for schools in tsunami hazard zones because accounts from the Great East Japan tsunami showed that schools who were well-practiced in tsunami evacuation were able to save all of their pupils (Yamori, 2013).

In New Zealand, all-hazards public disaster education is coordinated via the national Public Education Programme (PEP) (MCDEM, 2012), which comprises: a national media campaign 'Get Ready Get Thru' and supporting resources; WTPS; additional actions by MCDEM to support or build on these programmes; and actions undertaken by CDEM groups (MCDEM, 2007, p.3).

[3] WTPS is a school's resource developed in parallel with the 'Get Ready Get Thru' campaign, intended to engage school children in a programme of disaster education (MCDEM, 2007). The programme uses various teaching aids and information including handbooks, interactive activities and online resources to raise awareness and motivate preparedness specifically in school children.

The promotion of immediate evacuation in response to natural warnings, which is consistently in conflict with public pressure on councils to install tsunami sirens (Johnston et al., 2014), is a challenge for education in New Zealand. Likewise, the low frequency of tsunami and absence of damaging tsunami in the public memory somewhat relegates the hazard below other hazards that are higher priorities for coastal communities, e.g., earthquake and coastal erosion (Johnston et al., 2003). Drawing distinctions between appropriate evacuation actions in local, regional and distant-source is also a challenge, as research has shown confusion between likely arrival times and the use of sirens in the respective events (Currie et al., 2014; Dorfstaetter, 2012). Perceptions of available time for evacuation after a warning siren are often underestimated (Johnston et al., 2003, GNS unpublished data) due to invalid expectations of siren activation. Ongoing education and engagement activities such as community discussions of evacuation and sirens, and involvement of the community in evacuation mapping initiatives can broach these difficulties.

3.6 Evacuation planning

Evacuation planning aims to ensure life safety in a hazard event by guiding people out of the anticipated hazard area(s) to a safe place. A plan requires public education to deliver consistent, key messages on correct evacuation actions and familiarise people with evacuation strategies and information. This includes evacuation maps, signs and periodic exercise, assessment and upgrade of plans. Evacuation plans must be appropriate for the temporal and spatial scales of the hazard. Tsunami plans should therefore be available for local-source *and* distant-source events, as tsunami have the potential to occur on very different temporal and spatial scales. Primarily, the travel time of a distant tsunami provides sufficient time for gradual evacuation following an official warning and time for confirmation, whereas a local tsunami must be treated with the utmost urgency.

3.6.1 Evacuation maps

Evacuation maps are one component of an evacuation plan which should also include signage, public education and warnings and contributes to an effective warning system (Leonard et al., 2008b). Evacuation maps require delineation of hazard zones to represent the maximum possible inundation extent, multiple scenarios of differing extent, or zones that may show probability of inundation extent. Locations of key infrastructure such as assembly points or emergency services and location of concentrated vulnerable populations, e.g., care homes or schools, should be shown (MCDEM, 2008d). Styles of evacuation maps vary internationally in terms of the types of information shown and how this information is represented, i.e., number of evacuation/hazard zones, symbols, colours, scale and additional text information. International consistency is unrealistic, but a nationally consistent mapping approach and presentation style is desirable to ensure that people residing in or visiting a country can interpret the map at any coastal location. There was significant inconsistency in evacuation maps between administrative authorities in the United States (Kurowski, Hedley, and Clague, 2011; National Research Council, 2011) and Japan (Fraser et al., 2012a) but there has been a movement recently towards more consistent mapping outputs. The NTHMP Mitigation and Education Subcommittee (MES) (2011) sets evacuation mapping minimum requirements for all tsunami evacuation maps produced in the US after January 2012 and existing maps were updated through 2012 to ensure consistency (J. D. Schelling, personal communication, 9 March 2012).

MCDEM (2008d) provides guidelines for evacuation mapping in New Zealand to be carried out by local authorities and CDEM groups. It is recognised that resources and capabilities do not always enable the most detailed evacuation mapping, i.e., using scenario or probabilistic modelling, in every location. Therefore, four 'development levels' are outlined by the National Tsunami Evacuation Guidelines (MCDEM, 2008d) to enable a minimum (conservative) level of mapping to be carried out in the first instance, with further complexity added in subsequent generations of mapping, with the aim to refine the accuracy evacuation zones, but only ever by reducing the zone size. These development levels are:

1. Simple 'bathtub' model: maximum wave height is assigned at the coast, and this level is projected inland until the water surface intersects the land surface.

2. Rule-based wave height attenuation: maximum wave height is assigned at the coast, and this level is projected inland using linear height attenuation until the water surface intersects the land surface. This is recommended by MCDEM to be the minimum recommended level of development applied in New Zealand, and is the methodology implemented in the current generation of evacuation maps. It has been used to produce evacuation zones for several councils in New Zealand and has been validated against surveyed inundation extent in the 2011 Great East Japan tsunami (Appendix E).

3. Computer simulation of wave heights and inundation is conducted separately. PTHA generates wave height at shore for a catalogue of tsunamigenic earthquakes. De-aggregation is used to determine the extent to which each source contributes to the tsunami hazard (Power, 2013). Sources that approximate the wave height at particular probability are then simulated further to estimate flow depth and inundation extent. This method can take into account more complex features such as variable surface roughness and flow interaction than the Level 2 approach but requires high-resolution elevation data.

4. Zones that envelope all possible inundations from all possible sources, derived from 'multiple well-tested models', requiring PTHA analysis from source to inundation.

Level 3 is the minimum approach that provides wave arrival time via full numerical simulation. Therefore, an approach must be used that addresses this data requirement. MCDEM (2008d) also discusses the recommended content of evacuation maps as part of evacuation plan development. Recommendations include the optimum number of evacuation zones as a minimum of two zones and maximum of three zones (Textbox 3.5), as a balance between a) over-simplification (i.e., mapping only the maximum tsunami), which can lead to over-evacuation in most events and greater resource requirement; and b) potential public misunderstanding of too many zones. Spatial coverage of Light Detection and Ranging (LiDAR) can restrict application of higher development levels, as LiDAR is the optimal dataset with which to produce a Digital Elevation Model (DEM) of sufficient resolution for accurate simulation of tsunami inundation. In communities that have insufficient resource to achieve any of these development levels, the recommendation is to assign the whole community as being within the orange zone, until further research can be carried out (MCDEM, 2008d). In cases where future alterations are made to zone boundaries, the components, colours, and style of the maps will remain unchanged, in order to sustain community awareness and understanding of the maps.

The publication of evacuation maps in Wellington, New Zealand, is carried out alongside public education and collaborative planning for evacuation signage in each community. The roll-out process for maps requires community engagement and periodic review and amendments to draft plans, including for placement of evacuation signs. Community involvement benefits the project because it brings local knowledge to the planning process, and fosters a sense of community participation and ownership (Section 3.4; Paton et al., 2008). Community volunteer groups are provided a base map with evacuation zones shown, and with the assistance of local CDEM staff they develop appropriate evacuation routes and safe locations along with other relevant information such as street names, key buildings and/or local landmarks to aid understanding of the map. These features, in addition to roads and rivers, represent the recommended minimum information to present on evacuation maps (MCDEM, 2008d). The guidelines also mention vertical evacuation, stating that this option should be considered locally where required, and if applied this should be illustrated on evacuation maps.

Textbox 3.5 (Recommended tsunami evacuation zones in New Zealand) *Recommended tsunami evacuation zones to achieve national evacuation mapping consistency in New Zealand (MCDEM, 2008d):*

- *Red zone: the 'shore-exclusion', to be evacuated in all tsunami due to the likelihood of strong coastal currents. This level of evacuation is expected to be activated several times in a persons lifetime*
- *Orange zone: to be evacuated in official warnings of most regional and distant tsunami. Official warnings are expected to be available if evacuation of this zone is required*
- *Yellow zone: this zone accounts for inundation from the maximum credible local tsunami, and is to be evacuated in any local tsunami, which is expected to produce the largest tsunami. The expectation is that evacuation in this case should be prompted by recognition and understanding of natural warning signs or receipt of informal warnings*

3.6.2 Evacuation signs

Evacuation routes and destinations require identifiable and understandable signs to direct the public to safety. A range of sign styles and languages are used internationally, but all employ a tsunami wave in some form to ensure communication of the key message. Signs can be used to show route directions, the boundaries of tsunami zones, safe areas and maximum inundation height in previous events. The New Zealand signage standard has provision for each type of sign in a consistent format to bring national consistency and to promote greater public understanding and recognition (MCDEM, 2008c, Fig 3.2).

New Zealand signage uses blue and white colouring, as used in many places around the Pacific, but this is not globally consistent. Japan uses designs that have been accepted as an International Standards Office (ISO) international standard (Fraser et al., 2012a). These are consistent with the Caribbean, but are inconsistent with those in the rest of the Pacific and inconsistent between municipalities (Fraser et al., 2012a). Signs in Indonesia are red with a blue wave. A notable difference between signs in Japan and elsewhere, is the use of distance on evacuation signs, such as the distance to the nearest safe location (Appendix D). Sign placement should be planned during the community engagement process discussed in Section 3.6.1. In the community of Island Bay in Wellington, New Zealand, the discussion group proposed that a blue line be painted on the streets to mark the inland extent of the 'Yellow zone' (Wellington Emergency Management Office, 2001, Fig 3.3). This project, having generated significant national and international interest is now being implemented in other Wellington communities.

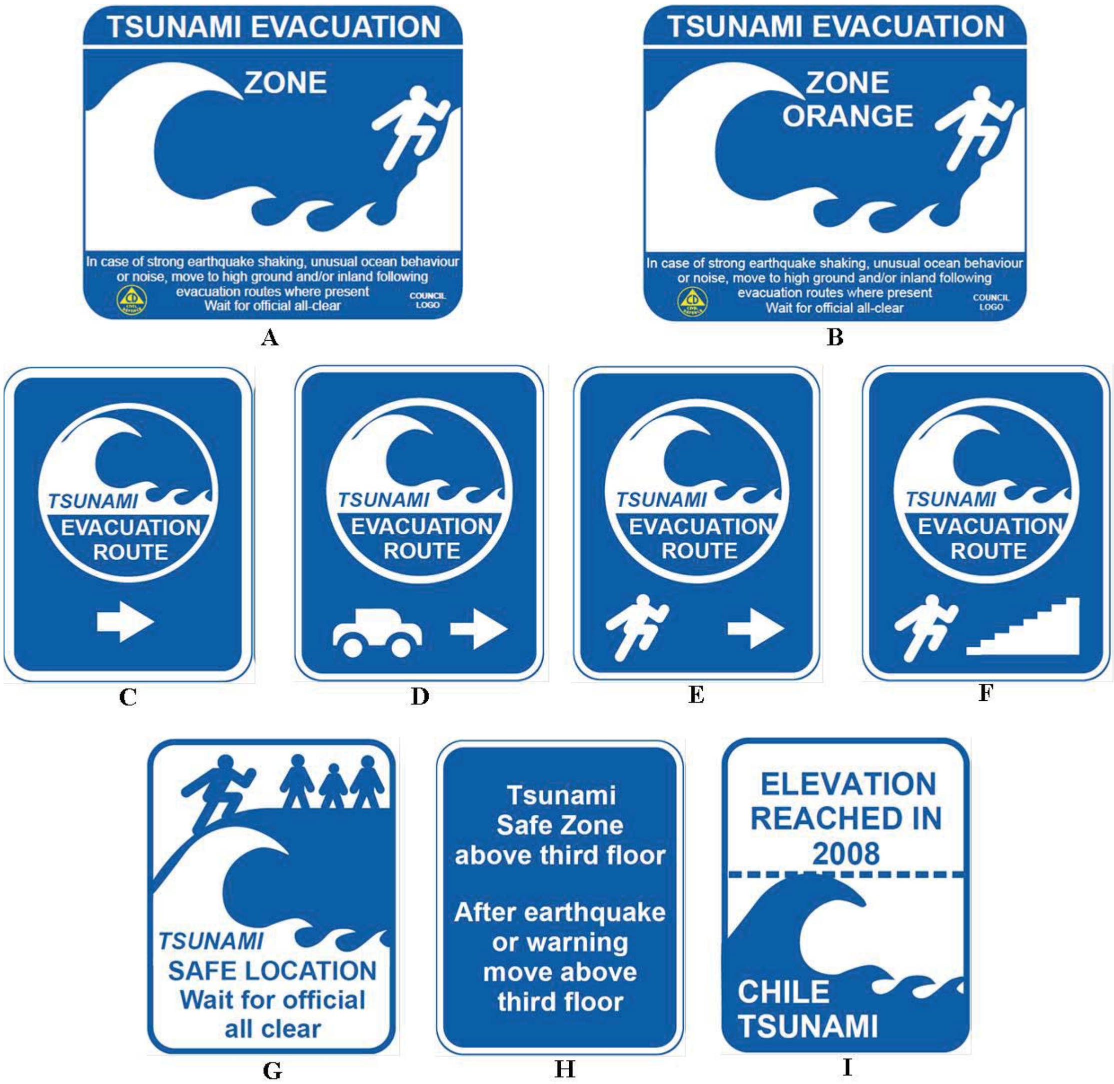


Fig. 3.2: Standard Tsunami signs for New Zealand (MCDEM, 2008c). Signs shown are A: Tsunami evacuation zone; B: Tsunami evacuation zone with reference to a specific zone; C: Evacuation route direction (arrow can be turned any direction); D: Vehicular evacuation route; E: Pedestrian evacuation route; F: Vertical evacuation route; G: Safe location for pedestrian routes; H: Safe location for vertical evacuation; I: Previous event sign, indicating maximum flow depth in that event.

(a) (b)

Fig. 3.3: Examples of the blue lines used in an increasing number of Wellington coastal communities. a) A blue line at the edge of the maximum inundation zone, credit: Nick Thompson. b) A directional sign with the distance to the blue line, credit: RadioNZ.

3.6.3 Evacuation exercises

Evacuation exercises provide the important 'testing' component of emergency planning (Quarantelli, 1982; Sutton and Tierney, 2006). The perceived value in evacuation exercises is that frequent, well-learned emergency practices are likely to increase the probability that in a real emergency people will respond in an informed manner (Johnston et al., 2011). In the case of schools, those with 'well developed and regularly practised emergency preparedness plans in place send a message to pupils and caregivers alike that in the case of an emergency, the school is prepared to protect the safety of the children' (Johnston et al., 2011). Exercises also provide valuable opportunities for interactive education and discussion of hazards and appropriate actions and the assessment and refinement of evacuation plans. However, exercises can be costly, time-consuming and the cost-benefit ratio in larger communities may make evacuation drills unfeasible (National Research Council, 2011). Exercises for distant-source scenarios are seen as unnecessary, given the length of time available to deploy emergency management resources to guide evacuations (National Research Council, 2011).

Fire drills are commonplace in institutional and businesses premises, many US States hold an annual ShakeOut[4] earthquake drill, in which people in low-lying areas of the Pacific States are encouraged to also conduct a tsunami evacuation drill. In Japan, tsunami evacuation exercises are an important component of tsunami preparedness. Local governments hold annual exercises on days that commemorate past significant tsunami, and drills are also organised by community-groups and schools, although the majority of participants have been the elderly and children (Ishiwatari and Arakida, 2011). Some community-groups incorporate vertical evacuation into local business premises during their drills (Fraser et al., 2012a). Tsunami exercises and education at schools in

[4] http://www.shakeout.org/

Japan are attributed as the reason for many lives being in the Great East Japan tsunami, including the so-called ‘Miracles of Kamaishi’ (MSN Sankei News, 2011). The principles of *tsunami tendenko*, taught in some areas of Japan, are: self-reliance, encouraging others to seek refuge, mutual trust in advance of an event, and reduced feeling of self-reproach among survivors (Yamori, 2013).

A number of limited tsunami evacuation exercises have been conducted and monitored in New Zealand; these are primarily organised by local CDEM groups (Leonard and Wright, 2011) or by individual schools. At least one opportunity to combine CDEM tsunami exercise with a school drill was missed in the Hutt Valley, due to a lack of communication that a drill was planned (Johnson, 2011). A national ShakeOut earthquake drill was conducted in New Zealand in 2012 but inclusion of tsunami evacuation in the exercise was limited to just 8% of schools (McBride et al., 2013).

3.6.4 Vertical evacuation

As introduced in Chapter 1, *vertical evacuation* provides safety by evacuation to elevations *above the tsunami flow depth within the hazard zone* in tsunami-resistant buildings or towers, or to raised areas of natural/artificial high ground. As a concept of raising oneself above flood levels, it has most likely existed for many generations as a basic survival technique. Spontaneous (unplanned) evacuation to the upper storeys of buildings occurred in the US during the 1960 Chilean tsunami (Atwater et al., 2005a) and 1961 Hurricane Carla (Ruch, 1984). Vertical evacuation was first explored by researchers as a planning option in the US in the 1970s and 1980s in hurricane-prone coastal areas (Ruch, 1984; Salmon, 1984) in response to intensifying coastal development and population density causing increased difficulty of hurricane evacuations. Concerns about practicalities, ethics and liability issues of vertical evacuation were raised early in this research by Salmon (1984), who noted that vertical evacuation ‘is resisted by planners who are concerned that its risks are too high and that partial acceptance of the concept would vitiate compliance with the horizontal component’ of evacuation. The issues around liability and responsibility raised by planners in the 1970s and 1980s are still of concern in current projects.

Vertical evacuation is often-discussed as a recognised strategy for reducing life risk in hurricane (e.g., Wolshon et al., 2005) and flooding (e.g., Kolen and Helsloot, 2012; Sorensen, 2000). It also features in tsunami planning guidelines (NTHMP, 2001) and a new European tsunami evacuation planning framework (Scheer et al., 2011). Coastal hotels are used in Hilo, Hawai’i, US, to evacuate tourists in tsunami (Staff Reporter, 2011). There are numerous vertical evacuation structures in Japan, including those in: Aonae, Okushiri Island; Nishiki, Mie Prefecture; Shirahama, Wakayama Prefecture; and Kaiyo, Tokushima Prefecture (Leonard et al., 2011; Scheer et al., 2011; Velotti et al., 2013). A combination of pedestrian bridge and tsunami towers have been proposed as solutions in dense urban environments (Muhari, Imamura, and Koshimura, 2012). Plans for a ‘tsunami evacuation raised earth park’ are underway in Padang, Sumatra[5] and several structures have been

[5] http://geohaz.org/projects/sumatra.html

constructed in Banda Aceh, Indonesia (Leonard et al., 2011). In New Zealand, vertical evacuation is defined in Appendix 2 of the MCDEM Guide to the National Plan (MCDEM, 2009a) but it is not explicitly discussed in the main text of the plan. Additionally, MCDEM (2008c) states that vertical evacuation options should be considered locally and indicated on evacuation maps with signage, where this option is implemented. However, there are no further guidelines available on the development or use of vertical evacuation for tsunami.

Tsunami vertical evacuation was considered in plans to redevelop the City Hall building in Cannon Beach, Oregon, US. This project exemplifies some of the key issues of vertical evacuation in terms of structure, risk-reduction context, community participation and funding. Primarily, the existing site is not large enough to accommodate a ramp of sufficient gradient for wheelchair access. Thus, the development does not meet requirements of the Americans with Disabilities Act (ADA). There was some resistance to the project in the local and scientific communities who believe that a better strategy for evacuation is to retrofit the main vehicular bridge in and out of town (Wang, 2009). The project is currently awaiting state or federal funding for construction in order to progress from the conceptual design stage. Project Safe Haven, a NTHMP-funded multi-agency project has identified multiple potential vertical evacuation locations on the Washington, US, coast using a community-participation model to decide on locations and the design of proposed buildings, towers or berms (Project Safe Haven, 2011a,b). While planning redevelopment of a school gymnasium, Ocosta School in Grays Harbor County decided to incorporate the means for vertical evacuation (Doughton, 2013). This will become the first TVEB in the US.

Several studies have considered the construction or design costs of TVEB, or compared the cost of a tsunami-resistant building with a non-engineered building. Costs are generally a function of structure type, required capacity and required structure height (Project Safe Haven, 2011a). The project costs for several refuges proposed by Project Safe Haven in Grays County and Pacific Harbor County were in the range United States Dollars (USD) 323,000 for berms with capacity of $<$100 people, to $>$USD 3.3 million for a tower with capacity of 1,700. The 'cost per evacuee' ratio varied between USD 1,000–6,400 per person, and demonstrates that potential costs vary significantly according to refuge design, and must be determined on a site-specific basis. It was estimated that to rebuild Cannon Beach City Hall to provide vertical evacuation refuge and be operational post-earthquake, would cost USD 4 million (double the cost of a wood-frame alternative) (Wang, 2009). At the same workshop it was noted that when constructing an engineered building, the additional cost of tsunami-resistance is reduced as a proportion of the building cost, although no estimates were provided. Mikhaylov and Robertson (2009) estimated that to provide additional tsunami resistance in a multi-storey RC building, $<$8% increase in weight of reinforcing steel and $<$3% increase in volume of concrete was required. This suggests that costs to modify planned seismically-engineered buildings for suitability as TVEB could be low, however, this is an area that should be subject to further research.

Informal discussions were conducted early in this research project with leaders of the Project

Safe Haven, Cannon Beach City Hall and Padang initiatives and emergency planners in Seaside, Oregon, US. These discussions highlighted barriers to development of vertical evacuation facilities as the agreement of business due to liability and 24-hour access issues. Many factors can influence the choice of site including availability and cost of land, legal and/or cultural issues, public opinion, and funding mechanisms. These issues vary according to whether a new construction is required or existing buildings can be modified. Community engagement has played a significant role in planning vertical evacuation in Washington State, US. Project Safe Haven uses a community-based approach to consult on the most appropriate location and design for vertical evacuation structures from the very beginning of the process (Project Safe Haven, 2011a,b). This approach helps to ensure that any vertical evacuation facility has an everyday use that is required by the community, which may help to cover construction costs, and keep the facility in regular use, raising peoples familiarity with the facility in advance of evacuations. TVEB in Japan are explored further in Section 5.

3.7 Summary and link to next chapter

This chapter has illustrated tsunami risk reduction measures, which have been implemented internationally and in New Zealand. Implementation of vertical evacuation should be framed in the context of these risk reduction options and leverage progress made in the last decades. The next chapter presents the results from numerical simulation of inundation due to the maximum credible local-source tsunami at Napier, New Zealand. These results provide the hazard context for subsequent vertical evacuation and behavioural evacuation modelling.

4. TSUNAMI INUNDATION IN NAPIER, NEW ZEALAND, DUE TO LOCAL EARTHQUAKE SOURCES (PAPER 1)

This chapter presents deterministic simulation of local-source tsunami on the east coast of New Zealand's North Island. This chapter characterises wave arrival times, flow depth and inundation extent due to the maximum credible local tsunami scenario. By presenting a new tsunami assessment, and data for subsequent investigations of evacuation behaviour and inform evacuation simulations, the chapter meets Objective 1. Section 4.1 contextualises the chapter by providing a general introduction to tsunami numerical modelling, which could not be included in the journal paper. The majority of this chapter (Sections 4.2–4.9) was originally published as *Fraser, S.A., Power, W.L., Wang, X., Wallace, L., Mueller, C., Johnston, D.M. 2014. Tsunami inundation in Napier, New Zealand, due to local earthquake sources. Volume 70, Issue 1, 415–445. doi: 10.1007/s11069-013-0820-x*. The article is reproduced with kind permission from Springer Science and Business Media. With the exception of formatting, the text presented here is unaltered from the published version. A statement of author contribution is provided in Appendix H.

4.1 Background to numerical modelling

The goal of tsunami numerical modelling is to simulate tsunami generation, propagation and inundation in a numerical domain. This requires accurate representation of seafloor or landslide motion as the source, transfer of source motion into displacement of the water column, propagation of waves through the deep ocean and finally inundation on shore. Numerical analyses can be broadly categorised as deterministic or probabilistic. Deterministic simulations apply one or more scenarios; these may be retrospective analyses of historic events, or assessment of a 'characteristic' or maximum credible earthquake. Such analysis is useful for elucidating the impacts of a given event, but probabilistic analysis is required to generate a full picture of the tsunami hazard including frequency. Probabilistic analysis is required for defining recurrence intervals of wave heights or impacts for loss assessment, land-use planning and engineering design standards. The choice of approach is determined by the goal of an analysis, but also due to practicality and budget, as the number of simulations involved in probabilistic analyses requires substantially more computational expense than deterministic analyses. Probabilistic analyses are becoming more commonplace as advances in computing make it possible to execute thousands of simulations. Still, they are limited to linear simulation of an offshore tsunami amplitude, for example at the 50 m isobath (Burbidge et al., 2008) because non-linear methods remain too computationally intensive to be utilised in probabilistic frameworks (Power, 2013).

Numerical simulation of tsunami is conducted using a number of available codes; some of these are summarised in Section 4.1.1 in terms of governing equations, calculation scheme, validation and previous application. The available codes are based on the physics of fluid motion, described by the non-linear partial differential Navier-Stokes equations. For flow that has a vertical dimension (depth, D) much smaller than the horizontal dimension (wavelength, λ), shallow water theory applies, which states that vertical acceleration is negligible relative to the horizontal velocity due to gravitational acceleration. Vertical motion therefore has no impact on pressure distribution and pressure is considered hydrostatic — a function of depth only. In these situations, the Navier-Stokes equations can be simplified by averaging the equations over the water depth to remove the vertical terms and form the Shallow Water Equations (SWE). Shallow water theory is applicable to tsunami in the deep ocean because the maximum depth of the ocean is generally <4 km and tsunami wavelength can reach hundreds of kilometres, thus, tsunami satisfy the dimensional requirements of SWE. The equations of mass conservation and momentum, neglecting vertical terms are then used to simulate tsunami:
Mass conservation:

$$\frac{\partial h}{t} + \frac{\partial(uh)}{\partial t} + \frac{\partial(vh)}{\partial t} = 0 \tag{4.1}$$

Momentum conservation in x-and y-directions:

$$\frac{\partial(uh)}{\partial t} + \frac{\partial(u^2h + \frac{1}{2}gh^2)}{\partial x} + \frac{\partial(uvh)}{\partial y} = 0 \tag{4.2}$$

$$\frac{\partial(vh)}{\partial t} + \frac{\partial(uvh)}{\partial x} + \frac{\partial(v^2h + \frac{1}{2}gh^2)}{\partial y} = 0 \tag{4.3}$$

The advantage of using SWE is their efficiency of use while being able to predict maximum run-up and the run-up process (Synolakis, 1991). However, their non-dispersive nature means they are not the most appropriate scheme for replicating waveforms due to some generation mechanisms, over complex bathymetry, or in shoaling/inundation stages. For large seismically-generated tsunami, frequency dispersion imparts only minor modifications on transoceanic propagation and for waves with $D/\lambda < 1/20$ velocity is independent of wavelength, therefore all waves travel at the phase velocity and are non-dispersive, so frequency dispersion can be neglected (Glimsdal et al., 2013). For SWE to be more applicable where $D/\lambda > 1/20$, or where distance of travel is sufficient for dispersion effects to accumulate, numerical dispersion can be applied in the SWE to mimic the neglected physical dispersion (Imamura, Shuto, and Goto, 1988; Wang, 2008). Fully-dispersive modelling is required to properly describe wave generation of tsunami generated by landslides or moderate magnitude earthquakes, which are strongly affected by dispersion (Glimsdal et al., 2013).

Equations that solve non-linear terms and frequency dispersion, such as the Boussinesq (Grilli et al., 2007) or the full Navier-Stokes equations, account for vertical flow structure and incorporate frequency dispersion but incur significant computational expense in doing so. This makes them too computationally intensive for use in most seismic-tsunami hazard assessments, limiting their practical utility to small-scale or near-field simulations and simulations where dispersion conditions demand their use.

In the deep ocean where tsunami amplitude is much smaller that water depth, bottom friction terms and non-linear convective terms are negligible. Therefore, bottom friction can be ignored in these deep ocean areas and the SWE can be used in their linear form. As the wave propagates onto the continental shelf water depth is reduced and tsunami amplitude increases (the ‘shoaling effect’, Fig 2.1) such that bottom friction effects (Dao and Tkalich, 2007) and nonlinear convective inertia force become greater, meaning non-linear terms are required (Shuto, 1991). The complexity is compounded by interactions with physical structures on shore (Charvet et al., 2010). SWE can be applied in their conservative form, solving for free-surface fluctuation and volume flux, or non-conservative form, which solve for velocity. The conservative form allows the model to perform better in situations where the shallow water theory breaks down, such as in areas of steep bathymetry (Wang and Power, 2011).

The governing equations are discretised and solved on a grid or mesh of individual cells or elements. Cell size used in analysis must be of a resolution sufficiently fine to resolve the tsunami wave to prevent decay in the wave profile (Shuto, 1991). Therefore, grid/mesh element size must reduce as water depth and wavelength decrease. On the other hand, cells with fine resolution carry a much greater computational expense, due to the increased number of calculations required. A grid tends to have cells of fixed dimensions within a model domain, while a mesh provides more flexibility to have cells of variable size in a single domain, with the advantage of better representation of topo/bathymetric features (Tinti, Gavagni, and Piatanesi, 1994). A grid of fixed cell size presents the problem of insufficient resolution in the onshore region and incurs unnecessary computation expense in deep ocean areas. To avoid this, some models ‘nest’ multiple grids of decreasing cell-size inside one another, with the smallest cell-size occurring in shallow or onshore areas. Accurate simulation of the moving wet/dry boundary is important (Shuto, 1991) to adequately simulate the cyclical ebb and flow of tsunami water at the shoreline. The moving boundary applied in fixed grid models is limited to the boundary of elements, so accuracy of the moving boundary is subject to the grid resolution. Among other schemes, linear extrapolation of water depths across cells can improve accuracy of the moving boundary (Lynett, Wu, and Liu, 2002).

Simulation can be implemented on Cartesian coordinates, but where trans-oceanic propagation is being simulated spherical coordinates must be used to represent the impact of Coriolis Force and curvature of the Earth (Shuto, 1991). These effects alter the path of waves and ultimately affect wave height at the coast and inundation. One of the primary causes of inaccuracy or uncertainty in tsunami simulations is the availability of bathymetry/topography data of sufficient resolution to adequately simulate the complex and influential interactions between tsunami and bathymetry. For example, focussing and de-focussing effects of variable ocean depth can impact tsunami amplitude by a factor of three (Okal, 1988). Therefore, it is important that bottom surface features are accurately represented by using the highest possible resolution bathymetry and topography.

Complexities in modelling and the variation in results from multiple tsunami numerical codes in analysis of the Indian Ocean tsunami showed a need for code validation (Synolakis et al., 2008). Synolakis et al. (2008) described a series of analytical, laboratory and field-data benchmark tests for validating the output of numerical codes. The tests include:

- Analytical — using analytical solutions for linear (solitary and N-wave) and nonlinear wave evolution on a simple sloping beach, solitary wave on a beach of variable slope, and subaerial landsliding;
- Laboratory — using scaled physical models representing solitary waves on simple and variable beaches, around a conical island and into a three-dimensional cove;
- Field-data — using observed data (tide gauge recordings, measured run-up heights, observed arrival times and wave direction) to verify the output of a tsunami simulation.

In validation against the benchmark tests, models must satisfy the basic hydrodynamic conditions of: mass conservation in the face of numerical approximations such as friction factors that stabilise computations but violate mass conservation principles; and convergence of calculated run-up with decreasing time-step size (Synolakis et al., 2008). There is also a requirement that models are evaluated for scientific use through documentation in peer-reviewed journals and formal evaluation (Synolakis et al., 2008). These benchmark tests were adopted by the operators of the major tsunami warning systems to reduce uncertainty in the long-range and operational forecasting required by such systems (Synolakis et al., 2007). Operational models (i.e., those used by warning centres in real-time forecasting) must be subject to additional constraints of time (producing run-up estimates before real-time tsunami arrival) and accuracy ('how well the computational procedure represents results of the parent equations'), of which propagation accuracy within 10% and arrival time accuracy of three minutes is now achievable (Titov et al., 2005).

4.1.1 Tsunami numerical model summary

There are several numerical codes in active development and available for use in tsunami simulation. Some of these are summarised below.

3DD

3DD is a three-dimensional hydrodynamic model used primarily in simulation of inter-tidal zones such as estuaries. Its robust wetting and drying scheme provides advantages for simulation of inundation over large areas of flat land. The scheme calculates water depth at each cell wall rather than at the centre of the cell, as used by most other models. As one or more wall may be wet or dry at any time) it smooths the transition between cells, reducing the chance of spikes in velocity values of shallow flow. An effective depth term is also used to prevent instabilities caused by bed friction. Other characteristics of the model are similar to other models: fully explicit time stepping, two-dimensional form based on momentum equation and conservation of mass (Prasetya et al., 2011b), explicit finite difference (Eularian) scheme, roughness length and eddy viscosity included, nonlinear convection acceleration and coriolis terms, free/no slip of land-sea boundaries, staggered grid, fully explicit leapfrog scheme. The fully explicit timestepping feature minimises numerical dispersion, however, this feature requires very small timesteps, which increases the computational expense of running this model. The model has been validated for tsunami using benchmark problems (Borrero et al., 2007) and other 'skill score' tests. 3DD allows the implementation of Boussinesq terms to simulate depth-dependent breaking and consequent energy loss. This model has been used by Prasetya et al. (2011b) to reproduce inundation and flow speeds in the 2004 Indian Ocean tsunami, in which they highlighted the importance of flow speeds in determining damage distribution and disparities in timing and spatial characteristics of return flow compared to onshore flow. Particularly, return flow was initiated before maximum inundation of prior wave is reached, is more concentrated than onshore flow and continues 500 m offshore (Prasetya et al., 2011b).

Australian National University-Geoscience Australia (ANUGA)

ANUGA[1] is an open source code developed to simulate tsunami as part of the Australian Tsunami Warning System. The conservative form of SWE are applied in a two-dimensional finite-volume method on a triangular mesh, with a focus on modelling inundation, therefore the model includes a wetting-drying function and ability to model hydraulic jumps (Geoscience Australia and the Australian National University, 2010; Jakeman et al., 2010), which makes it particularly suitable for modelling shallow flows around structures, such as in an urban environment. Frictional resistance is applied using Manning's formula. As with other two-dimensional models, ANUGA is limited from representing breaking waves or three-dimensional turbulence. Spherical coordinates are not supported, therefore large-scale analyses (larger than 6°) cannot be conducted, limiting use of the model to local and regional studies. Importantly, ANUGA does not allow explicit source modelling so the initial source must be modelled in another piece of software, and the results of propagation used as a boundary condition for ANUGA (Jakeman et al., 2010). ANUGA has been validated against physical modelling of the 1993 Okushiri Island tsunami and applied in simulation of the 2004 Indian Ocean tsunami (Jakeman et al., 2010). At present, ANUGA requires further refinement in order to satisfy conservation of physical energy, even in smooth, frictionless flows (Mungkasi and Roberts, 2013).

[1] https://anuga.anu.edu.au/

COrnell Multi-grid COupled Tsunami (COMCOT)

COMCOT enables linear and non-linear modelling of the conservative form of the SWE, in both Spherical and Cartesian coordinates. The conservative form solves for volume flux rather than velocity alone, therefore the equations retain validity in the nearshore area, where shallow water assumptions begin to break down due to the decreasing ratio of water depth to tsunami wavelength. The conservative form also provides better performance at local scales where bathymetric variation is significant (Wang and Power, 2011). An explicit leap-frog finite difference method is adopted to solve both linear and non-linear shallow water equations (Cho, 1995). Initial conditions comprise instantaneous and transient sea floor disturbance, landslides and initial water surface displacement.

COMCOT has been validated against analytical and experimental benchmark problems (Liu, Yeh, and Synolakis, 2008; Liu et al., 1995b; Wang and Liu, 2008) and has proven accurate in re-producing field observations of past events (Gica et al., 2007; Liu, Cho, and Fujima, 1994; Liu et al., 1995b; Wang and Liu, 2006). In recent years, COMCOT has been used extensively by GNS Science for tsunami modelling in New Zealand. These studies include inundation modelling of distant-source and local-source tsunami at Gisborne (Wang et al., 2009), and tsunami hazard from the Southern New Hebrides and Kermadec subduction margins (Power and Gale, 2011). The methods applied in these studies provide a guide for the set-up of a suitable model for use in this study, and indeed, some of the data used in this study was originally developed for these earlier studies.

Method of Splitting Tsunami (MOST)

MOST was developed by the United States (US) National Oceanic and Atmospheric Administration (NOAA) for tsunami modelling and real-time forecasting. It solves the nonlinear SWE in two directions, along-shore and onshore, separately rather than solving in two-directions. This involves splitting the governing equations into two sets — each with one spatial dimension x and y with a finite-difference method. The model has been validated against standard benchmarks problems (Liu, Yeh, and Synolakis, 2008). MOST is now used internationally for tsunami inundation forecast modelling, including the NOAA operational tsunami forecasting system. MOST has previously been used to simulate at-shore tsunami wave heights for various scenarios on the Hikurangi subduction zone interface (Power, Reyners, and Wallace, 2008).

River and Coastal Ocean Model (RiCOM)

RiCOM solves non-linear SWE with terms to describe non-hydrostatic forces on a mesh of triangular of quadrilateral elements (Downes et al., 2005; Lane et al., 2011, 2013; Walters, Barnes, and Goff, 2006). Finite-volume method is used to calculate fluxes through the face of each element. This permits natural simulation of wetting and drying in intertidal and onshore areas. Free surface displacement is used as initial tsunami condition — time histories of water level and current velocity (e.g., Lane et al., 2013) or water level corresponding to the a rapid (considered instantaneous) sea floor rupture (Walters, Barnes, and Goff, 2006). The model enables boundary conditions at the open sea boundaries to be set to radiate, mimicking the flow of tsunami out of the model domain without reflection from that boundary. The model has been validated for tsunami benchmark studies by Walters (2003) and has been applied in several local-source tsunami studies around the New Zealand coast (Lane et al., 2013; Walters, Barnes, and Goff, 2006; Walters, Goff, and Wang, 2006)

Tohoku University's Numerical Analysis Model for Investigation of Near-field tsunamis (TUNAMI)

The TUNAMI code comprises linear and shallow water codes operating on fixed and variable resolution grids, designed to simulate tsunami in the near-field and far-field (Imamura, Yalçiner, and Ozyurt, 2006). The TUNAMI -N2 (Goto et al., 1997) version uses a leap-frog finite difference scheme to solve the non-linear SWE. Modifications made by Dao and Tkalich (2007) introduced dispersion terms and the influence of Coriolis Force and the Earth's curvature. TUNAMI facilitates sea surface deformation due to multiple non-simultaneous ruptures, through the Mansinha and Smylie (1971a) fault model. TUNAMI has been validated against observations of past tsunami (Dao and Tkalich, 2007) and has been widely applied in simulation of tsunami in multiple regions (e.g., Mas, Adriano, and Koshimura, 2013; Mas et al., 2012a; Suppasri et al., 2012; Yalçiner et al., 2004; Zahibo et al., 2003).

The rest of this chapter presents the published paper, in which COMCOT is used to simulate local-source subduction zone tsunami inundation at Napier, Hawke's Bay, New Zealand.

4.2 Abstract

Deterministic analysis of local tsunami generated by subduction zone earthquakes demonstrates the potential for extensive inundation and building damage in Napier, New Zealand. We present the first high-resolution assessments of tsunami inundation in Napier based on full simulation from tsunami generation to inundation and demonstrate the potential variability of onshore impacts due to local earthquakes. In the most extreme scenario, rupture of the whole Hikurangi subduction margin, maximum onshore flow depth exceeds 8.0 m within 200 m of the shore and exceeds 5.0 m in the city centre, with high potential for major damage to buildings. Inundation due to single-segment or splay fault rupture is relatively limited despite the magnitudes of M_W 7.8 and greater. There is approximately 30 min available for evacuation of the inundation zone following a local rupture, and inundation could reach a maximum extent of 4 km. The central city is inundated by up to three waves, and Napier Port could be inundated repeatedly for 12 h. These new data on potential flow depth, arrival time and flow kinematics provide valuable information for tsunami education, exposure analysis and evacuation planning.

4.3 Introduction

The Hikurangi subduction margin is a potential source of 'large-to-great earthquakes' (Berryman, 2005) and the local nature of tsunami generated from such an earthquake is of significant concern to the New Zealand scientific and emergency management communities. New Zealand is also at risk of tsunami from regional and distant sources and is a member of the Pacific Tsunami Warning System (PTWS). The Ministry of Civil Defence and Emergency Management (MCDEM) aims to assess the tsunami threat to New Zealand and if appropriate disseminate a national tsunami advisory or warning within 15–30 minutes following receipt of a Pacific Tsunami Warning Center information bulletin, watch or warning, or a GNS Science earthquake report (MCDEM, 2010a). However, for local tsunami, defined in New Zealand as having travel time of <1 h from source to the coastal area of interest (MCDEM, 2010a), 15–30 min represents a significant portion of the time available for evacuation of coastal locations proximal to the source. Education and awareness of the local tsunami hazard are vital to enable the public to recognise the potential for tsunami following a local earthquake and act accordingly through immediate self-evacuation.

This paper enhances current knowledge of the local tsunami hazard in Napier, Hawke's Bay, by demonstrating potential tsunami inundation due to earthquakes at the Hikurangi subduction margin. Although the city has not experienced a significant local tsunami in recorded history, there are sites in Hawke's Bay that exhibit evidence of past tsunami in the form of high-energy marine deposits. Damaging local tsunami have been recorded elsewhere on the east coast of the North Island, most notably two local-source tsunami that affected Gisborne in 1947 (Downes et al., 2000). We provide the first published assessment of inundation in Napier based on simulation of the full tsunami process for multiple subduction zone tsunami scenarios. Previous consideration of tsunami generated by earthquakes on the Hikurangi subduction margin (Berryman, 2005; Power, Reyners, and Wallace, 2008) is limited to estimation of wave heights at shore with empirically estimated maximum run-up heights. In order to advance tsunami mitigation and evacuation planning in coastal communities, accurate estimates of flow depth and inundation extent are now required.

The scenarios applied in this study include the worst-case tsunami for use in community preparedness and tsunami mitigation activities but it is also important to investigate onshore impacts due to other plausible tsunamigenic earthquakes. The maximum credible earthquake is represented by a moment magnitude (M_W) 9.0 rupture of the whole subduction margin. This is considered as an upper limit to plausible magnitudes of such a rupture at this margin. We also demonstrate the potential for inundation due to smaller local ruptures that have been discussed in previous studies, but have not been used in simulation of onshore inundation. We describe tsunami impacts in terms of flow depth and structural damage potential, and present wave arrival times to constrain estimates of time available for evacuation.

4.4 Study area

Napier Territorial Authority (hereafter, Napier) is a coastal urban centre, identified at substantial risk of tsunami from previous hazards assessments (Berryman, 2005; Power, Reyners, and Wallace, 2008). There is a need for detailed tsunami hazard assessment to inform the development of evacuation plans and tsunami education to increase the resilience of individuals and the local community. Napier has an estimated resident population of 57,800 (Statistics New Zealand, 2013a, at June 30 2012). The same projections indicate that 10,200 (17.6%) of the population are over age of 65, which is the demographic group shown by recent experience to be the most vulnerable to tsunami. In the 2011 Great East Japan tsunami over 65% of deaths in the three worst-affected prefectures were of people over 60 years of age (Nakasu et al., 2011). Napier covers an area of 106 km^2, comprising residential suburbs, commercial and industrial areas and agricultural land including orchards and vineyards. Hawke's Bay Airport, which operates internal passenger and freight flights and would likely be required to provide access in response to an earthquake and tsunami, is situated on an area of land between 0.5 m and 1.5 m above mean sea level and 250–1,700 m from the coast in Bay View. Napier Port is the fourth largest in New Zealand in terms of the number of containers handled and second largest in the North Island based on export by volume, handling cargo including forestry products and container shipments (Port of Napier Limited, 2012). Stored timber and containers on site are a potential source of fire and damaging debris if entrained in tsunami flow.

The local topography is predominantly low elevation, except for Bluff Hill, which provides an area of high ground immediately north of the city centre to maximum elevation over 100 m (Fig 4.1). On the eastern shore of the city there is a steep gravel beach and berm stretching along the coastline south from Bluff Hill to the confluence of the Tutaekuri, Ngaruroro and Clive Rivers. This berm ranges in elevation above Mean Sea Level (MSL) from 4 m in the south and exceeding 7 m high at its northern end. North-west of Bluff Hill the suburbs of Ahuriri and Westshore are separated by a tidal inlet and small marina. Westshore is situated on a peninsula elevated 4–6 m above MSL. Bay View is the most northern suburb of Napier, extending north around the bay. Much of the land around the present Ahuriri Lagoon and airport was previously below sea level until uplift during the 1931 Hawke's Bay earthquake and artificial drainage in the years since (Hull, 1986). Some of this land remains below MSL. The Hawke's Bay earthquake destroyed many buildings in Napier and resulted in major reconstruction in the 1930s Art Deco style. The 1930s building stock is an important factor in the city's tourism activities. During peak tourist season (January to March), an average of 2,342 visitors stay in Napier accommodation every night (Statistics New Zealand, 2012c, 2006–2011 data).

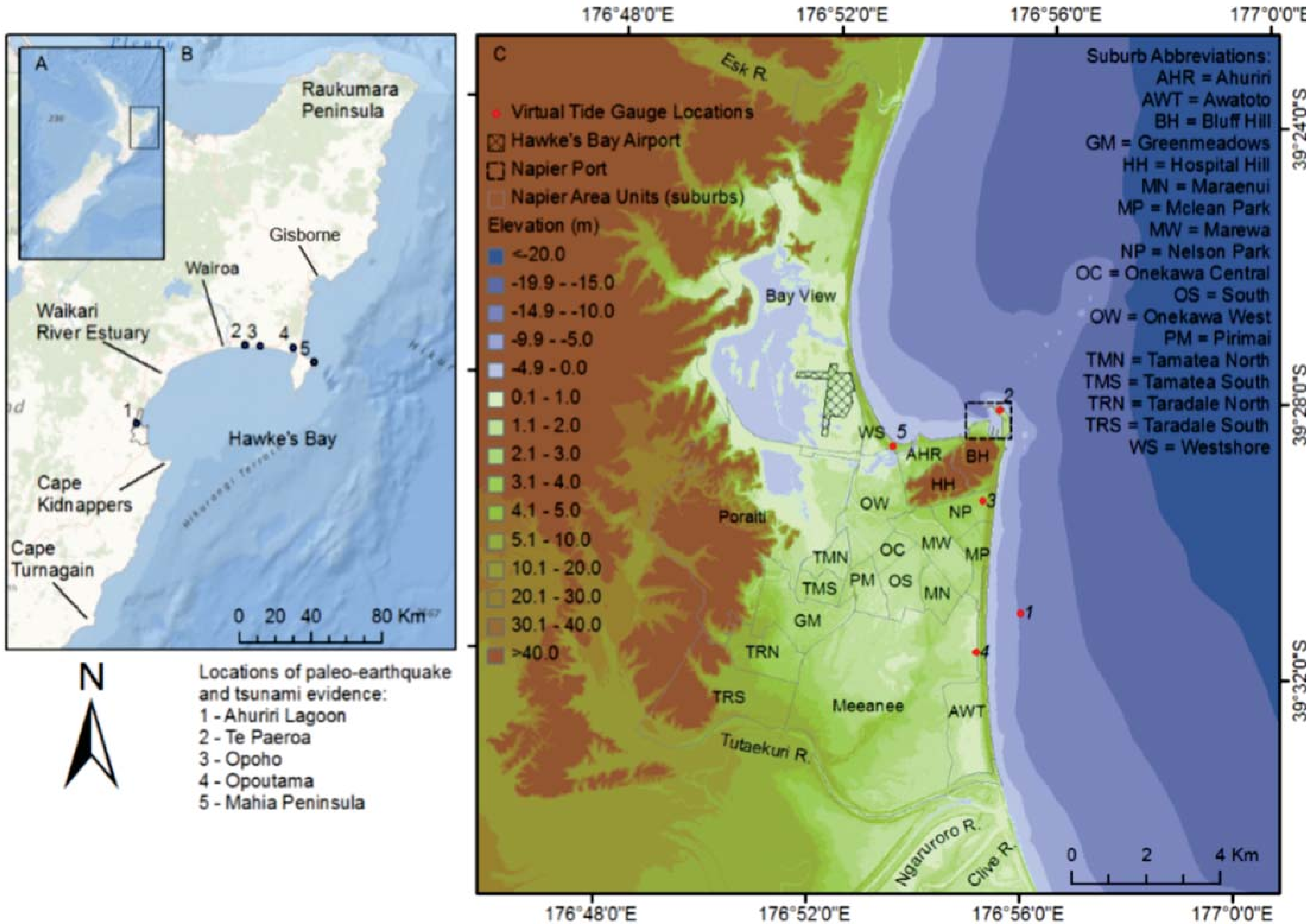


Fig. 4.1: A: Study area shown in the national context. B: Napier Territorial Authority in the Hawkes Bay regional context with numbered locations indicating palaeo-ecological analysis referred to in-text. The boundary of Napier Territorial Authority is shown and other locations referred to in-text are also indicated. C: 10 m DEM showing topography of Napier Territorial Authority with labelled unit areas (suburbs), rivers, Napier Port and Hawkes Bay Airport. Virtual tide gauges quoted in the text are identified

4.5 Hikurangi subduction margin

4.5.1 Tectonic setting and seismic potential

The Hikurangi Trough is the surface expression of westward subduction of the Pacific plate beneath the Australian Plate, situated approximately 50–100 km offshore of the East coast of New Zealand's North Island (Fig 4.2). The subduction margin continues to the north as the Kermadec Trench and the southern limit of subduction is located offshore of the northern South Island, where the plate boundary transitions to strike-slip (Wallace et al., 2012). Moderate subduction thrust earthquakes (Downes, 2006) and tsunamigenic slow slip earthquakes (Downes et al., 2000) have occurred on the Hikurangi subduction margin in recorded history (since c. 1840 A.D.), but no subduction thrust earthquakes greater than M_W 7.2 have been recorded.

Ansell and Bannister (1996) initially characterised the subducting slab using micro-earthquake seismicity and more recent work has provided detailed images of the subduction interface configuration (Barker et al., 2009; Henrys et al., 2006). Global Positioning System (GPS) and seismological observations have been used to define regions of distinctly different subduction interface behaviour and seismic potential (Wallace et al., 2009). Since early seismological studies of the Hikurangi subduction margin, it has been suggested that the plate interface below the lower North Island (Cook Strait to Cape Turnagain) is more likely to produce large subduction thrust events in comparison to the interface below the upper North Island (North of Mahia Peninsula, Fig 4.1B) (Reyners, 1998; Wallace et al., 2009). Convergence of the subducting plates is taking place at rates of around 50–60 $mm.yr^{-1}$ offshore of the upper North Island, while offshore of the lower North Island this rate is lower, at 20–25 $mm.yr^{-1}$ (Wallace et al., 2004).

Below the lower North Island, the plate interface is inter-seismically coupled (coupling coefficient: 0.8–1.0) to around 40 km deep and 90–180 km wide (Wallace et al., 2009). GPS data reveal that this part of the plate interface is building up significant elastic strain that will eventually be released in a large megathrust earthquake (Wallace et al., 2004). Wallace et al. (2009) estimates the lower North Island segment to be 230 km long and 150–185 km wide, and using Abe's 1975 fault scaling relationships translates this to a potential event of M_W 8.5–8.7 with 8–12 m of slip. If the current estimated slip rate deficit of 20–25 $mm.yr^{-1}$ is steady throughout the inter-seismic period, this results in a proposed return period of 300–625 years (Wallace et al., 2009), although uncertainty remains around the amount of slip and recurrence interval. It is also possible that this segment of the interface ruptures in smaller (M_W <8.0) earthquakes more frequently.

At the central North Island segment, including offshore Hawke's Bay, the plate interface currently exhibits low inter-seismic coupling, and is dominated by aseismic slip and slow slip events (Wallace and Beavan, 2010; Wallace et al., 2004), suggesting lower potential for 'stick-slip behaviour', whereby elastic strain accumulates during an inter-seismic period ('stick' component; Scholz, 1998), to be later released in a large earthquake ('slip' component). However, we cannot rule out the possibility of large or great earthquakes at any part of the margin (Wallace et al.,

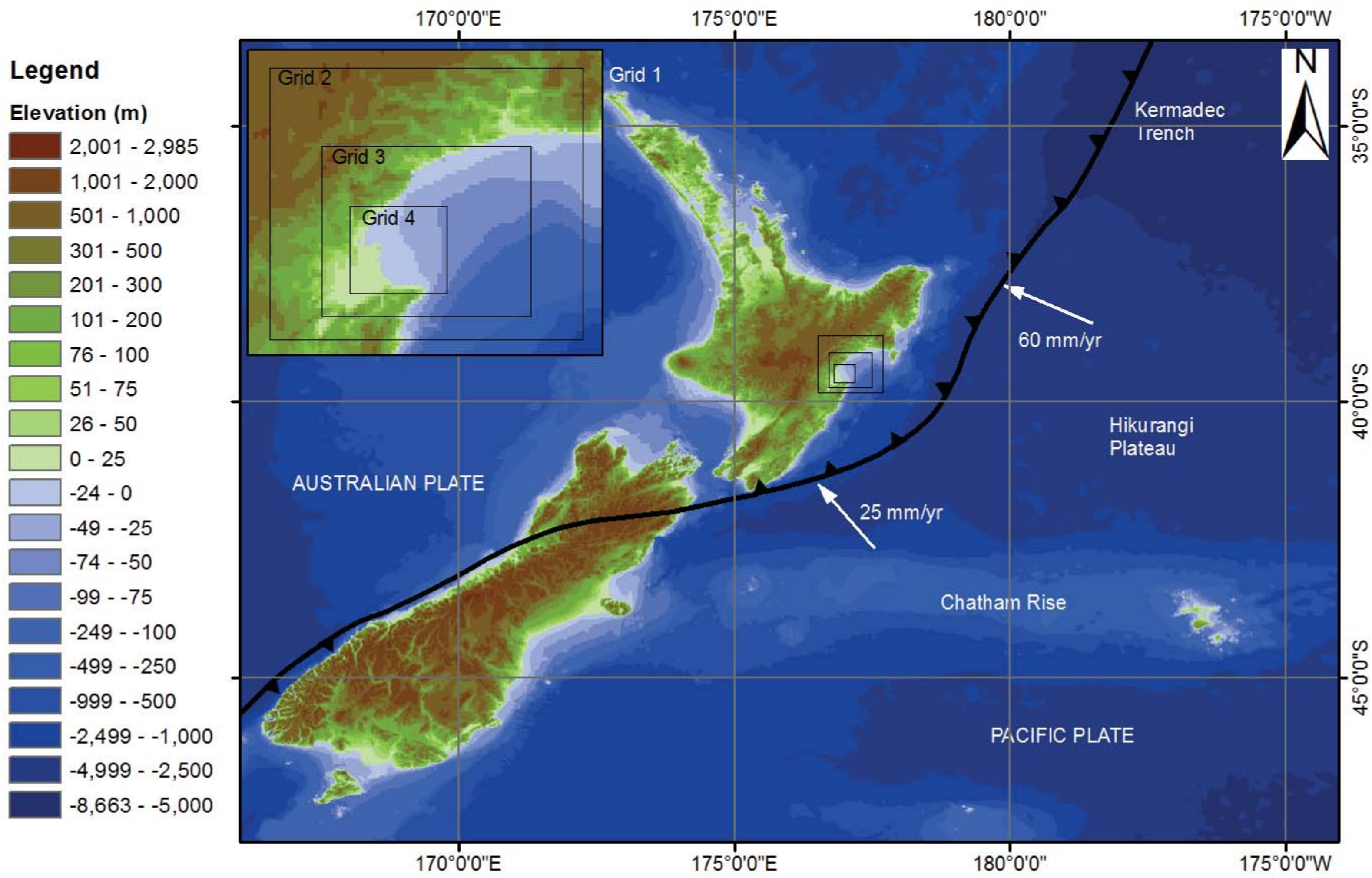


Fig. 4.2: Map illustrating the shaded bathymetry of the model domain. The main map shows grid 1 with the plate boundary marked. The inset shows Hawkes Bay and nested grids 2–4

2009). Despite the shallow inter-seismic coupling extending to only 15 km depth, and the low coupling coefficient, frequent rupture of small patches of the subduction plate occurs and is inferred to be localised asperities exhibiting stick-slip behaviour, possibly related to subducting seamounts (Bell et al., 2010). Subducting seamounts have been related to recurrent earthquakes internationally, including earthquakes of around M_W 7.0 with 30-year recurrence intervals offshore Tōhoku (Yamanaka and Kikuchi, 2004) and the M_W 7.0 Gulf of Nicoya earthquake, Costa Rica (Husen, Kissling, and Quintero, 2002), and have been related to local seismic coupling in an otherwise seismically decoupled subduction zone on the Tonga-Kermadec and Izu-Bonin Trenches (Scholz and Small, 1997).

The plates beneath the upper North Island are less strongly coupled (coupling coefficient: 0.1–0.2) in a region extending to 15 km depth beneath Hawke's Bay and the Raukumara Peninsula. This segment north of Mahia Peninsula is characterised by tectonic erosion and an indented toe, indicating the impact of seamounts on the subducting plate (Collot et al., 2001; Lewis, Collot, and Lallemand, 1998; Pedley et al., 2010). It is believed that this segment is particularly suited to producing tsunami earthquakes that involve a large amount of rupture close to the trench characterised by slow rupture velocities, long rupture durations, low local magnitude (M_L) compared to moment magnitude, and larger than expected tsunami compared to the earthquake magnitude (Kanamori, 1972; Pelayo and Wiens, 1992; Tanioka and Satake, 1996a). Two tsunami earthquakes occurred at the northern Hikurangi subduction margin in March and May 1947 (Downes et al., 2000) and prior to that in 1880, tentatively suggesting a return period of 70 years for tsunami earthquakes in the Gisborne region (Power, Reyners, and Wallace, 2008).

In addition to single-segment ruptures, the potential propagation of rupture across multiple segments must be considered (Power, Reyners, and Wallace, 2008; Wallace et al., 2009). The occurrence of multiple-segment rupture at other major subduction zones, for example during the 2011 Great East Japan (Ishii, 2011), 2010 Maule, Chile (Kiser and Ishii, 2011), 2007 Solomon Islands (Taylor et al., 2008) and 2004 Sumatra (Lay et al., 2005) earthquakes, supports this possibility. Simultaneous rupture of the northern and central segment of the margin could result in an earthquake greater than M_W 8.6, assuming 8 m or more of slip, while the expectation of a full margin rupture is that it would be greater than 650 km long by 100 km wide and M_W 8.8 or greater (Wallace et al., 2009). There also exists the remote possibility of a rupture involving segments on both the Hikurangi and Kermadec subduction margins (Power et al., 2012) but this extreme scenario is not investigated in this study.

4.5.2 Evidence of past earthquakes and tsunami

In recorded history, Napier has experienced distant tsunami in 1868 (due to an earthquake in Peru), flooding of a wharf in 1877 (earthquake, Chile) and 3 m flow depth onshore with damage to infrastructure, buildings and boats in 1960 (earthquake, Chile) (De Lange and Healy, 1986). The tsunami due to the 2010 Chilean earthquake was recorded at Napier with measured peak amplitude exceeding 1.4 m in Ahuriri Harbour and economic loss of NZD 80,000–100,000 due to closure of the Port (Hawke's Bay Regional Council, 2010). Records of tsunami generated within or proximal to Hawke's Bay are limited. Most recently, two slow-slip earthquakes at Gisborne in 1947 (26th March: M_W 7.0–7.1 and 17th May: M_W 6.9–7.1) caused 10 m and 6 m run-up, respectively, at the coast around Gisborne (Downes et al., 2000). There is a possible tsunami in 1937 or 1938 that may have affected Wairoa, recorded by Goff (2008b). In 1931, a sub-aerial landslide close to the Waikari River was triggered by the Hawke's Bay earthquake and in turn caused a localised tsunami with 15 m run-up in the Waikari River Estuary and 3 m at Wairoa (Fraser, 1998). See Fig 4.1B for locations referred to in this section.

In addition to the limited historic record, palaeo-seismic and palaeo-tsunami data are relied upon to enhance the record of pre-historic subduction earthquakes and tsunami. Goff (2008b) lists around ten possible events with deposits found in Hawke's Bay dated between the 15th Century and 8,000 calendar years before present (cal. yr BP), and several more that possibly occurred prior to Maori settlement. The certainty with which we can infer that deposits are due to tsunami varies significantly, but where a tsunami deposit is synchronous with an episode of sudden subsidence we can infer that a local earthquake was a possible trigger of the tsunami. Evidence of earthquake events on the Hikurangi subduction margin exists in the form of repeated sudden-subsidence and uplift events in Hawke's Bay. At Ahuriri Lagoon, Hull (1986) identified one or more rapid subsidence events totalling 8 m of subsidence between 1,750 and 3,500 radiocarbon years before present (14C yr BP) and one event of 1 m subsidence at 500 14C yr BP. This was supported by further micro-paleontological analysis at Ahuriri Lagoon by Hayward et al. (2006), who identified six separate subsidence events within the last 7,200 cal. yr with a recurrence interval of 1,000–1,400 cal. yr and a subsidence range of 0.5–1.8 m in each event. The approximate age of fifteenth-century tsunami deposits in Hawke's Bay (Goff, 2008b) coincides with the most recent episode of (1 m) subsidence in Ahuriri Lagoon (Hayward et al., 2006) suggesting that this represents the most recent local earthquake and tsunami event for which there is geological evidence.

