Institute of
GEOLOGICAL
& NUCLEAR
SCIENCES
Limited

Review of Tsunami Hazard and Risk in New Zealand

Confidential

Compiled by Kelvin Berryman

Client Report
2005/104
September 2005

Review of Tsunami Hazard and Risk in New Zealand

Compiled by Kelvin Berryman

Prepared for

Ministry of Civil Defence and Emergency Management

CONFIDENTIAL

Institute of Geological & Nuclear Sciences client report 2005/104
Project Number: 430W1154

The data presented in this Report are
available to GNS for other use from

January 2006

CONTENTS

EXECUTIVE SUMMARY

In this report we have examined all the likely sources of tsunami that can affect New Zealand, evaluating their potential to generate tsunami, the likely waves produced, and their impact on the principal urban centres around the New Zealand coastline. This review has been completed to the best possible standard, noting the short timeframe available and the requirement to use only existing information. A probabilistic methodology has been developed to achieve these objectives and is the first national-level probabilistic tsunami risk study undertaken in New Zealand. Few such studies have been attempted internationally, although many research groups are exploring probabilistic tsunami hazard models. Our decision to embark on a probabilistic approach was primarily to capture uncertainty in the calculations — identifying and amalgamating a range of viable alternative parameters and models is the most useful approach when attempting a hazard and risk estimate with weakly constrained data.

We have provided estimates of the tsunami hazard and risk, i.e., the probability that various localities will experience tsunami, and the likely losses in terms of the cost of damage, lives lost and injuries caused.

Identification of the sources of possible earthquake-generated tsunami has been careful and exhaustive, and every effort has been made to assign appropriate parameters to them in terms of magnitudes and recurrence intervals. But the seismological and geological data are limited so there are large uncertainties. Where possible, we have used historical and paleotsunami data to validate source models. The possibility of landslide and volcano generated tsunami have also been given close consideration, but these sources do not lend themselves to the empirical approach that has been required for this report. The contribution from earthquake-induced landsliding to tsunami risk is already incorporated within the Japanese data we used to derive the tsunami propagation relationship, but there may be rare cases of landslide-generated tsunami without an earthquake trigger. The risk from volcanic sources is partly mitigated by the long lead time of weeks or months that can be anticipated for some volcano sources and very dangerous volcanic sources are very infrequent. Explicit numerical modelling of both landslide and volcano-generated tsunami is recommended as a future activity.

The empirical relationships that relate tsunami height at source to earthquake magnitude, and subsequent propagation to both nearby and distant shores, have significant uncertainty. We have, in part, been able to place formal statistical uncertainties on the relationships and, from historical and paleotsunami information, we have sought to validate the empirical approach. However uncertainties remain high, and this is indicated by the wide range in the risk parameters calculated from the probabilistic modelling.

A GIS approach to tsunami inundation and loss modelling has been adopted for this project as the most effective way to complete a national review with existing data. Embedded within the GIS are empirical relationships derived from international data. There are substantial uncertainties involved in all of these components leading to loss estimation, but we believe we have been consistent in our analysis procedures, so that the range of loss estimates is a realistic representation of the uncertainty.

Limitations aside, the study shows that the ongoing risk from tsunami in New Zealand is significant, possibly rather higher than many people may realise. New Zealand has some experience of tsunami in the historical past, but few lives have been lost and damage to property and infrastructure has been modest. However, the large historical tsunami events that impacted New Zealand occurred when shoreline development was very modest by comparison with the present, so the fragility is now much greater.

Our study has not allowed for the possibility that there may be an effective warning before the arrival of a tsunami, and risk calculations have been made assuming night-time population characteristics, except for individual risk where we have assumed people are exposed for one half of the time. Warning systems will no doubt reduce deaths and injuries, so the estimates of casualties we present in this report are essentially "worst-case". Warning systems will not, of course, change in any significant way the estimated amount of property damage.

On a national basis we have been able to make a comparison with direct losses from earthquakes, which we have modelled previously. In summary, the median estimates of damage to property from tsunami is about twice what we expect from earthquakes with similar return period, and the deaths and injuries are many times more. However, the estimates for tsunami losses have great uncertainty, so the differences between earthquake and tsunami risk may be much greater or smaller than is apparent from median estimates. There is commonly a factor of ten difference in the loss estimate at the 68% confidence interval. Again note that the tsunami deaths and injuries will be reduced through effective warnings.

We have calculated the range in wave height of tsunami at the shoreline for 19 of the principal urban areas around the coast and, based on other considerations, have developed a map of estimated "best estimate" wave height for a 500 year return period for the whole country. We present this in Figure E1. We emphasise that this map is presented as indicative only and is in several parts based on judgement rather than calculation. Nevertheless, it does indicate a major variation in the tsunami hazard around New Zealand with the greatest hazard along the east coasts of both North and South Islands, and in Northland and Coromandel. Estimates for West Coast, South Island are quite uncertain, and no estimate is made for the Chatham Islands although, from historical records, this appears to be exposed to a greater hazard than any mainland site.

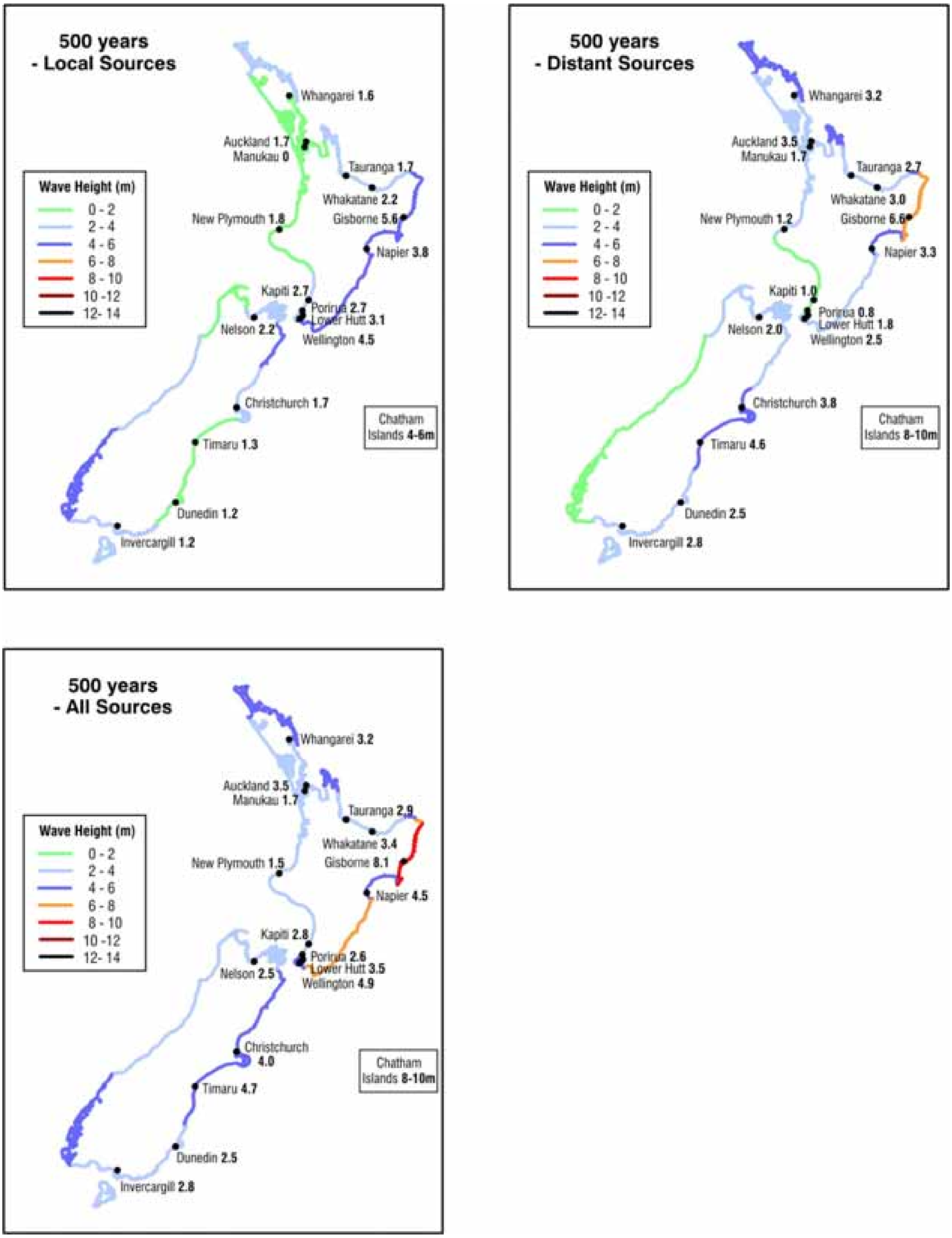


Figure E1 Generalised estimate of tsunami hazard in New Zealand expressed as expected mean wave height above mean sea level at the shore for 500-year return period. Significantly higher or lower water elevations may occur locally. These maps should not be used for site-specific assessments.

The national risk, in terms of mortality in the 19 urban centres assessed in this study, for a 500-year return period event (approximately 10% probability of occurrence in 50 years, or annual probability of about 0.2%) is shown in Table E1. This risk arises from losses in many towns and cities in New Zealand, but is predominantly from those along the east coasts of the North and South Islands as a result of large earthquakes in South America (a significant contribution to losses in all except two urban centres and accounting for about 60% of the total deaths) or along the Hikurangi subduction margin of the eastern North Island (a significant contribution to losses in about half of the urban centres and accounting for about 34% of the total deaths). Offshore local faults make a significant contribution to tsunami losses in about 20% of the urban centres and account for 5% of total deaths. In all of the highest risk centres, tsunami from local sources, either the Hikurangi subduction zone or local offshore faults, make a major contribution to the losses (39% of total at median estimate). Regional sources make almost no contribution to losses for the 500 year return period in the urban areas assessed, although they are expected to be relatively more important in the far north of the North Island (see Figure E1). We also note that local sources have <1 hr travel time to many nearby coastal sites, but they become regional in their travel time (1-3 hrs) for more distant parts of the coast. This is an important consideration for warning systems for local source tsunami, and applies particularly to sources in the Hikurangi subduction margin and thus to Bay of Plenty and the east coast of New Zealand. This is discussed further in the Preparedness Report.

Table E1 Ranking of losses (mortality) and tsunami sources for 500 year return period (10% probability in 50 years).

ranking of 10 centres according to mortality	**estimated deaths** low	median	high	**predominant tsunami sources**
Gisborne	110	440	2100	global ≈ local
Napier/Hastings	69	320	1300	local > global
Christchurch	60	280	1500	global » local
Wellington region	15	188	1678	local » global
Dunedin	16	160	920	global » local
Auckland region	24	122	519	almost entirely global
Whakatane	20	74	210	global » local
Tauranga	11	51	260	global » local
Timaru	8	24	76	almost entirely global
Nelson	5	10	27	local » global
National	**2900**	**5500**	**10,000**	**global > local » regional**

Note: Values assume no warning and are based on night-time population data. The national figures are complicated functions of those for the individual locations, not simple summations. National totals are aggregated for each individual event, so it is the frequency of occurrence of losses that are aggregated to the national total.

1.0 INTRODUCTION

1.1 Scope of this report

Following the disastrous tsunami in the Indian Ocean on December 26 2004, the New Zealand Government resolved to consider the risk of such events in New Zealand. The Director of Civil Defence and Emergency Management was required to develop a national picture of the risk of tsunami for New Zealand, the consequences, and New Zealand's preparedness to deal with these eventualities.

The Institute of Geological & Nuclear Sciences (GNS) was commissioned by the Ministry of Civil Defence and Emergency Management (MCDEM) to provide two reports, the first, known as the Science Report (this report) summarising the current state of knowledge of tsunami and using that knowledge to assess the level of risk at a national and regional level. The Institute has consulted widely and subcontracted elements of the work to NIWA, Waikato University, University of Auckland, and Barnett & McMurray Ltd. The Terms of Reference for the Science report were to:

- Review current and historical knowledge, including consideration of distant, regional and near source tsunami hazard and risk to communities for New Zealand;
- Identify areas where the current knowledge has significant limitations; and
- Present the findings in an easily understood and accessible manner for a wide variety of users, including non-specialists.

The scope of work, and methodologies utilised, were reviewed and advised by a Steering Group comprising representatives from MCDEM, Department of Prime Minister & Cabinet (DPMC), and the Ministry of Research Science & Technology (MoRST).

This report to MCDEM is a synthesis of available data as to the hazard and risk of distant-, regional- and local-source tsunami in New Zealand. It includes existing data sets on historic and geologically-derived information on the occurrence of tsunami, together with significant new numerical modelling and calculations of risk. It identifies gaps in knowledge towards which future research can be directed.

A second report, known as the Preparedness Report, reviews the current level of preparedness in New Zealand and compares this with the levels of risk derived in this report. The Preparedness Report also recommends measures for improving national and regional management of tsunami risk.

Risk can be measured in terms of casualties, direct economic loses, indirect (follow-on) economic losses due to business interruption, or wider social impact. For this report, the scope of the risk assessment has been limited to deaths, injuries, and the cost of damage to buildings, both domestic and commercial. Consequently, the emphasis has been on major coastal population centres (Table 1.1). The smallest centre incorporated is Timaru with a population of about 26,000. Because of limited time to complete the study not all coastal urban centres have been included and the study has not addressed issues of transient summertime populations, or overseas tourists, in coastal areas. Towns on the West Coast of the South Island have not been incorporated in the risk assessment for two reasons: firstly the population is low on the West Coast, and secondly the major source of damaging tsunami may be from nearby underwater landslides, for which there is inadequate knowledge to inform a hazard model (see Section 5.3.2 for more discussion).

Other simplifications to the risk modelling include the use of night-time population data, and an assumption that significant losses do not begin until the height of the water at the beach is 2 m or more above normal tide levels. The loss calculations are limited to a maximum return period of 2500 years, broadly consistent with the expectation that the provisions of the Building Act (2004), through reference to the New Zealand Loading Standard, AS/NZS 1170, maintain life safety up to approximately a 2500 year return period event.

It must be stressed that this first report looks at risk (in terms of casualties) assuming there is no effective warning of the event or no self-evacuation. This means that, although the level of risk may appear high, it can be significantly reduced by appropriate means. These issues are tackled in the Preparedness Report.

Table 1.1 Population centres considered in the study

City	Population
Whangarei	46,000
North Shore	205,000
Waitakere	186,000
Auckland	415,000
Manukau	317,000 (split into Manukau & Waitemata harbours)
Tauranga	95,000
Whakatane	34,000
New Plymouth	48,000
Gisborne	31,000
Napier/Hastings	100,000
Kapiti	33,000
Porirua	50,000
Lower Hutt	100,000
Wellington	179,000
Nelson	53,000
Christchurch	334,000
Dunedin	107,000
Timaru	26,000
Invercargill	46,000

Note – Wanganui, with a population of c. 39,000 has been excluded because no digital elevation model could be obtained for that city.

1.2 Contributors

Many people have worked on this project. The project has been divided into a series of tasks, approximately coinciding with major chapters of this report. The following researchers have contributed in the following tasks:

A. Existing tsunami datasets
   - (i) Historical – Gaye Downes (GNS), Willem de Lange (Waikato University)
   - (ii) Paleotsunami – Ursula Cochran & Kelvin Berryman (GNS), James Goff (NIWA), Scott Nichol (University of Auckland).
   - (iii) Numerical Modelling – William Power (GNS), Willem de Lange (Waikato University), Roy Walters (NIWA).

B. Tsunami source identification from
   - (i) Earthquake – Gaye Downes, Terry Webb, Kelvin Berryman, William Power, Martin Reyners, Russell Robinson, Mark Stirling, Laura Wallace, John Beavan, Rob Langridge (GNS), Phil Barnes & Geoffroy Lamarche (NIWA).
   - (ii) Landslide - Phil Barnes, Geoffroy Lamarche, Arne Pallentin (NIWA), Mauri McSaveney & Nick Perrin (GNS)
   - (iii) Volcanic Eruption – Ian Wright (NIWA), Willem de Lange (Waikato University)
   - (iv) Meteor Impact – Mauri McSaveney (GNS)

C. Tsunami propagation from source to site
   – William Power (GNS)

D. Inundation Modelling
   – Dave Heron, Biljana Lukovic, Mauri McSaveney (GNS), Alistair Barnett (Barnett & McMurray Ltd), Doug Ramsay (NIWA)

E. Asset Registers
   – Jim Cousins (GNS)

F. Fragility Modelling
   – Andrew King, Jim Cousins, Dave Heron, Mauri McSaveney (GNS), Doug Ramsay (NIWA)

G. Probabilistic Modelling
   – Mark Stirling, Warwick Smith, Kelvin Berryman, Terry Webb, William Power (GNS)

H. Risk Calculations
   – Warwick Smith & Jim Cousins (GNS)

I. Project Management & Report Preparation
   – Kelvin Berryman, Terry Webb, Hannah Brackley, Jane Forsyth, Sue Hatfield, Carolyn Hume, and Penny Murray (GNS).

1.3 Structure of this report

In the *Tsunami Basics* section of this report (Section 2) we describe what tsunami are, how they are generated, and what damage they can do. In the following section on historical and paleotsunami (Section 3) we present the current state of knowledge about tsunami that have occurred in our relatively recent recorded history and earlier tsunami that have left evidence in the form of sedimentary deposits.

Historical data are quite inadequate in terms of getting an accurate picture of risk and so we have used an approach that relies on empirical modelling informed by the historical data both from New Zealand and overseas. The methodology is explained in Section 4 and involves characterising tsunami sources that can affect New Zealand (Section 5), tsunami propagation across the oceans (Section 6), and inundation at the coast (Section 7).

Risk is calculated in terms of deaths, injuries and cost of damage to buildings. To do this, we consider the population and assets likely to be inundated by tsunami, together with their fragility to such inundation (Section 8).

Finally we present our results in terms of the risk at major population centres (Section 9) with final conclusions in Section 10. References are listed in Section 11, and in Section 12 we present a series of recommendations for further research to address the major areas of uncertainty in tsunami risk identification in New Zealand.

2.0 TSUNAMI BASICS

2.1 What is a tsunami?

A tsunami is a natural phenomenon consisting of a series of waves generated when a large volume of water in the sea, or in a lake, is rapidly displaced. Tsunami are known for their capacity to violently inundate coastlines, causing devastating property damage, injuries, and loss of life. The principal sources of tsunami are:

- large submarine or coastal earthquakes (in which significant uplift or subsidence of the seafloor or coast occurs)
- underwater landslides (which may be triggered by an earthquake, or volcanic activity)
- large landslides from coastal or lakeside cliffs
- volcanic eruptions (e.g., under-water explosions or caldera collapse[1], pyroclastic flows[2] and atmospheric pressure waves)
- a meteor (bolide) splashdown, or an atmospheric air-burst over the ocean.

In a tsunami, the whole water column from the ocean floor to its surface is affected, the initial disturbance creating a series of waves radiating outwards, until the waves either dissipate or collide with a shoreline. Tsunami waves can arrive at nearby shores within minutes, or travel across the deep ocean basins at speeds in excess of 500 kilometres per hour (km/hr). Very large sources (disturbances) are required to cause tsunami that are damaging at great distances from the source. For example, the magnitude (M) 9.5 Chile earthquake produced a 25 metre (m) high tsunami locally, over 10 m in Hawaii, and nearly 4 m in New Zealand. On the other hand, tsunami that are generated locally do not need such a large source to be large and damaging at nearby shores. For example, the 1947 M7.1 earthquake off Gisborne affected 120 km of coastline, with a tsunami of 10 m maximum height occurring along tens of kilometres of coast north of Gisborne.

The amplitude of tsunami waves[3] in deep water is generally less than one metre, producing only a gentle rise and fall of the sea surface that is not noticed by ships, nor able to be seen by

---

[1] CALDERA COLLAPSE refers to the formation of a large depression when the underlying magma chamber of a volcano collapses during or following an eruption or explosion. The collapsed caldera is a crater-shaped depression which may be many hundreds of square kilometres in area, and many hundreds of metres deep. The collapse needs to occur suddenly to cause a tsunami.

[2] A PYROCLASTIC FLOW is a ground-hugging avalanche of hot ash, pumice, rock fragments, and volcanic gas that rushes down the side of a volcano at hundreds of km/hr, and can have temperatures greater than 500°C. In a coastal setting, such flows cause tsunami when they enter the sea. Pyroclastic flows can also occur from underwater volcanoes.

[3] TSUNAMI HEIGHT (m) is the vertical crest-to-trough height of waves (which is approximately twice the AMPLITUDE). It is far from constant, and increases substantially as the wave approaches the shoreline. Usually only used in conjunction with measurements from sea-level gauges. In this report we use the term "wave height" meaning the height of water at the coast above the tide level at the time of tsunami arrival. It is essentially the same meaning as amplitude.

aircraft, although new satellites with sea-surface elevation technology can detect large tsunami in the deep ocean. When tsunami waves reach shallower waters, their speed decreases rapidly from their deep-ocean values, and at the same time their height increases (as the front of each wave slows down and the back of the wave, which is moving faster, catches up on the front, piling the water higher). A tsunami wave that is only half a metre high in the open ocean can increase to a devastating 10 m high wave travelling at 10-40 km/hr at impact with the shore.

Tsunami waves differ from the usual waves we see breaking on the beach or in the deep ocean, particularly in the distance between successive waves, and because tsunami waves occupy the whole ocean depth and not just the top few tens of metres as in storm waves. Both of these factors contribute to the huge momentum of water in a tsunami at the coast. In a tsunami, the distance between successive waves (called wavelength) can vary from several kilometres to over 400 km, rather than around 100 metres for normal waves at the beach. The time between successive tsunami wave crests (called period) can vary from several minutes to a few hours, rather than the few seconds usual for beach waves. Hence, when tsunami waves reach the shore, they continue to flood inland over many minutes, and then the waves may retreat over as many minutes, before the arrival of the next wave. The waves may come in at irregular intervals, often without complete withdrawal of the inundating water from previous waves due to retardation of the outflow and impoundments. The first wave to arrive may not be the largest wave.

New Zealand's location astride a plate boundary means that it experiences many large earthquakes. Some cause large tsunami. New Zealand's coasts are also exposed to tsunami from submarine and coastal landslides, and from island and submarine volcanoes. In addition, tsunami generated by large earthquakes at distant locations, such as South America, or western North America and the Aleutians in the north Pacific Ocean, can also be damaging in New Zealand.

Tsunami with run-up heights[4] of a metre or more have occurred about once every 10 years on average somewhere around New Zealand, a similar frequency to Hawaii and Indonesia, but about one third that in Japan. Smaller tsunami occur more frequently, the smallest of which are only detectable on sea-level recorders.

New Zealand can expect tsunami in the future. Some coasts are more at risk than others because of their proximity to areas of high local seismic activity, or exposure to tsunami from more distant sources. No part of the New Zealand coastline is completely free from tsunami hazard.

---

[4] TSUNAMI RUN-UP (m), a measure much used in tsunami-hazard assessment, is the elevation of inundation above the instantaneous sea level at the time of impact at the farthest inland limit of inundation. This measure has a drawback in that its relationship with the amplitude of the waves at the shore depends markedly on the characteristics of waves and on the local slopes, vegetation, and buildings on the beach and foreshore areas, so it is highly site-specific. In this study we approximate run-up via a series of inundation models (section 7).

2.2 What damage does a tsunami do?

Tsunami damage and casualties are usually from four main factors (see also Table 2.1):

- Impact of swiftly-flowing torrent (up to 40 km/hr), or travelling bores[5], on vessels in navigable waterways, canal estates and marinas, and on buildings, infrastructure and people where coastal margins are inundated. Torrents (inundating and receding) and bores can also cause substantial erosion both of the coast and the sea-floor. They can scour roads and railways, land and associated vegetation. The receding flows, or "out-rush", when a large tsunami wave recedes are often the main cause of drowning, as people are swept out to sea.
- Debris impacts—many casualties and much building damage arise from the high impulsive impacts of floating debris picked up and carried by the in-rush (inundating) and out-rush (receding) flows.
- Fire and contamination—fire may occur when fuel installations are floated or breached by debris, or when home heaters are overturned. Breached fuel tanks, and broken or flooded sewerage pipes or works can cause contamination. Homes and many businesses contain many harmful chemicals that can be spilled.
- Inundation and saltwater-contamination by the ponding of potentially large volumes of seawater will cause medium- to long-term damage to buildings, electronics, fittings, and to farmland.

---

5 Tsunamis often form bores in harbours, man-made waterways, and in coastal rivers and streams. A bore can be a smooth or turbulent, non-breaking step-like increase in water height resulting in wall-like change in water levels from normal to some higher level. They can travel 3 or more kilometres up a river with the water many metres above the normal level, sometimes well over the bank height, causing damage to bridges and wharves, and causing water to flood nearby flat areas.

Table 2.1 Summary of damage that can be caused by tsunami waves

People and animals	**Built environment**	**Natural environment**	**Shipping**
Washed off feet Drowned, especially in out-wash Injured by debris or impact with structures Skin may be removed by the "sand-blast" effect of suspended particles Injury/illness due to contact with contaminated water	Damaged by inundation and deposition of sand Damaged by floating debris (including cars and boats) Wooden buildings floated and damaged Reinforced concrete buildings damaged (with on-land water levels of 4m+) Reinforced buildings badly damaged (with on land water levels of 10m+) Coastal wharves, coastal defences (seawalls/gabions) & bridges damaged or destroyed Riverside wharves & bridges damaged or destroyed 3 km or more upstream by bores Walls, fences, road surfaces, power/telegraph poles damaged or destroyed Oil spills from overturned vehicles, heaters or floated storage tanks, with consequent fire danger Aqua-culture rafts, etc damaged Sewerage systems obstructed, or damaged, with consequent contamination	Erosion or deposition Trees snapped or uprooted Long-term sea-water contamination effects (salt) Sewage contamination Fish and shellfish thrown ashore, with consequent contamination Disturbance, siltation, contamination of the near shore marine environment with subsequent reduction in fish stocks	Ship and boat damage by impact with wharves, breakwaters or other boats Ship and boat damage by complete withdrawal of water, or too rapid a return of water to allow floating Ships and boats torn from moorings and thrown on shore Buoys moved Channels altered by scouring and deposition Shipping lanes littered with floating debris Oil spills from overturned boats and wharf installations with consequent fire danger Port and marina docking facilities & breakwaters

3.0 HISTORICAL AND PRE-HISTORICAL TSUNAMI DATABASES

3.1 Historical records

New Zealand has been affected by more than 40 tsunamis in the last 165 years (GNS unpublished historical tsunami database). Of these,

- 14 were from distant earthquake sources,
- 7 were from regional earthquake sources
- 9 were from local earthquake sources
- 4 were from local earthquakes accompanied by coastal landslides
- one was a spontaneous landslide without an earthquake
- 8 others were from unknown sources, one of which was possibly a submarine landslide.

At least three tsunami with run-up heights of 10 m or more have occurred in the last 165 years (the period of written history in New Zealand). Two of these tsunami were generated by local earthquakes (1855 and 1947), the other by a large South American earthquake (1868). Tsunami with run-up height of 30 m or more have been found in the geological (pre-historical) record of the last 6,000 years.

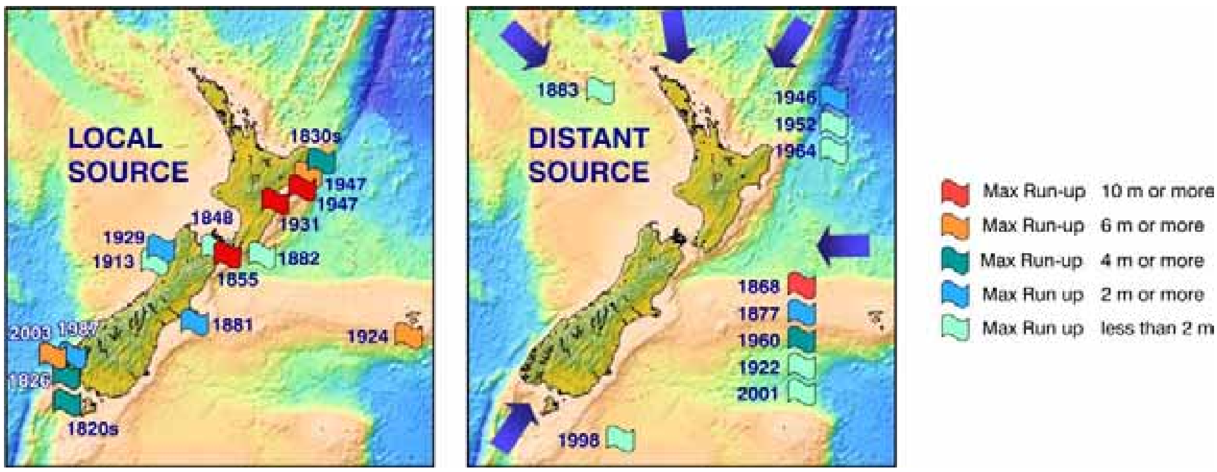


Figure 3.1 Largest historical tsunami in the historical record

The most significant historical tsunami were generated by the M8.2 1855 Wairarapa earthquake, by an earthquake 50 km offshore of Gisborne in March 1947, and the distant source tsunami from South America in 1868, 1877 & 1960.

The 1855 earthquake, which ruptured the Wairarapa fault east of Wellington, generated a tsunami with a maximum known run-up of 10 m at Te Kopi in eastern Palliser Bay and up to 4–5 m in several locations in Wellington and along the northern Marlborough coast. The Rongotai isthmus and Miramar were reportedly covered many times in water to about one metre depth, rushing in from Lyall Bay and from Evans Bay. In Lambton Quay, the tsunami was no more than 2-2.5 m high, washing into shops that fronted on to what was then the beach. Waves swept around Wellington Harbour and in Cook Strait for more than 12 hours, being observed as far south as the Clarence River Mouth and at least as far north as Otaki, where the run-up was probably about 2-3 metres. It is estimated that at least 300-500 km of coastline was affected with run-ups of 1 m or more, the first waves arriving within minutes in Wellington and within an hour of the earthquake at Otaki and Marlborough. While submarine and coastal landslides may have contributed to the tsunami, the raising and lowering of the sea bed, by as much as 6 m vertically upward near Turakirae Point on the south Wellington coast, was probably the main cause. Tides continued to be disturbed for the following week, suggesting that large aftershocks, perhaps with accompanying landslides, may have been the cause. Recent seabed imagery of the Cook Strait region obtained by NIWA has revealed many landslide scars and deposits but further work is required to establish their ages and mechanisms of formation.

In *March 1947*, a 120 km long stretch of coast, from Mahia Peninsula northwards, was struck by a tsunami, 30 minutes after a moderately felt earthquake. The maximum run-up height of about 10 m occurred at a near-deserted beach about 20 km north of Gisborne. Here, the bridge on the main road near Pouawa was swept hundreds of metres inland and all except one room of the only house nearby was destroyed, the five occupants surviving. Other houses were damaged a little further south and near Mahia. The earthquake that generated the tsunami was one of a class of earthquakes called "tsunami earthquakes[6]. Although the cause of the tsunami has been attributed by some to a submarine landslide (for example, de Lange and Moon, 2004), this is not in line with international research on this type of event, which suggests anomalous movement on the earthquake fault and seafloor (Downes et al., 2000). Landslides may have contributed to the tsunami, however.

[6] A "tsunami earthquake" is an unusual type of earthquake with a slow rupture pattern, and is associated with unusually large tsunami. The capacity of subduction zones to produce tsunami earthquakes is largely unknown. These events have the potential to be catastrophic locally, and in at least one notable event (the tsunami from the 1946 M7.9 Aleutian earthquake), catastrophic at large distances. In this event, the highest waves occurred in a very narrow beam across the Pacific from the source (maximum run-up: 35 m near source) through Hawaii (max. run-up: nearly 17 m) and parts of French Polynesia (max. run-up: nearly 15 m) and on to Antarctica. Generally, a much larger earthquake would be considered necessary to produce such a damaging Pacific-wide tsunami. Other than the larger-than-expected tsunami for the magnitude of the generating earthquake already mentioned, there are several other distinguishing features. These include the unusual seismic records, and the fact that they occur very close to the troughs or trenches that mark a subduction zone boundary. Techniques for recognising these events electronically and visually are being developed internationally, because of their importance for tsunami warning systems. Even if *tsunami earthquakes* could be recognised, a further challenge, because the tsunami generation process is not well understood, is estimating impact and developing realistic numerical models. Fortunately, *tsunami earthquakes* that are devastating at large distances do not appear to be common, and priority needs to given to modelling the more usual subduction interface earthquakes.

These tsunami are the largest earthquake-generated tsunami known since 1840, but another in May 1947, again caused by a "tsunami earthquake" along the east coast north of Gisborne, caused waves of up to 6 m.

In addition to events in the European historical period, an event in the 1820s reputedly drowned many Maori walking along the beach near Orepuki, Southland. The source was most probably local, or regional, and not from a distant source such as South America.

Three tsunamis, in 1868, 1877, and 1960 generated by Great earthquakes in South America caused significant and widespread damage and disruption along the east coast of the North and South Islands and in the Chatham Islands. The 1868 tsunami caused the only death attributable to tsunami since European settlement. The tsunami was generated by a magnitude ~M9.1 earthquake off southern Peru/northern Chile, in a similar location to the June 2001 Peru M8.4 earthquake. The greatest near-source run-up recorded for the 1868 tsunami was 18 m (ITDB, 2004). In New Zealand, run-up of 1-4 m occurred in the main New Zealand region and up to 10 m in the Chatham Islands. Considerable damage to houses, boats, shops, wharves, jetties, and boatsheds occurred along the whole eastern seaboard from Northland to Southland, and in the Chatham Islands. Westport also reported waves of 1-2 m. Damage was more limited than it could have been because the largest waves of the tsunami arrived within an hour or two of low tide at locations south of Napier. Smaller waves that occurred near high tide also caused damage.

The 1877 tsunami was caused by a magnitude ~M9 earthquake off northern Chile about 400 km south of the source of the 1868 event. The tsunami was up to 21 m high near its source, but in New Zealand the effects were generally not as extensive or as well recorded in historical documents as the 1868 tsunami. Nevertheless, the tsunami had peak run-ups of 3.5 m. Many of the places strongly affected in 1868 were again affected in 1877, but there were some notable differences showing the effect of source location. The tsunami was again evident for several days, and again damage was limited by the largest waves arriving at or near low tide along a large part of the east coast.

The 1960 tsunami was generated by a massive, M_w[7]9.4–9.5 earthquake in the subduction zone off central Chile. It was the largest earthquake in the 20th century. According to the Integrated Tsunami DataBase (ITDB), it caused a large local tsunami (maximum run-up 25 m) resulting in US$550 million in damage and 1,000 deaths. Another US$24 million in damage and 61 deaths occurred in Hawaii, and about US$500,000 to $1,000,000 in damage on the U.S. west coast. In Japan the waves were more than 6 m high causing 199 fatalities and US$50 million

[7] Earthquake magnitudes are noted in this report simply as "M", meaning Richter Magnitude or "M_w", meaning Moment Magnitude. Moment magnitude is a more useful estimate of the size of the largest earthquakes because it is based on an assessment of the dimensions of the earthquake source, whereas Richter Magnitudes typically are poor at estimating the size of the largest earthquakes because the instruments used to derive Richter Magnitude go off-scale above about M7.5.

in damage. There is as yet no estimate of the cost of the damage in New Zealand. As with the 1868 event, run-ups of 1-4 m occurred along the whole eastern seaboard from Northland to Southland, and in the Chatham Islands. Also, in places, some of the largest waves of the tsunami arrived within an hour or two of low tide, particularly in the lower half of the North Island and northern half of the South Island. The first waves of the tsunami also arrived at night, unobserved by most people. Considerable damage was done to houses, boats, shops, wharves, jetties, port facilities, and boatsheds, as well as threatening the lives of several people in Hawke's Bay, Gisborne and Bank's Peninsula.

The tsunami generated by the 1946 M7.9 earthquake in the Aleutian Islands caused minor damage and 1-2 m run-ups over a limited part of the coastline. This event is important, as it is the only distant earthquake under M8.5 to have a significant effect in New Zealand. However, it was a tsunami earthquake similar to, but much more distant than, the 1947 event(s).

The written historical record covers only 165 years, and this is too short a time to reflect the full range of possible events that New Zealand might experience. Many large earthquakes have recurrence intervals in hundreds of years for the smaller events (M8.5) to several thousand years for the largest earthquakes (e.g. M9.5). Also, historical record of small tsunami, or tsunami in the early years of our history, in sparsely populated places, or in remote places, such as Fiordland, is almost certainly incomplete. Nevertheless, New Zealand's historical tsunami database is one of the most comprehensive databases in the Pacific.

For this reason, the frequencies of occurrence for distant, regional and local source tsunami of specified run-up somewhere in New Zealand based on the historical record are only first estimates, and may severely under- or over- estimate the hazard. The historical record, for example, contains no local volcanic events, no large local or regional plate interface earthquakes, and large earthquakes have only occurred on a small proportion of a large number of local sources.

For risk management, and to provide all the necessary information for appropriate response in a tsunami warning situation, the historical record is at best indicative. It is, however, very useful for understanding the behaviour of tsunami in New Zealand, for public education, and for calibrating and validating numerical models.

3.2 Paleotsunami data

Paleotsunami are tsunami that occurred in the past, prior to the written record of historical events. The evidence for their occurrence comes from the sediments and debris that they deposited in the coastal zone (tsunami deposits). Studies of coastal sediments can be used to build up a record of paleotsunami that inundated coasts in the past. Such records extend the tsunami record much further back in time than the historical and instrumental record and thereby improving knowledge of tsunami hazard. Tsunami deposits, in addition to providing evidence for the occurrence of past tsunami attack, can also provide information about their sources, and their frequency and magnitude in the following ways:

Sources:

- The aspect and length of coast over which a tsunami deposit is found can provide information about the direction and distance offshore of the source (and thereby whether it was a local, regional or distant event).
- The type of source can sometimes be inferred from co-existence of the tsunami deposit with physical evidence of deformation (e.g., subsidence and liquefaction features would imply an earthquake source). Correlation of the deposit with a known tsunami-causing event can be used to infer a source where high-resolution age control is available.

Frequency:

- Where a long geological record of tsunami deposits exists, it is possible to estimate recurrence intervals for paleotsunami. This type of information is particularly important where no large tsunami have occurred in historical times but where large events are represented in the geological record frequently enough to suggest they will occur again in the future.

Magnitude:

- Sedimentary deposits are usually evidence of moderate to large paleotsunami because small tsunami are unlikely to leave obvious evidence of their occurrence in the geological record.
- The physical extent of tsunami deposits along and across coastal topography, as well as the height above sea level that deposits reach, provide minimum estimates for tsunami inundation distance and run-up height.

Although paleotsunami datasets have a unique contribution to make to tsunami hazard assessment, there are some major limitations that must be taken into account. For a start, paleotsunami datasets will always be incomplete because:

- Many paleotsunami are not present in the geological record:
  - Not all tsunami leave a recognisable deposit.
  - Not all deposits are preserved for long periods of time.

- Many paleotsunami cannot be identified:
  - Not all deposits contain unique tsunami signatures.
  - Deposition is patchy so evidence may be missing from a particular site.
  - Storm surge deposits may be misinterpreted as tsunami deposits.

Paleotsunami research is in its infancy, both internationally and in New Zealand, so there are relatively few researchers working in this field. There is, as yet, a lack of coverage of key sites and little detail at many of the sites that have been studied. Paleotsunami research is time-consuming so the focus of many studies has been on the initial identification of tsunami deposits. Additional work that is crucial for the assessment of tsunami source, frequency and magnitude, such as detailed mapping of the extent of the deposit, high-resolution age control, and investigation of multiple events at any one site, is yet to be carried out in many cases.

In New Zealand, paleotsunami have been identified at many places around the coastline as a result of targeted research by a few scientists over the last decade (Fig. 3.2). Identification of paleotsunami in New Zealand has provided evidence for the occurrence of past large events and has improved awareness of New Zealand's tsunami risk. New Zealand tsunami deposits for which details have been formally published in the scientific literature are presented in Appendix 1. Numerous deposits that are currently unpublished or documented in conference proceedings and client reports have not been included because of the time required to collate such information and the lack of external peer-review associated with these forms of publication. Deposits are listed by location, generally running from north to south, and with a brief summary of their characteristics as outlined in the relevant publication. Currently there are 26 published tsunami deposits representing up to 15 paleotsunami that have occurred over the last 7500 years (see Appendix 1). While only published data are considered when considering the size and frequency of events, preliminary indications from currently unpublished work have been considered when building source models for the probabilistic risk modelling (section 5).

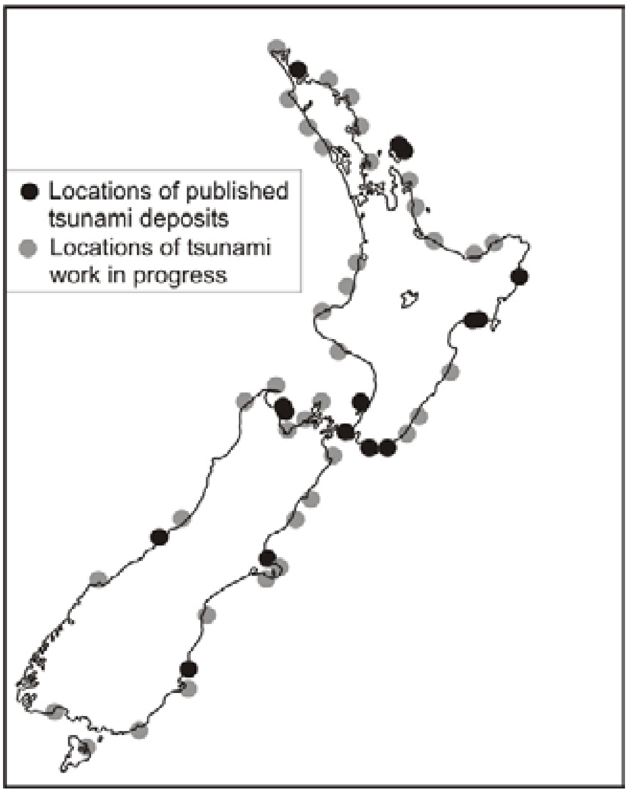


Figure 3.2 Map of New Zealand showing localities of formally published tsunami deposits (black dots) and localities where tsunami work is currently in progress (grey dots). Locations of published tsunami deposits define six main regions of paleotsunami occurrence (ellipses). Arrows indicate likely directions from which the paleotsunami approached each of these regions.

New Zealand's paleotsunami dataset is not currently of adequate detail and extent to be used independently to provide tsunami source, frequency and magnitude information. However, it provides useful supplementary information for use with other data sets. Deposits have been published from six main regions of New Zealand (Fig. 3.2) and their characteristics can be used to check that the source characterisation accommodates the location, inland extent (inundation models) and elevations (wave height at the coast leading to run-up) of the paleotsunami deposits (Table 3.1).

Table 3.1 Implications for paleotsunami source, frequency and magnitude derived from occurrence of tsunami deposits around New Zealand. NB: only formally published tsunami deposits have been used to construct this table.

Areas defined by locations of tsunami deposits	**Sources**		**Frequency**	**Magnitude**	
	Scale	Location	(using published deposits)	Observed run-up or extent inland (max. for region)	Inferred wave heights at coast (m)
Far North	Regional	N of North Island	2 events in 3000 years	32 m height	10-12
Eastern North Island	Local	E of North Island	3 events in 7100 years	2000 m inland	5
Central New Zealand	Local (regional impact?)	Central NZ or trans-Pacific	4-5 events in 3400 years	10.5 m height	10
Western South Island	Local	W of South Island	2 events in 600 years	100 m inland	10
Otago	Local	E of NZ or trans-Pacific	1 event in c. 600 years	750 m inland	5
Canterbury	Local	E of NZ or trans-Pacific	2 events in 4000 years	6 m height	6+

4.0 METHODOLOGY OF RISK CALCULATION

For hazards that occur frequently (e.g. floods) historical data give us a reasonably accurate picture of the long-term risk in terms of casualties or damage to dwellings. In the case of more infrequently occurring natural hazards, such as earthquakes or tsunami, historical data are insufficient to enable us to accurately assess the long-term risk. This is especially the case in New Zealand with a relatively short period of recorded history compared with Asia, Europe or South America.

We showed in Section 3.2 that paleotsunami data are used to supplement historical data, but in New Zealand such data are incomplete. To supplement incomplete data we can use modelling to determine, as best we can, the level of risk from infrequent but high-impact events. For tsunami, risk is dependent on combining the following factors:

- Tsunami-generating source (size and frequency of earthquakes, landslides, volcanoes);
- Wave propagation through water;
- Flooding of the water across land (Inundation);
- Location and distribution of assets at risk (people, dwellings, other buildings);
- How easily the assets and people are damaged (Fragility)

We can approach the risk assessment in two different ways. The first would be to determine the impact of a number of different scenario events, for example historical events in a modern context (in terms of people now at risk). While this can be informative, it does not tell us about the likely long-term risk from all possible events.

A second approach that does consider all likely future events involves examining the likely size, frequency and effects of all sources. The smaller events are usually much more frequent than the larger events (about 10 times more for each magnitude unit in the case of earthquakes). This latter approach is known as a probabilistic assessment and is the one we have used in this report (Figure 4.1). More details about the probabilistic methodology are given in Appendix 2.

We have endeavoured to estimate, where possible, the frequency of occurrence for each of our tsunami sources. Details of sources at distant, regional, and local distances are discussed in Section 5. All of these sources involve displacement of water through either seafloor uplift or subsidence, or a change in water volume; it is then necessary to model how the displaced water propagates as a tsunami to sites around our coasts. Ideally this would be done by running detailed numerical models for each source. This is again a new and rapidly developing area of science and so, at present, these comprehensive models do not exist for all of the source to site combinations relevant to the New Zealand coast. In time this will need to be done to gain confidence in both the tsunami propagation and inundation components of risk assessment, but resources and time are insufficient at present. For the purposes of this report we have had to rely mostly on empirical relationships that relate source magnitude, source-to-site distance, and wave height at the site (Figure 4.1). A few numerical simulations and historical data have been used to inform choices of parameters for the empirical models. More details about numerical modelling are included in Section 6.

For inundation, there are a number of empirical models to choose from, as well as, in the ideal world, very detailed numerical models that are continuous from source to inundation. As was the case for the ocean propagation, inundation models are in a rapid phase of development and are very incomplete for New Zealand, but they can be used to inform choices of empirical models (Figure 4.1). Inundation models are discussed in Section 7.

The final information we used to arrive at our risk estimates is the number of people at risk, the amount of assets and their associated fragility. For example, what proportion of people are likely to be killed by a 2m wave with a given velocity? What damage will be done to buildings by such a 2m wave? The derivation of this information is discussed in Section 8.

In developing probabilistic models we also have to contend with lack of knowledge (uncertainty) and nature's inherent variability. Lack of knowledge can be included as alternative models or parameters for which there is no 'right' choice. The normal approach is to consider all competing models and assign them weights using expert judgement (Figure 4.1). The results obtained from the different models are combined using the assigned weights, and a distribution of possible answers is obtained. Depending on the nature of the problem, answers in the range between the median value and the 84^{th} & 16^{th} percentiles are used to assess uncertainty in the risk analysis. In matters of life safety the 84^{th} percentile is typically used, reflecting the need for a conservative approach (ANCOLD, 2003). In the analysis in this report we show the 16^{th}, median and 84^{th} percentile values, the spread reflecting knowledge uncertainty. A more detailed discussion of the uncertainty treatment is contained in Appendix 2. In Figure 4.1 we show how just a single source is liable to develop a range of risk estimates because of uncertainty and alternative viable models. This "logic tree" approach is conceptually simple but difficult to manipulate when there are a large number of steps in the probabilistic construction. We actually use a Monte Carlo sampling technique (see Smith, 2003 for full discussion of the technique) to assess all combinations of choices of all parameters

Uncertainty and variability affect the confidence of any calculated value, so this estimate of confidence is extremely important in risk calculations. The range of parameters (injuries, deaths and dollar losses) in our risk calculations at the 84^{th} & 16^{th} percentile are viable alternate values, not statistically different from mean estimates.

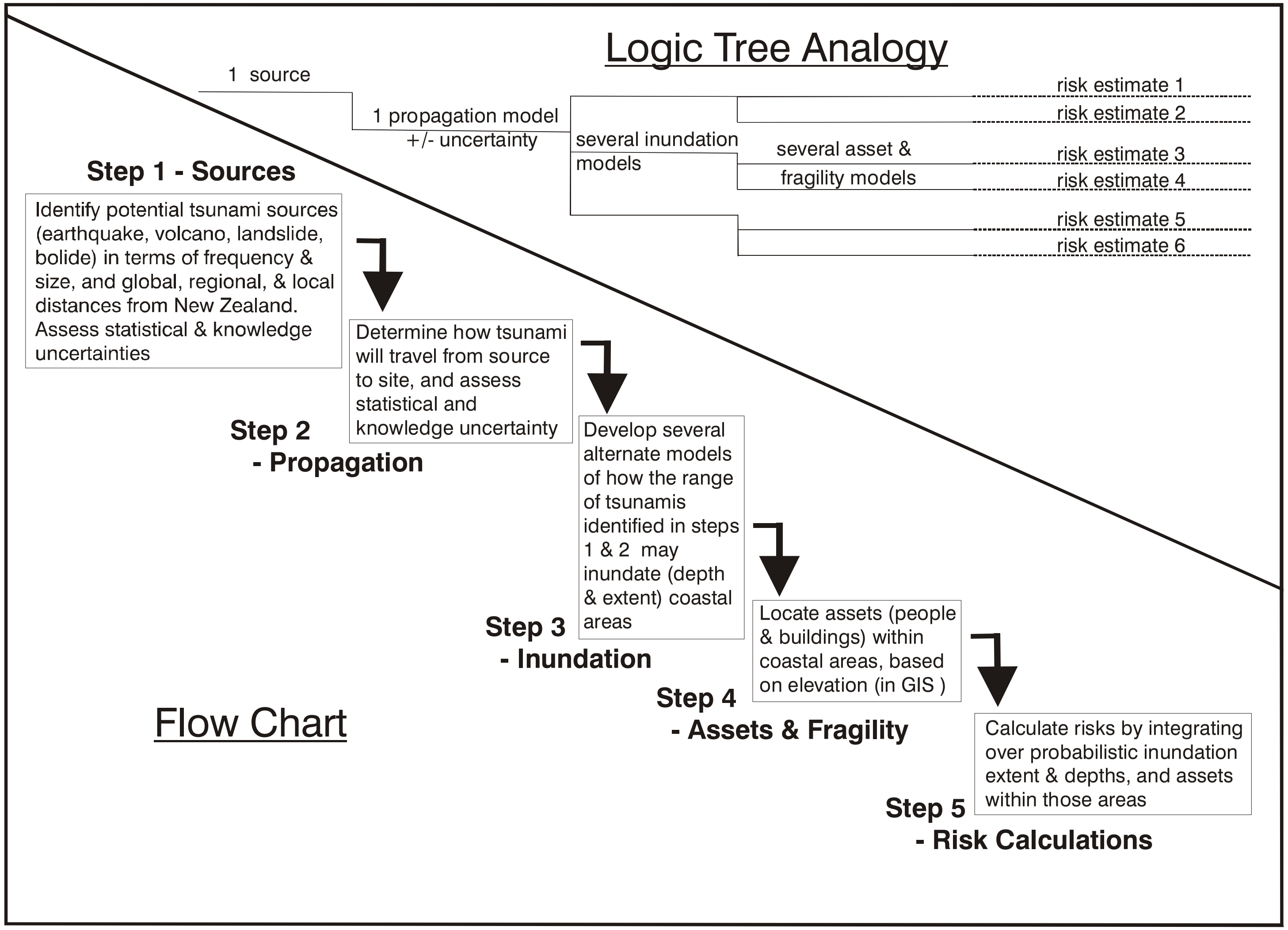


Figure 4.1 Flowchart of steps for developing probabilistic tsunami risk in New Zealand. The logic tree analogy is much simplified, presented here only to illustrate how each source is represented by multiple risk estimates. Risk has actually been calculated from all of the combinations of all flowchart steps.

5.0 DEFINING TSUNAMI SOURCES

This section contains all known information about the possible sources of tsunami that could cause damage in New Zealand. For the purposes of emergency management and the time needed to respond and act on warnings, it is convenient to categorise tsunami as distant, regional or local source, depending on the shortest travel time of a tsunami from its source to the area of concern, in this case, the closest part of the New Zealand coastline. This is also fairly consistent with where sources are located, in that distant sources for New Zealand are mainly Pacific rim, while local sources relate to the New Zealand 'continent'. The categorisation that we adopt for this report is:

- Distant source — more than 3 hours travel time from New Zealand
- Regional source — 1–3 hours travel time from New Zealand
- Local source — 0–60 minutes travel time to the nearest New Zealand coast (most sources are <30 minutes travel time)

It should be noted that a local source tsunami, impacting at the nearest shore within 60 minutes, may take more than sixty minutes to travel to other New Zealand locations. This affects the time available for Emergency Management to issue a warning and so needs to be kept in mind when warning systems are being considered.

5.1 Distant Sources

5.1.1 Earthquake

Large to Great (M>8) earthquakes are the most frequently-occurring source of damaging tsunami worldwide and 80% of these earthquakes occur around the margins of the Pacific Ocean where the Pacific plate is forced beneath (subducted) other crustal plates (often but not always corresponding with the continents) of the circum-Pacific (Fig 5.1). Typically the down-going plate gets stuck in its movement beneath the adjacent continent and this stored energy is released in large earthquakes. The Boxing Day 2004 tsunami was generated by this process in the Indian Ocean where the Australia plate is subducted beneath the Asia plate along the Sumatran subduction zone.

The potential of subduction zones to produce tsunami that could cause wave heights of 2 m or more, at the urban centres where risk is being estimated in this report, has been assessed from all available data including historical occurrences, numerical modelling and literature on earthquake recurrence and magnitude. The evaluation revealed that only sources in the circum-Pacific region (including New Zealand's subduction zones and some offshore faults) are likely to generate tsunami at > 2 m wave heights (Figure 5.1). Tsunami are recorded from other sources (for example the Boxing Day 2004 tsunami from the Indian Ocean) but these are not expected to exceed 2 m in the maximum 2500 year return period considered in this study. Source characterisation has been based on up-to-date review literature of particular Pacific rim regions but a complete literature compilation is beyond the scope of this review. Where it has been available we have included insights from numerical modelling of tsunami source parameters and propagation effects but this data are sparse as they apply to New Zealand, and very little new modelling, specifically for the purpose of this study, has been undertaken.

5.1.1.1 South America (Figure 5.1)

The west coast of South America is one of the most frequent sources of tsunami in the Pacific, resulting from great earthquakes on the boundary between the Pacific and South American tectonic plates. Earthquakes along this coastline produce tsunami that are often well directed towards New Zealand both by the orientation of the plate boundary on which the earthquakes occur and by focussing of the tsunami by the sea-floor shape between South America and New Zealand. There are few island chains to scatter the tsunami waves.

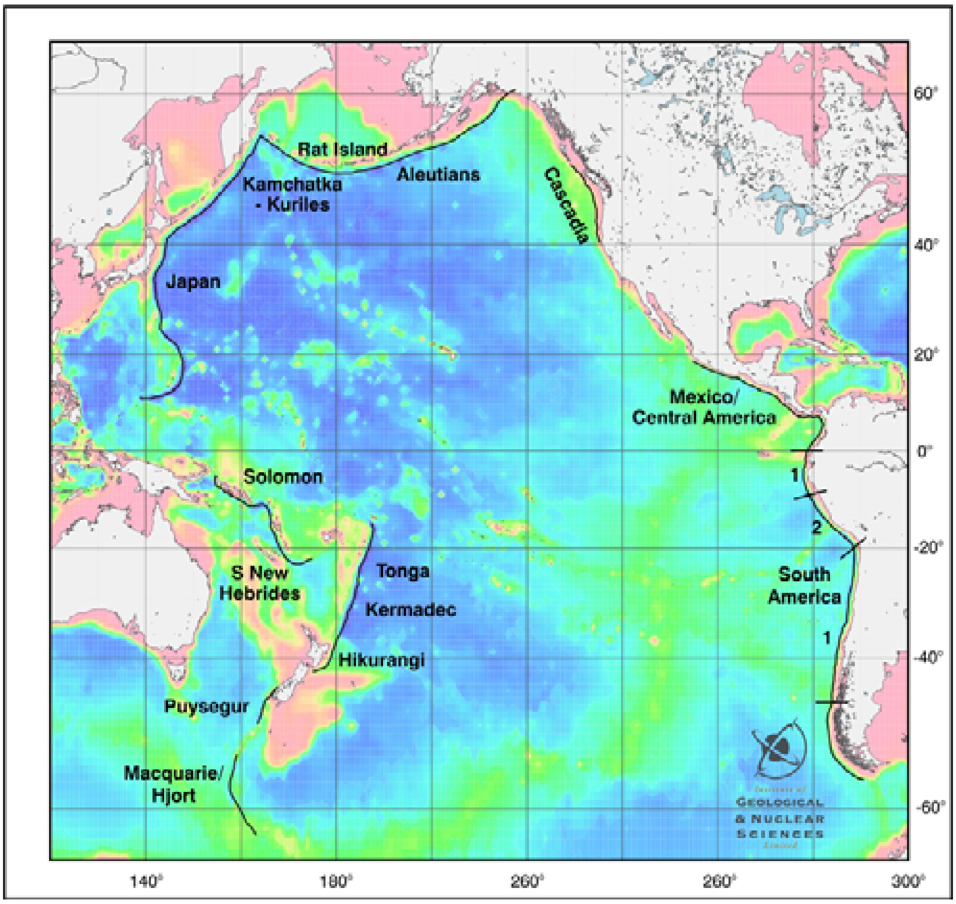


Figure 5.1 Subduction margins in the circum-Pacific region discussed in the text. The "1 & 2" shown along the South America margin reflect the partitioning of that margin into regions that propagate tsunami either westward toward eastern New Zealand, especially eastern South Island (region 2) or direct tsunami further northward and more likely to affect northern North Island and the north Pacific (region 1). The 1868 tsunami was generated in region 2 while the much larger but less damaging (in New Zealand) 1960 tsunami originated in region 1.

For example, the distant-source tsunami that caused the most damage to New Zealand in historical times was caused by a magnitude 9.1 earthquake on the southern coast of Peru in 1868 (region 2 of Fig 5.1). This area of South America's coastline is orientated in such a way that the tsunami energy is more effectively directed towards New Zealand than further north into the Pacific. Should a larger earthquake than the 1868 event occur in this part of the coast, the effects in New Zealand could be considerably greater than occurred in 1868.

In contrast, the 1960 tsunami, although caused by a much larger earthquake (M_w9.4, possibly M_w9.5), occurred on a part of the South American plate boundary that is not as well oriented to New Zealand as the 1868 location (region 1 of Fig 5.1). It produced a smaller tsunami in New Zealand than would have occurred had the location been ideally oriented. Nevertheless, the 1960 tsunami caused run-ups of up to 4 m in parts of the North and South Islands.

The magnitude of the 1960 earthquake, at M_w9.4-9.5, probably represents the upper limit for earthquakes for the whole South American coastline (and worldwide). It is uncertain whether the whole South American coast is capable of producing earthquakes of this size, or whether most parts have more frequent but relatively smaller earthquakes of M_w8-9. When the earthquake catalogue for the whole South American margin is inspected, the frequency of large earthquakes appears to decrease with increasing magnitude in such a way that for every unit increase in magnitude the frequency of earthquakes drops by approximately a factor of ten (the b-value, see Appendix 4).

Computer models (Power et al., 2004), combined with historical observations, suggest that there is minimal risk of a damaging tsunami in New Zealand generated by South American earthquakes with magnitudes less than 8.5.

The historical record of Peru and Chile, which is hundreds of years longer than New Zealand's, indicates that large earthquakes and tsunami have occurred relatively frequently in the last 450 years (Table 5.1). Nine earthquakes with estimated magnitudes of M_w> 8.5 caused near-source run-up heights near to, or greater than, those produced locally by the 1868 or 1877 events, and hence probably produced significant tsunami in New Zealand prior to European settlement. The average return period (50 years) is about the same as has occurred in the last 160 years, and provides an indication of the frequency of potentially damaging South American source tsunami in New Zealand.

As tsunami from South America approach New Zealand from the east, the east coast is more affected than the west coast. However, waves do propagate around New Zealand as well as through Cook Strait, and the west coast will have significant waves in some cases.

Table 5.1 Large South American earthquakes that have produced tsunami with maximum wave heights greater than 8 m locally (extracted from Gusiakov, 2001). Those events in bold are either known to have caused, or have the potential to have caused, significant impact in New Zealand comparable with the 1868, 1877 and 1960 tsunami. The magnitudes for early events (shown by grey shading) may have large errors. Note: M_b/M_s –body wave/surface magnitude; M_w –moment magnitude; M_t –tsunami magnitude [Abbreviations: S = south; N = north;].

Year	MM	DD	Lat. (°N)	Long. (°E)	M_b/M_s	M_w	M_t	Max. run-up at source (m)	Source	Max run-up in NZ (m)
1562	**10**	**28**	**-38.70**	**-73.20**	**8.0**			**16**	**S. Central Chile**	
1586	**7**	**9**	**-12.20**	**-77.70**	**8.5**			**26**	**Off Lima, Peru**	
1604	**11**	**24**	**-18.50**	**-70.35**	**8.4**			**16**	**Africa, N. Chile**	
1657	3	15	-36.80	-73.00	8.0			8	Conception, S. Chile	
1687	10	20	-13.50	-76.50	8.5			8	Callao, Lima, Peru	
1730	**7**	**8**	**-32.50**	**-71.50**	**8.7**			**16**	**Valparaiso, Chile**	
1746	**10**	**29**	**-12.50**	**-77.00**	**8.0**	**8.6**	**9.2**	**24**	**Callao, Lima, Peru**	
1806	12	1	-12.10	-77.10	7.5			6	Peru	
1835	**2**	**20**	**-36.50**	**-72.60**	**8.5**			**14**	**Conception, S. Chile**	
1837	11	7	-42.50	-74.00	8.5		9.2	8	Corral, S Chile	
1859	10	5	-27.00	-70.40	7.7			6	Caldera, Chile	
1868	**8**	**13**	**-17.70**	**-71.60**	**8.8**	**9.1**	**9.0**	**18**	**Arica, S. Peru**	**4; (10 Chatham Islands)**
1877	**5**	**10**	**-21.06**	**-70.25**	**8.8**	**9.0**		**21**	**Iquique, N. Chile**	**~3.5**
1922	11	11	-28.31	-70.28	8.3	8.7		9	Caldera, Chile	~1
1929	8	9	-23.60	-70.40				8	N. Chile	
1960	**5**	**22**	**-38.31**	**-72.65**	**8.6**	**9.5**	**9.4**	**25**	**S. Chile**	**~4**
1960	11	20	-6.64	-80.55	6.9	7.7	7.7	9	N. Peru	
1996	2	21	-9.71	-79.86	6.6/7.5	7.8	7.8	5	Peru	

5.1.1.2 Mexico & Central America (Figure 5.1)

The maximum historical earthquake in this area is less than M_W 8.5, too small generally to produce a damaging Pacific-wide tsunami. The potential for a much larger earthquake is thought to be small, and the coastline in this region is not oriented toward New Zealand. We have not modelled the likelihood of tsunami travelling to New Zealand from this source area. Hence, the area is not included as a source of tsunami in our New Zealand risk study.