Cochran et al. (2006) recorded net subsidence of 4 m over the last 7,200 cal. yr at Te Paeroa Lagoon in northern Hawke's Bay and of 6 m at Opoho, 10 km to the east. At each site, two episodes of subsidence have been dated to c. 5,550 and c. 7,100 cal. yr BP suggesting that in each case, either a single large earthquake caused synchronous vertical deformation at both sites, or that each site underwent separate incidents of localised subsidence very close together in time. At both sites, subsidence is synchronous with a high-energy marine deposit of coarse sand and gravel inferred to be due to tsunami inundation (Chagué-Goff et al., 2002; Cochran et al., 2005). This deposit extends to 2 km inland at Te Paeroa, representing a significant inundation extent. Three lakes, 60 km and 30 km away from the core sites, formed at c. 7,100 cal. yr BP (Page and Trustrum, 1997) provide further evidence for an earthquake occurring with sufficient intensity to cause co-seismic landslides (Cochran et al., 2006). There are three other marine-source high-energy deposition units identified by Cochran et al. (2005) at Opoho and three at nearby Opoutama that may represent tsunami deposits but have not yet been determined to be synchronous with subsidence events.

In addition to subsidence episodes, investigations of Holocene marine uplifted terraces along the east coast of the North Island indicate episodes of rapid co-seismic uplift (Berryman, Ota, and Hull, 1989; Clark et al., 2010), inferred as being due to rupture of local upper plate faults occurring either in conjunction with or independently of plate interface rupture (Berryman, Ota, and Hull, 1989; Berryman et al., 2011). Berryman et al. (2011) postulate that several anomalously young dates (with respect to the height of the terrace or age of nearby terraces) obtained for terraces in the lower North Island are due to tsunami depositing sediments on terraces which had been uplifted during previous deformation events. In particular, four marine uplift events are believed to have resulted in localised tsunami deposition along as much as 100 km of the North Island coast, at 1,463–1,670 AD, 1,282–1,408 AD, 267–449 AD and 270–405 AD. No uplifted terraces have been recognised as synchronous with the subsidence episodes identified at Opoho and Te Paeroa, as the respective records overlap by only 500 years, although there is a possibility of synchronous uplift-subsidence event at c. 5,500 cal. yr BP (Cochran et al., 2006). Dating of the known uplift episodes has not been carried out to sufficient detail to identify whether any of the episodes occurred synchronously between sites long distances apart, which would suggest a significant plate interface rupture (Wallace et al., 2009).

Cochran et al. (2006) used forward elastic-dislocation modelling to demonstrate that the magnitude and distribution of subsidence recorded in northern Hawke's Bay and uplift of Mahia Peninsula could be approximately replicated by several vertical deformation scenarios. They tested scenarios of 8 m slip on the plate interface, 8 m slip on the Lachlan Fault and a combination of both. Replication of the correct uplift-subsidence distribution and amount of subsidence due to rupture of the Lachlan Fault alone is at the lower limit of that recorded in cores. Although permanent coastal deformation was replicated for the plate interface rupture with no Lachlan Fault component, uplift at the Mahia Peninsula is most likely due to a component of upper plate thrusting, rather than isolated rupture of the plate interface, therefore a combined rupture of plate interface and upper plate faults is favoured as the cause of recorded subsidence-uplift distributions (Cochran et al., 2006). The scenarios identified by Cochran et al. (2006) inform the choice of scenarios tested in this study.

4.5.3 Previous tsunami hazard assessment

There have been several investigations into likely severity of tsunami generated by an earthquake on the Hikurangi subduction margin, which have provided estimates of at-shore wave heights. The first New Zealand National Tsunami Hazard Review (Berryman, 2005) estimated probabilistically a median wave height of 4.5 m from all sources at Napier/Hastings to be a 1 in 500 year event. The review estimated that such an event would cause 320 deaths and 2,100 injuries in Napier and Hastings. Power, Reyners, and Wallace (2008) simulated tsunami generated by 17 rupture scenarios on the margin, producing modelled tsunami wave heights at-shore for each scenario. The largest at-shore wave heights at Napier are in excess of 5 m and are produced by an M_W 9.0 rupture of the whole margin and an M_W 8.2 simultaneous rupture of the plate interface offshore Hawke's Bay and the Lachlan Fault in Hawke's Bay. Rupture of the lower North Island segment produced wave heights of up to 3 m at Napier. Maximum wave height at Napier due to rupture of the segment offshore of the Raukumara Peninsula was 1 m and simulations of the 1947 slow-slip events resulted in negligible waves at Napier. It has not yet been possible to directly validate these tsunami inundation scenarios against observed or measured tsunami inundation due to the absence of well-recorded historical tsunami events at the study area (with the exception of the 1947 Gisborne earthquakes). Therefore, despite evidence supporting the potential for such events, the results of these scenarios retain a high level of uncertainty. Additionally, RiskScape contained Lachlan Fault scenarios (King and Bell, 2009), but omitted subduction zone earthquake scenarios.

Utilising detailed topographic data, Hawke's Bay Regional Council (HBRC) produced tsunami hazard maps (Hawke's Bay Civil Defence And Emergency Management, 2011) using an incident wave of 10 m amplitude relative to high tide, initiated approximately 20 km offshore of Napier (Craig Goodier, personal communication, April 15th 2013). Results presented here support the inundation extent of the HBRC hazard maps but, due to the use of an incident wave rather than an earthquake source mechanism, the HBRC study is unsuitable for estimation of wave arrival time and does not demonstrate the variability of inundation resulting from different local-source ruptures.

4.6 Methodology

Tsunami generation, propagation and onshore inundation are modelled using the Cornell Multi-grid Coupled Tsunami (COMCOT) model. COMCOT solves the conservative form of shallow water equations SWE in terms of flow velocity and volume flux within an explicit staggered leap-frog finite difference scheme (Cho, 1995; Liu, Woo, and Cho, 1998; Wang and Power, 2011). A nested grid configuration is used to maximise both computational efficiency and accuracy by applying linear SWE in grids 1–3 and non-linear SWE in the onshore grid 4. In the near-shore, numerical dissipation replicates the energy dissipation of wave breaking, although wave-breaking cannot be explicitly modelled. A moving boundary scheme tracks the moving shoreline during non-linear simulation of onshore inundation. The model has been validated in numerous analytical and physical modelling benchmark tests (Liu et al., 1995a,b; Wang and Liu, 2008), has been used in previous studies of tsunami affecting New Zealand (e.g., Power et al., 2012, 2013) and several globally significant tsunami (e.g., Baptista et al., 2011; Wang and Liu, 2006).

4.6.1 Model setup

The model comprises four levels of nested grids (Fig 4.2) with maximum grid cell resolution of 15 m in the onshore area of interest (Table 4.1). Although the DEM is at 10 m resolution, significant computational cost is associated with processing non-linear shallow-water equations at 10 m cell size. We conducted model sensitivity tests to determine the influence of model grid resolution on computational expense and congruence of inundation extent in 13 simulations before selecting the appropriate resolution to apply in the model. Compared to the highest resolution model (7 m in grid 4, identical resolution in grid 1–3), the model run at 15 m resolution produces $<1\%$ difference in inundation area and inland extent, but requires only 13% of the computational time.

Tab. 4.1: COMCOT model domain information, showing spatial extent and cell resolution of model grids in arc seconds and metres, data source and data resolution.

Model grid number	Long. extent (degrees)	Lat. extent (degrees)	Model grid resolution (arc sec)	Model grid resolution (m)	Bathymetry / topography source and resolution
1	166.0 to 186.0	-48.0 to -33.5	60	1239–1852	30 arc sec ETOPO1 updated with GEBCO08/LINZ charts/CMAP
2	176.5 to 177.7	-39.85 to -38.8	12	284–370	10 arc sec interpolated LINZ charts /CMAP
3	176.7 to 177.5	-39.75 to -39.1	2.4	57–74	10 arc sec LINZ charts /CMAP
4	176.81 to 177.18	-39.66 to -39.33	0.48	11–15	10 m DEM Created for this study – LiDAR, LINZ Nautical charts

Grids 1 to 3 are based on worldwide ETOPO1 global relief data (Amante and Eakins, 2009), General Bathymetric Chart of the Oceans data (GEBCO, 2008), and LINZ (Land Information New Zealand, 2006) charts at 10 arc seconds (Grids 2 and 3) and 30 arc seconds resolution (Grid 1) (Table 4.1). In order to achieve high-resolution inundation modelling in grid 4, we developed a seamless 10 m horizontal resolution digital elevation model (DEM) comprising Light Detection and Ranging (LiDAR) ground elevation data for onshore topography and interpolated LINZ digital bathymetric sounding depths. Original sounding depths are available at irregular spacing on the order of several kilometres distance so we augmented these data by digitising LINZ nautical charts to provide irregularly-spaced depths at distances on the order of several hundred metres. To produce a regularly-spaced grid of data for use in COMCOT, all bathymetry and topography data were interpolated to a 10 m grid using the ArcGIS Topo To Raster algorithm, based on the ANUDEM program (Hutchinson, 1989).

Bottom friction, or surface roughness, is an important cause of tsunami flow resistance and energy dissipation, particularly in shallow water (0–10 m depth) of the near-shore and onshore areas (e.g., Myers and Baptista, 2001). Onshore, land cover is used to define surface roughness, commonly in terms of Manning's coefficient (Arcement and Schneider, 1989). The influence of surface roughness on inundation extent, flow depth and velocity in high-resolution modelling has been demonstrated by comparisons between several approaches to implementation of roughness. Muhari et al. (2011) describes the available approaches as: *Topographic Model* whereby building geometry and elevation are incorporated into the DEM; *Constant Roughness Model*, whereby a uniform surface roughness coefficient is applied throughout the study area; and *Equivalent Roughness Model*, whereby spatially varying land cover and density of buildings are used to assign variable roughness coefficient in a model domain. The resolution of our model (15 m), being coarser than many buildings and streets, precludes accurate representation of buildings in a topographic model, or application of high roughness coefficients to individual buildings with lower roughness representing streets between (e.g., Gayer et al., 2010; Kaiser et al., 2011). We apply the *Equivalent Roughness* approach, using New Zealand Landcover Database version 2 (LCDB2; Ministry for the Environment, 2009) to assign a roughness coefficient to each generalised land cover category in Napier, resulting in variable roughness across the study area (Fig 4.3). Urban landcover is accounted for using a single roughness coefficient without the consideration of individual buildings.

We assign urban areas as $n = 0.030$, arable land as $n = 0.019$ and woodland as $n = 0.026$, after Wang et al. (2009). We consider the urban value appropriate for the low building density in Napier (10%–30% density in 92% of city meshblocks and maximum building density of 67%). This is a lower roughness coefficient than those used in other recent studies for medium-density urban areas ($n = 0.059$; Kaiser et al. (2011)) and populated areas ($n = 0.045$; Kotani, Imamura, and Shuto (1998) in Muhari et al. (2011)). Sensitivity testing was conducted on the roughness values applied to the Central Business District (CBD) (n =0.030, or n =0.200), as part of the model development process. It was shown that a high roughness value of $n = 0.2$ reduced inundation extent by 8 km^2 compared to $n = 0.030$. The higher n value also reduces inundation extent by upto 50% at a time of 1 hr after the earthquake. In a study that is being used to focus on evacuation modelling, conservatism in the resulting inundation extent is desired, hence the low roughness friction implemented. The values used for arable and woodland areas are also lower than those used elsewhere in the literature for various types of vegetated and forested land which vary between $n = 0.025$ and $n = 0.26$ (Kaiser et al., 2011; van der Sande, de Jong, and de Roo, 2003). Consistent with the previous studies of roughness influence, roughness coefficients applied in this study are static through time and do not account for destruction of buildings in tsunami flow. The sea bed is represented by homogenous bed friction of $n = 0.013$ in all grids, although at most water depths in grids 1 to 3 the impact of friction is negligible.

Five 'virtual' tide gauges (Table 4.2) are used to record time-series water level and flow depth

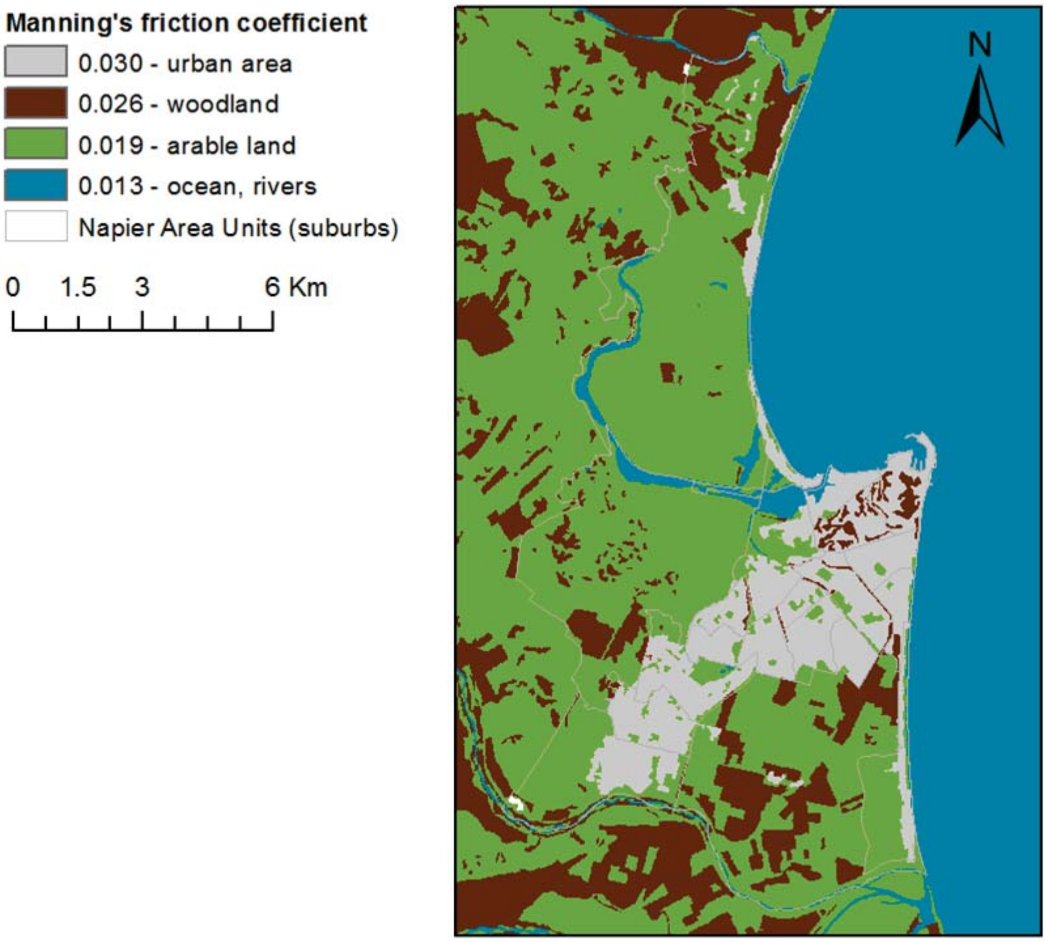


Fig. 4.3: Surface roughness values (Mannings coefficients) applied in Napier, based on New Zealand Land-cover Database 2 data (Ministry for the Environment, 2009, LCDB2;)

data for the 12 hours of simulated flow at key areas of interest. Gauge 1 is located in the near-shore area east of Napier and gauges 2–5 are located onshore at the Port, in the eastern city and at Westshore (Fig 4.1C). These virtual gauges exist only in the model to record simulated flow time-series.

Tab. 4.2: List of virtual tide gauges with their location and elevation.

Gauge Number	Location	Long.	Lat.	Elevation / depth relative to MSL (m)
1	Nearshore	176.93	–39.52	–10.4
2	Port	176.92	–39.47	1.8
3	City	176.92	–39.49	3.2
4	City	176.92	–39.53	1.2
5	Westshore	176.89	–39.48	2.63

4.6.2 Earthquake source mechanisms

The earthquake source mechanisms used in this study represent scenarios local to Hawke's Bay that are discussed in previous studies as subduction zone earthquakes with the potential to cause significant at-shore wave heights in Hawke's Bay or replicate geologically recorded subsidence-uplift patterns (e.g., Cochran et al., 2006; Power, Reyners, and Wallace, 2008; Wallace et al., 2009). These scenarios are implemented in COMCOT as instantaneous ruptures using vertical deformation as an initial surface condition (Fig 4.4). Vertical deformation is modelled using elastic fault dislocation theory (Okada, 1985) and coseismic deformation is accounted for during inundation modelling.

Although not considered in this initial investigation of inundation, implementation of dynamic rupture may affect arrival times and wave heights particularly where rupture length is on the order of several hundred kilometres (Suppasri, Imamura, and Koshimura, 2010). A mean water depth of approximately 1,000 m between the Hikurangi Trench and the coast of the North Island gives wave celerity of approximately 99 m/s using $c = \sqrt{gD}$ (where g is gravitational acceleration and D is water depth). Applying typical rupture velocities of 1–2.5 km/s to calculate the ratio of rupture velocity to wave celerity (Suppasri, Imamura, and Koshimura, 2010), the ratio for our study area is <40. Based on results of testing by Suppasri, Imamura, and Koshimura (2010) this indicates that dynamic rupture is likely to influence wave height and arrival time at the east coast of the North Island. Due to the influence of propagation direction and distance from the tsunami source on the magnitude of this effect, and the rapidly shallowing bathymetry between the Hikurangi Trench and the coast (water depth = 3,400 m offshore Hawke's Bay; Fig 4.2), further research expanding this study is required to constrain the potential influence of dynamic rupture in the context of our study

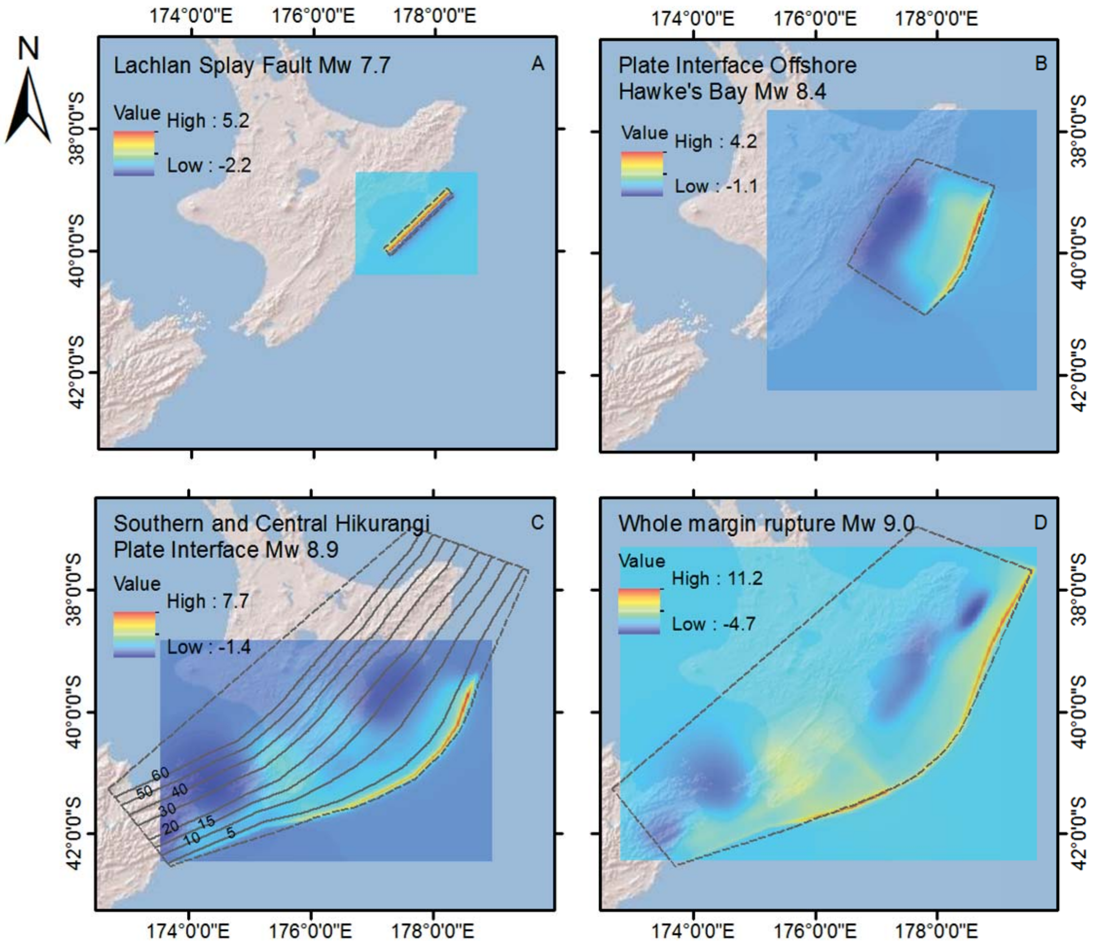


Fig. 4.4: Vertical deformation applied as tsunami generation in COMCOT, with source patches delineated (*grey dashed lines*). A: Lachlan Fault rupture using simple fault geometry and 9.0 m slip (M_W 7.7); B: Rupture of the plate interface offshore of Hawkes Bay (M_W 8.4); C: Rupture of southern and central Hikurangi subduction margin (M_W 8.8); D: Rupture of the whole Hikurangi subduction margin (M_W 9.0). Vertical scale differs on each image. The background value of approximately zero deformation is retained to indicate the extent of vertical deformation domain. Depth contours (km) of the plate interface model (Ansell and Bannister, 1996) are shown in C

area.

Tidal level at the time of tsunami arrival can be an important factor in determining inundation extent and flow depth. We test the impact of tidal level on inundation in scenarios A and D by simulating the events at Mean High Water (MHW) (MHW = MSL + 0.75 m) and discussing the results with reference to the two tidal conditions. There remains significant uncertainty in the specific fault geometry, magnitude and spatial distribution of slip and temporal development of potential ruptures of the Hikurangi Margin due to the limited current understanding of the Hikurangi subduction margin. Nevertheless, our application of this range of scenarios provides an extension of current knowledge of potential inundation due to local earthquake-generated tsunami.

Scenario A: Lachlan Fault rupture using simple fault geometry (M_W 7.7)

The Lachlan Fault is an active upper plate splay fault with a west-dipping thrust fault mechanism and a listric geometry, steepening from a shallow dip of ∼15° at 7–8 km depth to 55–70° in the upper 1 km, emerging at the sea floor 3–8 km offshore (Barnes, Nicol, and Harrison, 2002). We use a simplified geometry to represent the Lachlan Fault, applying a uniform dip of 60°. Barnes, Nicol, and Harrison (2002) identified three segments on the fault with a total length of 80 km, and acknowledged there may be a fourth segment present. We extend the length of the Lachlan Fault source to the south, to a conservative length of 139.79 km to account for the possibility of continuation of Lachlan Fault rupture onto other nearby splay fault structures further along strike (such as those related to the Cape Kidnappers anticline) as rupture of multiple splay faults beneath southern Hawke's Bay could pose a greater danger to Napier than an isolated Lachlan Fault rupture.

Berryman (1993) identified four Holocene uplift events at the nearby Mahia Peninsula, with a maximum uplift of 4 m and attributed this uplift to movement of the Lachlan Fault. Barnes, Nicol, and Harrison (2002) projected this uplift across the Lachlan Fault and, based on the ratio of previous surface deformation to modelled subsurface displacement on nearby faults, estimated an average dip-slip displacement of 5.0–9.0 m. We define three scenarios of whole-fault rupture at the upper end of this range with respective uniform dip-slip values of 7.0 m, 8.0m and 9.0 m (Fig 4.4A; Table 4.3); for the 9.0 m scenario, we simulate for both MSL and Mean High Water (MHW) conditions. We derive the seismic moment (M_0) for each scenario using the relationship $M_0 = \mu SD$ (where S = average slip (m), D = fault area (m^2) and μ = rigidity, assumed in all scenarios to be $3 * 10^{10}$ Pa; Stirling et al. (2012)). The magnitude of each slip scenario is M_W 7.7, using $M_W = (LOG(M_0) - 9.1)/1.5$ (IASPEI, 2013), which is consistent with estimates that a rupture of all segments of the Lachlan Fault could generate an event of M_W 7.6–8.0. (Barnes, Nicol, and Harrison, 2002). This level of slip is believed to represent a recurrence interval of approximately 1,000 years, corresponding to the mean recurrence interval of the four Holocene uplift events (Berryman, 1993). The most northerly segment of the Lachlan Fault has a recurrence interval of 615–2,333 yr based on the ratio of surface displacement to surface slip rate 0.30–0.65

cm/yr (Barnes, Nicol, and Harrison, 2002).

Scenario B: Rupture of the plate interface offshore Hawke's Bay (M_W 8.2–8.4)

Cochran et al. (2006) showed that rupture of the plate interface offshore Hawke's Bay is potentially responsible for past subduction earthquakes and tsunami in Hawke's Bay and Wallace et al. (2009) estimate that rupture of the full segment could result in an M_W 8.3 event. To test the potential tsunami inundation from such an event, we apply a non-uniform slip distribution on a model of plate interface geometry derived from seismicity and seismic reflection data (Ansell and Bannister, 1996). The source model comprises 14,143 individual slip patches with 195–219° strike and dip of 5–8° at 3–15 km depth increasing to 10–17° at 15–27 km (see Table 4.3 for summarised parameters).

We assume slip within the source area of previous slow-slip events at the central Hikurangi subduction margin, which are located at the down-dip limit of shallow ($<$10–15 km) inter-seismic coupling (Wallace and Beavan, 2010). Rupture occurs with an oblique thrust mechanism and strike-slip component of 1 m. Maximum dip-slip (5.7 m) occurs at a depth of between 3 km and 5 km offshore of Mahia Peninsula where coupling coefficient is $>$0.5 (Wallace and Beavan, 2010) and slip rate deficit exceeds 25 $mm.yr^{-1}$ (Wallace et al., 2012). Slip diminishes with increasing depth, reducing to zero below the area of slow slip at a depth of 20–27 km. The seismic moment of each patch sums to a total $M_0 = 2.80 * 10^{21}$ Nm, equivalent to M_W 8.2. In order to explore the impact of increasing slip on inundation, we have applied a linear scaling relationship of 150% and 200% to produce three different magnitude events with an unchanged slip distribution: M_W 8.2, M_W 8.3 and M_W 8.4 (Table 4.3). Rupture of this segment alone is unlikely to produce an earthquake of greater than M_W 8.3–8.4 due to the size of the segment so M_W 8.4 represents an extreme case of rupture on this fault, and results in maximum subsidence of –0.5 m in the south-east of Napier (Fig 4.4B).

Tab. 4.3: Scenario fault parameters. *Denotes that the scenario uses variable slip parameters on multiple source patches, for which this table presents a summary. A range of slip values, strike and dip angles are given for these events. Full variable slip parameters are provided on the accompanying CD.

Scenario	Focal Plane Centre Long / Lat	Focal Plane Centre Depth (km)	Focal Plane Depth Range (km)	Length (km)	Width (km)	Strike (deg)	Dip (deg)	Rake (deg)	Max. Dip-slip (m)	Max. Strike-slip (m)	Seismic Moment (Nm)	Moment Mag. (M_W)
A: Lachlan Fault	177.72, –39.53	6.25	0.5–12.0	139.8	13.3	218.5	60.0	90.0	7.0 8.0 9.0	0.0	3.90E+20 4.46E+20 5.01E+20	7.7 7.7 7.7
*B: Offshore Hawke's Bay	177.77, –39.66	10.6	3.0–26.9	213.7–254.0	121.4–157.3	195.3–219.0	5.0–17.0	62.9–90.0	5.7 8.5 11.4	1.3 2.0 2.6	2.80E+21 4.20E+21 5.60E+21	8.2 8.3 8.4
* C: Southern to central Hikurangi	176.38, –39.87	28.6	3.0–69.6	643.0–736.2	188.9–297.5	195.3–256.0	5.0–30.3	11.3–90.0	22.0	13.6	2.27E+22	8.8
* D: Whole Margin	176.38, –39.87	28.6	3.0–69.6	643.0–736.2	188.9–297.5	195.3–256.0	5.0–30.3	11.3–90.0	33.4	27.1	4.56E+22	9.0

Scenario C: Rupture of southern and central Hikurangi subduction margin (M_W 8.8)

This non-uniform slip scenario represents a combined rupture of the lower North Island segment from Cook Strait to Cape Turnagain and the central segment from Cape Turnagain to Mahia Peninsula. This type of scenario was proposed as a cause of subsidence events recorded in Hawke's Bay (Cochran et al., 2006) and the resulting vertical deformation, which is –0.3 to –0.5 m in Napier, is shown in Fig 4.4C. We apply non-uniform slip distribution on the model of plate interface geometry of Ansell and Bannister (1996), comprising 38,186 individual patches. The interface has a strike of 195–220° north of –41.0° S, increasing to 235–255° as subduction becomes more oblique in the southern North Island and beneath the Cook Strait. Dip angle is shallow (5–14°) between 3 km and 20 km depth, gradually steepening to 30° at 70 km depth (Table 4.3).

Significant dip-slip (15–21 m) is applied in the slow-slip event source area beneath Hawke's Bay at depths of 3–10 km where coupling coefficient is 0.5–1.0 (Wallace and Beavan, 2010) and slip rate deficit is 15–30 mm.yr^{-1} (Wallace et al., 2012). The lesser amount of slip (9–15 m) applied in the southern part of the margin represents a recurrence interval of 500 years based on slip deficit derived from inter-seismic locking patterns from GPS data (Wallace et al., 2012). Slip generally occurs with an oblique thrust mechanism (rake of 70–90°) but there is a patch of greater strike-slip component (maximum of 13 m slip) at 30 km depth below the Kapiti coast. Summing all source patches gives $M_0 = 2.27 * 10^{22}$ Nm, equivalent to M_W = 8.8.

Scenario D: Rupture of the whole Hikurangi subduction margin (M_W 9.0)

This scenario represents the maximum credible subduction zone earthquake and an upper limit of magnitude due to rupture of the whole margin. To approximate a worst case scenario, we apply a non-uniform slip distribution on the same plate interface geometry (Ansell and Bannister, 1996) detailed above (Table 4.3). Our scenario locates an area of peak dip-slip (20–33 m) offshore the southern North Island at depths of 3–10 km where slip rate deficit is 20–30 mm.yr^{-1} (Wallace et al., 2012), but where the plates are strongly coupled (Wallace and Beavan, 2010) and approximates a recurrence interval of 1,000 years. This recurrence interval is analogous to those of great earthquakes at the Japan Trench, first identified by Minoura et al. (2001). The amount of slip during the Great East Japan earthquake and tsunami (Simons et al., 2011), the 1,144 year interval since the last comparable event (Jogan 869 AD) and their similar inundation extents (Goto et al., 2012a; Sugawara and Goto, 2012; Sugawara et al., 2013), suggests they were generated by a similar style and magnitude of earthquake.

A moderate amount of slip (generally 2–17 m) is transferred north through the central and upper North Island segments into the less coupled slow-slip event source areas. This mirrors slip propagation during the 2011 Great East Japan earthquake, when slip propagated southward into a slightly less coupled area at the southern end of the rupture (Maercklin et al., 2012). An additional patch of high slip (20–33 m) is incorporated at depths of 3–10 km at the northern end of the margin, to account for higher convergence rates (50–60 mm.yr^{-1}; Wallace et al., 2004). As with scenario C, slip generally occurs with an oblique thrust mechanism (rake of 70–90°) but there is an area with a greater strike-slip component (rake 11–30°) of up to 27 m at 30 km depth below the Kapiti coast due to increasing obliquity of motion down-dip. Summing all source patches gives a seismic moment of $M_0 = 4.56 * 10^{22}$ Nm, equivalent to M_W 9.0. Vertical deformation in Napier resulting from this slip distribution is between –0.6 m in the south-east of Napier and –0.3 m in the north-west (Fig 4.4D). This scenario is tested under both MSL and MHW conditions.

4.7 Results

4.7.1 Flow depth and inundation extent

Flow depth and inundation extent define the tsunami hazard from each scenario, determining the area to be evacuated and providing an important control on the potential for structural damage. Flow depth is defined as the water surface level relative to ground level at the point of measurement. In calculating flow depth for each of the scenarios, co-seismic deformation has been included, so as to represent flow depth above simulated post-earthquake ground elevation. Flow velocity is also an important control on damage, but the absence of explicit modelling of buildings in this analysis precludes analysis of accurate flow velocity results in the onshore urban area, and is not discussed here. The sections below present maximum inundation extent and peak flow depth in each scenario for the most-commonly inundated suburbs and inundation extents (Table 4.4). There are local variations in flow depth, which are evident in flow depth maps (Fig 4.5 and 4.6).

Scenario A: Lachlan Fault rupture using simple fault geometry (M_W 7.7)

The M_W 7.7 Lachlan Fault rupture with uniform slip of 9.0 m under MSL conditions causes maximum inundation of 1 km and flow depth of 1.0–3.0 m in the 100 m closest to the eastern shore and 3.8 m at the Port (See Fig 4.5A1 for inundation mapped in the whole Territorial Authority and Fig 4.6A1 for inundation mapped in the city centre). When the amount of slip is reduced to 8.0 m, flow depth does not exceed 2.5 m and maximum inundation is 800 m inland from the eastern shoreline. For the 7.0 m slip scenario, maximum inundation is 300 m and flow depth does not exceed 1.5 m except at the Port, where it reaches a maximum of 2.6 m. Simulation of scenario A with 9.0 m slip at MHW results in more extensive inundation at Westshore and Ahuriri than at MSL (Fig 4.5A2 and 4.6A2). Westshore experiences flow depth up to 1.6 m in some residential areas, generally up to 0.25 m in Ahuriri and in the eastern city maximum flow depth is generally up to 3.5 m. This event generates at-shore wave heights of 4–5 m, comparable to a 1 in 500 year to 1 in 1,500 year tsunami based on the last National Tsunami Hazard Review (Berryman, 2005).

Tab. 4.4: Approximate peak flow depth and maximum inundation extent in selected suburbs. Refer to Fig 4.5 for inundation mapped for all suburbs. Values refer to inundation at MSL conditions, unless scenario is denoted with *, in which case the first value refers to inundation under MSL conditions, the second to MHW conditions. Where no inundation occurred, this is denoted by '–'.

Scenario	Maximum Inundation Extent (m)	Maximum Flow depth (m)						
		Nelson / Mclean Park	Napier Port	Ahuriri	West-shore	Bay View	Hawkes Bay Airport	Maraenui / Marewa
A: Lachlan Fault 7m slip — M_W 7.7	300	0.25	2.6	–	–	–	–	–
A: Lachlan Fault 8m slip — M_W 7.7	800	0.5	2.8	–	–	1	–	–
A: Lachlan Fault 9m slip — M_W 7.7 *	1,000 / 1,300	0.8 / 1.0	3.8 / 4.0	– / 0.25	0.7 / 1.6	2.2 / 3.4	– / <0.25	0.8 / 1.0
B: Plate interface offshore Hawkes Bay M_W 8.2	100	–	1.3	–	–	–	–	–
B: Plate interface offshore Hawkes Bay M_W 8.3	100	–	1.7	–	0.6	–	–	–
B: Plate interface offshore Hawkes Bay M_W 8.4	600	0.25	2.9	1	2	2.2	0.4	–
C: Southern and central Hikurangi margin M_W 8.8	3,500	4.2	6.4	2	3.7	6.5	1.3	1
D: Whole Hikurangi margin M_W 9.0 *	4,000 / 5,000	4.5 / 5.5	6.9 / 7.5	6.5 / 6.9	4.1 / 4.5	7.5 / 8.1	2.1 / 2.2	2.6 / 3.2

Scenario B: Rupture of the plate interface offshore Hawke's Bay (M_W 8.2–8.4)

An M_W 8.2 plate interface rupture of a single segment offshore Hawke's Bay is expected to cause very limited inundation to maximum flow depth of 1.3 m at the Port only. The M_W 8.3 scenario results in additional inundation at Westshore, exceeding 0.6 m in residential areas. At the eastern shore, there is inundation of the first 100 m on land to a maximum depth of 0.25 m but inundation does not occur inland of the gravel berm.

The M_W 8.4 scenario (Fig 4.5B and 4.6B) causes inundation to 600 m inland in Mclean Park with maximum flow depth of 1.8 m. Napier Port is inundated to maximum depth of 2.9 m and the eastern part of the Airport is subject to flow depth up to 0.4 m. Ahuriri, Westshore and the northern part of Onekawa West experience flow depth up to 1.0 m. This scenario results in at-shore wave heights of approximately 4–5 m, which corresponds to a tsunami with return period between 1 in 500 years to 1 in 1,000 years (Berryman, 2005). These estimated wave heights compare well with those generated by Power, Reyners, and Wallace (2008) for an M_W 8.7 earthquake on the same segment. Analysis of inundation due to combined vertical deformation of scenario A and B suggests that flow depth is similar to that of the Lachlan Fault component alone. Inundation extent is up to 600 m further inland at Bay View and up to 1 km further inland at Nelson Park with flow depth generally <0.25 m. Elsewhere, inundation extent is the same as for the Lachlan Fault component.

Scenario C: Rupture of southern and central Hikurangi subduction margin (M_W 8.8)

An M_W 8.8 rupture of the southern and central segments of the margin (Fig 4.5C and 4.6C) results in maximum flow depth exceeding 7.5 m on the eastern side of Bluff Hill, and exceeding 5.0 m in the first 100 m inland at Nelson Park and Mclean Park. All other areas of Nelson Park and Mclean Park, and large areas of Maraenui and Marewa, experience flow depth of 1.0–4.0 m. Flow depth at Ahuriri and Westshore is generally between 1.0 m and 2.0 m but exceeds 3.7 m locally at Westshore. Maximum flow depth at Napier Port is approximately 6.4 m. Inundation extends over 3 km inland at Bay View with flow depth in residential areas and at the Airport generally up to 1.5 m. This event, with at-shore wave heights of 7–8 m represents a 1 in 2,500 year return period tsunami (Berryman, 2005) but are greater than those generated by Power, Reyners, and Wallace (2008), largely due to the additional rupture of the central segment of the margin that is included in the present study.

Scenario D: Rupture of the whole Hikurangi subduction margin (M_W 9.0)

Of the tested scenarios, greatest inundation and flow depth occurs due to the M_W 9.0 whole margin rupture. Inundation extends 4 km inland in the city and over 3 km at Bay View (under MSL conditions). Areas in the 100 m closest to the eastern shore could expect flow depth exceeding

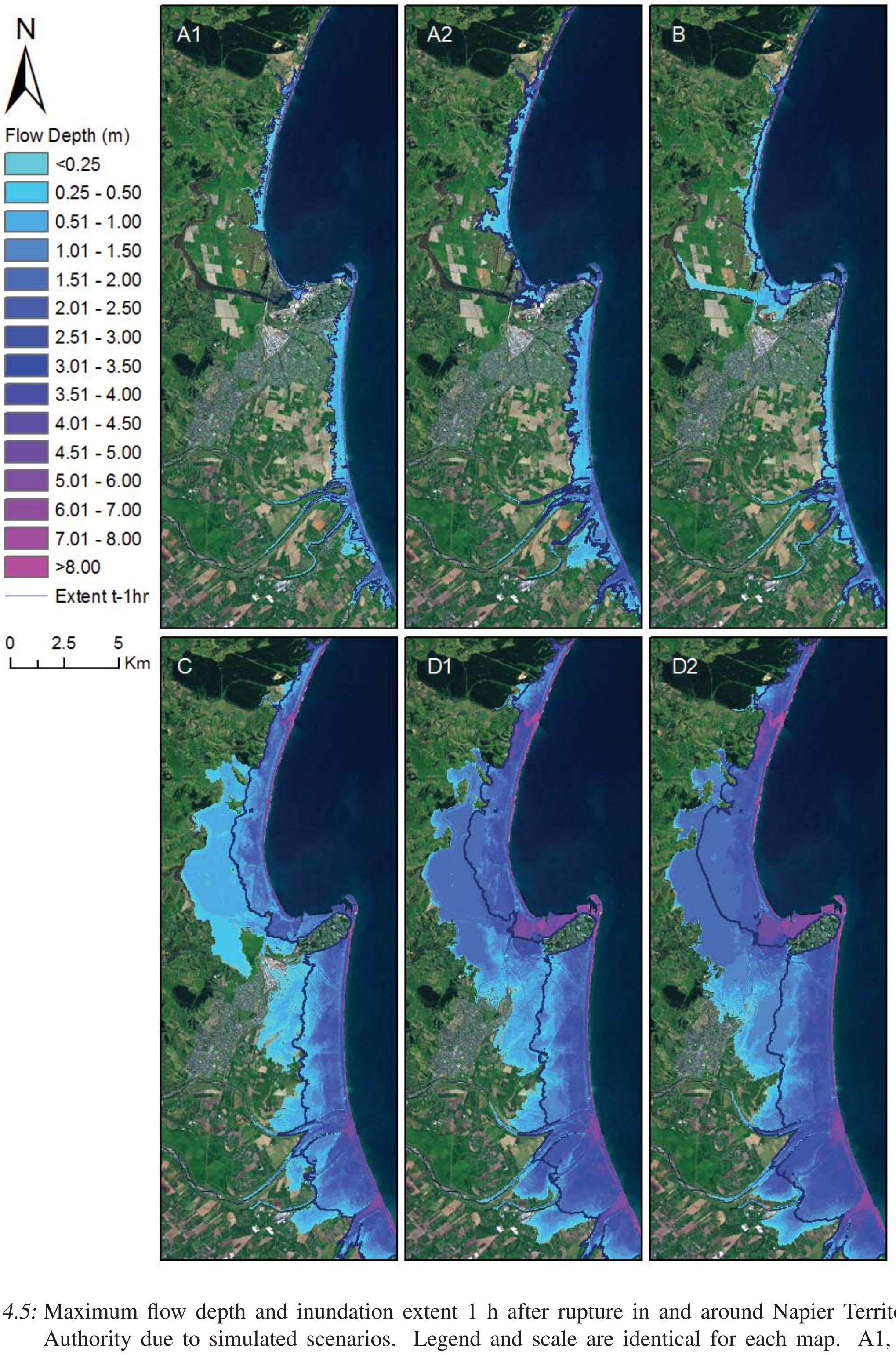


Fig. 4.5: Maximum flow depth and inundation extent 1 h after rupture in and around Napier Territorial Authority due to simulated scenarios. Legend and scale are identical for each map. A1, A2: Lachlan Fault rupture using simple fault geometry with 9.0 m slip (M_W 7.7) at MSL and MHW, respectively; B: Rupture of the plate interface offshore Hawkes Bay (M_W 8.4) at MSL; C: Rupture of southern and central Hikurangi subduction margin (M_W 8.8) at MSL; D1, D2: Rupture of the whole Hikurangi subduction margin (M_W 9.0) at MSL and MHW, respectively

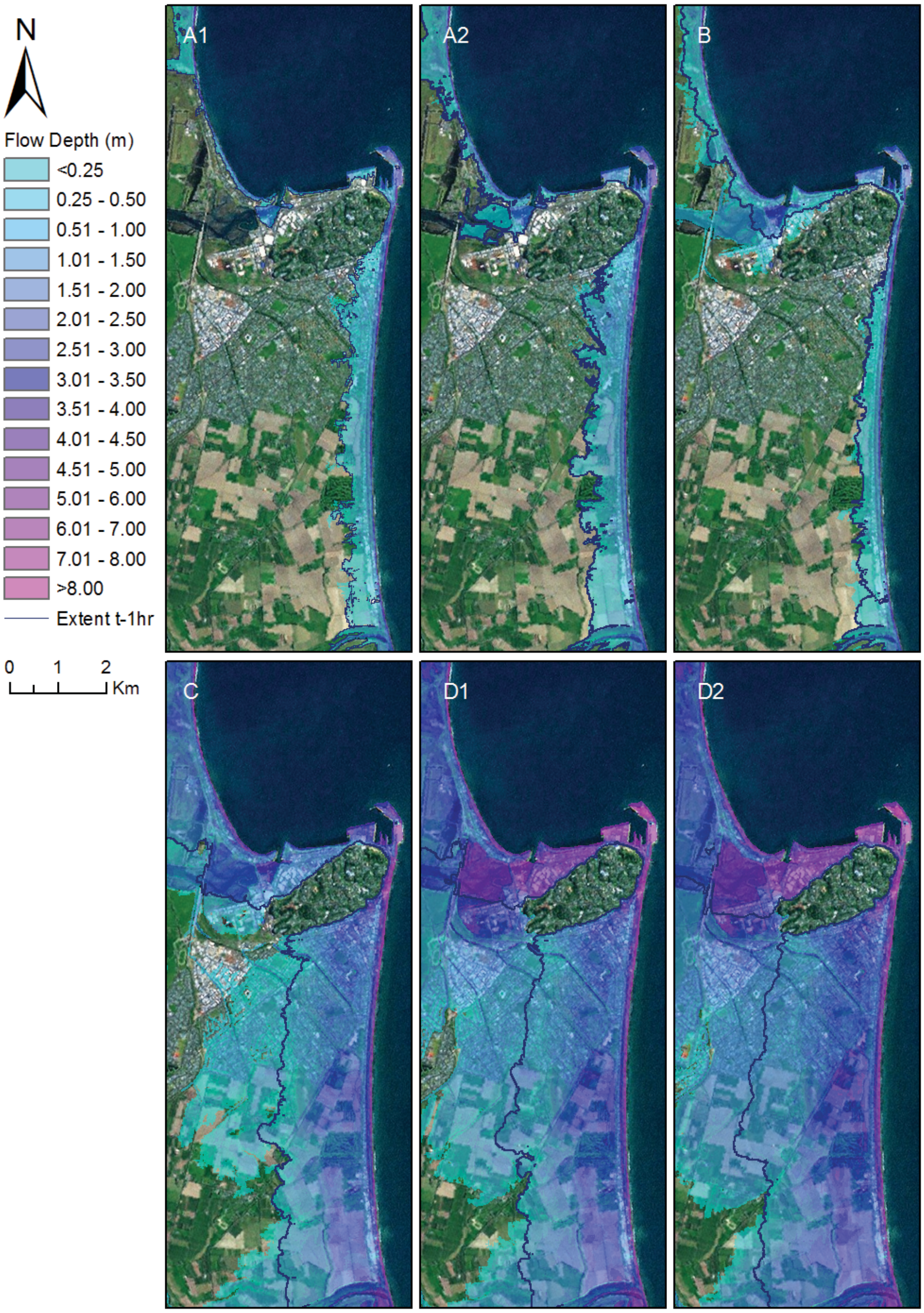


Fig. 4.6: Maximum flow depth and inundation extent 1 h after rupture in Napier city due to simulated scenarios. Legend and scale are identical for each map. A1, A2: Lachlan Fault rupture using simple fault geometry with 9.0 m slip (M_W 7.7) at MSL and MHW, respectively; B: Rupture of the plate interface offshore Hawkes Bay (M_W 8.4) at MSL; C: Rupture of southern and central Hikurangi subduction margin (M_W 8.8) at MSL; D1, D2: Rupture of the whole Hikurangi subduction margin (M_W 9.0) at MSL and MHW, respectively

5.5 m in Nelson Park (Fig 4.5D1 and 4.6D1) while elsewhere on the east side of the city between flow depth is 1.5–4.5 m. Flow depth at Napier Port exceeds 6.0 m, Ahuriri is entirely inundated to 4.5–6.5 m at Westshore flow depth is 1.0–4.1 m. In this scenario, the inland suburbs of Tamatea North and South are also inundated to a depth of <1.0 m. At Bay View, the majority of residential areas and the Airport are inundated with flow depth of 1.5–2.0 m.

Simulation of scenario D under MHW conditions increases maximum flow depth generally by up to 1.0 m. Inundation extent increases to between 4.5 km and 5 km in the city (Fig 4.5D2). The relative distribution of flow depth remains consistent with simulation inundation at MSL conditions. Flow depth in Nelson Park and Mclean Park is generally 2.0–4.0 m (Fig 4.6D2). Marewa and Maraenui experience flow depth between 1.0 and 3.0 m, and further than 1 km inland, flow depth is consistently <1.5 m. Maximum flow depth at the Port is 7.5 m and depth consistently exceeds 5.0 m in Ahuriri and 3.0 m in Onekawa West. Flow depth at Westshore is 1.0–4.5 m. Bay View experiences flow depth of 1.5–2.5 m in the majority of residential areas and 2.2 m at the Airport. At-shore wave heights due to this event generally exceed 8 m, which is equivalent to 1 in 2,500 year tsunami based on hazard curves generated by Berryman (2005) and of similar order to those generated by Power, Reyners, and Wallace (2008) for a M_W 9.0 whole margin rupture.

4.7.2 Tsunami arrival time and waveforms

Estimated arrival time of the first wave above a given threshold, relative to time of source rupture, is a key determinant in evacuation planning and public education on the need for immediate self-evacuation. Effective tsunami warning and evacuation messages should include advice to the effect *'The first wave may arrive later and may not be the largest. Waves may continue for several hours'* (MCDEM, 2010a, p.43). Analysis of tsunami travel time (Fig 4.7) and time-series data from five virtual tide gauges (Fig 4.8) reinforces the importance of these messages in Napier and provides data with which to conduct simulation of urban tsunami evacuation. Arrival time is recorded when the waveform first exceeds 0.05 m (Table 4.5), and provides approximate arrival time for the area around each virtual gauge.

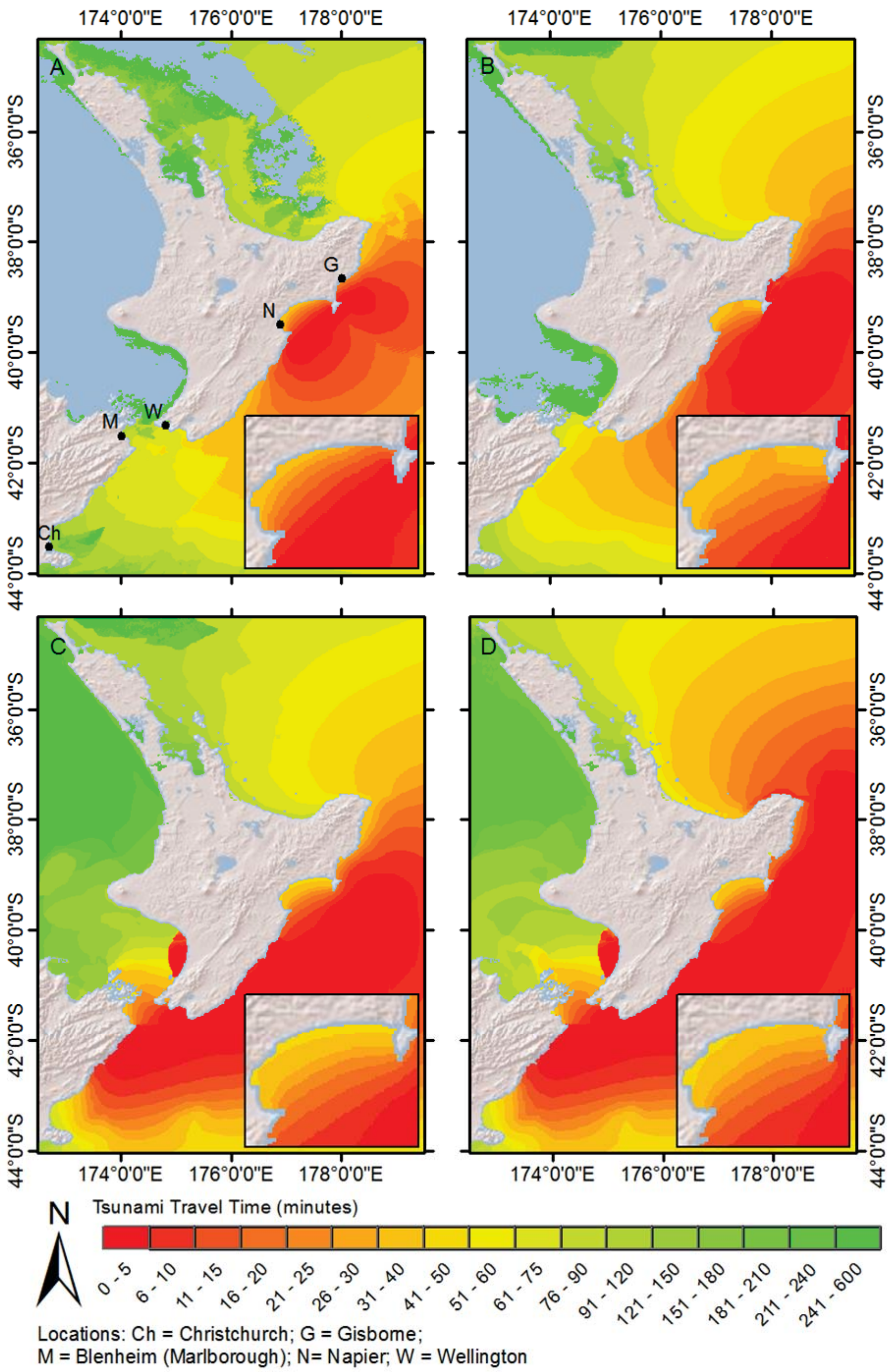


Fig. 4.7: Tsunami travel times for the North Island and northern South Island with key urban centres indicated. Arrival times are shown for waves above the 0.05 m threshold. Insets show arrival times in Hawkes Bay. A: Lachlan Fault rupture using simple fault geometry and 9.0 m slip (M_W 7.7); B: Rupture of the plate interface offshore of Hawkes Bay (M_W 8.4); C: Rupture of southern and central Hikurangi subduction margin (M_W 8.8); D: Rupture of the whole Hikurangi subduction margin (M_W 9.0)

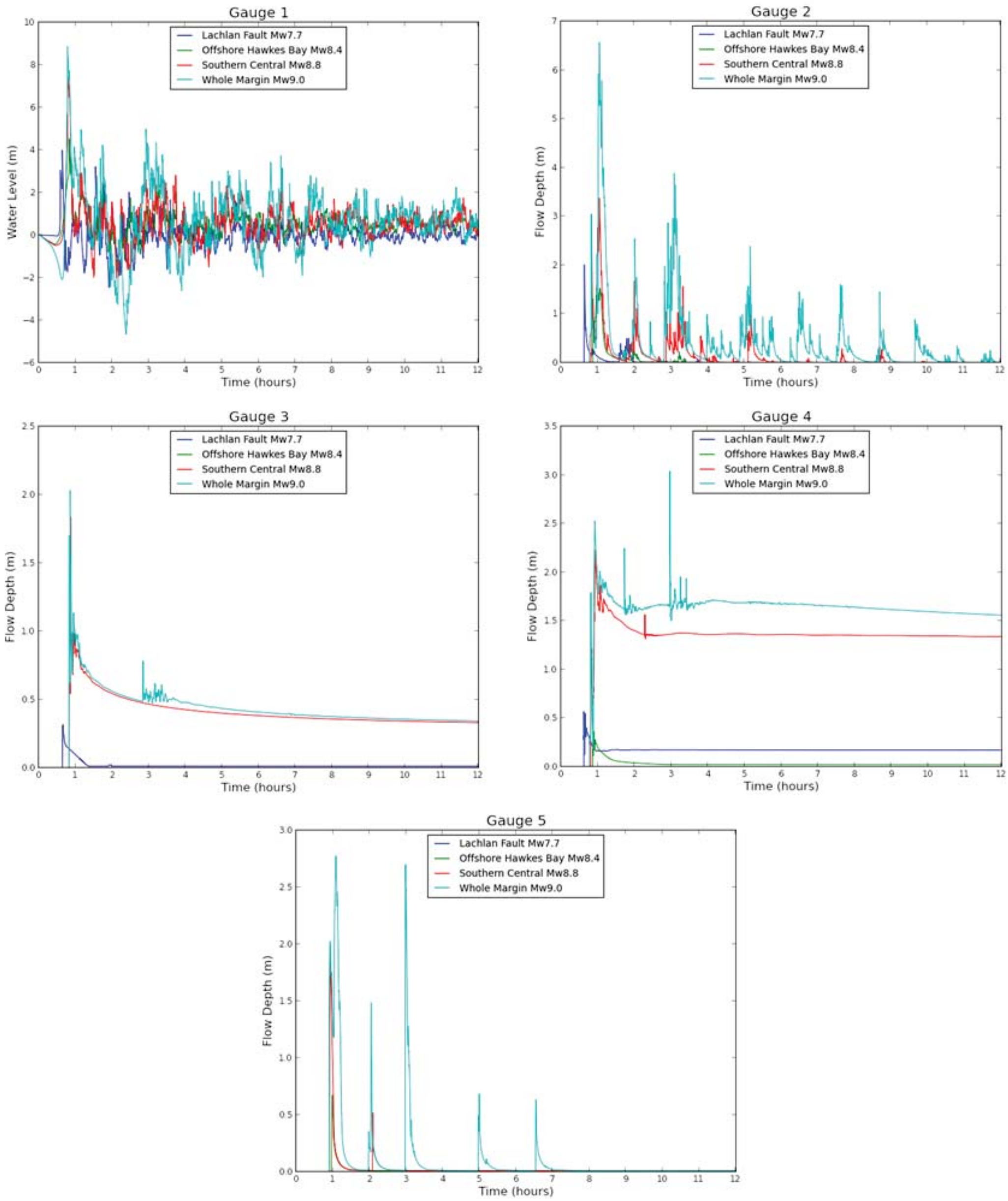


Fig. 4.8: Comparison of simulated wave forms at key offshore and onshore gauges. Water level (m) is shown for offshore gauge 1, and flow depth (m) is shown for onshore gauges 2, 3, 4 and 5. Water level is adjusted for coseismic deformation

Tab. 4.5: Key parameters of waveforms at virtual tide gauges. Arrival time is relative to a threshold of 0.05 m. Height refers to water level for offshore gauge and flow depth for onshore gauges. The first peak is recorded, and if that peak is negative the first positive peak is shown in order to demonstrate lag-time of the drawdown and peak water level. Only data due to maximum slip are shown for scenarios A and B.

Scenario	Parameter	Gauge — offshore		Gauge — onshore							
		1		2		3		4		5	
		height (m)	t (mins)	height (m)	t (mins)	height (m)	t (mins)	height (m)	t (mins)	height (m)	t (mins)
A	arrival time		33		38		39		37		nan
	first peak	3	35	2	39	0.3	40	0.6	38	n/a	n/a
	12-hr max	4	39	2	39	0.3	40	0.6	38	0	0
	12-hr min (offshore only)	–2.5	115								
B	arrival time		4		52		nan		52		58
	first peak	–0.4	27	1.3	53	n/a	n/a	0.4	52	0.7	59
	first (+) peak	4.5	50								
	12-hr max	4.5	50	1.6	59	0	0	0.4	52	0.7	59
	12-hr min (offshore only)	–1.8	130								
C	arrival time		4		49		50		49		55
	first peak	–0.5	27	3	50	1.6	50	1.6	49	1.9	56
	first (+) peak	7.4	47								
	12-hr max	7.4	47	3.4	63	1.8	52	2.2	56	1.9	56
	12-hr min (offshore only)	–2	127								
D	arrival time		4		47		49		47		54
	first peak	–2.1	38	3	50	1.7	50	1.8	49	2	55
	first (+) peak	8.9	47								
	12-hr max	8.9	47	6.6	63	2	52	3	178	2.8	65
	12-hr min (offshore only)	–4.7	143								

The south and east coasts of the North Island and the northern South Island are at risk of very short arrival times in the simulated scenarios and Napier is just one of several urban centres at risk. There is potential for very short arrival times (within 5–10 minutes) at Wellington, Gisborne and the Marlborough coast from at least one of these scenarios (Fig 4.7). Minimum travel time to Christchurch from these scenarios is 51–60 minutes. Within Hawke's Bay, the northern coast around Wairoa experiences similar arrival times to Napier.

Due to the west-dipping thrust mechanism of scenario A, wave arrival at gauge 1 offshore Napier is a positive motion occurring at 33 min and water level rapidly increases to 3.0 m at 35 min (Table 4.5). Maximum water level is 4.0 m at this gauge, occurring only 3 min later. Wave arrival onshore at the Port (gauge 2) occurs 5 min after wave arrival at gauge 1 (38 min after rupture) in scenario A. Maximum flow depth occurs on the first wave (2.0 m at 39 min). For scenarios B-D, wave arrival at the Port occurs 47–52 min after rupture with a first peak of 1.3–3.0 m within 3 min of this time. Maximum water level at the Port is 1.6 m, 3.4 m and 6.6 m, respectively, occurring at 59–63 min in each case.