5.1.1.3 Cascadia (Figure 5.1)

The Cascadia margin refers to the boundary between the Pacific and North American tectonic plates between northern California and Vancouver Island. Rupture of the plate interface is thought to occur either as whole-region ruptures of about magnitude 9.0 at intervals with approximately 800 year recurrence intervals (Witter et al., 2003), or in earthquakes with magnitudes less than 9.0 which may occur more frequently (Clague, 1997). The smaller earthquakes would probably not bring about a significant tsunami risk to New Zealand.

The last great Cascadia earthquake occurred in 1700 AD, identified from historical tsunami records in Japan, and consistent with geological evidence from the US and Canada. This date is beyond written records in New Zealand, as it is in the US and Canada, and the only means to estimate likely impact here is by using numerical modelling. Japanese researchers have estimated the magnitude of the 1700 event at M_w 9.0. The resolution of the New Zealand information is poor, but research suggests that this source could result in wave heights of possibly 3 m in places along the north and east coasts, but apparently would not result in wave heights of more than 2 m at the urban centres assessed in this study.

We include this source in our risk modelling, using the preliminary modelling to derive a source-to-site B parameter (see Section 6.2 and Appendix 4 for discussion).

5.1.1.4 Alaska & Aleutians (Figure 5.1)

The plate boundary between Alaska and the Aleutians is a highly active source of great plate interface earthquakes and tsunami in the Pacific. Historically, three earthquakes – the 1964 M_W 9.4 Alaska, the 1957 M_W 8.7-9.1 Rat Island, and the 1946 M_W 7.9 Aleutian earthquakes, have caused run-ups of up to 2 m along the north and east coasts, but not at any of the urban centres in this risk evaluation.

The historical record here has not captured the full range of tsunami that New Zealand might experience from the Alaskan and Aleutians region. However, most parts of this coastline produce tsunami that are not particularly well directed to New Zealand, with exception of the area around the source zone of the 1957 Rat Island earthquake. We include the Rat Island source in the risk model.

5.1.1.5 Kurile Islands, Kamchatka (Figure 5.1)

The largest earthquake to have occurred in this area in New Zealand's historical record is an M_w9 earthquake south of Kamchatka Peninsula in 1952. This event produced a maximum of nearly 19 m run-up locally, and a maximum in New Zealand of over 1 m in Gisborne. A larger tsunami, with a maximum run-up of 63 m locally and 15 m at a distance of over 1000 km, was recorded in 1737 from a M8.3 earthquake. Its effects in the larger Pacific area are unknown. The capacity of the area to produce earthquakes with magnitudes greater than the M9.0 in the historical record is unknown, and no numerical modelling of potential effects in New Zealand has been carried out

The assessment panel thought it may be possible for wave heights of 2-3 m at amplifying sites, but because of lack of information and modelling, the area is not included as a source of 2 m or more wave height at the urban areas included in the risk evaluation.

5.1.1.6 Japan (Figure 5.1)

The subduction zones off Japan are some of the most active in the Pacific. The region also has one of the longest historical records of large earthquakes and tsunami, spanning several hundred years. In that time, no events are thought to have reached magnitude 9, although there are many events over magnitude 8. In New Zealand's historical record, only very small wave heights of less than a metre have been recorded from Japanese earthquakes. Although several key events have not yet been researched for their effects here, the orientation of the subduction zone and the island-studded propagation path are thought to protect New Zealand from wave heights of 2 m or more. Hence, the area is not included as a source of 2 m or more run-up in the risk evaluation.

5.1.1.7 Solomon Islands, Papua New Guinea (Figure 5.1)

Historically, these areas have produced few earthquakes over magnitude 8.5, and the expert panel thought that they have little capacity to do so. Few tsunami have produced wave heights exceeding 1-2 m at a large distance from the source. Further, the orientation of the subduction zones would not direct waves towards New Zealand, and islands between the sources and New Zealand would scatter the waves. A few wave heights of considerably less than a metre from this source have been recorded in New Zealand.

Hence, the area is not included as a source of tsunami 2 m or more in height in the urban centres of the risk evaluation.

5.1.1.8 Summary Comment

Few areas can, with certainty, be excluded as a source of damaging tsunami until all earthquake sources are considered and numerical modelling has revealed the extent, or lack of, a threat. At global distances there are significant uncertainties about the potential for northern South American, Cascadian (western USA), Alaskan and the Aleutians sources, not necessarily to the major urban centres considered in this study, but to local, potentially more exposed sites.

5.1.2 Landslide

The role of submarine landslides and their potential to produce local, regional and Pacific-wide tsunami have undergone critical international scientific review and debate in recent years, particularly as a result of the devastating 1998 Papua New Guinea tsunami. Some scientists have attributed this larger-than-expected tsunami to the magnitude and seismic characteristics of the generating earthquake, others to the occurrence of an offshore landslide a few minutes after the earthquake. This has led many tsunami researchers to recognise that submarine landslides may play a greater part in generating local tsunami than previously thought. Submarine landslides have also been argued to have added substantially to the trans-Pacific tsunami resulting from the 1946 earthquake from the Aleutians (Fryer et al., 2004). They argue that the narrow "beam" of devastating tsunami that swept Hawaii and the Marquesas Islands, and had run-up of 4 m in Antarctica was the result of a 200 km^3 landslide triggered by the M_w 7.9 subduction earthquake. Others (e.g. Tanioka & Seno, 2001) have suggested the earthquake had very large slip for its apparent magnitude, such that it would fall into the "tsunami earthquake" category.

Huge sector collapses (1000-5000 km^3) of the flanks of the Hawaiian volcano chain have been modelled to produce Pacific-wide tsunami as well as very large local tsunami of hundreds of metres (McMurtry et al., 2004). While it is likely that flank collapses of this scale would produce large tsunami in New Zealand, their return periods from any one source are well in excess of the return periods of interest in this risk study. Therefore, no landslides at global distances are considered viable tsunami sources within the 2500 year period of interest in this risk study.

5.1.3 Volcano

Other than the potential for flank collapse on the slopes of volcanoes, no volcanoes in the historical record are known to have directly produced significant tsunami at great distances. In the great 1883 Krakatau, Indonesia, eruption, tsunami-like water level oscillations observed at great distances from the source have been attributed to a coupling of an atmospheric pressure wave with the ocean. These waves, given the name *rissaga*, or atmospheric tsunami, are outside the scope of this review. Not enough is known about this mechanism to categorise it as a tsunami source for the purposes of this review. Nevertheless, oscillations in New Zealand following the Krakatau eruption included 1.8 m at Whitianga and in the anchorage area at Auckland (although only 0.9-1.2 m at the Auckland docks) (de Lange & Healy, 1986).

5.1.4 Bolide

As an island nation surrounded by a large deep sea, New Zealand has a tsunami hazard from impacts of asteroids and comets. This hazard is real, finite and determinable, but the probability of a damaging tsunami from these sources is low. One such large event is known to have occurred on Earth within recorded human history – a meteor exploded over Constantinople on a clear afternoon in 472 AD, hitting the city with a wave that knocked sailboats flat in the water.

Asteroids and comets are collectively known as Near Earth Objects (NEOs) when they approach close to Earth, especially if their closest approach is less than the distance to the moon. If they enter the Earth's atmosphere, they are collectively called bolides. The visible track of a bolide across the sky is a meteor, or shooting star. The solid objects that sometimes are recovered after meteors are meteorites. A meteorite survives its passage through the atmosphere and hits Earth about once every two hours.

Current technology allows us to detect and track the larger NEOs (larger than a few metres in diameter) and calculate their probability of hitting Earth, days, weeks, and sometimes months in advance of their closest approach. The larger the body, the further out it can be identified and tracked. At any time, there are always some NEOs, and many approaching. (A current list of NEOs can be viewed at http://neo.jpl.nasa.gov, and is updated at least daily). If a NEO large enough to be of concern were likely to hit the Earth, substantial advance warning would be given; in fact several warnings have been made public before very near misses. All significant objects on a collision course can be tracked, and their likely impact site on Earth predicted, with known uncertainty, some substantial time in advance of impact. Large bolides, however, have never been so common that they have featured prominently in human history.

Numerical estimates of the frequency of impact of a meteorite of sufficient size within a distance range of New Zealand that could cause a damaging tsunami appear to have a recurrence interval many times longer than the 2500 years considered in this project (see Appendix 3 for details of the calculation). This estimate of long recurrence interval for meteorite generation of damaging tsunami is consistent with their scarcity in human records. Because of the apparent long return period for a damaging tsunami generated by meteorite to affect New Zealand we do not consider this source further in our source characterisation.

5.2 Regional Sources

The 1-3 hours warning time for regional source tsunami presents a real challenge to monitoring and warning agencies. To locate an event, evaluate its tsunami potential and issue a warning in so short a time is problematic, requiring pre-planning and scenario development. Self-evacuation of residents will be required at short notice. As outlined in the following sections, regional source tsunami may represent a significant hazard and risk, and these may be catastrophic on rare occasions.

Regional sources include earthquakes and volcanoes (eruption and flank collapse) from tectonically active regions to the north of New Zealand, and south of New Zealand from about 50-60ºS. Sources of tsunami to the east and west are highly unlikely. Hence, the coasts most at risk from regional source tsunami are the northern half of the North Island and the southern half of the South Island.

The following sections outline what is known about the historical impact of regional source tsunami, about the sources of potentially damaging tsunami, what has been learnt and what can be learnt from numerical modelling, and from geological studies of pre-historical tsunami, as well as what is known about the frequency and magnitude of events that New Zealand might expect to experience.

5.2.1 Earthquake

In New Zealand's historical record, the largest earthquakes along the arc between New Hebrides (Vanuatu), Kermadec Islands and Tonga have been less than magnitude 8.5. Only one of these is known to have caused run-ups in New Zealand approaching 1 m. Although the record of run-ups in New Zealand may be incomplete, we would expect a large event to have been noted.

To the south of New Zealand, only a few large earthquakes have occurred since the 1960s, when the installation of a worldwide seismic network allowed large earthquakes to be identified and located. The only three large earthquakes in the last 40 years had magnitudes between 7.8 and 8.4, and all were in areas of the plate boundary where earthquakes with horizontal (strike-slip) movement occur predominantly. These earthquakes do not usually generate large tsunami and none had run-up of > 1 m in New Zealand (along the south and west coasts of the South Island).

In this section we address the potential of each subduction zone at regional distances, to generate tsunami that could produce wave heights of 2 m or more at the locations where risk is being estimated, and within the 2500 year return period considered in this risk estimation project.

Evaluation is based on opinion of the review panel and is based on the historical record of events at source and in New Zealand, numerical modelling in a few cases, and background knowledge. Comprehensive evaluation based on the scientific literature is beyond the scope of this review, as is any new numerical modelling specifically for the purpose of this review.

5.2.1.1 Southern New Hebrides

Large earthquakes of no more than magnitude 8.5 causing tsunami with run-ups of 12 m locally have occurred near Vanuatu in the central part of the New Hebrides region. The subduction zone is not well oriented to direct tsunami towards New Zealand except at its southern part, where the record of earthquakes is probably only complete since 1960.

Preliminary modelling of a magnitude 8.6 earthquake on the southern section of the New Hebrides region (Fig 5.1) indicates that this could present a significant hazard for Northland. An under-sea ridge extends north from Cape Reinga and acts as a waveguide (see the discussion of waveguide effects in Section 6.1), leading to potentially hazardous wave heights in northern North Island. Wave heights over 10m seem possible at highly amplifying sites in the far north. For the urban centres considered in the current risk-evaluation there appears to be a small possibility of wave heights exceeding 2m at those sites on the north and west coasts of the North Island. We include this source in the risk model with 600 or 2100 years recurrence, based on GPS data and rates of occurrence of small to moderate magnitude earthquakes in the New Hebrides region (Appendix 4).

5.2.1.2 Tonga, and northern Kermadec trench

Historically, earthquakes have not exceeded magnitude 8.5 in the Tonga-northern Kermadec subduction margin, and the tsunami produced have not affected New Zealand, probably because of the orientation of the zone. It is uncertain whether larger earthquakes with larger tsunami could occur and whether they could be a threat.

Therefore, we interpret the potential of the zone to produce tsunami with wave heights of 2 m or more, at the urban sites of interest for the risk evaluation, to be low, and this source has not been included in the risk evaluation.

For the purposes of tsunami warning systems and to ensure appropriate response should an event occur in the future, the zone warrants in-depth re-evaluation of the seismicity and tectonics, as well as scenario and numerical modelling to determine its potential to be a significant risk to the Northland-Auckland-Bay of Plenty regions.

5.2.1.3 Southern Kermadec trench

The c. 1000 km long southern Kermadec Trench has a moderate level of historical seismicity (263 events of magnitude 5-7 in 29 years from 1976 to 2005) originating on the shallow part (≤ 40 km depth) of the plate interface (based on thrust mechanisms). We have used this seismicity catalogue to forecast the possible recurrence interval for large magnitude earthquakes that could generate a damaging tsunami in New Zealand.

Minimum distances from the southern Kermadec subduction zone to coastal New Zealand cities and towns are at least 500 km, and using the empirical relation of Abe (1975) we can assert that only those earthquakes of about M 8.5 and above could produce a damaging tsunami above 2 m run-up in urban areas at least 500 km distant. Therefore it is the recurrence of M 8.5 earthquakes from this source that needs to be included in the risk model. From seismotectonic considerations and comparisons with other subduction margins similar to the Kermadecs (Mariana, for example) we expect that the maximum magnitude earthquake that could occur in this subduction zone is about M 8.5, but there is doubt that an earthquake of this size could be generated. McCann et al. (1979) proposed that the region is not capable of producing earthquakes larger than the M 7 event recorded in the catalogue. Alternately it may be that an earthquake of about M 8 could be the maximum possible. We introduce each of these possibilities into the risk model by weighting the likelihood that each of these alternative models is correct. Considering the short historical interval covered by the catalogue, and the occurrence of an unexpected magnitude 8 earthquake in the southern Mariana subduction zone in 1993, we consider the M 8 maximum magnitude as the most likely and weight it at 50%, and weight the magnitude 7 and magnitude 8.5 models at 25% each. Therefore the damaging tsunami generated by the M 8.5 earthquake is included in the risk model at 25% of its nominal recurrence interval.

5.2.1.4 South of New Zealand (including Macquarie Ridge)

Most plate boundary zones in the Southern Ocean are strike-slip and large earthquakes in these zones are unlikely to produce large tsunami. There are no highly active subduction zones in the Southern Ocean. The Hjort Trench (56°S-60°S) and subduction zone is the only part of the margin where orientation of the zone would partially direct tsunami towards New Zealand. However, recent studies of the Hjort trench area (Meckel et al., 2003) suggest immature subduction in this region lacking significant down-dip dimension so that large thrust earthquakes are unlikely to occur.

Historically, large earthquakes along the Macquarie Ridge (M_w8.1 earthquakes in 1989 and 2004), and further south near Balleny Islands (M_w8.1 in 1998) have been strike-slip events, producing small tsunami (less than 50 cm) in southern New Zealand. The effects of an M8.3 earthquake on the Macquarie Ridge in 1924 are not yet researched. Hence, at present, the potential of the zone to produce tsunami with run-ups of 2 m or more at the sites of interest for the risk evaluation is considered very unlikely and therefore no tsunami sources south of New Zealand are incorporated into the risk model.

5.2.2 Volcano

There are 26 volcanoes (>10 km in diameter) along the active Taupo - Kermadec arc that lie between 300 km and 1000 km from mainland New Zealand (Fig. 5.2). Three "scenarios" of how these volcanoes represent possible regional tsunami sources are:

- catastrophic submarine silicic eruption and caldera collapse
- large catastrophic sector collapse
- small, frequent, avalanching of edifice flanks.

5.2.2.1 Catastrophic submarine silicic eruption and caldera collapse

Submarine eruptions of silicic type magma can occur in a series of explosive pulses, each of which can generate tsunami. Associated caldera collapse, such as occurred at Kratatau in 1883, is another possible tsunami source.

South of 30°S, four silicic (explosive eruption style) caldera complexes have been surveyed – Macauley, Havre, Brothers and Healy – and a fifth caldera (Rumble II West) has a partial silicic composition, and may thus be tsunami-generating on occasion. Macauley is the largest caldera and source of the 6.3 ka Sandy Bay Tephra pyroclastic eruption. Estimates of the eruption volume vary; Latter et al., (1992) estimated 100 km^3, Lloyd et al. (1996) estimated a lower limit of 1-5 km^3, and recent sea floor mapping reveals an unfilled caldera volume of 17.4 km^3 (Wright et al., in press) that can be interpreted to represent an eruptive volume of 35-58 km^3. Havre is a silicic caldera volcano mantled in pumice of unknown age, but is interpreted to be older than the Sandy Bay Tephra eruption. Brothers and Healy volcanoes have <3.5 km wide calderas, and comprise explosive type lavas (Wright and Gamble, 1999). Healy was probably formed by catastrophic submarine rock and ash flow eruption with the destruction of a 2.4 -3.6 km^3 volcanic cone and formation of a caldera. The eruption is tentatively correlated with part of the Loisels Pumice of c. 600 years ago which is found along much of the eastern North Island coastline (Wright et al., 2003).

5.2.2.2 Large catastrophic sector collapse

Seafloor mapping reveals that many of the southern Kermadec volcanoes have undergone large-scale mass-wasting or sector collapse. Volumes of each sector collapse are currently undocumented. However, an upper limit to any individual sector collapse is probably 4-5 km^3 as evinced by the collapse of the western flank of Rumble III (Wright et al., 2004). Both the age of the Rumble III collapse in particular, and frequency of large sector collapse in general, are unknown, but possibly have recurrence intervals of >10,000 years for any one volcano.

5.2.2.3 Small, frequent, landsliding and debris avalanches

All Kermadec volcanoes, to varying degrees, show evidence of small and frequent landsliding and debris avalanching (Wright et al., in press). Typically these collapses are <1 km^3. The timing and frequency of such failures is almost entirely unknown, but the one example of repeat multi-beam surveys for Monowai volcano reveals the collapse of 0.03 km^3 between 1998 and 2004 (Wright unpublished data). Similar shallow failures, typically 10-300 m thick, occur on all southern Kermadec volcanoes. The recurrence interval of such events is unknown but could be 10 years for any one volcano.

5.2.2.4 Summary of Kermadec volcanoes as tsunami sources in NZ

No historical records exist of volcanic activity in the Kermadec chain producing tsunami in New Zealand or elsewhere. Therefore we have little basis for modelling possible tsunami from activity in the Kermadec volcanoes (Table 5.2, Fig. 5.3). In general, the volumes of eruptions, associated caldera collapses and the scale of sector collapse features so far identified are significantly (at least an order of magnitude) smaller than has been proposed in the literature for damaging tsunami effects at distances of 1000 km or so. Additionally, a numerical model of a 1 km^3 rock and ash avalanche entering the sea from Mayor Island in the

Bay of Plenty produced only a 0.5 m tsunami on the coast about 30 km distant (de Lange and Prasetya, 1997) so we expect that events with volumes typically 10 times larger but at 10-30 times the distance will have effects no larger than indicated by the modelling of the Mayor Island event. We have not included the Kermadec volcanoes as a potential tsunami source in our risk model. However, significant doubts remain about the source characterisation, and about the effectiveness of rock and ash flows/avalanches and collapsing high altitude eruption columns in producing tsunami that could be damaging at the 300-1000 km distances between the volcanoes and New Zealand. Volcanic unrest in the Kermadec volcanoes leading to a major eruption is expected to have a long lead time, so an extended period of preparation prior to any tsunami should be possible.

5.2.3 Landslide

No landslide sources, at regional distances, have been thus far identified that are sufficiently large or frequent to justify the inclusion of regional distance landslides into the tsunami source model for this study. However, further consideration of this potential source, by searching for giant landslides such as the Matakaoa and Ruatoria features of eastern North Island (section 5.3.2.1) along the Tonga-Kermadec and Puysegur-Macquarie margins is warranted.

Table 5.2 Summary of available data from Kermadec chain volcanoes. * = local sources < 100 km from New Zealand

Volcano	Edifice/Caldera Volume (km^3)	Eruptive Volume (km^3)	Collapse Volume (km^3)	Age of Last Event (yrs)	Frequency (yrs)
Macauley		100			
	17.4	<5		6,300	?
		35-58			
Havre	6.8	~<10		>?10,000	?
Brothers	2.8	~5		>~5,000	?
Healy	2.4-3.6	10-15		600	?
Rumble III			4.4	unknown	?10,000
Generic volcano			0.03	?2	?100
Mayor Is.*		~1		6,300	~10,000
White Is.*			0.01	?100	?100

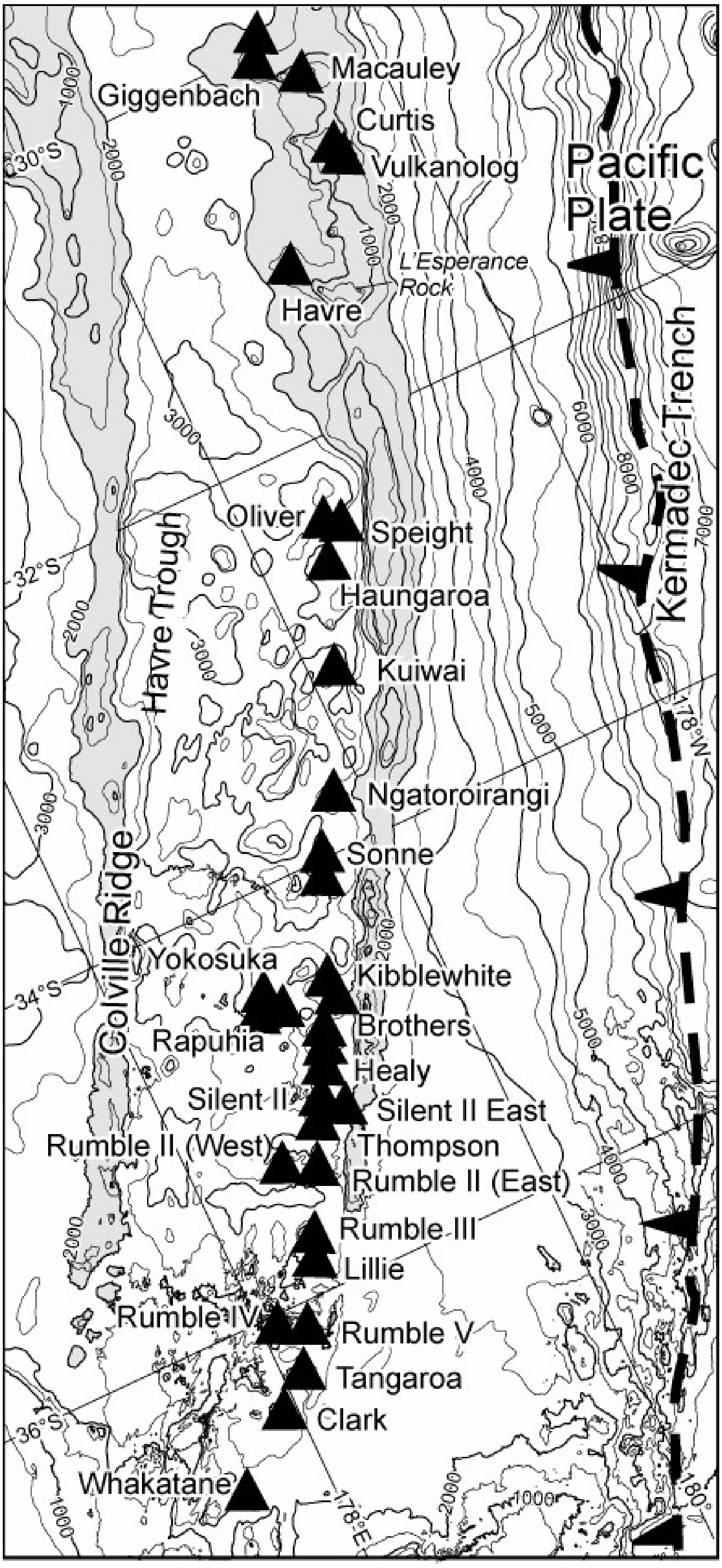


Figure 5.2 Distribution of submarine volcanoes along the southern Kermadec arc between 30°S and 36°30'S (after Wright et al. in press).

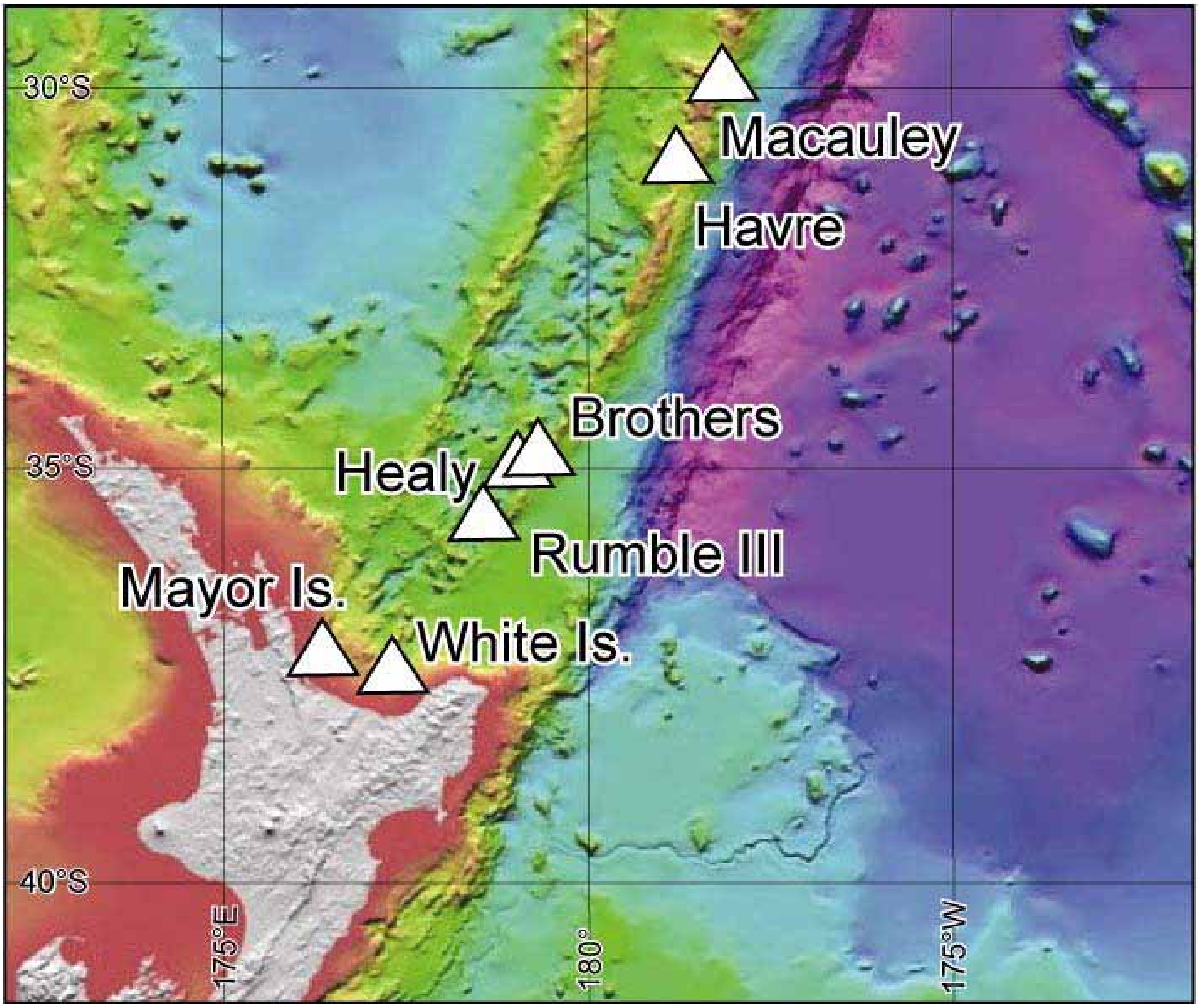


Figure 5.3 Location of possible tsunamigenic volcano sources along the southern Kermadec arc.

5.3 Local Sources

By definition tsunami, generated by local sources, arrive at the nearest coastline within an hour, and many can arrive within minutes. New Zealand's location astride a plate boundary means that it experiences many large earthquakes, some of which cause local-source tsunami. It is also exposed to local-source tsunami from submarine and coastal landslides, and island and submarine volcanoes.

5.3.1 Earthquake

Local earthquakes have the potential to produce catastrophic tsunami, with 7-10 m or more run-up, over a small length of coast (local impact, i.e. tens of kilometres of coast) or over a longer length of coast (regional impact, i.e. hundreds of kilometres of coast). The impact depends on the extent of fault rupture and seafloor deformation, which in turn depends on the magnitude of the earthquake. The tsunami resulting from a very large, 200-300 km long rupture of the plate-interface on the east coast of the North Island may affect 200-300 km or more of the nearby coast with large run-ups. Such an event could cause significant to severely damaging waves along much of the east coast and in the Chatham Islands.

Some coasts are more at risk from tsunami than others because of their proximity to areas of high local seismic activity, but no part of New Zealand coastline can be considered completely free from local source tsunami hazards. The tsunami hazard also is high around the shores of our larger freshwater lakes, although consideration of this hazard is not within the scope of this study.

Information on historical earthquake occurrence and active fault mapping in the offshore areas around New Zealand have been the primary methods of developing a local, earthquake-driven, tsunami source model. This model has been supplemented and calibrated against historical occurrence of tsunami from local sources, which have occurred on at least 13 occasions in the past 100 years (Section 3.1), and from data on paleotsunami deposits where they suggest tsunami of local origin. In a few cases numerical models of earthquakes causing sea bed displacement on offshore fault sources have assisted in assigning key parameters to the fault sources. Numerical models have been completed for normal faults in northern North Island, a reverse fault and the subduction zone in offshore Hawkes Bay and the Alpine Fault and Puysegur subduction zone in Fiordland (see Appendix 5 for a list of modelling studies). Key fault parameters required for assessment as a tsunami source include fault location and earthquake magnitude associated with seafloor rupture. We use the empirical equations developed by Abe (1979) to estimate the maximum wave height at source and as the wave height at sites of interest (see Section 6 and Appendix 5 for explanation of empirical relationships).

5.3.1.1 Tsunami sources in offshore eastern North Island

We recognise that a significant source of vertical-slip faulting exists in conjunction with the Hikurangi subduction margin off the eastern North Island. Tsunami could be generated by large to great earthquakes (M7.5-8.5) on the plate interface itself as co-seismic slip between the two opposing plates, or as rupture of steeper faults that break up through the Australian plate (see Figure 5.4).