Maximum flow depth in the city centre (gauge 3) and south-eastern city (gauge 4), albeit limited to 0.3 m and 0.6 m, respectively, occurs at 38–40 min after rupture in scenario A. Scenarios B-D cause negative wave arrival at gauge 1 only 4 min after rupture, with peak drawdown of approximately –0.5 m at 27 min (scenarios B and C) and –2.1 m at 38 min (scenario D). In these scenarios the first positive peak at gauge 1 occurs at 47–50 min, measuring 4.5 m, 7.4 m and 8.9 m respectively. The lag time between peak drawdown and peak positive wave at gauge 1 is 23 min, 21 min and 9 min, respectively, and there are at least 43 min between nearshore wave arrival and occurrence of onshore inundation. Therefore, wave arrival and drawdown of the sea provide additional natural warnings after ground shaking, with some subsequent time to evacuate. Wave arrival at Westshore (gauge 5) occurs 6–7 min later than at the eastern side of the city. In scenario B, gauge 5 records maximum flow depth of 0.7 m at 59 min. Scenario C results in peak water level of 1.9 m at gauge 5 on the first wave at 56 min. Scenario D shows similarly rapid rise of flow depth to 2.0 m upon wave arrival at 55 min at gauge 5, with peak flow depth of 2.8 m occurring 10 min later.

Further waves and reflections occur around the coastline for several hours causing significant fluctuations in water level. Scenario D shows five periods of drawdown greater than –2.0 m over 7 h at gauge 1 and wave heights of 2 m are recorded as much as 12 h after rupture. Minimum water level (–5.3 m) occurs at 143 min, followed by a further peak water level exceeding 4 m at 175 min. Despite several later wave arrivals, the high beach and gravel berm at the eastern shore (Fig 4.1C) provide protection to the city centre. The berm prevents onshore inundation due to most later wave arrivals, but also mitigates the impact of initial waves of significant height. For example, following rupture of the whole margin, gauge 1 records a peak water level of 8.3 m on the first wave, which is mitigated to flow depth of 1–3 m in Nelson Park and Mclean Park, immediately onshore. Despite the presence of the berm, the largest wave at gauge 4 occurs at 178 min (the third wave arrival), which highlights the importance of not returning to the inundation zone after the first wave. A greater number of waves inundate the more-exposed Westshore Peninsula and the Port, with three waves greater than 1.0 m affecting the Port in 9 h due to scenario C, and at least nine waves in 9 h due to scenario D with a period of approximate 60 min. Westshore is inundated by five waves during the 6.5 h following a whole margin rupture. Inundation reaches its maximum extent in much of the city within 60 min of rupture in scenarios A and B, and reaches close to its full extent after approximately 70 min in scenarios C and D. The simulations also suggest that standing water remains for up to 12 min, in some cases exceeding a metre for much of that time, which may have implications for emergency first responders.

4.7.3 Structural damage potential

An estimated 92% of structures in the study area are of 1–2 storey light timber construction, 3% are 1–2 storey reinforced concrete shear wall and 3% 1–2 storey concrete masonry (Cousins, 2009; King and Bell, 2009; King et al., 2008). The high proportion of light timber structures is typical of the national building stock (Shelton and Beattie, 2011). Onekawa West and Nelson Park have lower proportion of light timber construction as these suburbs contain a greater proportion of industrial buildings and commercial buildings respectively. Nelson Park, the main commercial and civic services area, shows a particularly high proportion of concrete masonry and RC shear wall construction.

Comparison of simulated flow depth in Napier with a large tsunami fragility dataset from the Great East Japan tsunami (Ministry of Land Infrastructure Transport and Tourism, 2012; Suppasri et al., 2013a) and fragility curves derived from the American Samoa 2009 and Chile 2010 tsunami (Mas et al., 2012b) shows that there is significant potential for structural damage from the simulated scenarios. In the absence of detailed data on tsunami resistance of New Zealand structures these fragility data provide an approximation of likely damage. We do not consider here the likely damage to structures in Napier due to the initial earthquake. There is likely to be increased vulnerability of some buildings to tsunami loading due to ground-shaking induced weakening of structures and the presence of loose debris that may be entrained in the tsunami flow.

Maximum flow depth in our simulations exceed the depth threshold of 2 m, at which damage to timber frame building stock becomes significant enough to cause collapse, based on the 2011 data and earlier international datasets reviewed by Suppasri et al. (2013a). Fig 4.9 shows the probability of moderate damage, major damage and collapse of one-storey timber frame buildings and two-storey reinforced concrete building for scenario D using fragility curves from Suppasri et al. (2013a) and Mas et al. (2012b). The figure also shows the probability of moderate damage to timber frame structures in each of the other three simulated scenarios. For both RC and timber buildings, there is greater than 90% probability of moderate damage (defined as *'Slight damages to non-structural components', 'Possible to be use[d] after moderate reparation'*; Suppasri et al.

(2013a)) in much of the inundated area. Damage potential remains similar for buildings of the same construction with one or two storeys but probability of collapse is significantly reduced when a building of a particular construction type is three storeys in height.

Probability of major damage (‘*Heavy damages to some walls but no damages in columns*’, ‘*Possible to be use[d] after major reparations*’; Suppasri et al. (2013a)) exceeds 50% for both construction types within 1,000 m of the coastline (which includes many of the commercial, industrial and civic structures, the Port and Airport) in scenario D and is generally 10–50% further inland. Probability of collapse (‘*Destructive damage to walls (more than half of wall density) and several columns (bend or destroyed)*’, ‘*Loss of functionality (system collapse). Non-repairable or great cost for retrofitting*’; Suppasri et al. (2013a)) of timber buildings exceeds 40% within 1,000 m of the shore and is generally $<30\%$ further inland. In contrast, probability of collapse of RC buildings is $<30\%$ for most of the inundated area. Damage potential based on Mas et al. (2012b) is comparable to those of Suppasri et al. (2013a), showing slightly higher probability of collapse for both construction types. Fig 4.9G–I show the damage potential for one-storey timber frame building for scenarios A-C for comparison. The limited inundation extent of scenarios A and B precludes the potential for damage at large distances inland and in scenario A probability of moderate damage exceeds 60% within 150 m of the shore but rapidly diminishes to $<10\%$ further inland. At 150–600 m inland probability of moderate damage in scenario B exceeds 60% locally, and is $>80\%$ within 150 m of the shore. Scenario C shows greater inland attenuation of damage potential than scenario D but there remains a probability of $>80\%$ of moderate damage for areas closest to the coast.

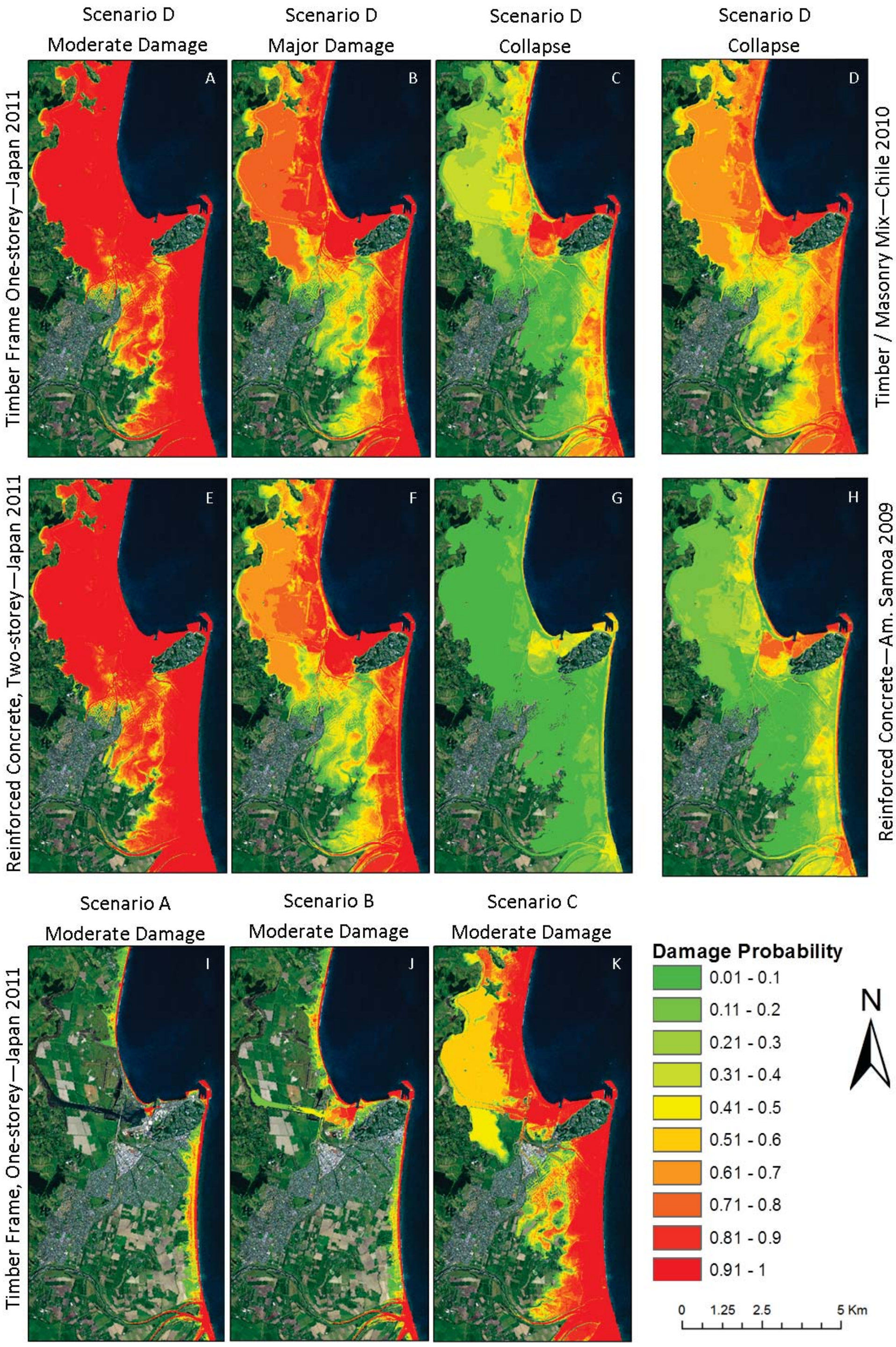


Fig. 4.9: Damage potential maps providing comparison between: i. timber frame building damage levels due to a whole-margin rupture using fragility curves from Japan 2011 (Suppasri et al., 2013a) (A–C) and Chile 2010 (Mas et al., 2012b) (D); ii. RC building damage levels due to a whole-margin rupture using fragility curves from Japan 2011 (Suppasri et al., 2013a) (E–G) and American Samoa 2009 (Mas et al., 2012b) (H); iii. probability of moderate damage to timber frame building due to each scenario using fragility curves from Japan 2011 (Suppasri et al., 2013a) (A, I–K)

4.8 Conclusions

Deterministic analysis of local tsunami generated by subduction zone earthquake sources proximal to Napier, Hawkes Bay, New Zealand, demonstrates the potential for extensive inundation with flow depth sufficient to cause major damage to structures. We demonstrate the variability of inundation in Napier due to different local earthquake scenarios in addition to the maximum credible earthquake. The scenarios analysed are based on geodetic and geophysical characteristics of the Hikurangi subduction margin, and geological evidence for significant pre-historic subduction earthquake and tsunami.

Rupture of multiple segments of the plate interface causes the most extensive inundation, to 4 km inland, and greatest flow depth generally up to 3 m in the city centre, but between 4.5 and 8.0 m in Ahuriri, close to Bluff Hill and at the Port. At the upper limits of their potential magnitude range, ruptures of the Lachlan Fault and the plate interface offshore Hawkes Bay also have the potential to cause onshore inundation with sufficient flow depth to cause moderate damage to timber frame and reinforced concrete structures. In the lower magnitude ranges of these events, Napier Port is at risk, but inundation is relatively limited in the rest of the city and extensive damage unlikely. At mean high water, flow depth can increase by the order of 0.5 m and inundation by several hundreds of metres compared to tsunami occurring when the tide is at mean sea level. The maximum simulated flow depths result in high probability of moderate to major damage of timber frame and RC structures in large areas of the city, particularly within 1 km of the coast. There is low probability that RC buildings would suffer collapse due to the maximum simulated flow depths, but there remains a moderate probability of the tsunami causing collapse of timber frame buildings. The results of this analysis are encouraging for the consideration of a vertical evacuation strategy in Napier, which would likely use RC buildings as refuges, but suggest high economic losses among residential building stock, high entrainment of debris in the tsunami flow and a high probability of casualties.

Onshore inundation commences only 37 min after rupture of the Lachlan Fault and at close to 50 min in the other scenarios, suggesting that there is time for evacuation to high ground (Bluff Hill) if evacuation is started immediately. Distances of up to 4 km to the inland extent of inundation in scenarios C and D are likely to present significant challenges for large numbers of people to travel in the time available, and Bluff Hill remains the closest area of land to the city centre that does not become inundated. Evacuation simulations will provide greater detail on this issue. The occurrence of multiple waves onshore reinforces the need for education on staying out of the inundation area until receiving an ‘all clear’ message. Although it would be impossible for those experiencing ground shaking in Napier and any other coastal areas to determine tsunami potential in real time, the short arrival times promote the need to consider ground shaking a natural warning of imminent tsunami. Tsunami earthquakes, during which ground shaking may not be felt onshore, are not considered amongst these scenarios and future research should investigate the potential impact of such events.

The data generated in this study provide dynamic flow input for agent-based evacuation simulations and provide detailed inundation scenarios from which to analyse tsunami exposure and casualty potential. Although we provide an enhanced view of the variability of potential inundation in Napier, several aspects of this work require further research to continue improving tsunami hazard assessment in Napier. This study does not address the frequency of local tsunami hazard due to the current absence of data with which to confidently constrain dates of past ruptures and recurrence intervals of local earthquake sources.

We incorporate co-seismic vertical deformation in this study, but we do not consider the potential for the gravel berm to be destabilised during ground shaking or tsunami inundation, nor do we consider earthquake-induced structural damage and liquefaction prior to inundation. These should be included in future hazard assessments. Probabilistic tsunami hazard analysis incorporating spatially and temporally variable slip distribution should be carried out to investigate the impact of source parameters on inundation. Finally, onshore inundation should be simulated with buildings modelled explicitly to analyse flow velocities and accurately assess the structural impact of tsunami loads.

4.9 Acknowledgments

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4.10 Comparison of numerical simulation against a rule-based evacuation mapping approach

To provide pseudo-validation of the maximum credible evacuation zone for Napier based on numerical modelling of a maximum credible tsunami scenario, the maximum credible evacuation zone has been derived from the attenuation-rule-based methodology developed by Leonard et al. (2008b), and validated against observations from the 2011 Great East Japan tsunami (Fraser and Power, 2013, Appendix E). The Digital Elevation Model (DEM) is the same as that discussed in Section 4.6.1, and river polygons are derived from the DEM and ArcGIS basemap imagery. The 2013 National Tsunami Hazard Review (Power, 2013) estimated the 1 in 2,500 year return period maximum amplitude at the coast (84% percentile of uncertainty) from all possible sources as 13.4

m (Fig 4.10). This gives an estimated maximum potential run-up of 26.8 m, which provides the input level to the attenuation rule calculations. Tidal level is also included, using a value of 0.75 m, which represents Mean High Water at Napier (Section 4.6.2). The resulting maximum indicative evacuation zone for all events is shown in Fig 4.11, and is generally consistent with the output of numerical modelling (Fig 4.5D2).

4.11 Link to next chapter

This chapter has provided detail on the local-source tsunami hazard at Napier, to establish the local-source tsunami hazard zone and demonstrate the differences in potential inundation from different local-source earthquakes. The resulting maximum credible tsunami inundation extent is subsequently applied in pedestrian evacuation modelling. The next chapter presents features of vertical evacuation refuges present in Tōhoku at the time of the 2011 Great East Japan tsunami, and observations on the use of these buildings during the 2011 event.

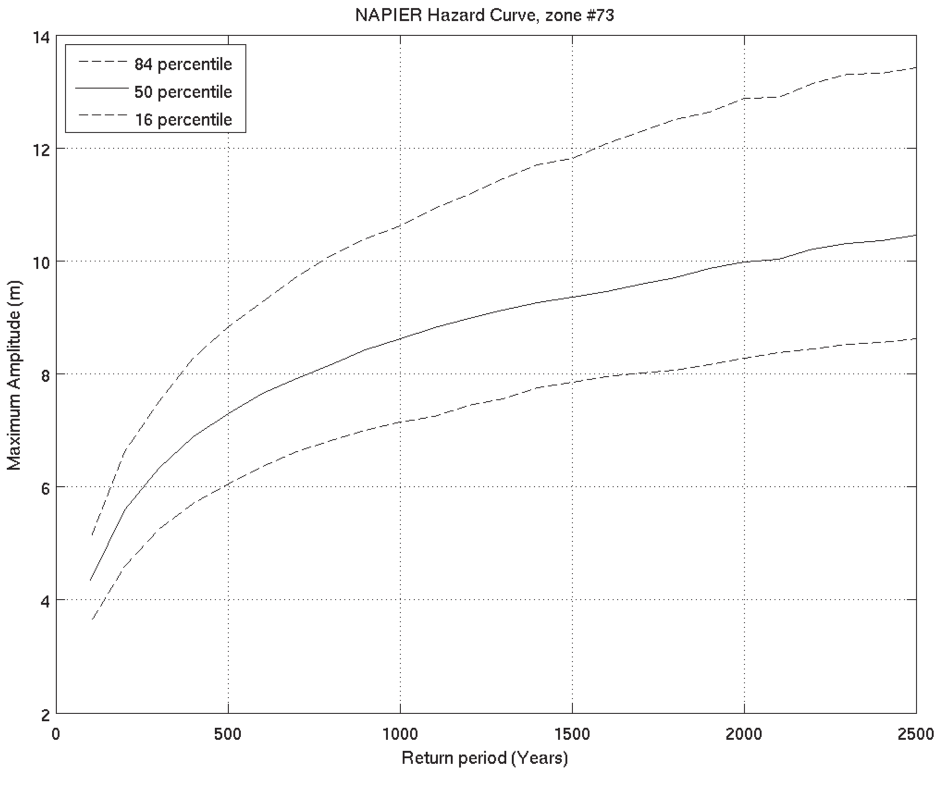

Fig. 4.10: Probabilistic hazard curve for Napier, showing maximum amplitude of tsunami at the coast due to all possible tsunami sources (Power, 2013).

Fig. 4.11: The Geographic Information System (GIS)-calculated attenuation rule based evacuation zone for Napier, compared against the simulated inundation zone from a scenario of a whole margin rupture (M_W 9.0).

5. TSUNAMI VERTICAL EVACUATION BUILDINGS — LESSONS FOR INTERNATIONAL PREPAREDNESS FOLLOWING THE 2011 GREAT EAST JAPAN TSUNAMI (PAPER 2)

This chapter presents observations of damage to Tsunami Vertical Evacuation Buildings (TVEB) during the 2011 Great East Japan Tsunami and key features of those buildings for effective evacuation. These observations meet Objective 2 by providing examples of the use of TVEB in a recent local-source tsunami, and demonstrating potential mechanisms for the planning and operation of a vertical evacuation strategy in New Zealand. The text was originally published as *Fraser, S., Leonard, G. S., Murakami, H., and Matsuo, H. 2012. Tsunami Vertical Evacuation Buildings — Lessons for International Preparedness Following the 2011 Great East Japan Tsunami. Journal of Disaster Research, Vol.7, Special Issue, August 2012, pp. 446-457*. The text is unaltered from the submitted version. A contribution statement, outlining author contributions to the paper, is provided in Appendix H.

5.1 Abstract

Tsunami vertical evacuation is an important strategy for enhancing disaster preparedness because it provides an alternative to evacuation inland or to high ground in areas at risk of local tsunami. A large number of tsunami vertical evacuation buildings provided safe refuge in the inundation zone during and immediately after the Great East Japan tsunami on March 11th 2011. This paper discusses observations of such buildings in connection with themes that arose during semi-structured interviews with local disaster prevention and emergency services officials in Iwate and Miyagi Prefectures in October 2011. The implementation of key factors in the development of tsunami vertical evacuation strategies are assessed with reference to previously published guidelines, enabling lessons to be applied in the current and future development of such strategies internationally. The most important factors for designating tsunami vertical evacuation buildings are that they be reinforced concrete construction with sufficient height in relation to inundation depth. Also important to the success of such vertical evacuation strategies are community engagement, building owner agreement, consistent and clear signage, 24-hour access and evacuee welfare.

5.2 Introduction

Tsunami vertical evacuation strategies are designed to provide safe refuge within a tsunami-inundated area by offering sufficient elevation above the maximum water level. Safe elevation may be provided by artificially-raised open ground, by towers designed specifically for evacuation or by buildings in daily use that can be used for evacuation when required. There is a need for such strategies, particularly where there is a local tsunami hazard, because many people may not be able to evacuate inland or to natural high ground (the recommended best option) due to short tsunami arrival times in the face of long evacuation distances, road congestion or damaged infrastructure.

Japan has led initiatives in vertical evacuation through the establishment of government guidelines for the construction and management of TVEB (Cabinet Office Government of Japan, 2005), although it was noted during this research that such buildings had been designated prior to the publication of these guidelines, e.g., as early as 1982 in Kesennuma City. Similar guidelines have since been published in the United States by the Federal Emergency Management Agency (FEMA, 2008, 2009), in addition to numerous studies on structural requirements of evacuation structures with respect to tsunami forces (e.g., Fujima et al., 2009; Lukkunaprasit, Ruangrassamee, and Thanasisathit, 2009; Lukkunaprasit, Thanasisathit, and Yeh, 2009; Yeh, 2007). Although extremely important, less research has been carried out on evacuation dynamics inside TVEB (Yagi and Hasemi, 2010). In addition to structural issues, a vertical evacuation strategy requires the consideration of community engagement, building owner agreement, consistent and clear signage, 24-hour access and evacuee welfare.

The 2011 Great East Japan tsunami provided the first opportunity to assess a tsunami vertical evacuation strategy experiencing significant inundation heights in multiple locations. The use of TVEB (in Japan, called 'tsunami-hinan' buildings) effectively mitigated loss of life in the locations visited during this research. At least 5,428 people took refuge in 37 designated TVEB and in four of the six locations the average number of people per TVEB exceeded 150 (Table 5.1). This paper discusses key factors in the success of this strategy through observations made at TVEB and the outcomes of interviews with local officials, to inform future development of tsunami vertical evacuation strategies internationally.

5.3 Method of investigation

A field survey was carried out during October 2011 to investigate tsunami vertical evacuation on March 11th, 2011, in six towns and cities in Iwate and Miyagi Prefectures. Four locations — Kamaishi City, Ōfunato City, Kesennuma City, and Minami-Sanriku Town — are located on a ria ('drowned river') coastline. Two other locations — Ishinomaki and Natori Cities — are located on flat low-lying coastal plains (Fig 3.1). All of these locations represent densely developed coastal urban environments less than 20 m above sea level with varying degrees of mixed commercial and industrial land-use around a port and dense residential housing further inland (Table 5.1). The major differentiator between locations is the physical environment and the impact of this on tsunami height: the ria coastline suffered extreme run-up (Mori et al., 2011) due to amplification of the tsunami in narrow bays, while lower maximum tsunami height but greater inland extent was typical on the plains (Table 5.1).

Planned interviews were carried out with officials from municipality government civil protection, emergency management, fire, and police departments. The aim was to gain knowledge of TVEB designation, requirements for effective use during evacuation, locations of TVEB, public awareness and use of vertical evacuation during the Great East Japan tsunami, and the nature of any post-event strategy review. Interviews provided insightful comparisons of the strategy in place on March 11th 2011, regarding recommendations in government guidelines (Cabinet Office Government of Japan, 2005). Written questions were translated into Japanese and provided to interviewees in advance of interviews, which were carried out in Japanese using a semi-structured format (Fraser et al., 2012a). Several local residents were also interviewed during field investigations. Simultaneous spoken translation between Japanese and English was provided during all interviews by the Japanese authors and a professional translator.

Due to the timing of fieldwork seven months after the tsunami, interviews drew upon information obtained by local researchers and collated by municipal governments. Observations made by the authors in the field contribute to the discussion of damage sustained by TVEB and building features such as signage and access routes. These observations are drawn from the present field survey and a previous investigation in June 2011 in which the authors participated (EEFIT, 2011; Fraser et al., 2013).

Tab. 5.1: Summary of TVEB in locations visited during this research. Field observations were not made at all buildings listed. A full inventory of known building features is provided by Fraser et al. (2012a). Not all buildings were available for observation during field investigations, but data on those buildings has been collected through interviews. (a) Tsunami data from field surveys [30]; (b) Casualty data at 14th February 2012 [31];(c) Buildings designated as refuge for multiple hazards evacuation, not specifically as TVEB; (d)Number of people saved is available for only one TVEB in Ōfunato City; (e) Number of people saved at Sendai International Airport is not included.

City / Town	Kamaishi City	Ōfunato City	Kesennuma City	Minami-Sanriku Town	Ishinomaki City	Natori City
Environment	Rias	Rias	Rias	Rias	Plains	Plains
Max. Tsunami Height (a)	30.40 m	31.99 m	23.00 m	20.54 m	25.84 m	12.96 m
Mean Tsunami Height (a)	14.31 m	13.13 m	10.50 m	12.63 m	6.51 m	4.36 m
First wave arrival time after EQ (a)	28 mins	25 mins	Not available	Not available	23 mins	63 mins
Land-use	Industrial (port + steel factory) small commercial + residential further inland	Commercial industrial at port front, residential	Largely industrial and commercial at port front, residential further inland	Residential and commercial	Extensive commercial + industrial at port front, residential further inland	Largely residential
No. Fatalities (b)	1047	425	1368	875	3739	966
Fatality rate of area inundated	8%	2%	3%	6%	3%	8%
No. TVEB	3	7	16	4	3	4(c)
No. people saved in TVEB	50	22(d)	2426	694	500	1736(e)
Average no. people saved in each TVEB	17	22(d)	152	174	167	579(e)

Continued on next page

Table 5.1 – continued from previous page

City / Town	Kamaishi City	Ōfunato City	Kesennuma City	Minami-Sanriku Town	Ishinomaki City	Natori City
No. built with TVEB in mind	0	0	2	1	0	0
TVEB Construction	RC, Steel Frame	RC, Steel Frame	RC, Steel Frame	RC	RC Steel Frame	RC
Range of TVEB storeys	2 to 3	1 to 3	1 to 4	2 to 4	1	1
No. TVEB with external signage	2	0	2	1	0	0
Dedicated welfare resources	0	0	2	0	0	2

5.4 Key features of TVEB

5.4.1 Tsunami-resistant construction

For a building to be officially designated as a TVEB in Japan, it must meet several construction requirements specified in government guidelines (Cabinet Office Government of Japan, 2005). These dictate that a building must be of Reinforced Concrete (RC) or composite steel-reinforced concrete construction and conform to 1981 building code seismic standards, while also being able to withstand tsunami loading appropriate to the expected inundation depth. The building must satisfy minimum height requirements according to estimated maximum inundation depth: where expected maximum inundation depth is less than one metre, the building must be two storeys or higher; three storeys or higher for less than two metres in depth; and four storeys or higher where inundation depth of three metres or more is expected. Of TVEB observed during this research, 80% were of RC construction and 20% were steel frame, 31% were three-storey and 34% were four-storey or greater.

Post-tsunami building damage surveys from Tōhoku underline previous field observations (e.g., Lukkunaprasit et al., 2008; Rossetto et al., 2006) that RC construction is the most resistant to tsunami wave loading and debris impact. There were many cases of RC structures failing in Tōhoku: overturning was observed in Onagawa Town (EEFIT, 2011; Fraser et al., 2013) and Otsuchi (American Society of Civil Engineers, 2011) where tsunami height exceeded 16 m. In Minami-Sanriku Town, scour of foundations caused building collapse and debris strike caused the collapse of upper storeys of some RC buildings (EEFIT, 2011). Damage to designated TVEB, however, was generally limited to broken glazing, damaged fixtures and fittings, and debris impact to external cladding, stairwells, railings or balconies, even at flow depths of up to 20 m, as in Minami-Sanriku. No observed TVEB sustained sufficient earthquake damage to prevent its use during the subsequent tsunami evacuation.

The extent of foundation scour sustained during the tsunami reportedly resulted in some TVEB requiring demolition, but these buildings fulfilled their immediate vertical evacuation function. The Matsubara apartments at the harbour front in Minami-Sanriku (A in Fig 5.1) were scoured at all corners of the building to at least two metres below previous ground level, exposing numerous piles that then were submerged by encroaching sea water. The welfare centre and prefectural government offices in Kesennuma (F and H, Fig 5.2) suffered less extensive scour, but exhibited scour holes of significant depth at one or two locations at each building (EEFIT, 2011). The occurrence of significant foundation scour highlights the need for new methods of scour-resistant design for TVEB, although the buildings in question maintained life-safety in this event and could, with further detailed investigation, provide good models for future TVEB.

Significant debris strike occurred at Shizugawa Hospital in Minami-Sanriku (C in Fig 5.1), where the shore-facing side of the buildings exhibited many broken RC columns at third storey balconies (EEFIT, 2011). An office building at the inner harbour in Kesennuma (A in Fig 5.2)

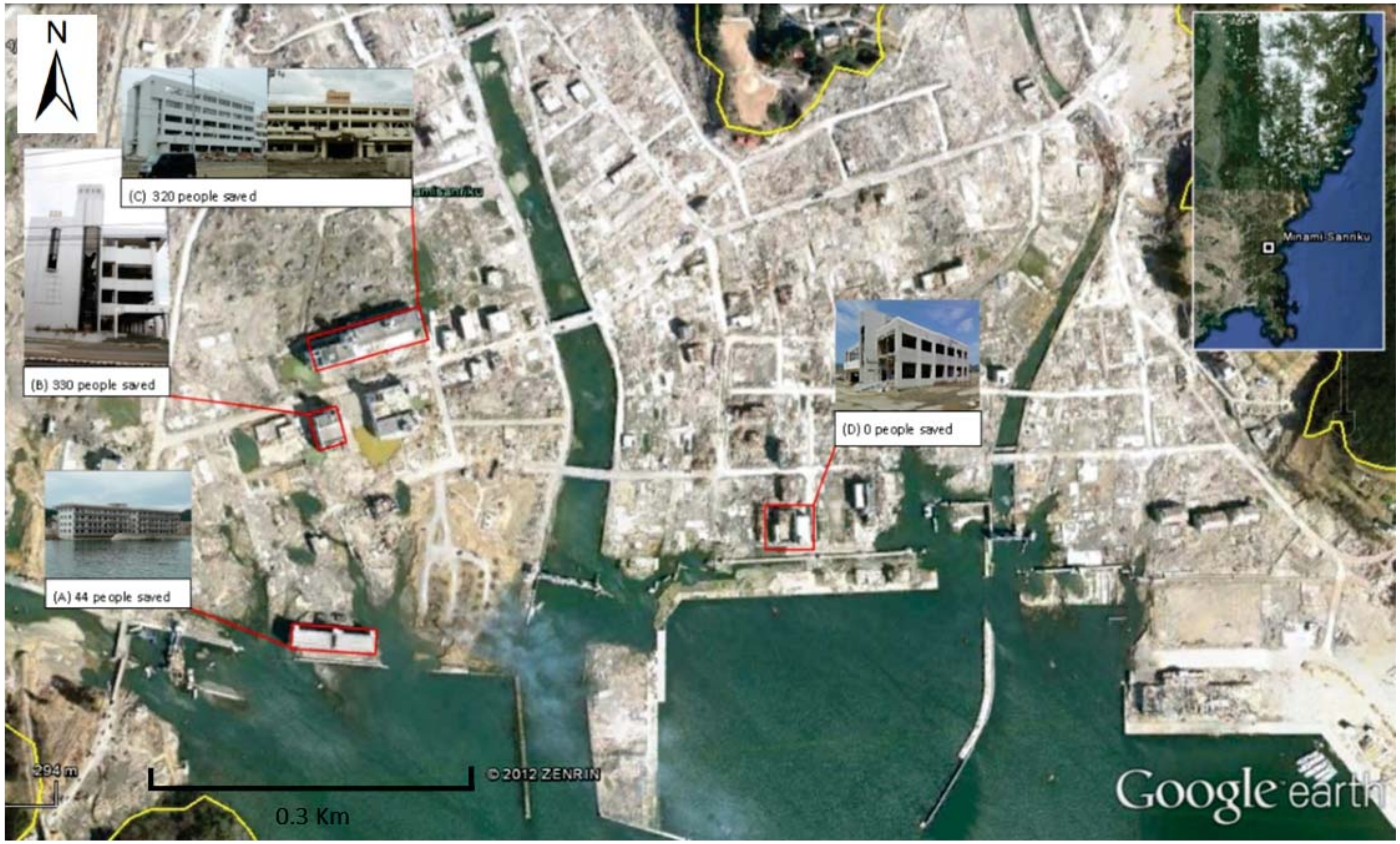

Fig. 5.1: Map and images of TVEB in Minami-Sanriku Town, including numbers of people saved and tsunami inundation marked in yellow (University of Tokyo, 2011). (A) Matsubara apartment block; (B) Takano-Kaikan conference venue; (C) Shizugawa Hospital; (D) Fishing Cooperative.

sustained debris damage to external stairwells, but the stairwells appeared functional. Although TVEB generally sustained minor damage due to debris strike, it was not possible to confirm the type of debris that caused the observed damage. It is therefore not possible in this paper to explicitly evaluate the resistance of the observed TVEB to debris impact, for example to ascertain the level of damage in the case of a large ship striking the TVEB.

The performance of steel-frame buildings warrants a brief discussion here to clarify the suitability of steel-frame construction for TVEB. Numerous steel-frame structures remained standing with extensive removal of external cladding up to the level of inundation (EEFIT, 2011), suggesting that the tsunami flowed 'through' the structure once cladding and external walls were washed away. Despite this, many other steel buildings exhibited bending, buckling, twisting and fracture of structural columns or joints (Lignos, 2011). It is therefore possible that steel-frame buildings can provide life safety during tsunami, provided that they are of sufficient height. However, the substantial damage to cladding and high potential for failure of structural members from wave loading or debris strike makes them unsuitable for official designation as TVEB.

Observations from this event suggest that construction requirements for designating TVEB in Japan were sufficient with respect to extreme tsunami wave heights up to 20 m. Government guidelines (Cabinet Office Government of Japan, 2005) therefore provide suitable guidance for appropriate construction of TVEB internationally. Of course, Japan benefits from well-developed seismic codes and this provides a suitable basis for tsunami-resistant construction, which may not be available in all countries. Detailed structural evaluations will provide more robust analysis of the tsunami impact than the external investigations possible during this research, and are vital to inform construction requirements in the future.

5.4.2 Sufficient height of safe storeys

The provision of safe storeys in TVEB — storeys providing refuge above the maximum tsunami height — is a vital component of a vertical evacuation strategy. Japanese government guidelines provide graded requirements for TVEB safe storeys (see Section 5.4.1), but on March 11th there was inundation of storeys considered safe in previous hazard assessments. During interviews, local officials expressed concern about the current recommended height of TVEB.

In Kesennuma, several TVEB were within one metre of being overtopped when the tsunami arrived at low tide. The four-storey Wedding Plaza in Ōfunato, Shizugawa Hospital (four- and five-storey buildings) and Matsubara apartments (four storeys) in Minami-Sanriku were all inundated to the fourth storey, leaving only the roof as a safe refuge. At Shizugawa Hospital, 320 people survived on the roof and fifth storey of the west building, but it was not possible to move many immobile patients to a safe storey (The Kahoku Shimpo, 2011). Despite being only two storeys in height, the fishing co-operative building in Minami-Sanriku (D, Fig 5.1) was designated as a TVEB through its ownership by a public organisation looking to protect its workers. Fortunately

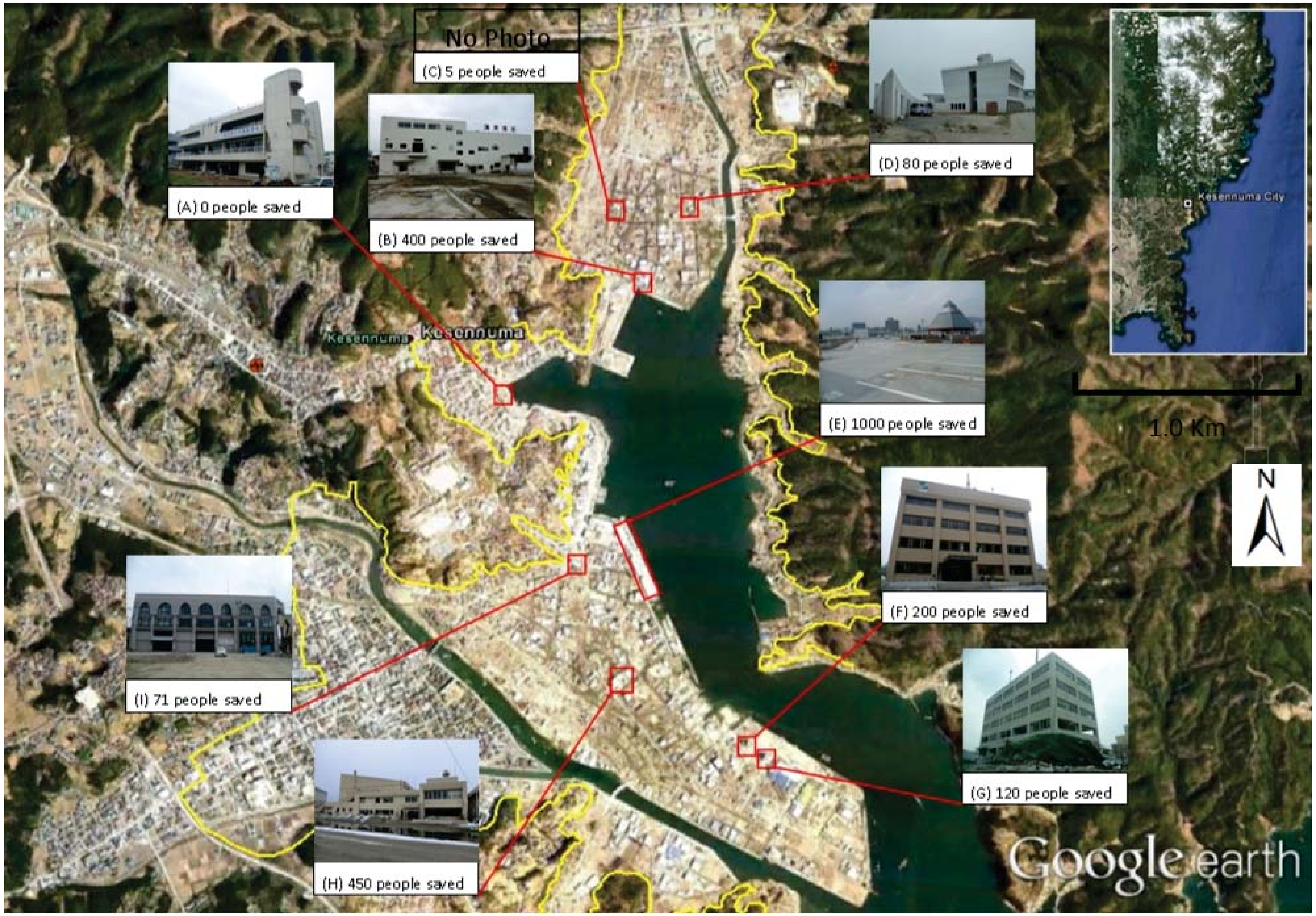

Fig. 5.2: Map and images of nine vertical evacuation buildings in Kesennuma City, including numbers of people saved and tsunami inundation marked in yellow (University of Tokyo, 2011). These comprise office buildings (A, F, G, I); a cannery (B), a retail building (C), welfare centre (D), a car parking deck (E) and a community centre (H).

the building was unused on March 11th as people travelled to nearby high ground; flow depth of around 12 m (twice the building height) occurred at this building.

In light of the examples above, interviewed officials in Kesennuma and Minami-Sanriku suggested that a minimum height of five storeys should be set for future designation of TVEB. Although increasing the height threshold for safe storeys appears an obvious solution, the use of a single minimum height on a national scale may rule out using suitable buildings of lesser height in areas where the maximum potential tsunami height has been robustly assessed to be lower. For example, on the coastal plains where maximum tsunami heights were lower than on the ria coastline, many single-storey and two-storey buildings in Natori and Ishinomaki provided safe refuge on March 11th, indicating the value of low-rise buildings where it is appropriate to the inundation height. Rather than construct all TVEB to achieve a single 'safe-storey threshold' at five storeys, robust probabilistic hazard assessment and site-specific analyses using maximum credible tsunami generating earthquakes (especially local-source subduction events) could provide suitable local thresholds. This approach would allow continued use of current Japanese government guidelines in areas of lower maximum inundation height and provide greater flexibility in designating TVEB of fewer storeys.

5.4.3 Building location planning

Government guidelines (Cabinet Office Government of Japan, 2005) encourage planning of TVEB locations to provide adequate refuge capacity and distribution in areas where it is not possible to evacuate to high ground. Optimum distribution of buildings can be derived from local population estimates, evacuation routes and walking speeds (e.g., Goto et al., 2012b; Imamura et al., 2012; Wood and Schmidtlein, 2012). Where there is reliance on existing buildings in a developed urban area, the number and distribution of TVEB may be constrained by the availability of suitable buildings or land on which to build. As a result of this and variable estimated tsunami hazard, TVEB were distributed very differently in the six locations investigated.

Kesennuma City had 16 officially designated TVEB relatively well distributed across the coastal areas of the city; nine are in the area shown in Fig 5.2. With the exception of the car park deck over the fish market (E, Fig 5.2) and the prefectural government office (F, Fig 5.2), which were constructed with tsunami vertical evacuation as a planned function, these buildings were all existing structures that were identified as suitable TVEB because they conformed to government guidelines. These provided refuge to 2,326 people, although the number of people sheltering in each building was highly variable. For example, the car park deck in the busy dock area and fish market received 1,000 people and substantial numbers went to other TVEB in areas far from high ground (B, F, G, and H in Fig 5.2). Buildings closer to high ground received very few people (buildings A and C in Fig. 2 received zero and five people respectively). It is expected that the variability in number of people at each TVEB is due to the concentration of population at the time of evacuation, proximity of the TVEB to high ground, awareness of the TVEB function and variable evacuation response to natural or official tsunami warnings (Fraser et al., 2012a). However, data on evacuee travel routes and TVEB choice was not available at the time of this study, so it is not possible here to robustly determine reasons for the variability.

Minami-Sanriku Town had four official TVEB (Fig 5.1), of which only the Matsubara apartment building was constructed with prior consideration of vertical evacuation functionality. Constructed in 2007, this TVEB was intended to provide refuge to large crowds at the adjacent sports ground. There were initial public concerns about the building being used for tsunami evacuation due to its port-front location, but the local community was informed that the roof level would constitute a safe elevation. It was reported during interviews that large numbers of people taking refuge in TVEB primarily comprised people who were in the building or in the immediate vicinity at the time of the evacuation warning, suggesting that people did not travel far to TVEB. At Shizugawa Hospital, 69% of the 320 evacuees were hospital staff or patients and at the Takano Kaikan building, the majority of the 330 people saved were attending a community meeting at the building.

There were only two TVEB in Kamaishi City (Kamaishihamachō Post Office and a government office, Fig 5.3). Relatively few people (50) took refuge in these buildings during the tsunami, perhaps owing to the 66.4% rate of immediate evacuation (NPO CeMI, 2011) and access to high ground within one kilometre of the port and industrial areas. The government office provided refuge to people who became stuck in vehicles due to traffic congestion. An additional building, the Hotel Horaikan at nearby Unosumai, was constructed with vertical evacuation in mind (see Section 5.4.8). Additional TVEB had been planned in the port area of Kamaishi, but they had yet to be constructed by March 11th.

In locations where minimal tsunami inundation was expected based on previous events and numerical modelling, there was little planning for vertical evacuation and therefore few designated TVEB, however, informal vertical evacuation to non-designated buildings was significant in mitigating loss of life. Around 500 people sought refuge at three designated buildings in Ishinomaki City: York Benimaru shopping centre, the Homac hardware centre, and the Hotaru funeral facility. The local interviewee reported that an additional 50,000 people took refuge in approximately 260 official earthquake and landslide evacuation buildings and other schools, temples, shopping centres and housing. Informal vertical evacuation also occurred in Kamaishi City and Ōfunato City in cases where buildings suggested by the community did not met official designation criteria (see Section 5.4.9), but the number of non-designated buildings was not available to quantify this further.

Four public buildings in Natori City had been specified by the municipality government as general hazard evacuation centres (but not specifically TVEB): Yuriage Community Centre, Yuriage Junior High School, and Yuriage Elementary School. Sendai International Airport at Kitakama was also an evacuation location. These buildings were not designated as TVEB because they were located outside of the estimated tsunami hazard zone, but proved effective for vertical evacuation

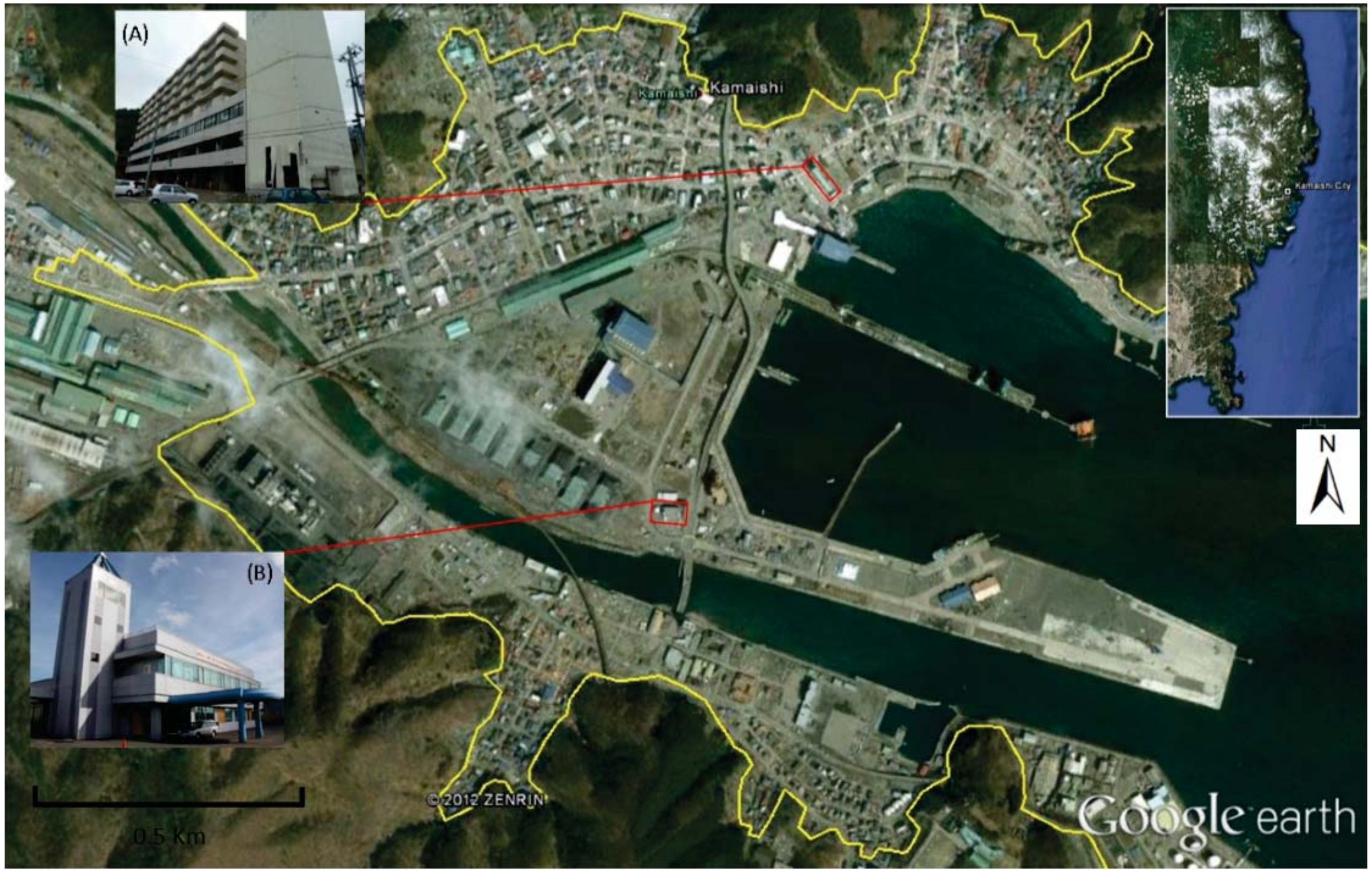

Fig. 5.3: Map and images of vertical evacuation buildings in Kamaishi City and tsunami inundation marked in yellow (University of Tokyo, 2011). These are the Kamaishihamachō Post Office and apartment building (A) and government offices (B).

in this event in further examples of informal vertical evacuation.

These observations show that vertical evacuation can be successful where the best possible distribution of TVEB cannot be achieved, and that informal vertical evacuation saved many additional lives in areas of low to moderate tsunami height. Planning TVEB in the redevelopment of tsunami-affected areas in Tōhoku is encouraged, but where there are suitable existing buildings, those buildings should also be used as effectively as possible.

5.4.4 Building capacity

Any building designed as an evacuation refuge must have sufficient capacity for the estimated number of evacuees. Analysis of potential demand can be carried out using estimates of local population, evacuation routing, travel speed and distribution of safe refuges, including safe areas outside of the inundation zone and vertical evacuation structures (Goto et al., 2012b; Imamura et al., 2012; Wood and Schmidtlein, 2012). Facility capacity also relies on estimates of in-refuge space required by each evacuee (Cabinet Office Government of Japan, 2005; FEMA, 2008).

Detailed study of building capacity or evacuees' experience while in the buildings was not carried out as part of this research. During interviews, however, there were no reported cases of buildings exceeding capacity on March 11th. The majority of designated buildings were substantial structures with a requirement for large capacity in their regular function (e.g., schools, apartments), therefore are more likely to satisfy government guideline capacity requirements (Cabinet Office Government of Japan, 2005). It was noted in several interviews that even where TVEB existed, the recommended primary evacuation action was to go to high ground (to exit the tsunami hazard zone, rather than remain in it). This guidance may also have acted to reduce evacuee demand on TVEB where they were close to high ground (see Section 5.4.3).

5.4.5 Building access

TVEB must provide access to safe storeys at all times. The type of access (internal or external stairs, width of entrances) is a key factor in the time required to access the building and move to safe storeys (Yagi and Hasemi, 2010). External stairs are commonly installed for emergency exit from buildings in Japan, e.g., in fires or earthquakes, and offer the most efficient way to access safe storeys of an evacuation building (Yagi and Hasemi, 2010). These stairs may not always lead directly to the roof, but should enable direct access to safe storeys.

External stair or vehicle ramp access was the most commonly recorded access method at TVEB investigated, available at nine (33%) of observed TVEB (Table 5.2). Where direct external access from the ground floor to safe storeys is not available, people may need to gain access by alternative methods, which are included in government guidelines (Cabinet Office Government of Japan, 2005) and were cited in our interviews (Table 5.2):

- Some private buildings have security personnel present overnight who will open doors for emergency access, e.g., the Prefectural Office in Kesennuma.

- Due to regular building function it is staffed or has residents present 24 hours a day, e.g., Shizugawa Hospital, Hotel Horaikan, the Matsubara apartments, and two other TVEB.

- Representatives of local residents act as key holders to enable access outside of office hours, e.g., two community representatives living near the government building, Kamaishi; two Yuriage schools and a community centre, where key holders are informed by telephone that they need to open the building.

- Building owners agree to the forcible breaking of doors and windows to enable emergency access, e.g., Kesennuma Junior High School and the National Office in Kesennuma.

The provision of 24-hour access may require installation or retrofitting of adequate stairs and entrances, or additional investment in structural renovation and staffing requirements. It can also affect building security and lead to concerns about crime (Yagi and Hasemi, 2010). During our interviews there were no reports of restricted building access on March 11th, because the tsunami occurred during at 14:46 (local time) when TVEB were unlocked and occupied. It was acknowledged by several interviewees that access issues may have hindered evacuation if the tsunami had occurred at night. In Natori City, interviewees noted that although two key holders were trained to go to each evacuation building in case of night-time evacuation, they had not been trained for this scale or type of evacuation. This highlights the importance of appropriate training and responsibility on the part of key holders to immediately open TVEB in the event of tsunami.

Allowing evacuees to enter TVEB by force is unlikely to be a suitable solution for buildings containing sensitive data, such as public offices or commercial premises. Satisfying access requirements of TVEB in different communities and with varying regular functions requires dialogue among evacuation planners, building owners and the community (see Section 5.4.9) on a case-by-case basis to define the most appropriate solution for each building and to ensure that the local community is aware of and trained in the correct access method.

Tab. 5.2: TVEB 24-hour access methods, showing numbers of buildings for each method in the locations surveyed. Data on external stairs is from field observations. Data on alternative access methods is from local interviews. Not all TVEB were accessible for observation during field investigations. [a]Schools in Natori have external stairs but staff members are also organised to open the building.

City / Town	Kamaishi City	Ōfunato City	Kesennuma City	Minami-Sanriku Town	Ishinomaki City	Natori City	All locations
Total no. of TVEB	3	7	16	4	3	4	37
Building open 24-hrs	0	1	2	1	0	0	4
Night-time residents	0	0	0	1	0	0	1
External stairs	1	1	2	1	2	2[a]	9
Local key-holders	1	0	0	0	0	3	4
Forced entry allowed	0	0	2	0	0	0	2
Night-time security staff	0	0	1	0	0	0	1
No external stairs, alternative access unknown	1	1	3	1	1	1	8
Access method unknown (building not observed)	0	4	6	0	0	0	10

5.4.6 Fire resistance

One reason for promoting evacuation to high ground rather than into TVEB is that safety cannot be guaranteed in the event of large debris strike or fire at such buildings. Fire was a significant issue during and immediately after this tsunami; many buildings burned and some evacuation centres narrowly avoided catching fire while occupied by evacuees. In Kesennuma, over 50,000 litres of oil spilled from ruptured oil tanks and engulfed several areas around TVEB. It was reported that a government committee had been set up to prevent such spillage from occurring again, and the fire-proofing of evacuation structures was raised as a consideration for the future design of such buildings. In Ishinomaki, fire spread within one hour of the earthquake to the Kadonowaki school building where people had taken refuge, but evacuees were fortunately able to relocate to high ground nearby before fire spread to the school.

Observations from Tōhoku support the need for solutions to minimise the spread of fire and to prevent fire damage to TVEB, such as fire-retardant cladding and shutters. The potential for fire damage also led to one interviewee citing the need for emergency communication links in TVEB in case of urgent need of rescue (see Section 5.4.10).

5.4.7 Evacuation signage

Effective route signage is a key component of tsunami evacuation strategies, for on-going education and awareness training as well as for direction in an evacuation (Dengler, 2005). Signage is required inside a building to show exits and safe routes and to speed up the movement of evacuees (Yagi and Hasemi, 2010). Signage is also necessary outside a TVEB to highlight the building function and to show the most appropriate access route to safe floors, particularly for those who may be unfamiliar with a building and its vicinity, e.g., tourists and emergency responders. There has been previous recognition of the disparity in tsunami hazard awareness between resident and non-resident populations (Johnston et al., 2005); it is vital that a vertical evacuation strategy accounts for both groups, and displaying effective consistent signage is one method of achieving this. This study did not investigate the use of TVEB specifically by non-resident (transient) populations in Tōhoku because this level of data was not available. Consistent vertical evacuation signage (Fig 5.4) for buildings is recommended in government guidelines (Cabinet Office Government of Japan, 2005) but unfortunately, prior to March 2011, the application of such signage was limited and the retrofitting of signage for existing buildings was uncommon. Only five buildings were observed during our field survey to have official signage: the Kamaishihamachō Post Office and Hotel Horaikan in Kamaishi, Matsubara apartments in Minami- Sanriku, the prefectural government office and the Yoyoi cannery, both in Kesennuma. The high numbers of evacuees taking refuge in designated buildings despite the absence of signage suggests that awareness of TVEB was high among people in the area at the time of the tsunami, although further research into evacuee behaviour should aim to identify any impact that signage may have had on destination of evacuees. In the meantime, consistent signage should be adopted and applied to all TVEB, including retrofitting of existing buildings that become designated. Signs should be clearly displayed at the top of each building and above entrances to clearly indicate the most appropriate access route to upper storeys. Signage should be nationally consistent with approved standards for style and messaging.

Fig. 5.4: Vertical evacuation signage used in Japan. (A) Sign displayed prominently on the Kamaishihamachō Post Office, (B) signage on the Matsubara apartment block in Minami-Sanriku, (C) a sign displayed above an entrance to the Kamaishihamachō Post Office (Translation: Evacuation building entrance (stairways)).

5.4.8 Building owner agreement

The need to gain agreement of building owners to designate their buildings as TVEB is an issue that has been raised in projects in the United States (Project Safe Haven, 2011a,b), New Zealand (Leonard et al., 2011) and Japan (Cabinet Office Government of Japan, 2005). During our interviews, local officials indicated that owners were generally receptive to the requirement for TVEB when approached about using their building for vertical evacuation, although some owners had concerns over the access and responsibility of evacuees.

Disaster prevention officials in Kesennuma found building owners to be extremely cooperative in the designation of buildings. The owner of the Hotel Horaikan in Kamaishi had proposed that her building be designated as an alternative to construction of defences that would block beach access. She had previously seen evacuation to buildings in the 2004 Indian Ocean tsunami and had built her hotel as a three-storey building so it could be used in tsunami evacuation. The owners of the Takano Kaikan in Minami-Sanriku (B, Fig 5.1) were described as recognising the corporate social responsibility of agreeing to use their building for evacuation, and the Minami- Sanriku fishing cooperative encouraged the designation of its building (D, Fig 5.1) to protect its workers. There was no disagreement from building owners in Ishinomaki when they were approached by the city; in this case, it was agreed that the city would pay compensation to building owners in the event of damage or costs incurred when people evacuate to the property, which follows government guidelines (Cabinet Office Government of Japan, 2005).

One interviewee reported initial resistance in Ōfunato City from building owners approached about the potential use of their buildings as TVEB. The owners' concerns focussed on night-time access and on who would be responsible for evacuees while in the building, but following discussions with the community the owners agreed to their buildings being used. This suggests that leveraging community interest and encouraging owners to see the provision of the building as a benefit to the community was an effective way to gain support of building owners in Japan, and that a similar approach should be taken in implementing vertical evacuation strategies elsewhere.

5.4.9 Community engagement

The use of workshops in consultation and negotiation for tsunami vertical evacuation strategies is a key component of Japanese guidelines (Cabinet Office Government of Japan, 2005), and participation of local community volunteer disaster prevention groups in building identification and evacuation mapping were common themes in our interviews. Community engagement to encourage ownership and awareness are also important components of tsunami preparedness initiatives in the United States (Dengler, 2005; Project Safe Haven, 2011a,b) and New Zealand (MCDEM, 2008d).

In Ōfunato City, the identification of buildings suitable for vertical evacuation was led by community groups that approached the municipal government with potential structures for designation. Some of those structures did not meet official structural requirements, so they did not become officially designated, yet these buildings were used successfully on March 11th in informal vertical evacuation (see Section 5.4.3). In Kamaishi, several community-identified structures did not meet government requirements therefore local authorities did not advise their use during tsunami evacuation. Only the building owners used these buildings on March 11th 2011 and although the lowest three storeys were damaged, the occupants survived. Community disaster prevention groups in Kesennuma reportedly approached the owners of the Yoyoi cannery in the Hamacho neighbourhood (B, Fig 5.2) about using it for vertical evacuation, after which it became officially designated.

Engagement with the community after building designation is important for developing and maintaining awareness of the vertical evacuation strategy, and is a key component of government guidelines. The Yoyoi cannery had signage at entrances and was used in ongoing training as part of local biannual evacuation exercises. In contrast, once the use of official buildings in Ishinomaki had been agreed, the arrangement was broadcast on local news, but their function was not publicised widely and no signage was applied. In Minami-Sanriku, exercises reportedly involved evacuation to high ground only, but signs depicting past tsunami heights include directions to TVEB. It is unclear from the interviews how widespread the incorporation of TVEB into annual evacuation exercises is elsewhere in Iwate and Miyagi Prefectures, but these observations suggest a high degree of variability among municipalities.

Community engagement in the development of vertical evacuation strategies should be encouraged to foster familiarity with TVEB as part of wider preparedness and evacuation plans. TVEB should be incorporated into tsunami evacuation drills to enhance the awareness of their availability and use. Evacuation to high ground should remain the training priority and preferred option, but the use of TVEB should be practised where conditions are likely to prevent people reaching high ground during a local tsunami.

5.4.10 Evacuee welfare in TVEB

Evacuees were stranded in some TVEB for up to two days during and following the Great East Japan tsunami due to standing water and debris blocking building exits. Our interviews examined the availability of welfare in TVEB, such as the provision of food and water, shelter, warm blankets and clothing, sanitation, and emergency communication links to disaster prevention officials or emergency services. It is noted that in Japan, TVEB are considered primary refuges for short-term use and that welfare provisions for medium- to long-term care are usually provided at secondary evacuation or welfare centres.

It was reported during interviews that provisions were available at the Prefectural Office in Kesennuma and at South Kesennuma Elementary School, but these were appropriate for a six-hour occupancy period only. It had been assumed that after six hours residents would be able to get to welfare centres. However, evacuees had to remain in these building until March 13th, when they were rescued after debris had been cleared. Similarly, evacuees at Yuriage Elementary and Yuriage Junior High schools were required to remain until March 12th, when they had to exit by walking through standing water. The Junior High School had very limited provisions for evacuees, and those at the community centre were on the ground level, which became inundated. There was no emergency communication equipment at either location, although this is recommended in government guidelines (Cabinet Office Government of Japan, 2005).

In Ōfunato, provisions were said to be available at the shopping centre due to the regular function of the building, but no specific arrangements had been made to provide short-term support for occupants in the event of a tsunami. As with retail units, apartment buildings are likely to have some provisions and shelter due to their regular residential use. The official interviewed in Ōfunato highlighted the importance of providing communications links in all refuges to facilitate contact with emergency services, especially in cases requiring urgent rescue when cell phones or other radio systems are not functioning, e.g., if threatened by fire or serious illness.

Several interviewees cited cases of people leaving TVEB prematurely and being killed by subsequent tsunami arriving. Although adequate provisions may help reduce the need or urge for evacuees to leave a refuge earlier than necessary, further work is recommended to assess evacuee decision-making in this regard. With long-term tsunami preparedness in mind, Sharma and Patt (2012) show that evacuees' previous experience in the quality of their stay in an evacuation shelter positively influenced their response to warnings in future. Therefore, the provision of amenities for evacuations in the short-term may yield benefits for long-term mitigation.

An important challenge recognised by the official interviewed in Minami-Sanriku and an area requiring further work is the assessment of adequate resources for a TVEB. It is difficult to say how many people will use any given building and therefore ensure adequate welfare resources, although evacuation modelling can help to estimate likely evacuee numbers once the coverage area of a TVEB is established (Cabinet Office Government of Japan, 2005).

The upper storeys of TVEB should ideally have emergency shelter, food and water sufficient for several days' occupancy, given the potential for extended periods of isolation. Communication links to civil defence or emergency services should also be provided. Such provisions were lacking in TVEB at the locations investigated, but there were no reports of this resulting in deaths at TVEB. Therefore, availability of short-term welfare should be considered secondary to the structural requirements for providing life-safety, and the designation of suitable buildings should not be delayed or prevented because of inadequate welfare provisions.

5.5 Conclusions

Safe refuge was provided by many TVEB during the 2011 Great East Japan tsunami, highlighting the value of a vertical evacuation strategy in areas at risk of tsunami. These buildings are not a replacement for evacuation to high ground, but provide effective alternative options for those unable to evacuate the inundation zone prior to tsunami arrival. This research presents a reconnaissance-level view of the implementation of tsunami vertical evacuation guidelines in Japan and the performance of TVEB in an extreme event. Observations and interviews have shown that in the locations visited, there was variable adherence to published tsunami vertical evacuation guidelines and that there are some aspects in which implementation of the strategy could be improved.

The positive structural performance of TVEB with respect to wave impact, foundation scour and debris strike in extreme tsunami indicates that construction requirements for designating TVEB in Japan provide a sound basis for the future development of TVEB in Japan and internationally. Due to previous underestimation of tsunami hazard in Tōhoku, some TVEB were (or were close to being) overtopped and safe storeys inundated. Future designation of suitable TVEB height for safe storeys must be based on robust hazard assessment to ensure the height is appropriate to the estimated local maximum tsunami height. Although TVEB escaped fire damage in this event, the widespread occurrence of fire and damage, e.g., to a school that had been occupied by evacuees shows the continuing importance of minimising the spread of fire and preventing fire damage to

TVEB.

All of the locations investigated in this work were developed urban areas and the vertical evacuation strategy relied largely on using existing buildings, thereby limiting planners' ability to achieve an ideal distribution of TVEB — an issue likely to occur internationally. Experience in this event shows that this is not, however, a barrier to effective vertical evacuation because loss of life was mitigated even where the best possible distribution of buildings could not be achieved.

Observations from this work provide several examples of building access methods that should be considered in the development of TVEB internationally. Although special access plans were not enacted in this event due to its day-time occurrence, concern was expressed in some interviews over the efficacy of night-time access preparations. It is therefore important that 24-hour building-appropriate access and subsequent community evacuation training are given high priority in future strategy development. The provision of access and responsibility for evacuees represent concerns for building owners when the use of their buildings as TVEB is considered. In the development of strategies internationally, this important issue will require engagement between the community and building owners, which helped to gain agreement of owners in Japan.

Two significant aspects of Japanese government guidelines that were largely absent from observed TVEB were signage and welfare provisions. More effective implementation of external signage might have helped to minimise loss of life through greater use of TVEB, particularly among transient populations unfamiliar with local evacuation planning, although further research is required to confirm this. The majority of TVEB had no dedicated welfare provisions or had provisions suitable only for several hours of building occupancy. Observations from this event show that potential occupancy period should be considered in terms of days rather than hours, and indicates a particular need for emergency communications equipment in TVEB.

In Tōhoku, the planning of optimal TVEB locations may now be possible during extensive redevelopment, and greater adherence to existing government guidelines is encouraged. Internationally, the development of vertical evacuation strategies can benefit by recognising the Japanese government guidelines and by learning from experiences in the Great East Japan tsunami.

Further study of evacuees' experiences in identifying, accessing and taking refuge in TVEB would enhance the understanding and use of TVEB. Approaches to improving the integration of TVEB in evacuation exercises and more clearly identifying welfare requirements should be explored. In addition, detailed structural analyses of specific TVEB and their performance with respect to tsunami loading, debris strike and foundation scour are expected to enhance structural resistance against tsunami.

5.6 Acknowledgements

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5.7 Link to next chapter

This chapter has presented examples of existing vertical evacuation buildings, providing guidance for design of building, in terms of physical features, logistics and resource issues that should be considered when designing a vertical strategy in New Zealand. The next chapter (Paper 3) presents the results of tsunami evacuation behaviour surveys that were conducted at Napier. The results are intended to inform subsequent evacuation modelling in this thesis, and drive public education to address outstanding issues in tsunami understanding and evacuation response. The survey collected some data on perceptions of TVEB in Napier, which are intended to inform TVEB development strategies.

6. INTENDED EVACUATION BEHAVIOUR IN A LOCAL EARTHQUAKE AND TSUNAMI AT NAPIER, NEW ZEALAND (PAPER 3)

This chapter presents the results of surveys that explored intended tsunami evacuation behaviour in Napier, New Zealand. The survey was conducted to inform modelling of evacuation in Chapter 7 and to provide preliminary data on the perception of using Tsunami Vertical Evacuation Buildings (TVEB), defined as Objective 3. The work was originally published as *Fraser, S. A.; Leonard, G. S.; Johnston, D. M. 2013. Intended evacuation behaviour in a local earthquake and tsunami at Napier, New Zealand, GNS Science Report 2013/26. 55 p*. With the exception of formatting, the text presented here is unaltered from the published version. A contribution statement, outlining author contributions to the paper, is provided in Appendix H.

6.1 Abstract

We conducted surveys of 136 residents of and visitors to Napier, Hawke's Bay, New Zealand, to understand hazard awareness and intended evacuation behaviour in a hypothetical local earthquake and tsunami. The results provide a unique investigation of evacuation intentions in the context of local tsunami hazard in New Zealand. The data support observations from previous surveys and international literature, and provide new data on intended evacuation destinations, travel mode and opinions of tsunami vertical evacuation buildings.

There were high levels of recall of hazard information among residents in Napier and although the results suggest a low level of information provision to visitors by the tourist industry, there is a high level of tsunami hazard awareness among both groups. There is a reasonably good understanding of potential tsunami arrival times, but an expectation that official tsunami warnings will be given via sirens or TV/radio in the case of local tsunami. Intended behaviour suggests that ground shaking might trigger appropriate earthquake response actions but people may not extend their actions to include appropriate tsunami evacuation response. Location at the time of the earthquake and gender influence respondents' intention to evacuate and their intended travel mode. A moderate proportion of respondents stated that they would evacuate to high ground and some respondents identified their home or prominent locations in the city as intended evacuation destinations, despite those locations being within the tsunami hazard zone. Respondents were receptive to vertical evacuation as an alternative to high ground, but generally consider it a last resort and expressed concern about structural integrity and sufficient height.

6.2 Introduction

This study was undertaken to understand hazard awareness and intended tsunami evacuation behaviour of residents and visitors in the context of local earthquake and tsunami at Napier, Hawke's Bay, New Zealand. Previous research has documented the seismic hazard associated with the Hikurangi subduction margin, 100–150 km offshore of the east coast of the North Island (e.g., Wallace et al., 2009) and palaeo-earthquake and tsunami in Hawke's Bay (Cochran et al., 2005, 2006). Numerical modelling has demonstrated that in the worst-case scenario of a whole margin rupture, large areas of urban Napier could experience flow depth exceeding 3 m with maximum inundation extent of 4 km (Fraser et al., 2014). Tsunami wave arrival could occur in as little as 27 minutes after earthquake rupture. The resident population of 57,800 (Statistics New Zealand, 2013a) and large numbers of visitors to the city represent high exposure to the local tsunami hazard. We require improved understanding of tsunami awareness and evacuation intentions to help in designing community engagement programmes and resources, and efficient evacuation strategies in case of local tsunami.

Extensive literature on evacuation behaviour provides a basis for tsunami evacuation planning, but this has been generated largely through the study of U.S. hurricane evacuations and an understanding of tsunami evacuation remains limited (Lindell and Prater, 2010). Behavioural models based on hurricane evacuation data may be applicable to distant tsunami due to the similar availability of official warnings and lead-time of several hours or more. However, the short lead-time of local tsunami requires that we investigate behaviour in a different context, where the challenges of rapidly detecting tsunami and disseminating warnings preclude issuing official warnings ahead of tsunami arrival. In practice, natural and informal warnings are likely to be the predominant source of warnings in such a situation. Much of the evacuation behaviour data has been collected in the United States, which allows us to consider those findings appropriate to New Zealand in the broad cultural context, as the two countries share a similarly individualistic culture, although a complicating factor is the use of mandatory evacuation in some states, whereas in New Zealand evacuation may be advised but is not regulatory.

We conducted 136 face-to-face questionnaire surveys in Napier from Friday 1st March to Sunday 3rd March 2013. The survey focussed on assessing respondents' understanding of tsunami potential, expected wave arrival time and subsequent evacuation intentions, given a scenario of long or strong ground shaking at Napier. Intention data or 'stated preference' data are able to provide insight where a type of event occurs infrequently, precluding observation of actual behaviour. Context to this research is given by an overview of relevant evacuation decision-making and behaviour literature (Section 6.3). Description of the survey aims and methodology (Section 6.4) is followed by results and discussion of data analysis (Section 6.5). Data presented here will inform behavioural assumptions in tsunami evacuation simulations, inform tsunami education, and provide a focus for future social science research into tsunami evacuation in New Zealand.

6.3 Evacuation behaviour

We use the term evacuation to mean short-term evacuation undertaken prior to impact with the aim of minimising losses due to the event, labelled ‘preventative evacuation’ by Perry, Lindell, and Greene (1981). Evacuation is a complex and dynamic process and evacuation behaviour — the choices made and protective actions taken in an emergency or crisis — is influenced by situational, social and cultural contexts, environmental cues and warnings. Personal characteristics are important for recognition and interpretation of warnings, personalisation of risk, and decision-making. Substantial numbers of people choose not to evacuate or are unable to evacuate in disasters. Factors influencing non-evacuation in previous events may include: low personal risk perception due to previous experience, lack of belief in the hazard (Lindell and Perry, 1992); a lack of understanding of warnings (Gregg et al., 2006); situational impediments such as mobility issues or separation from family (Lindell and Perry, 2012); logistical challenges (Lindell, Kang, and Prater, 2011); or lack of knowledge on available protective options (Burton, Kates, and White, 1978). Previously studied personal characteristics include age, gender, income, ethnicity, disability, composition of the household, presence of an adaptive plan, warning factors (source, content, clarity, consistency of message, number of warnings), risk perception, challenges of evacuation, previous experience of similar emergencies, and geographic location — all of which have been shown to have some degree of positive or negative influence on likelihood of evacuation (Dash and Gladwin, 2007, and references therein). Much of the available data on evacuation behaviour comes from US hurricanes (e.g., Lindell, Kang, and Prater, 2011; Lindell and Prater, 2007), undoubtedly owing to the frequency of hurricanes and ease of access to the study areas. Additional data comes from nuclear accidents in the United States (e.g., Urbanik, 1994, 2000).

There is limited discussion in the literature of the extent to which rate of evacuation is affected by receipt of a mandatory or voluntary evacuation order in the United States. Although these are used for hurricane, tsunami and wildfire, the most-studied is mandatory hurricane evacuation. The use of mandatory evacuations in hurricanes varies by state, with respect to the use of this term, the extent to which such an order is enforced, and by which agency (Wolshon et al., 2005). Both types of order may be issued in the same event to different geographic areas and groups of people, based on level of hazard and whether they reside in a mobile home or a more substantial construction (Dash and Morrow, 2001). Mandatory evacuations do not necessarily result in complete compliance, and may even result in lower evacuation than for a voluntary evacuation order during the same event (Dash and Morrow, 2001). Mesa-Arango et al. (2012) suggests that there is a greater correlation between stated preferences and actual behaviour when a mandatory evacuation has been issued, than for voluntary evacuations.

Following the globally significant tsunami of 2004 and 2011 and increased research on tsunami in the intervening years, tsunami evacuation behaviour has been more extensively studied but remains limited (Dash and Gladwin, 2007; Lindell and Prater, 2010). Several studies have described evacuation in the 2011 Great East Japan tsunami including evacuation (or non-evacuation) actions and timing (Yun and Hamada, 2012), use of vertical evacuation buildings (Fraser et al., 2012b) and evacuation rates and use of vehicles (Murakami and Kashiwabara, 2011). Mas et al. (2012a) applied observed behaviours in testing an agent-based model of evacuation against observed evacuation rates. Several other international events have resulted in studies of behavioural response to tsunami (Bird, Chagué-Goff, and Gero, 2011; Gregg et al., 2006; McAdoo, Moore, and Baumwoll, 2009; McAdoo et al., 2006; Okumura, Harada, and Kawata, 2011). In New Zealand, Walton and Lamb (2009) carried out an experimental study of intended post-earthquake travel behaviour and following the 2007 Gisborne earthquake conducted surveys to investigate actual travel behaviour (Lamb and Walton, 2011). Several studies of evacuation behaviour have been carried out in the course of on-going research (Currie et al., 2014; Dorfstaetter, 2012; Stewart et al., 2005) and following distant tsunami events (Rogers, 2010).

Evacuation decision-making factors, such as personal experience, perception of threats and protective actions, family context, environmental and social cues, have been incorporated previously into decision theory models to determine their relative importance in taking protective actions (Lindell and Perry, 2012; Perry, Lindell, and Greene, 1981) and to aid in estimating evacuation rates. Agent-based models have also become more commonplace in the study of tsunami evacuation (Goto et al., 2012b; Johnstone, 2012; Mas, Adriano, and Koshimura, 2013; Mas et al., 2012a). Agent-based models allow simulation of individual components (agents) within a system, each with a particular set of characteristics and rules governing their behaviour, the interactions between multiple agents and interactions between agents and the simulated environment (Crooks and Heppenstall, 2012). In the context of tsunami evacuation, agents represent individuals or family groups, each with a set of characteristics (e.g., physical, experiential) which determine the likely evacuation actions (and efficacy of those actions) they take in the event of a tsunami in their environment (modelled roads, buildings etc.). Therefore, prior knowledge about the influence of personal characteristics and experience on likely behaviours is essential to inform assumptions within the model. This behavioural data is something that has been poorly integrated into the assumptions used in many of these evacuation models (Lindell and Prater, 2007). The following sections provide background to several key behaviours that are explored in this study, to provide context to the results and discussion.

6.3.1 Tsunami warnings and response

Environmental cues or natural phenomena have been observed prior to wave arrival in many previous tsunami. Japanese data from as early as 1896 and 1933 includes accounts of audible cues such as ‘continuous sound like a locomotive’ and ‘thunder-like’ sounds (Shuto, 1997). In Thailand the majority of people surveyed following the Indian Ocean tsunami reported seeing or hearing something unusual in the sea (Gregg et al., 2006). Visible cues can, but do not always, include drawdown of the water at the coast, exposing the seabed or reefs prior to wave arrival, and other unusual wave activity such as a wall of water, a rapidly rising tide, large eddies, and frothing or ‘boiling’ of the sea surface. These phenomena can provide a natural warning of tsunami in the case of distant, regional and local tsunami as they are due to the mass movement of water occurring at any distance from the source event. In the case of local tsunami generated by an earthquake, ground shaking may also provide a natural warning due to the proximity of the epicentre to the coastline.

Although early earthquake warning systems exist in Japan and are able to provide a tsunami warning within three minutes (Japan Meteorological Agency, 2013), such technology has flaws which were exposed in March 2011, primarily the incorrect automatic estimation of wave heights and mis-communication of subsequent warning messages (Fraser et al., 2012a). Current technologies allow approximation of earthquake magnitude by the global seismic network almost immediately upon detection of ground shaking. However, the time required to refine source magnitude and mechanism in order to issue accurate tsunami warnings is too great to be applied effectively in a local tsunami.

Fixed position, tone-only tsunami siren systems have been installed in several regions of New Zealand[1] and further discussion is underway regarding siren installation (e.g., in Tauranga City) but such systems have flaws, which are particularly important to consider in the context of short tsunami arrival times. Aside from the potential for siren systems to fail due to power outages in a significant local earthquake, and the potential for false alarms[2], a major criticism of the warning provided by sirens (particularly tone-only sirens with no voice message) is that they do not deliver a specific, detailed message to the surrounding area (Leonard, Saunders, and Johnston, 2007). As a result, there is a period of time in which the public may hear the siren but not respond until they are sure of the meaning. In Napier, the council instructs people to listen to local radio for further information; the tsunami siren system in Auckland gives three different tones for ‘threat of tsunami’, ‘immediate evacuation’ and ‘threat has passed’ — the public are expected to interpret these in case of the siren sounding.

In order to make such siren systems effective, they must exist within the framework of an effective early warning system with, among other components, a public education component required to enhance awareness and understanding of the system (Leonard et al., 2008a). Even with such a campaign, understanding of the siren may not be enhanced substantially. A tsunami siren system has been present in Hawai’i for several decades but Gregg et al. (2007) found that only 13% of the population understand the meaning of the siren, despite high awareness of sirens and siren tests.

[1] Including Napier (http://www.napier.govt.nz/index.php?pid=234), Northland Region (http://www.nrc.govt.nz/civildefence/tsunami/tsunami-sirens/), Auckland (http://www.aucklandcouncil.govt.nz/en/environmentwaste/naturalhazardsemergencies/civilDefence/Pages/civil_defence_and_emergency_management_home.aspx), and Christchurch (http://www.ccc.govt.nz/homeliving/civildefence/informationondisastershazards/tsunami.aspx)

[2] In Whitianga, Thames-Coromandel District, several false alarms occurred in 2012 due to accidental triggering by a cleaner and a flat battery (www.stuff.co.nz/national/7223142/Whitianga-tsunami-siren-gets-unplugged)

This level of understanding represents a small increase from 5% in 1960 (Lachman, Tatsuoka, and Bonk, 1961). The complexity of siren systems, requirement for multiple sirens to provide audible coverage to the entire community at risk (indoors and outdoors, in poor weather conditions including high winds and rain which can reduce the audible distance of a siren), and the requirement for redundancy in the system in case of power failure, result in significant installation and maintenance costs ranging from tens of thousands to millions of New Zealand Dollars (Leonard, Saunders, and Johnston, 2007; Leonard et al., 2006).

Hastings District Council (Hawke's Bay) and Wellington City have mobile sirens, to be driven in a vehicle around the coastline issuing voice messages in the event of tsunami. Although this method overcomes the issues of tone-only sirens for distant tsunami, these are not suitable for local tsunami as they require time to deploy the sirens and personnel to drive into the tsunami hazard zone to issue the warning. Given the current technological limitations of siren systems for local tsunami, it is important to understand the general population's awareness and interpretation of natural phenomena as warning of tsunami to inform tsunami education, and assumptions of how people in Napier would respond to a natural tsunami warning and try to improve this response mode in future.

Evacuation triggered by natural warnings has saved many lives in previous events (McAdoo, Moore, and Baumwoll, 2009; Yamori, 2013). In some cases, ground shaking has been felt but not interpreted as a warning of the subsequent tsunami, resulting in delayed or non-evacuation (Gregg et al., 2006; Murakami and Kashiwabara, 2011; Yun and Hamada, 2012). The importance of immediate evacuation is shown in the data from witnesses to the Tōhoku 2011 tsunami: 75% of people who did not evacuate (n = 228) did not survive, whereas 73% of people who evacuated in less than 20 minutes (n = 461) survived (Yun and Hamada, 2012). A person's belief that their current location was safe from tsunami, in part due to previous experience of earthquakes without subsequent tsunami, was a factor in producing a sense of safety (Yun and Hamada, 2012). However, it may also be extremely difficult for people to estimate, based on ground shaking alone, whether or not the source earthquake is located offshore and is severe enough to pose a tsunami risk. This is particularly true for long duration, low intensity 'tsunami earthquakes' (Kanamori, 1972) which are capable of causing devastating tsunami with little ground shaking to act as a warning, for example Java in 2006 (Reese et al., 2007). Initiation of evacuation in response to ground shaking in the Canterbury earthquakes was highly dependent on the actions of others rather than demographic factors or risk perception and hazard knowledge — 76% of people responded in the same way as neighbours in September 2010 and 98% did during the major aftershocks (Dorfstaetter, 2012). Individuals' reliance on others' behaviour was also reported in Japan, with 39.4% of people reported to have evacuated due to following other people's direction (Yun and Hamada, 2012).

Significant tsunami inundation has not occurred in New Zealand during recorded history. Consequently, there is little previous experience for coastal populations to draw upon, and previous data suggests a low evacuation response to natural warnings. Only 7.7% of people in a study of travel following an earthquake in Gisborne in 2007 travelled to higher ground to avoid a potential tsunami (Lamb and Walton, 2011). Following the September 2010 Canterbury earthquake only 21% of coastal residents evacuated in case of tsunami (Dorfstaetter, 2012). High levels of media coverage of recent international tsunami events may improve evacuation rates in the future, however, New Zealand presently largely relies on education to raise tsunami hazard awareness and preparedness in case of such an event. Tsunami education particularly emphasises the need for immediate evacuation in the case of long duration (lasting for a minute or more) or strong earthquakes (hard to stand up) (MCDEM, 2010a, p. 9, See text box 6.1). The Ministry of Civil Defence and Emergency Management (MCDEM) message is designed to include the potential for subduction zone events, tsunami earthquakes and upper plate ruptures — all of which can be tsunamigenic but are likely to cause a different style and intensity of shaking at a given location:

Textbox 6.1 (MCDEM Evacuation message: Local Source Tsunamis)

Special Consideration — Local Source Tsunamis
A tsunami generated in conjunction with a nearby large earthquake or undersea landslide may not provide sufficient time to implement official warning procedures.
Persons in coastal areas who:

- *experience strong earthquakes (hard to stand up);*
- *experience weak earthquakes lasting for a minute or more;*
- *observe strange sea behaviour such as the sea level suddenly rising and falling, or hear the sea making loud and unusual noises or roaring like a jet engine;*

should not wait for an official warning. Instead, let the natural signs be the warning. They must take immediate action to evacuate predetermined evacuation zones, or in the absence of predetermined evacuation zones, go to high ground or go inland.

6.3.2 The household / family unit

Evacuation behaviour literature has repeatedly cited the importance of the household unit or family because household members attempt to reunite with, or at least account for, all members before evacuating together (Drabek, 1996; Lindell and Perry, 1992, 2012; Perry, Lindell, and Greene, 1981). This has been shown to be the case for events with lead-times of several hours to days. Although there are fewer data for events with a shorter lead-time of less than one hour, there is anecdotal evidence (Fraser et al., 2012a) and survey data (Yun and Hamada, 2012) from the 2011 Great East Japan tsunami showing that parents travelled to collect children from schools and some families returned home to collect elderly relatives despite imminent tsunami arrival. Those actions resulted in additional deaths as inundation trapped people travelling through unsafe coastal areas following the earthquake and tsunami warnings. In an experimental investigation of post-earthquake intentions in New Zealand, Walton and Lamb (2009) found that around half of the people intending to travel from home or work after an earthquake would travel to reunite with friends or family. It is anticipated that the same actions could occur in New Zealand during a local tsunami, and therefore influence evacuation travel mode, routes and time, ultimately influencing the rate of successful evacuation.

6.3.3 Pre-evacuation actions and departure time

The time at which a person or group begins to evacuate, after receipt of a hazard warning, is closely associated with reception and understanding of an official, informal or natural warning and immediate actions taken. This 'pre-evacuation time' (Purser, 2010) is the first of the two time phases in evacuation and has two main behavioural components: recognition, which starts with the cue or warning and ends with the first response to the alarm; and response, which starts the first response and ends with person beginning to travel towards an exit or safe location. Response time can include gathering possessions, helping or warning others, investigating the emergency, and is affected by key behavioural factors such as alertness, familiarity with surroundings and warnings, previous experience or training, group interactions, and commitment to on-going activities. Pre-evacuation time is followed by the travel time, which is the subsequent time taken to reach safety. The two are additive to produce the overall evacuation time.

The importance of immediate evacuation was highlighted in Section 6.3.1. Yun and Hamada (2012) reported that the most common pre-evacuation actions taken by people who died in the 2011 Japan tsunami as: helping others (22.4%), finding family or relatives (9.7%) and doing rescue work (13.9%). Intention surveys in Wellington suggest that over 30% of respondents would evacuate immediately in case of an earthquake, and 22% would help others (Currie et al., 2014).

The use of stated intentions to estimate approximate evacuation departure times can provide some insight in the absence of observations of actual evacuation behaviour in real events, but there is the potential to underestimate departure if we rely on this alone. Mas et al. (2012a) showed that there was greater correlation between tsunami wave arrival time and actual evacuation departure time ('revealed preference') given in six post-tsunami surveys than there was between 'stated preference' evacuation departure time and a given hypothetical arrival time. To address this issue in modelling, they implement departure time as a Rayleigh distribution with intended departure time as a lower bound and tsunami wave arrival as an upper bound. Kang, Lindell, and Prater (2007) showed that the reliability of people's estimates of time required to carry out pre-evacuation actions is determined by the nature of the action, particularly whether it is a usual, repetitive action.

6.3.4 Travel mode and destination

Travel mode is a key aspect of evacuation planning as it characterises how quickly and at what density people can travel through a transport network. The evacuation behaviour literature suggests that private vehicles are the primary travel mode during evacuation (Lindell, 2008; Lindell, Kang, and Prater, 2011; Perry, Lindell, and Greene, 1981). Lindell (2008) directly relates the proportion of evacuating households in an area who have access to a private vehicle, to the number of vehicles involved in an evacuation (for transients this is based on number of hotel rooms, assuming one vehicle per room). Familiarity with a transport route and expectations of travel time, safety and convenience influences hurricane evacuation route choice, with evacuees taking the routes that are most familiar to them (Lindell, Kang, and Prater, 2011). Due to the short lead-time of local tsunami, traffic congestion in the inundation zone can result in loss of life and the potential for congestion can be exacerbated by damage and disruption to evacuation routes during the prior earthquake ground shaking. A study of witness data suggests that 26% of people who died in the 2011 tsunami were caught in traffic jams (Yun and Hamada, 2012).

The assumption that everyone choosing to evacuate will use a vehicle may be appropriate for long lead-time, long distance evacuations but may not be appropriate in the context of local tsunami where available travel time and distance are shorter. Having said that, a survey of evacuation intentions in the Sendai Plains area of Miyagi, Japan, revealed that 80% of those intending to evacuate inland ahead of a tsunami ($n = 215$) and 38% of those intending to travel to an evacuation building ($n = 93$) would use a car (Suzuki and Imamura, 2005). In 2011, the tsunami warnings prompted 60% of evacuees to use vehicles in this area, with the level of vehicle use influenced by high daily use of vehicles (Murakami and Kashiwabara, 2011). Walton and Lamb (2009) reported that hypothetical travel distance influenced intended travel mode in a survey of post-earthquake evacuation intentions. The frequency with which people reported intentions to drive a vehicle increased with increasing distance, and vice versa for intended pedestrian evacuation. Based on the log-trend of reported frequencies, vehicles were preferred for travelling distances 3.25 km and over. The distance factor may also contribute to the variation in travel mode according to destination reported by Suzuki and Imamura (2005).

New Zealand has a high rate of vehicle ownership, which suggests that there is high daily vehicle use, and therefore there is likely to be a high-use of vehicles during evacuation. This was borne out by Lamb and Walton (2011) who showed that 95% of trips made immediately following the 2007 Gisborne earthquake were made by vehicle. Sixty percent of Papamoa residents reported that their intended evacuation travel mode following a tsunami warning in 2010 had been to drive, while 25% intended to walk and 8% intended to cycle (Rogers, 2010). Recent education and media coverage of the 2011 Japan tsunami may have acted to raise awareness of traffic congestion during tsunami evacuation, therefore reducing the intended levels of vehicle use. A recent survey in Wellington suggested that over 40% of respondents intend to evacuate on foot (Currie et al., 2014). Local topography and urban density are likely factors in the rate of those intending to walk versus drive as they influence distance to high ground, road layout and network capacity, local transportation trends and the presence of additional pedestrian-only tracks and trails. For example, in Hawke's Bay Region 11% of all journey legs travelled are pedestrian, compared to 18% in Gisborne and 25% in Wellington (Statistics New Zealand, 2013b). In Wellington and Kapiti urban area 16% of journeys are made by public transport with or without walking, and 11% are pedestrian journeys (Statistics New Zealand, 2013c). These are higher than the New Zealand average for urban areas[3] (4% and 6%, respectively), therefore, the expectation is that in a daytime evacuation in Wellington the proportion of the local population having access to a vehicle in the urban area would be lower than in other areas so a greater proportion would opt to evacuate on foot.

Recognition that high ground provides safety from tsunami was reported to be very high (90%) in New Zealand in the 2003 National Coastal Survey (Stewart et al., 2005). We expect that due to the topography of Napier and the recognition that high ground provides safety, Bluff Hill (as the closest high ground to the city centre) will be a primary evacuation destination. However, as already noted in Section 6.3.1 very few people actually went to high ground following the 2007 Gisborne earthquake, so recognition of the appropriate action is not always acted upon.

6.3.5 Transient populations

Transient populations (e.g., tourists, temporary workers), have long been neglected in studies of evacuation behaviour and warnings (Quarantelli, 1960; Sorensen, Vogt, and Mileti, 1987). This remains true for vulnerable populations in general, not just transient populations (Drabek, 1994; Phillips and Morrow, 2007) and has been reported internationally (Becken and Hughey, 2013). There are complex dynamics in the evacuation of transient populations. The national guidelines for mass evacuation planning in New Zealand (MCDEM, 2008a) outline some of the perceived challenges in evacuation of tourists and reasons why they are classified as a vulnerable population, as: '[tourist] numbers are variable and imprecise'; 'tourists do not know the local area' ; and 'they are likely not to know how to evacuate or where to access help'.

On the other hand, evacuation logistics may be simpler for transient populations than resident families, as they have fewer possessions or property to protect (Lindell, 2008; Lindell and Prater, 2007). This benefit may be more relevant for slow-onset events rather than rapid-onset events where there is less focus on property protection than immediate life preservation. Evacuation intention data from hypothetical tsunami scenarios in Thailand (Charnkol and Tanaboriboon, 2006) and U.S. hurricane data (Drabek, 1996) suggests that transient populations were likely to evacuate faster than permanent residents; Charnkol and Tanaboriboon (2006) suggest that this is due to the

[3] Includes: Auckland main urban area (MUA), Christchurch MUA, Dunedin MUA, Hamilton Zone, Tauranga MUA and Wellington (+ Kapiti). Data for Gisborne and Napier are not available at this resolution.

reticence of residents to leave their homes.

Direct warning from accommodation staff to guests may expedite the response of visitors (Drabek, 1996), as occurred in Western Samoa (EEFIT, 2009). This could also apply to confirmation of natural warnings in a local tsunami scenario, but this relies on adequate levels of hazard awareness and prior training of staff, and is likely to be affected by the complex and sometimes conflicted evacuation decision-making of staff (Drabek, 1994). Disparate levels of tsunami preparedness between residents and visitors were observed in Ocean Shores, Washington, U.S. (Johnston et al., 2007), and Long Beach, Washington (Johnston et al., 2009) where levels of preparedness and staff training were found to be low despite moderate to high levels of awareness among residents. There is a concern that a disparity between visitors' and residents' awareness of the tsunami hazard and appropriate response actions could be present in New Zealand coastal areas. Becker, Paton, and McBride (2013) found that 'there appears to be little or no outreach when it comes to educating visitors regarding the risks in Hawke's Bay Region' and tourism operators are not well integrated with Civil Defence and Emergency Management (CDEM) activities in the Northland Region of New Zealand (Becken and Hughey, 2013).

6.4 Survey method

6.4.1 Aims

The survey was carried out to collect Napier residents' and visitors' intended, or 'stated preference', evacuation behaviour in the context of local tsunami. This data was collected in lieu of behavioural observations collected during or after a real event, which is the preferred method of data collection (Lindell and Prater, 2010). 'Stated preference' surveys have been used to inform evacuation assumptions in several recent studies of evacuation behaviour (Mas et al., 2012a; Solís, Thomas, and Letson, 2010). Whitehead (2005) demonstrated that intention data have some degree of predictive validity for hurricane evacuation behaviour and Kang, Lindell, and Prater (2007) demonstrated, for some aspects of behaviour, correlation between expectations and actions actually taken when an event occurred. There appears to be a greater correlation between intended and actual evacuation behaviour where there has been prior experience of an event, for behaviour of a repetitive nature, or for behaviours that are based on a dichotomous choice, i.e., to evacuate or not to evacuate (Kang, Lindell, and Prater, 2007). Further research is required to strengthen the validity of this approach, but research to date shows good agreement at the aggregate data level (proportions citing intended behaviours) (Kang, Lindell, and Prater, 2007), which is the main focus for this study.

Within our overall aim of enhancing knowledge of tsunami evacuation behaviour in New Zealand, we explore awareness of the local tsunami hazard and recognition of natural warnings of tsunami. We establish the range of actions that people intend to take prior to evacuating, in order to inform modelled pre-evacuation behaviour and calibrate estimates of pre-evacuation time for simulation. We investigate intended congregation behaviour of family units to assess the extent to which this might be observed during a local tsunami in Napier. This can inform education regarding the dangers of travelling through tsunami hazard zones and facilitate inclusion of such actions in evacuation simulations and planning initiatives.

We identify preferred travel modes and destinations, hypothesising that these would vary according to the location in Napier at which people experience a local earthquake, due to distance to high ground, proximity of family, and availability of resources. Increased understanding of intended evacuation destinations can inform community engagement and planning for evacuation routes and emergency response. We include visitors in our survey to investigate comparative levels of tsunami hazard awareness and differences in intended response actions between residents and visitors. This represents the first study of visitors' tsunami evacuation intentions in New Zealand, and aside from informing evacuation simulations, will help to develop a knowledge base for more extensive research on this issue. This study does not extend to evacuation behaviour of tourist industry staff, nor does it investigate interactions between industry staff and guests.

6.4.2 Survey structure

The survey used a combination of closed-response and open-ended questions to capture hazard awareness and behavioural intention data. Survey questions were piloted by a group of GNS Science summer students (Currie et al., 2014) in the Greater Wellington region and tested with a number of GNS Science staff prior to implementation. The written survey is presented in Section 6.10. Section 6.11 shows a copy of the information sheet that was offered to respondents following completion of the survey providing further information on the issues raised during the survey.

The survey captured details of the respondent's status as a resident of Napier, a visitor from the Hawke's Bay Region (hereafter, regional visitor), from elsewhere in New Zealand (national visitor) or from overseas (international visitor) and their recollection of receiving hazards information in Napier. The key part of the survey was an investigation of respondents' tsunami hazard awareness, types of tsunami warning and estimates of arrival times given an official warning or a natural warning, and intended evacuation behaviour in a local tsunami. To achieve this, two scenarios were presented — each framed by the experience of long or strong ground shaking, defined as 'ground shaking lasting longer than a minute or during which it was hard to stand up'. The first scenario required that the respondent consider they were undertaking the same activity at the same location as when the survey was conducted (hereafter, 'survey location'); the second scenario was for the respondent being at home (if resident or regional visitor) or at their temporary accommodation in Napier (if national or international visitor). In each case, respondents were asked to describe their actions during and after ground shaking. If they failed to mention evacuation, they were prompted as to whether they would evacuate, and this prompt was noted on the survey. If they stated that they would not evacuate, the reasons for this were solicited. If evacuation was stated (either prompted or unprompted), we asked how long after the earthquake they would evacuate and what, if anything, they would do before evacuating. We also asked where they would evacuate to and by what travel mode.

The survey concluded with an investigation of opinions about using tsunami vertical evacuation buildings. These were open-ended in order to solicit un-prompted responses and act as pilot questions for later surveys which may focus more closely on this issue. We first asked respondents to provide all of the types of places they could think they could evacuate to if a tsunami was imminent, to see if the concept of evacuation into buildings occurred to them independently. We then asked how respondents would feel about evacuating into a building in a tsunami, and what might particularly encourage or discourage them from taking this course of action.

6.4.3 Sampling method

Surveys were conducted by convenience sampling at several locations in Napier from Friday 1st to Sunday 3rd March 2013 inclusive. Convenience sampling was applied in order to solicit qualitative responses and data specific to peoples' actions at the survey locations, which were selected on the basis of having high levels of day-time foot-traffic. These high-traffic locations are the locations with high population concentrations during a usual day-time in Napier and are likely to have a high population exposure during a tsunami occurring in the daytime. As the focus of the survey was to understand people's intended actions when in the city at the time of an event, the study benefited from face-to-face interviewing at the location of interest, rather than providing scenarios in written form using a postal survey. As a non-probability sample, it is not possible to know the relationship between our sample and the entire population (Bryman, 2012), therefore this method precludes extrapolation of data to the entire population and it is not valid to estimate a margin of error. Despite these limitations, the sample remains useful to gain preliminary understanding of intended evacuation behaviour, and as a basis to develop a series of subsequent probability-sample surveys in Napier and elsewhere in New Zealand.

There is a certain amount of self-selection in our sample (the sample only includes those who frequented the survey locations on the survey days) and systematic exclusion of some sections of the population who do not frequent the survey locations, for example, due to health or socio-economic reasons. In order to minimise further bias in the convenience sample we recruited respondents in an unbiased manner by approaching every individual or small group who passed on the street while we were not actively interviewing a respondent. We did not record the rate of participation. To ensure our sample was as representative as possible of the people who frequent the city at different times, we surveyed in several different locations and throughout the day on one week-day and two weekend days, one of which was a busy market day.

The total number of surveys carried out was 136, comprising 97 residents of Napier Territorial Authority and 39 visitors (10 regional, 14 national, 15 international). One survey was incomplete (only questions 1 to 6 were answered), therefore was used in analysis of hazard awareness, but excluded from analysis of evacuation intentions. The majority of surveys (78%) were conducted in the city centre main shopping area on Emerson Street and the surrounding streets. Further surveys were conducted at Marewa shopping centre (9%), Ahuriri marina (6%) and Westshore Beach (7%) to investigate intended behavioural responses at different locations (see Figure 6.1).

6.4.4 Study area and demographics

Napier Territorial Authority (hereafter, Napier) is a generally low-elevation coastal area of 106 km^2, comprising residential suburbs, commercial and industrial areas and agricultural land including orchards and vineyards. Bluff Hill provides an area of high ground immediately north of the city centre to maximum elevation over 100 m. Napier Port is the fourth largest in New Zealand, handling cargo including forestry products and container shipments, with storage of timber and containers on site (Port of Napier Limited, 2012). The estimated population of Napier in 2013 is 57,800 based on medium growth projections from the most recent census in 2006 (Statistics New Zealand, 2013a). During peak tourist season (January to March), an average of 2,342 visitors stay in Napier accommodation every night (Statistics New Zealand, 2012c, 2006–2011 data). Numerous accommodation facilities (59), schools (34, plus one tertiary education campus), early childhood centres (64) and care homes or retirement villages (17) form concentrations of people who may be less able to evacuate effectively in a local earthquake and tsunami due to mobility issues or deficiency in local knowledge.

At the eastern shore of the city there is a steep gravel beach and berm stretching along the coastline south from Bluff Hill, where it is approximately 7 m above Mean Sea Level (MSL) to the confluence of the Tutaekuri, Ngaruroro and Clive Rivers, where it is 4 m above MSL. Northwest of Bluff Hill the suburbs of Ahuriri and Westshore are separated by a tidal inlet and small marina. Westshore is situated on a peninsula elevated 4–6 m above MSL. Bay View is the most northern suburb of Napier, extending north around the bay. Much of the land around the present Ahuriri Lagoon was previously below sea level until uplift during the 1931 Hawke's Bay earthquake and due to artificial drainage in the years since (Hull, 1986).

The 1931 Hawke's Bay earthquake destroyed many of the buildings in Napier and triggered a rebuild in 1930s Art Deco style. The current building stock retains a large number of one- and two-storey 1930s structures, which are an important factor in the city's tourism activities. Ninety-five percent of the building stock in Napier is one or two storeys in height (Fig 6.2). Ninety-two percent of structures are of light timber construction, 3% are reinforced concrete shear wall and 3% are concrete masonry (Cousins, 2009; King and Bell, 2009; King et al., 2008). The remainder are Brick Masonry, Light Industrial, Reinforced Concrete Moment Resisting Frame, Steel Braced Frame, Steel Moment Resisting Frame, or Tilt-up Panel construction. The small number of tall buildings in Napier has implications for tsunami evacuation. The suburban building stock primarily

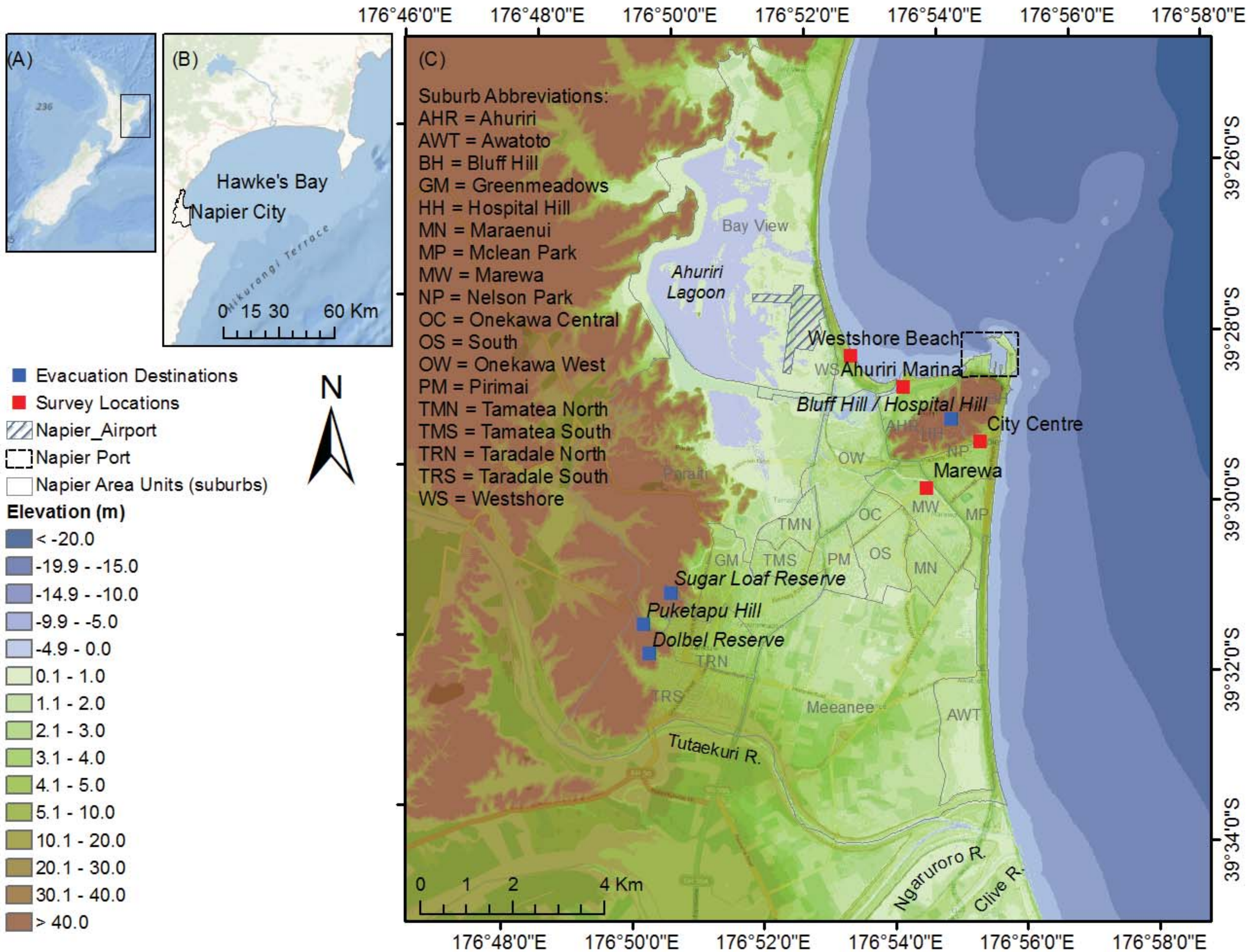

Fig. 6.1: A) Location of Hawke's Bay on a national scale; B) Location of Napier Territorial Authority in the context of Hawke's Bay; C) Napier Territorial Authority boundary overlain on a Digital Elevation Model (DEM) to illustrate local topography; D) Map of survey locations and evacuation destinations overlain on the DEM and road network. Basemap sources: GEBCO, NOAA, National Geographic, DeLorme, and Esri; OpenStreetMap and contributors, Creative Commons-Share Alike License (CC-BY-SA).

comprises single-storey family homes or small commercial premises and the only concentration of taller buildings occurs in the primary retail, tourist and civic area of Nelson Park.

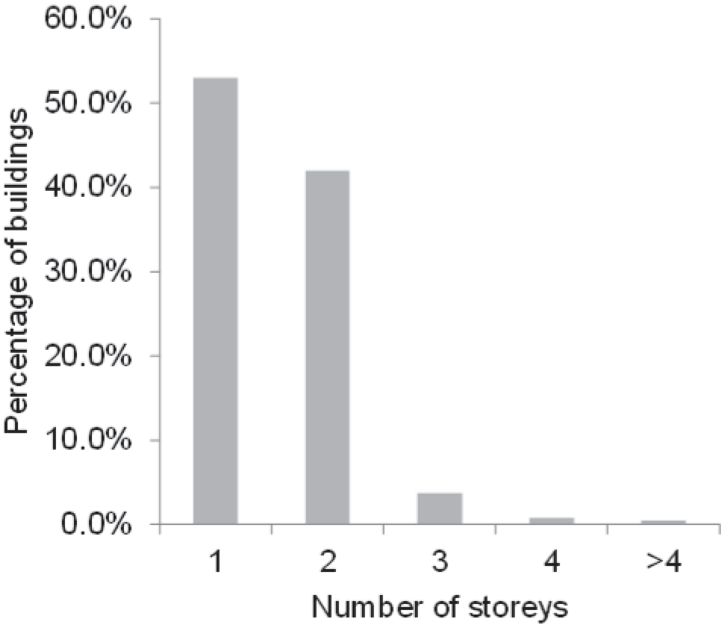

Fig. 6.2: Heights of buildings in Napier, assuming that one storey is approximately 3 m in height. Data source: Napier City Council.

We compared the demographics of the resident portion of our sample (71%; Table 6.1) with that of the estimated 2013 population in Napier. We present the demographics of visitors (29%) but available visitor statistics do not allow comparison to assess sample bias. Our sample represents age distribution of the population of Napier very well (Table 6.2), slightly over-represents females (Table 6.3) and slightly under represents Maori but otherwise represents ethnicity relatively well (Table 6.4). Highest level of education (Table 6.5) significantly under-represents people with no qualification or a trade qualification and over-represents those with school, undergraduate or postgraduate qualifications. Neither Territorial Authority nor regional census data is available for comparison of household income (Table 6.6) and length of time living in Napier (Table 6.7).

6.4.5 Data analysis

We apply a thematic analysis approach to analyse survey responses at a semantic level (Braun and Clarke, 2006), in that we focus on coding and reporting the explicit meaning of responses to develop knowledge of evacuation intentions, without interpreting social or psychological influences on those responses. Data were coded manually and analysed using IBM SPSS Statistics version 20. Our coding is theoretically driven, shaped by previous findings in the evacuation behaviour litera-

Tab. 6.1: Residential status of respondents. Residents are classed as those living in Napier Territorial Authority. Visitors are separated into those from Hawke's Bay, those from the rest of New Zealand and those from overseas. Percent values may not sum to 100% due to rounding.

Residential status	Total (n = 136)
Resident: Napier Territorial Authority	71%
Regional visitor	7%
National visitor	10%
International visitor	11%

Tab. 6.2: Distribution of age group in the survey sample and the Subnational Population Estimates: At 30 June 2012 (SNPE; http://www.stats.govt.nz/browse_for_stats/population/estimates_and_projections/). Age group shows 16–39, while the SPE original data showed 15–39. SNPE data for ages <15 are omitted from the total. Percent values may not sum to 100% due to rounding.

Broad Age Group	Survey residents (n = 97)	Survey visitors (n = 39)	Survey total (n = 136)	Napier subnational population estimates (n = 46,100)
16–39*	35%	28%	33%	36%
40–64	44%	46%	45%	41%
65 and over	19%	18%	18%	22%
Not provided	2%	8%	4%	n/a

Tab. 6.3: Distribution of gender within the survey sample and the 2006 census data for Napier City, excluding people under the age of 15.
Source: http://www.stats.govt.nz/Census/about-2006-census/regional-summary-tables.aspx. Percent values may not sum to 100% due to rounding.

Gender	Resident (n = 97)	Visitor (n = 39)	Total (n = 136)	Napier 2006 census (n = 43,650)
Male	42%	59%	47%	42%
Female	58%	39%	52%	58%
Not Provided	0%	3%	1%	0%

Tab. 6.4: Distribution of ethnicity within the survey sample and the 2006 census data for Napier City. *For the census, people stating multiple ethnic groups are included in as many groups as they list, so one person listing their ethnic group as European and Maori is counted once in each of the separate groups. All ages are included in the census totals as the data does not allow exclusion of people under the age of 16. Source: http://www.stats.govt.nz/Census/about-2006-census/regional-summary-tables.aspx. Percent values may not sum to 100% due to rounding.

Ethnicity	Resident (*n* = 97)	Visitor *n* = 39)	Total (*n* = 136)	Napier 2006 census (*n* = 53,970)
European / NZ European / Pakeha	71%	85%	75%	72%
Maori	11%	5%	10%	18%
New Zealander	7%	3%	6%	14%
Asian	2%	5%	3%	3%
European and Maori	3%	0%	2%	n/a *
Pacific Islands	1%	0%	1%	3%
Latin American	1%	0%	1%	0%
Other	1%	0%	1%	0%
Not Provided	2%	3%	2%	n/a

Tab. 6.5: Distribution of highest level of education within the survey sample. *Trade qualification includes Level 1, 2, 3, 4, Certificates gained post-school; Undergraduate includes Level 5 and 6 Diplomas, Bachelor degree and Level 7 qualifications. Source: http://www.stats.govt.nz/Census/about-2006-census/regional-summary-tables.aspx. Percent values may not sum to 100% due to rounding.

Highest Level of Education	Resident (*n* = 97)	Visitor (*n* = 39)	Total (*n* = 136)	Napier 2006 census (*n* = 43,647)*
None	0%	3%	1%	27%
School	39%	36%	38%	30%
Trade Qualification	10%	5%	9%	15%
Undergraduate	34%	36%	35%	16%
Postgraduate	9%	13%	10%	2%
Other	2%	0%	2%	0%
Not Provided	5%	8%	6%	10%

Tab. 6.6: Distribution of household income within the survey sample. Household income statistics are not available at the Territorial Authority or regional level for the 2006 census or more recently. Percent values may not sum to 100% due to rounding.

Household Income (banded)	Resident (n = 97)	Visitor (n = 39)	Total (n = 136)
Benefit	2%	0%	2%
Under $20,000	10%	13%	11%
$20,001–$30,000	7%	8%	7%
$30,001–$50,000	12%	3%	10%
$50,001–$70,000	21%	13%	18%
$70,001–$100,000	9%	10%	10%
Over $100,001	13%	28%	18%
Not Provided	25%	26%	25%

Tab. 6.7: Length of time residents have lived in Napier. Percent values may not sum to 100% due to rounding.

Length of residence in Napier	Total (n = 97)
Less than 1 year	10%
1 to 5 years	21%
6 to 10 years	10%
11 to 20 years	20%
21 to 30 years	16%
31 to 40 years	8%
Greater than 40 years	16%

ture, which formed expectations of intended behaviour and informed the development of research and survey questions. Due to the relatively short responses to each open-ended question we assigned codes using the full response rather than an excerpt of the response. We coded responses to each open-ended question into common themes before reviewing, refining and editing the themes. In many cases, a response was coded into several themes. Initially, some themes comprised a single response but after reviewing the themes, these were grouped under 'Other'. Responses grouped under 'Other' are reported in our results.

We conducted frequency analysis to determine the most commonly reported intentions and cross-tabulation to assess the correlation of evacuation intentions with demographic variables. Statistical analysis and correlation with demographics have been conducted where the sample size was sufficient. Analysis of survey responses primarily focussed on the respondents' gender and status as resident or visitor. Due to low numbers of respondents of non-European ethnicity, the influence of ethnicity has not been analysed. Several demographic variables have been grouped to facilitate analysis of those demographics. These are: Household income (grouped to: under \$30,000, \$30,001–\$70,000, \$70,001–\$100,000, >\$100,001); Education (School and trade qualification, undergraduate and postgraduate); Length of residence (<5 years, 6 to 20 years, 21 to 40 years, >40 years).

6.5 Results and discussion

6.5.1 Hazards information in Napier

Receipt of hazards information in Napier

Public education is a key component of raising awareness of natural hazards, encouraging household preparation and increasing community resilience. Various channels of information are used, from information in telephone books and newspapers, community meetings, online and social media campaigns, and the MCDEM ShakeOut national earthquake exercise. We asked a series of questions designed to investigate the level to which residents of Napier and visitors to Napier recall previously receiving information about natural hazards in Napier. We also enquired as to the source and format of that information in order to provide feedback to authorities about which types of information are most commonly received and recalled.

The majority (71%) of the total number of residents in our sample (n = 97) recalled previously receiving information about natural hazards. This represents good progress since the 2003 National Coastal Survey, in which only 30% reported having seen tsunami information (Stewart et al., 2005). There was no gender influence on receipt of information. Amongst visitors, the proportion of respondents who recalled receiving information was lower (60% for regional visitors, 50% for national visitors and 47% for international visitors). The difference in receipt of information between residents and visitors (combined) is statistically significant (p=0.04 at 95% confidence interval) using the Fisher Exact test with Freeman-Halton extension, and confirms that visitors are likely to receive less local hazard information than residents. The visitor sub-samples are too small to analyse according to visitors' origin.

There did not appear to be a strong correlation between residents' receipt of information and residents' age or highest level of education. There was some correlation between length of residency and information receipt, and household income and information receipt. Fifty-three percent of people resident for five or fewer years recall receiving hazards information; 80% for 6–10 years, 21–30 years and >40 years, 68% for 11–20 years; and 100% for 31–40 years. Sixty percent and 55% of residents in household income categories $50,001–$70,000 and $70,001–$100,000 reported having received information, but for all other categories (three lower, one higher) this proportion is 75% to 86%. Further analysis of receipt of information among residents revealed no statistical relationship between receipt of information and age (Fisher Exact Test at 5% significance and 95% confidence interval: p=0.078), gender (p=0.553), length of residence in Napier (p=0.084), highest level of education (p=0.420), household income (p=0.873) or ethnic group (p=0.304).

Source of hazard information

The most-quoted source of hazards information among residents who recalled receiving information (n = 69) was 'Civil Defence' (32%), 'Council' (19%) and 'Radio, TV or media' (15%). Other sources quoted were: 'newspapers' (n = 3), 'work' (2), 'school' (2), 'siren tests or previous warnings' (2), 'New Zealand Earthquake Commission (EQC)' (2), 'New Zealand ShakeOut'[4] (1), and 'information at the museum or aquarium' (2). Few visitors who recalled receiving information (n = 20) were able to elaborate on the source of any previous information they had received, however, two regional visitors recalled the source as 'Civil Defence', one international and one national visitor quoted 'guidebooks' and one international visitor received information on their 'cruise ship'.

Further clarity on the source of information was provided when we asked the question 'how was the information provided'. There appears to have been some confusion in these questions between the use of 'source' (intended to mean 'who provided the information'), and 'how' (intended to mean 'the format of information received'), which will be revised in further surveys. Of those residents who recalled receiving information (n = 69), the most common format was 'TV/Radio' (45%), 'newspaper' (32%), 'brochures or leaflets' (17%), through 'work or school' (16%) and 'mail-drop' (10%). Other formats reported by residents include: 'informal or conversational' (n = 6), 'telephone book' (5), 'siren test or previous warnings' (4), 'tourist industry' including heritage signs and publicity of the 1931 earthquake through Art Deco Week[5] (4), 'council website'

[4] New Zealand ShakeOut was the first nationwide earthquake drill to take place in any country. The first NZ ShakeOut took place on 26 September 2012, organised by MCDEM and preceded by a national public information campaign to encourage individuals, organisations and communities to participate (http://www.shakeout.govt.nz/)

[5] Art Deco Week takes place in Napier annually in February to celebrate the Art Deco architecture of Napier — a result of rebuilding after the 1931 earthquake (http://www.artdeconapier.com/)

(2), 'signs' (2), 'community meetings' (1), and 'previous experience' (1). Among visitors who recalled receiving information (n = 20), the most common formats were 'TV/Radio' (25%), 'informal/conversational' (25%), 'brochures or leaflets' (15%), 'signs' (15%) and 'books or guidebooks' (15%). This small sample suggests further differences in receipt of information based on a visitor's home location. The most commonly-cited format for international visitors (n = 7) was 'guidebooks' (43%), for national visitors (n = 7) it was 'signs', 'TV or radio' and 'informal or conversational' (each 29%) and regional visitors (n = 6) it was 'TV or radio' (50%).

In summary, the majority of residents recalled receiving hazards information, and most reported receiving this via 'TV/Radio' or 'newspaper' media. A wide range of other information formats were recalled but by far fewer respondents. A moderate proportion of visitors recalled receiving information and there was only one report of receiving information from tourist industry staff. This data is encouraging in that there is a high rate of residents receiving hazard information. This also provides a basis for more detailed investigation of the extent to which local hazards information is delivered to visitors and the formats being used, in order to improve communication of hazards information to this group in the future.

6.5.2 Tsunami hazard awareness and understanding

Despite increasing tsunami education and media coverage of tsunami since 2004 we have concerns that although people are aware of the tsunami hazard in New Zealand, there is confusion around the different warnings for local, regional and distant tsunami as defined by travel time. This is particularly true of the role and function of tsunami warning sirens. Therefore, we use the survey to investigate hazard awareness and understanding of tsunami warnings.

Hazard awareness

Respondents recognised that several natural hazards, from a list that was read to them, could affect Napier (Table 6.8). 'Earthquake' (98%) and 'tsunami' (93%) are the hazards most cited by residents (n = 97), ranking higher than any of the other hazards. 'Storm', 'river flood' and 'landslide' were each cited by between 74% and 76% of residents, with 'wildfire' cited by 30%. The same relative trend between hazards was observed in visitors' responses, although the rate of recognition was lower in each case, including: 87% for 'earthquake' and 82% for 'tsunami'.

There was a strong correlation between recognition of both earthquake and tsunami as local hazards: residents (92%), regional visitors (90%) and national visitors (93%) believed both earthquake and tsunami could affect Napier (Table 6.9). There were more varied responses from international visitors, 42% of whom believed both hazards could affect Napier, reflecting a lower level of local hazards knowledge, as expected.

While the recognition of both earthquake and tsunami as hazards at Napier is high, it is important to explore the understanding of the relationship between these hazards. There was a high level

Tab. 6.8: Percentage of respondents who believed each hazard has the potential to cause damage or casualties at Napier.