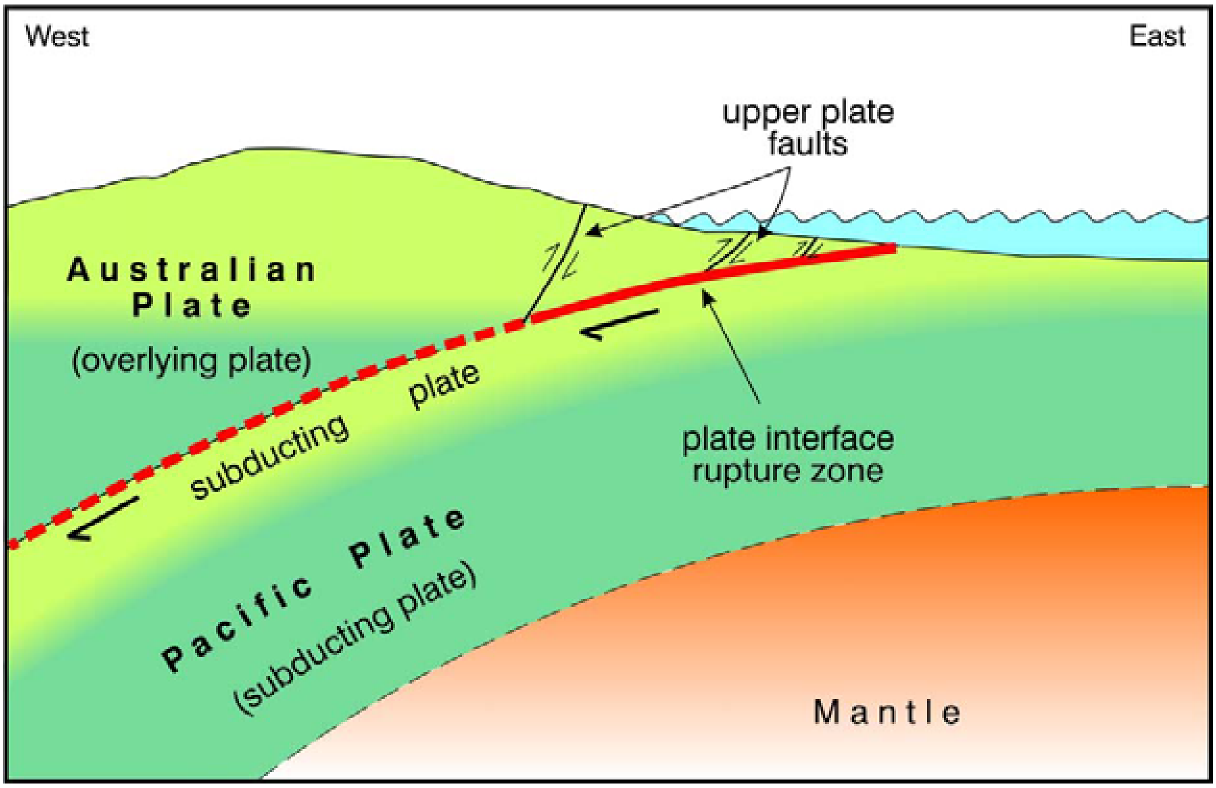


Figure 5.4 Schematic cross-section through the Hikurangi subduction zone.

NIWA scientists have mapped many faults in the offshore area from the inner shelf (~ 50 m water depth) to the deep ocean (>2000 m water depth) of the Hikurangi subduction margin (e.g. Barnes et al., 1998). This mapping has defined the subduction front and structural features on the shelf and slope. Many of these structures mimic onshore structures, having lengths of tens of kilometres and heights of up to 500 m.

Some information on fault slip rates comes from studies on specific faults such as the Lachlan Fault, offshore of Mahia Peninsula (Barnes et al., 2002) and from the presence of uplifted Holocene (c. <10,000 years) marine terraces along the east coast (Berryman et al., 1989; Berryman, 1993). Data from these linked studies provide a basis for assigning fault parameters to other structures when location and fault length are the only data available. For example, studies of the uplifted marine terraces on Mahia Peninsula and the offshore seismic stratigraphy of the Lachlan Fault show that this fault is capable of generating a large surface (=sea-bed) rupturing earthquake every 615-2333 yr (Barnes et al., 2002), confirmed by the presence of five uplift events on the peninsula in the last c. 5000 yr (Berryman, 1993). Other data that provide tie-points for assigning fault parameters include the source dimensions and magnitude of the M 7.8 Hawkes Bay earthquake of 1931.

We have assigned parameters to more than 80 faults in the continental shelf and slope part of offshore eastern North Island, where strong bedrock is interpreted to occur. Further offshore the fault structures have developed in weaker rocks that are unlikely to be strong enough to break independently in large earthquakes. We assume these "outer margin" faults only rupture in association with major subduction thrust events. Based on the length of the faults (seabed expression) and estimated slip rates, we calculate earthquake magnitude and recurrence intervals as input to tsunami source characterisation.

Subduction thrust earthquakes in the Hikurangi margin are recognised as a potential large-to-great earthquake (and tsunami) hazard. However few data are available on the timing and size of large-to-great earthquakes from this source. We have developed the source model with a range of possible earthquake sizes and recurrence intervals based on plate motion rates, GPS data where available, and summing the rates from known faults onshore and offshore as a component of plate motion. A particular difficulty is that in most subduction zones some of the movement between the plates occurs as stable sliding which does not generate large earthquakes. The Hikurangi margin is apparently more efficient at making large subduction thrust earthquakes in the southern part adjacent to Wellington than further north off the Raukumara Peninsula (Reyners, 1998). We reflect this in our assigned parameters, but uncertainties in both the magnitude of earthquake and its recurrence interval are large along the whole length of the subduction zone.

The locations of the endpoints of five subduction thrust segments have been identified and shortest distances to coastal urban centres from Auckland to Christchurch have been measured. Tsunami wave heights at these coastal sites depend on earthquake magnitude at source and the propagation distance (Abe, 1979).

5.3.1.2 Tsunami sources from faults in the Bay of Plenty

There are many active faults in the offshore area of the Ruapehu-White Island volcanic zone. These faults typically have smaller dimensions than the faults offshore of the eastern North Island, and the maximum earthquake that these faults can produce is about M 7 with 2-3 m of potential seabed displacement on a fault up to 30 km long. These relatively small sources are not capable of producing large tsunami. Based on Abe's (Abe, 1979) empirical equation linking tsunami wave height to earthquake magnitude and source-to-site distance, we expect that fault sources more than 30 km from the coast will not produce tsunami wave heights greater than 2 m (this assessment includes consideration of uncertainties in the Abe data). Thus, we have limited the fault sources in the Bay of Plenty to those less than 30 km from Whakatane. No active fault sources are known in the Bay of Plenty that are within 30 km of Tauranga.

5.3.1.3 Tsunami sources from faults near Auckland

The active Kerepehi Fault probably extends into the Hauraki Gulf about 40 km east of Auckland, and is the only offshore active fault known in the Auckland region. The fault can produce earthquakes up to about M 7, similar to those in the Bay of Plenty. At 40 km distance, we consider it unlikely that the fault poses a tsunami hazard to Auckland. In addition, de Lange & Healy (2001) completed some numerical modelling of a tsunami generated by the Kerepehi Fault source, and found it would not produce run-up of 2 m or more in Auckland. Therefore, no local fault sources are included in the tsunami hazard model for Auckland.

5.3.1.4 Tsunami sources from faults in the Cook Strait & offshore Marlborough

Numerous active faults occur in the Cook Strait area and offshore Marlborough (Barnes et al., 1998), including the offshore southern part of the Wairarapa Fault that, in 1855, generated a tsunami with 10 m of local run-up (and up to 5 m run-up in Wellington). The active faults have been characterised from their length and by assigning earthquake magnitudes based on their onshore continuations in Marlborough and southern North Island. The southern section of the Wairarapa fault ruptured into Cook Strait with at least 6 m of vertical movement, and this produced the tsunami mentioned above. Using the Abe local source equation (see section 6 and equation 6.1 for details) we calculated that the offshore section of the fault, to produce the observed tsunami run-up in the Wairarapa, Wellington, and Kapiti Coast, would be equivalent to a M_w 7.7 earthquake. We use this magnitude for the source characterisation of the Wairarapa fault. This approximation appears to be reasonable based on a recent numerical propagation model of this source (Rob Bell, pers comm.., 2005). Other Marlborough and Wellington region faults, including Wellington, Ohariu, Awatere and Wairau were modelled for tsunami hazard for the Te Papa project and found not to produce damaging tsunami because of their strike-slip character (Barnett et al., 1991). Elsewhere the largest earthquakes assigned to offshore faults in this region are M 7.5-7.8.

5.3.1.5 Tsunami sources from faults in the western Cook Strait & offshore Manawatu

An extensive marine survey in the region has recently been completed in the Manawatu-Kapiti region (Lamarche et al., 2005), and has provided valuable new insight into the location and characteristics of offshore faults in the region. These structures have a modest potential to generate tsunami (maximum earthquake magnitude of M 7.4 with c. 2000 year return period), but they may be important at short distances to urban areas on the Kapiti coast, Porirua and northern South Island.

5.3.1.6 Tsunami sources from faults in southern South Island

In the offshore Fiordland region plate boundary structures including the Alpine Fault and the Puysegur subduction zone are capable of producing large-to-great earthquakes of >M 8. This, coupled with early historical records of drownings on the south Fiordland coast, probably by a tsunami in the 1820s, has led to recent numerical simulations of tsunami generation and propagation from these sources (Walters et al., unpublished data. 2005). Because the Alpine

Fault is predominantly a strike-slip fault the structure is not considered likely to generate significant tsunami except at localised areas where the fault steps from one strand to another, and locally large vertical movements are possible. Thus, the tsunami source tends to be very localised, which could generate a large run-up locally, but it is not a very coherent source to travel as far as Invercargill. The subduction interface source that has been modelled is for a magnitude 8.7 earthquake and this is considered to be at the upper bound of what is likely. The bathymetry off the southern South Island appears to offer some natural protection to southern shores. This is because the water shallows at a substantial distance from the coast and much of the energy is dissipated in shoaling at the shelf break.

5.3.2 Landslide

Being an island nation surrounded by a large deep sea, New Zealand has a tsunami hazard from coastal and submarine landslides. Several landslides that have been triggered by earthquakes have resulted in significant tsunami, at least locally. These include a landslide and local tsunami north of Westport triggered by the 1929 Buller earthquake, a local tsunami in an estuary north of Napier triggered in the 1931 Hawkes Bay earthquake, and a local but large tsunami (4-5 m run-up) in Gold Arm of Charles Sound in the 2003 Secretary Island earthquake in Fiordland (Hancox et al., 2003). The observed sea level fluctuations that lasted for up to a week following the M_w 8.2, 1855 earthquake in the Wellington region may involve landslides, perhaps triggered by large aftershocks or as delayed slope failures.

There is no doubt that large submarine landslides feature prominently over much of the sea floor around New Zealand, and that future large submarine landslides will cause large tsunami at some time. Mass failure of sediment is a ubiquitous geological process on New Zealand's continental margin (e.g. Lamarche et al., 2003). Mass failures are recognised essentially along the entire margin from north of Bay of Plenty to south of Fiordland.

Most historical landslide-generated tsunami have been associated with earthquakes, but earthquakes are not the only cause. Wave action in large storms can trigger coastal and submarine landslides, heavy rain or a wet season can trigger coastal landslides, and a few landslides occur without an obvious trigger.

5.3.2.1 Submarine landslides

Submarine landslides on the New Zealand margin are recognised in water depths ranging from a few tens of metres to several kilometres, and sizes vary greatly from relatively small slides of < 0.25 km^3 volume (Walters et al., submitted) to giant debris avalanches of thousands of cubic kilometres. The c. 170,000 year-old, giant Ruatoria debris avalanche on the northern Hikurangi margin, with a volume of more than 3000 km^3 (Collot et al. 2001), was undoubtedly a high-speed landslide, and must have generated a large tsunami. Estimates of the likely height of the tsunami generated by this landslide vary widely (125–700 m, Barnes, pers comm. 2005), depending on which empirical formula is used. These very large landslides fortunately happen very rarely.

Off the east coast, landslides contribute to deposits in the Hikurangi and Bounty Troughs with recurrence intervals of the order of several hundred years (Carter and Carter, 1993; Lewis et al., 1998; Lewis and Pantin, 2002). Not all landslides however, disaggregate and reach such basins, and the recurrence interval for failures of various sizes in different areas of the margin is poorly known. It has been estimated that significant landslides occur about once every 200 years or so in Kaikoura Canyon (Lewis and Barnes, 1999), and as frequently as once every 13-45 years in the northern Hikurangi (Poverty) margin (de Lange and Moon, 2004). In contrast, the giant Ruatoria avalanche is thought to have occurred some 170,000 years ago (Collot et al., 2001; Lewis et al., 2004), and such catastrophic events, involving enormous sections of the margin, may be very infrequent.

Whilst advances have been made in recent years using geophysical and bathymetric data sets from isolated areas and specific landslides, there is only sparse survey coverage at the level of resolution required for a nationwide evaluation of landslide tsunami hazards. Detailed landslide geomorphology, dating of existing failures, geotechnical data concerning slope stability, and landslide recurrence intervals are lacking in most regions. Furthermore, there have been very few studies made to model the tsunami waves that could have been, or might be in the future, generated from New Zealand submarine landslides (Magill, 2001; Walters et al., submitted).

5.3.2.2 Estimating tsunami wave amplitudes from submarine landslide geomorphology

In the absence of sufficient modelling of New Zealand tsunamigenic landslides, this study uses a simplistic empirical approach to estimate the characteristic maximum tsunami wave amplitudes (H_{max}) generated at source over the centre of a landslide (Watts et al., 2003; McAdoo and Watts, 2004). This approach is based on a series of laboratory experiments in which a solid body slides down an inclined plane, and is uni-directional. From the magnitude of the wave trough that follows the blockslide other parameters such as the wave height in front of the blockslide and run-up on a sloping shore behind the blockslide, can be estimated. The approach is not applicable to landslides from the sides of submarine canyons because the slides are not uni-directional, resulting is a different wave form.

Landslides were identified in high quality submarine geomorphology datasets for an area of Cook Strait and Bay of Plenty. Key parameters in estimating maximum wave height at source by landslide generation include: average slope angle of the failure surface θ, width w, length l, headscarp height d, and water depth at the mid-point of the centre of the mass failure h_o (Figure. 5.5). The landslides examined cover a wide range of water depths from about 100 m to 2000 m, and the majority have surface areas of <5 km^2, with a maximum of 28 km^2.

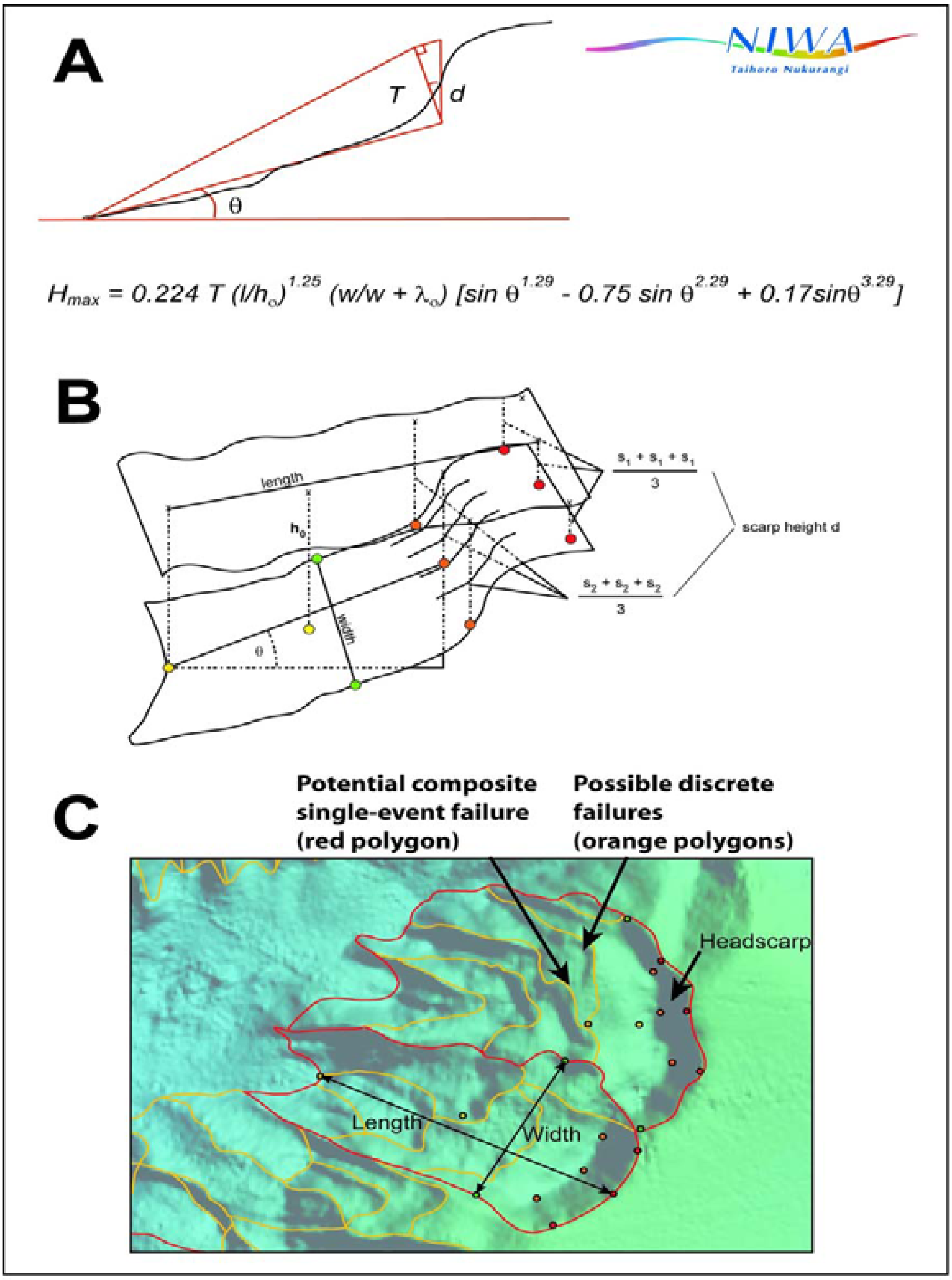


Figure 5.5 Method of derivation of tsunami wave amplitudes at source using submarine landslide geomorphology. (A). Simplified longitudinal cross-section down a translational landslide showing selected geometric parameters (McAdoo et al., 2000). (B). Geometric landslide parameters measured for application in tsunami wave amplitude equations of Watts et al., (2003), where *θ* is the average slope angle of the failure surface, *w* is the landslide width, *l* length, *d* headscarp height, T, normal thickness, h_o water depth at the mid-point of the centre of the mass failure, and λ is the characteristic tsunami wavelength at the source. (C) Example of landslides revealed in Cook Strait multibeam data showing locations of measured features in B.

Only small portions of the New Zealand continental shelf are known in sufficient detail to recognise and count all the submarine landslides there. In a 3309 km^2 portion of southern Cook Strait for which high-resolution swath bathymetry is available, 1304 landslides are recognised, and in a 2009 km^2 sample area in the Bay of Plenty, 194 are recognised (NIWA data). In both samples, the distribution of landslide areas (and, by inference, volumes) is log-normal, similar to size and frequency scaling for earthquakes. Initiation of landslides underwater is controlled by friction and pore-water pressure changes, and earthquake shaking is generally regarded as a likely trigger for most of the larger landslides. Larger earthquakes probably trigger more, and larger, landslides (as they do on land).

None of the ages of the landslides in these samples is known, although it is expected that many of the Cook Strait landslides could date from strong shaking in the M_w 8.2 1855 Wairarapa earthquake. The Wairarapa Fault has produced three other similar-sized earthquakes in the last 7000 years; but there are many other faults in the area that could produce frequent earthquakes up to about M 7.8 capable of triggering underwater landslides.

Numerical modelling represents the most tractable way of estimating the size of tsunami that any particular underwater landslide is likely to generate (e.g.. Magill, 2001; Walters, et al. submitted), but there are too many landslides for this approach to be applied at this time at a national scale. Simplistic, largely empirical relationships have been used elsewhere (Watts et al. 2003; McAdoo and Watts, 2004) to estimate possible tsunami amplitude at source but these approaches do not account for propagation of the tsunami. The amplitude and propagation of tsunami generated by landslides are critically co-dependent on water depth at source, the ratio of the width of landslide to length of run-out, the thickness and cohesion of the landslide material, the velocity of the landslide, and the orientation of the landslide with respect to sites. Variations in each of these parameters have a dramatic influence on the tsunami amplitude at source and at some distant site. The wave height at a distant shore is just as likely to depend on initial water depth or width to length ratio as it is to landslide area. Therefore empirical transfer functions cannot be easily developed without an extensive series of numerical simulations to identify the dominant parameters. This work is beyond the scope of this project.

Although there are insufficient constraints to include landslide sources as distinct tsunami sources in the risk model, we can make some general conclusions about the effectiveness of landslides in generating damaging tsunami at local distances. These include:

- Tsunami driven by landslides that initiate in shallow water (~100-300 m) are much more effective than those generated in water greater than 1000 m deep.
- Landslides with higher material density and larger volumes generate larger tsunami.
- In normal circumstances, there is a rapid reduction in wave height with distance because the tsunami is initiated at a “point source”, in contrast to the “line source” typical of fault movement initiation.

- Confining and guiding the landslide path on the sea floor is effective in focussing tsunami propagation so that the normally rapid reduction in wave height with distance is reduced.
- Coastal topography may focus the waves and result in tsunami height several times the wave height at source.

For the dominant size class of landslides identified in the Cook Strait and Bay of Plenty case study areas (1-10 km^2), originating in c. 1000 m water depth, damaging tsunami of >2 m wave height may be limited in source-site distance to less than 30-50 km. These values are at best indicative only, as there are known to be large regional variations in the occurrence of underwater landslides.

While we have been unable to explicitly include landslide-generated tsunami into the risk model for the major population centres of New Zealand, we can consider the conclusion of Watts (2004). He proposed that about 30% of historical tsunamis worldwide are likely to have been generated or enhanced by landslides. If the tsunamis were merely enhanced by a landslide contribution then, provided New Zealand and Japan are somewhat similar in this respect, the landslide effect is probably already incorporated as part of the uncertainty in Abe's (1979) empirical relation (see section 6 for discussion of the Abe relationship and its derivation from historical Japanese data). If however the tsunami were generated without a seismic trigger we should increase the hazard. We note that very few tsunami have occurred in the historical record without an association with an earthquake, so we presume that the contribution to hazard from landslides without seismic association is small, and captured within the present uncertainty of the risk assessment. We do however recommend some future quantification and modelling of the probable landslide contribution to tsunami risk. This may be particularly pertinent for the West Coast of the South Island where Alpine fault earthquakes will not in themselves generate a major tsunami, but the strong shaking could generate landslides of variable size and location, such that the resulting tsunami may not scale with earthquake magnitude.

Coastal and submarine landslides can be spontaneous, or triggered by earthquakes or by their aftershocks. They may occur during the earthquake or some time later. At the time a landslide initiates a tsunami there are no means to forecast the impending effects or to relate seismograph records, if they existed, to landslide parameters such as volume, depth, etc. Further, as seismograph records of landslides are very different from those of earthquakes, they may not trigger a GeoNet response, and even if they did, interpretation is not yet possible.

5.3.2.3 Coastal landslides

Terrestrial landslides entering the sea (or lakes), especially into deep water, can generate major but local tsunami. Some historical examples were noted in Section 5.3.2. There is no systematic monitoring of coastal cliff stability around New Zealand. At any time, there are always coastal cliffs approaching or at marginal stability, requiring only a minor trigger to collapse them.

We have carried out a qualitative assessment of this hazard in the vicinity of each of the urban centres considered in this project. Criteria for assessing tsunami-inducing coastal-landslide hazard have included:

- topography (steep, high slopes close to water).
- geology (strength and structure of rock relevant to landsliding)
- known landslides (presence and types that can be identified reaching the water)
- historical evidence – e.g. 1931 Napier, 1855 Wellington, 1929 Murchison (note – all are associated with large earthquakes. There is a much lower risk of similar landslides without earthquakes).

Whangarei	Whangarei Heads could pose a small threat. Landslides at Onerahi too small to cause significant waves.
North Shore	No risk - no steep, large slopes at coast.
Waitakere	Little risk (apart from west coast beaches and north side of Manukau Heads, which have significant landslide potential – possibly waves of a few metres over a distance of up to 1 km).
Auckland	Some risk at St Heliers - Achilles Point - Karaka Bay. Coastal-cliff collapses in the order of 100 m wide, but into shallow water.
Manukau	Probably has greatest risk in Auckland region, especially north side from Green Bay to Manukau Heads.
Tauranga	Although there are many landslides, none seem capable of more than small wave generation except for a small chance of large failures of Mount Maunganui.
Whakatane	Possibly greatest risk is from Moutohora Island just offshore. It has collapsed to the north pre-historically, and there may be a risk of collapse to the south. Whakatane headland collapse could pose a danger although rock strength is good
Gisborne	Low hazard, almost no risk. Possible nearshore uplift caused by landslides, but very rare. Hill at Titirangi has greatest potential to cause waves, but very small – only 100m high and not steep enough.
New Plymouth	Collapse of Paritutu cliffs could cause modest waves, but Whitecliffs is too far away.

Napier	Local risk on east side of Bluff Hill – small rockfalls (none into sea in 1931). Greater risk is presented by landslides between Napier and Wairoa, as in 1931, but likely to affect only limited area (<10 km).
Wanganui	Landslides at Castlecliff unlikely to cause any wave. Greatest risk of wave generation from landslide is from Shakespeare Bluff into the river. Effects likely to be small.
Kapiti	Some risk between Pukerua Bay and Paekakariki. Brendan's Beach and restaurant south of Paekakariki are at greatest risk.
Porirua	Titahi Bay - small risk. Little risk elsewhere.
Lower Hutt	Eastbourne/Gracefield/Seaview is at some risk. Some risk from Wellington fault scarp affecting Petone. Only likely to occur in association with large earthquakes.
Wellington	Coastal collapse between Ohiro Bay and Sinclair Head a hazard for south coast bays. Some risk from fault scarp collapse into harbour. Some risk in larger landslides such as at Worser Bay, but effects likely to be limited, and only likely in the event of large earthquakes.
Nelson	Possible but low likelihood of large scale movement at Tahunanui causing heave at toe of slide out to sea.
Christchurch	A small risk from rockfalls into Lyttelton and Akaroa harbours. No very large-scale landslides are apparent, and most slope instability is shallow failures in loess and regolith.
Timaru	Low cliffs at Caroline Bay/Dashing Rocks pose a negligible risk (high quality rock).
Dunedin	No large landslides, capable of causing large waves, known adjacent to Otago Harbour. Outer coast cliffs both east and west of city (Highcliff, Lawyers Head, St Clair cliffs, Tunnel Beach) have potential for landslides large enough to cause waves at coastal suburbs. At least one large prehistoric landslide (Lovers Leap) is known but in general rock appears solid.
Invercargill	May be affected by tsunami from very large landslides in Fiordland, but only as a result of very large earthquake. Otherwise very low risk. No apparent risk at Bluff Harbour.

5.3.2.4 Conclusions

- The likelihood of coastal landslides inducing tsunami is low except during large earthquakes, in which case other tsunami-generating phenomena are likely to be more important.
- The greatest potential for very large landslides is in relatively uninhabited areas of very high relief such as Fiordland, but the risk of such events must be orders of magnitude lower under static conditions than during earthquakes.

5.3.3 Volcano

5.3.3.1 Mayor Island and White Islands

Mayor and White island volcanoes are very near-field tsunami sources. Mayor Island has produced both explosive and lava flow eruptions, and includes three phases of caldera collapse. The last caldera collapse, associated with the largest eruption, occurred 6,300 years ago (Houghton et al., 1992) and included the transport of rock and ash flows into the sea. This 6,300 year ago event is probably the only recorded instance of rock and ash flow entering the sea within the New Zealand region. Numerical modelling of a credible 1 km^3 (“Mt St Helens scale”) rock and ash flow from Mayor Island, that enters the sea, would produce a 0.5 m high tsunami on the adjacent coast around Whakatane (de Lange and Healy 1986; de Lange 1997).

White Island is the emergent summit of a larger submarine volcano. Eruptions have included both lava flow and small explosive eruptions of mostly andesite (typically moderately explosive style), but including dacite (associated with a more energetic eruptive style), though the volcanic history of the volcano is poorly recorded. A small collapse of the inner crater wall in 1914 produced a debris avalanche that may have entered the sea. The active hydrothermal system weakens the volcano structure and enhances potential sector collapse on both the outer subaerial and submarine flanks.

The generation of significant tsunami sourced from White Island is considered low (de Lange and Healy 1986; de Lange and Prasetya, 1997), not least because the most likely sector collapse direction toward the east and any tsunami generated would be directed offshore. Other small caldera volcanoes and associated pumice deposits occur on the outer Bay of Plenty continental slope (Gamble et al., 1993; NIWA unpublished data). Based on the low likelihood of damaging tsunami indicated by these specific modelling studies, we find no reason to add these volcano or landslide sources to the tsunami source model in this project.

6.0 TSUNAMI PROPAGATION

In this Section we first give an overview of what has been learnt from numerical modelling of tsunami. We then briefly discuss the amplitude-distance relationships used to estimate wave heights from distant and local tsunami sources. These estimates of wave heights at the coast were then used as input into inundation models (Section 7).

6.1 Insights from numerical modelling

Numerical modelling of tsunami serves a double purpose: it allows us to estimate the effects of events which have yet to happen, and it enables us to evaluate our understanding of past tsunami.

The process of numerical tsunami modelling can considered as three stages:

- Source modelling, in which the generation of the tsunami, either by earthquake, landslide, volcano or bolide impact, is simulated.
- Propagation modelling, in which the dispersal of the tsunami waves around the ocean, sea, or lake, is simulated.
- Inundation modelling, in which the water flow over dry land is simulated.

The modelling process is usually performed using specially designed computer programs. The latest 3-dimensional tsunami models simulate both propagation and inundation, overcoming the difficulty of changing boundary conditions at the shore, which is the most dynamic and complex phase of a tsunami.

Tsunami source models are well developed for earthquakes, where the surface deformation is estimated by assuming that the earthquake represents a finite dislocation within an elastic body. These techniques have been tested against data from numerous real events and generally demonstrate a reasonable agreement, although the 26 December 2004 earthquake has highlighted some areas for improvement (Lay et al, 2005). Both landslides and volcanoes tend to have great variability in the mechanisms by which they initiate tsunami, and the physics of those mechanisms is in some cases only partly understood. Consequently, while modelling of past events can be undertaken, and specific scenarios for future events can be investigated, it is harder to develop general insights.

Propagation modelling, in which the processes by which tsunami waves spread out from the source are simulated, is well understood in terms of the underlying physics, though uncertainty in some parameters remain. This area of modelling is now at a stage where many useful insights can be gained (see Figures 6.1 and 6.2 by way of illustration).

Inundation modelling is an area in which numerical modelling is at a preliminary stage because of limitations of resources and data availability. There are many different processes taking place during inundation, each of which may be well understood in isolation, but effective modelling of the combined processes remains challenging. Developing high-resolution models can capture these processes but are time-consuming and require high capacity computing. Useful insights for inundation modelling can be gained from studying the impacts of real tsunami.