Status	Earthquake	Tsunami	Landslide	Storm	Flood	Wildfire	Don't know
Resident (n = 97)	98%	93%	75%	74%	76%	30%	0%
Visitor (n = 39)	87%	82%	51%	51%	41%	23%	3%
Total (n = 136)	95%	90%	68%	68%	66%	28%	1%

Tab. 6.9: Cross-tabulation of the percentage of residents and visitors who regard earthquake and tsunami as hazards in Napier. The table captures presents belief in neither hazard, both hazards, or one hazard but not the other affecting Napier.

Status	Earthquake	Tsunami	
		Yes	No
Residents (n = 97)	Yes	92%	6%
	No	1%	1%
Regional Visitors (n = 10)	Yes	90%	10%
	No	0%	0%
National Visitors (n = 14)	Yes	93%	0%
	No	7%	0%
International Visitors (n = 15)	Yes	47%	27%
	No	13%	13%

of recognition that tsunami is possible after experiencing ground shaking in Napier (Table 6.10). Eighty-eight percent of residents, 95% of regional and national visitors (combined) and 57% of international visitors said that a tsunami would be possible after ground shaking. Residents' responses displayed some difference between males and females, with 95% of females but only 78% of males believing that a tsunami is possible after ground shaking. The reason for this disparity has not been explored as it requires a larger sample to allow cross-tabulation across all demographics. These results suggest that people are aware of the potential for tsunami following a local earthquake. However, results of open-ended questions discussed in the following section show that this does not necessarily translate into understanding that the earthquake is a warning of tsunami.

Understanding of tsunami warnings

Tab. 6.10: Respondents' opinions on whether a tsunami might be possible after long or strong ground shaking at Napier.

Status	Gender	Yes	No	Don't Know
Resident	Male (n = 41)	78%	20%	2%
	Female (n = 56)	95%	4%	2%
	Total (n = 97)	88%	10%	2%
Visitor	Male (n = 22)	82%	5%	14%
	Female (n = 14)	79%	14%	7%
	Total (n = 36)	81%	8%	11%
Total (n = 133)		86%	10%	5%

Respondents were asked to provide responses to the open-ended question 'What would warn you of a potential tsunami in Napier?' and were prompted to provide as many responses as possible. Contrary to the well-recognised link between earthquake and tsunami in the previous section, the percentage of respondents considering 'earthquake' (17%) as warning of tsunami is low in comparison to the percentage of respondents citing 'sirens' (67%) and/or 'TV or radio' (65%) as a potential tsunami warning (Table 6.11). This is also true of 'tidal changes or seeing waves' (13%) and there was no mention of unusual sounds from the sea. Fourteen percent of respondents cited 'public reaction' or 'hearing by word of mouth from family or friends', while 13% would expect a warning via 'social media' or 'cell-phone' alerts. A greater proportion of visitors cited natural warnings than residents ('earthquake': 23% and 14% respectively; 'tidal changes or seeing waves': 15% and 11%) with little variation due to visitors' home location. Other responses included hearing from 'school', being 'contacted by work' and 'seeing ships moving out of port into deep water'.

These results reaffirm our concern that many people expect to rely on tsunami sirens as a warning rather than reacting to natural warnings and that there is a disconnect between people's high level of hazard knowledge and their warning expectations. Our findings replicate those of an earlier survey of New Zealand coastal communities following the Chile 2010 tsunami (GNS Science unpublished data)[6], which indicated that:

- Although 60–70% of respondents believed that in a local tsunami, ground shaking or sea level drawdown or unusual waves would occur, 57% believed that a siren warning is likely to be given for a local tsunami.

- A siren warning for local tsunami was rated more likely than for regional or distant events, indicating confusion between technological warning capabilities for different types of tsuna-

[6] These unpublished data refers to survey data which, at the time of writing is under analysis. These data will be published as a GNS Science report in due course. The data can be obtained from g.leonard@gns.cri.nz or d.johnston@gns.cri.nz. Unless otherwise indicated by a footnote, further references to unpublished data in this chapter refer to the same data.

Tab. 6.11: Percentage of respondents citing potential information sources of tsunami warning. Respondents were requested to name as many formats as possible.

Information Format	Residents (n = 97)	Visitor (n = 39)	Total (n = 136)
Siren	67%	67%	67%
TV / Radio / News	73%	46%	65%
Earthquake	14%	23%	17%
Public reaction / word of mouth / family / friends	12%	18%	14%
Alert (incl. Text / social media /online)	14%	8%	13%
Tidal change / see waves	11%	15%	13%
Civil Defence / council	11%	3%	9%
Other	7%	10%	8%
Emergency Services	3%	8%	4%
Animal response	3%	0%	2%
Don't know	1%	5%	2%
No response	1%	5%	2%
Other person in authority	0%	5%	1%

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- Sirens were the most-requested improvement to current warning and evacuation procedures, which supports anecdotal evidence from emergency managers that sirens are seen as the most important solution by their communities.

During recent surveys in Wellington most respondents reported an expectation that sirens would provide a tsunami warning but also reported confusion over the signal and efficacy of such a system (Currie et al., 2014).

Perceived tsunami arrival times

To investigate the perception of potential tsunami arrival times with respect to receipt of an official warning and occurrence of a natural warning, we asked respondents which time frames they thought might apply in each situation. Responses in both cases were skewed towards arrival times of less than one hour (Table 6.12). Encouragingly, among residents who believe a tsunami could be possible after ground shaking (n = 85), the most common anticipated time frames for the case of a natural warning were 'less than 10 minutes' (24%), '10–30 minutes' (28%) and '30–60 minutes' (20%). Only 6% of residents believed that following a local earthquake, a tsunami could take between '1–3 hours' to arrive, and no residents thought it would take 'longer than 3 hours'. These data support 2010 survey results, which found that 57% of people in Napier believe that a tsunami could arrive within 30 minutes if ground shaking was felt at the beach (GNS Science unpublished data). Previously, the 2003 National Coastal Survey revealed that 45% of respondents believed a tsunami could follow ground shaking within 30 minutes (Stewart et al., 2005) so this finding is relatively consistent over the last ten years. Simulations of local tsunami at Napier show that tsunami arrival can occur in as little as 27 minutes after rupture (Fraser et al., 2014), so residents' estimates of arrival time after a natural warning were reasonably accurate. There is a more diverse range of anticipated timeframes from visitors (*n* = 30), with 7% anticipating arrival after '3–10 hours', but the most-anticipated timeframe is 'less than 10 minutes' (38%), which would likely encourage immediate evacuation.

In the case of receiving an official warning (Table 6.13), the most common anticipated timeframes were '10–30 minutes' (19% of all respondents) and '30–60 minutes' (20%). Ten percent of respondents cited arrival time of '3–10 hours' and 10% cited 'greater than 10 hours'. The distribution of responses was similar between residents and regional visitors. A greater proportion of national visitors tended to underestimate arrival time after an official warning (36% — 'less than 10 minutes'; 29% — '10–30 minutes'; 36% — '30–60 minutes'). To some extent this was also true of international visitors (21% — '10–30 minutes'; 29% — '30–60 minutes'). These results show some recognition that there would be a longer interval between an official warning and subsequent tsunami than there would be between a natural warning and tsunami but there is an underestimation of the likely time available between an official warning and tsunami arrival. It is encouraging that responses err on the shorter end of the scale as it is possible, particularly in the case of regional tsunami, that an official warning could precede a tsunami by timeframes on the order of minutes rather than hours.

A substantial portion of respondents replied 'don't know' or could not specify a time period (23% for official warning and 18% for natural warning). Additional comments from respondents reveal that this was due to an appreciation that arrival time depends on earthquake location. However, this also reveals that those respondents did not relate the type of warning to the general earthquake location and therefore make an inference of arrival time on that basis.

6.5.3 Evacuation intentions in a local tsunami

In order to investigate evacuation intentions in a local tsunami scenario, respondents were asked a series of questions relating to their intended actions during and after a local earthquake. To assess the influence of location on intended actions, this set of questions was asked first in the context of them being at the survey location, and then for a situation in which they were at home.

Tab. 6.12: Percentage of respondents who anticipate tsunami arrival in each timeframe following a natural warning. Respondents were requested to select all categories that they believed to be applicable — percentage reflects the 'Yes' responses in each timeframe as a percentage of the status group. Only respondents who answered 'Yes' to the previous question (Do you believe that a tsunami may be possible after long or strong ground shaking?) were asked to provide estimates of arrival time.

Status	<10 min	10-30 min	30 min-1hr	1–3 hrs	3–10 hrs	>10 hrs	Don't Know
Resident (*n* = 85)	24%	28%	20%	6%	0%	0%	18%
Regional visitor (*n* = 10)	30%	30%	0%	10%	0%	0%	20%
National visitor (*n* = 12)	58%	17%	33%	8%	0%	0%	8%
International visitor (*n* = 8)	25%	0%	0%	25%	25%	0%	25%
Total (*n* = 115)	27%	25%	18%	8%	2%	0%	18%

Tab. 6.13: Percentage of respondents who anticipate tsunami arrival in each timeframe following an official warning. Respondents were requested to select all categories that they believed to be applicable — percentage reflects the 'Yes' responses in each timeframe as a percentage of the status group.

Status	<10 min	10–30 min	30 min-1hr	1–3 hrs	3–10 hrs	>10 hrs	Don't Know
Resident (*n* = 97)	11%	20%	18%	14%	10%	9%	23%
Regional visitor (*n* = 10)	10%	0%	10%	10%	10%	0%	40%
National visitor (*n* = 14)	36%	29%	36%	21%	21%	14%	14%
International visitor (*n* = 14)	7%	21%	29%	7%	0%	14%	21%
Total (*n* = 135)	13%	19%	20%	14%	10%	10%	23%

Intention to evacuate or not evacuate

The first question, ‘What would you do after an earthquake that lasted for more than a minute or during which it was hard to stand up?’ was designed to investigate whether or not tsunami was one of the respondents’ immediate concerns during an earthquake and what they might do in relation to that concern. This question solicited open-ended responses, and if respondents made no mention of evacuation (or non-evacuation) after being prompted for as many action intentions as they could think of, a prompt (‘Would you evacuate?’) was given. For the case of evacuation from the survey location, 64% of residents and 57% of visitors required prompting before mentioning evacuation. When given the situation of evacuation from home, the majority again required prompting (66% of residents, 55% of visitors). This demonstrates that when provided a scenario of ground shaking, the majority of respondents do not consider the tsunami risk but focus solely on response to the earthquake, suggesting that there might be a low rate of evacuation to high ground.

After prompting, the majority of respondents (residents: 85%; regional visitors: 100%; national visitors: 92%; and international visitors: 67%) reported their intention to evacuate from the survey location (Table 6.14). The proportion of female residents intending to evacuate the survey location was higher (89%) than that of male residents (78%) and among visitors there is less difference (female: 87% versus male: 83%). A smaller proportion intends to evacuate the home (residents: 57%; regional visitors: 20%; national visitors: 69%; international visitors: 67%). The low proportion for regional visitors reflects the fact that most of these respondents’ homes are further inland than Napier therefore perceived to be safe from tsunami. Male residents are more likely to evacuate the home (63%) than female residents (52%) but among visitors, females are more likely to evacuate the home or accommodation (60%) than males (52%). The influence of location on intention to evacuate demonstrates the existence of a spatial dimension (both topographic elevation and distance to coast) in rate of evacuation in addition to the temporal influence of whether people are awake or asleep, or facing the prospect of night-time evacuation when a natural warning occurs.

Given the similar proportions of residents and visitors intending to evacuate, we look at the impact of further demographics on the total sample. As age increases there is a lower intention to evacuate the survey location. In each of four age categories covering the range 16–34, over 91% of respondents would evacuate the survey location. In each of five categories between age 40 and 64, the percentage intending to evacuate is between 80% and 93%. For the age group 65 and over, the percentage intending to evacuate is lower, at 68%. The percentage of respondents who intend to evacuate the home or temporary accommodation is more variable: 62–88% for ages 16–34, 36–77% for ages 40–64 and 48% for age 65 and over.

There is little variation in intention to evacuate with respect to household income category except for lower intention to evacuate in one middle-income category. In all categories 90–93% report an intention to evacuate, except for those with a household income of $30,001–$50,000,

Tab. 6.14: Percentages of respondents who would evacuate from the survey location or from home, split by residential status and gender. These values represent intentions after prompting in the survey to consider tsunami evacuation.

Status	Gender	Evacuate from survey location			Evacuate from home	
		No	Yes	Don't Know	No	Yes
Residents	M (n = 41)	22%	78%	0%	37%	63%
	F (n = 56)	11%	89%	0%	48%	52%
	Total (n = 97)	15%	85%	0%	43%	57%
Visitors	M (n = 23)	13%	83%	4%	48%	52%
	F (n = 15)	13%	87%	0%	40%	60%
	Total (n = 38)	13%	84%	3%	45%	55%
All respondents	M (n = 64)	19%	80%	2%	41%	59%
	F (n = 71)	11%	89%	0%	46%	54%
	Total (n = 135)	15%	84%	1%	44%	56%

in which case 69% would evacuate. Similar consistency occurs between most household income categories for evacuation from the home with 50–60% reporting an intention to evacuate in most categories. The exceptions are $30,001–$50,000, again showing much lower evacuation intention (38%), and $70,001–$100,000 with higher evacuation intention (85%).

Evacuation from the survey location is similarly high at all levels of education (Table 6.15), with postgraduates showing higher proportion of evacuation (93%), and undergraduates the lowest (77%). Respondents educated to post-graduate level are least likely to evacuate the home (21%), while 75% of those educated to trade qualification level would evacuate the home. The greatest difference between proportions intending to evacuate based on survey location is for postgraduates, while those with a trade qualification retain the most consistent intentions based on location.

We can conclude from this, that there is a higher intention to evacuate from the survey location than from the home or accommodation and that a slightly greater proportion of females than males intend to evacuate the survey location. Household income, education and ethnicity influence the disparity in intention to evacuate the survey location and the home to different extents, but full exploration of this dynamic requires a larger sample of data.

The three most-commonly reported intentions of respondents who would evacuate from the survey location were to 'move out of and away from buildings' (39%), evacuate to 'high ground' (28%) and to 'drop, cover, hold' (15%) (Table 6.16). A greater percentage of visitors reported intentions to 'help others' (16%, versus 5% of residents), otherwise the most common responses were replicated in similar proportions for both residents and visitors. Due to the small sub-samples of visitors reporting across a large number of intended actions, with few responses in each category, we do not present the disaggregated responses of the visitor sub-samples. The same actions are

Tab. 6.15: Influence of level of education on intention to evacuate from the survey location and from the home. Percentage values refer to the number of respondents quoting each theme.

Level of Education	Evacuate from survey location			Evacuate from home	
	No	Yes	Don't Know	No	Yes
School (n = 52)	12%	88%	0%	37%	63%
Trade (n = 12)	17%	83%	0%	25%	75%
U/graduate (n = 47)	23%	77%	0%	45%	55%
P/graduate (n = 14)	7%	93%	0%	79%	21%
Not Provided (n = 7)	0%	86%	14%	43%	57%
None (n = 1)	0%	100%	0%	100%	0%
Other (n = 2)	0%	100%	0%	50%	50%
Total (n = 135)	15%	84%	1%	44%	56%

predominant among those respondents who intend to evacuate from home or accommodation (n = 76; Table 6.16), although there is a greater influence of gender on some of these actions: 'move out of or away from the building' (32% of males, 45% of females), 'drop, cover and hold or equivalent' (18%, 37%), 'shelter in a doorway' (18%, 16%) and / or evacuate to 'high ground' (18%, 13%). Eleven percent of people would 'seek further information' and 15% would 'contact friends or family'. No visitors discussed intentions to seek guidance from accommodation staff. Intention to 'evacuate inland' was reported less frequently than evacuation to high ground — only 3% would evacuate inland from home and only 10% from the survey location.

The high response rate for moving away from buildings at the survey location is likely due to the fact that the majority of surveys were conducted in the main shopping streets of Napier, where shops are primarily two-storey with awnings, thus prompting respondents to consider the danger of building damage and falling debris. In referring to building collapse and falling debris, several respondents quoted either direct experience or media coverage of damage due to the 2010–2011 Christchurch earthquake sequence. These data suggest that response to ground shaking is focussed primarily on earthquake hazard rather than tsunami hazard and is highly dependent on evacuee location at the time of ground shaking. This is particularly important for the percentage of respondents intending to evacuate to high ground. Less than one-third of people who are in the city, for example, shopping or working, are likely to evacuate to high ground upon experiencing ground shaking. This percentage drops to less than one-fifth for those who are at home in that situation. The predominant destination would be to areas of high ground, rather than inland.

Of those people not evacuating the home (n = 59), the most common intended actions are to 'drop, cover, hold' (41%) or 'shelter in a doorway' (24%) and 'seek further information' or 'contact

Tab. 6.16: Percentage of respondents citing intended evacuation actions at the survey location and the home. Action themes are sorted (descending order) by percentage citing the action at the survey location.

Intended action	At survey location			At home		
	Resident (n = 82)	Visitor (n = 32)	Total (n = 114)	Resident (n = 55)	Visitor (n = 21)	Total (n = 76)
Out of or away from buildings to open space	37%	44%	39%	33%	52%	38%
Evacuate to high ground	29%	25%	28%	16%	14%	16%
Drop, cover, hold (or variation)	15%	16%	15%	29%	24%	28%
Evacuate inland	9%	13%	10%	4%	0%	3%
Evacuate (unspecified destination)	7%	9%	8%	7%	0%	5%
Help others	5%	16%	8%	0%	5%	1%
Get emergency supplies / kit	7%	3%	6%	5%	0%	4%
Wait until safe or shaking has stopped	5%	3%	4%	2%	14%	5%
Other	6%	0%	4%	4%	10%	5%
Shelter in doorway	2%	3%	3%	20%	10%	17%
Check on / contact loved ones	4%	0%	3%	15%	0%	11%
Panic	2%	3%	3%	0%	0%	0%
Go home	2%	0%	2%	0%	0%	0%
Seek information	0%	3%	1%	11%	5%	9%
Wait for sirens / warning	1%	0%	1%	2%	0%	1%
Into building	0%	3%	1%	0%	0%	0%
No response	0%	0%	0%	2%	0%	1%
Go to school / community Centre	0%	0%	0%	2%	0%	1%
Stay put	0%	0%	0%	2%	0%	1%
Check property / clear up	0%	0%	0%	0%	5%	1%
Go to upper floor of building	0%	0%	0%	0%	0%	0%

Tab. 6.17: Reasons given for non-evacuation of the survey location. *Four of these responses were given at Clive Square and one at Marewa shops, both of which are located within the tsunami hazard zone.

Respondents' reasons for non-evacuation of survey location	Count
Safe at the survey location *	5
Dangerous to evacuate	4
Don't know where to go	2
Evacuation is impossible	2
No transport	2
Need to help others	2
No response	2
Never had tsunami here	1

friends or family' (14%). The most common reasons given for not evacuating from home are because it is located 'too far inland' to be in danger of inundation (12%) or located 'on high ground' (20%). Additional common responses were that it was 'more dangerous to evacuate' than stay put (14%), already being in an 'earthquake safe building' or 'feeling safe at home' (14%), and being 'unconcerned about tsunami' (14%). Other themes created from responses include 'don't know what to do' or 'don't know if I need to evacuate', 'wait for advice' and feeling that it is 'impossible to evacuate'. Mapping respondents' intentions reveals that although some correctly consider themselves safe at home, others are in fact located within the tsunami hazard zone according to numerical simulation of the maximum credible inundation scenario (Fig 6.3A).

Twenty respondents stated they would not evacuate the survey location in case of ground shaking. This is too small a sample to analyse effectively; however, it is worth noting the common themes into which the responses have been grouped (Table 6.17). These reflect issues which should be investigated further as they have the potential to contribution to a low evacuation rate if not addressed through education.

Previous research has highlighted active responses in disasters including information-seeking, helping others (Rodriguez, Quarantelli, and Dynes, 2006) and the desire to bring the family together before evacuating in the case of warned events (see Section 6.3.2). In responding to the initial question, few respondents referenced information-seeking or efforts to bring families together immediately following ground shaking. When ground shaking is experienced at home, only 11% of respondents reported that they would 'seek further information' and 13% of respondents intend to 'check on or contact loved ones', although inherently emotional responses such as these may be the most sensitive to being misrepresented in stated intention surveys compared to actual behaviour. For evacuation from the survey location these actions were reported by 1% and 3% re-

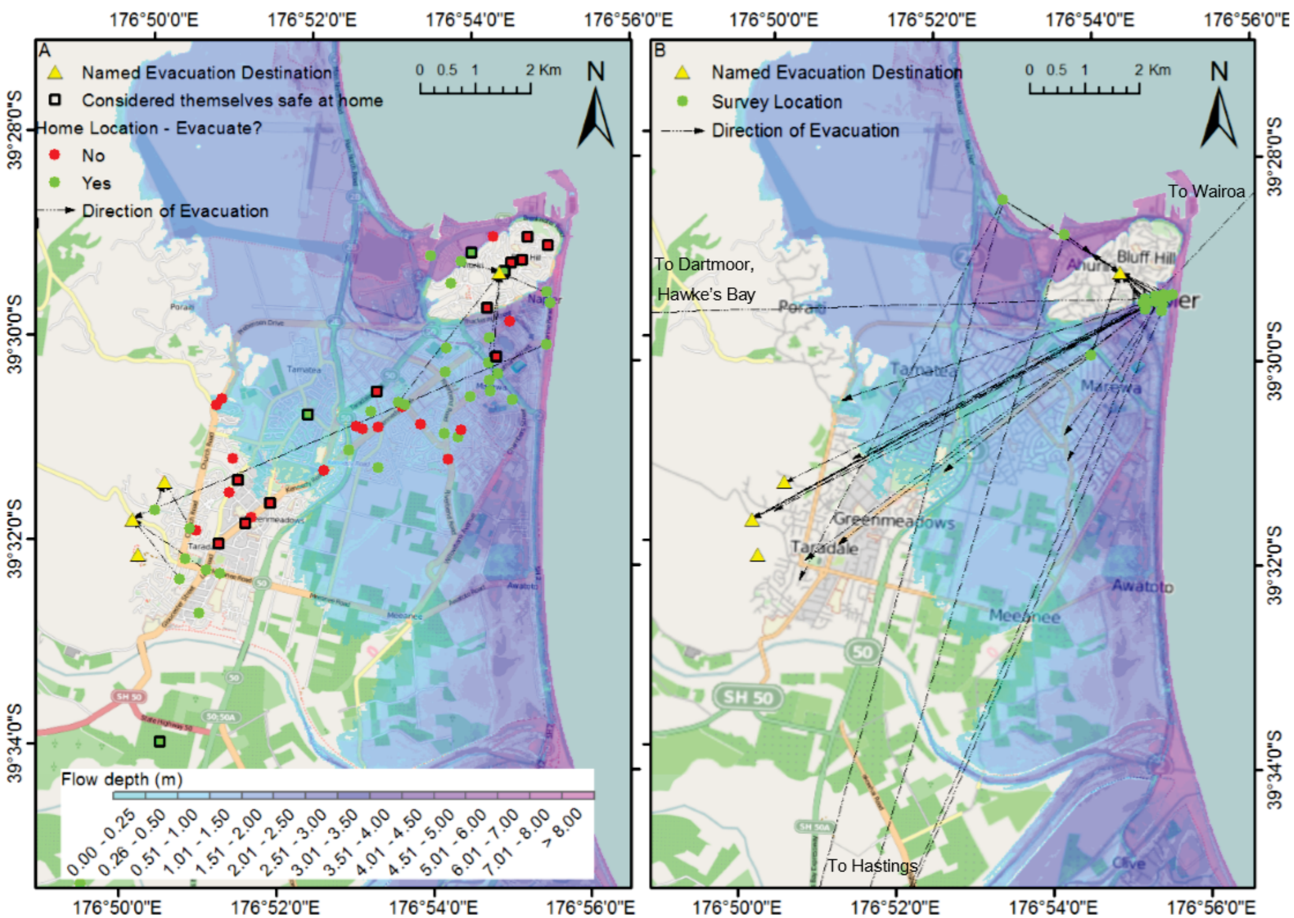

Fig. 6.3: A) Residents' approximate home location and their intention to evacuate or remain at home following ground shaking. Green circles show intention to evacuate, with evacuation arrows indicating direction to their stated destination (if named during the survey). Red circles mark intention to not evacuate and a square indicates that the reason was because they believed themselves to be safe at that location. B) Survey locations with evacuation direction to respondents' stated destination (if named during the survey) or their home if that was their intended destination. Evacuation arrows which end off the map indicate evacuation to Hastings, Wairoa and Dartmoor as labelled. Tsunami flow depth and inundation extent generated by Fraser et al. (2014) for an M_W 9.0 rupture of the Hikurangi margin is including on the map to indicate the worst-case tsunami hazard zone. Basemap source: OpenStreetMap and contributors, Creative Commons-Share Alike License (CC-BY-SA).

spectively. With respect to household preparedness, only 5% of respondents reported intentions to 'get an emergency kit or emergency supplies' if they experienced ground shaking at home. These findings are somewhat surprising, but these expected behaviours were referenced more commonly in subsequent questions and are discussed in the next section.

Pre-evacuation actions and estimated departure time

It is important to gain information on likely pre-evacuation actions that respondents might take and the delays caused by these actions, given that there is little time available to evacuate. We anticipated that intended actions will be similar to those described in previous literature (Section 6.3.3). Respondents who indicated their intention to evacuate (from survey location n = 114; from home or accommodation n = 76) were asked when they would intend to evacuate. For both scenarios the most common response for both residents and visitors was 'as soon as possible' (48% of respondents at survey location and 55% at home) followed by 'immediately' (19% from the survey location, 9% from home or accommodation). When a specific time was provided regarding evacuation of the survey location (by 5% of respondents) the stated times were '20 seconds' (n = 1), '5 to 10 minutes' (n = 2) and '10 to 15 minutes' (n = 3). A specific time was provided by 12% of respondents regarding evacuation of the home, comprising '5 to 10 minutes' (n = 4), '20 minutes' (n = 2) and '30 minutes' (n = 2).

The actions that respondents intend to take before departing include: 'help others' (at survey location: 22%; at home: 4%) or 'check on, travel to or gather loved ones' (29%; 23%); 'get emergency kit' (1%; 19%); 'get / secure property' (4%, 19%); and 'nothing' — i.e., evacuate immediately without stopping to do anything (34%, 19%). There is little difference between the proportions of visitors and residents taking each action. Within these results the influence of location is apparent. When in public a greater proportion of people intend to help others, while at home this is cited less often, perhaps because there are likely to be fewer people in immediate proximity when at home. The proportion of respondents intending to check on, travel to or gather loved ones is also lower for the home situation, perhaps due to respondents considering that loved ones will all be together when at home. The other actions apparently influenced by location is the use of emergency kits and collecting or securing property, which were more frequently reported as actions taken at home where emergency kits and property are more readily accessible to people. It is encouraging that people recognise the need to take emergency kits, but the proportion of people citing kits or supplies is low to moderate.

Regarding pre-evacuation actions at the survey location, 29% of respondents reporting 'as soon as possible' also responded that their departure would be delayed by 'checking on loved ones' or 'travelling to or gathering loved ones', 25% would delay by 'helping others', and 45% would e-vacuate as soon as possible with no delaying action reported. Therefore, around half of those reporting 'as soon as possible' are likely to experience a delay but this is difficult to quantify without further data on how long it might take to complete such actions. Further research should link pre-evacuation actions with respondents' household composition (i.e., whether there are children to care for) and collect data on time required for each action. The high number of respondents citing short intended evacuation start time is encouraging for tsunami education, however, the fact that these are intentions means they should be treated with caution as they may not correlate well with actual behaviour (Kang, Lindell, and Prater, 2007; Mas et al., 2012a).

Evacuation destination

The topography of Napier provides few options for evacuating to high ground and the general expectation is that people evacuating the city centre will go to the nearest area of high ground, which is Bluff Hill. It is important to understand whether this is in fact the case, and where people located further from Bluff Hill would intend to go. This will help emergency managers to prepare primary evacuation routes and anticipate where concentrations of evacuees might relocate to in a local tsunami event, which has implications for route congestion and emergency response planning.

When asked to provide an evacuation destination if evacuating from the survey location, the most common intended destinations were 'Bluff Hill' (Fig 6.1 and Fig 6.3B — residents: 33%; regional visitors: 10%; national visitors: 33%; international visitors: 10%) and 'unspecified high ground' (residents: 15%; regional visitors: 20%; national visitors: 33%; international visitors: 0%) (Table 6.18). It is notable that a very low number of international visitors reported 'high ground' as their intended destination and that 50% gave no response or reported 'don't know'. This specific question about destinations solicited a higher percentage of responses citing high ground than the more general question about actions following an earthquake (28%, Section 6.5.3). Fifteen percent of residents would evacuate to 'home', and 22% of visitors (origins combined) would evacuate 'further inland'. Several of those intending to evacuate to their home would still be in the tsunami hazard zone there, while others would be sufficiently inland towards the Taradale Hills to be safe (Fig 6.3B). Ten percent of respondents would intend to evacuate to 'Clive Square' (Fig 6.1). This was a focus for evacuation during the 1931 earthquake, but is not currently an official Hawke's Bay Civil Defence and Emergency Management assembly point (Marcus Hayes-Jones, personal communication, 4 April 2013) and is located within the published tsunami hazard zone (Hawke's Bay Civil Defence And Emergency Management, 2011).

When considering evacuation from the home, 19% of residents cited 'unspecified high ground', and others named their high ground destinations as: 'Bluff Hill' (11%), 'Sugar Loaf Reserve' (6%), and 'Puketapu Hill' (6%) (Fig 6.3A). In the visitor sub-samples, 33% of national visitors cited 'Bluff Hill', but otherwise 'high ground' was not well-cited as a destination, whereas 'beach', 'open areas' and 'away from buildings' were all cited in each sub-sample, although the small sub-sample precludes drawing further conclusions at this level of detail. In terms of the two major status groups 11% of residents but no visitors would travel 'further inland'. Twenty-five percent

Tab. 6.18: Respondents' reported destinations if intending to evacuate from the survey location.

Reported destinations from the survey location	Resident (*n* = 82)	Regional visitor (*n* = 10)	National visitor (*n* = 12)	International visitor (*n* = 10)
Unspecified or other high ground	15%	20%	33%	0%
Bluff Hill	33%	10%	33%	10%
Sugarloaf Reserve	1%	0%	0%	0%
Taradale Hills	5%	0%	0%	0%
Unspecified or other place inland	10%	20%	25%	20%
Civil Defence centre / school	4%	0%	0%	0%
Open areas — e.g., park	5%	0%	8%	10%
Home	15%	20%	8%	0%
Away from buildings	1%	0%	8%	0%
Clive Square	11%	20%	0%	0%
Don't Know	2%	0%	0%	20%
Other	5%	30%	0%	10%
No response	1%	0%	0%	30%

of residents and 48% of visitors reported their intention to 'move away from buildings' or go to an 'open area' such as a park, a field or to the end of the driveway, which again suggests a primary aim of being outside in case of further aftershocks rather than any intention to evacuate in case of potential tsunami inundation.

Travel mode during evacuation

The preference to evacuate in vehicles for long-distance and long-lead time evacuations has been discussed, as have variable rates of vehicle use in recent tsunami warnings (Section 6.3.4). To investigate the intended travel mode at Napier, we asked the open-ended question 'How would you travel to your intended destination?'. It is hypothesised that the majority of respondents will prefer to use their vehicles, on the basis of previous response to earthquake and tsunami in New Zealand (Lamb and Walton, 2011) and the belief that vehicles are the most commonly used form of evacuation transport in developed countries due to daily reliance on vehicles (Murakami and

Tab. 6.19: Proportion of residents and visitors with vehicle or pedestrian intended travel modes. Respondents were able to answer with more than one travel mode, therefore percentages may sum to greater than 100%.

Status and Gender		Evacuate from survey location			Evacuate from home		
		n	Vehicle	Foot	*n*	Vehicle	Foot
Residents	Male	32	50%	50%	26	73%	31%
	Female	50	34%	68%	29	34%	66%
	Total	82	40%	61%	55	53%	49%
Visitors	Male	19	47%	53%	12	17%	58%
	Female	13	69%	23%	9	33%	67%
	Total	32	56%	41%	21	24%	62%

Kashiwabara, 2011).

The most-cited intended travel modes (Table 6.19) for residents evacuating the home ($n = 55$) were evacuation in a 'vehicle' (53%) and 'walk or run' (49%) whereas a greater proportion of residents evacuating the survey location intend to 'go on foot' (61%) than use a 'vehicle' (40%). A greater proportion of female residents intend to walk or run than do male residents when evacuating the home or survey location. Among visitors, 62% intend to 'walk or run' when evacuating the home and 24% intend to use a 'vehicle' and there is little variation between visitor sub-samples. The majority of regional visitors (60%) and international visitors (70%) would evacuate the survey location in a 'vehicle' but the majority of national visitors (67%) would 'walk or run'. Only two respondents offered cycling as a potential means of evacuation.

There is a certain degree of recognition that using a vehicle may not be possible in a post-earthquake situation — 13% of respondents expressed such concern, although many did so in the context of their preference to drive, including responses such as 'Drive — if road weren't damaged', 'Car if possible' and 'Car. If roads bad, run'. Analysis of household income categories and level of education reveals no consistent influence on intended travel mode.

6.6 Vertical evacuation buildings

The final set of questions in the survey explored respondents' views and concerns about the use of tsunami vertical evacuation buildings in Napier. Previous experience in Japan highlights the value of a vertical evacuation strategy (Fraser et al., 2012b), but also the components required for a strategy to be successful. A scoping study has previously looked at the potential for using existing buildings for vertical evacuation in New Zealand (Leonard et al., 2011) and with increased international research and development of design guidelines for such facilities (FEMA (2008, 2009) and forthcoming update by the ASCE 7 Subcommittee on Tsunami Loads and Effects[7]) it is importan-

[7] http://nthmp.tsunami.gov/2012tsuhazworkshop/abstracts/Chock_abs.pdf

t to understand public opinion of such strategies to guide further community engagement on the topic.

Respondents were first asked to name all of the possible types of places they could think that might provide safety in a tsunami, with no prompting about vertical evacuation. The overwhelming majority of respondents (80%) referred in their response to 'high ground or uphill' (Table 6.20). Thirty-eight percent referred to moving 'inland or away from coast', while 15% cited buildings as a safe destination, indicating a relatively low level of consideration of vertical evacuation. Nine percent cited 'Civil Defence centre or school' as a safe location, and other interesting but uncommon responses included 'away from waterways' or rivers (2%), 'tall trees' (2%) and one respondent specifically indicated that they would 'not evacuate into a building'. The trend in responses is generally consistent between genders and resident or visitor status. The only group with more respondents citing evacuation to buildings rather than evacuation inland was national visitors, 29% of whom cited buildings versus 14% who cited going further inland. There is no apparent correlation in this limited sample between the respondent's home city and their recognition of buildings as a safe location, which might suggest familiarity with tall buildings at home and work, but this issue should be explored further in later surveys.

Of those respondents citing evacuation to the 'upper storeys or roof of building' (n = 20), there were repeated references to building height and strength, demonstrating understanding of the requisites of a building to be safe in a tsunami. References to height were made by 19 of these respondents, including three references to evacuation above three storeys and others referring to the roof, top of the building or use of a tall building. Four respondents referred to the building being strong, and one cited the need for an open ground floor. Five respondents said they would use a building as a last resort if they could not reach a hill or go inland.

Next, respondents were given some context to the subsequent questions, by stating 'In Japan, many people survived the tsunami by evacuating to the third storey or above in reinforced concrete buildings. This is an approach that we could consider for New Zealand, and we are interested in your thoughts on this.' They were then asked 'How would you feel about evacuating to the upper floors of a reinforced concrete building'. The themes that arose in respondents' views on evacuation buildings have been grouped into encouraging themes and discouraging themes. Of the respondents who gave factors that would encourage their use of buildings (n = 35), 40% would be encouraged if they knew the building was reinforced or if the building was described officially as safe or reinforced (including signs on the building). Twenty-nine percent were encouraged if it was the safest option in the available time for evacuation and 14% if there was easy access. These opinions are in line with the factors considered in official designation of vertical evacuation facilities in Japan (Cabinet Office Government of Japan, 2005) and identified as important features of vertical evacuation buildings from their performance in the 2011 Japan tsunami (Fraser et al., 2012b). Discouraging factors were grouped into themes including: having doubts or being unsure about safety due to the height or strength of available buildings (43% of respondents); potential to

Tab. 6.20: Percentage of respondents citing different possible safe locations in a tsunami.

Safe Evacuation Location	Respondent Status – Resident / Visitor				
	Resident (*n* = 97)	Regional Visitor (*n* = 10)	National Visitor (*n* = 14)	International Visitor (*n* = 15)	Total (*n* = 136)
High ground / uphill	83%	80%	93%	53%	80%
Inland / away from coast	39%	70%	14%	33%	38%
Upper storeys / roof of building	13%	10%	29%	13%	15%
CD centre / school	9%	20%	7%	0%	9%
Away from buildings	1%	10%	7%	13%	4%
Open areas – e.g., park	2%	10%	0%	13%	4%
Tall tree	1%	0%	7%	7%	2%
Home	3%	0%	0%	0%	2%
Away from waterways	2%	0%	7%	0%	2%
Not up building	0%	10%	0%	0%	1%
Don't Know	0%	0%	0%	7%	1%
Other	4%	0%	0%	20%	5%
No response	2%	0%	7%	0%	2%

be trapped with no or slow access to safe floors (20%); potential for panic or overcrowding (19%); and visible building damage or falling debris (14%). Twenty-six percent of people provided factors that would encourage them to seek safety in a building during a tsunami, 55% gave discouraging factors and 21% provided no response. There is little difference in the responses of males and females, except that a high proportion of females provided encouraging or discouraging factors, rather than a non-committal response. The potential for fire, further earthquakes, being afraid of heights or worried about hygiene were also given as discouraging factors. Concern about the availability of supplies in the building was raised by a single respondent. Within these responses, several respondents reiterated their preference to go to high ground rather than into buildings.

These data demonstrate that many people would consider the visible structural integrity of the building and the time available to get to the often-preferred option of high ground or inland as determining factors in their decision to evacuate into a building. It is apparent that a key component of tsunami evacuation is provision of clear information about which buildings would be safe for tsunami evacuation use in a post-earthquake situation. The risk of fire and provision of food or emergency supplies within a building are considered by few respondents, but these components should also be addressed in any education or evacuation planning that includes a vertical evacuation component.

6.7 Conclusions

A survey of 136 residents and national and international visitors in Napier was carried out to investigate hazard awareness and intended evacuation behaviour in a local earthquake and tsunami. This study provides a unique investigation of evacuation intentions in the context of local tsunami hazard in New Zealand. The data supports several observations of previous surveys, demonstrating high levels of tsunami hazard awareness but confusion around warning expectations, and evacuation behaviours cited by respondents are in line with findings in international evacuation behaviour literature. The survey provides new local data on intended evacuation destinations, travel modes, and opinions on tsunami vertical evacuation buildings, while demonstrating the existence of demographic influence on decision-making.

There is a high level of receipt of hazards information among residents in Napier, primarily via TV, radio and newspaper media. Each group of visitors demonstrated a moderate receipt of information, and responses suggest a low level of information provision by the tourist industry. Awareness of earthquake and tsunami hazard in Napier is high, the majority of respondents recognise that tsunami could follow a local earthquake and there is good perception that wave arrival would occur within one hour after local ground shaking. There is a good level of understanding that earthquake location influences tsunami wave arrival time. Some respondents appreciate that following an official warning, wave arrival is likely to be later than following local ground shaking. However, many respondents believe there will be less than one hour after an official warning until wave arrival, and while this is possible in a regional tsunami, it is an underestimation of the time available for evacuation following an official warning of a distant tsunami.

Consistent with previous research findings, we report the high expectation that official tsunami warnings will be given via sirens or TV/radio in the case of local tsunami. There is relatively low recognition that ground shaking would provide a natural warning despite education messages to this effect from Hawke's Bay CDEM and MCDEM, and visitors reported greater recognition of natural warnings than residents. Given that respondents recognise the potential for a short arrival time of tsunami after ground shaking, it appears that this expectation is due to a misunderstanding of the warning process and current technological capabilities governing the time to warning dissemination. This expectation may be a function of the fact that the majority of past events have been from distant sources, therefore tsunami is associated with official warnings. Further communication of siren functions and importance of the natural warning is required to address these prevalent expectations.

The intended behavioural responses to an earthquake suggest that in an earthquake ground shaking might trigger appropriate earthquake response actions but people may not extend their actions to include appropriate tsunami evacuation response, as most respondents did not consider tsunami until prompted. Respondents expressed a greater intention to evacuate when they were at the survey location than they did for an event occurring when they were at home, with similar proportions of residents and visitors stating an intention to evacuate. There were variations between genders, with females more likely to evacuate the survey location and males more likely to evacuate the home. Intention to evacuate the survey location reduces with increasing age. Further research is required to confirm and explain these trends. Many people reported that if they were at home at the time of the earthquake, they would evacuate the building (i.e., to open space) but did not indicate intention to evacuate further (i.e., to high ground). Others would be reluctant to evacuate the home as they feel that it is safer to remain in place rather than try to evacuate, or that they are not at risk of tsunami, which is true in some cases but not all. There is a high proportion of responses recognising the need for evacuation as soon as possible and the range of pre-evacuation actions are consistent with those previously cited in hurricane evacuation literature. The data did not permit detailed analysis of evacuation departure times.

Evacuation to high ground is recognised as an appropriate evacuation action, but only a moderate proportion of respondents stated that they would evacuate to high ground. The reported evacuation destinations suggest that in an event, there would be concentrations of evacuees on Bluff Hill and in the Taradale Hills. Some respondents identified their home as an intended evacuation destination, despite that location being within the tsunami hazard zone. Reported intentions to use Clive Square as an evacuation point are of concern, as Clive Square is situated within the tsunami hazard zone and congregation at that location could result in many deaths. Tsunami hazard maps available for Napier should be used to ensure that people are aware of whether or not their intended destination is in the hazard zone when planning for evacuation. Travel mode intentions suggest an approximately equal proportion of people evacuating on foot and in a vehicle, which is relatively in line with travel mode observations from Japan. Travel mode appears to be location-dependent with a greater proportion of residents using vehicles if they are at home rather than at the survey location whereas the opposite is true for visitors. Gender also appears to influence travel mode, with a greater proportion of female residents than male residents reporting intention to evacuate on foot. Some respondents recognise that evacuation by vehicle may not be possible in a post-earthquake situation. Cycling is rarely reported as an intended travel mode, and several respondents reported a reliance on others for transport.

'Buildings' ranked below 'high ground' and 'travelling inland' as possible safe locations in a tsunami. Most respondents were concerned about structural integrity and sufficient height of buildings but many also cited the available time to evacuate to their first choice destination as factors in deciding to use vertical evacuation. Vertical evacuation is recognised as a potentially life-saving option if is not possible to reach high ground. Responses indicate the importance of ensuring that the public has prior knowledge about the safety or designation of buildings, or can see signage to this effect on the building. There is a common concern that few suitable buildings exist in Napier.

This survey has a number of limitations that should be addressed in future research, although it provides a useful base for subsequent surveys, informs evacuation modelling, community engagement on evacuation planning and vertical evacuation, and hazard education of resident and transient populations. The survey did not attempt to investigate evacuation behaviour within educational or care-giving facilities or the role of tourist industry staff in evacuations, which are important groups to study in terms of group evacuation. Household composition and its influence on evacuation behaviour should be studied more closely in subsequent surveys, and pre-evacuation actions should be linked more closely with the estimated time required for each action. In order to investigate the provision of information to visitors in Napier, a more focussed survey of accommodation providers and tourism operators should be carried out. We should also explore peoples' intended actions when they have reached a safe place, specifically with respect to returning to inundation zone before an 'all clear' message.

The fact remains that data presented here are stated intentions given for a hypothetical tsunami scenario and behaviours are likely to show some differences in an actual event. Although other researchers have previously shown good agreement between some aspects of expected and actual behaviour for hurricane evacuation, the comparison of such data for tsunami is limited to evacuation departure time and travel mode. Of particular concern is the validity of such data where there has been little or no experience of a similar event in recent memory, which is the case for local tsunami in New Zealand. In order to collect a larger, more geographically diverse sample of evacuation intentions this survey should be refined and administered as a postal survey using probability sampling in multiple study areas for residents and visitors. We should also develop a corresponding survey to assess the same behaviours in an actual event, in case of a local tsunami in New Zealand. Consistent collection of data across the two surveys will allow for a comparison of intended and observed behaviours for further improvement of evacuation planning and testing of the validity of stated intention data.

6.8 Acknowledgements

We would like to thank Ella Kroch for her efficiency and enthusiasm in conducting surveys for this study, and Kim Wright, Emma Hudson-Doyle and Maureen Coomer for their review of this report. We thank Hawke's Bay Regional Council and Hawke's Bay Emergency Management Group for their support of this research and provision of building stock data. This research is supported by public research funding from the Government of New Zealand.

6.9 Link to next chapter

This chapter has presented survey results that help to anticipate behaviour of the public in local-source tsunami. These data can be used to refine the behavioural aspects of evacuation models, in order to improve estimations of evacuation time and improve evacuation planning and response. The next chapter proposes a method to assess the requirement for vertical evacuation refuges, using Geographic Information System (GIS)-based evacuation modelling. The methodology augments current least-cost distance modelling and presents an assessment of pedestrian evacuation potential in the maximum credible local-source tsunami at Napier. The need for vertical evacuation in Napier is demonstrated, with preliminary analysis of the optimal locations of refuges.

6.10 Appendix 1: Survey questions

This survey was implemented face-to-face in the streets of Napier. The questions were delivered verbally and responses recorded by the interviewer. An exclamation ([!]) after a question indicates that the interviewers will prompt the respondent to offer any other responses until those responses are exhausted. Respondents were offered an information sheet following completion of the survey (see Appendix 2). A question code was included on the survey for coding purposes (e.g. *[resvis]*).

Clipboard Questionnaire: Awareness of hazards and intended response actions

Q1 *[resvis]* Are you resident in Napier City or visiting? ☐1 Resident ☐2 Visitor

Q2 **If resident,**

a. *[reslen]* How long have you lived in Napier?________________________

b. *[resloc]* What is your home address (or nearest intersection)?
____

c. *[resact]* What are you doing here today? ☐1 Commute/Work ☐2 Visiting friends/family ☐3 Leisure activities ☐4 Other ______________________________________

d. *[resinf]* Do you recall previously seeing or hearing information about natural hazards in Napier?
☐1 Yes ☐2 No ☐3 Don't know

e. *[resinfsrc]* **If yes,** who was the source of this information?
____

f. *[resinftyp]* **If yes,** how was the information provided? (tick all that apply) ☐1 TV/Radio broadcast ☐2 Brochure/Leaflet ☐3 Mail-drop ☐4 In phonebook ☐5 Council website ☐6 Community meeting ☐7 Informal/Conversational ☐8 Other____

Q3 **If visiting,**

a. *[visorg]* Where are you visiting from? (**city & country**) ____________________________________

b. *[visact]* What is the purpose of your visit? ☐1 Business ☐2 Holiday ☐3 Visiting friends/family ☐4 Other ____

c. *[visreg]* How regularly do you visit Napier? ☐1 First time ☐2 Weekly ☐3 Monthly ☐4 Annually/less

d. *[acctype]* What type of accommodation are you staying in? ☐1 Hotel ☐2 Motel ☐3 Backpackers ☐4 Holiday Park ☐5 Home of friends/family ☐6 Holiday Home/Bach ☐7 Other ______________

e. *[hazinfo]* Have you seen or heard any information about natural hazards in Napier? ☐1 Yes ☐2 No ☐3 Don't know

f. *[hazinfo]* **If yes,** who was the source of this information?
____

g. *[hazinftyp]* **If yes,** how was the information provided? (tick all that apply) ☐1 TV/Radio broadcast ☐2 Brochure/Leaflet ☐3 Mail-drop ☐4 In phonebook ☐5 Council website ☐6 Community meeting ☐7 Informal/Conversational ☐8 Other___________________

Q4 *[haznpr]* Which of the following hazards do you think could cause damage or casualties **in Napier City**?

☐1 Wildfire/Bushfire ☐2 Earthquake ☐3 Storm/Cyclone ☐4 Tsunami ☐5 Flood ☐6 Landslide ☐7 Don't know ☐8 Other (please give details): ________________________

Q5 *[tsuwrn]* What would warn you of a tsunami potentially affecting Napier? [!]

____

Q6 If you were to hear an official tsunami warning (via siren, police, tv, radio),

a. *[offarr]* How long do you think there would be until the first tsunami waves might arrive at Napier? (**tick all that apply**)

☐1 < 10 min ☐2 10 - 30 min ☐3 30 min - 1 hr ☐4 1 - 3 hr ☐5 3 - 10 hr ☐6 > 10 hr
☐7 Don't know

Q7 If you were to experience ground shaking that lasted for more than a minute or during which it was hard to stand up,

a. *[nattsu]* Do you think that a tsunami may be possible? ☐1 Yes ☐2 No ☐3 Don't know

b. *[natarr]* **If Yes,** How long do you think there would be until the first tsunami waves might arrive at Napier? (**tick all that apply**)

☐1 < 10 min ☐2 10 - 30 min ☐3 30 min - 1 hr ☐4 1 - 3 hr ☐5 3 - 10 hr ☐6 > 10 hr
☐7 Don't know

<u>State</u>: '**Two** different **scenarios** will now be presented':

First, please consider, for **what you are doing right now:**

Q8 *[evcnatactN]* What would you do after an earthquake that lasted for more than a minute or during which it was hard to stand up? [!] then prompt: "**Would you evacuate?**"
[Note if prompt required: ☐]

____

a. *[evcnonN]* **If No**, what are your reasons for not evacuating?

____

b. *[evcdprtN]* **If Yes,** How long after the earthquake do you think you would begin evacuation?

____

c. *[evcdlyN]* What would you do, if anything, before evacuating?

____

d. *[evcdestN]* Where would you evacuate to? [**landmark / intersection / suburb / city**]

____

e. *[evctrvlN]* How would you travel to your intended destination?

____

Now please consider, **if you were at home (or at your accommodation):**

Q8 *[evcactH]* What would you do after an earthquake that lasted for more than a minute or during which it was hard to stand up? [!] then prompt: "**Would you evacuate?**"
[Note if prompt required: ☐]

____

a. *[evcnonH]* **If No**, what are your reasons for not evacuating?

____

b. *[evcdprtH]* **If Yes,** How long after the earthquake do you think you would begin evacuation?

____

c. *[evcdlyH]* What would you do, if anything, before evacuating?

____

d. *[evcdestH]* Where would you evacuate to? [**landmark / intersection / suburb / city**]
____

e. *[evctrvlH]* How would you travel to your intended destination?
____

Q10 *[evclocs]* Can you list all of the types of places you think you could evacuate to if a tsunami was imminent? ____

<u>For context:</u> In Japan, many people survived the tsunami by evacuating to the third storey or above in reinforced concrete buildings. This is an approach that we could consider for New Zealand, and we are interested in your thoughts on this.

Q11 *[evcbld]* How would you feel about evacuating to the upper floors of a reinforced concrete building, and why? ____
____
____

Q12 *[evcbld]* Is there anything that would encourage/discourage you from evacuating into a building during a tsunami? ____

<u>Demographics:</u> (**These are confidential responses, used only to check our survey sample**):

Q13 *[demyr]* In what year were you born? 19_______ ☐1 Declined to answer

Q14 *[demedu]* What is the highest level of education you have completed? ☐1 School ☐2 Trade Qualification ☐3 Undergraduate (e.g. Bachelors) ☐4 Postgraduate (e.g. Masters, PhD) ☐5 Declined to answer

Q15 *[deminc]* What is your household income category? ☐1 Under $20,000 ☐2 $20,001-$30,000 ☐3 $30,001-$50,000 ☐4 $50,001-$70,000 ☐5 $70,001-$100,000 ☐6 Over $100,001 ☐7 Declined to answer

Q16 *[demethn]* What is your ethnic group? ☐1 European ☐2 Maori ☐3 Pacific Island ☐4 Middle East ☐5 Latin America ☐5 Africa ☐6 Other ______________________________ ☐7 Declined to answer

Q17 *[demgen]* Gender**:** ☐1 Male ☐2 Female

6.11 Appendix 2: Information sheet

Thank you for taking time to complete this survey

GNS Science and Hawke's Bay Civil Defence and Emergency Management Group are interested in what people know about tsunami and warnings, to help improve education. This survey is being conducted by a student from Massey University in collaboration with GNS Science and Hawke's Bay Civil Defence and Emergency Management Group.

Further information regarding tsunami hazard, warnings and evacuation in Napier can be found on the Hawke's Bay Emergency Management Group web pages:
http://www.hbemergency.govt.nz/

Natural warning signs of tsunami are: Strong earthquake shaking; Weak, rolling earthquake shaking of unusually long duration (i.e. a minute or more); Out of ordinary sea behaviour (e.g. unusual and sudden sea level fall or rise); The sea making loud and unusual noises, especially roaring like a jet engine.

When experiencing any of the above go immediately to high ground or as far inland as possible. Do not wait for an official warning. Let the natural signs be your warning – the first wave may arrive within minutes. Once away from the water, listen to a radio station for information from local civil defence about further action you should take. Wait for official all clear before returning.

If you have any questions please contact Stuart Fraser or Graham Leonard at GNS Science: s.fraser@gns.cri.z or g.leonard@gns.cri.nz or 04 570 1444

7. VARIABLE POPULATION EXPOSURE AND TRAVEL SPEEDS IN LEAST-COST TSUNAMI EVACUATION MODELLING (PAPER 4)

This chapter proposes a methodology for assessing the need for vertical evacuation refuges in a tsunami hazard zone, and demonstrates the use of this methodology in Napier, Hawke's Bay, New Zealand. This work draws upon data generated in Chapters 4–6 and achieves Objective 4. The main parts of this chapter (Sections 7.1 to 7.7) have been published as *Natural Hazard and Earth Systems Science* as *Fraser, S. A., Wood, N. J., Johnston, D. M., Leonard, G. S., Greening, P. G., and Rossetto, T. Variable population exposure and distributed travel speeds in least-cost tsunami evacuation modelling. Natural Hazards and Earth System Sciences, 14(11), 29752991. doi:10.5194/nhess-14-2975-2014*. Section 7.8 provides detailed results for Napier, which were deemed too site-specific for publication in an international journal. The methodology developed to achieve variable population exposure and travel speeds is presented in Appendix G. A contribution statement, outlining author contributions to the paper, is provided in Appendix H.

A Least-Cost Distance (LCD) approach is applied in this study, despite the increasing use of Agent Based Model (ABM) approaches in tsunami evacuation studies (Goto et al., 2012b; Imamura et al., 2012; Johnstone, 2012; Mas et al., 2012a). ABMs enable simulation of individual components (agents) within a system, each with a particular set of characteristics and rules governing their behaviour, the interactions between multiple agents, and interactions between agents and their environment (Crooks and Heppenstall, 2012). There is great flexibility to conduct theoretical and empirical studies with ABMs (Manson, Sun, and Bonsal, 2012) and they offer great detail in their output, however, as a result they are computationally expensive may not be the most efficient way to obtain similar results (O'Sullivan et al., 2012). In the context of tsunami evacuation, agents represent individuals or family groups, each with a set of characteristics (e.g., physical, experiential) which determine the likely evacuation actions (and efficacy of those actions) they take in the event of a tsunami in their environment (modelled roads, buildings etc.). Therefore, prior knowledge about the influence of personal characteristics and experience on likely behaviours is essential to inform assumptions within the model; this is a level of data that are not available for local-source tsunami evacuation. As this represents the first study to simulate tsunami evacuation behaviour based on New Zealand data, and because data on evacuation are insufficient to link to personal characteristics, it is was decided to use an LCD model to generate an aggregate view of evacuation. It is the intention to apply ABM in subsequent studies to investigate the influence of evacuation behaviour on aggregate evacuation outcomes.

7.1 Abstract

Evacuation of the population from a tsunami hazard zone is vital to reduce life-loss due to inundation. Geospatial least-cost distance modelling provides one approach to assessing tsunami evacuation potential. Previous models have generally used two static exposure scenarios and fixed travel speeds to represent population movement. Some analyses have assumed immediate departure or a common evacuation departure time for all exposed population. Here, a method is proposed to incorporate time-variable exposure, distributed travel speeds, and uncertain evacuation departure time into an existing anisotropic least-cost path distance framework. The method is demonstrated for hypothetical local-source tsunami evacuation in Napier City, Hawke's Bay, New Zealand. There is significant diurnal variation in pedestrian evacuation potential at the suburb-level, although the total number of people unable to evacuate is stable across all scenarios. Whilst some fixed travel speeds approximate a distributed speed approach, others may overestimate evacuation potential. The impact of evacuation departure time is a significant contributor to total evacuation time. This method improves least-cost modelling of evacuation dynamics for evacuation planning, casualty modelling, and development of emergency response training scenarios. However, it requires detailed exposure data, which may preclude its use in many situations.

7.2 Introduction

Local-source (or near-field) tsunami can cause loss of life due to onshore inundation within minutes after a source event. Prompt evacuation of the hazard zone maximises a person's chance of surviving tsunami inundation. Well-planned routes and refuges facilitate evacuation by minimising travel time to safety and maximising the number of people reaching safe refuge. Evacuation modelling is an important tool for estimating exposure to the hazard and the time required to evacuate the hazard zone.

Least-cost distance (LCD) analysis is an established method for tsunami evacuation modelling (González-Riancho et al., 2013; Graehl and Dengler, 2008; Post et al., 2009; Scheer et al., 2011; Wood and Schmidtlein, 2012, 2013). LCD analysis is a Geographic Information System (GIS)-based method that computes the minimum cost of travel (generally expended energy or time) between specified source and destination cells in a raster domain (i.e., a cell-based grid). Travel speed values can be applied to the cost distance surface to generate a time surface representing the time to travel from source to destination. Travel time maps enable emergency managers to visualise spatial variation in evacuation time (Wood and Schmidtlein, 2012). Comparison of travel time to wave arrival in tsunami inundation scenarios enables identification of areas that cannot be evacuated before wave arrival. Combining travel time and population exposure data gives an indication of the number of people potentially unable to evacuate in the available time, which facilitates planning of additional evacuation and emergency response solutions.

In order to simulate evacuation processes at the community scale, a model must represent the physical environment, spatial extent and timing of the hazard, population exposure, and human behaviour with respect to evacuation decisions and timing. To date, LCD models have been tested for sensitivity to elevation and landcover data (Wood and Schmidtlein, 2012). Wood and Schmidtlein (2012) concluded that the use of anisotropic path distance provides a more realistic cost distance estimate than the previous use of isotropic cost distance. Post et al. (2009) applied increased complexity to LCD analysis by including network capacity and evacuee density as modifiers of travel cost. Three other evacuation factors – population exposure, departure time and travel speed – have been consistently applied as static values in previous LCD approaches, which may not represent the potential variability in these factors.

The objective of this paper is to demonstrate a method for introducing variability in population exposure scenarios, evacuation departure times and travel speeds into an anisotropic, least-cost, path distance model of pedestrian evacuation potential. The importance of traffic modelling, network capacity issues, evacuee interactions and disruption to evacuation routes due to earthquake damage are recognised; however, in order to focus on modelling the variability in exposure, departure and travel phases, these aspects have not be incorporated into the demonstrated process. Population-time profiles are developed to model the distribution of residents and visitors at any time of day, for a weekday or weekend, in any month of the year. Incorporating distributions to model departure time and evacuation travel speed better reflects evacuee behaviour in a real-world evacuation than current GIS-based approaches to mapping evacuation potential. The ability to model temporally-variable exposure facilitates derivation of hazard exposure, evacuation demands and optimal evacuation routes and refuges for specific scenarios. Emergency managers can use multiple exposure scenarios to develop evacuation training exercises, evacuation planning and casualty estimation.

7.3 Study area

To demonstrate the proposed method, we focus on the coastal community of Napier, Hawke's Bay, New Zealand, which faces a significant local-source subduction zone tsunami hazard (Fraser et al., 2014; Power, 2013). Napier is a coastal city of almost 60 000 people located on largely flat, low-lying topography (Fig. 7.1a), on the east coast of New Zealand's North Island. A single numerically simulated inundation scenario is used to demonstrate the proposed evacuation modelling method. The scenario is a tsunami generated by the maximum credible M_{W} 9.0 local-source earthquake on the Hikurangi subduction zone (Fraser et al., 2014). Simulated wave arrival at shore occurs 38 min after rupture and inundation reaches its maximum extent (> 4 km inland) 32 min later. Flow depths exceed 8 m in the first 100 m onshore and generally up to 3 m further than 1 km inland (Fig. 7.1b). The simulated maximum credible inundation zone is taken to be the tsunami hazard zone and is referred to as such in the rest of this paper.