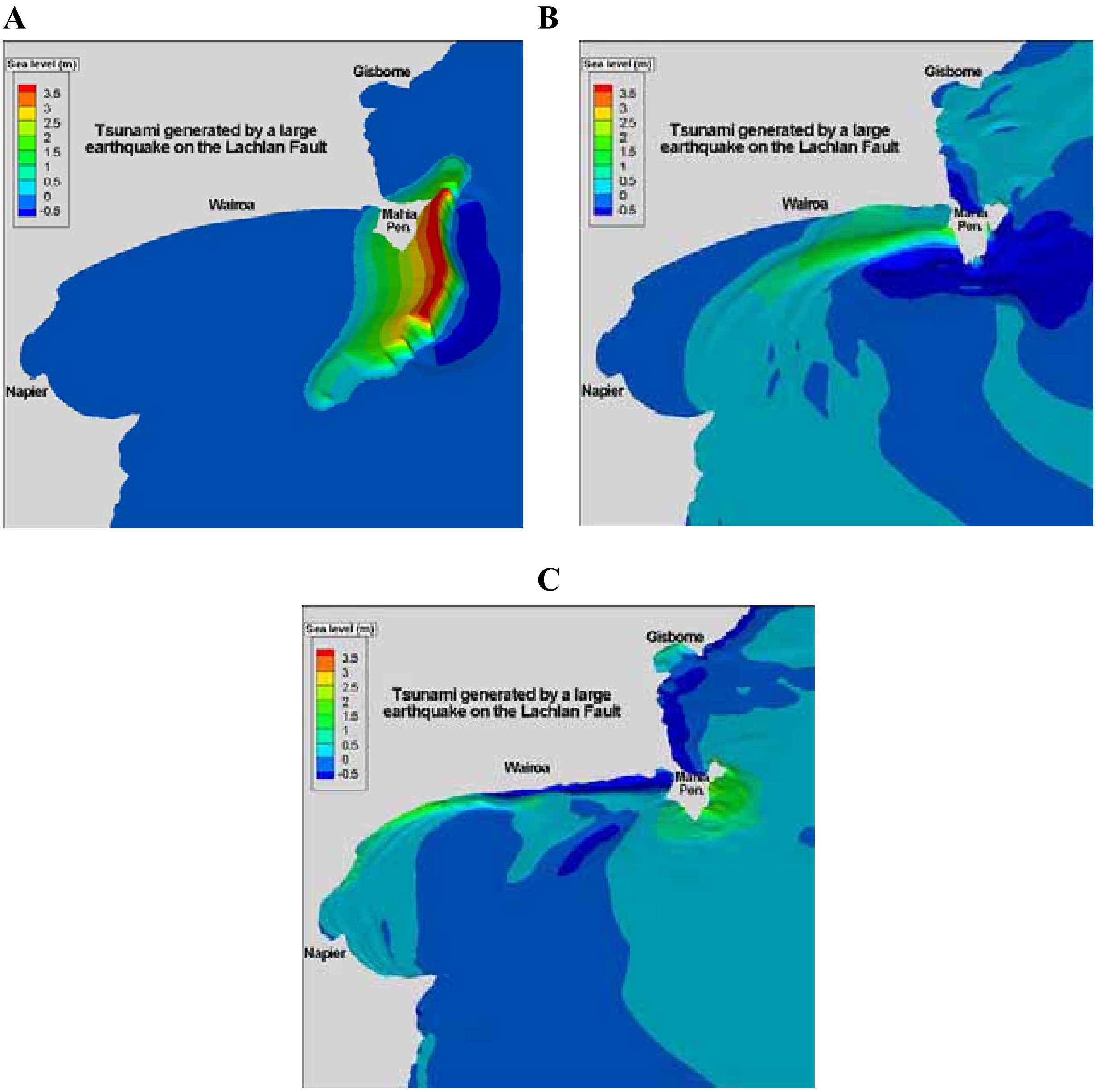


Figure 6.1 A series of images illustrating the propagation of a tsunami generated by an earthquake on the Lachlan fault. Modelling by Roy Walters (NIWA) for the Hawke's Bay Aquarium.

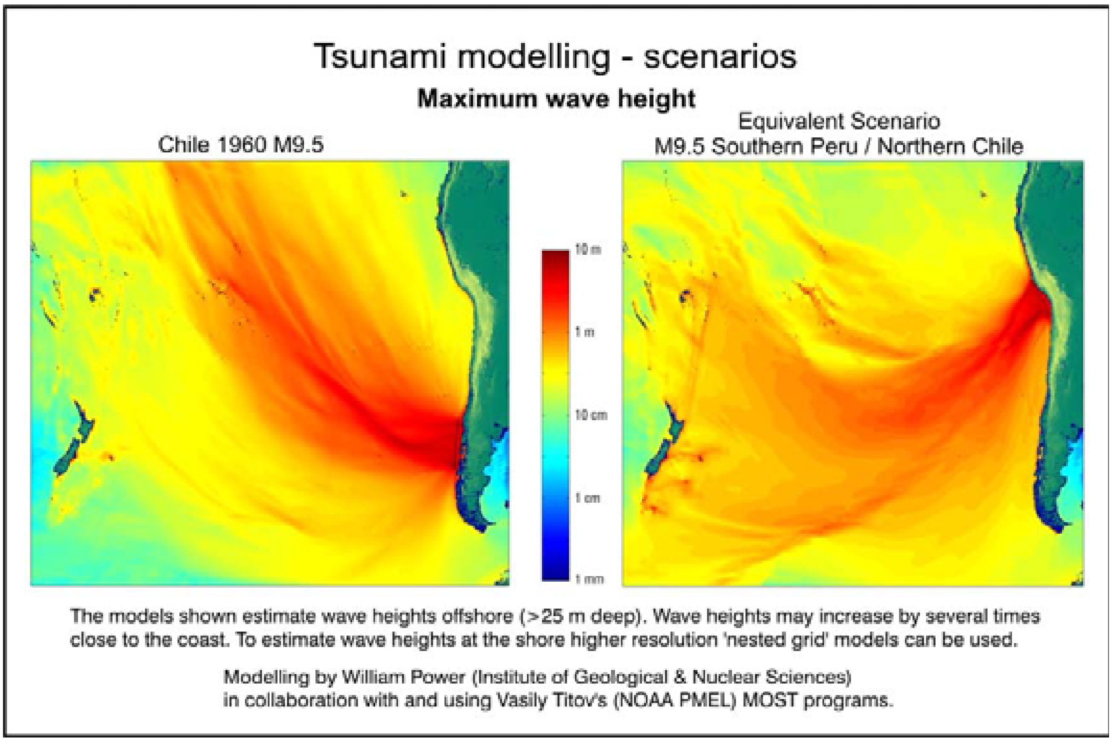


Figure 6.2 A comparison of two scenarios for South American tsunami affecting New Zealand, illustrating the effect that directivity of the source can have on distant locations.

Some general insights from numerical modelling:

- Earthquake-generated tsunami typically propagate in such a way that most of the wave energy is directed perpendicular to the fault on which the earthquake occurred, and the initial wave is separated into two components travelling in opposite directions.
- Landslide sources can be highly directional, sending a fairly concentrated tsunami 'beam' perpendicular to the slope which has given way and in the direction of the landslide movement (Ward, 2001; Walters et al, submitted). Many volcano sources can also be highly directional, but more typically radiate in a circular pattern.
- Where the dimensions of the tsunami source are small, less than a few 10's of km in the case of ocean sources, the resulting waves are subject to dispersion, in which the different frequencies present in the tsunami wave propagate at different speeds. This leads to a stretching-out of the tsunami wave train, and generally lower amplitudes. This is one reason why landslides and volcanoes tend not to be a tsunami risk at large distances.
- Tsunami waves tend to become concentrated above undersea ridges because of refraction. In this situation the ridge acts as a 'waveguide', which can lead to enhanced tsunami wave heights at locations where these ridges lead to the shore (Koshimura 2001). In New Zealand a good example is given by the Chatham Rise, an area of shallow bathymetry which lies between Banks Peninsula and the Chatham Islands. The presence of this ridge leads to larger wave heights reaching Banks Peninsula than would otherwise be the case.
- Bays and inlets around the coast have specific natural frequencies, determined by the time it takes for water to slosh into and out of the bay (e.g. Walters & Goff, 2003). If the natural frequency of a bay matches that of the tsunami waves then amplification will occur. This can often explain variations in tsunami height, which may at first appear

random, along a given section of coastline. Identifying the natural frequencies of coastal bays and comparing them with characteristic frequencies for tsunami is a useful first step towards identifying those areas most at risk.

Specific insights regarding New Zealand:

- Of the South American tsunami sources, it is those lying between the Peru-Chile border (19°S) and the 8°S line of latitude, which are most effective at directing tsunami towards New Zealand. The tsunami of 1868, which was the worst distant source tsunami of historical times in this country, originated from the southern half of this region (about 17.7°S). The last large tsunami from the northern half of this region (about 12.5°S) was in 1746, too early to appear in written records in NZ, but modelling suggests that such tsunami are likely to also have a strong impact here. Locations on the east coast of New Zealand tend to be the most vulnerable to South American tsunami, but the ability of tsunami to bend around corners in the coastline, means that they can still pose a hazard to locations which are out of the line-of-sight.
- Distant tsunami originating from locations in the Northern hemisphere, such as Cascadia, and the Aleutians, and also from areas of the southwest Pacific north of New Zealand, tend to have their greatest impact on Northland, the Coromandel, and the Bay of Plenty.
- Local tsunami generated by submarine landslides and thrust faults can have a large local impact on the east coast of New Zealand from Kaikoura northwards to Northland.

Numerical modelling of relevance to New Zealand is tabulated in Appendix 4.

Problems and limitations of tsunami modelling:

- In many areas of the world, including New Zealand, there are very limited data on, for example, wave period, number of waves in the tsunami, and variability along a coast during historic tsunami which can be used to validate models.
- A critical input to propagation models is the bathymetry of the seafloor. This is because the speed, and ultimately the direction, of the tsunami are controlled by the depth of water. Consequently the model results are only as good as the bathymetry data allow. Much good bathymetry data exists, but the processes of combining different sources of bathymetry and processing it into the required form is one of the most labour-intensive aspects of tsunami modelling. The proprietary nature of many bathymetry databases is also an obstacle to the preparation and use of bathymetry grids for tsunami modelling.
- Most propagation models assume that coastlines behave as perfect reflectors of tsunami waves, but this omits the natural dissipation of tsunami energy which occurs when they run up against the shore (Dunbar 1989), leading to a gradual reduction of the accuracy of the model. This is a particular problem for modelling the effect of tsunami from distant sources, as incoming waves may arrive over the course of several hours and interact with earlier waves, especially in locations where tsunami waves may become 'trapped' within bays and inlets.
- Inundation modelling requires detailed data on the topography of the areas being considered, ideally with a vertical resolution of less than 0.25 m. Currently there are very few areas of New Zealand which have topography mapped to this resolution. High-resolution inundation modelling also benefits from data on the size and shape of buildings and on the nature of different land surfaces, e.g. whether forested, cultivated, urban, etc. Ideally the nearshore bathymetry and on-land topography and cultural roughness can be

obtained as a seamless digital elevation dataset to enable simulations using the full power of high resolution hydraulic modelling software.
- Source characterisation represents a problem for tsunami modelling. Where models are used for real-time forecasting it is usually only possible to determine very basic information on the characteristics of the source in the time available. This problem also applies to modelling of past tsunami because there may be little source information available. This is particularly true for local-source tsunami because the waves are often strongly influenced by the details of the source, for example the distribution of fault-slip in an earthquake. Deep-water wave buoys maybe useful in forecasting the potential effects of distant tsunami, as they "record" the source characterization in that particular event.

6.2 Estimating wave heights from distant-source tsunami

Based on a compilation of historic, largely Pacific Ocean, data, Abe (1979) proposed the following equation for estimating the wave height, H, of a tsunami at a distant shore due to an earthquake of magnitude M_w

$$H = 10^{(M_w - B)} \qquad 6.1$$

where B is a parameter that varies for each site and earthquake source. B can be determined using either historical data, or numerical modelling, or a combination of both. The data that Abe (1979) based this equation on has considerable scatter, so the relationship has significant uncertainty. This has been incorporated into the calculations in this study, and are discussed in more detail in Appendix 5.

Five distant source regions were identified in this study:
- Region 1: South America between 45°-19°S and 8°-0°S
- Region 2: South America between 19°S and 8°S
- Region 3: Cascadia (NW USA and Vancouver Island, Canada)
- Region 4: West Aleutians / Rat Island
- Region 5: Southern New Hebrides

Region 5 is strictly speaking a regional source, as the travel time to New Zealand is just under 3 hours, however it was convenient to describe this source here.

The historical evidence suggests that the South American sources are the most important of these regions. Historical data for Region 1 come from the tsunami of 1877 and 1960, and data for Region 2 come from the tsunami of 1868 and 2001. Some sites have no historical data for these events, in these cases numerical model results were substituted. The model used for this substitution was chosen on the basis of giving the 'best-fit' to the data at sites where observations were recorded.

The historical data, and models of historical events, were not themselves sufficient to accurately quantify B for all sites and sources, so additional synthetic (non-historical) scenarios were used. Two scenarios each were modelled for Regions 1 and 2, and one scenario each for the other Regions. Within Regions 1 and 2 the locations for the synthetic earthquakes were chosen to represent the geographical spread of possible event within the regions.

This combination of tsunami-height information from historical observations, reconstructions of historical events, and synthetic models, was then used to estimate B for each site and source region. More details of this analysis, including the uncertainty treatment, are given in Appendix 5.

6.3 Estimating wave heights from local source tsunami

For local source tsunami, the equivalent Abe relationship to that used for distant sources is given by

$$H = 10^{M_w - \log R + 5.55 + C} \qquad 6.2$$

where H is the wave height at a local coast, *R* is the source-to-site distance and *C* is a parameter that varies for each site and earthquake source. The best available values of *C* are derived from Japanese data and have possible values of 0.0 and 0.2, depending upon location. For our analysis we have used both values with equal weight. This equation estimates the tsunami height based only on earthquake magnitude and distance, and takes no account of the effects of bathymetry or source orientation, consequently it is important to take into account the uncertainty in its estimates. More details of this analysis, including the uncertainty treatment, are given in Appendix 5.

7.0 INUNDATION MODELS

Estimating inundation has been one of the most difficult aspects of this project for the several reasons. Most importantly, the number, heights and wavelength of future tsunami waves will be highly variable depending on source, propagation, and shoaling effects. This variability is combined with very complicated flow of water across rough surface topography. Features such as dunes and coastal vegetation, buildings, topographic irregularities and rivers all significantly affect where, and to what depth, inundation will occur. In the future numerical models incorporating some of these complexities will provide more confident scenarios of particular inundation, but for the purposes of this study where a rapid, New Zealand-wide review, using only existing data, was established as the terms of reference, an alternative approach has been needed.

Our approach has been to develop, in a Geographic Information System (GIS), a series of alternate inundation models, developed from basic empirical relations, which we expect will bound the range of possible inundation. Also, our task is to obtain an overview of national and regional risk, not to explicitly model any individual tsunami inundation. We expect that the complexities noted above will be "averaged-out" through the loss model calculations. In other words we have not searched for or advocated a correct model, but rather the inundation will be no more than an upper bound (maximum inundation) model, and no less than the lower bound (least inundation) model. This approach is thus completely consistent with developing probabilistic risk estimates with imperfect data.

Three inundation models were run within ArcINFO GIS. A simple numerical model was also run for Christchurch to obtain calibration of the average acceptability of the three GIS-based models.

The key data layers used in the modelling were elevation and ground roughness. Elevation data were obtained from local authorities and used to create DEMs (digital elevation models) with a 10 m cell size. Typically the raw data were contours at 2 m intervals derived from photogrammetry, but in some areas there were spot heights derived from LIDAR, and in a few areas there were existing DEMs. In some areas contours with 10 elevations were the best data available. Table 7.1 details the data types available for each area. The DEM was used to create a grid of slope values for each study area.

Roughness data were created by extracting land use data from the LINZ 1:50 000 topographic database and converting the polygon data to a grid. The roughness values applied in this process were those used in the Tsunami Risks Project of the UK Tsunami initiative (http://www.nerc-bas.ac.uk/tsunami-risks/) and are shown in Table 7.2 with one addition for river areas used in two of the models and one average value used in the fourth model.

Table 7.1 Elevation data type and resolution used to build DEMs for inundation modelling.

TERRITORIAL AUTHORITY	DATA TYPE	CONTOUR INTERVAL AND/OR SPOTHEIGHT SPACING AND/OR DEM RESOLUTION	COVERAGE
Auckland City	Contour	1m	whole TA
Manukau City	Contour	2m urban, 5m rural	whole TA
Waitakere City	Contour	2m	part TA
North Shore City	DEM	10m	whole TA
Christchurch City	Spotheight	c.2m	whole TA
Dunedin City	Contour	2m urban, 10m rural	part TA
Gisborne District	Contour	0.5m below 20 m, 1m above 20m	part TA
Hastings District and Napier City	DEM	10m	whole TA
Lower Hutt City	Contour	0.5	part TA
Wellington City	Contour	2m	part TA
Porirua City	Contour	2m	part TA
Kapiti Coast District	Contour	0.5m	part TA
	Spotheight	c.4m	
Invercargill City	Contour	1m	part TA
Nelson City	TIN	unknown	whole TA
Tauranga District	Contour	1m	part TA
Whakatane District	Spotheight	10m	part TA
Timaru District	Contour	2m	part TA
New Plymouth District	Spotheight	2m	part TA
Whangarei District	Spotheight	10m	part TA

Table 7.2 Roughness coefficients used in modelling tsunami inundation, terrane types for which they were originally defined (UK Tsunami initiative), and as used in this modelling.

ORIGINAL MODEL	TERRAIN TYPE MODELS 1 AND 2	MODEL 4	ROUGHNESS COEFFICIENT
Mud flats, ice, open fields without crops	Default areas		0.015
Built-up areas	Residential areas		0.035
City centre	City centre		0.1
Forests, jungles	Trees, forest		0.07
	Rivers, lakes		0.007
		All terrains	0.040

The first (Model 1) was described in the UK Tsunami initiative for inundation on flat-lying coastal plains. The original equation for inundation distance from the shore (X_{max}) was

$$X_{max} = 0.06 H_0^{4/3} / n^2 \quad 7.1$$

where $\mathbf{H_0}$ is the wave height at the coast, and **n** is the surface roughness coefficient.

This equation was modified for the work in Hawke's Bay (McSaveney and Rattenbury 2000) and Wellington to include a slope factor

$$H_{loss} = (167\ n^2 / H_0^{\ 1/3}) + 5\ \sin S \qquad 7.2$$

where $\mathbf{H}_{loss}$ is the loss in wave height per metre of inundation distance, $\mathbf{H}_0$ is the wave height at the coast, **n** is the surface roughness coefficient, and **S** is the slope.

The equation was implemented using the ArcINFO cost-distance function which determines the least cumulative cost to travel over a cost surface. The source for the function is a grid of cells representing the sea, and the cost surface is a grid of cells representing the loss in wave height ($\mathbf{H}_{loss}$) as determined by equation 2 with **n** being read from the roughness grid and **S** being read from the slope grid. One issue with this model is that the cost grid must be calculated before the cost-distance function is run. The cost (in terms of roughness) is independent of travel direction and is not a problem, whereas the cost in terms of slope is dependent on travel direction. The issue is that the slope function in ArcINFO determines the absolute value of the maximum slope using the DEM and this may or may not be the slope in the direction of movement. As a consequence the model will tend to underestimate inundation distance. The model was run at a cell resolution of 10 m.

The second model (Model 2) was taken from the US Army Corps of Engineers publication (Camfield 1980) and has not been previously used in New Zealand. The equation for relative wave run-up (R/hs) is

$$R / h_s = (1+A)(1+2A)/(2A^2)\ (1 + (8gn^2 / 0.91\ A^2 S\ h_s^{1/3})) \qquad 7.3$$

where **R** is the run-up, hs is the wave height at the coast, and A is an experimental constant (taken as 0.5), **n** is the surface roughness coefficient, g is the gravitational acceleration (9.8 m/s^2), and **S** is slope.

The equation was implemented using the same source and roughness grids as used for Model 1. The model moves the tsunami inland from the coast by visiting each cell and calculating the eight possible water heights at that cell based on information gathered from each of the eight neighbouring potential source cells. The model used the current water height in an adjacent cell, the ground slope between that cell and the cell being processed, and the average roughness of the two cells to estimate a new water height using equation 3. Once each neighbouring cell had been processed the maximum water height was used to populate the cell being processed. Only cells that had not already been populated were investigated in successive iterations. By this process the water moved from the coast inland cell by cell. Initial runs of this model showed promise but also a limitation in that the water tended to travel only normal to the coast and areas in the lee of hills were protected from inundation even when the difference in height of the water in adjacent cells was large. This was the result of the processing technique and was considered unlikely to occur in the real world. The model was changed to allow previously populated cells to be recalculated at subsequent iterations and the cell value changed if the maximum possible water height calculated for a cell at that step was greater than that already in the cell. This effectively allowed water to flow in any direction. Where flows were down slope, the results of equation 3 were ignored and the water depth was kept constant. Allowing the model to revisit previously calculated cells resulted in long run times and it was proved necessary to run this model with a cell resolution of 50 m.

The third model (Model 3) was a simple bath-type model which allowed a wave to flow inland until it reached an elevation equal to the wave start height. The model pays no attention to roughness or slope. As a result, waves run further inland in areas of low slope in this model as roughness in the other models impedes wave progress, but not as far inland in areas of high slope as run-up in the other models is increased in such areas.

Once each model had been run for initial shoreline tsunami wave heights of 2, 4, 6, 8, 10, 12, 14, 16, 18, and 20 m, inundation levels for each mesh block were determined by dropping the mesh block centroid on to the inundation models and the cell value at the point recorded.

For cities with estuaries and harbours, two variants of Models 1 and 2 were run. Data from the 1960 tsunami at Whangarei indicate that a wave height of approximately 2 m at the open coast was attenuated across the harbour to 1 m at the wharf (a distance of just over 17 km). Variant 1 (Model 1a and Model 2a) modelled an initial wave that started at the open coast and used a roughness on the harbour area to attenuate each wave by 1 m as it approached the wharf. Variant 2 (Model 1b and Model 2b) attenuates the initial wave to half its original height as it crosses the harbour. These adjusted roughness values were significant in loss estimation for Lower Hutt, Whakatane, Dunedin, Invercargill, Gisborne and Timaru (see Section 7.1 for further discussion).

The fourth model (Barnett, 2005) was run for a wave reaching 6 m wave at the Christchurch coast. The model assumes the wave travels along a straight axis with lateral variation in the topography introduced by means of cross-sections. The cross-sections were created from data extracted from the elevation model used in the GIS modelling, with heights extracted every 10 m along lines space 100 m apart normal to the direction of wave travel.

A wave shape at the coast was developed by propagating a solitary wave shape at 1000 m depth along a transect perpendicular to the coast, while attempting to match a specified peak height at the coast. The resulting wave was routed over the terrain model and inundation levels and fluxes determined for every 100 m. The model used a fixed roughness coefficient of 0.040 (see Table 7.2 above for values used in Models 1 and 2).

The modelled inundation levels for a 6 m tsunami at the coast near Christchurch are shown in Figure 7.1 and percent area flooded and inundation depth (to illustrate the effect of these alternate models) are shown in Table 7.3. In Table 7.4 we show the effect of alternate inundation models on losses (their derivation is discussed in Section 8), in order to illustrate the effect that uncertainty in inundation models has on risk.

Table 7.3 Summary of inundated area and mean inundation depth from the five models for a 6 m tsunami at Christchurch.

MODEL	INUNDATED AREA (km^2)	INUNDATED AREA (% of land in model)	MAXIMUM INUNDATION DEPTH (m)	MEAN INUNDATION DEPTH (m)	STANDARD DEVIATION (m)
1a	13.4	3%	6	2.4	1.54
1b	12.6	3%	6	2.3	1.55
2a	51.5	12%	6	3.2	1.58
2b	51.5	12%	6	3.1	1.57
3	120.6	26%	6	2.5	1.48
4	58.1	41%	7.37	2.3	1.54

As can be seen for the 6 m tsunami at Christchurch in Figure 7.1 and Table 7.3, Model 1 inundates the smallest area (13 km^2 or 3% of the land area in the Christchurch model). Model 3 inundates the greatest area (121 km^2 or 26% of the land area). The area inundated by Model 2 (52 km^2 or 12% of the land area) is between that inundated by other two models. This pattern generally holds true for the other modelled areas. The area inundated by Model 4 (58 km^2) is greater than in Model 2 even though it does not extend as far north as that model. Model 4 was not run for other areas.

Maximum and mean inundation depths (Table 7.3) are similar for Models 1, 2, and 3 whereas those for Model 4 are lower. As discussed above, inundation depth at any point where the ground rises steeply will be greater in Models 1 and 2 than in Model 3 due to the run-up factor that is built into those first two models.

Also evident in Figure 7.1 and Table 7.3 are the small differences in inundated area between the variants of Model 1 (1a and 1b) and Model 2 (2a and 2b) when compared to differences between Models 1, 2, 3, and 4. As discussed above, these variants (1a and 1b, 2a and 2b) were an attempt to model the effect of harbours and estuaries. Inundation extent and mean inundation depths also show less variation between Models 1a and 1b and Models 2a and 2b than between Models 1, 2 , 3, and 4. The small differences between variants of Models 1 and 2 are in this instance due to the short length of the Christchurch estuary. For other modelled areas, where the harbour or estuary is longer, the variation between Models 1a and 1b and Models 2a and 2b increases.

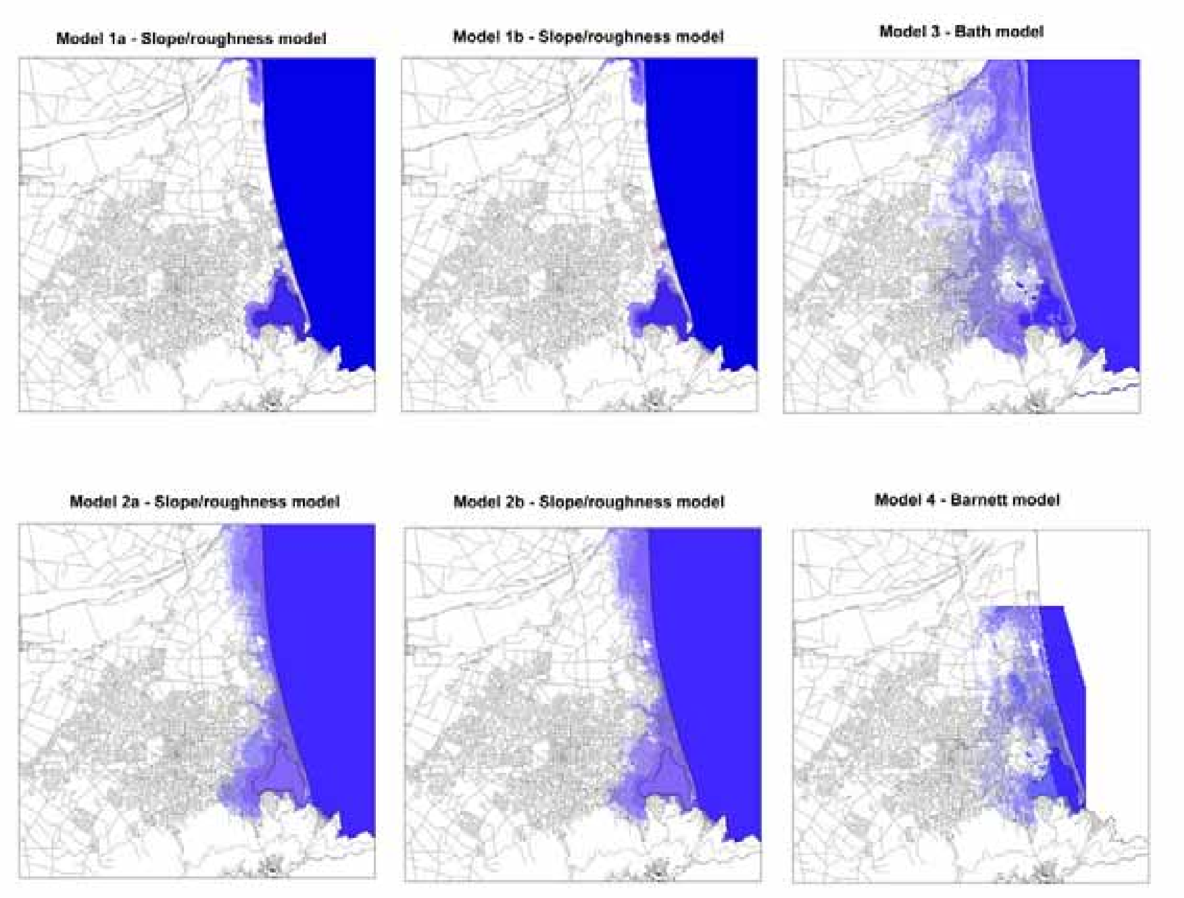


Figure 7.1 Modelled inundation from 6 m tsunami at Christchurch from the four models. Model 1 produces the least inundation. The differences between 1a and 1b are minimal since the different roughness factors used to attenuate wave height across estuary have little effect over such a short distance. Model 2 produces larger inundation, and again the differences between 2a and 2b are minimal. Model 3, the simple "bath" model produces the greatest inundation. Model 4 produces a result similar in extent to Model 2 but with generally shallower depths of water.

Table 7.4 Losses and casualties arising from four inundation models (1, 2, 3 & 4) and two harbour attenuation models (a & b) for a nominal 6m tsunami impacting Christchurch. The upper table gives the estimated losses, and the lower table gives the ratios between them, with model 4 being taken as a reference.

Model	Shoreline Tsunami Depth (m)	Deaths	Injuries	Losses ($millions)
1a	6.0	120	740	720
1b	6.0	100	670	700
2a	6.0	1,400	5,500	3,700
2b	6.0	1,300	5,100	3,500
3 (bath)	6.0	2,900	16,000	11,000
4 (Barnett)	6.0	1,700	8,800	6,000

Model	Ratio Compared to Model 4			
	Shoreline Tsunami Depth	Deaths	Injuries	Losses
1a	1.0	0.1	0.1	0.1
1b	1.0	0.1	0.1	0.1
2a	1.0	0.8	0.6	0.6
2b	1.0	0.8	0.6	0.6
3 (bath)	1.0	1.7	1.8	1.8
4 (Barnett)	1.0	1.0	1.0	1.0

7.1 Limitations in Inundation Modelling

In the introduction to this section we explained why the empirical GIS approach has been taken in this study. The limitations noted above with respect to that approach should be kept in mind. In addition, we have also identified other technical limitations within the range of empirical models utilised. These are discussed below.

Parameter sensitivity testing of Models 1 and 2 showed that the extent of inundation was highly susceptible to changes in roughness. The roughness values applied to terrain types were those published with Model 1, with some additions. It was not possible to test if these values were appropriate for this implementation of the inundation models. Land use data from the LINZ 1:50 000 topographic maps was used to assign roughness values to the model without any checking of the correctness of the land use. In some areas the database is known to be out of date. No roughness is used in Model 3. Model 4 used a single average roughness value.

Sensitivity testing of Models 1 and 2 showed slope was a less important parameter than roughness. Models 1 and 2 used data of differing resolution (10 m and 50 m respectively). As a consequence, slope values used in the two models for any area will differ slightly. Maximum slope values extracted from the two resolution elevation models for the study area in Whangarei are 5.4^{o} (Model 1) and 4.6^{o} (Model 2) and the mean slope values are 5.1^{o} and

3.9^{o} respectively. In addition, the slope value used by Model 1 is always the maximum slope rather than the slope in the direction of travel and is a further source of error.

Inundation models 1 and 2 only include roughness and slope parameters. The equation used in Model 2 includes wave velocity as a function of wave height and it appears that the equation used in Model 1 may do so as well. Both models assume an unlimited supply of water (more appropriate to distant- than local-source tsunami) and no attempt has been made to modify this by calculating wave volumes.

The inundation models used were developed from published empirical relations developed using small physical models in laboratories and with limited comparison to real events. Little good historical data of tsunami inundation in New Zealand is available to assist in model calibration and results of inundation modelling could only be compared with results from other modelling or expert opinion (e.g. DTEC Consulting, 2001). Consequently, we cannot have a lot of confidence in any one model. However, we can see that Model 3, the "bath tub" model is certainly a worst-case, and this shows up in the sensitivity testing. The bath-tub model is incorporated into the probabilistic modelling as a lowly rated model, along with Model 1b that has maximum roughness and very little inland dimension to inundation. These two models at the optimistic and pessimistic ends of the inundation range and are considered to be at 2 standard deviations from the mean in a Normal distribution.

Two variant models, designated "a" and "b" were used for the attenuation of tsunami waves travelling along lengthy harbours. Model "a" used the assumption that the tsunami wave would lose 1 m of height in 17 km of travel over the water and/or mudflats of the harbour, and model "b" that a 50% loss in wave height would occur over the same distance. Model "a" nearly always resulted in higher losses than Model "b". Thirteen of the study localities were affected by the models. For six of them the differences between the losses estimated using two variants were zero or negligible (<20%) i.e. for Tauranga, Whakatane, Hawke's Bay, Porirua, Nelson and Christchurch. For two (North Shore and Dunedin) the differences were moderate (20% to 50%) and for five (Whangarei, Waitakere, Auckland, Manukau and Invercargill) they were considerable (> 50%).The variant giving the highest losses, "a", was used in the probabilistic modelling.

Two of the inundation models, Models 1 and 2, required a high-resolution elevation model whereas the third inundation model, Model 3 (Bath model), was able to make use of a low-resolution elevation model that covers all of New Zealand. A problem encountered was that the high-resolution model did not completely cover all of the potential asset inundation areas in some of the localities being modelled, with the result that Models 1 and 2 were in this respect constrained to underestimate the losses in those localities. Two arbitrary ways of estimating the losses for the areas lacking high-resolution coverage were used, (a) the losses were assumed to be zero, and (b) the losses were assumed to be half of those generated by the bath inundation model.

Methods (a) and (b) should give identical loss estimates for localities with complete high-resolution coverage, whereas for localities with incomplete high-resolution coverage method (b) will give higher losses than method (a). Localities for which the differences between methods (a) and (b) were zero or insignificant (<10%) were Whangarei, Waitakere, North Shore, Auckland, Manukau, Tauranga, Hawke's Bay, Porirua, Nelson, Christchurch, Wellington and Kapiti (12 in total). For one locality (Hutt) the difference was moderate, 5% to 50% depending on the type of loss (deaths, injures or dollars) and the height of wave. For 5 localities (Whakatane, Dunedin, Invercargill, Gisborne and Timaru) the differences were considerable (>50%) indicating a poor level of coverage by the high-resolution elevation model.

Method (b) was the one adopted for use in the probabilistic loss modelling on the grounds that it at least gave non-zero estimates for the components of loss arising in places not covered by the high-resolution elevation model.

8.0 ASSET REGISTERS & FRAGILITY MODELS

8.1 Building Assets Model

The building assets model comprises estimated replacement values and floor areas for all buildings in New Zealand, aggregated to census data held by Quotable Value New Zealand (QVNZ) and described as “meshblocks”. In all there are 38,000 such data aggregates, each of which has been associated with a single geographic location, the centroid of the meshblock. Within urban areas the spacing between the point locations is about 100m, increasing to roughly 1-10km in sparsely populated rural areas.

The base data for the buildings model were aggregated rating values, floor areas and plan areas. Replacement values, which are required for loss modelling, were estimated from the base data by using the supplied data to generate “corrected” floor areas, which then were multiplied by estimated construction costs. Average building heights over a meshblock were obtained by dividing the floor area by the plan area.

The original data were subdivided into nine usage categories (e.g. commercial, industrial, residential dwellings) but were condensed to just “workplace” and “residential” for the model. The estimated replacement values for all residential and workplace buildings in New Zealand were respectively $375 billion and $180 billion.

8.2 Tsunami Forces and Building Strength

The forces exerted by a tsunami depend on the depth and velocity of the water in it and entrained debris. The velocity is highly variable depending on whether the tsunami is acting like a rapidly rising tide or is surge-like in behaviour. When the tsunami is tide-like the velocities are likely to be low, typically 1 m/s, and most of the initial damage will result from buoyant and hydrostatic forces and the effects of flooding. Higher velocities and greater damage often occur during the subsequent withdrawal of the water (Camfield, 1980).

When the tsunami takes the form of a surge the current velocities associated with the surge are proportional to the square root of the surge height (Equation 8.1) (Camfield, 1980).

$$V = 2 \sqrt{(g * D)} \qquad 8.1$$

where:
V = inundation velocity
D = inundation depth
g = acceleration due to gravity

Velocities in surging flows are usually much higher than 1 m/s and damage arising from surge and drag forces is much greater than that due to buoyant and hydrostatic forces. Expected velocities are given in Table 8.1 along with surge and drag forces estimated using formulae presented in Camfield (1980).

Table 8.1 Estimated surge and drag forces for tsunami waves of various depths impacting on flat walls. In each case the wall is assumed to be higher than the depth of the wave. The forces are expressed as kN per metre length of wall perpendicular to the direction of flow of the wave.

Water depth (m)	Water Velocity (m/s)	Surge Force (kN/m)	Drag Force (kN/m)
0.2	2.8	30	4
0.5	4.4	70	10
1	6.3	140	40
2	8.9	270	160
5	14	720	1000
10	20	1600	4000
20	28	4200	16,000

Buildings in New Zealand are designed to withstand the horizontal forces imposed by wind and earthquakes. Minimum strengths for houses are prescribed in NZS3604:1999 (Standards New Zealand, 1999). Examples of code-based strengths (Tables 8.2 and 8.3) show that the highest design levels for wind and earthquakes are not very different.

Table 8.2 Examples of prescribed minimum horizontal strengths (Bracing Demands) for wind resistance in the highest wind zones of New Zealand. The strength is expressed as kN per m length of wall perpendicular to the wind. BU is "bracing unit", a term from the code.

House Type	Height to Apex of Roof (m)	Bracing Demand (BU/m)	Bracing Demand (kN/m)
Average 1-storey	5	100	5
Average 2-storey	8	202	10
Tall 2-storey	11	352	18

Whole-house racking tests carried out by Thurston and King (2003) have demonstrated that houses constructed in accordance with the requirements of NZS3604 may in fact be twice as strong as implied by the bracing demands for wind in a high-wind zone. Hence the actual horizontal strengths of houses could be in the range 10 to 40 kN/m. Nevertheless, as indicated by the results of Table 8.1, the strength of even a well-built house is likely to be exceeded by the drag and surge forces exerted by a 1m deep tsunami.

Table 8.3 Examples of prescribed minimum horizontal strengths (Bracing Demands) for earthquake resistance in the most earthquake-prone zones of New Zealand. A rectangular house measuring 8m x 12m is assumed with the strength (Lineal Bracing Demand) expressed as kN per m length of the 8m wall.

House Type	Bracing Demand (BU/sq.m)	Bracing Demand (kN/sq.m)	Lineal Bracing Demand (kN/m)
Light 1-storey	10.5	0.53	6
Heavy 1-storey	23.7	1.19	14
Heavy 2-storey	37.3	1.87	22

Field surveys of tsunami-damaged areas indicate that relatively weak houses typical of coastal villages of the Philippines and Indonesia are likely to be pushed off their foundations by about 1m depth of water (Imamura et al 1995, Tsuji et al 1995a,b), whereas relatively well-built Japanese houses that are bolted to concrete foundations require 1.5 to 2m depth (Shimamoto et al 1995).

8.2.1 Sensitivity of loss to fragility model

The differences between losses estimated using the three models are in fact relatively small, much smaller than the differences due to differing inundation models. Figure 8.4 illustrates the differences for the Hutt Valley, and similar relativities were found for Christchurch and Gisborne. The two inundation models are probably extremes, with a preferred model lying somewhere in between.

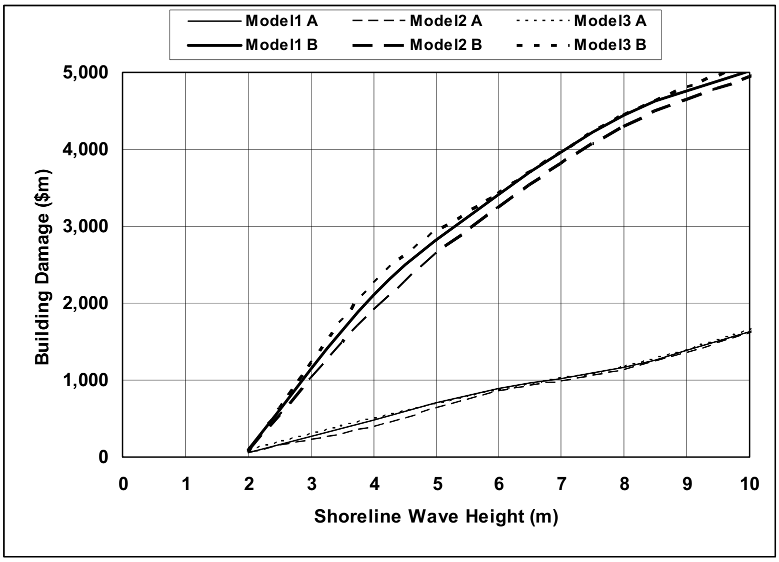


Figure 8.1 Effect of fragility model on estimated losses for tsunami inundation of the Hutt Valley, for two inundation models. Inundation model A is one with a high degree of attenuation, model B is for zero attenuation (the so-called "Bath" model).

8.3 Population Model

Two models for the locations of people are available. Model 1 comprises night-time populations for each meshblock, derived from census data. The model has the advantage of being based on actual head-counts, but it is for night-time only. Model 2 involves allocating people to each data aggregation point in proportion to the total floor area of the buildings associated with it. First, an occupancy rate is estimated for each region of New Zealand using the total population (Statistics NZ, 2003) and total floor area for the region, and then that occupancy rate is applied to all aggregation data points within the region.

Model 2 has the disadvantage of being a derived model, but covers both day-time and night-time situations. It also distinguishes between the type of location, i.e. workplace, home and outdoors. This is of importance when casualty rates depend on the type of building. Earthquake casualty modelling is a case in point because the collapse rates of workplace buildings differ significantly from those of residential buildings.

Model 1 has been used for the present tsunami study where night-time scenarios only were being considered.

Occupancy rates range from 82m^2 per person in Auckland to 160m^2 per person in Southland.

At any time of the day some people are indoors at their places of work, some are indoors at home, and some are outdoors. For the purposes of the loss model "work" means "not at home" and so includes students, shoppers, hospital patients etc. The locations of people for day-time and night-time scenarios are given in Table 8.1 (Spence et al, 1998).

Table 8.4 Estimated locations of people for day-time and night-time disaster scenarios.

Time of day	Indoors at Workplace	Indoors at Home	Outdoors
Workday (11 a.m.)	0.58	0.22	0.20
Night-time (2 a.m.)	0.04	0.95	0.01

8.4 Death and Injury Models

8.4.1 Introduction

A number of surveys of impacted areas following tsunami have documented casualties as a proportion of the prior population (e.g. Imamura et al., 1995; Lynett et al., 2003; Shimamoto et al., 1995; Tsuji et al., 1995a, 1995b). There is more work on assessing casualties for significant floods including dam breaks, typically in Europe and the USA. Ramsbottom et al (2003) provides a summary of methods for assessing the impact of floods on people and property, but flood casualty models are much more conservative than the field data from tsunami would indicate. We expect that significant new data will come from the Boxing Day 2004 tsunami when reports from all of the countries affected is reported, so the model we develop may well need refining in future.

8.4.2 Derivation of a model

A brief search of the literature revealed some good data on mortality as a proportion of people at risk at sites of known tsunami-inundation depth (Figure 8.2), but very few data on injuries in relation to water depth. Although the variation in mortality with water depth shows much scatter (Fig. 8.2), it is evident that the likelihood of death varies essentially linearly with depth of inundation.

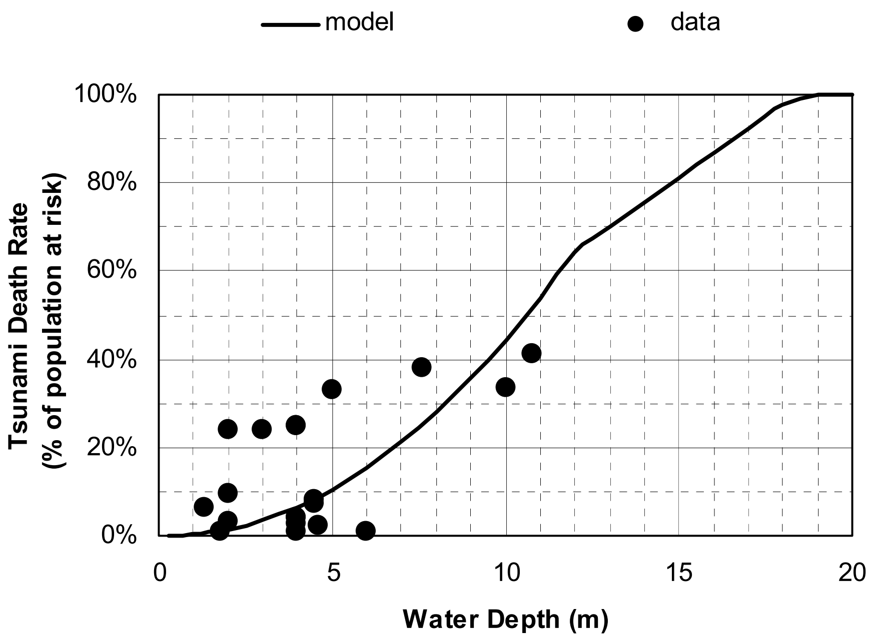


Figure 8.2 Mortality rates experienced during recent tsunami. In nearly all cases there had been very little or no warning, hence negligible self-evacuation. (Data are from Tsuji et al. 1995a, 1995b, Imamura et al. 1995, Shimamoto et al. 1995, Sugimoto et al. 1995, Dengler and Preuss 2003, and Lynett et al. 2003). See text and Figure 8.3 for explanation of the odd, two-part function fitted to the data.

Because we wished to estimate injuries as well as deaths, we formulated a model which estimated first the likely proportion of casualties amongst the population at risk, where casualties means deaths plus injuries, and then deaths as a proportion of the casualties. We chose to fit the simplest possible theoretical models consistent with the data, and hence assumed that the proportion of people who become casualties varies linearly with water depth above some threshold depth, until all the people exposed are either killed or injured. We have no data on casualties with which to calibrate this model, and so proceeded further to a model for death rate as a proportion of casualty rate. The simplest such model is that death rate is a constant proportion of casualty rate. This has a theoretical defect that it is impossible to reach a mortality rate of 100% of the population at risk, whereas in severe cases this is not correct. To overcome this issue we used the casualty-depth function for estimating deaths. This implies that at low water depths deaths are proportional to the square of water depth until all of the people at risk are injured (or killed), and thereafter, deaths are a linear function of depth until all of the surviving injured are killed (Figure 8.3). The combination of these two simple models provided an acceptable fit to the available mortality data (Figure 8.2). The statistical uncertainty of the model fit to the available death-rate data is ±20% (at one standard deviation) over a depth range of 0-12 m, for which there is some data.

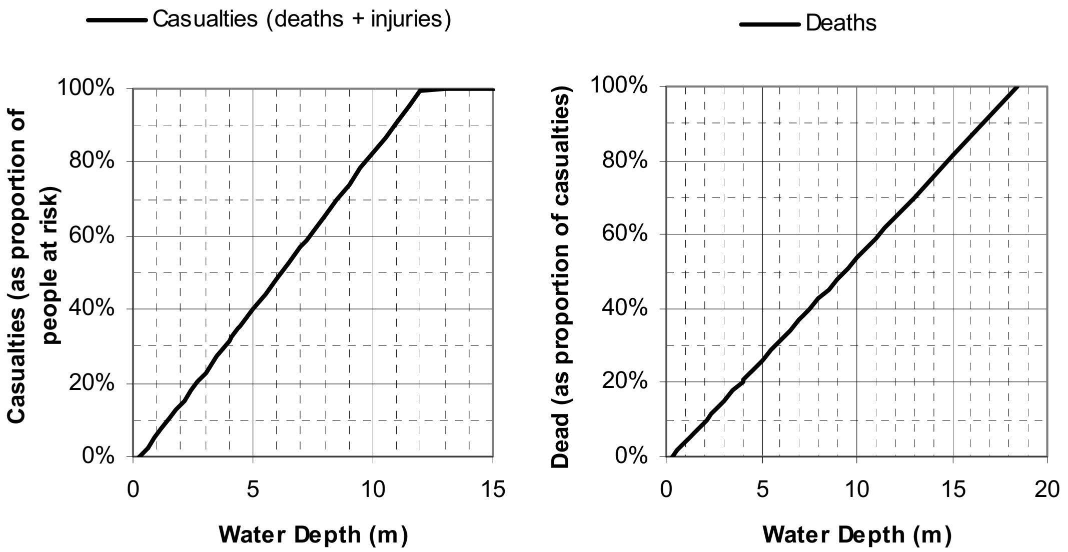


Figure 8.3 Proposed casualty rate and death rate functions. Note that the linear death rate is as a proportion of casualties and not as a proportion of people at risk. Hence it follows that death rate as a proportion of the population at risk is the odd, partly linear, partly quadratic, function shown in Figure 8.2.

Following the above concepts we express the casualty rate (c) as a linear function of the depth of water above a threshold, i.e.

$$c = 0.085(d - 0.3) \qquad 8.2$$

Here "d" is the total depth of water and the threshold depth has been arbitrarily set at 0.3 metres. It is the depth below which the risk of being killed or injured is negligible.

The death rate (m) is then modelled as being proportional to the casualty rate, i.e.

$$m = 0.65c, \text{ or} \qquad 8.3$$

$$m = 0.05525(d - 0.3) \qquad 8.4$$

Note that m is the proportion of casualties who are killed.

The number of casualties (i.e. dead plus injured) (N_c) of the people at risk within each mesh block (P_m) becomes:

$$N_c = cP_m = 0.085\,(d - 0.3)\,P_m \qquad 8.5$$

with the restriction that $N_c \leq P_m$ (i.e. the number of casualties cannot exceed the number of people at risk).

The number deaths N_d is calculated as:

$$N_d = mN_c = mcP_m \qquad 8.6$$

This effectively has two forms,

$$N_d = 0.0047\,(d - 0.3)^2\,P_m \qquad 8.7$$

while $N_c \le P_m$, and

$$N_d = 0.05525(d - 0.3)\,P_m \qquad 8.8$$

once all people have become casualties. The restriction $N_d \le P_m$ also applies. Figure 8.4 shows the resultant models for casualties, deaths and injuries, with all now being expressed as proportions of the population at risk. The two standard deviation confidence limits on casualty, death and injury numbers calculated through this model are approximately ±50% for tsunami depths below 11m.

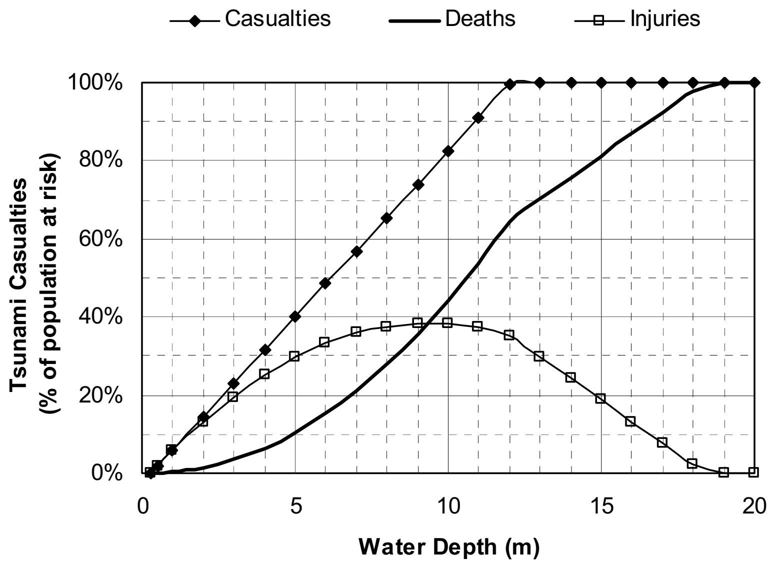


Figure 8.4 Models for casualty, death and injury rates for people impacted by Tsunami. Casualties = deaths + injuries.

8.4.3 Effect of inundation models

The estimated numbers of dead and injured in any given area thus are dependent on only two factors: the depth of inundation and the number of people inundated. The number of people present to be inundated is known to the resolution of census mesh-block data, but the area (numbers of mesh blocks) able to be inundated, and the depth of inundation must also be obtained by modelling.

When water in a tsunami runs into relatively steeply sloping land, the momentum of the fast-moving water can carry it for short distances higher than the tsunami wave height at the shore – this is runup. If the land surface is rough, and particularly if the land is flat, or very gently sloping, the flowing water looses energy in its passage over land, so that it fails to reach heights inland as high as it was on first reaching shore. Between these, for particularly long wavelength tsunami, the water may fill an area, like a bath, to the height of the tsunami. These are not just three alternative models for calculating tsunami inundation, they are different inundation modes adopted by different real tsunami. The influence of various inundation models is compared in relation to tsunami hitting the Hutt Valley at the head of Port Nicholson (Figure. 8.5).

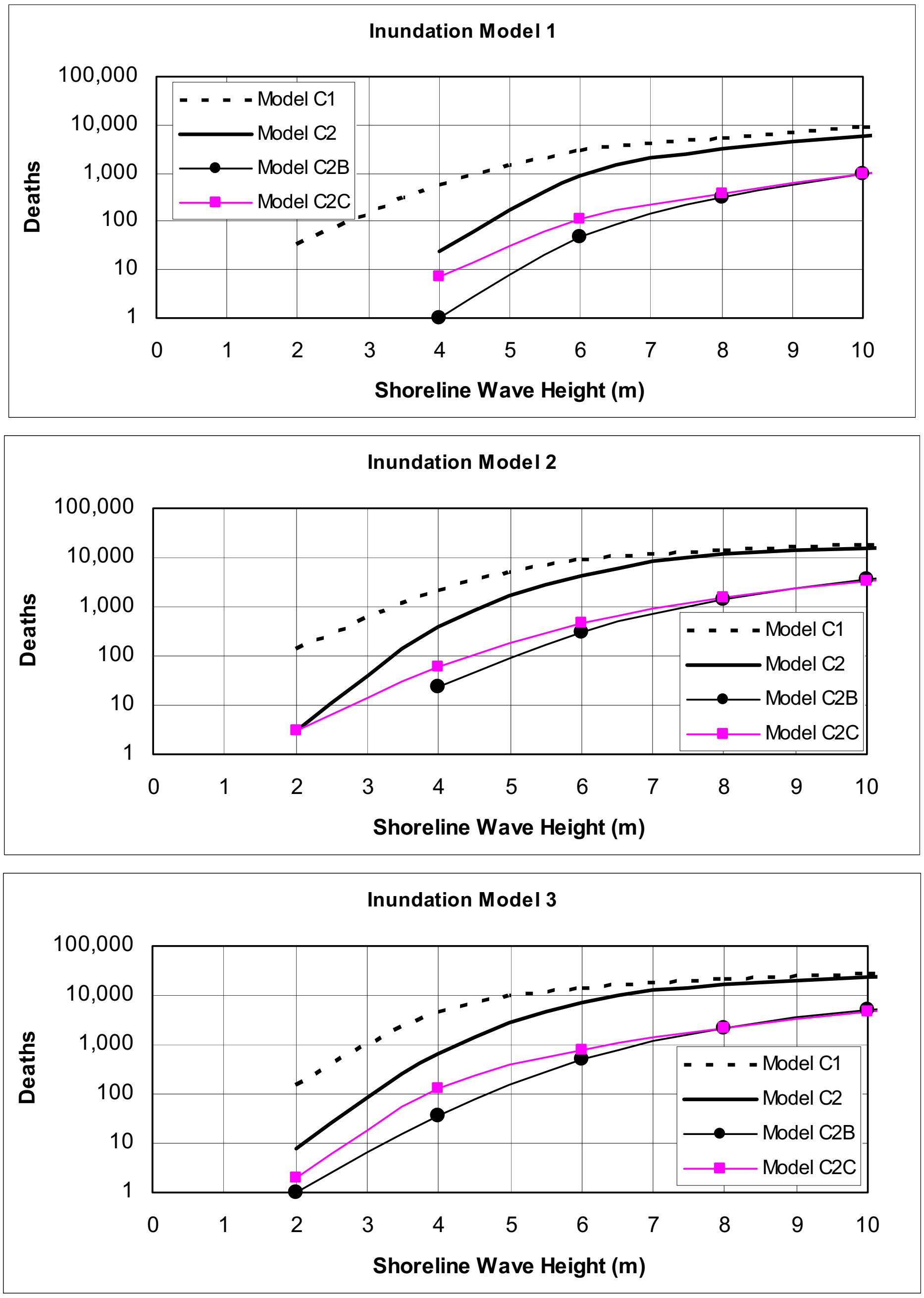


Figure 8.5 Numbers of deaths in Lower Hutt estimated using three inundation models and four casualty models. Inundation Model 1 has attenuation due to surface roughness, Inundation Model 2 includes slope, runup, and attenuation due to roughness, and Inundation Model 3 is a "bath model". Casualty model C1 is based on the methods of Ramsbottom et al. (2003) and leads to grossly excessive estimates of mortality. Model C2C is the model discussed above that is calibrated by mortality statistics from past tsunami. Models C2 and C2B were other more complex models considered before the simpler Model C2C. They serve to illustrate that estimates of mortality depend much more on the inundation model, and the population exposed to the hazard, than they do on the details of the casualty model.

8.4.4 Limitations in casualty models

The casualties models are based on data from historical tsunami. Weaknesses in the modelling include the following.

- The data are limited in number for good constraint of the death-rate model and show significant natural variability;
- There are very limited data on injury rates. This will improve as post-Sumatra data become available;
- The data apply to high velocity tsunami waves and so the models are likely to overestimate casualties in the relatively less common tsunami that behave like slowly rising tides; and
- Secondary impacts such as contamination of water and food supplies, and pollution, have not been included.

Less serious weaknesses include the following:

- No allowance has been made for the height of buildings. This is not a serious problem for night-time events because nearly 100% of the residential accommodation in New Zealand is low-rise (i.e. 1 to 3 stories high). Building height is likely to be significant for day-time events because the upper stories of strongly-built high-rise buildings may suffer little or no damage above ground floors during even quite large tsunami.
- No allowance has been made for higher rates of casualties amongst especially vulnerable groups of people, such as the infirm, the very young, or the elderly. This is not a significant deficiency when the assumption of zero warning is in force.
- The effects of warning and response to it have not been modelled here. They are covered in the Preparedness Report.

9.0 RESULTS OF RISK MODELLING

9.1 For individual urban centres

The following pages present the results of our modelling, with one page devoted to each location. We present four plots showing the modelled hazard and risk as a function of return period: the wave height at the shoreline in metres, the cost of damage to buildings, estimated numbers of deaths and injuries. We also give, in tabular form, the actual data that are plotted.

The term *return period* may need clarification. We have essentially calculated the annual probability that these measures of hazard and risk will occur: wave height, cost, deaths and injuries. These are cumulative measures. e.g. we have calculated the probability that a given wave height *or greater* will occur within any given year. But if these results were plotted showing annual probability they would be hard to interpret. We have instead plotted the severity of the event against return period. The return period is the average interval between occurrences of the event, and is equal to the reciprocal of the probability. So a return period of 200 years is equivalent to a probability of 1 in 200 that the event will occur in any one year.

There are two common misconceptions about the concept of return period. One is that it is the time period within which the event size given (wave height, cost, deaths, injuries) can be expected to occur. The other is that it is the largest that can be expected within that period. *Neither of these is true.* If a 3 metre wave has a return period of 100 years, for instance, waves larger than 3 metres could occur within that period, or such a wave might not occur at all within that period. The return period is simply a measure of annual probability, used because the plots and the numerical results are easier to interpret in this form.

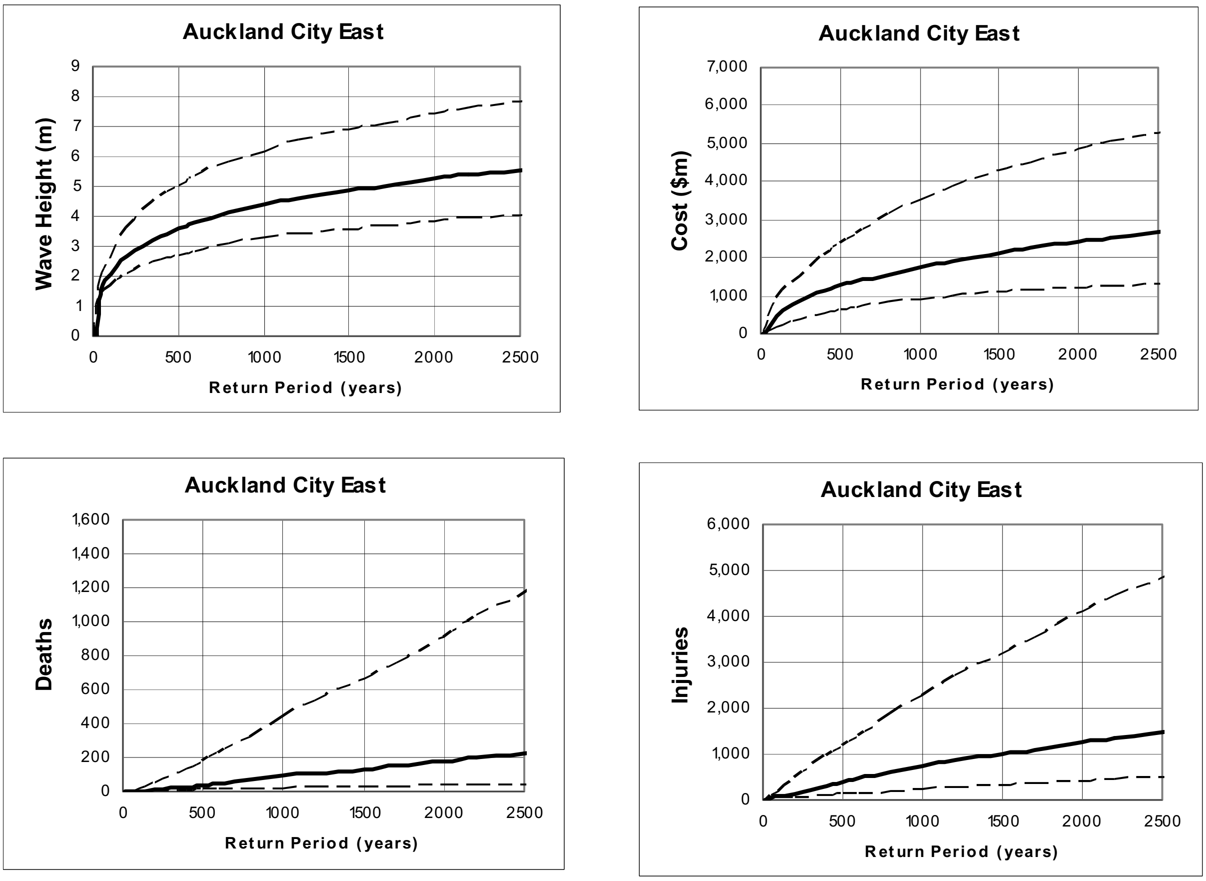
The graphs show the median estimates of the risk for the various parameters, together with measures of the uncertainty. We analysed the inherent variability of the tsunami process, such as the magnitudes and locations of earthquakes that can occur in any given source region, and the consequent variability in wave heights generated, and produced loss curves. But there is also uncertainty in many of the parameters that we had to assume, so each point on a median loss curve actually represents a distribution of likely losses. The breadth of this distribution is indicated by the two dashed lines in each plot: these are the 16^{th} and 84^{th} percentiles of the distribution. The bold line represents the median and this is our best estimate of the risk, but the two dashed lines give an indication of the uncertainty. It is very important that this uncertainty is kept in mind when considering the results because even at the 16^{th} & 84^{th} percentiles there is still only a 68% probability that the correct value lies between these bounds. We believe we have been consistent in our analysis procedures, so that these percentiles are a realistic representation of the uncertainty. We caution that the median values have little confidence if they are considered in isolation from the uncertainty treatment. We also caution that for wave heights below 2 metres the calculations are poorly constrained and should be regarded as indicative only.