Bluff Hill (maximum elevation > 100 m) provides the only area of high ground at the coast for refuge, although other areas of high ground exist further inland of the hazard zone (Fig. 7.1a). The existing building stock is overwhelmingly 1–2 storey light timber (92 %), with a small proportion of 1–2 storey reinforced concrete (RC; 3 %) and 1–2 storey concrete masonry (3 %) (Cousins, 2009). Approximately 60 buildings (0.05 %) are three storeys or more in height, 40 % of which are of RC construction. The second storey may provide sufficient height for safe refuge in inland areas of the city but this is less likely in the 1 km closest to shore. The probability of moderate to major structural damage due to tsunami loading in the maximum credible tsunami is greater than 80 % for RC and greater than 90 % for timber structures in the maximum credible tsunami (Fraser et al., 2014). Structural assessments are yet to confirm the tsunami-resistance of multi-storey buildings in the city. Therefore, this study does not include any existing buildings as potential refuges when considering pedestrian evacuation potential.

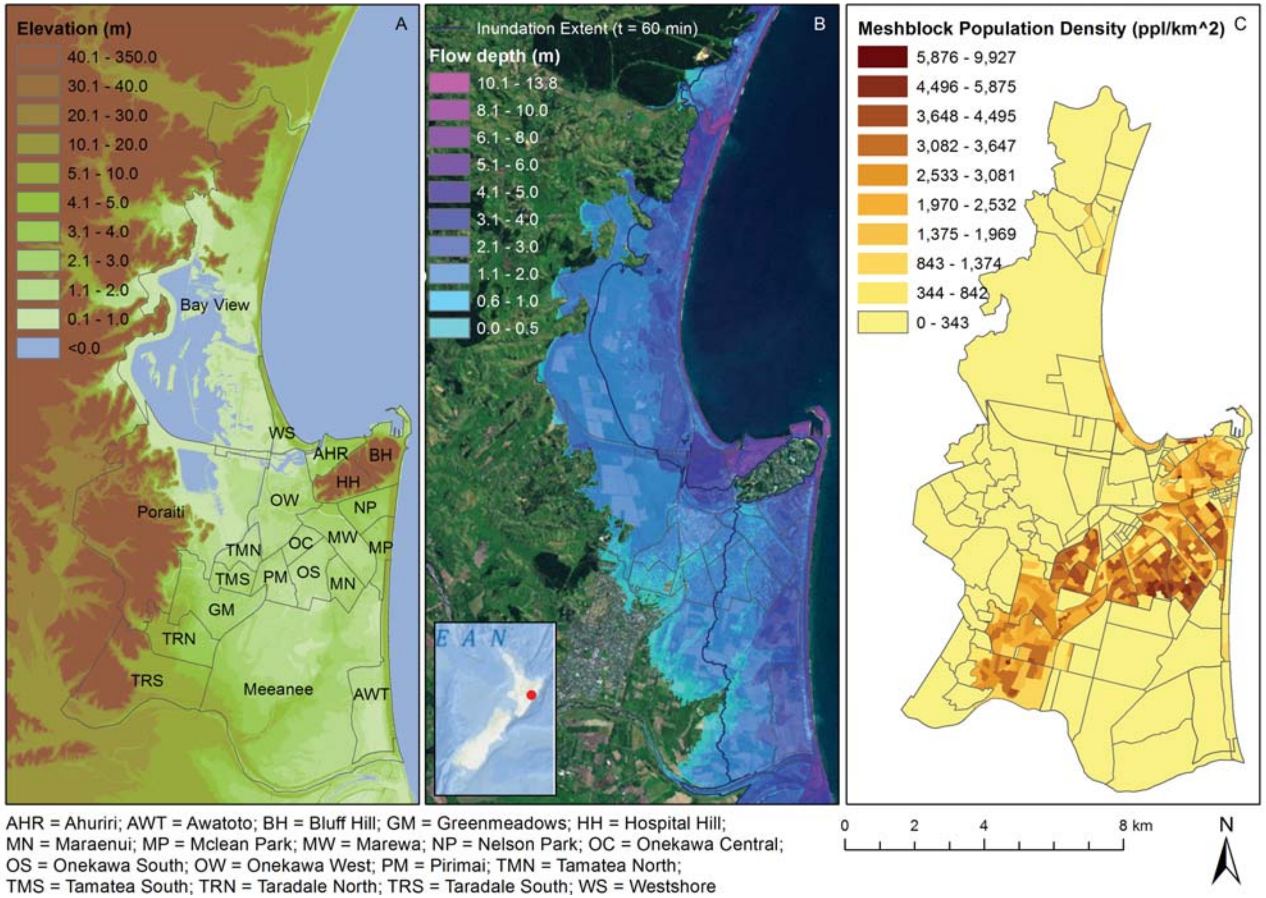

Fig. 7.1: A: Study area topography and locations of suburbs in Napier Territorial Authority. B: Simulated flow depth due to the maximum credible local-source subduction earthquake and inundation extent at 60 min after rupture (Fraser et al., 2014). Inset shows the position of Napier in the national context. C: Meshblock boundaries and 2013 estimate of Usually Resident Population (URP) density for each meshblock (for clarity, smaller meshblocks are shown without boundaries). URP density is classified using Natural Breaks (Jenks).

7.4 Methodology: Least-cost path distance approach to determining pedestrian evacuation potential

The steps implemented in this methodology are described in this section. First, an anisotropic least-cost path distance analysis is set up, using physical data and hazard data for a chosen area. Second, several time-variable population exposure scenarios are created using building locations and various population statistics. Third, estimates of evacuation departure time and pedestrian travel speed are combined with the two prior components, to produce an overall view of pedestrian evacuation potential for the population in question.

7.4.1 Anisotropic least-cost path distance analysis

LCD analysis is conducted in ESRI ArcGIS 10.1 following the *anisotropic least-cost path distance* method of Wood and Schmidtlein (2012). Least-cost path distance determines the minimum path distance from every cell in the hazard zone to the nearest point of safety outside the hazard zone. The hazard zone and tsunami arrival time are identified by numerical inundation modelling (Fraser et al., 2014, Fig. 7.1b). Use of arrival time at shore provides a conservative estimate of arrival time for most locations in the hazard zone because there is additional time before inundation reaches its maximum inland extent.

The anisotropic approach accounts for the cost associated with direction of travel over sloping terrain of different surface type. High-resolution ground surface Light Detection and Ranging (LiDAR) data are used to generate a digital elevation model (DEM) at 2 m horizontal resolution. Most short-span bridges in Napier are represented in the LiDAR data but manual augmentation is required to include the deck elevation of longer span bridges. These would otherwise be omitted, resulting in a road being erroneously intersected by steep terrain, artificially increasing the path distance value on that route. Tobler's hiking functions (Tobler, 1993) are used to convert directional slope (derived from the DEM) into a travel speed cost, interpreting travel in a downhill direction as a benefit and uphill travel as an additional travel cost.

Land cover data are compiled from aggregated polygon data (Ministry for the Environment, 2009) representing ground surface cover. The aggregated data do not include roads, waterways or buildings, so additional polygon and polyline data are combined into a single comprehensive land cover raster. Land cover is represented in the LCD analysis by using a Speed Conservation Value (SCV), which is a speed-reduction factor representing the ease of travel over that land cover (Wood and Schmidtlein, 2012). Any cell representing a road is assigned SCV $= 1.0$ (having no impedance on travel speed) and any cell representing a water body or building is defined as impassable, to ensure evacuation routing around these features. Other land cover categories in the study included: Dirt road (SCV $= 0.9091$), Light brush (0.8333), Heavy brush (0.6667), Hard sand and Swampy bog (both 0.5556).

7.4.2 Time-variable population exposure

Estimates of population located within a hazard zone (the exposed population) are required to provide evacuees' starting locations. Exposure is typically derived directly from census data, which primarily indicates night-time population distributions. Day-time exposure can be estimated by augmenting census data with additional information, such as maximum building capacity determined by floor area (Cousins, 2009), employment records (Wood and Schmidtlein, 2012), or average rates of schooling, employment and numbers of cars at home (Southworth, 1991). In addition to the location of residents who are at home or a workplace, exposure models should include those in institutional facilities, in transit, working outdoors or undertaking leisure activities. Models should also include visitors and commuting patterns. Previous LCD tsunami evacuation models have used up to two exposure scenarios or the maximum exposure, derived from a night-time scenario and a day-time scenario. Random distribution of population has been used to represent exposure uncertainty in stochastic agent-based simulations (Mas et al., 2012a). Recent progress has been made in modelling population dynamics by assigning population-time profiles to different types of locations (Cockings, Martin, and Leung, 2010) and by using transport data in short time-slices to estimate diurnal changes in spatio-temporal population distribution (Kobayashi, Medina, and Cova, 2011). However, such time profiles have yet to be applied in tsunami evacuation modelling.

In this study, total night-time population is obtained from 2006 census Usually Resident Population (URP) data at meshblock-resolution and adjusted to 2013 values based on local population projections (Statistics New Zealand, 2006, 2012a). A meshblock is a New Zealand cadastral entity, generally covering less than 1.0–4.4 km^2 in Napier (Fig. 7.1c). Five population groups are defined on the basis of predominant diurnal activity and age: *school/childcare*, *working-age adults*, *independent elderly*, *dependent elderly* and *visitors*. Whilst it is recognised that physical and intellectual disabilities can affect evacuation decision-making and mobility in evacuation, resulting in an increase in required evacuation time, it is not possible to determine the magnitude of impact of each type of disability registered. By using age to determine mobility impairment, we have captured the majority of mobility impairment in the population, however, this represents an important area of further study.

The groups are used in the model to assign exposure locations and travel speed distributions. Employment data, education rolls and care facility capacities are used to define the proportion of URP in each population group. These data are site-specific; data relevant to the local area should be sought for in analyses for other areas.

Population-time profiles are used to define the certain proportion of each group at different types of location according to the month, day and time of the chosen exposure scenario (Fig. 7.2). The profiles define three types of location as: home or temporary accommodation (also includes elderly care facilities), work or school/childcare, and unspecified location to represent people in transit or outdoors. Time profiles are developed using employment shift patterns (Statistics New

Zealand, 2006), regional commuting patterns[1], US diurnal activity patterns (Klepeis et al., 2001), and local knowledge of school hours and peak commuting hours. Building locations and occupancy type are obtained from a regional exposure model developed for the national asset and loss model, *RiskScape* (Cousins, 2009). Two population-time profiles are developed for each group, one for a weekday and one for a weekend, to account for differing diurnal activity on working and non-working days. To include seasonal distribution of tourists in the exposed population, regional and local monthly visitor data are converted to an average daily number of visitors for each month. A description of the development of each population group and the respective population-time profile follows in Sects.

Twelve exposure scenarios are generated using the time-variable exposure model, then analysed for evacuation demand. The scenarios comprise: 02:00 weekday, 12:00 weekday and 12:00 weekend, repeated for February, May and November (high-, low- and mid-tourist season, respectively). February weekday 08:00 and 17:00 scenarios, are generated to represent peak commuting times and January weekend 12:00 to demonstrate peak tourist numbers. This range of scenarios demonstrates the flexibility of the time-variable exposure model and assesses the influence of changing exposure on evacuation demand.

Exposure distribution – methods applicable to all population groups

The proportion of each population group assigned as being at home is combined into a single "residential population group". Each meshblock is assigned a residential population for that exposure scenario, according to the proportional contribution of the meshblock to total URP. The derived population of each meshblock is then distributed to randomly-selected buildings in that meshblock, in a household group of variable size. Household group size is sampled from a weighted distribution of "number of household occupants": 36 % of households in Hawke's Bay comprise two people, 25 % have one person; 15 % have three people and 13 % have four (Statistics New Zealand, 2006). Distribution in a group enables a single travel speed to be assigned to the group, to represent the effect of household evacuation as a group.

To distribute the proportion of each population group assigned to an unspecified location, a spatially-weighted distribution is developed using a GIS weighted overlay algorithm. In a mixed-density mixed-use urban area, population distribution is unlikely to be entirely random because people spend a significant majority of their time in residential buildings (Klepeis et al., 2001; Leech et al., 2002) and are likely to otherwise congregate around commercial services and community facilities. Therefore, building density is used as a proxy to determine the locations of population who are not defined as being at a residence, workplace, school/childcare centre or care-home. Raster surfaces of (a) commercial-use building density and (b) non-commercial building

[1] Source: Statistics New Zealand, customised report and licensed by Statistics NZ for re-use under the Creative Commons attribution 3.0 New Zealand license

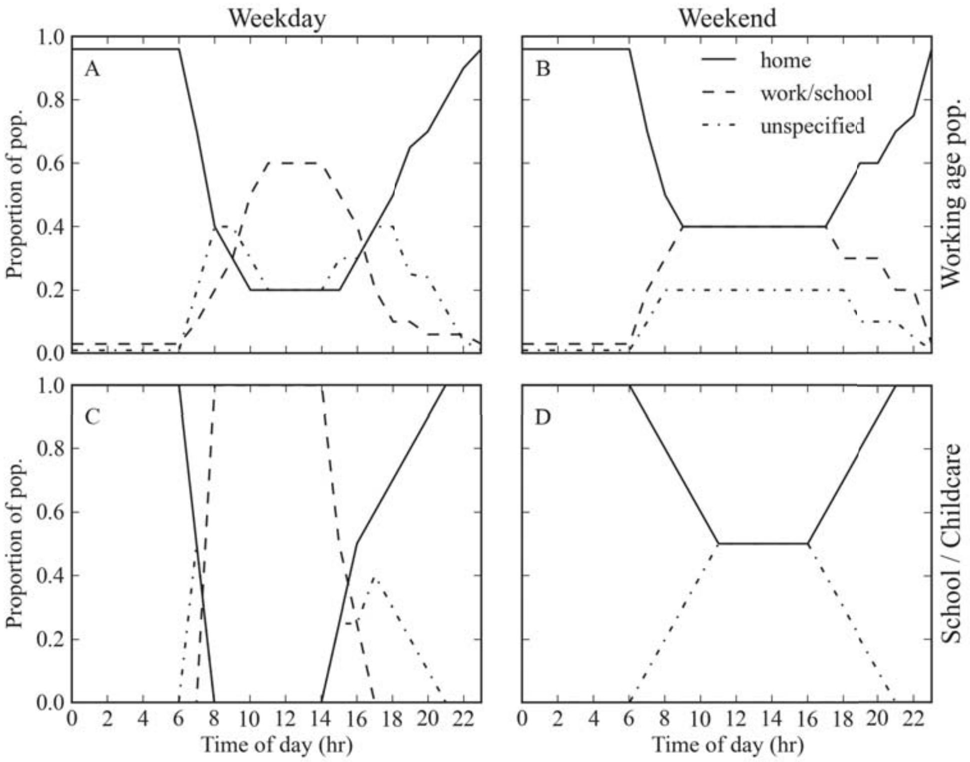

Fig. 7.2: Population-time profiles to distribute working-age adults (A, B) and children (C, D) to home, work/school and unspecified locations. Profiles are shown for a weekday (A, C) and weekend (B, D).

density are calculated using the Kernel Point Density tool in ArcGIS 10.1. The two surfaces are combined using importance-weights of 70 and 30 % respectively, subjectively defined to represent the relatively greater importance of commercial buildings for congregation of population, then reclassified to a combined weighting. In the combined raster, highly-weighted cells reflect areas of highest building density, based on building footprint. The population is then distributed according to the weighted surface using a spatial analysis platform (Geospatial Modelling Environment; Beyer, 2012). This approach ensures that while each individual's location is random, the model contains realistic aggregations of population around commercial and public services and facilities in the city.

Distribution of working-age adults

Population assigned to a workplace is distributed to randomly-selected commercial, industrial, or community-use buildings until the maximum person-capacity of the building is satisfied. Capacity is determined using the building floor area (m^2) and required floor area per person (Cousins, 2009). The proportion of this group assigned to residences and to unspecified locations is distributed according to the method in Sect. 7.4.2. The number of working-age adults (aged 18–65 years) is derived from census data (Statistics New Zealand, 2012b). All members of this group are assigned an "adult unimpaired" travel speed.

Employment statistics[1] show that approximately 80 % of this group are in employment (Napier City Council, 2013). Regional employment shift data show that 89 % of working-age adults are in day-time employment[1]. Therefore on a weekday, 60 % of working-age adults are assigned to commercial or industrial buildings between 10:00–16:00, and 20 % to unspecified locations to represent people working in outdoor locations or in transit while working (Fig. 7.2a). The remaining 20 % are distributed to randomly-selected residential buildings to represent those at home during the day (working and non-working population). In the hours 08:00–10:00 and 16:00–18:00, the proportion of people at unspecified locations peaks to represent commuting between residences and workplaces. There is no data available to inform the rate of movement of people at these times, so the population-time profiles curves are developed using expert judgement to assume movement to residential buildings during this time. Regional commuting data shows a net reduction of c. 7000 people in the working-age population during weekdays (assumed to be 08:00–17:00) due to the disparity in numbers of incoming and outgoing commuters. The net balance of commuters is expected to be much less on weekends, so the effect of commuters is only included on weekday. The weekend population-time profile assumes, using expert judgement, that 40 % of working-age adults are at workplaces during the day, with 40 % at home and 20 % at unspecified locations (Fig. 7.2b). To account for night-shift workers in buildings, 2.5 % of working-age adults are assigned to workplaces during evening hours and 0.5 % of them are assigned to unspecified locations. The distribution of people working in evenings (8 %) and overnight (3 %) is based on employment shift data[1].

Distribution of children to schools and childcare centres

School rolls are obtained for the 34 schools and one tertiary college in Napier (Ministry of Education, 2012a). Attendance rolls for 64 childcare centres are obtained from the Ministry of Education (2012b). Where published roll data are not available for a centre, the mean attendance roll of all other centres is applied. The weekday distribution of children places 100 % of children assumed to be in school or childcare during 08:00–14:00, and at home during 21:00–07:00 (Fig. 7.2c). No data are available to inform the distribution of children between school or childcare centre, home and unspecified locations in the intervening hours, so this is subjectively assigned. The combined school and childcare roll (21 200) is greater than the 2013 adjusted population for age group 2–18 yr (13 933). The surplus is assumed to be schoolchildren commuting in from other territorial authorities and they are not included in exposure scenarios between 17:00–07:00.

To account for the total number of people on site, staff numbers are included in the exposure estimates of childcare facilities using a ratio of one staff member per ten children (Napier Kindergartens, 2012). Staff-to-student ratios are assumed negligible due to the large school population and lower ratio of staff to schoolchildren. All people distributed to education sites are assigned *child* travel speed, due to the expectation that schools will evacuate in class groups, therefore have reduced speed. Currently, data are not available to elaborate on the effect of group evacuation on travel speed.

Distribution of dependent and independent elderly

The population at 17 elderly care facilities and retirement villages (1000 people) is defined as *dependent elderly* and assigned to the slowest travel speed group (*elderly*). There are an estimated 10 000 people above 65 years who are considered for this analysis to reside at home, defined in this model as *independent elderly*. This group are considered to be more mobile than dependent elderly, so are assigned to the *adult impaired* travel speed group.

Both groups are part of the non-working population, assumed based on expert judgement to be located at home or care facility between 18:00–06:00 (Fig. 7.3a and b). Day-time location is assumed to be 60 % at home/facility between 10:00–14:00 and 40 % at unspecified locations. The distribution in the intermediate periods of time (07:00–09:00 and 15:00–17:00) assumes a linear trend to represent travel patterns between home and unspecified locations.

Distribution of visitors

The daily number and seasonal variation of overnight and day-trip visitors to Napier are derived from local and regional tourist data (Ministry of Economic Development, 2013a,b; Statistics New Zealand, 2012a,c). Overnight visitors are distinguished by accommodation type (commercial or

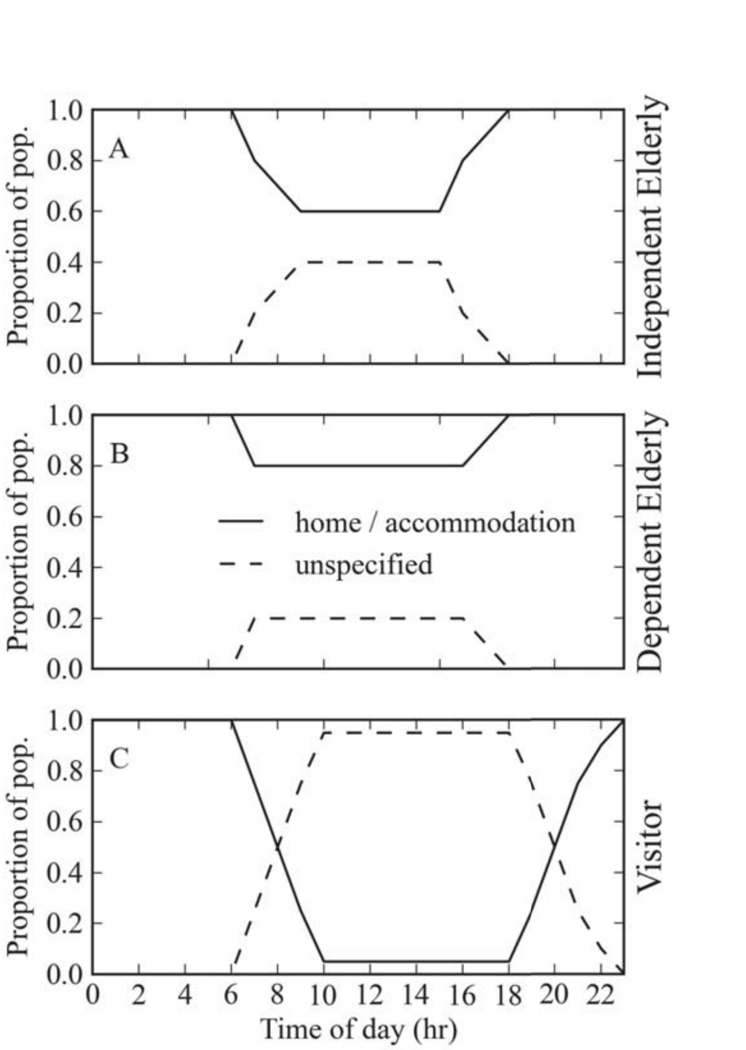

Fig. 7.3: Population-time profiles to distribute visitors **(A)**, independent elderly **(B)** and dependent elderly **(C)** to home or accommodation, and unspecified locations. Profiles for these groups are the same for weekdays and weekends.

private) and distributed to the appropriate building type in night-time exposure scenarios. Between 23:00–06:00, visitors in private accommodation are distributed in groups of two (mean number of guests per stay night = 1.67) to randomly-selected residential buildings in Napier (Fig. 7.3c). Those in commercial accommodation are distributed in groups of two to randomly selected tourist accommodation (hotel/motel/backpacker/holiday park) according to facility capacity as a proportion of total commercial accommodation capacity. Based on expert judgement, 95 % of visitors are distributed to unspecified locations between 10:00–18:00 using the spatially-weighted approach, and 5 % are assumed to be at their accommodation. The estimated number of daytrip visitors is distributed with the spatially-weighted random distribution for exposure scenarios between 08:00–20:00.

7.4.3 Estimation of evacuation time

A person's total evacuation time is represented by a series of discrete time components that include event detection, warning transmission and reception, evacuation preparation and evacuation travel (e.g., González-Riancho et al., 2013; Post et al., 2009; Purser, 2010; Urbanik et al., 1980). An evacuation time sequence for an individual or group can be defined as: $ET_t = EA_t + AD_t + WD_t + ID_t + EP_t + TT_t$ where ET_t is total evacuation time; EA_t is time required to detect an event and assess the threat; AD_t is authorities' decision-making time for issuing an advisory/warning after a threat assessment; WD_t is warning dissemination time between the decision to issue a warning and warning receipt by the public; ID_t is individual decision-making time on whether to evacuate or to seek further information; EP_t is individual preparation time between an evacuation decision and initiating movement; and TT_t is evacuation travel time that is spent in transit between location at the time of warning and safe destination. An individual is considered to have the potential to evacuate successfully if ET_t is less than wave arrival time.

In local-source tsunami, short wave arrival times and technological limitations mean that the detection and warning phases may not be completed fast enough to provide warning with sufficient time for the subsequent evacuation phases. Instead, tsunami education encourages immediate evacuation on recognition of natural warnings such as earthquake ground shaking or observations of unusual marine phenomena. Therefore, total evacuation time in the case of local-source tsunami is a function of the time for individuals to recognise a threat and decide to evacuate (ID_t), the time it takes them to prepare to evacuate (EP_t), and their travel time (TT_t) so that: $ET_t = ID_t + EP_t + TT_t$.

In this proposed method, evacuation preparation time (Sect. 7.4.3) and travel time (Sect. 7.4.3) are estimated separately and summed to yield total evacuation time for each individual (ET_t). To account for uncertainty in evacuation time for each exposure scenario, 500 simulations of evacuation time are conducted for each individual in the population to generate mean ET_t. From these 500 simulations, the 95 % confidence interval is less than 2 % of the mean population at 20–30 min, and less than 11 % in the tail of the curve (Fig. 7.4a, which shows the distribution of population for

ET_t in the range 0–90 min). The 95 % confidence interval range based on 1000 simulations is less than 1–7 %. Five hundred simulations were therefore conducted because they provide comparably accurate view of the evacuation time curve for a 50 % reduction in computational expense. Individuals whose mean ET_t exceeds wave arrival time are subject to further spatial analysis to calculate the population unable to evacuate the hazard zone before wave arrival (P_{VE}). P_{VE} represents the demand for additional evacuation capacity, such as vertical evacuation refuges in the hazard zone.

Evacuation departure time ($ID_t + EP_t$)

Modelling evacuation departure time is complex and uncertain. Activities in this phase may include gathering possessions, warning/helping others, confirming warnings, seeking additional information, and re-uniting or making contact with family before evacuating together (Drabek, 1986; Lindell and Perry, 1992, 2012). These types of behaviour have been reported in local-source tsunami (Fraser et al., 2012b; Yun and Hamada, 2012), but literature concerning tsunami evacuation behaviour remains relatively limited (Dash and Gladwin, 2007; Lindell and Prater, 2010). Quantitative data available to constrain tsunami evacuation departure to specific time ranges are limited to very few studies (Mas et al., 2012a; Suzuki and Imamura, 2005).

Substantial numbers of people choose not to, or are unable to evacuate upon receiving hazard warnings (Johnston et al., 2005; Lindell, Kang, and Prater, 2011; Lindell and Perry, 1992, 2012), resulting in compliance rate much less than 100 %. Earthquake ground shaking is often not interpreted by people as a tsunami warning (Gregg et al., 2006), therefore not all people evacuate the hazard zone. Compliance rate is little-studied for local-source tsunami, but may be influenced by proximity to the shoreline, property ownership, age and preparation of household plans (Charnkol and Tanaboriboon, 2006; Murakami and Kashiwabara, 2011). Tsunami evacuation intention surveys in our study area suggest relatively high but location-dependent compliance rate based on a natural warning: 84 % for respondents on the street at the time of an earthquake, 56 % when at home (Fraser, Johnston, and Leonard, 2013). A spatially-variable compliance rate is supported in the proposed method but due to the focus on travel speeds in this analysis, compliance rate is assumed to be 100 %.

Preliminary surveys of intended evacuation behaviour among residents and visitors in Napier were unable to quantify evacuation decision-making and preparation time but confirmed that people's intended actions would delay evacuation (Fraser, Johnston, and Leonard, 2013). Therefore, departure time is represented by a time sampled randomly from a Rayleigh distribution. Sigmoid curves have been previously used to simulate an initially slow rate of increase in the number evacuating, followed by a more rapid rate of evacuation for hurricanes and nuclear accidents (e.g., Lindell et al., 2002; Southworth, 1991; Tweedie et al., 1986). Observed departure times in tsunami events are well-correlated with the Rayleigh function (Imamura et al., 2012; Mas et al., 2012a). Suzuki and Imamura (2005) estimated that an optimum evacuation curve has a mean value of 7

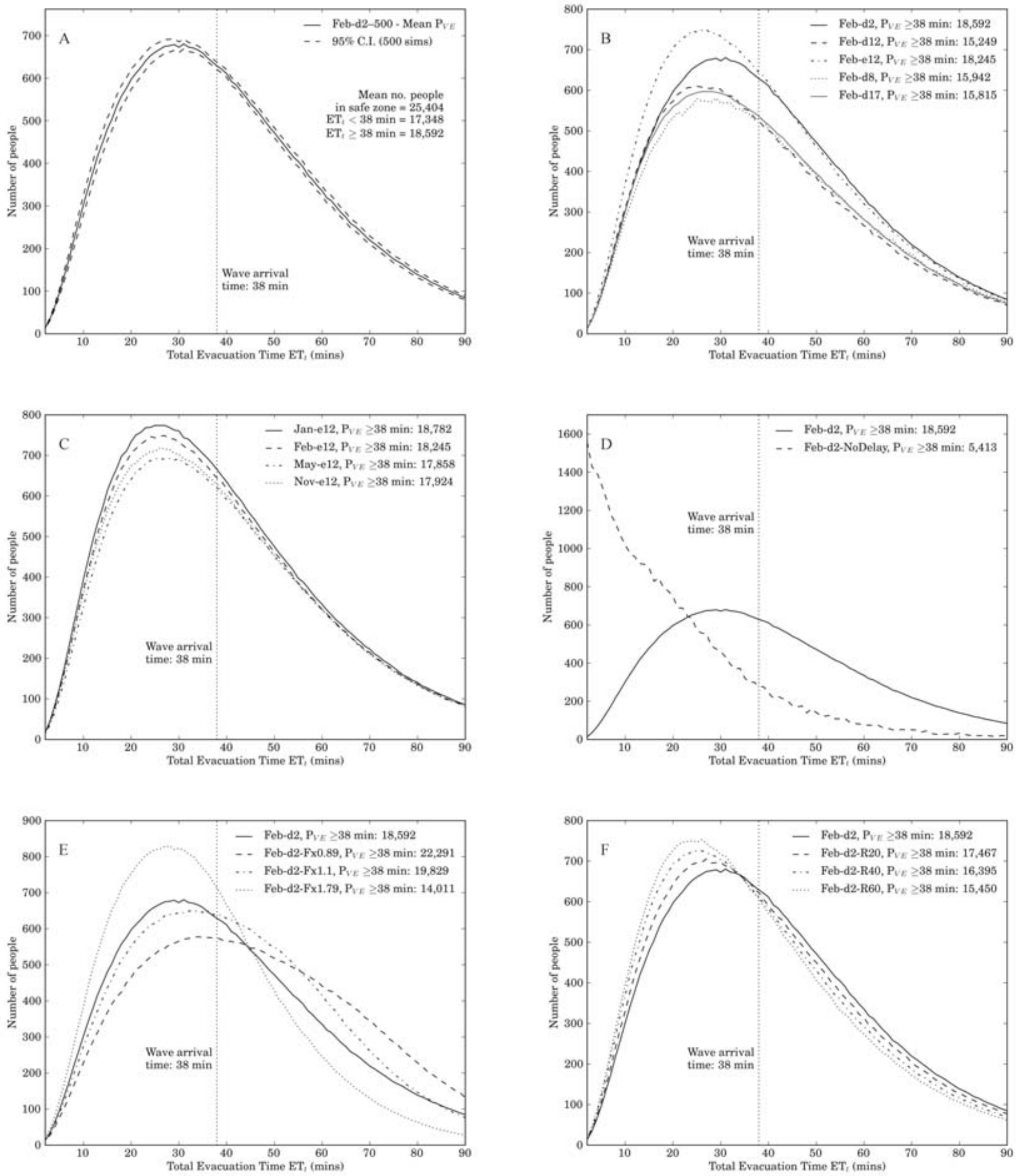

Fig. 7.4: Evacuation time curves in the range 0–90 min, showing wave arrival time and P_{VE} values for each curve. 'd' refers to a weekday scenario, 'e' to a weekend scenario. The number following 'd' or 'e' refers to the hour of the day (24 hr clock). A: Mean P_{VE} and 95% confidence intervals based on 500 simulations for the February weekday 02:00 exposure scenario; B: Diurnal variation in evacuation time for February weekday and weekend scenarios; C: Seasonal variation in evacuation time for a weekend 12:00 scenario; D: Comparison of evacuation time curves for a February 02:00 scenario, with and without evacuation departure time; E: Comparison of analysis with distributed travel speeds compared to fixed speeds for a February 02:00 scenario; and F: The impact of applying a different probabilities that unimpaired adults and children run to evacuate.

min, while Mas et al. (2012a) proposed that a worst-case curve tends towards arrival time, as people wait until later to evacuate. Following the approach of Mas et al. (2012a), Rayleigh curves with mean values of 7 min and 38 min are applied in this analysis as lower and upper bounds potential evacuation-time curves (Fig. 7.5). For each simulation, a mean departure time value is randomly selected from the range 7–38 min, to generate a new Rayleigh function that falls in the shaded area of Fig. 7.5. Every individual or group is then assigned an evacuation departure time sampled from the corresponding probability density function. Fraser, Johnston, and Leonard (2013) suggested different intended actions based on gender and location at the time of earthquake, however, in the absence of quantitative data to inform a relationship between the two, departure time is treated as independent of any demographic characteristics or situational/spatial context.

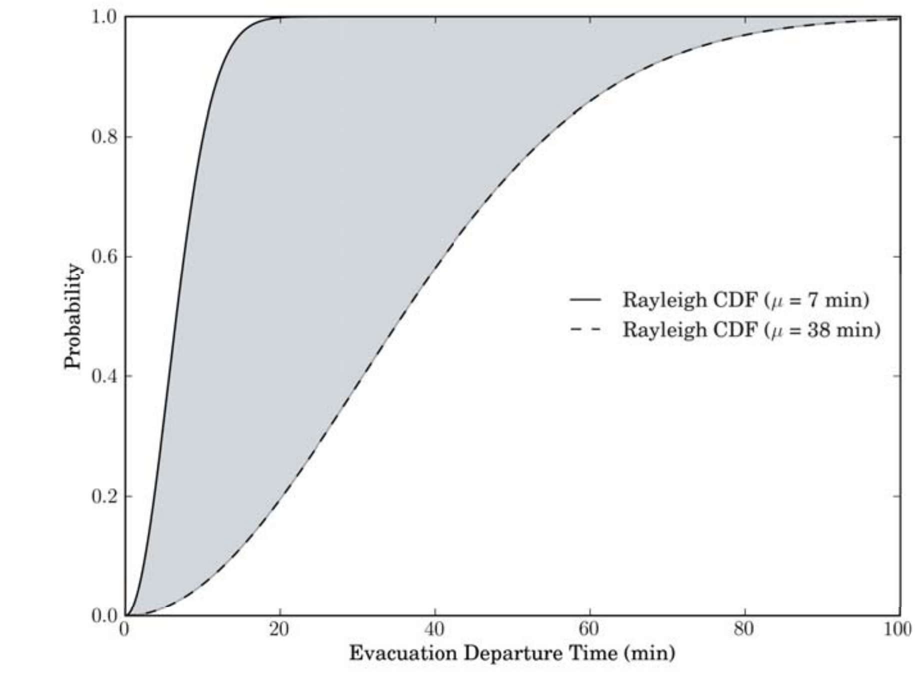

Fig. 7.5: Minimum and maximum bounds of evacuation departure time, represented by Rayleigh functions with μ=7 min and μ=38 min. In each simulation, mean evacuation departure time is sampled from the range 7–38 min, and a new Rayleigh function generated. Each individual's evacuation departure time is then sampled from that curve, which falls in the shaded area.

Evacuation travel time (TT_t)

Evacuation travel mode, generally pedestrian or vehicular, determines the speed and density at which people can travel through a transport network. Travel mode is influenced by distance to destination (Lamb and Walton, 2011), starting location (Fraser, Johnston, and Leonard, 2013), and local context such as regular transportation modes (Murakami and Kashiwabara, 2011; Okumura, Harada, and Kawata, 2011). Tsunami education promotes pedestrian evacuation in local-source tsunami to minimise traffic congestion that can slow evacuation. Previous LCD pedestrian evacuation models have used a single walking speed for all evacuees, or used a different speed for each of several demographic groups, representing the impact of age and relative mobility (Table 7.1).

Variability in travel speed is included in this study by sampling from a speed distribution that is developed using previously-published speeds. To assign distributed travel speeds to the modelled population, walking speeds identified in the literature are grouped into one of five travel speed groups: *Elderly*, *Child*, *Adult impaired*, *Adult unimpaired*, and *Running* (Table 7.1). The five travel speed groups are based on the categories given in the originating studies. The travel speeds found in the literature range between 0.21 and 3.83 $m\,s^{-1}$. There is a range of 1.92 $m\,s^{-1}$ in the adult unimpaired group, 1.54 $m\,s^{-1}$ for children, and 1.09 $m\,s^{-1}$ for elderly. These ranges represent variability in walking speeds that has not been captured by previous studies that apply a fixed speed to each category.

The mean speed and standard deviation for each travel speed group (Table 7.2) are used to generate normal distributions of travel speed (Fig. 7.6). For each individual, a new travel speed is sampled from the corresponding travel speed distribution in each of the 500 simulations. The inverse of sampled travel speed is multiplied by the least-cost path distance value at the individual's location, to calculate travel time to safety (TT_t).

Whilst 65 years (the nominal retirement age in New Zealand) is used in this modelling as a threshold to consider people as non-working, this is arbitrary as a threshold for implementing slower evacuation speeds. Assigning a very slow travel speed to everyone above 65 years is unwarranted, as deterioration in mobility is gradual and highly variable. Therefore, different minimum-age thresholds (65, 70, 75, 80 and 85 years) for assigning the *elderly* travel speed are tested in this analysis.

The proposed method for allocating travel speeds allows for the definition of a probability that an unimpaired adult or child will run in the evacuation, reducing their travel time. The probability of any child or unimpaired adult running is set to 20 %, 40 %, and 60 % in three tests. For each child or unimpaired adult in the exposure model, a randomly sampled value between 0–1 determines whether that individual is assigned to the *running* travel speed group, or to their original travel speed group. The proportion of individuals and groups who might run rather than walk in an evacuation is not empirically known. To minimise this uncertainty when investigating temporally-variable exposure, running speeds are omitted from the diurnal and seasonal scenarios. This also makes the travel speed model more conservative. Sensitivity tests are conducted during this analysis to test the impact of people running on evacuation potential (Sect. 7.5.4).

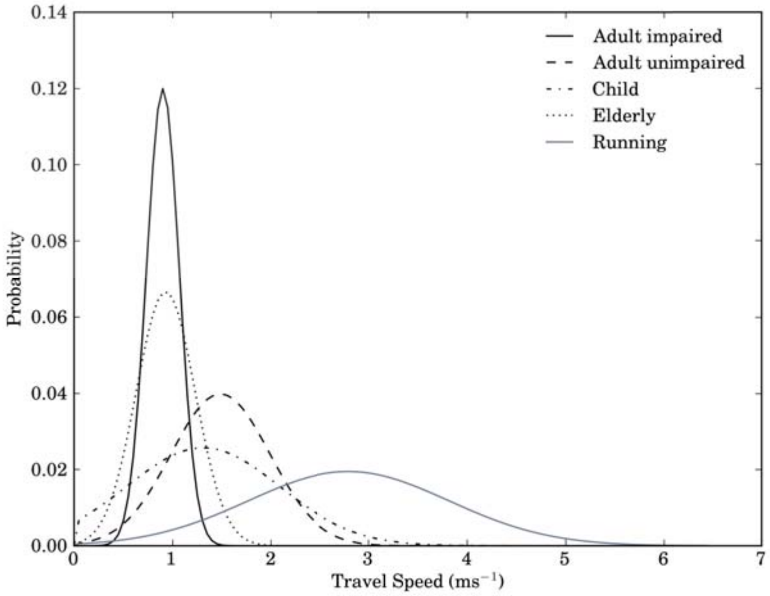

Fig. 7.6: Normally-distributed travel speed for each population group based on statistics presented in Table 7.2. Distributions are derived from the range of travel speeds identified for different groups in the evacuation literature (Table 7.1).

Tab. 7.1: Pedestrian travel speeds used in previous evacuation analyses; these speeds are used in this study to generate travel speed distributions. Sources — 1: FEMA (2008, P646 pg. 52); 2: Wood and Schmidtlein (2012); 3: Cabinet Office Government of Japan (2005); 4: Yagi and Hasemi (2010); 5: Chooramun, Lawrence, and Galea (2012); 6: Revi and Singh (2006); 7: Knoblauch, Pietrucha, and Nitzburg (1996); 8: Park et al. (2012a); 9: Liu et al. (2009); 10: Johnstone (2012); 11: Liu, Hatayama, and Okada (2006); 12: Goto et al. (2012b); 13: Sugimoto et al. (2003);14: Post et al. (2009); 15: Mas et al. (2012a).

Source	Original description	Assigned travel speed group	ms^{-1}	Max. distance (km) in 38 min
1	Mobility impaired	Adult impaired	0.89	2.04
	Non mobility impaired	Adult unimpaired	1.79	4.08
2	Running — fast, moderate, slow	Running	3.83, 2.68, 1.79	8.73, 6.11, 4.08
	Walking — fast, moderate, slow	Adult unimpaired	1.52, 1.22, 0.91	3.47, 2.78, 2.07
	Walking — U.S. crosswalk standards	Adult unimpaired	1.10	2.60
3	Walking: old man alone	Elderly	1.30	2.96
	Walking: crowd, 'sighted'	Adult unimpaired	0.88, 1.29	2.01, 2.94
	Walking: people with disability	Adult impaired	0.91	2.07
	Walking up stairs: old man	Elderly	0.21	0.48

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Table 7.1 – continued from previous page

Source	Original description	Assigned travel speed group	ms^{-1}	Max. distance (km) in 38 min
4	Walking (horizontal)	Adult unimpaired	1.00	2.28
	Walking (up stairs)	Adult impaired	0.58	1.32
5	Unimpaired walking speed	Adult unimpaired	1.50	3.42
6	Adult mean walking speed	Adult unimpaired	1.39	3.17
	Older person mean walking speed	Elderly	1.11	2.53
	Children mean walking speed	Child	0.56	1.27
7	Younger person (14–64) design speed, 15th %ile	Adult unimpaired	1.22, 1.25	2.78, 2.85
	Older person (65+) design speed, 15th %ile	Elderly	0.91, 0.97	2.07, 2.21
8	Age 65+	Elderly	1.25	2.86
	Age 13–64	Adult unimpaired	1.51	3.44
9	Age 6–17	Child	1.20	2.74
	Age 18–69	Adult unimpaired	1.40	3.19
	Age 70+	Elderly	1.00	2.28
10	All	Adult unimpaired	1.25	3.00
11	Young walking	Adult unimpaired	1.10	2.51
	Old walking	Elderly	0.80	1.82
12	Normal walkers max speed	Adult unimpaired	1.50	3.42
	Slow walkers max speed	Adult impaired	0.75	1.71
13	Person: pushing a perambulator, with a child	Adult impaired	1.07, 1.02	2.44, 2.33
	Walking elderly person: independent, group	Elderly	0.95, 0.75	2.16, 1.71
14	Age 15–62: Male, female	Adult unimpaired	2.80, 2.70	6.38, 6.16
	Age $<$14	Child	2.10	4.79
	Age $>$62	Elderly	0.70	1.60
15	All — Maximum walking speed	Adult unimpaired	1.33	3.03

Tab. 7.2: Travel speed statistics (ms^{-1}) for each travel speed group, compiled from travel speeds in the citations given in Table 7.1.

	Adult impaired	Adult unimpaired	Child	Elderly	Running
n	7	19	3	11	3
Min	0.58	0.88	0.56	0.21	1.79
Max	1.07	2.80	2.10	1.30	3.83
Mean	0.88	1.46	1.29	0.90	2.77
SD	0.17	0.50	0.78	0.30	1.02

7.5 Results

The results of this analysis are presented in the form of two products that would be intended to provide emergency management personnel with the spatio-temporal view of evacuation success required for effective evacuation planning. The first product, a set of evacuation time curves (Fig. 7.4), demonstrates the distribution of the population with evacuation time from zero (no evacuation required) to the upper limit of evacuation time. These curves enable emergency managers to make quick comparisons of the total population unable to evacuate in different scenarios, whether, facilitating comparison of proposed evacuation routing options, the effect of introducing vertical evacuation facilities, and comparison of evacuation in different exposure scenarios. They also enable a rapid assessment of the evacuation potential in inundation scenarios for which tsunami arrival has been estimated, which can provide benefit in actual events rather than planning situations. The second product, maps showing density of populations who cannot evacuate successfully (e.g., Fig. 7.7), demonstrate the spatial density of population who cannot evacuate in time. These maps can emergency managers to prioritise areas in which to improve evacuation potential and increase preparedness, but can also provide decision support in real-time, in terms of directing emergency response personnel to rescue people in an event, ahead of tsunami arrival.

7.5.1 Spatio-temporal variation in evacuation demand

The results reported in this section use consistent assumptions to demonstrate the influence of exposure changes: 38 min wave arrival time, elderly age threshold of 80 years (Sect. 7.4.2), and 100 % compliance rate.

Total population in each scenario ranges between 92 % of URP for a weekday 17:00 scenario, and 110 % on a weekend at 12:00. The 17:00 scenario omits non-resident school-children and resident (outgoing) commuters, who are assumed to be outside the study area at that time. The weekend 12:00 scenario has a high population because it includes resident commuters and an additional 4000 day-trip visitors. There is substantial diurnal variation in exposure distribution on weekdays. Individual suburbs show population change of -55–150 % when comparing exposure at 02:00 to exposure at 12:00, as residential population is re-distributed to schools and commercial/industrial areas during the day. Variation between suburbs is also significant when comparing weekday and weekend exposure (-54–75 %), but seasonal variation in all suburbs is relatively limited (generally < 11 %).

For this case study, there is some diurnal variation in P_{VE} (Fig. 7.4b) but little seasonal variation (Fig. 7.4c). It is estimated that 15 200–18 800 people (25–30 % of the total population) are unable to evacuate before wave arrival at 38 min and require additional evacuation options. Highest P_{VE} occurs on a weekday at 02:00 (29–30 %) and weekend at 12:00 (28–29 %). The weekday 12:00 scenario shows the lowest P_{VE} (25–26 %). Peak commuting scenarios have P_{VE} of 26 % for 08:00 and 29 % for 17:00.

Although absolute P_{VE} shows minor fluctuations (5 % of the total population) between each exposure scenario, this masks the significant localised variation in P_{VE} at suburb level between exposure scenarios (Fig. 7.7a–c). The darker shades in Fig. 7.7 indicate high concentrations of P_{VE}. These locations have the greatest requirement for additional evacuation capacity and could potentially have the highest number of casualties or people trapped in a tsunami. The 02:00 scenario shows a large area of peak P_{VE} density in the residential suburbs, which have high concentrations of URP at residential locations overnight. P_{VE} on a weekday at 12:00 is strongly influenced by the large population concentrations at several schools, which show as two distinct areas of peak density. Otherwise, the P_{VE} density evident at 02:00 is more evenly distributed in the 12:00 scenario.

Maximum P_{VE} density occurs in a weekday 02:00 scenario (2800 people km^{-2}) and is 33–41 % lower for all other scenarios. In the weekend 12:00 scenarios, a smaller proportion of the city has high P_{VE} density (greater than 1500 people km^{-2}) compared to weekday 02:00. However, density increases along the coastline and commercial-use areas in weekend day-time scenarios, to a moderate P_{VE} density of 200–1000 people km^{-2}. P_{VE} in the top three suburbs (in terms of P_{VE} at 02:00) decreases in all diurnal comparison scenarios compared to a weekday 02:00. These decreases are on the order of 29–52 % (1000–1900 people). Conversely, other suburbs show increases of up to 1600 people (500 %).

It is important to represent the local variation in P_{VE} and influence of the weekend/peak-commute scenarios to inform appropriate siting choices when planning evacuation. Multiple exposure scenarios can be combined into a maximum exposure surface for a single analysis to provide maximum potential P_{VE} at every location (Fig. 7.7d). Maximum P_{VE} occurs at weekday 02:00 for seven of the 14 suburbs in the study area. The other 50 % of suburbs experience their maximum P_{VE} at weekday 08:00 or at weekend 12:00. Therefore, consideration of only the weekday 02:00 and weekday 12:00 scenarios (i.e., night-time and day-time using employment records) would not, for this study location, accurately represent the maximum P_{VE}.

In addition to changes in P_{VE} distribution, composition of P_{VE} also varies between exposure scenarios. In a weekday 02:00 scenario at Napier, 91 % of P_{VE} are people located at home, so the majority of evacuees will be with their household group. At 12:00 on a weekday the distribution is more diverse, posing different challenges for evacuation and emergency response than a night-time scenario. Twenty-five percent of the population are at home, 31 % are children at school, 20 % are people at work, and 21 % are tourists, resident adults and elderly people at unspecified locations. In these scenarios, evacuation of large groups becomes more prevalent and immediate actions are likely to include connecting with family and travelling to schools before evacuating. At 12:00 on a weekend, P_{VE} comprises 47 % at home, 14 % work, and 31 % of people at unspecified locations (an equal composition of resident adults, children, and tourists). One of the most-vulnerable groups, people in elderly care facilities, comprises < 1 % of P_{VE} ($<$ 200 people) in each scenario.

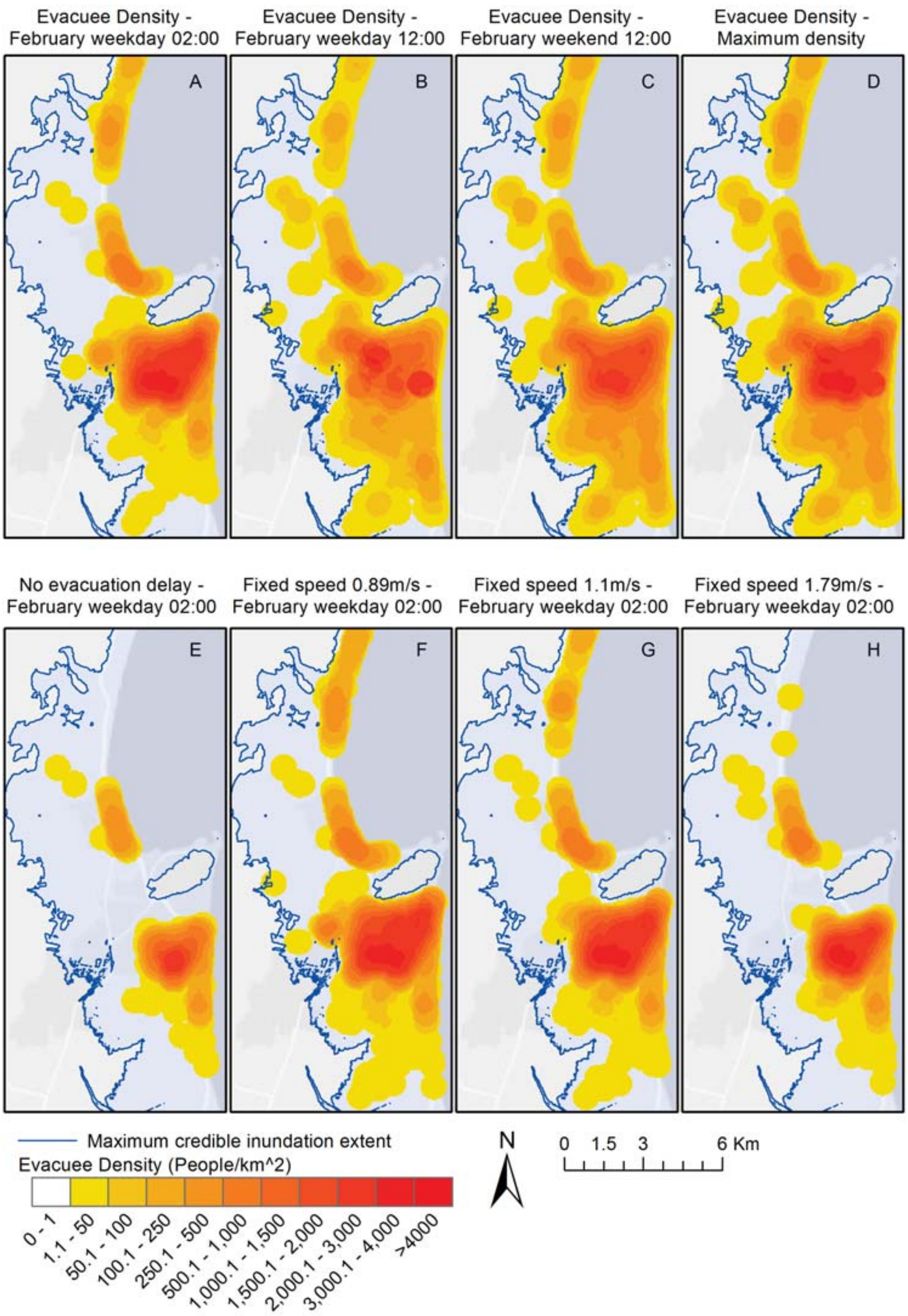

Fig. 7.7: Point density maps showing the density of population with an evacuation time greater than wave arrival time P_{VE}. Generated using the distributed travel speed approach, these maps indicate the variation due to diurnal changes in population distribution. A: Feb weekday 02:00; B: Feb weekday 12:00; C: Feb weekend 12:00; D: Maximum density from all tested exposure scenarios; E: Feb weekday 02:00 with evacuation delay omitted (evacuation travel time only); F: Feb weekday 02:00 using fixed speed of 0.89 ms^{-1}; G: Feb weekday 02:00 using fixed speed of 1.1 ms^{-1}; H: Feb weekday 02:00 using fixed speed of 1.79 ms^{-1}.

7.5.2 Evacuation departure time

To demonstrate the importance of including evacuation departure time in evacuation modelling, analysis was conducted with the decision-making and preparation time phases ($\mathrm{ID_t} + \mathrm{EP_t}$) omitted. When evacuation departure time is omitted, in a February 02:00 scenario, $\mathrm{ET_t}$ is reduced by 15 min on average, reducing P_{VE} from 30 % of total population to 9 %. This represents a reduction of 11 800 people who require additional evacuation capacity (Fig. 7.4d and 7.7e). Without evacuation departure time, $> 50\,\%$ of the population have $\mathrm{ET_t} < 10$ min and several suburbs show no requirement for additional evacuation capacity. This represents a significant possibility for under-estimating P_{VE} and requirements for additional evacuation capacity, reinforcing the need to adequately account for the pre-travel phases of evacuation in LCD modelling. Positively, it also demonstrates the significant reduction in $\mathrm{ET_t}$ that can be achieved through minimising evacuation delays.

7.5.3 Impact of distributed travel speed

The impact of simulating evacuation with distributed travel speeds in a LCD framework has been tested against three fixed travel speeds: 0.89, 1.1 and 1.79 m s^{-1}. These represent fixed speeds for a mobility impaired adult (FEMA, 2008), unimpaired adult based on US crosswalk standards (Wood and Schmidtlein, 2012), and an unimpaired adult (FEMA, 2008) (Table 7.1).

The use of fixed speeds can produce comparable results to distributed travel speeds. This is dependent on the fixed speed corresponding with the mean of travel speed distributions. In this case study, a fixed speed of 0.89 m s^{-1} estimates that 37 % of the exposed population cannot evacuate in time. Simulation with 1.1 m s^{-1} estimates 33 % and 1.79 m s^{-1} estimates 23 %. This compares to 38 % for analysis with distributed travel speeds. This corresponds to a P_{VE} range of 4600 people across the three fixed speed estimates, which is a significant variation in the estimate of required additional evacuation capacity. The use of 1.1 m s^{-1} provides a reasonable assumption to estimate total P_{VE} where travel speed distributions cannot be modelled (Fig. 7.4e). However, the 1.1 m s^{-1} fixed speed curve results in a greater number of people with $\mathrm{ET_t}$ of 38–80 min than a distributed speed analysis, which contains more people with $\mathrm{ET_t} > 90$ min. Therefore, P_{VE} is more sensitive to changes in evacuation time when a fixed speed of 1.1 m s^{-1} is used. If this fixed speed is used to assess the impact of education to reduce evacuation delays, it is likely to show greater reductions in evacuation demand than analyses with distributed speed. A fixed speed of 0.89 m s^{-1} provides a conservative estimate of P_{VE}, which is generally desirable for evacuation planning, but is less suitable for estimating evacuation demand when designing evacuation refuge capacity and informing investment decisions. A fixed speed of 1.79 m s^{-1} underestimates P_{VE} compared to the distributed speed approach.

The application of fixed speeds also affects spatial distribution of P_{VE}, which can influence casualty estimation and decisions on where to site evacuation refuges. The first locations to be affected by altering travel speed are those located closest to the safety zone, because a small change in travel speed determines whether ET_t exceeds wave arrival time or not. Distribution of P_{VE} density for a fixed speed of 0.89 m s^{-1} corresponds closely to that of the distributed speed analysis, although the extent of high density (> 1500 people km^{-2}) is greater than for distributed speeds (Fig. 7.7f). At 1.1 m s^{-1}, the spatial extent of high density begins to reduce, with no reduction in peak P_{VE} density (Fig. 7.7g). For 1.79 m s^{-1} several suburbs are estimated to have no requirement for additional evacuation capacity (Fig. 7.7h); use of this speed could lead to locations that require vertical evacuation being overlooked in decision-making processes.

Due to the similarity of mean travel speed in the distributions compiled for *elderly* and *impaired adults* (Fig. 7.6), application of different minimum-age thresholds (65, 70, 75, 80 and 85 years) for the *elderly* travel speed causes less than 1 % variation in population unable to evacuate before wave arrival. In their current form, and for this exposure case study, the two current travel speed distributions could be combined with minimal impact on results, but in order to demonstrate the functionality of the proposed method, both curves were retained in this study. In other case studies, a proportionally larger elderly population, or concentrations of elderly populations in areas with great travel distances may result in this group having a larger impact. Improved data on evacuation walking speeds of the elderly, and age-related decline in walking speeds, would enable validation and adjustment of this threshold if required.

7.5.4 Application of running speeds

The proposed method enables application of faster travel speeds to proportions of unimpaired adult-s or children, to test the effect on P_{VE} of the probability that people may run to evacuate. In three different tests, probability of an unimpaired adult or child being assigned a travel speed sampled from the *Running* speed distribution (Fig. 7.6) is set to 20, 40 and 60 %. With a 20 % probability of running, P_{VE} is reduced by 6 %. A 12 % decrease in P_{VE} is achieved with 40 % probability and 17 % reduction with a 60 % probability (Fig. 7.4f). These results show the tangible impact (reduction in number of casualties) that is possible due to an increase in travel speeds, and demonstrates the utility of this method in testing the impact of faster evacuation due to education and evacuation training. This approach could also be used to quantify the potential benefits of increased bicycle use in evacuations, to determine whether it is worthwhile trying to increase the use of bicycles in evacuation.

7.6 Conclusions

This study has proposed a method that augments a GIS-based least-cost distance evacuation model, to account for temporally variable exposure, uncertain departure time and variability in pedestrian travel speeds. Population-time profiles are developed to provide exposure distributions for several population groups for any month, day or time. A Rayleigh function is applied to account for uncertain evacuation departure time. A review of pedestrian evacuation models shows that a wide range of travel speeds have been applied as one or several fixed speeds in previous analyses. It is postulated that this is not representative of natural variability in pedestrian travel speeds of a population. Previously-used travel speeds are collated into travel speed distributions for different population groups based on age and relative mobility.

Modelling multiple exposure scenarios facilitates visualisation of the temporal dimension, in addition to spatial distribution, of evacuation demand. This enables emergency managers and planners to understand how the time of an event can affect hazard exposure and potential casualties. Pre-calculated P_{VE} maps and statistics, derived from a large enough range of exposure scenarios, could assist in: real-time decision-making to expedite emergency response to areas with greatest P_{VE}; casualty estimation; public education; and evacuation planning. Robust evacuation planning requires knowledge of maximum potential P_{VE} at any location to ensure that routes and refuges have sufficient capacity in any event. Whilst this approach displays several benefits, the large amount of detailed data required to develop a detailed temporally-variable exposure model poses a significant challenge to its wider application.

In this case study location, P_{VE} varies little due to diurnal changes in exposure, however, significant temporal variations in P_{VE} are apparent when comparing individual suburbs. A typical analysis using two-scenarios (day-time/night-time) has the potential to overlook the full range of diurnal variation in evacuation demand, particularly in areas that have large exposure of transitional populations at peak commuting times and on weekends. Seasonal variation is found to be less important for this case study but should not be ruled out for other locations with a higher ratio of visitors to residents. Maximum potential P_{VE} can be calculated in a single $\mathrm{ET_t}$ analysis, but the estimation of maximum exposure should be based on multiple exposure scenarios, including peak commuting hours and weekends, rather than just two scenarios covering night-time and day-time.

Development of population-time profiles for Napier required several assumptions due to the limited amount of data on diurnal activity patterns in New Zealand and internationally. There remains some disparity in diurnal patterns between the population-time profiles developed for this study and those determined from large samples in the US and Canada. The improvement of diurnal activity data and temporally-variable exposure datasets would benefit future risk assessments and evacuation modelling for all hazards. This analysis applied 500 simulations of evacuation time to a population distribution that was unchanged in each exposure scenario. Future analyses should aim to use probabilistic exposure distribution in each simulation to better represent uncertainty in exposure.