9.2 Deaggregation

It is important to know the likely sources of tsunami. A community that is more prone to local tsunami will take different precautions from one whose peril comes mostly from distant tsunami. The table at the foot of each page deaggregates the hazard to show the sources from which significant waves originate, for each of the locations studied. This is done separately for wave heights with 100 years and 500 years return period, at each location. The sources are broken down by percentage contribution to the total risk. For the purposes of simplicity, some sources have been amalgamated, e.g. the two South American sources and the five comprising the Hikurangi subduction zone. Where there are contributions from a number of local faults, these have also been amalgamated.

To the right of the deaggregation table, a further table expresses these same data in terms of the delay time from the various sources. This table reflects the fact that for some locations, e.g. Gisborne, the subduction zone is less than 1 hour away, whereas for others such as Dunedin it is in the 1-3 hrs category.

Auckland City - East Coast



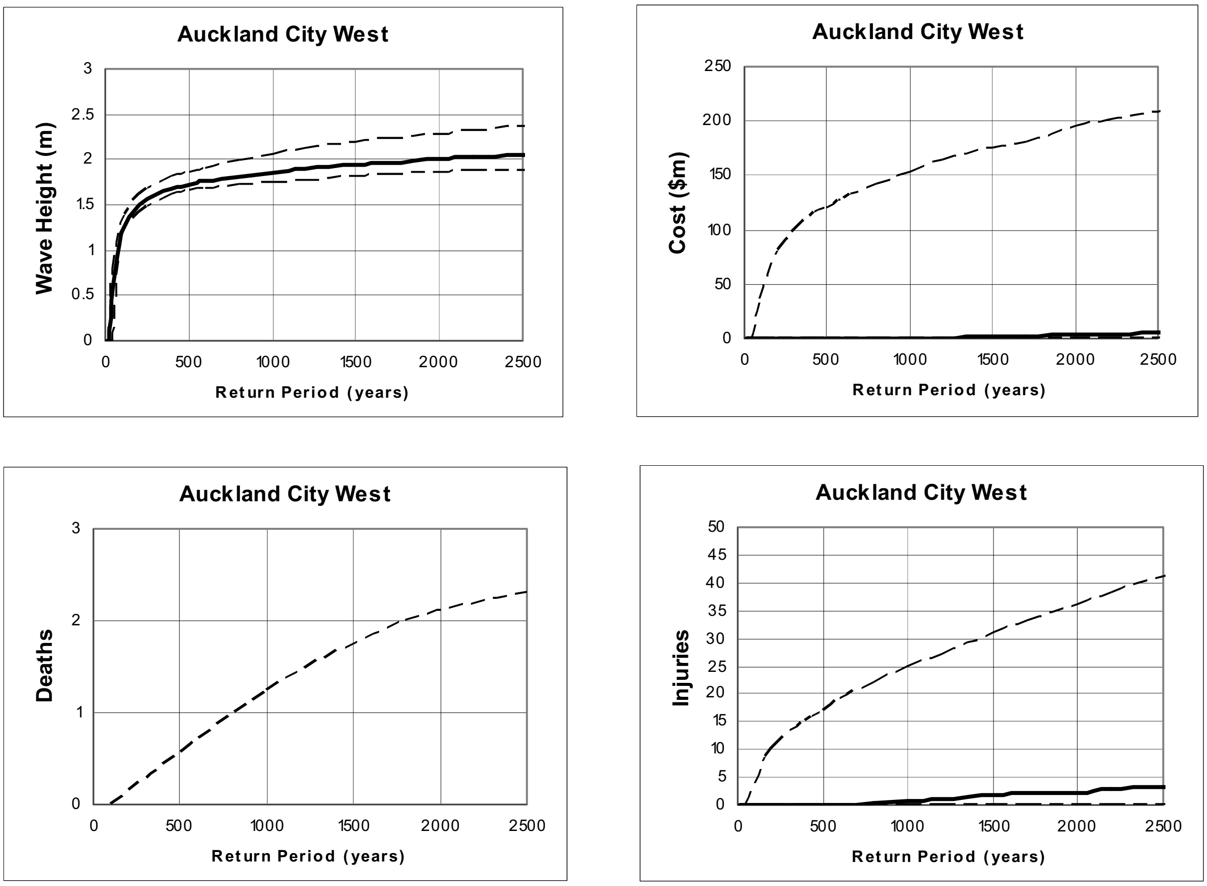
Data plotted above		50 yrs	100	200	500	1000	2500
Height (m)	84%	1.9	2.6	3.6	5.0	6.1	7.8
	50%	1.6	2.1	2.7	3.6	4.4	5.5
	16%	1.3	1.7	2.1	2.7	3.2	4.0
Cost ($m)	84%	480	910	1400	2400	3500	5300
	50%	170	480	800	1300	1800	2700
	16%	37	130	290	600	890	1300
Deaths	84%	1	8	42	170	430	1200
	50%	0	1	7	36	89	220
	16%	0	0	1	6	15	39
Injuries	84%	67	180	470	1200	2300	4800
	50%	26	69	150	400	750	1500
	16%	7	23	52	130	230	470

Deaggregation	2.0m (100 yrs)	3.6m (500 yrs)
S America	68%	80%
Aleutians	16%	14%
Subduction zone	10%	2%
Kermadec	4%	3%
S New Hebrides	1%	1%
Cascadia	1%	

Delay	100 yrs	500 yrs
< 1 hr	0%	0%
1-3 hr	15%	6%
> 3 hr	85%	94%

Figure 9.1. Risk curves and data for Auckland City – East Coast.

Auckland City – West Coast



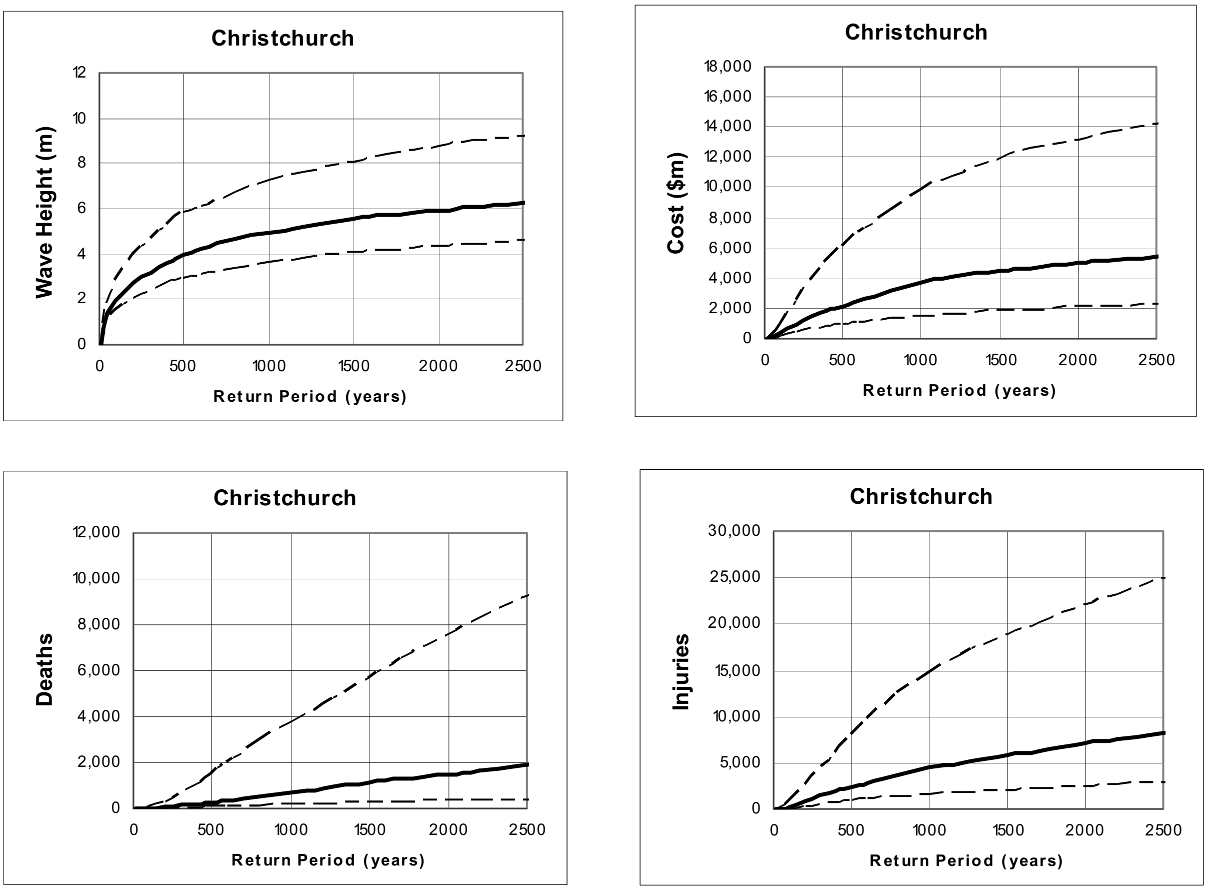
Data plotted above		50 yrs	100	200	500	1000	2500
Height (m)	84%	0.8	1.3	1.6	1.9	2.1	2.4
	50%	0.6	1.2	1.5	1.7	1.9	2.1
	16%	0	1.1	1.4	1.7	1.8	1.9
Cost ($m)	84%	0	36	80	120	150	210
	50%	0	0	0	0	0	6
	16%	0	0	0	0	0	0
Deaths	84%	0	0	0	1	1	2
	50%	0	0	0	0	0	0
	16%	0	0	0	0	0	0
Injuries	84%	0	4	10	17	25	41
	50%	0	0	0	0	1	3
	16%	0	0	0	0	0	0

Deaggregation	1.2m (100 yrs)	1.7m (500 yrs)
S America	75%	64%
Aleutians	19%	27%
S New Hebrides	3%	5%
Cascadia	3%	4%

Delay	100 yrs	500 yrs
< 1 hr	0%	0%
1-3 hr	3%	5%
> 3 hr	97%	95%

Figure 9.2. Risk curves and data for Auckland City – West Coast

Christchurch



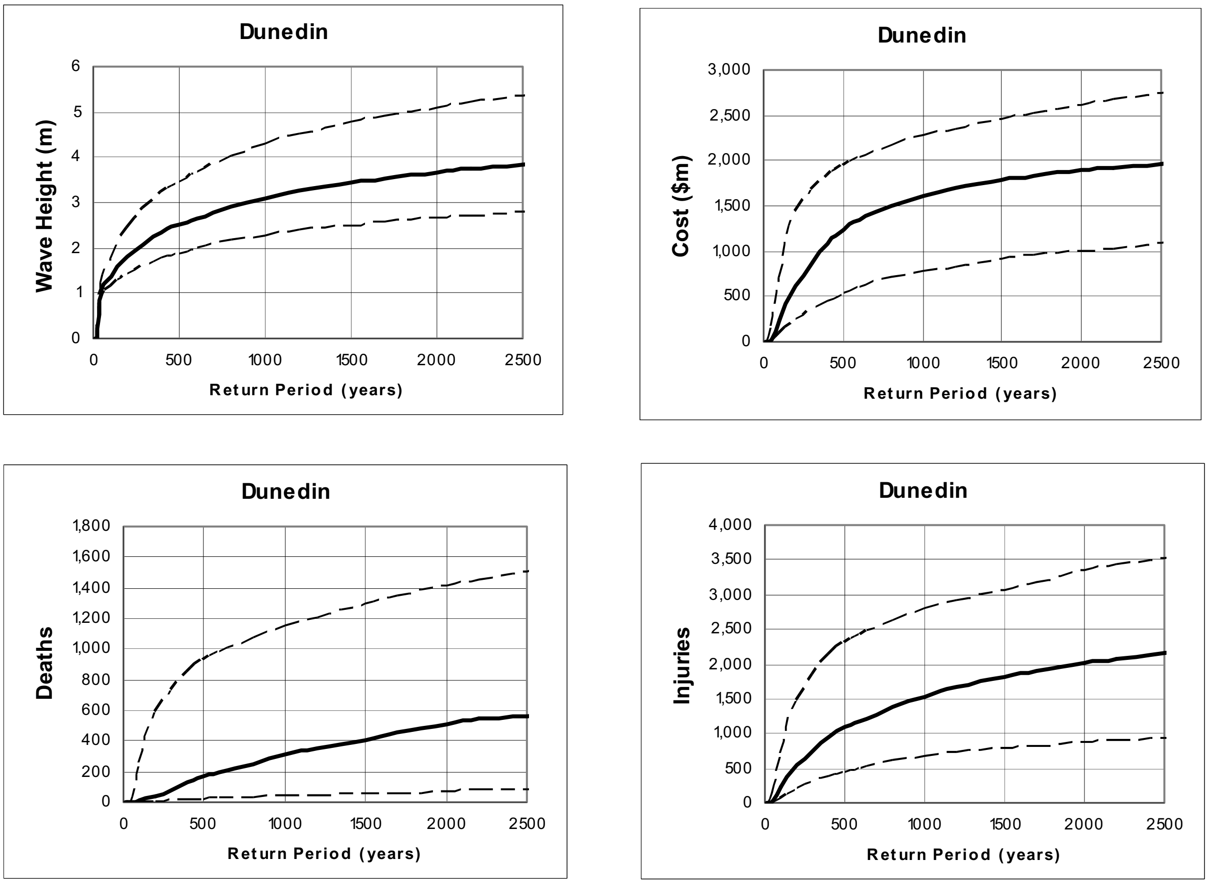
Data plotted above		50 yrs	100	200	500	1000	2500
Height (m)	84%	1.9	2.8	4.0	5.8	7.2	9.2
	50%	1.4	2.0	2.7	4.0	5.0	6.3
	16%	1.1	1.5	2.1	2.9	3.6	4.6
Cost ($m)	84%	320	970	2500	6000	9800	14,000
	50%	100	390	950	2200	3700	5500
	16%	2	110	330	950	1500	2300
Deaths	84%	6	53	280	1500	3800	9200
	50%	1	7	47	280	670	1900
	16%	0	0	6	60	170	380
Injuries	84%	200	800	2600	7900	15,000	25,000
	50%	67	260	770	2400	4400	8200
	16%	11	74	220	820	1500	2800

Deaggregation	2.0m (100 yrs)	4.0m (500 yrs)
S America	80%	88%
Subduction zone	17%	11%
Aleutians	2%	
Local faults	1%	1%

Delay	100 yrs	500 yrs
< 1 hr	1%	1%
1-3 hr	17%	11%
> 3 hr	82%	88%

Figure 9.3. Risk curves and data for Christchurch

Dunedin



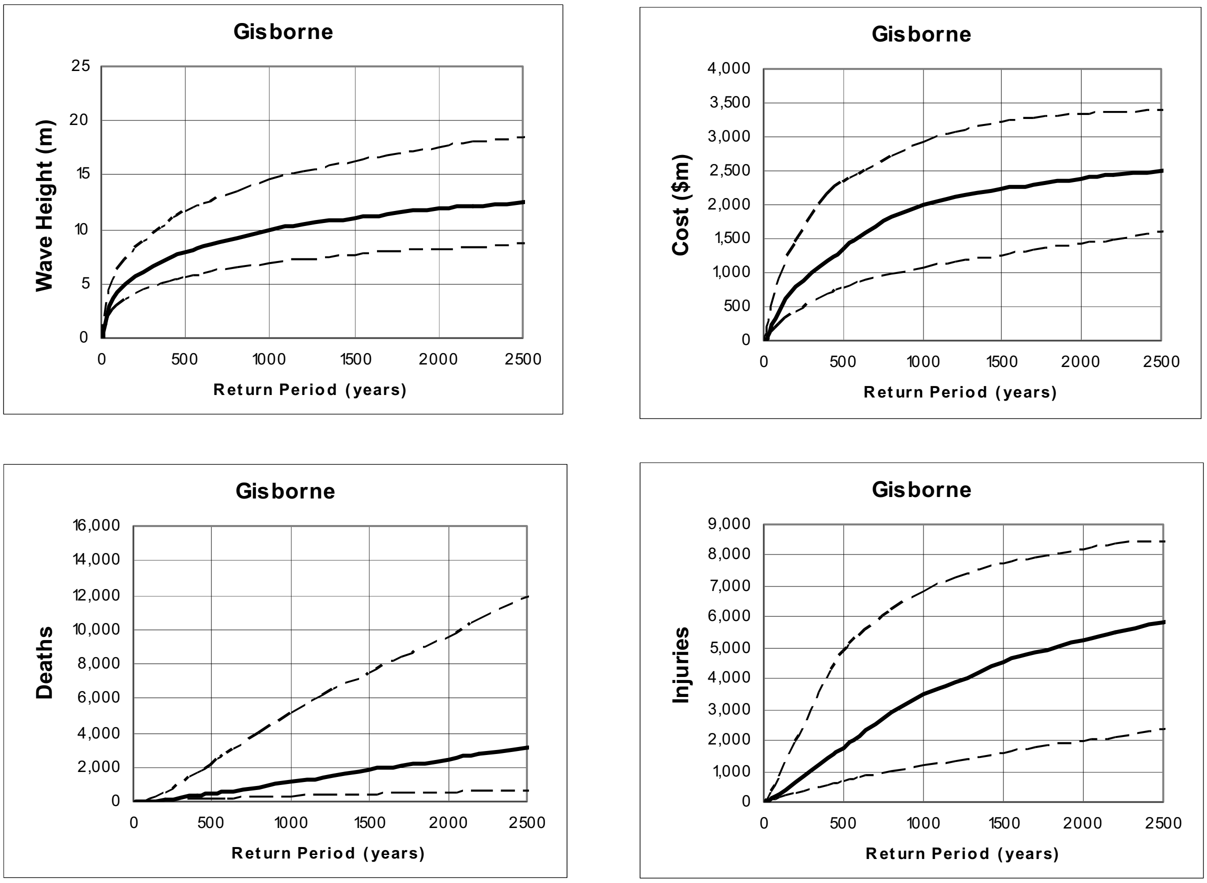
Data plotted above		50 yrs	100	200	500	1000	2500
Height (m)	84%	1.3	1.8	2.4	3.5	4.3	5.3
	50%	1.0	1.4	1.8	2.5	3.1	3.8
	16%	0.9	1.1	1.4	1.9	2.3	2.8
Cost ($m)	84%	180	710	1400	1900	2300	2700
	50%	17	250	620	1200	1600	2000
	16%	0	79	250	520	770	1100
Deaths	84%	6	260	580	920	1100	1500
	50%	0	8	39	160	310	570
	16%	0	0	5	16	36	82
Injuries	84%	150	720	1500	2300	2800	3500
	50%	19	220	560	1100	1500	2200
	16%	0	62	190	440	660	920

Deaggregation	1.4m (100 yrs)	2.6m (500 yrs)
S America	83%	93%
Subduction zone	15%	7%
Aleutians	2%	

Delay	100 yrs	500 yrs
< 1 hr	0%	0%
1-3 hr	15%	7%
> 3 hr	85%	93%

Figure 9.4. Risk curves and data for Dunedin

Gisborne

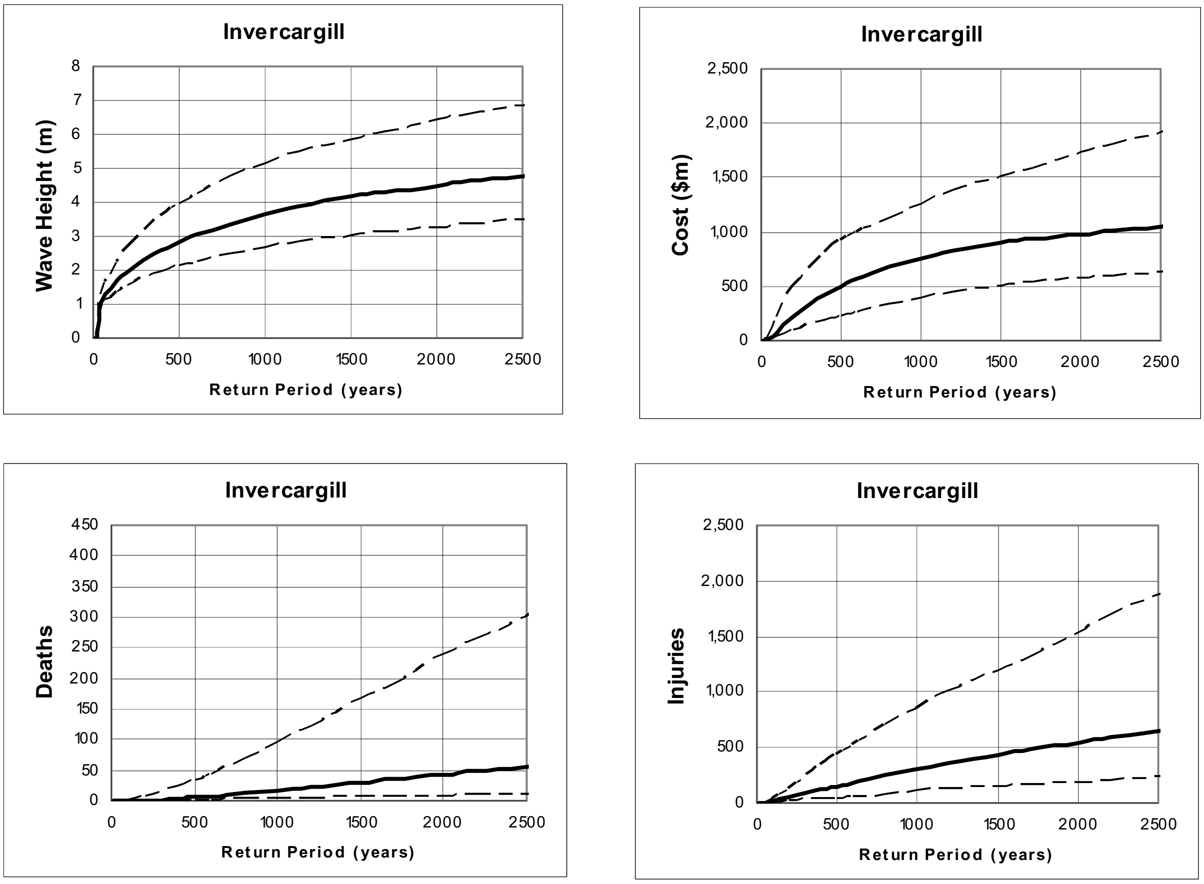


Data plotted above		50 yrs	100	200	500	1000	2500
Height (m)	84%	4.4	6.2	8.3	11.6	14.5	18.5
	50%	2.9	4.2	5.7	8.0	9.9	12.5
	16%	2.0	2.9	4.0	5.6	6.9	8.6
Cost ($m)	84%	500	910	1400	2300	2900	3400
	50%	230	450	790	1400	2000	2500
	16%	120	240	410	770	1100	1600
Deaths	84%	46	160	520	2100	5100	12,000
	50%	11	37	110	440	1200	3100
	16%	1	11	32	110	240	640
Injuries	84%	330	850	2000	4800	6800	8400
	50%	150	290	650	1800	3500	5800
	16%	77	160	270	640	1100	2300

Deaggregation	4.2m (100 yrs)	8.0m (500 yrs)		Delay	100 yrs	500 yrs
S America	47%	53%		< 1 hr	53%	47%
Subduction zone	48%	42%		1-3 hr	0%	0%
Local faults	5%	5%		> 3 hr	47%	53%

Figure 9.5. Risk curves and data for Gisborne

Invercargill



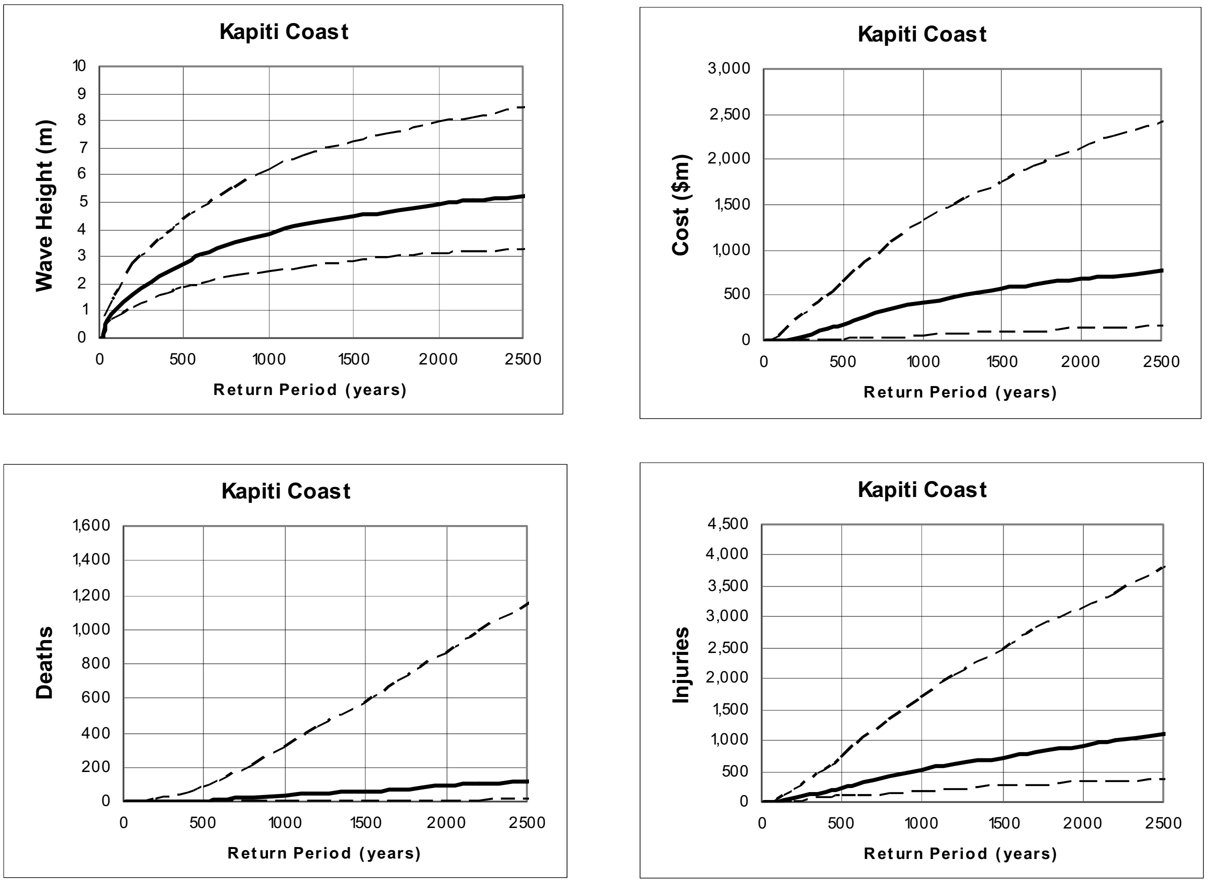
Data plotted above		50 yrs	100	200	500	1000	2500
Height (m)	84%	1.3	1.9	2.6	4.0	5.1	6.8
	50%	1.1	1.5	2.0	2.9	3.7	4.8
	16%	0.9	1.2	1.5	2.1	2.7	3.5
Cost ($m)	84%	53	230	490	910	1200	1900
	50%	10	80	210	510	750	1000
	16%	0	31	84	220	390	630
Deaths	84%	0	1	5	34	96	300
	50%	0	0	0	5	17	56
	16%	0	0	0	0	3	10
Injuries	84%	8	39	130	430	840	1900
	50%	2	14	46	150	300	640
	16%	0	4	11	43	100	230

Deaggregation	1.5m (100 yrs)	2.9m (500 yrs)
S America	86%	97%
Subduction zone	8%	1%
Local faults	5%	2%
Aleutians	1%	

Delay	100 yrs	500 yrs
< 1 hr	5%	2%
1-3 hr	8%	1%
> 3 hr	87%	97%

Figure 9.6. Risk curves and data for Invercargill

Kapiti Coast



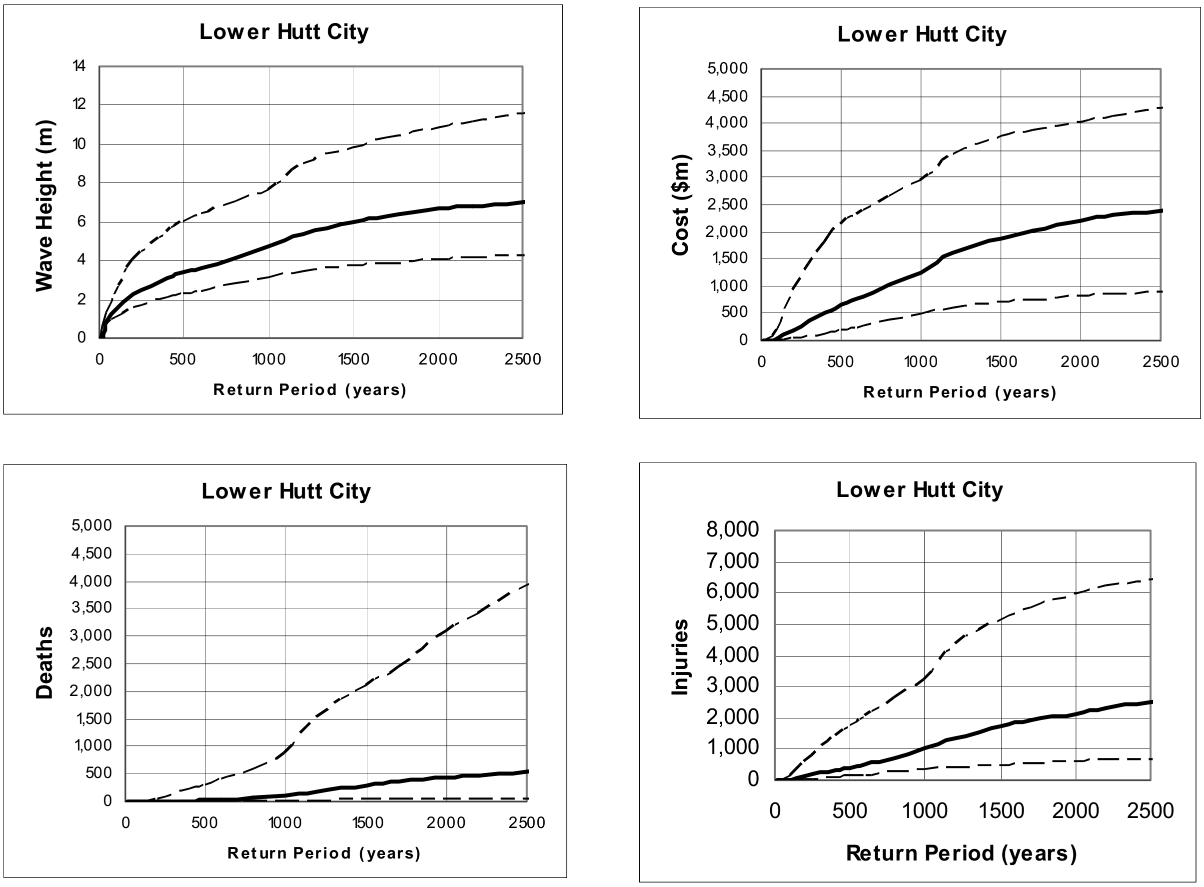
Data plotted above		50 yrs	100	200	500	1000	2500
Height (m)	84%	1.0	1.6	2.7	4.4	6.0	8.4
	50%	0.7	1.1	1.7	2.8	3.9	5.3
	16%	0.5	0.8	1.1	1.8	2.5	3.3
Cost ($m)	84%	0	50	230	670	1300	2400
	50%	0	0	25	190	430	780
	16%	0	0	0	13	59	180
Deaths	84%	0	1	9	90	360	1200
	50%	0	0	0	6	35	130
	16%	0	0	0	0	1	7
Injuries	84%	0	64	240	760	1800	3800
	50%	0	8	71	250	500	1000
	16%	0	0	9	84	180	360

Deaggregation	1.1m (100 yrs)	2.8m (500 yrs)
Subduction zone	61%	60%
Local faults	22%	37%
S America	16%	3%
Aleutians	1%	