Results of evacuation modelling are highly sensitive to the travel speeds applied. The use of fixed speeds c. 1.1 $\mathrm{m\,s^{-1}}$ results in P_{VE} that is consistent with distributed speeds, demonstrating that this fixed-speed assumption can be used as a suitable assumption for aggregate analyses. However, the slowest speeds used in previous analyses would over-estimate evacuation demand,

and the fastest would significantly under-estimate demand. There is a requirement to constrain travel speeds in community-scale evacuations. Collection of travel speed data for a range of demographic groups in monitored evacuation exercises could improve distributed travel speed models. This is particularly important for schools and other institutions where group dynamics are likely to affect evacuation speeds. Evacuation decision-making and travel time are likely to be affected by physical and intellectual disability (omitted in this analysis), and further research should focus on the impact of this on evacuation time.

There are currently insufficient data on the time required to conduct preparation activities, to quantify preparation time according to personal characteristics and situational context. Quantification of departure time according to different preparation activities would benefit evacuation modelling and planning, and enable validation of Rayleigh functions. It has been demonstrated that a reduction in departure time can significantly reduce evacuation time and increase the proportion of the population able to reach safety. It is important that models incorporate departure time, and that reduction of this phase is a central aim of tsunami education.

Finally, the proposed method provides spatio-temporal variation in evacuation demand for the maximum credible local-source tsunami in the case study location. This highlights the locations in which emergency managers should focus on increasing evacuation potential, for example, through installation of vertical evacuation refuges. While this analysis focusses on pedestrian evacuation potential, this represents only one part of a robust evacuation plan. Complementary agent-based evacuation simulation should be used to validate the results of this least cost distance method and to elaborate on traffic modelling, network capacity issues and evacuee interactions. The potential disruption to evacuation routes, damage to buildings and infrastructure as a result of earthquake ground shaking, and the effect of aftershocks on evacuation should be considered in future analyses.

7.7 Acknowledgements

We would like to thank Jim Cousins (GNS Science) for valuable discussion of exposure models; Megan Harris (Hawke's Bay Tourism) for provision of tourism data; Lisa Pearse (Hawke's Bay Civil Defence Emergency Management Group) and Craig Goodier (Hawke's Bay Regional Council) for provision of topography data; Robyn Tuohy (Massey University) for discussion of age-dependent mobility; and Jeanne Jones (USGS) for providing information on application of ArcGIS anisotropic least-cost path distance module. We would also like to thank two anonymous reviewers and Dr Sergio Freire (European Commission Joint Research Centre (JRC)) for their review comments, which have helped to improve this manuscript. This research was supported by public research funding from the Government of New Zealand and the US Geological Survey (USGS) Land Change Science Program. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the US Government.

7.8 Napier specific results

This section documents the results of LCD evacuation modelling at the suburb-level. Variation between suburbs was summarised in Section 7.5 but the detailed values were not presented in the paper. This section does not form part of the paper intended for publication, and is intended instead for publication as a GNS Science Report for presentation to the regional and local Civil Defence Emergency Management (CDEM) groups.

Average evacuation times (ET_t) for the population in Napier are shown in Fig 7.8. Each point represents an individual or group of individuals. Points coloured yellow to red have ET_t greater than wave arrival time. Suburbs with the longest evacuation times are northern Westshore, Maraenui and Awatoto, due to their long path distance to safety. Average ET_t in the southern part of Westshore are in the range of 38–60 min, assuming that the bridges connecting Westshore to Ahuriri can be crossed by pedestrians following the earthquake. Even with functioning bridges, this analysis suggest that Westshore requires vertical evacuation to provide safety of its residents, in flow depths of up to 9 m. If these bridges were damaged such that they could not be used, ET_t in Westshore would increase with the requirement to travel north to the safety zone. Population with $ET_t \geq 38$ min are also located in Bay View, Meeanee, Onekawa West, Onekawa Central, Nelson Park and Mclean Park, while Ahuriri, Tamatea North, Poraiti and Pirimai have much lower ET_t. This is reflected in the P_{VE} values provided in Table 7.3.

Across the whole Territorial Authority, the number of people who do not have the potential to evacuate in the available time (P_{VE}) is on the order of 15,000–18,000 (25%–30% of total population) in any exposure scenario (Fig 7.4b, Table 7.4). The suburbs with highest numbers of people requiring additional evacuation capacity are Onekawa South, Marewa, Maraenui, and Meeanee (Fig 7.7; Fig 7.9; Table 7.3). Each of these suburbs have a mean P_{VE} $\geq$2,000 and a range of $>$1,000 across all scenarios.

Diurnal changes in exposure suggests that night-time and weekend 12:00 scenarios, which maximise the number of day trip visitors, result in the highest P_{VE}, whilst P_{VE} in weekday scenarios is around 3,000 lower. Table 7.3 presents absolute P_{VE} for different exposure scenarios for each suburb. Seasonal variations in tourist numbers has relatively little impact on P_{VE}, with weekend lunchtime estimates all in the range 17,000–18,000 for January, February, May and November scenarios.

In order to reduce P_{VE}, evacuation time must be reduced by reducing delay time and / or travel time. The latter may be achieved by reducing distance to safety or increasing travel speed. Based on maximum potential P_{VE} density, the five most optimal locations for vertical evacuation refuges have been identified (Fig 7.10). These locations are indicative only; they are not related in anyway to physical or built features, such as roads for access or available parcels of land. The locations are selected using an iterative process described in Fig G.7. The point of highest P_{VE} density is selected as the optimal location. This location is added to the original safety zone, and a new path distance analysis conducted based on the new safety zone. This accounts for evacuation to the newly-added refuge. Meanwhile, a specified area around the location is removed from the P_{VE} density data, which are re-analysed to find the new point of maximum density. Thus, the next most-optimal location is identified and path distance analysed with this refuge included as a point of safety. Path distance analysis considering the development of multiple refuges can be conducted by augmenting the safety zone with more than one refuge.

In order of priority, the refuges should be located on the border of Onekawa South and Maraenui, in south Marewa, in Onekawa Central, in Mclean Park, and in Westshore. According to the maximum simulated flow depth at the locations identified, the minimum elevation of the refuges should be $\geq$3 m for sites 1, 3, and 5 (Fig 7.11), based on the FEMA (2008) guidelines for minimum height (Section 3.2.2). Sites 2 and 4 would require the refuge to be at a minimum elevation of $\geq$ 6 m. Any refuges in Ahuriri, Westshore, northern Onekawa West, the Port, and locations on the eastern shore would require refuge elevation of $\geq$ 9 m.

The impact of implementing the top two proposed refuge locations, separately and in combination, on the evacuation time curve for a February 02:00 scenario is shown in Fig 7.12. Implementing the most optimal refuge has the potential to save 3,800 people, providing a facility of that capacity is constructed (Table 7.5). A facility at the second-most optimal location could provide refuge for 2,700 people, and in combination the potential lives saved could equal exceed 5,000. These values are calculated according to the total number of people located in a radius of 1,200 m, which is the maximum distance that can be covered in the simulated arrival time with a travel speed equal to the slowest mean distributed travel speed in the analysis (0.88 ms^{-1}). They provide an indication of the life-saving potential only; the design of structures should endeavour to meet these estimates when considering the maximum capacity of safe storeys. The P_{VE} estimates given here are a first attempt to quantify evacuation potential. Refinement of the modelling to include dynamic inundation would likely reduce P_{VE}, while the inclusion of non-compliance would increase P_{VE}.

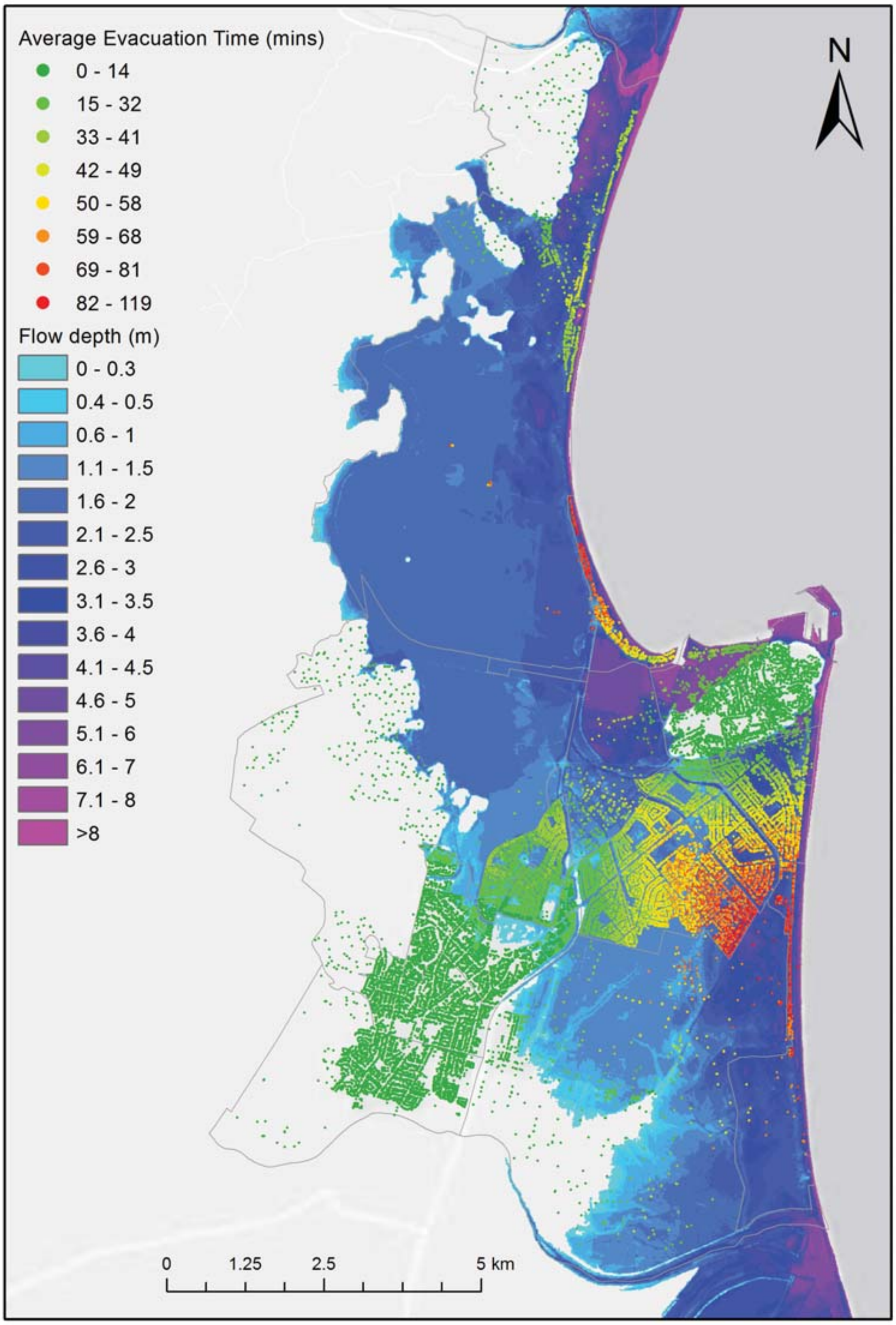

Fig. 7.8: Average total evacuation time (ET_t) for the population in Napier, in a February 02:00 exposure scenario. Time data is overlaid on maximum flow depth values, indicating that the areas of maximum ET_t are also those with flow depths >3 m.

Tab. 7.3: Absolute P_{VE} for each suburb in Napier across modelled exposure scenarios, with relevant statistics.

Suburb	Jan-e12	Feb-d2	Feb-d12	Feb-e12	Feb-d8	Feb-d17	Nov-d2	Nov-d12	Nov-e12	May-d2	May-d12	May-e12	Mean	StDev
Onekawa South	3,009	4,470	2,749	2,908	3,187	2,806	4,332	2,690	2,885	4,414	2,668	2,883	3,250	711
Marewa	2,727	3,558	1,765	2,626	2,074	2,525	3,448	1,746	2,594	3,526	1,757	2,631	2,581	669
Maraenui	2,439	3,688	1,786	2,388	2,086	2,314	3,660	1,739	2,356	3,649	1,741	2,345	2,516	739
Mclean Park	1,971	2,657	2,558	1,954	2,702	1,744	2,563	2,535	1,927	2,544	2,500	1,868	2,294	362
Meeanee	2,075	320	1,177	1,949	1,135	1,549	293	1,130	1,917	313	1,062	1,791	1,226	655
Onekawa Central	962	1,097	1,465	983	1,471	892	1,038	1,488	974	1,095	1,479	981	1,160	240
Westshore	1,204	1,318	840	1,135	898	939	1,273	841	1,102	1,229	768	1,083	1,053	189
Onekawa West	1,476	126	1,168	1,434	688	853	110	1,477	1,424	120	1,429	1,687	999	600
Bay View	1,265	797	641	1,197	707	1,013	655	678	1,177	738	628	1167	889	253
Nelson Park	773	1,170	462	737	986	742	1,008	716	771	1069	818	838	841	190
Awatoto	1,012	387	657	972	559	753	378	576	870	396	580	855	666	225
Pirimai	206	339	119	241	137	267	266	140	256	404	164	324	239	89
Tamatea North	126	249	87	160	80	173	144	118	162	264	79	192	153	61
Ahuriri	26	34	10	31	39	33	52	13	27	35	23	44	31	12

Continued on next page

Table 7.3 – continued from previous page

Suburb	Jan-e12	Feb-d2	Feb-d12	Feb-e12	Feb-d8	Feb-d17	Nov-d2	Nov-d12	Nov-e12	May-d2	May-d12	May-e12	Mean	StDev
Poraiti	23	0	10	22	14	29	0	21	38	0	17	37	18	13
Hospital Hill	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bluff Hill	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Tamatea South	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Green-meadows	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Taradale North	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Taradale South	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	19,295	20,210	15,494	18,737	16,763	16,632	19,220	15,908	18,480	19,796	15,713	18,726	17,915	1,700

Tab. 7.4: Population values for each tested exposure scenario. Columns show the number of people in the safe zone, with sufficient evacuation potential (<38 min), and with insufficient evacuation potential (≥38 min).

Scenario	Pop. in safe zone	<38 min	≥38 min (P_{VE})	Total
Feb d2	25,404 (41%)	17,348 (28%)	18,592 (30%)	61,344 (100%)
Feb d8	30,152 (49%)	15,140 (25%)	15,942 (26%)	61,234 (100%)
Feb d12	30,099 (49%)	16,200 (26%)	15,249 (25%)	61,548 (100%)
Feb d17	23,728 (43%)	15,881 (29%)	15,815 (29%)	55,424 (100%)
Feb e12	28,046 (43%)	19,667 (30%)	18,245 (28%)	65,958 (100%)
Jan e12	28,708 (42%)	20,488 (30%)	18,782 (28%)	67,978 (100%)
May d2	25,152 (42%)	16,536 (28%)	18,173 (30%)	59,861 (100%)
May d12	29,153 (49%)	15,268 (26%)	15,176 (25%)	59,597 (100%)
May e12	26,129 (42%)	18,127 (29%)	17,858 (29%)	62,114 (100%)
Nov d2	25,342 (42%)	17,508 (29%)	17,726 (29%)	60,576 (100%)
Nov d12	29,646 (49%)	15,385 (25%)	15,490 (26%)	60,521 (100%)
Nov e12	27,129 (42%)	18,922 (30%)	17,924 (28%)	63,975 (100%)

Tab. 7.5: The potential impact of implementing TVEB at the two most optimal locations, on P_{VE} in a February 02:00 scenario. Percentage change shows the impact of implementing TVEB on P_{VE}, relative to the situation with no TVEB.

	no TVEB	TVEB 1	TVEB 2	TVEB 1+2
Safe	25,404	25,461	25,442	25,477
<38 min	17,976	21,762	20,693	23,005
≥38 min (P_{VE})	17,964	14,120 (-21%)	15,208 (-15%)	12,861 (-28%)
Potential evacuees		3,844	2,756	5,103

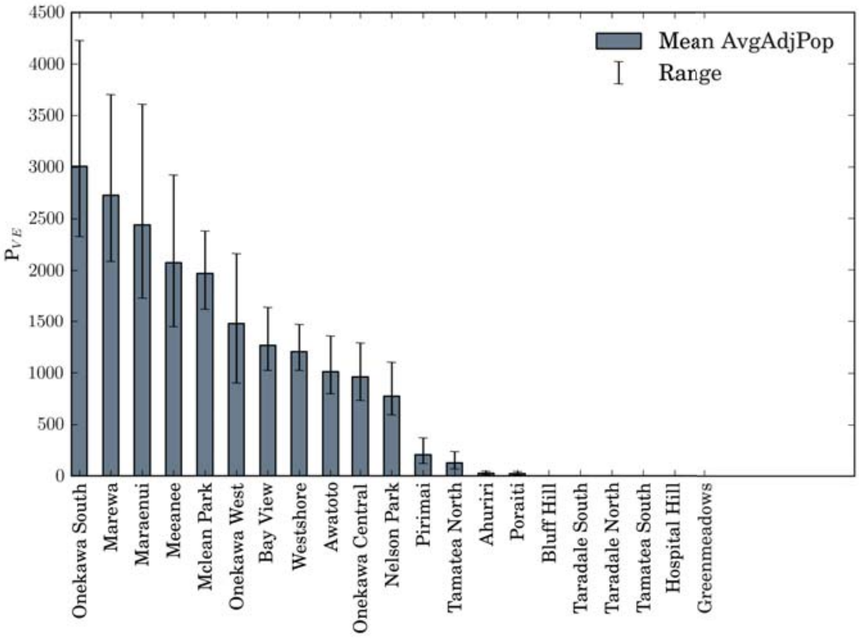

Fig. 7.9: Mean and range of P_{VE} for each suburb in Napier, across all modelled exposure scenarios.

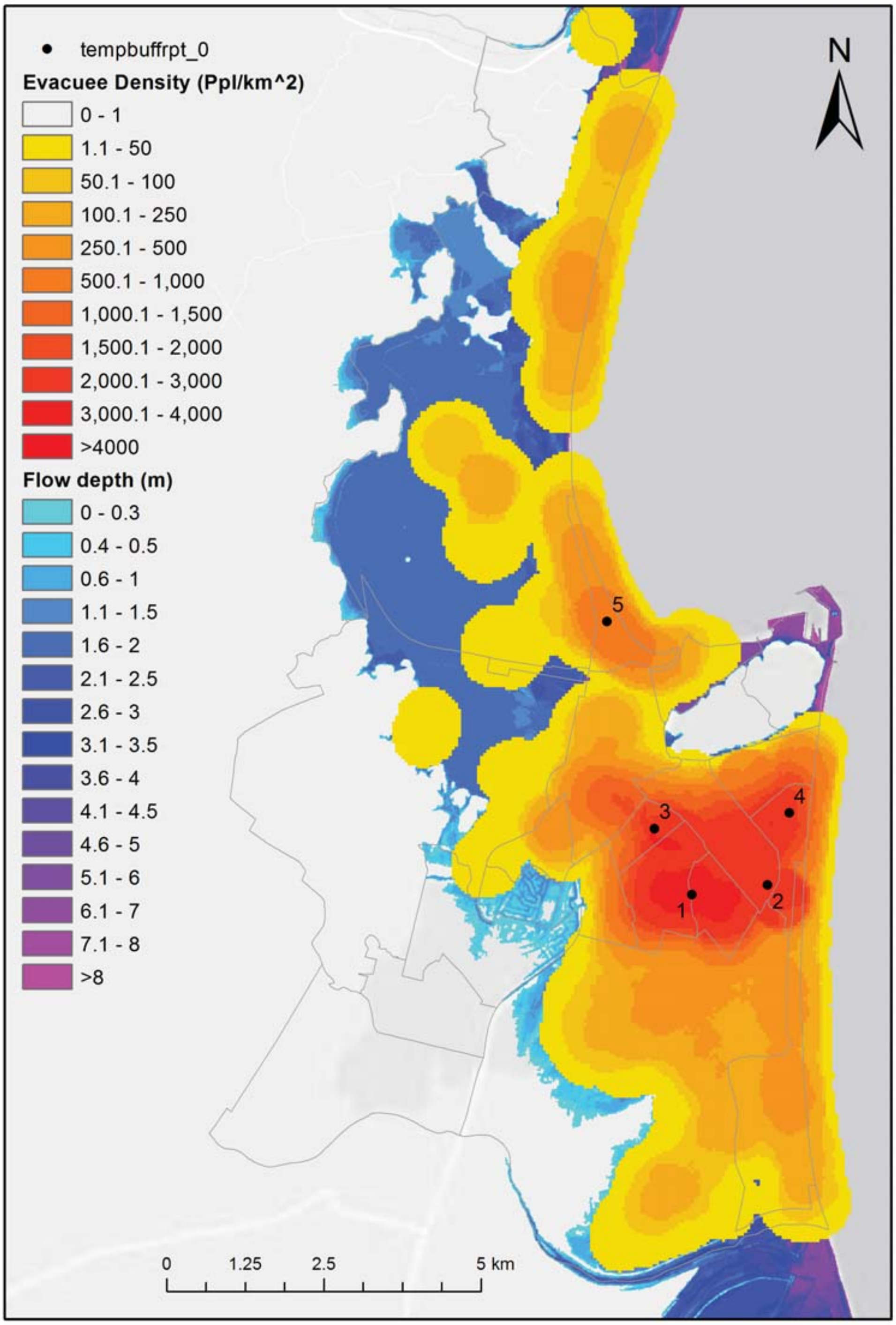

Fig. 7.10: Top five locations for Tsunami Vertical Evacuation Buildings (TVEB) in Napier, based on maximum evacuee density across all scenarios.

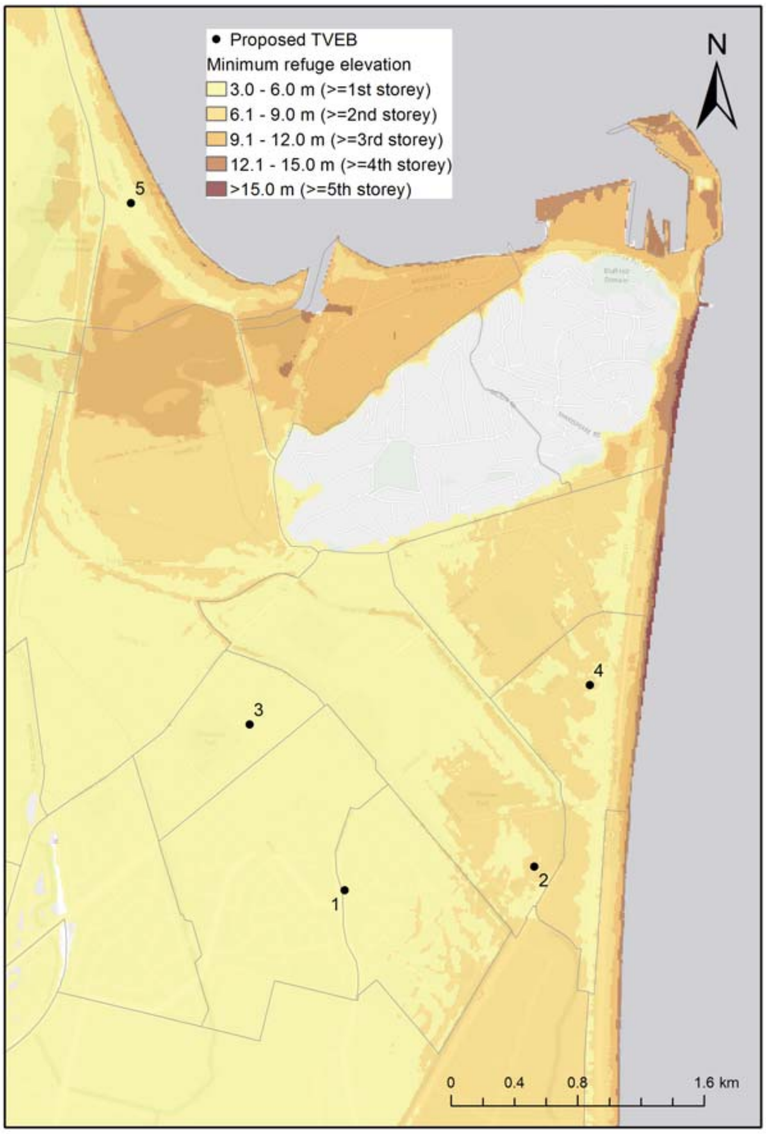

Fig. 7.11: Minimum elevation of vertical evacuation refuge, according to FEMA (2008) guidelines and maximum credible flow depth (Fraser et al., 2014).

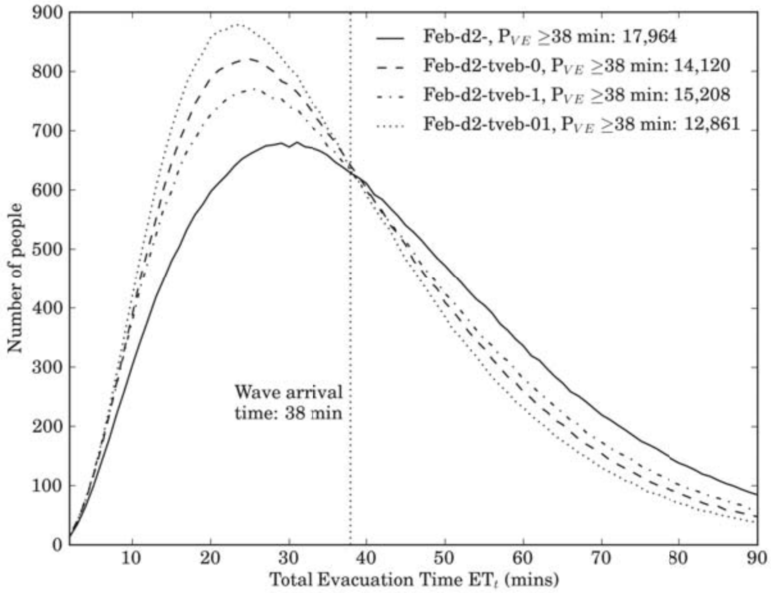

Fig. 7.12: Potential impact on the February 02:00 evacuation time curve due to implementation of the two most-optimal TVEB, individually and in combination.

7.9 Link to next chapter

This chapter has presented a methodology that combines anisotropic least-cost path distance evacuation modelling with an enhanced view uncertain parameters, namely temporally variable exposure and distributed travel speeds. The method has been used to identify the optimal locations for TVE-B in Napier, based on the simulated density of population who may not be able to evacuate the hazard zone prior to wave arrival in the maximum credible local-source tsunami. The next chapter presents a synthesis of the work that has been presented in the previous four stand-alone papers (chapters 4, 5, 6 and 7). Recommendations are made for the development of vertical evacuation strategies in New Zealand on the basis of work presented in this thesis.

8. DISCUSSION

Evacuation is a 'necessary consideration for public safety' (Garside et al., 2009), particularly in local-source tsunami. This thesis aimed to enhance the theoretical and methodological basis for development of vertical evacuation strategies in New Zealand. In doing so, it has filled a major gap in current tsunami risk reduction activities. To achieve the overall research aim, four research objectives have been addressed:

1. Determine maximum credible inundation extent, flow depth and available evacuation time due to local-source subduction zone tsunami at a case study location in New Zealand (Chapter 4);
2. Elucidate experiences of vertical evacuation in the March 2011 Great East Japan tsunami to inform vertical evacuation planning in New Zealand (Chapter 5);
3. Explore intended evacuation behaviours in local-source tsunami in New Zealand, and gather preliminary research on public perception of vertical evacuation facilities (Chapter 6);
4. Develop a method to assess pedestrian evacuation potential of the exposed population to inform decision-making on evacuation planning, including vertical evacuation strategies (Chapter 7).

This discussion chapter synthesises the findings from the four research phases conducted to address the above objectives. It outlines their contribution to knowledge of local-source tsunami evacuation and makes recommendations for the development of vertical evacuation as a component of comprehensive tsunami evacuation strategies in New Zealand.

8.1 Local-source tsunami hazard in New Zealand and the need for vertical evacuation

Numerical simulation of four local-source tsunami scenarios has been conducted using the latest information on seismic potential at the Hikurangi subduction margin, offshore of the east coast of New Zealand's North Island (Chapter 4). The simulations show the potential for variable inundation and arrival times on the order of 30–40 min from such events. Inundation is expected to reach 4–5 km inland at Napier due to the maximum credible event, a M_W 9.0 rupture of the whole margin. Wave arrival at Napier is expected to occur approximately 38 min after earthquake rupture. Flow depth would be expected to exceed 8 m in areas closest to shore. Comparison of flow depth against fragility curves from the Great East Japan tsunami demonstrates the potential for major damage to timber frame buildings and moderate-major damage to Reinforced Concrete (RC) buildings. The simulated inundation extent is consistent with inundation maps generated independently by Hawke's Bay Regional Council (Hawke's Bay Civil Defence And Emergency Management, 2011) and the worst-case evacuation zone produced using the New Zealand national standard rule-based evacuation mapping approach (Section 4.10). The data produced in Chapter 4 were used as the basis for hypothetical scenarios in the investigation of intended evacuation behaviour (Chapter 6) and for pedestrian evacuation modelling (Chapter 7).

Preliminary ground shaking intensity mapping and estimates of rupture duration in the maximum credible scenario suggest intensity of Modified Mercalli Intensity (MMI) 7–10 at Napier and ground shaking of at least 2 min (Appendix F). This is 'damaging' to 'very damaging' shaking, during which people would find it hard to stand up (Table F.2). Therefore the earthquake should result in sufficient strength and duration of ground shaking to be taken as an unambiguous natural warning of tsunami, in line with tsunami education in New Zealand. Unfortunately, this research has suggested that many people would react to the earthquake, but that there may be low levels of subsequent tsunami evacuation.

The numerical modelling also highlights the relevance of this thesis to tsunami risk reduction in several other coastal urban areas of New Zealand. Following rupture of the Hikurangi subduction margin, there is likely to be $<$60 min available for evacuation of the coastline in the Gisborne, Wellington, Horizons-Manawatu, and Marlborough regions (Fig 4.7). The national tsunami hazard review (Power, 2013) indicates significant maximum amplitude at the 1 in 2,500 years return period (84th percentile) in these regions: Gisborne (14 m), Tauranga ($\sim$9 m), Wellington Harbour (11 m), and Kaikoura ($>$10 m). Additionally, there are long distances and limited routes to high ground from in some of these areas, notably in Tauranga (Papamoa) and Wellington harbour (Petone and Kilbirnie/Lyall Bay in particular), with the potential to require vertical evacuation. This research has focussed on a single case study location but the data and proposed methodologies are also applicable to these locations.

8.2 Design of vertical evacuation refuges

8.2.1 Structural requirements

The Great East Japan tsunami highlighted the potential of vertical evacuation to save many lives in local-source tsunami. Most Tsunami Vertical Evacuation Buildings (TVEB) fulfilled their designated evacuation function despite, in some cases, flow depth $>$10 m inundating several storeys. However, some TVEB and evacuation sites on high ground were overtopped or inundated, resulting in loss of life. The elevation of those sites had been designed on the basis of historic tsunami inundation, which underestimated the maximum credible inundation. Robust long-term hazard assessment is required to ensure that any evacuation refuge is located at sufficient height to provide safety above the maximum credible flow depth.

Current guidelines provide equations for derivation of tsunami design loads and required refuge height based on maximum run-up and flow depth. A significant amount of new fragility and tsunami loading data is being analysed internationally to update approaches to estimation of tsunami loading (Section 3.2.2). In the United States (US), guidelines are planned for publication in the 2016 edition of the *American Society of Civil Engineers (ASCE) 7 Standard, Minimum Design Loads for Buildings and Other Structures* (Chock, 2012). Fire protection and measures to prevent buildings over-turning are required in the updated guidelines, based on evidence from the Great East Japan tsunami. The New Zealand emergency management and engineering communities should be encouraged to assess and adapt, where required, the revised tsunami loading guidelines for implementation into the New Zealand Building Code.

The calculation of design tsunami loads for implementation of current and forthcoming structural guidelines requires estimation of flow depth. In order to ensure that adequate tsunami loading is applied in design, maximum credible flow depth should be obtained by numerical simulation of low-frequency tsunami scenarios (e.g., 1 in 2,500 year return period), derived from Probabilistic Tsunami Hazard Assessment (PTHA). The recently-published New Zealand national tsunami hazard review (Power, 2013) provides the ability to select extreme local-source tsunami on the basis of maximum amplitude at the coast and should be used to define the maximum credible tsunami at each site to assess flow depth for vertical evacuation design. The experiences related by civil protection and emergency services staff during our interviews in Japan (Chapter 5) highlight the importance of considering non-structural aspects of TVEB, some of which have been previously raised in the limited published literature on vertical evacuation (Section 3.6.4). The following paragraphs outline the features that must be addressed when developing vertical evacuation refuges. Although these were explored in the context of TVEB, they are also relevant to the development of towers and berms too.

8.2.2 Refuge capacity

It is important to estimate the required capacity of each planned refuge to ensure that all evacuees who go there can access a safe elevation. Chapter 7 proposes a method to select optimal locations for evacuation refuges based on the density of population requiring additional evacuation options, and provides an estimate of the required capacity to provide refuge to all people in a radial catchment area. Minimum space requirements for refuge occupants (e.g., FEMA, 2009) should be used to estimate the floor-space requirements of each refuge. In the design of vertical evacuation strategies, the achievable capacity will determine whether the required capacity can be achieved, within budget constraints and practical limitations.

Refuge capacity (i.e., over-crowding) was not raised as an issue during our interviews about evacuation in the Great East Japan tsunami because most people prioritised high ground as a destination. Evacuation behaviour surveys in Napier suggest that buildings are seen by respondents as a 'last-resort' option, suggesting that most people would attempt to travel to high ground rather than go to buildings. This may reduce the potential for over-crowding of refuges where high-ground is an option, but the potential for over-crowding cannot be discounted, particularly where there is clearly no other option. Results of the survey in Napier suggested that concerns about slow access and over-crowding must be addressed in public education, to ensure that people are not discouraged from using available refuges when required.

8.2.3 Access to safe refuge level

Access to the safe elevation of a refuge is required at all times for vertical evacuation to be effective. Various approaches to ensuring 24-hour access to TVEB are proposed following the example of Japanese facilities (Chapter 5). It is expected that access arrangements (e.g., via external stairs, staff opening the building, forced entry or community key-holders) would be decided on a case-by-case basis during the refuge design and designation process, through dialogue with building owners and local communities. Generally, access to berms would be provided by ramps or stairs. It would be prudent to ensure redundancy in access options by making provision for more than one method of access to any refuge.

Planning guidelines should outline all possible options with corresponding legislative framework to facilitate the most suitable option in each case. For example, Section 87 'Entry on premises' of the Civil Defence Emergency Management (CDEM) Act 2002 (New Zealand Government, 2002) may provide some legislative precedent for gaining entry to designated TVEB in the event of needing to enable people to evacuate vertically (Textbox 8.1). Local-source tsunami evacuation is likely to occur prior to any declaration of a state of emergency, therefore, current provisions for forced entry are unsuitable.

Textbox 8.1 (Section 87 'Entry on premises' of the CDEM Act 2002)

If a state of emergency is in force in any area, a Controller or a constable, or any person acting under the authority of a Controller or constable, may enter on, and if necessary break into, any premises or place within the area or district in respect of which the state of emergency is in force if he or she believes on reasonable grounds that the action is necessary for—
(a) saving life, preventing injury, or rescuing and removing injured or endangered persons; or
(b) permitting or facilitating the carrying out of any urgent measure for the relief of suffering or distress.

New Zealand Government (2002)

8.2.4 Evacuation signage

Clear and consistent evacuation signage is required to promote awareness of the existence and location of vertical evacuation refuges, and to direct evacuees and emergency responders to the refuge in an emergency. Signs should be clearly displayed in large format at high elevation, e.g., on multiple sides at the top of buildings, and above all entrances. At entrances, signs should indicate the most appropriate access route to upper storeys, as observed at newer TVEB in Japan (Appendix D). Signage should be consistent with current the New Zealand national tsunami signage standard (M-CDEM, 2008c), which includes provisions for vertical evacuation. However, the current standard sign indicates evacuation via stairs (Fig 3.2F) and the sign indicating safe refuge level includes no symbology (Fig 3.2H). These may be appropriate when referring to external staircases, or hillside paths such as those common in the hillsides of Wellington, but they do not unambiguously depict the role of TVEB. To address this issue, it is proposed that additional signage, based on the depiction of a building on Japanese signs, be included into the national standard (Fig 8.1). The text on Fig 8.1b could be replaced with a distance and directional arrow for placement on the street, directing evacuees to the refuge.

(a)

(b)

Fig. 8.1: Proposed options for vertical evacuation signs for improved representation of TVEB. Symbology is consistent with current signage standards but provides clearer depiction of the role of buildings and refuges. Image (b) shows an example of the sign with additional directional information noting the safe storey or distance to refuge.

8.2.5 Evacuee welfare

In any vertical evacuation refuge, there should be provision of shelter, food and water, and communication links to civil defence and emergency services at the refuge level. Provision of shelter and supplies is important given the potential for refuges being in use for up to a few days if tsunami waters subside slowly or if debris prevents egress from the refuge. Communication equipment is important in case fire threatens a refuge during a tsunami, or if there are medical emergencies among the evacuees. Adequate provisions may help reduce any need or urge of evacuees to leave the refuge earlier than it is safe to do so (i.e., before an all-clear message from CDEM). The amount of provisions should be commensurate with the refuge capacity, and be subject to a plan for maintaining and refreshing supplies periodically. Duration of refuge occupancy is difficult to estimate, but evidence from Japan suggests that it is reasonable to expect that a refuge could be occupied for >24 h, and potentially ≥ 48 h.

8.3 Community participation

Community engagement has been an important component of designating private buildings as TVEB in Japan, the positive progress of 'Project Safe Haven' in Washington State, US, and the successful approach taken to evacuation mapping in Wellington, New Zealand. Leveraging community interest and encouraging owners to see the provision of the facility as a benefit to the community was effective in Japan for allaying the concerns of building owners, which centred around liability for evacuees and access issues. These initiatives and the preparedness literature suggest that development of any vertical evacuation strategy should be strongly community-based to incorporate local knowledge and communities' requirements, to encourage community partnership and ownership, and to promote discussion and education.

Due to the anticipated investment costs of construction and designation, any refuge is likely to require a non-emergency use in order to be funded. Project Safe Haven showed that community workshops can be forums for development ideas to design refuges that meet regular requirements of the community. This is particularly necessary if the refuge is a public building (Project Safe Haven, 2011b). Longstanding uncertainty around liability for evacuees using TVEB, and ethics of vertical evacuation (Ruch et al., 1991) have not been addressed during this research, and these issues must be fully explored in the future in the preparation of vertical evacuation guidelines. These are issues that will likely influence whether refuges are incorporated into public or private developments.

8.4 Education

8.4.1 Tsunami warning expectations and response

Surveys conducted in Napier reveal high awareness levels of tsunami hazard and appropriate actions to take in tsunami, consistent with previous surveys (Chapter 6). There remains a worrying level of confusion around the different warning dynamics in local, regional and distant-source events — namely the common expectation that an official warning will be issued via sirens, television or radio in the event of a local-source tsunami. As this is a long-standing problem in New

Zealand, there should be focussed research into the efficacy of currently-used natural warning messages and an investigation of whether more-effective messages could be developed.

Despite a high awareness of the role of earthquakes in tsunami generation, and of appropriate tsunami actions, when reporting intentions in a hypothetical local-source tsunami most survey respondents did not cite tsunami evacuation as an intended action after citing initial responses to ground shaking (Chapter 6). Earthquake and tsunami education in coastal areas should aim to promote a combined response in order that people act in response to tsunami in addition to the earthquake. Education should emphasise the importance of taking proactive evacuation decisions and the need to base one's actions on observations of the evolving hazard situation. For instance, a person's initial evacuation destination may not remain safe for the duration of the tsunami, therefore people should be prepared to move to a location further inland or higher, if required.

A bias towards short expected wave arrival times after ground shaking is encouraging, but a similar bias following official warnings, reported in Napier surveys, is a concern. The latter could lead to fatalism and a tendency for people to not attempt evacuation. Education should challenge these beliefs by focussing on improving understanding of warning dynamics, and emphasising that every step further inland means inundation will be less severe, and chances of survival increase.

8.4.2 Evacuation actions

New data on intended actions during or immediately after a local-source earthquake in New Zealand are consistent with actions reported in previous studies. Actions such as helping others, checking on and gathering family, and collecting or securing property are expected to cause delays in tsunami evacuation, although this study was unable to quantify the delay. Further research should aim to obtain timing information for intended actions, particularly with respect to situational context such as being at home or not, or evacuation occurring at night or on in the day. These data should be collected in contexts consistent with naturally-warned, short lead-time events, in order to be applicable to local-source tsunami. Identification of intended actions also enables development of education aiming to reduce evacuation delays. For example, ensuring shared knowledge of school evacuation plans between school staff, parents and children may mitigate the desire or need for parents to travel to a school to collect their children, which can endanger the safety of parents and children. Longitudinal studies should be used to track changes in intended behaviour and the efficacy of evacuation education messages.

Intended evacuation travel modes in Napier were relatively evenly split between vehicle and pedestrian evacuation. The surveys revealed an understanding in Napier that road damage may preclude the use of vehicles for evacuation. Tsunami education should continue to promote the message that pedestrian evacuation is most desirable. Murakami and Kashiwabara (2011) suggested that chosen travel mode in evacuations is influenced by a person's regular travel mode in non-emergency situations. Therefore, an increase in regular 'everyday' cycle use could increase the number of people using a bicycle to evacuate, expediting evacuation without increasing traffic congestion.

8.4.3 Vertical evacuation refuges

Education highlighting the availability and appropriate use of refuges is an important part of developing a vertical evacuation strategy. This is particularly true where vertical evacuation is a novel concept. Education should communicate the tsunami-resistance and design features of refuges, and their expected performance in events, to counter the reported primary concerns around the strength and height of a refuge (Section 6.6). The situations in which they are appropriate for use, i.e., following the occurrence of a long or strong earthquake, is a key message. The concept of vertical evacuation and use of refuges should be communicated in conjunction with ongoing education on tsunami hazard, warning expectations and evacuation actions to ensure its integration into tsunami evacuation practice and to communicate its role with respect preparedness activities. The initiation of discussions around vertical evacuation planning is likely to be the focus of media attention, triggering community discussion and interest, with potentially positive benefits for preparedness. The findings

Education should address concerns about evacuation into buildings such as those raised by respondents of the Napier surveys (Section 6.6), but also any new concerns that might be raised through community engagement. It is important that people have a good understanding of the likely time-frame of tsunami arrival after ground shaking in order to make informed judgements on the most appropriate destination. Destination choice should be informed through prior education and encouragement to prepare household/workplace evacuation plans. Education about vertical evacuation should cover the following points:

- Vertical evacuation refuges offer an alternative to the primary destinations of high-ground / inland, primarily in local-source tsunami but also regional-source events
- Vertical evacuation refuges do not guarantee safety, due to the risk of debris-strike or fire
- Benefits of vertical evacuation refuges (for non-emergency public-use, but also as encouragement for owners to facilitate use as refuge)
- Expectations of occupancy period and instructions to remain in the refuge until an official 'all-clear' message
- The welfare that is available at refuges in case of extended occupancy or emergency
- How specific refuges may be accessed for evacuation (particularly required for TVEB). The incorporation of refuges in evacuation exercises would be a benefit, as long as care is taken to prioritise evacuation to high ground over the use of vertical evacuation

- Structural strength and designation process of refuges

Consistent messaging for broadcast on television and radio should be developed to reiterate the availability and appropriate use of vertical evacuation refuges. Although it is preferable that the population has a high-level of evacuation training and pre-event education, broadcast messages would provide information for people seeking further information prior to evacuation in a local-source event. This messaging would reiterate the availability of vertical evacuation, but that the priority destination should be high ground. Once operational, vertical evacuation refuges should be incorporated into evacuation exercises as an education tool and to foster familiarity with the concept and refuge itself. Messages advising of vertical evacuation refuges could also be used in regional-source events.

8.5 Evacuation modelling for local-source tsunami

A method has been proposed to enhance current Geographic Information System (GIS)-based Least-Cost Distance (LCD) evacuation modelling methods. Temporally-variable population exposure, distributed travel speeds and uncertain evacuation delay time have been incorporated into assessment of pedestrian evacuation potential (Chapter 7). The additional components improve representation of variability in evacuation travel speeds in a population and explicitly account for actions that delay evacuation. The application of temporally-variable exposure is advantageous because it enables emergency managers to investigate the localised impacts of diurnal, weekly and seasonal changes in spatial distribution of evacuation demand. This information can be used to plan emergency response resources, conduct scenario-based casualty estimates, and optimise evacuation planning by derivation of maximum potential evacuation demand. Using the model, researchers and emergency managers are able to test different exposure scenarios and alter travel speed distributions, evacuation delay distributions, and spatially-variable compliance rates. These can be used to update evacuation estimates to assess the impacts of improved education on intended evacuation actions, and to set targets for education by ascertaining the reduction in evacuation time required to achieve certain life-safety targets.

The proposed method utilises commonly available exposure data and generic-format hazard data that can be generated by most numerical modelling codes, and implements standard GIS procedures in an open-source coding environment. The common nature of the data format and code provides potential for the evacuation method to provide a seamless tsunami inundation and evacuation modelling work-flow within the current tsunami modelling frameworks. The applicability of the method to other locations enables assessment of evacuation requirements for proposed and ongoing coastal development projects and proposed land-use changes in areas of known tsunami hazard. It could also benefit national asset and loss modelling if incorporated as an evacuation assessment module into the GNS Science/National Institute of Water and Atmospheric Research (NIWA) RiskScape software. The exposure model also has utility in national assessment of tsunami exposure, in conjunction with a proposed national evacuation mapping project, using attenuation rule-based analysis to establish tsunami evacuation zones for the whole of New Zealand.

The method has been demonstrated in the case of maximum credible local tsunami at Napier. It has shown the inter-suburb variability in evacuation demand throughout the day, and identified the areas of maximum potential evacuation demand. In doing so, it has confirmed the requirement for vertical evacuation in a number of suburbs of Napier, and provides the optimal locations for implementation of a limited number of refuges, in order to maximise their impact on life safety.

8.6 Dissemination of research findings to date

Research conducted during this doctoral project has been disseminated to practitioners and academics via peer-reviewed journal papers, GNS Science reports and conference presentations (Appendix I). Reconnaissance findings from Japan were presented to emergency management personnel and a wider audience of academics and practitioners in the United States, at Washington State Emergency Management Division in December 2011. Observations from Japan were also presented to catastrophe risk analysts at Aon Benfield, London and members of the UK Institution of Structural Engineers (IStructE) in London in 2011. The research has also been presented at several international conferences: American Geophysical Union 2011, European Geophysical Union 2012, Australasian Natural Hazards Management Conference 2012, and International Tsunami Symposium 2012. Findings on evacuation behaviour contributed to a distant-source tsunami evacuation planning workshop in Wellington, hosted by Wellington Regional Emergency Management Office (WREMO) and New Zealand Transport Agency (NZTA) in February 2013. The combined research findings were presented to CDEM and emergency services personnel during an evacuation planning workshop in Napier in March 2014.

8.7 Limitations and future work

8.7.1 Hazard modelling

Numerical modelling of inundation used deterministic source scenarios with instantaneous rupture and distributed slip. The maximum credible scenario was developed on the basis of the Great East Japan rupture pattern (section 4.6.2). While this method was the best available at the onset of this numerical modelling, it does not capture the potential for progressive rupture of the subduction margin, or account for uncertainty in slip distribution. Based on the analysis of Suppasri, Imamura, and Koshimura (2010), incorporating dynamic rupture of the Hikurangi subduction margin is likely to result in later arrival time and increased maximum amplitude (Section 4.6.2). Future iterations of this modelling should apply maximum credible source scenarios derived from the PTHA method used in the 2013 National Tsunami Hazard Review (Power, 2013), which approximates the effect of variable slip and uncertainties in the modelling approach.

Roughness coefficients were used to represent the impact of buildings and landcover on tsunami flow over land. However, the presence of buildings in the inundation zone channels tsunami flow through pathways, which can increase flow depth and velocity in narrow channels. In order to refine tsunami flow parameters in the urban area, high resolution inundation modelling should be conducted with explicit modelling of buildings and aim to produce onshore flow velocity estimates for the derivation of tsunami loads.

8.7.2 Evacuation refuges and behaviour

Investigations in Japan yielded qualitative data on the selection, designation and operation of TVE-B, the number of people saved in each community and observations on the types of damage sustained. Whilst civil protection officials were able to relay evacuation behaviours observed on 11 March 2011, and information about local vertical evacuation strategies, the research did not extend to direct interviewing of people who had used vertical evacuation buildings. Direct dialogue with building users may provide further insight than that gained from local officials.

Surveys of intended evacuation behaviour in local-source tsunami should be conducted more widely in New Zealand and internationally in order make cross-cultural comparisons. These should aim to quantify evacuation delay time with respect to specific evacuation preparation actions. The surveys conducted in Napier suggest demographic influence on intended evacuation behaviour, but consistent surveys should be extend this to a larger sample. The dynamics of group evacuation should be more thoroughly explored, for example through monitoring tsunami evacuation exercises in schools. Ultimately, intended and observed evacuation data could be developed into a database for experimental validation and bench-marking of evacuation models.

Further research should improve understanding of the impact that situational and environmental factors have on evacuation delay, compliance rate and travel mode and speed. This includes the impact of evacuation occurring in daylight or at night, in good or poor weather, whether evacuating as a group or alone, and where they are when the earthquake occurs. It is important to recognise that actual behaviour may differ from stated intentions. Data on intended actions should be validated against observations of evacuations, such as evacuee accounts of their actions and the actions of others. Recent progress has been made by including questions on evacuation actions in recent surveys about the 2010/2011 Canterbury Earthquakes and the 2013 Cook Strait earthquakes. Validation against data obtained by alternative methods is also desirable, for example the use of Computer-Assisted Personal Interviewing (CAPI), which is currently being utilised by other researchers to investigate tsunami evacuation behaviour. Intended behaviours should be monitored in longitudinal studies to assess the effectiveness of education that promotes immediate evacuation on feeling a long or strong earthquake, and the minimisation of evacuation delay action.

There should be greater focus in future work on mobility impairment due to physical (including mobility, visual, and auditory impairments) and intellectual disabilities. Disabilities can affect evacuation decision making and mobility in evacuation, resulting in an increase in required evacuation time. In addition to the disabled persons' live being endangered by the difficulties in evacuation, responders lives are also endangered in the process of helping disabled people to evacuate. In the modelling conducted here, it was not possible to determine the magnitude of impact of each type of disability registered in the census. There has been limited consideration of disabilities in previous evacuation modelling (e.g., Christensen and Sasaki, 2008; Manley and Kim, 2012) but this can be developed further in the tsunami context, with greater understanding of the needs and means to evacuate disabled people in a local-source tsunami. In designing vertical evacuation strategies, evacuation planning should include representation by the disabled community in order to meet the needs of that community. Refuge location could be optimised to minimise the distance that disabled people have to travel. With regards to refuge design, particular attention must be paid to ensuring adequate access and movement within the refuge for disabled occupants.

8.7.3 Evacuation modelling

Although the evacuation model applied here has enhanced existing modelling techniques, there remain several limitations in this component of the research. Improved data on evacuation behaviour (Section 8.7.2) would enable development of more robust evacuation delay curves. Improved data on diurnal activity patterns would improve the underlying temporally-variable exposure model. Future evacuation modelling should explicitly account for evacuation of people with disabilities, as discussed in the previous section.

The current method applied a static, maximum inundation hazard zone, which provides a conservative estimate of the available evacuation time. Incorporation of a dynamic representation of the inundation would account for the time taken for inundation to progress from the shoreline to its maximum extent (a further 32 min in Napier), which is likely to mitigate current estimates of evacuation time and reduce evacuation demand. Conversely, the modelling does not account for potential earthquake damage and disruption to road infrastructure. This could slow evacuation, increasing total evacuation time and estimated evacuation demand. Consideration of non-compliance, i.e., people choosing not to evacuate, would increase potential for casualties.

The assessment of evacuation time and evacuation demand should be validated against outputs of other GIS-based and Agent Based Model (ABM) approaches. Demographic influences on behaviour should be explored further in an ABM environment to determine the influence of individuals' evacuation dynamics on community-level evacuation success. ABM has an important role in evacuation modelling, complementing GIS-based approaches by providing greater detail on individual behaviour and interactions. They are particularly useful for testing the influence of different behaviours on evacuation potential, and for site-specific analysis in the design of vertical evacuation refuges.

8.8 Conclusions — Development of national vertical evacuation guidelines

This thesis has made a methodological contribution to evacuation simulation by proposing that evacuation estimates be based on distributed time components and variable exposure. It has enhanced the theoretical basis for evacuation planning by exploring evacuation behaviour specifically in the context of local-source tsunami and documenting the use of vertical evacuation in a major local-source tsunami. As stated in Section 1.3, the research contributes to the initial stages of evacuation planning, and must be incorporated into a wider framework in order to applied effectively. To utilise the data presented in this thesis and provide consistent guidance to local authorities on development of vertical evacuation strategies in New Zealand, it is proposed that a set of national vertical evacuation guidelines be developed. A nationally-consistent approach to the development of vertical evacuation strategies would support understanding of the benefits and issues of vertical evacuation and ensure that the development of vertical evacuation strategies aligns with international best-practice. Guidelines would support Local Authorities and CDEM Groups in development of vertical evacuation in conjunction with other evacuation provisions, and provide a single point of reference for all stake-holders concerned with evacuation planning, research and education.

The guidelines should frame the role of vertical evacuation in the context of existing guidance and standards for tsunami evacuation (MCDEM, 2008a,d), signage (MCDEM, 2008c), and messaging (MCDEM, 2010a) around earthquake response and local-source tsunami evacuation. The findings summarised in Sections 8.1–8.5 provide the knowledge base for the guidelines in terms of local-tsunami evacuation behaviour and required features of refuges. The thesis has used the city of Napier, New Zealand as a case study for tsunami inundation and evacuation modelling. There are of course site-specific aspects of this case study that may be distinct from other coastal sites where vertical evacuation may be considered for implementation. The findings of the studies at Napier can be generalised for use at other sites and in the development of guidelines, due to the generic methodologies applied, and the vertical evacuation location planning principles (i.e., use as a secondary evacuation option) are also applicable elsewhere. Structural guidelines should be based on forthcoming internationally-developed tsunami loading guidelines and be developed in the context of New Zealand building legislation. Further work would be required to satisfy the needs of a national guidelines with regards to ethics and liability for evacuees using vertical evacuation, and to address funding issues for public buildings, and incentives for development or incorporation of refuges into private buildings or on private land. Guidelines would also be required to provide guidance in the context of the Resource Management Act (RMA), New Zealand Coastal Policy Statement (NZCPS) and land-use planning regulation.

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APPENDICES

A. GNS SCIENCE REPORT: SCOPING STUDY FOR EVALUATING THE TSUNAMI VULNERABILITY OF NEW ZEALAND BUILDINGS FOR USE AS EVACUATION STRUCTURES

This appendix contains the published report *Leonard, G.S., Evans, N., Prasetya, G., Saunders, W.S.A., Pearse, L., Monastra, D. & Fraser, S.A. (2011). Scoping study for evaluating the tsunami vulnerability of New Zealand buildings for use as evacuation structures. Science Report 2011/036. GNS Science, Lower Hutt, New Zealand. p.37.* The report is included here for reference due to repeated references to it in the main text. Fraser contributed several recommendations based on observations from Japan and the United States to this report.

The report is included as electronic supplementary material on the enclosed CD.

B. EXCERPTS FROM EEFIT REPORT: THE M_W9.0 TŌHOKU EARTHQUAKE AND TSUNAMI OF 11TH MARCH 2011 — A FIELD REPORT BY EEFIT

This appendix presents text excerpted from *EEFIT, 2011. The M_W9.0 Tohoku earthquake and tsunami of 11th March 2011 - A field report by EEFIT, with permission of the Earthquake Engineering Field Investigation Team, UK (www.eefit.org.uk), [Online], http://www.istructe.org/resources-centre/technical-topic-areas/eefit/eefit-reports*. Two sections of the report are included: *7. Field observations on tsunami damage to buildings* and *10. Tsunami preparedness, warning and evacuation*. The text is presented in its original publication format.

The paper is included as electronic supplementary material on the enclosed CD.

C. BULLETIN OF EARTHQUAKE ENGINEERING: TSUNAMI DAMAGE TO COASTAL DEFENCES AND BUILDINGS IN THE MARCH 11TH 2011 M_W 9.0 GREAT EAST JAPAN EARTHQUAKE AND TSUNAMI

This appendix contains the published paper *Fraser, S.A., Raby, A., Pomonis, A., Goda, K., Chian, S.C., Macabuag, J., Offord, M., Saito, K. and Sammonds, P. (2013). Tsunami damage to coastal defences and buildings in the March 11th 2011 M_W9.0 Great East Japan earthquake and tsunami. Bulletin of Earthquake Engineering. 11 (1). p.pp. 205239.* The published work is the result of significant combined effort on the part of the Earthquake Engineering Field Investigation Team (EEFIT) team, therefore is not included as a main chapter in this thesis. However, the paper is included here for reference due to repeated references to it in the main text, and the work conducted by Fraser during this field investigation played an important role in informing subsequent research in this thesis.

The paper is included as electronic supplementary material on the enclosed CD.

D. GNS SCIENCE REPORT: TSUNAMI EVACUATION: LESSONS FROM THE GREAT EAST JAPAN EARTHQUAKE AND TSUNAMI OF MARCH 11TH 2011

This appendix contains the published report *Fraser, S.A., Leonard, G.S., Matsuo, I. & Murakami, H. (2012). Tsunami Evacuation: Lessons from the Great East Japan earthquake and tsunami of March 11th 2011. Science Report 2012/17. GNS Science, Lower Hutt, New Zealand. p.89.* This is the full report of fieldwork conducted in the Tōhoku region of Japan, in October 2011. This report presents data on tsunami warnings and evacuation additional to that presented in Chapter 5, but is referred to regularly in-text.

The report is included as electronic supplementary material on the enclosed CD.

E. GNS SCIENCE REPORT: VALIDATION OF A GIS-BASED ATTENUATION RULE FOR INDICATIVE TSUNAMI EVACUATION ZONE MAPPING

This appendix contains the published report *Fraser, S.A. & Power, W.L. (2013). Validation of a GIS-based attenuation rule for indicative tsunami evacuation zone mapping. Science Report 2013/02. GNS Science, Lower Hutt, New Zealand. p.21.* The report is included here for reference due to references to the methodology and validation in the main text.

The report is included as electronic supplementary material on the enclosed CD.

F. POTENTIAL GROUND SHAKING AT NAPIER DUE TO A M_W 9.0 SUBDUCTION ZONE EARTHQUAKE

Simulation of ground shaking and detailed analysis of earthquake-induced damage in the study area are outside of the scope of this research project. However, earthquake ground-shaking is acknowledged in the main text, as being an important factor in evacuation the process. The whole discussion of immediate evacuation response to natural warnings hinges on the fact that a local-source tsunamigenic earthquake would impart sufficient ground shaking so as to be too strong to stand up in, or lasting longer than a minute.

We can obtain a first-order approximation of this using the typical rupture velocity (0.7–2.8 kms^{-1} Suppasri, Imamura, and Koshimura, 2010) and the rupture length of the slip plane. The 2011 Great East Japan earthquake ruptured with a velocity of 1.5–2.5 kms^{-1}, with rupture duration of 150-160 s (Ammon et al., 2011).

In Table F.1 we provide a range of rupture length and rupture velocities to show the variation in estimates. These indicate a rupture duration of at least 2 min 0 s in any of these scenarios, which was the duration of the 400 km-long rupture of the 2004 Indian Ocean earthquake. We can therefore be confident that a rupture of this magnitude will be sufficiently long to for people to recognise the severity of the earthquake as larger than they have experienced previously.

In order to estimate ground shaking intensity, a Modified Mercalli Intensity (MMI) map was generated for rupture of the subduction zone. This was conducted using the finite source mode of the open-source software package *OpenSHA*. In order to test the appropriateness of site parameter assumptions made in the *OpenSHA* analysis, mapped isoseismals from two point-source events were compared using (a) *OpenSHA* and (b) the isoseismal equation developed from statistics of

Tab. F.1: Estimated rupture duration (s) from a range of rupture length (km) and rupture velocity (kms^{-1}) values. *Denotes the lower and upper limits of the M_W 9.0 earthquake applied in Chapter 4

Rupture length (km)	Rupture velocity 1.0 kms^{-1}	Rupture velocity 2.0 kms^{-1}	Rupture velocity 2.5 kms^{-1}
300	5 min 0 s	2 min 30 s	2 min 0 s
400	6 min 40 s	3 min 20 s	2 min 40 s
600	10 min 0 s	5 min 0 s	4 min 0 s
640	10 min 40 s	5 min 20 s	4 min 16 s
740	12 min 20 s	6 min 10 s	4 min 56 s

New Zealand earthquakes (Dowrick and Rhoades, 2005a).

First, isoseismal distance on the ellipse major-axis for each intensity isoseismal, using values for the main seismic region of New Zealand (Dowrick and Rhoades, 2005a, Table 6). Isoseismal distance on the minor axis is given by a separate equation (Dowrick and Rhoades, 2005b, p199). Isoseismals were plotted for M_W 9.0 and M_W 8.0 at 2 point-source locations: 2075681.85619 E, 5573458.20855 N; and 1897881.50059 E, 5391424.51115 N (New Zealand Transverse Mercator). The same point-sources were used to test the congruence with United States Geological Survey (USGS) Shakemap functions in *OpenSHA*. Based on the fact that *OpenSHA* is congruent with Dowrick for an M_W 9.0 point-source, a finite-source model was run using source dimensions from the National Seismic Hazard Map (NSHM) and the fault trace used in Fraser et al. (2014) — see framed box, below, for parameters. *OpenSHA* analysis was tested with different site classifications: BC, C, D, and CD. Wills Site Classification CD provided the best match, therefore shear velocity at Napier was assigned as Wills Classification CD (V_{s30} equivalent = 270–555ms^{-1})[1], which is supported by USGS V_{s30} mapping (Fig F.1). Testing of the assumed Rake angle between 50–70°, had no discernable impact on distribution of MMI.

This preliminary analysis suggests that Napier is likely to experience MMI VII-IX for the maximum credible local earthquake. This range of estimated intensity is loosely supported by the range observed in the 2011 Great East Japan earthquake (Fig F.3). At these ‘damaging’ to ‘destructive’ intensities people will experience difficulty standing, and damage would range from ‘damage to weak buildings’ at MMIVII, to damage to some moderate-strength building and destruction of many weak buildings (Table F.2).

The subduction zone rupture was approximated in *OpenSHA* with the following input:

IMR Param List:
IMR = ShakeMap (2003); Gaussian Truncation = None; Truncation Level = 2.0; Tectonic Region = Active Shallow Crust; Component = Average Horizontal; Std Dev Type = Total
IMT = MMI

Region Param List:
Min Longitude = 173.0; Max Longitude = 180.0; Min Latitude = -43.0; Max Latitude = -37.0; Grid Spacing = 0.1; Set Site Params = Apply same site parameter(s) to all locations; Wills Site Class = BC

[1] http://www.opensha.org/glossary-willsSiteClass

Custom Eqk Rupture Param List:
Rupture Type = Finite source rupture; Magnitude = 9.0; Rake = 90.0;
Set Fault Surface [Num. of Fault Trace Points = 11 ; Num. of Dips = 1 ;
Fault Latitudes [Lat-1 = -37.666 ; Lat-2 = -38.38 ; Lat-3 = -38.714 ; Lat-4 = -39.209 ; Lat-5 = -40.227 ; Lat-6 = -40.665 ; Lat-7 = -41.026 ; Lat-8 = -41.302 ; Lat-9 = -41.578 ; Lat-10 = -41.788 ; Lat-11 = -41.845] ;
Fault Longitudes [Lon-1 = 179.591 ; Lon-2 = 179.163 ; Lon-3 = 178.992 ; Lon-4 = 178.773 ; Lon-5 = 178.402 ; Lon-6 = 178.097 ; Lon-7 = 177.697 ; Lon-8 = 177.193 ; Lon-9 = 176.584 ; Lon-10 = 175.765 ; Lon-11 = 175.47] ;
Depths [Depth-1 = 5.0 ; Depth-2 = 24.0] ; Dips [Dip-1 = 9.0] ;
Grid Spacing = 1.0 ;
Finite Fault Type = Stirling's];
Set Hypocenter Location = false

TimeSpan Param List:
No Timespan exists for the selected Rupture

Calculation Param List:
Use Approximate Distance = true; Point-Source Correction = false; NSHMP Pt Src. Corr. = false

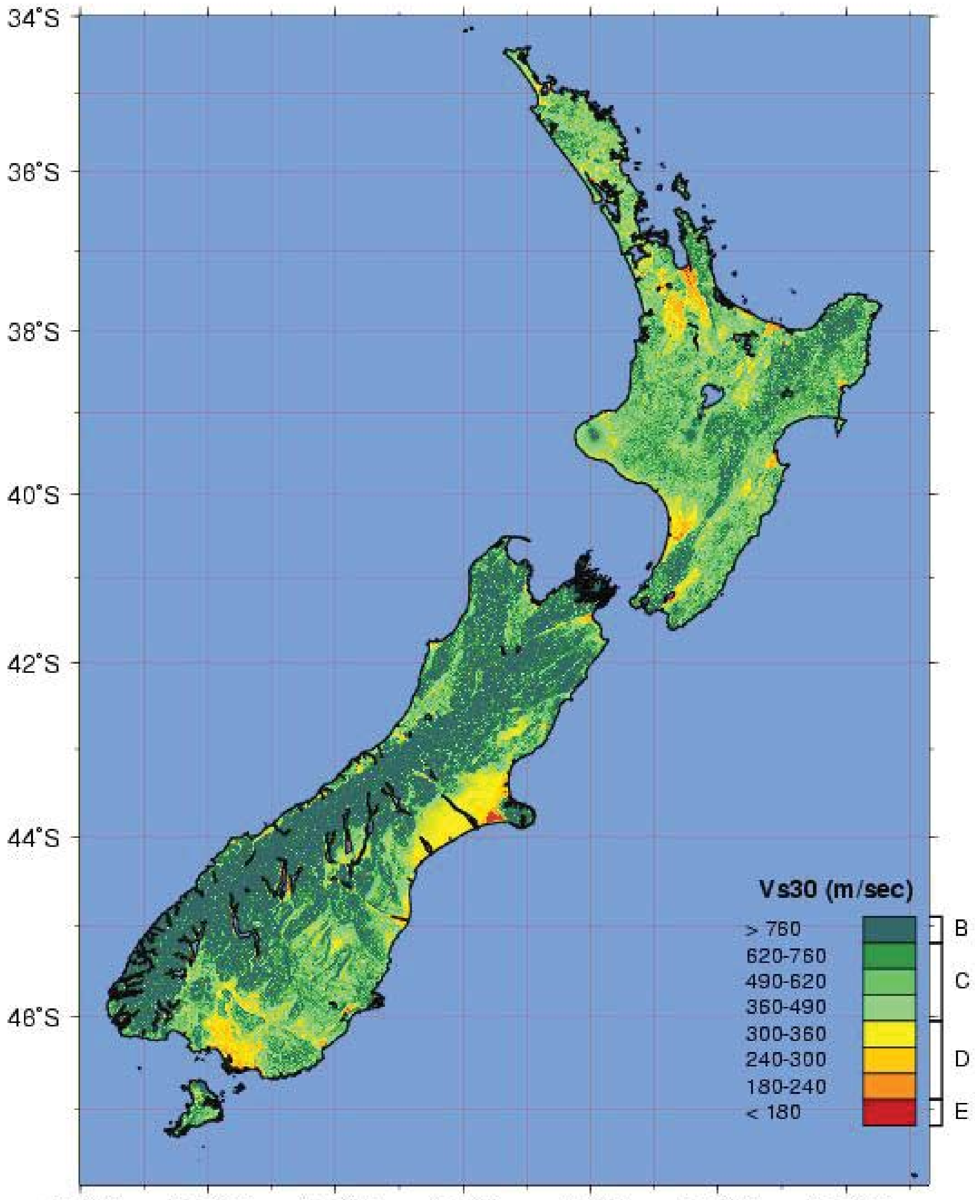


Fig. F.1: USGS Predefined Vs30 Mapping for New Zealand. Source: http://earthquake.usgs.gov/hazards/apps/vs30/predefined.php

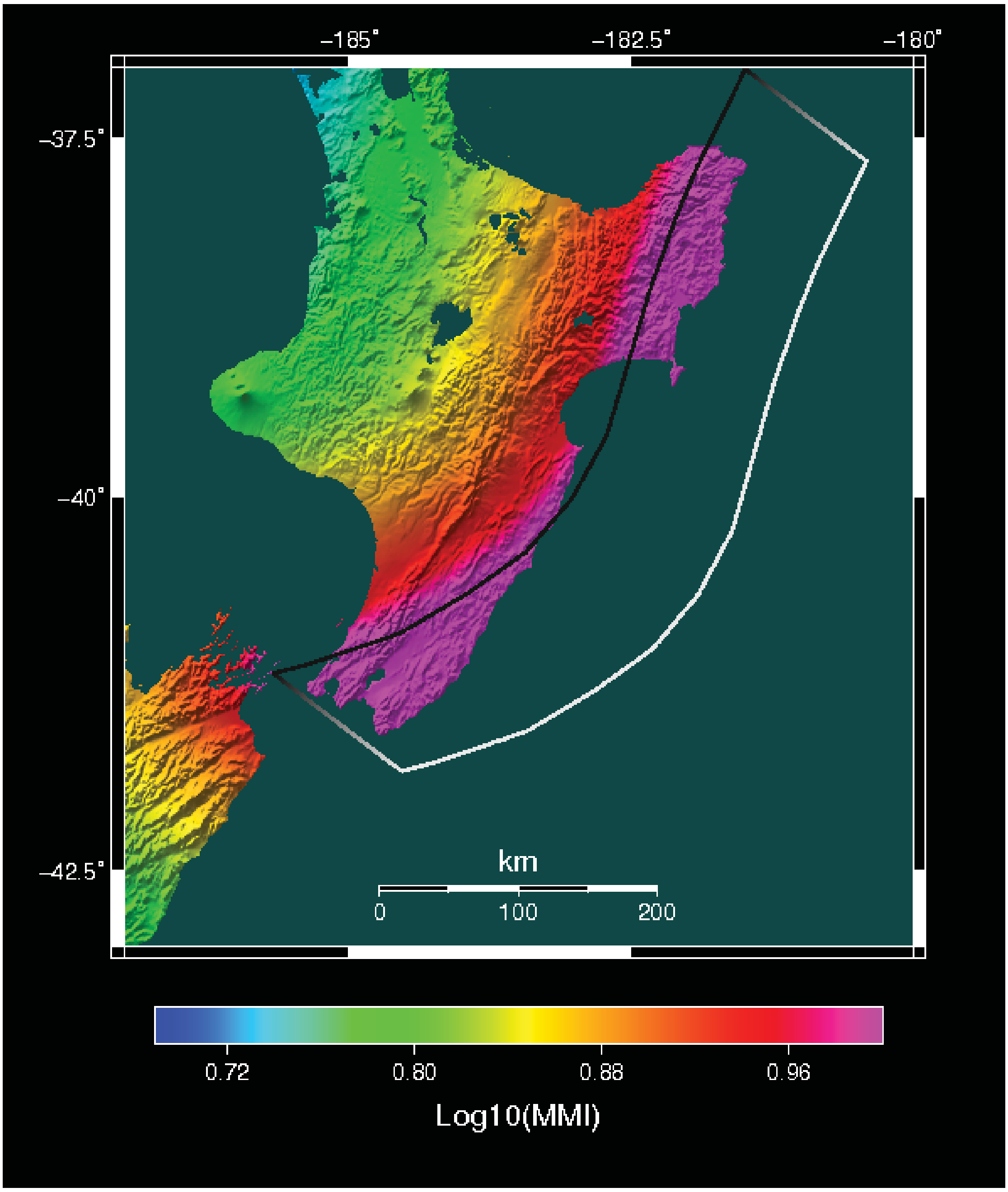
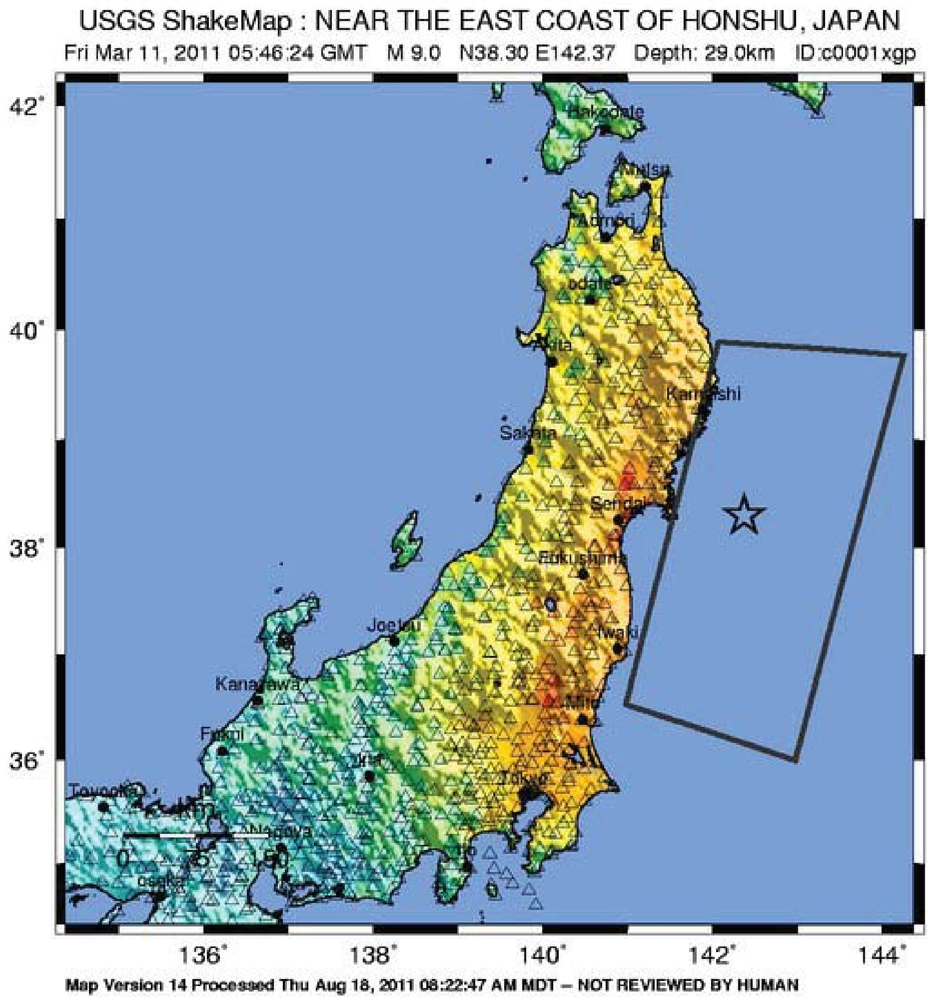


Fig. F.2: MMI ShakeMap produced for a M_W 9.0 earthquake finite-source model on the Hikurangi subduction margin, using *OpenSHA*. Log10(MMI) = 0.96 corresponds to MMI IX; Log10(MMI) = 0.96 corresponds to MMI VIII



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Fig. F.3: USGS ShakeMap estimated MMI for the 2011 Great East Japan earthquake. Source: http://earthquake.usgs.gov/earthquakes/shakemap/global/shake/c0001xgp/

Tab. F.2: The New Zealand MMI scale. Source: http://info.geonet.org.nz/display/quake/Shaking+Intensity.

Intensity	Modified Mercalli Level	Description
unnoticeable	MM 1 - imperceptible	Barely sensed only by a very few people.
	MM 2 - scarcely felt	Felt only by a few people at rest in houses or on upper floors.
weak	MM 3 - weak	Felt indoors as a light vibration. Hanging objects may swing slightly.
light	MM 4 - light	Generally noticed indoors, but not outside, as a moderate vibration or jolt. Light sleepers may be awakened. Walls may creak, and glassware, crockery, doors or windows rattle.
moderate	MM 5 - moderate	Generally felt outside and by almost everyone indoors. Most sleepers are awakened and a few people alarmed. Small objects are shifted or overturned, and pictures knock against the wall. Some glassware and crockery may break, and loosely secured doors may swing open and shut.
strong	MM 6 - strong	Felt by all. People and animals are alarmed, and many run outside. Walking steadily is difficult. Furniture and appliances may move on smooth surfaces, and objects fall from walls and shelves. Glassware and crockery break. Slight non-structural damage to buildings may occur.
severe	MM 7 - damaging	General alarm. People experience difficulty standing. Furniture and appliances are shifted. Substantial damage to fragile or unsecured objects. A few weak buildings are damaged.
	MM 8 - heavily damaging	Alarm may approach panic. A few buildings are damaged and some weak buildings are destroyed.
	MM 9 - destructive	Some buildings are damaged and many weak buildings are destroyed.
	MM 10 - very destructive	Many buildings are damaged and most weak buildings are destroyed.
	MM 11 - devastating	Most buildings are damaged and many buildings are destroyed.
	MM 12 - completely devastating	All buildings are damaged and most buildings are destroyed.

G. EVACUATION MODELLING PROCESS CHARTS

This appendix contains a series of flow charts that outline the exposure and evacuation modelling process. Figure G.1 demonstrates the original method of Wood and Schmidtlein (2012) and Wood and Schmidtlein (2013) to the point that it is augmented with the new process developed in the current research. The subsequent figures show portions of the analysis. Each figure follows on from the previous, i.e. the output of one process is used as the input in the following process.

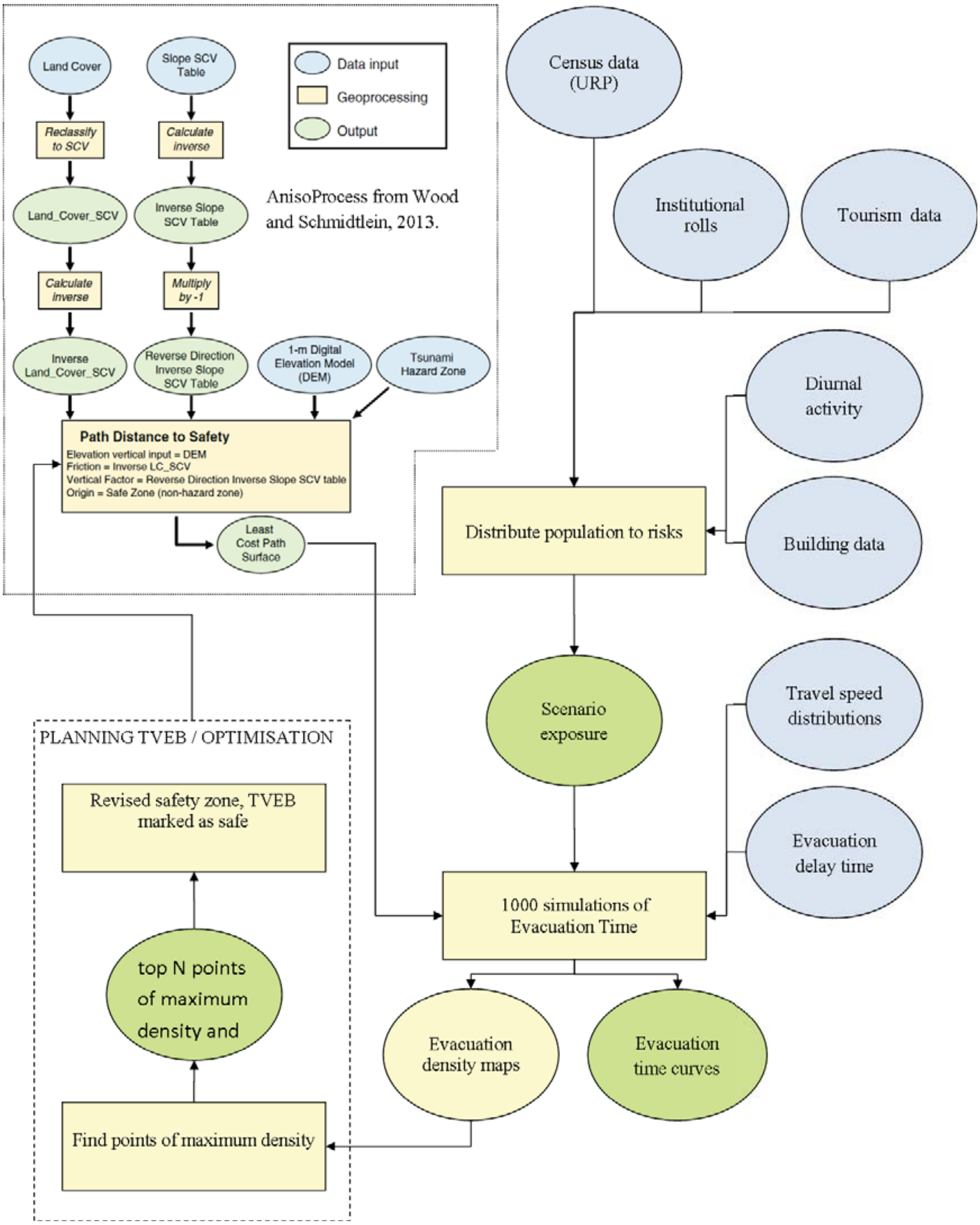


Fig. G.1: Model diagram of the model methodology developed in this thesis, which augments the method of Wood and Schmidtlein (2012, 2013).

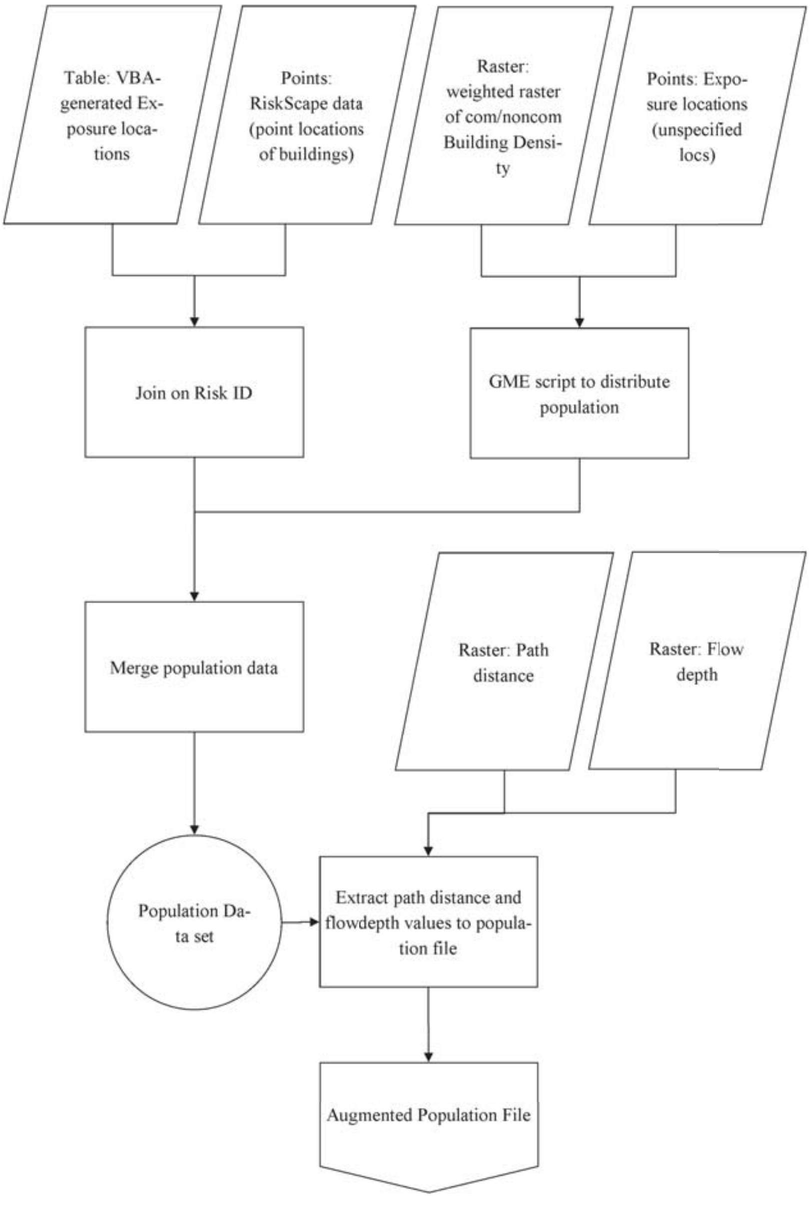


Fig. G.2: Flow chart indicating the process developed to generate distributed exposure datasets.

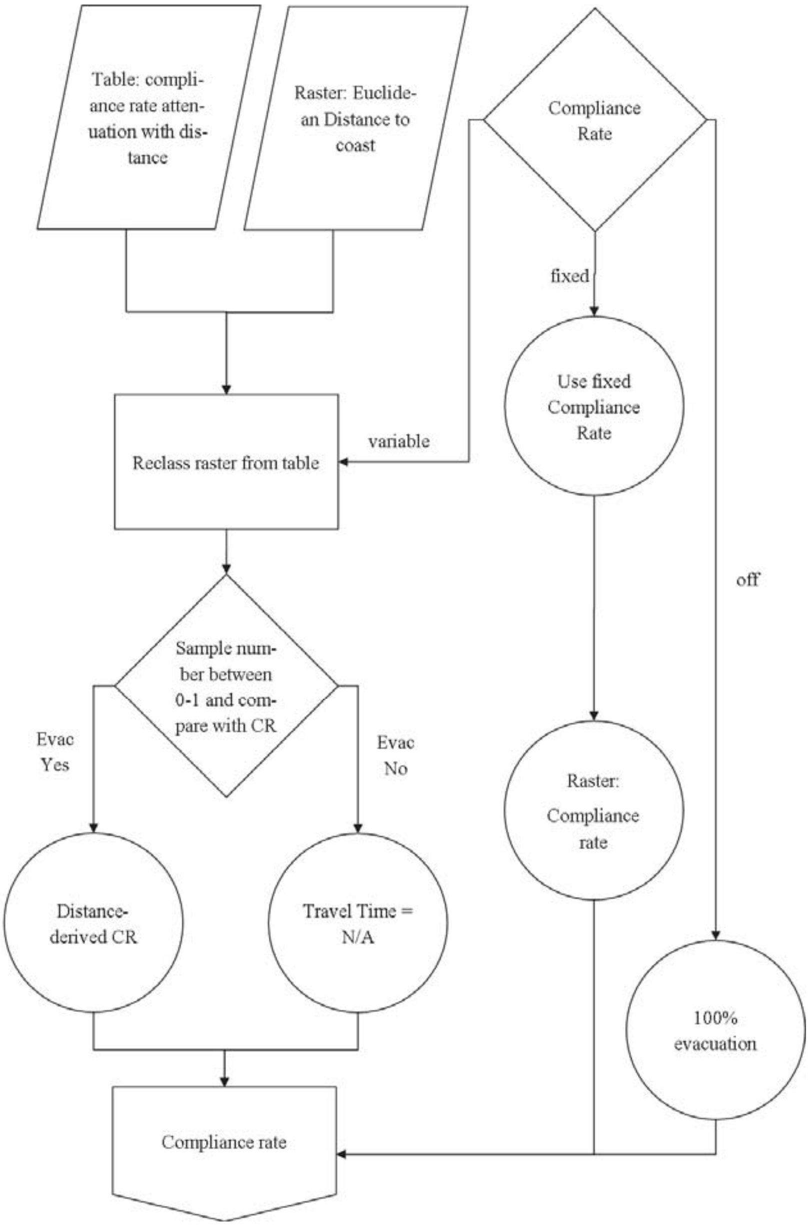


Fig. G.3: Flow chart indicating the process developed to generate evacuation compliance rate (CR).

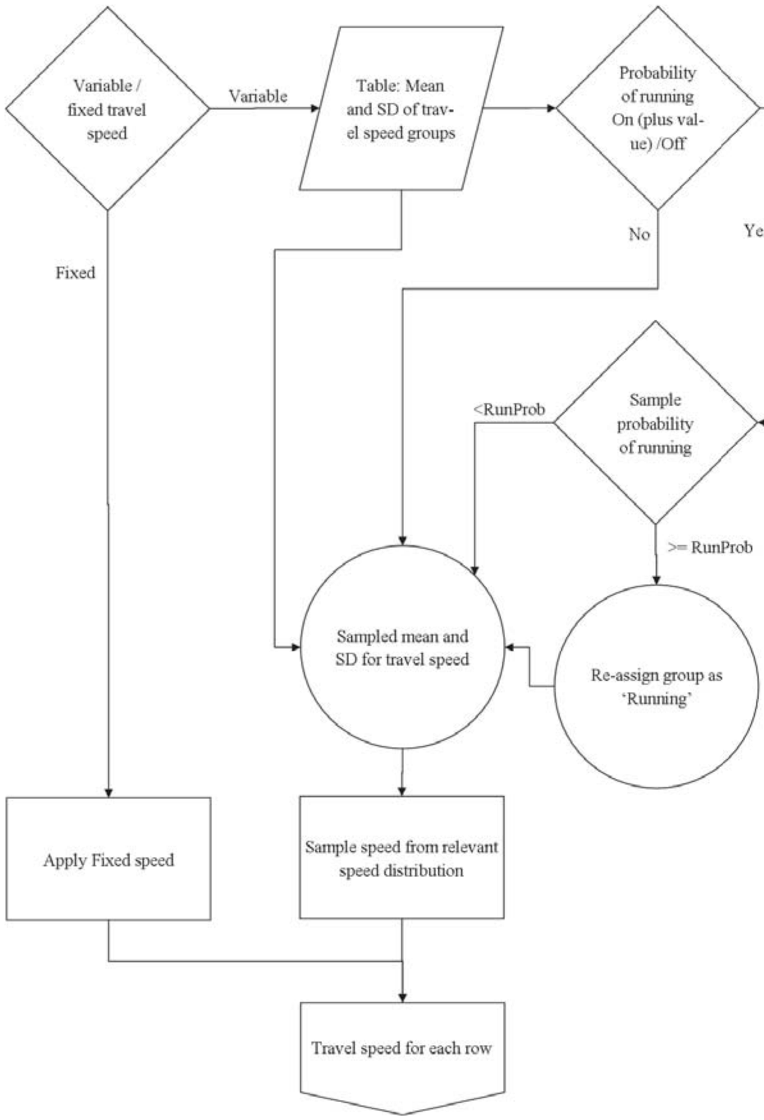


Fig. G.4: Flow chart indicating the process developed to apply variable travel speeds into methodology.

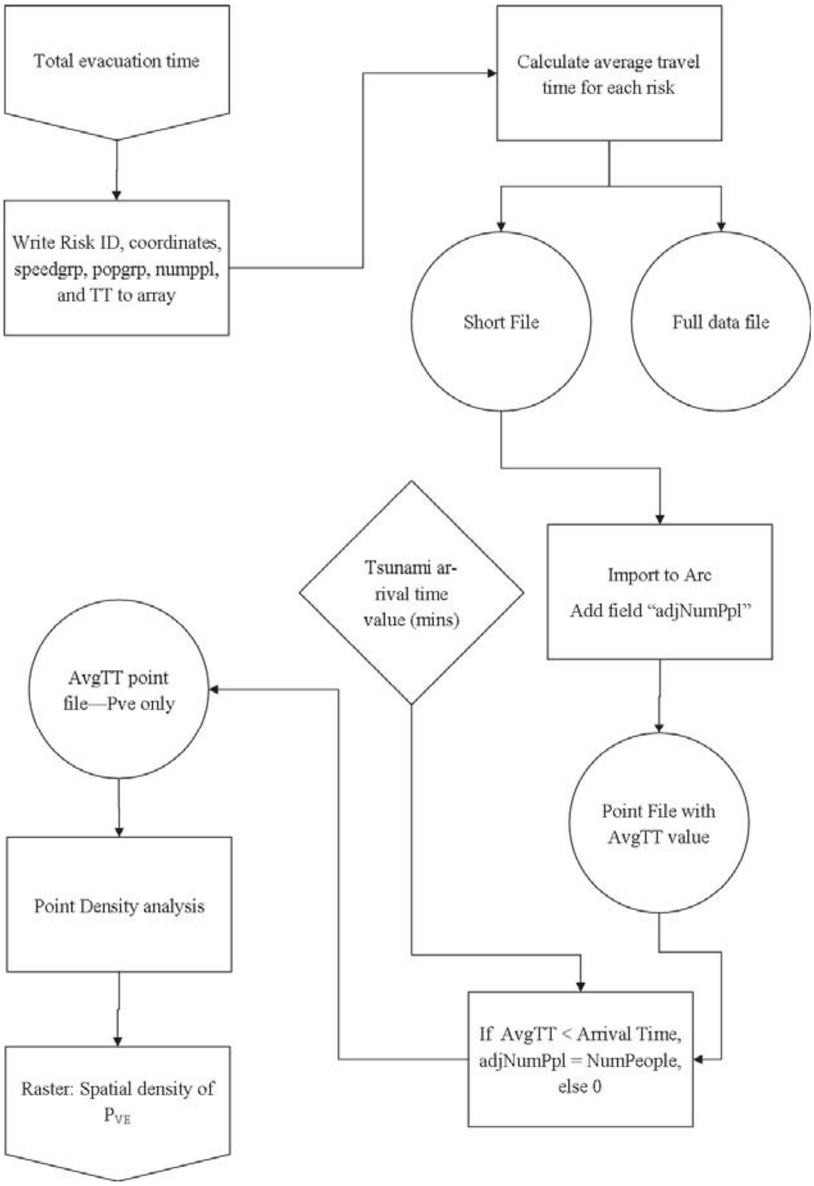


Fig. G.5: Flow chart indicating the process developed to generate P_{VE} raster.

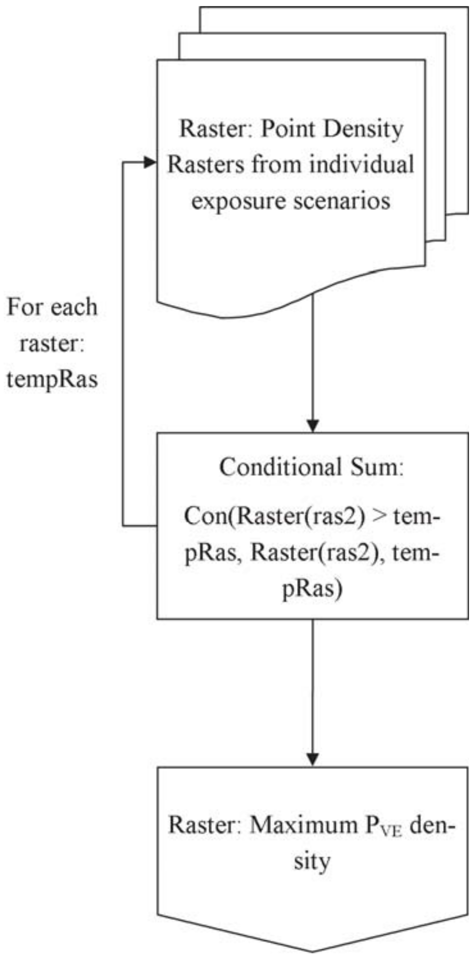


Fig. G.6: Flow chart indicating the process developed to generate Maximum P_{VE} raster

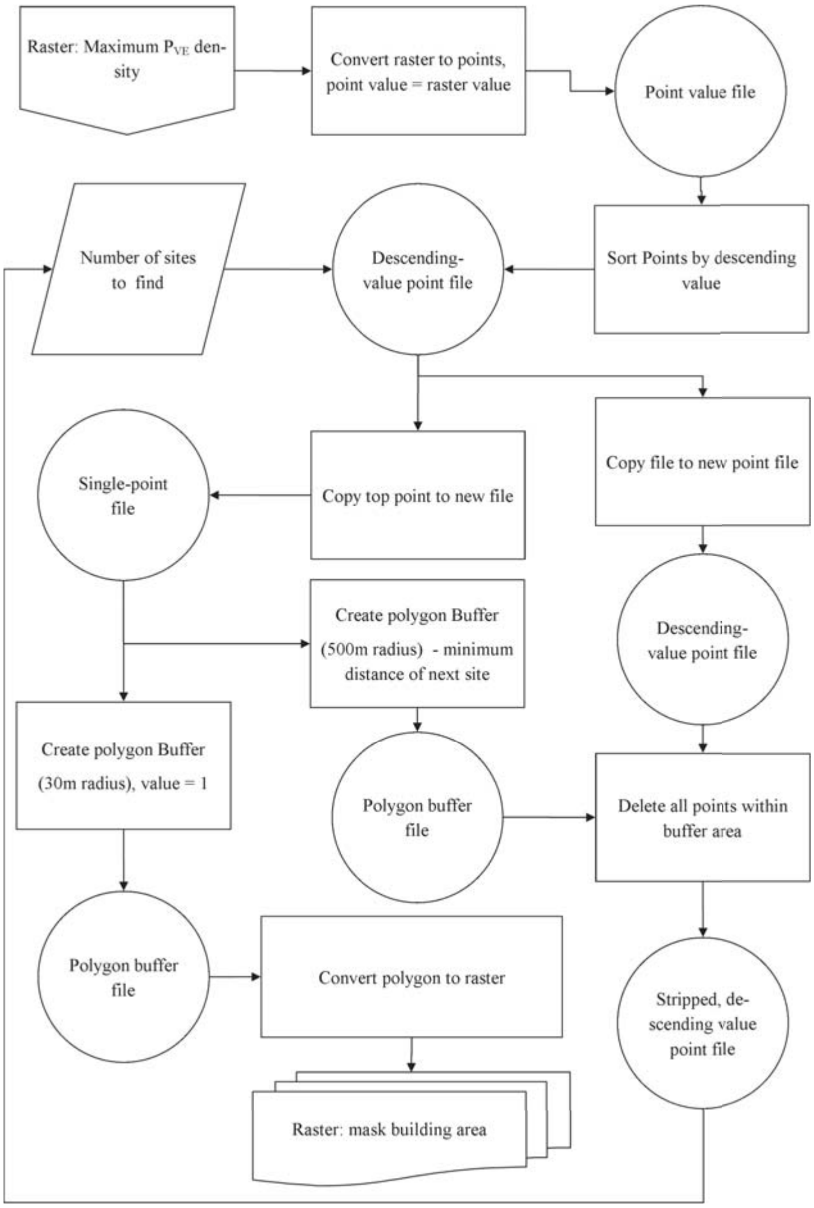


Fig. G.7: Flow chart indicating the process developed to develop a raster of safe zones at vertical evacuation facilities.

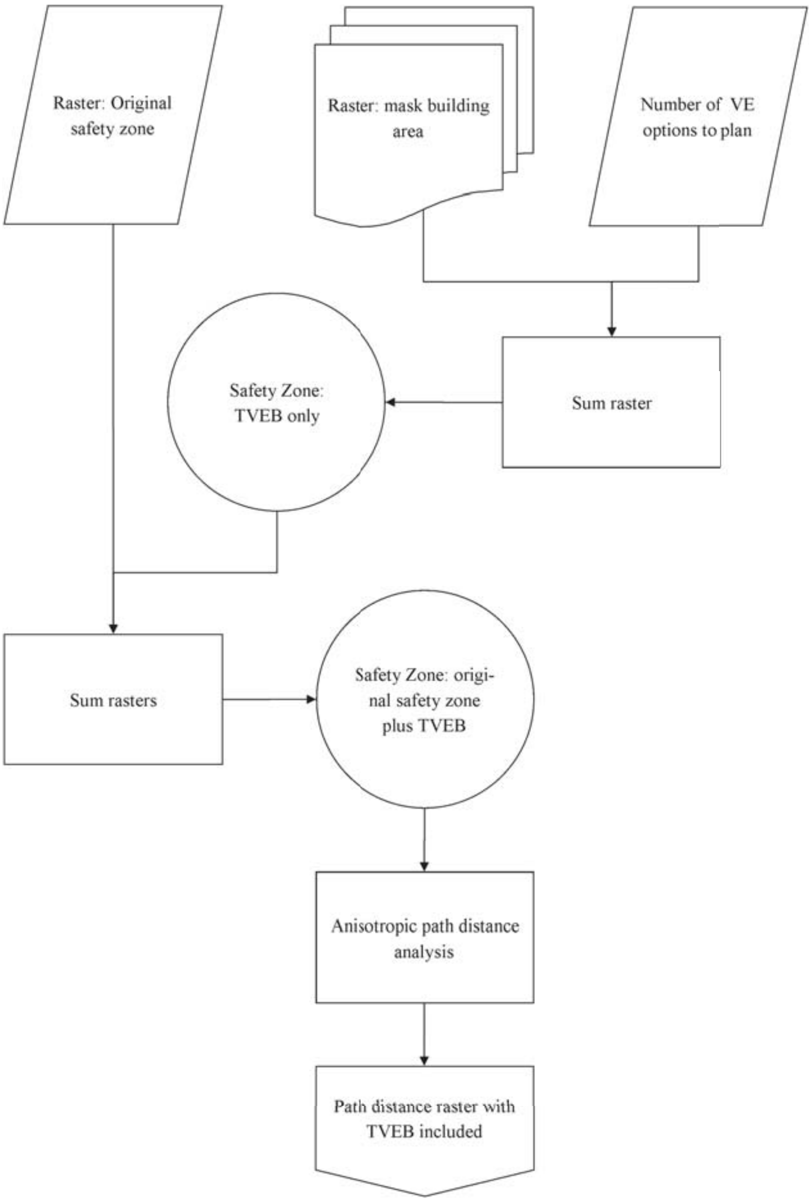


Fig. G.8: Flow chart indicating the process developed to develop a revised path distance raster including vertical evacuation buildings as safe zones. This raster is applied in further evacuation analyses to assess the impact of different combinations of TVEB sites.

H. CONTRIBUTION STATEMENTS FOR CO-AUTHORED PAPERS

In line with Massey University requirements, the following pages contain a statement of author contribution for each published work presented in the main body and appendices of this thesis. The statements are presented in the order that the corresponding publication appears in the thesis.

MASSEY UNIVERSITY
GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION TO DOCTORAL THESIS CONTAINING PUBLICATIONS

(To appear at the end of each thesis chapter/section/appendix submitted as an article/paper or collected as an appendix at the end of the thesis)

We, the candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of Candidate: Stuart Fraser

Name/Title of Principal Supervisor: Prof David Johnston

Name of Published Research Output and full reference:

Fraser, S.A., Power, W.L., Wang, X., Wallace, L., Mueller, C., Johnston, D.M. 2014. Inundation due to local tsunami at Napier, New Zealand. Natural Hazards. Volume 70, Issue 1, 415--445. doi: 10.1007/s11069-013-0820-x

In which Chapter is the Published Work: Chapter 4

Please indicate either:

- The percentage of the Published Work that was contributed by the candidate:

  and / or

- Describe the contribution that the candidate has made to the Published Work:

  The candidate designed the research methodology and conducted all numerical analysis that contributed to the published work, with technical advice from X. Wang, W. Power and D. Johnston. Earthquake source models were provided by L. Wallace; the candidate modified these where required and incorporated these into tsunami simulation. The candidate conducted the post-processing using tools developed in collaboration with C. Mueller, and analysis of simulations to develop the published output. The published work was written by the candidate with review and amendments provided by co-authors.

Candidate's Signature — 2 April 2014 (Date)

Principal Supervisor's signature — 2 April 2014 (Date)

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Name of Candidate: Stuart Fraser

Name/Title of Principal Supervisor: Prof David Johnston

Name of Published Research Output and full reference:

Fraser, S., Leonard, G. S., Murakami, H., and Matsuo, H. 2012. Tsunami Vertical Evacuation Buildings - Lessons for International Preparedness Following the 2011 Great East Japan Tsunami. *Journal of Disaster Research*, Vol.7, Special Issue, August 2012, pp. 446-457.

In which Chapter is the Published Work: Chapter 5

Please indicate either:

- The percentage of the Published Work that was contributed by the candidate:

  and / or

- Describe the contribution that the candidate has made to the Published Work:

The candidate designed the research methodology based on prior experience in the study area, with guidance from G. Leonard on interviewing strategy. The candidate and G. Leonard jointly conducted interviews and field work in collaboration with H. Murakami and I. Matsuo. The candidate analysed all interview data and wrote the published work, with review provided by all co-authors.

S Fraser

Candidate's Signature

2 April 2014
Date

D Johnston

Principal Supervisor's signature

2 April 2014
Date

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GRADUATE RESEARCH SCHOOL

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Name/Title of Principal Supervisor: Prof David Johnston

Name of Published Research Output and full reference:

Fraser, S. A.; Leonard, G.S.; Johnston, D.M. 2013. Intended evacuation behaviour in a local earthquake and tsunami at Napier, New Zealand, GNS Science Report 2013/26. 62p. Lower Hutt, New Zealand.

In which Chapter is the Published Work: Chapter 6

Please indicate either:

- The percentage of the Published Work that was contributed by the candidate:

  and / or

- the contribution that the candidate has made to the Published Work:

  The candidate designed the research methodology with advice from supervisors. The candidate conducted the field work, all data analysis and wrote the report, which was reviewed by supervisors.

SFraser

Candidate's Signature

2 April 2014
Date

DJohnston

Principal Supervisor's signature

2 April 2014
Date

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Name of Candidate: Stuart Fraser

Name/Title of Principal Supervisor: Prof David Johnston

Name of Published Research Output and full reference:

Fraser, S.A., Wood, N.J., Johnston, D.J., Leonard, G.S., Greening, P. and Rossetto, T.R. Variable population exposure and travel speeds in least-cost tsunami evacuation modelling. Submitted for publication in Natural Hazards and Earth Systems Science.

In which Chapter is the Published Work: Chapter 7

Please indicate either:

- The percentage of the Published Work that was contributed by the candidate:

  and / or

- Describe the contribution that the candidate has made to the Published Work:

Stuart Fraser (SF) proposed the research aims and developed the extensions to the anisotropic least-cost path distance methodology, which forms the basis for this analysis and was originally developed by N. Wood (NW) and his co-author in a previous paper. SF designed and developed the new exposure model. SF developed the Python code required to action the extensions to NW's original method, conducted the data analysis, and wrote the manuscript. NW provided technical advice and review, and thorough manuscript review and editing. All other co-authors provided methodological discussion and review of the manuscript.

SFraser

Candidate's Signature

11 April 2014
Date

DJohnston

Principal Supervisor's signature

11 April 2014
Date

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Name/Title of Principal Supervisor: Prof David Johnston

Name of Published Research Output and full reference:
Leonard, G. S.; Evans, N.; Prasetya, G.; Saunders, W.S.A.; Pearse, L.; Monastra, D. and Fraser, S. 2011. Scoping study for evaluating the tsunami vulnerability of New Zealand buildings for use as evacuation structures, GNS Science Report 2011/36 39 p.

In which Chapter is the Published Work: Appendix A
Please indicate either:

- The percentage of the Published Work that was contributed by the candidate:

  and / or

- Describe the contribution that the candidate has made to the Published Work:
  The candidate contributed observations of tsunami resilient buildings and vertical evacuation projects in Japan and the United States (section 3) and several recommendations (section 6) to the report, based on research in the Great East Japan tsunami and provided review of the report.

Candidate's Signature — 11 April 2014 (Date)

Principal Supervisor's signature — 11 April 2014 (Date)

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STATEMENT OF CONTRIBUTION TO DOCTORAL THESIS CONTAINING PUBLICATIONS

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Name of Candidate: Stuart Fraser

Name/Title of Principal Supervisor: Prof David Johnston

Name of Published Research Output and full reference:
EEFIT, 2011. The Mw9.0 Tohoku earthquake and tsunami of 11th March 2011 - A field report by EEFIT, Earthquake Engineering Field Investigation Team, The Institution of Structural Engineers, London, UK, [Online]. http://www.istructe.org/resources-centre/technical-topic-areas/eefit/eefit-reports.

In which Chapter is the Published Work: Appendix B

Please indicate either:

- The percentage of the Published Work that was contributed by the candidate:

  and / or

- Describe the contribution that the candidate has made to the Published Work:
  All authors contributed to field investigation design and planning. All authors conducted field investigation, analysed data and wrote report sections in their own area of interest/expertise. SF compiled and edited the research report. Specifically, Sections 7 and 10 of the report pertain to the research presented in this thesis. All authors contributed to general damage surveys. Stuart Fraser (SF) designed the detailed surveys in Kamaishi City (section 7.2.2, conducted by SF and Joshua Macabuag (JM)) and Kesennuma Town (section 7.2.5, conducted by SF). All authors contributed to Section 7, the majority of which was written by Antonios Pomonis, SF and JM. SF conducted specific surveys of buildings suitable for vertical evacuation and wrote section 10 ('Tsunami preparedness, warning and evacuation').

Candidate's Signature | 2 April 2014 Date

Principal Supervisor's signature | 2 April 2014 Date

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STATEMENT OF CONTRIBUTION
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We, the candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of Candidate: Stuart Fraser

Name/Title of Principal Supervisor: Prof David Johnston

Name of Published Research Output and full reference:
Stuart A. Fraser, Alison Raby, Antonios Pomonis, Katsuichiro Goda,Siau Chen Chian, Joshua Macabuag, Mark Offord, Keiko Saito, and Peter Sammonds. Tsunami damage to coastal defences and buildings in the March 11th 2011 Mw9.0 Great East Japan earthquake and tsunami. Bulletin of Earthquake Engineering, 11(1):205-239, 2013.

In which Chapter is the Published Work: Appendix C
Please indicate either:

- The percentage of the Published Work that was contributed by the candidate:

  and / or

- Describe the contribution that the candidate has made to the Published Work:
  Stuart Fraser (SF) compiled the paper based on the previously-published EEFIT report, with review and editing of the paper by all other authors. All authors contributed to field investigation design and planning. All authors conducted field investigation, data analysis/interpretation and writing of the field report in their respective research areas. Sections 5 and 6 of the paper pertain to the research conducted in this thesis. Stuart Fraser wrote section 5 ('Vertical evacuation structures'). All authors contributed to the general damage surveys documented in Section 6, which was written based on contributions to the report primarily by Antonios Pomonis, SF and Joshua Macabuag (JM). SF designed the detailed surveys in Kamaishi City (section 6.2, conducted by SF and JM) and Kesennuma Town (section 6.4, conducted by SF).

Candidate's Signature — 2 April 2014 (Date)

Principal Supervisor's signature — 2 April 2014 (Date)

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GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION
TO DOCTORAL THESIS CONTAINING PUBLICATIONS

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Name of Candidate: Stuart Fraser

Name/Title of Principal Supervisor: Prof David Johnston

Name of Published Research Output and full reference:

Fraser, S., Leonard, G.S., Matsuo, I., Murakami, H. 2012. *Tsunami Evacuation: Lessons from the Great East Japan earthquake and tsunami of March 11th 2011*. Lower Hutt: GNS Science. GNS Science Report 2012/17. 89p.

In which Chapter is the Published Work: Appendix D

Please indicate either:

- The percentage of the Published Work that was contributed by the candidate:

  and / or

- Describe the contribution that the candidate has made to the Published Work:

The candidate designed the research methodology based on prior experience in the study area, with guidance from G. Leonard on interviewing strategy. The candidate and G. Leonard jointly conducted interviews and field work in collaboration with H. Murakami and I. Matsuo, who also provided language translation. The candidate analysed all interview data and wrote the published work, with review provided by all co-authors.

S Fraser

Candidate's Signature

2 April 2014
Date

D Johnston

Principal Supervisor's signature

2 April 2014
Date

MASSEY UNIVERSITY
GRADUATE RESEARCH SCHOOL

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Name of Candidate: Stuart Fraser

Name/Title of Principal Supervisor: Prof David Johnston

Name of Published Research Output and full reference:

Fraser, S. A. and Power, W. L. 2013. *Validation of a GIS-based attenuation rule for indicative tsunami evacuation zone mapping*. Lower Hutt: GNS Science. GNS Science Report 2013/02. 17p.

In which Chapter is the Published Work: Appendix E

Please indicate either:

- The percentage of the Published Work that was contributed by the candidate:

  and / or

- the contribution that the candidate has made to the Published Work:

  The candidate applied a previously-developed research methodology to a new study area. The candidate sourced data, developed new digital elevation models, conducted the analysis and wrote the report. W. Power provided technical advice and review.

Candidate's Signature — 2 April 2014 Date

Principal Supervisor's signature — 2 April 2014 Date

I. PUBLICATIONS AUTHORED DURING THE COURSE OF THIS PHD

JOURNAL PUBLICATIONS

[1] S. A. Fraser, N. J. Wood, D. M. Johnston, G. S. Leonard, P. D. Greening, and T. Rossetto, “Variable population exposure and distributed travel speeds in least-cost tsunami evacuation modelling,” *Natural Hazards and Earth System Sciences*, vol. 14, no. 11, pp. 2975–2991, Nov. 2014. [Online]. Available: http://www.nat-hazards-earth-syst-sci.net/14/2975/2014/

[2] S. A. Fraser, W. L. Power, X. Wang, L. M. Wallace, C. Mueller, and D. M. Johnston, “Tsunami inundation in Napier, New Zealand, due to local earthquake sources,” *Natural Hazards*, vol. 70, no. 1, pp. 415–445, 2014.

[3] S. A. Fraser, G. S. Leonard, H. Murakami, and I. Matsuo, “Tsunami Vertical Evacuation Buildings — Lessons for International Preparedness Following the 2011 Great East Japan Tsunami,” *Journal of Disaster Research*, vol. 7, no. 7, pp. 446–457, 2012.

[4] S. A. Fraser, A. Raby, A. Pomonis, K. Goda, S. C. Chian, J. Macabuag, M. Offord, K. Saito, and P. Sammonds, “Tsunami damage to coastal defences and buildings in the March 11th 2011 Mw9.0 Great East Japan earthquake and tsunami,” *Bulletin of Earthquake Engineering*, vol. 11, no. 1, pp. 205–239, 2013.

[5] K. Goda, A. Pomonis, S. C. Chian, M. Offord, K. Saito, P. Sammonds, S. A. Fraser, A. Raby, and J. Macabuag, “Ground motion characteristics and shaking damage of the 11th March 2011 M w9.0 Great East Japan earthquake,” *Bulletin of Earthquake Engineering*, vol. 11, no. 1, pp. 141–170, Aug. 2013.

[6] S. Wilkinson, D. Grant, E. Williams, S. Paganoni, S. A. Fraser, D. Boon, A. Mason, and M. Free, “Observations and implications of damage from the magnitude Mw 6.3 Christchurch, New Zealand earthquake of 22 February 2011,” *Bulletin of Earthquake Engineering*, vol. 11, no. 1, pp. 107–140, Nov. 2013. [Online]. Available: http://www.springerlink.com/index/10.1007/s10518-012-9384-5

REPORTS

[1] S. A. Fraser, D. M. Johnston, and G. S. Leonard, "Intended evacuation behaviour in a local earthquake and tsunami at Napier, New Zealand," GNS Science, Lower Hutt, New Zealand, Science Report 2013/26, 2013.

[2] S. A. Fraser and W. L. Power, "Validation of a GIS-based attenuation rule for indicative tsunami evacuation zone mapping," GNS Science, Lower Hutt, New Zealand, Science Report 2013/02, 2013.

[3] S. A. Fraser, G. S. Leonard, I. Matsuo, and H. Murakami, "Tsunami Evacuation: Lessons from the Great East Japan earthquake and tsunami of March 11th 2011," GNS Science, Lower Hutt, New Zealand, Science Report 2012/17, 2012.

[4] G. S. Leonard, N. Evans, G. Prasetya, W. S. A. Saunders, L. Pearse, D. Monastra, and S. A. Fraser, "Scoping study for evaluating the tsunami vulnerability of New Zealand buildings for use as evacuation structures," GNS Science, Lower Hutt, New Zealand, Science Report 2011/036, 2011.

[5] EEFIT, "The Mw9.0 Tohoku earthquake and tsunami of 11th March 2011 - A field report by EEFIT," Earthquake Engineering Field Investigation Team, The Institution of Structural Engineers, London, UK, Field Report, 2011. [Online]. Available: http://www.istructe.org/resources-centre/technical-topic-areas/eefit/eefit-reports

[6] J. G. Beban, W. J. Cousins, X. Wang, and S. A. Fraser, "Modelling the evacuation rates required to achieve an acceptable level of health and safety risk in Te Tumu from the Variation to the Southern Kermadec Scenario," GNS Science, Lower Hutt, New Zealand, Consultancy Report 2012/291, 2012.

[7] G. S. Leonard, D. M. Johnston, C. E. Gregg, R. Garside, W. S. A. Saunders, J. S. Becker, and S. A. Fraser, "Evaluation and recommendations for tsunami

and lahar exercises in Washington State," GNS Science, Lower Hutt, New Zealand, Science Report 2011/32, 2011.

CONFERENCES

[1] S. A. Fraser, N. J. Wood, D. M. Johnston, and G. S. Leonard, "Simulation of local tsunami and evacuation of urban areas, informed by population exposure analysis and studies of tsunami evacuation behaviour." in *EGU General Assembly Conference Abstracts*, vol. 15, Vienna, Austria, 2013, p. 3635.

[2] S. A. Fraser, "The Role Of Tsunami Vertical Evacuation Buildings In The 2011 Great East Japan Tsunami, and Lessons For New Zealand," Presentation at the 6th Annual Australasian Natural Hazards Management Conference, 21-22 August 2012, Christchurch, New Zealand., 2012.

[3] S. A. Fraser, G. S. Leonard, D. M. Johnston, and P. Greening, "Potential for using mid to high-rise buildings as vertical evacuation structures in near-source earthquake and tsunami events," Poster presented at 5th Annual Australasian Natural Hazards Management Conference, 18th to 21st July 2011, Gold Coast, Australia. Awarded 3rd Prize in Student Poster Award., 2011.

[4] S. A. Fraser, G. S. Leonard, and D. M. Johnston, "Observations of vertical evacuation structures in the 2011 Tohoku earthquake and tsunami," Poster presented at 5th Annual Australasian Natural Hazards Management Conference, July 18-21 2011, Gold Coast, Australia., 2011.

[5] S. A. Fraser, G. S. Leonard, D. M. Johnston, and P. Greening, "Implications of the 11th March Tohoku tsunami on warning systems and vertical evacuation strategies," Poster presented at American Geophysical Union Conference, December 5-9 2011, San Francisco, United States., 2011.

[6] D. M. Johnston, W. S. A. Saunders, G. S. Leonard, J. Beban, K. Wright, and S. A. Fraser, "History of Tsunami Planning in New Zealand: 1960 to the present," in *UHPH_14: Landscapes and ecologies of urban and planning history, Proceedings of the 12th conference of the Australasian Urban History / Planning History Group*, M. Gjerde and E. Petrović, Eds. Wellington, New

Zealand: Australasian Urban History / Planning History Group and Victoria University of Wellington, 2014, pp. 361–372.

[7] D. M. Johnston, S. A. Fraser, G. S. Leonard, W. S. A. Saunders, and K. Wright, “Developing an effective community response to the next ”Great East Coast Subduction Zone Earthquake and Tsunami”,” White paper presented at GeoPRISMS - Planning Workshop for the New Zealand Primary Site, Wellington, New Zealand, April 15-17, 2013, 2013.

[8] G. S. Leonard and S. A. Fraser, “Developing an effective community response to the next subduction zone earthquake, East Coast, New Zealand,” Conference workshop convened at 6th Australasian Natural Hazards Management Conference, August 23 2012, Christchurch, New Zealand., 2012.

[9] C. Mueller, W. L. Power, S. A. Fraser, and X. Wang, “Towards a robust framework for Probabilistic Tsunami Hazard Assessment (PTHA) for local and regional tsunami in New Zealand,” in *EGU General Assembly Conference Abstracts*, vol. 15, Vienna, Austria, 2013, p. 3631.

[10] ——, “Towards a robust framework for Probabilistic Tsunami Hazard Assessment (PTHA) for local and mid-range Tsunami in New Zealand,” Abstract presented at Geoscience Society of New Zealand (GSNZ) Annual Conference, November 25-28 2012, Hamilton, New Zealand, 2012.

[11] H. Murakami, S. A. Fraser, G. S. Leonard, and I. Matsuo, “A Field Study on conditions and Roles of Tsunami Evacuation Buildings in the 2011 Tohoku Pacific Earthquake and Tsunami.” in *Joint Conference Proceedings: 9th International Conference on Urban Earthquake Engineering / 4th Asia Conference on Earthquake Engineering, March 6-8, 2012, Tokyo Institute of Technology.*, Tokyo, Japan, 2012.

[12] W. L. Power, C. Mueller, A. Barberopoulou, L. M. Wallace, X. Wang, and S. A. Fraser, “The New Zealand probabilistic tsunami hazard model (Invited),” Abstract NH24A-01 presented at 2012 Fall Meeting, AGU, San Francisco, Calif., 3-7 Dec, 2012.

[13] K. C. Wright, W. J. Cousins, G. S. Leonard, D. M. Johnston, and S. A. Fraser, “When engineering isnt enough planning for immediate evacuation in Wellington Region following major subduction zone earthquakes,” Poster paper #64 presented at 2013 NZSEE Conference, April 26-28 2013, Wellington, New Zealand., pp. 1–8, 2013.

[14] S. Chian, A. Pomonis, K. Saito, K. Goda, P. Sammonds, A. Raby, M. Offord, S. A. Fraser, and J. Macabuag, "Post Earthquake Field Investigation of the Mw9.0 Tohoku Earthquake of 11th March 2011," in *Proceedings of the 15th World Conference on Earthquake Engineering*, Lisbon, Portugal, 2012.

[15] K. Goda, S. C. Chian, S. A. Fraser, J. Macabuag, M. Offord, A. Pomonis, A. Raby, K. Saito, and P. Sammonds, "EEFIT field observations and lessons from the 11th March 2011 Mw9.0 Tohoku earthquake: ground motion and shaking damage," in *Proceedings of the 15th World Conference on Earthquake Engineering*, Lisbon, Portugal, 2012.