Delay	100 yrs	500 yrs
< 1 hr	83%	97%
1-3 hr	0%	0%
> 3 hr	17%	3%

Figure 9.7. Risk curves and data for Kapiti Coast

Lower Hutt



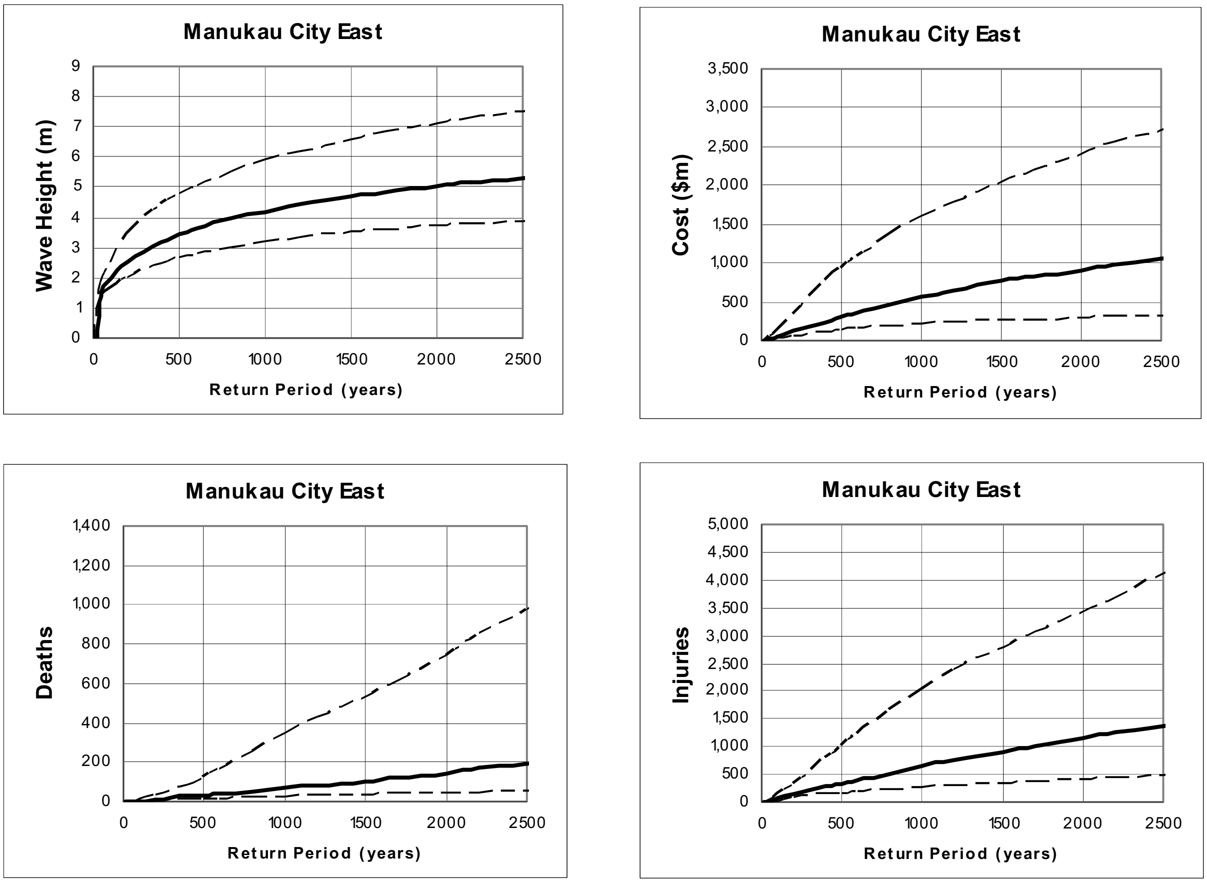
Data plotted above		50 yrs	100	200	500	1000	2500
Height (m)	84%	1.4	2.3	4.1	6.0	7.9	12.1
	50%	1.0	1.6	2.4	3.6	5.1	7.2
	16%	0.8	1.1	1.6	2.4	3.3	4.3
Cost ($m)	84%	30	210	920	2200	3200	4300
	50%	0	46	220	800	1500	2500
	16%	0	7	43	200	540	940
Deaths	84%	0	3	45	310	1100	4600
	50%	0	0	3	34	150	650
	16%	0	0	0	2	13	54
Injuries	84%	15	120	550	1900	3700	6500
	50%	3	28	140	470	1200	2600
	16%	0	6	29	140	330	680

Deaggregation	1.6m (100 yrs)	3.6m (500 yrs)
Subduction zone	41%	68%
Local faults	28%	20%
S America	31%	12%

Delay	100 yrs	500 yrs
< 1 hr	69%	88%
1-3 hr	0%	0%
> 3 hr	31%	12%

Figure 9.8. Risk curves and data for Lower Hutt City

Manukau City – East Coast



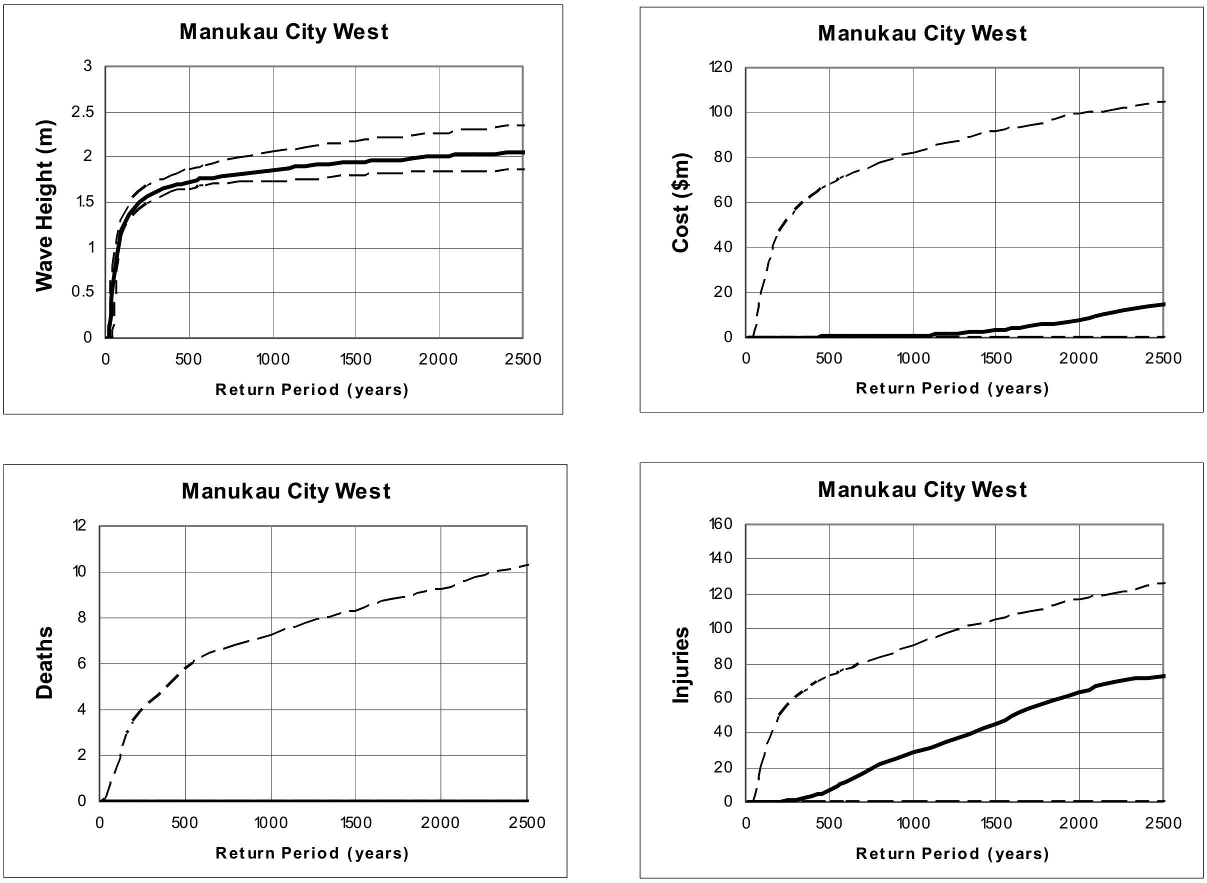
Data plotted above		50 yrs	100	200	500	1000	2500
Height (m)	84%	1.9	2.5	3.4	4.8	5.9	7.5
	50%	1.5	2.0	2.5	3.4	4.2	5.3
	16%	1.3	1.6	2.0	2.6	3.2	3.9
Cost ($m)	84%	45	130	340	930	1600	2700
	50%	15	53	120	300	560	1100
	16%	6	18	46	130	200	320
Deaths	84%	3	11	32	120	340	970
	50%	0	3	10	34	66	190
	16%	0	0	0	10	23	49
Injuries	84%	48	140	340	1000	2000	4100
	50%	13	58	140	340	650	1400
	16%	5	15	54	160	260	480

Deaggregation	2.0m (100 yrs)	3.6m (500 yrs)
S America	68%	80%
Aleutians	16%	14%
Subduction zone	10%	2%
Kermadec	4%	3%
S New Hebrides	1%	1%
Cascadia	1%	

Delay	100 yrs	500 yrs
< 1 hr	0%	0%
1-3 hr	15%	94%
> 3 hr	85%	6%

Figure 9.9. Risk curves and data for Manukau City – East Coast

Manukau City – West Coast



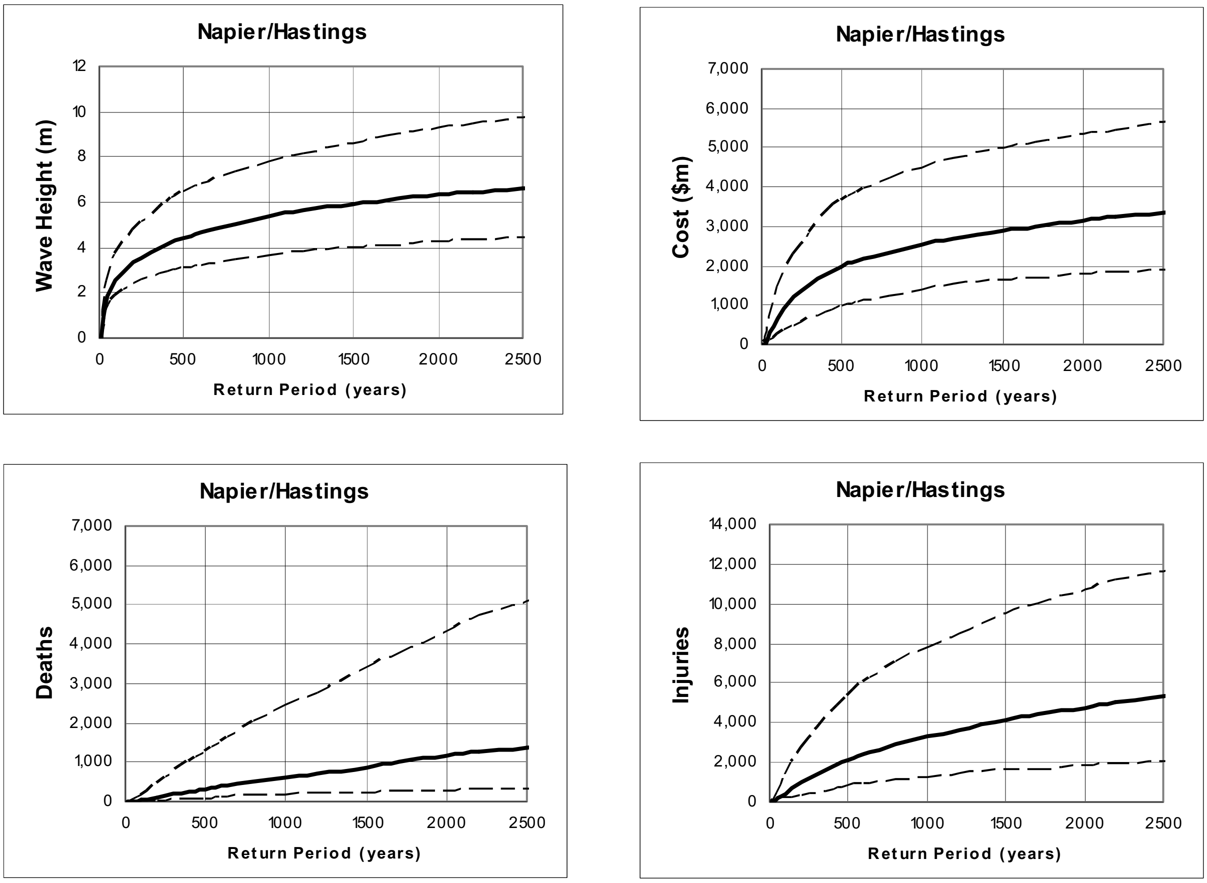
Data plotted above		50 yrs	100	200	500	1000	2500
Height (m)	84%	0.8	1.3	1.6	1.9	2.1	2.3
	50%	0.6	1.2	1.5	1.7	1.9	2.1
	16%	0	1.1	1.4	1.6	1.7	1.9
Cost ($m)	84%	0	20	47	68	82	100
	50%	0	0	0	1	1	14
	16%	0	0	0	0	0	0
Deaths	84%	0	1	4	6	7	10
	50%	0	0	0	0	0	0
	16%	0	0	0	0	0	0
Injuries	84%	0	21	49	72	90	130
	50%	0	0	0	7	29	72
	16%	0	0	0	0	0	0

Deaggregation	1.2m (100 yrs)	1.7m (500 yrs)
S America	75%	64%
Aleutians	19%	27%
S New Hebrides	3%	5%
Cascadia	3%	4%

Delay	100 yrs	500 yrs
< 1 hr	0%	0%
1-3 hr	3%	5%
> 3 hr	97%	95%

Figure 9.10. Risk curves and data for Manukau City – West Coast

Napier / Hastings



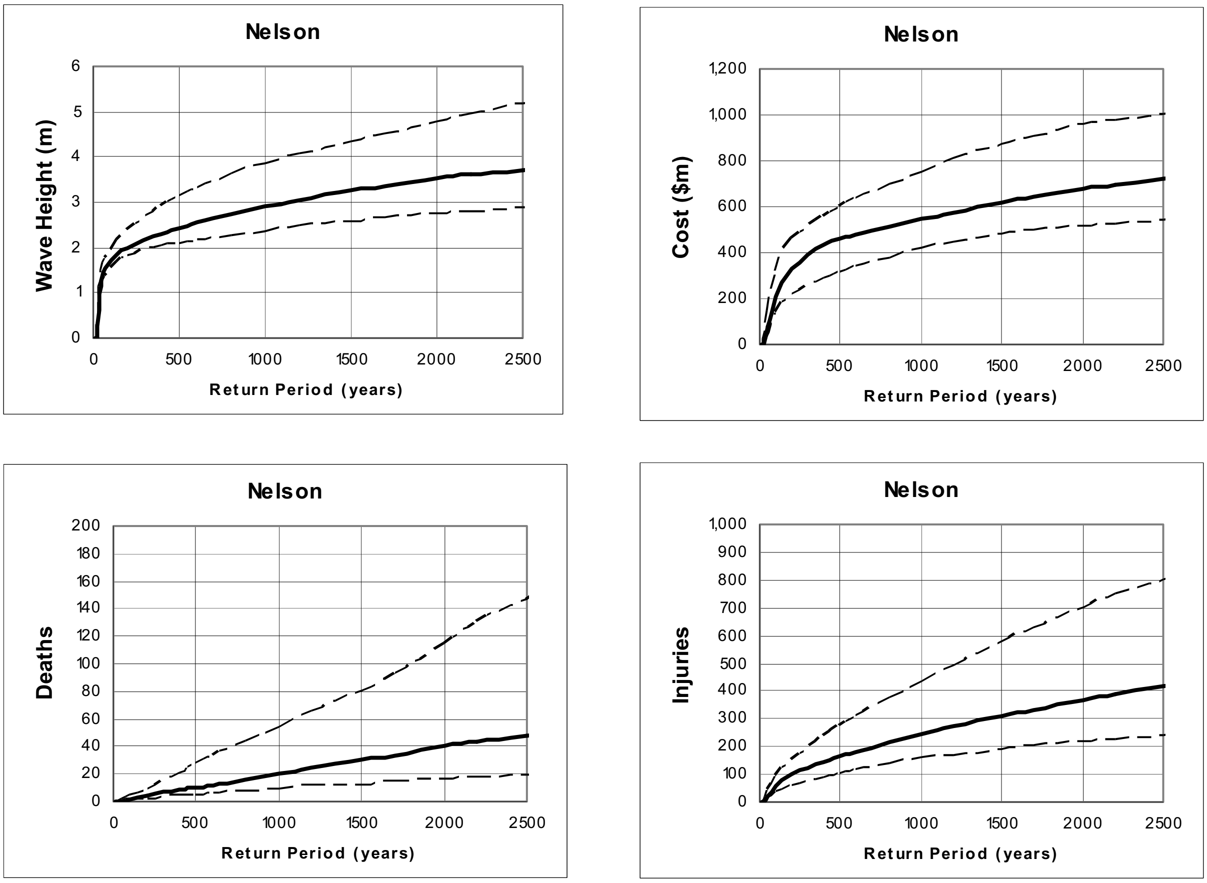
Data plotted above		50 yrs	100	200	500	1000	2500
Height (m)	84%	2.6	3.7	4.8	6.4	7.7	9.7
	50%	1.8	2.6	3.3	4.5	5.4	6.6
	16%	1.3	1.8	2.3	3.1	3.6	4.5
Cost ($m)	84%	690	1500	2300	3700	4500	5600
	50%	300	650	1200	2000	2500	3400
	16%	110	270	480	950	1400	1900
Deaths	84%	37	160	440	1300	2400	5100
	50%	6	30	110	320	610	1400
	16%	1	6	17	69	160	320
Injuries	84%	470	1400	2700	5300	7700	12,000
	50%	170	440	990	2100	3300	5300
	16%	60	160	310	760	1200	2000

Deaggregation	2.5m (100 yrs)	4.3m (500 yrs)
Subduction zone	53%	58%
S America	36%	32%
Local faults	9%	9%
Kermadec	1%	1%
Aleutians	1%	

Delay	100 yrs	500 yrs
< 1 hr	62%	67%
1-3 hr	1%	1%
> 3 hr	37%	32%

Figure 9.11. Risk curves and data for Napier / Hastings

Nelson



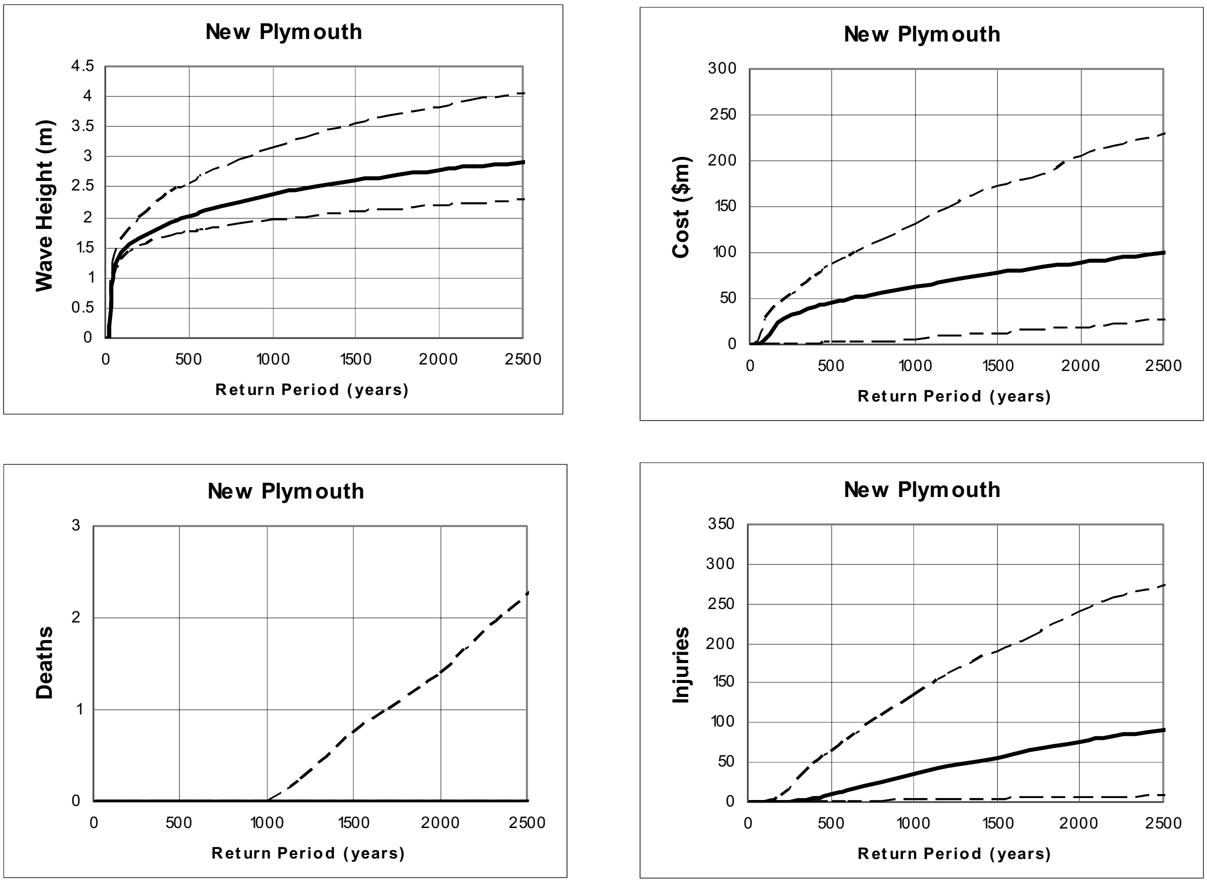
Data plotted above		50 yrs	100	200	500	1000	2500
Height (m)	84%	1.5	1.9	2.4	3.1	3.9	5.2
	50%	1.3	1.7	2.0	2.4	2.9	3.7
	16%	1.1	1.5	1.8	2.1	2.4	2.9
Cost ($m)	84%	150	320	460	600	750	1000
	50%	81	210	330	460	550	720
	16%	32	140	220	310	420	540
Deaths	84%	1	4	9	27	53	150
	50%	0	2	5	10	20	48
	16%	0	1	2	5	9	19
Injuries	84%	41	95	150	280	430	800
	50%	23	57	100	170	240	420
	16%	11	35	57	100	160	240

Deaggregation	1.7m (100 yrs)	2.4m (500 yrs)
Subduction zone	51%	71%
S America	36%	24%
Aleutians	6%	2%
Local faults	5%	3%
S New Hebrides	1%	
Cascadia	1%	

Delay	100 yrs	500 yrs
< 1 hr	5%	3%
1-3 hr	51%	71%
> 3 hr	44%	26%

Figure 9.12. Risk curves and data for Nelson

New Plymouth



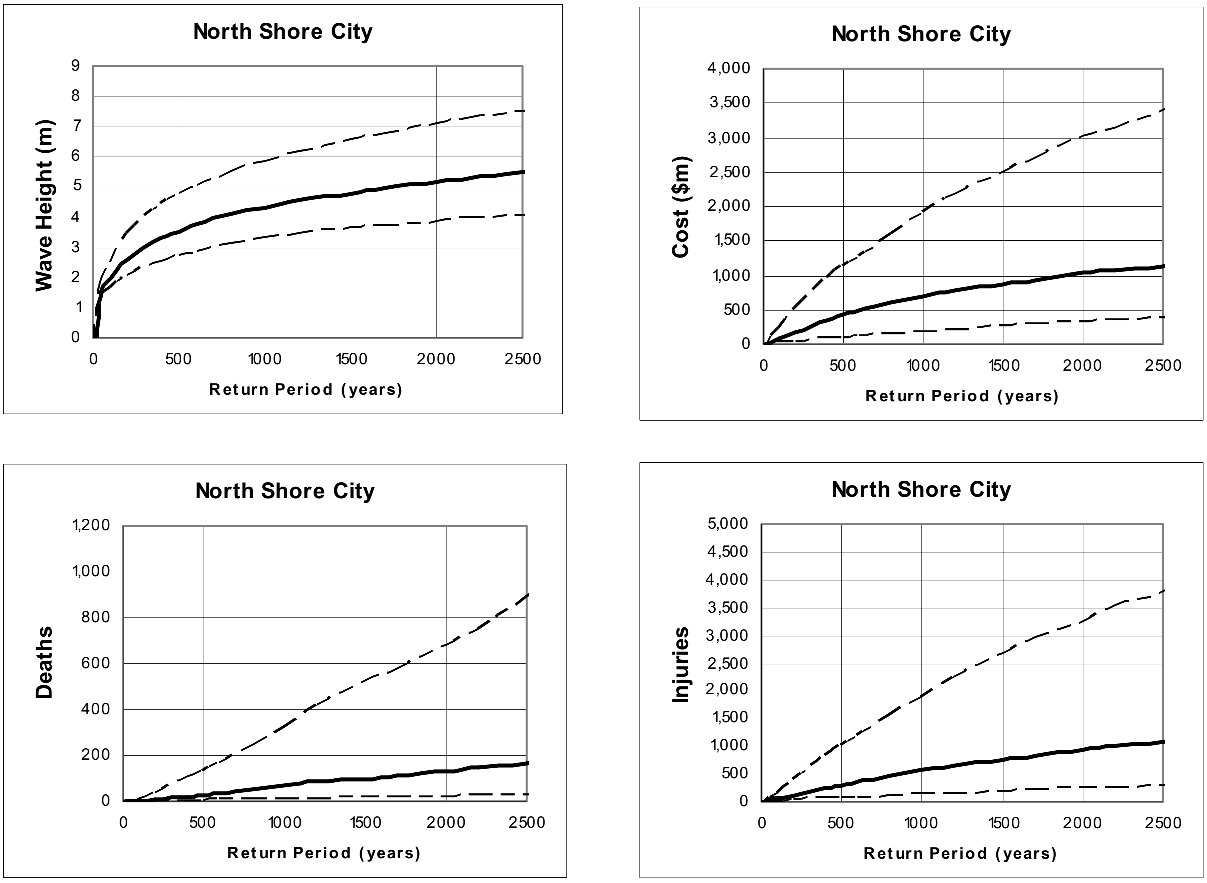
Data plotted above		**50 yrs**	**100**	**200**	**500**	**1000**	**2500**
Height (m)	84%	1.3	1.6	2.0	2.6	3.1	4.1
	50%	1.1	1.4	1.7	2.0	2.4	2.9
	16%	1.0	1.3	1.5	1.7	1.9	2.3
Cost ($m)	84%	3	28	47	87	130	230
	50%	0	7	28	45	64	99
	16%	0	0	0	1	5	25
Deaths	84%	0	0	0	0	0	2
	50%	0	0	0	0	0	0
	16%	0	0	0	0	0	0
Injuries	84%	0	0	8	64	130	270
	50%	0	0	1	10	36	90
	16%	0	0	0	1	2	7

Deaggregation	**1.4m (100 yrs)**	**2.0m (500 yrs)**
Subduction zone	47%	60%
S America	34%	15%
S New Hebrides	5%	10%
Aleutians	11%	7%
Local faults	2%	8%
Cascadia	1%	

Delay	**100 yrs**	**500 yrs**
< 1 hr	2%	8%
1-3 hr	47%	60%
> 3 hr	51%	32%

Figure 9.13. Risk curves and data for New Plymouth

North Shore



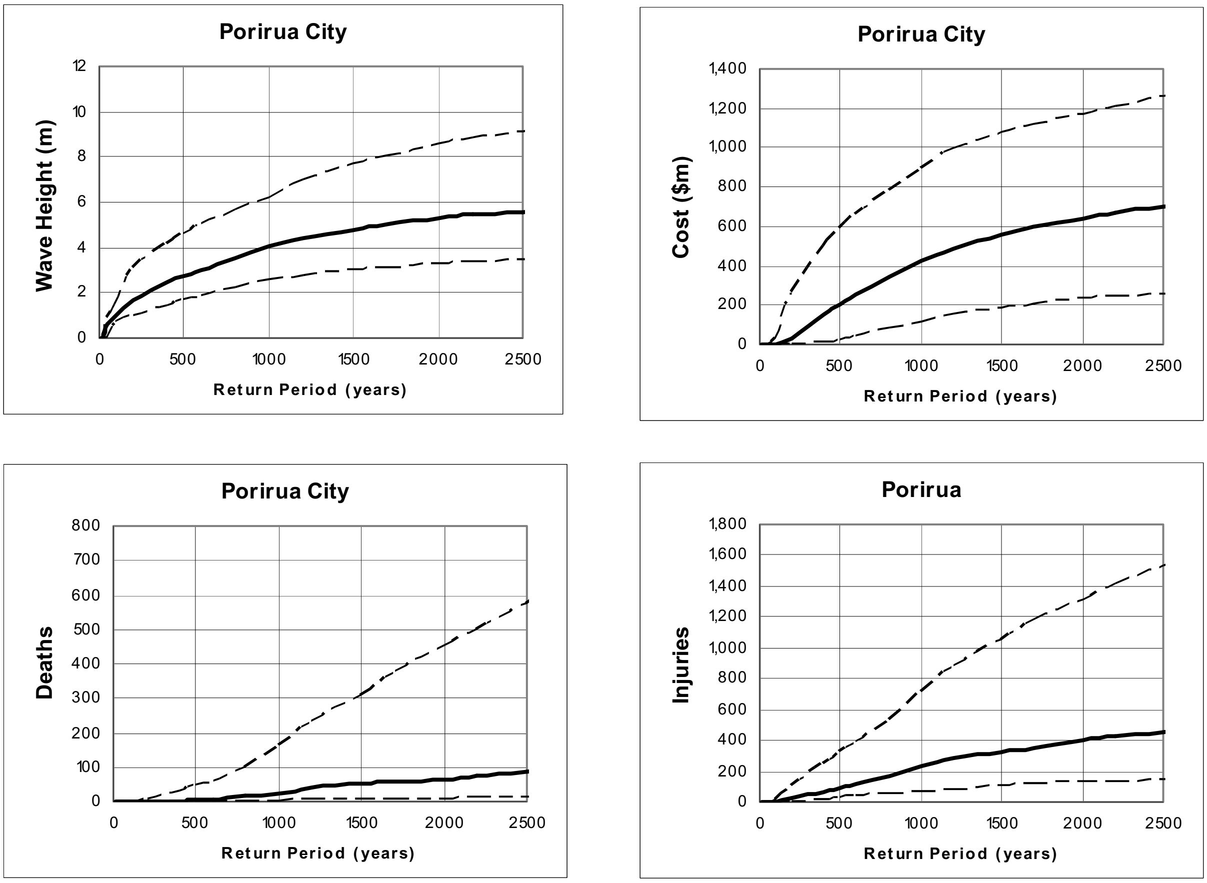
Data plotted above		50 yrs	100	200	500	1000	2500
Height (m)	84%	1.9	2.5	3.4	4.8	5.9	7.5
	50%	1.5	2.0	2.6	3.5	4.3	5.5
	16%	1.3	1.7	2.1	2.7	3.3	4.1
Cost ($m)	84%	100	250	510	1100	1900	3400
	50%	26	97	180	430	700	1100
	16%	6	16	38	91	180	380
Deaths	84%	2	8	36	130	320	890
	50%	0	2	5	28	67	170
	16%	0	0	1	4	8	27
Injuries	84%	54	150	380	1000	1900	3800
	50%	19	55	110	300	560	1100
	16%	3	11	36	76	130	280

Deaggregation	2.0m (100 yrs)	3.6m (500 yrs)
S America	68%	80%
Aleutians	16%	14%
Subduction zone	10%	2%
Kermadec	4%	3%
S New Hebrides	1%	1%
Cascadia	1%	

Delay	100 yrs	500 yrs
< 1 hr	0%	0%
1-3 hr	15%	94%
> 3 hr	85%	6%

Figure 9.14. Risk curves and data for North Shore City

Porirua



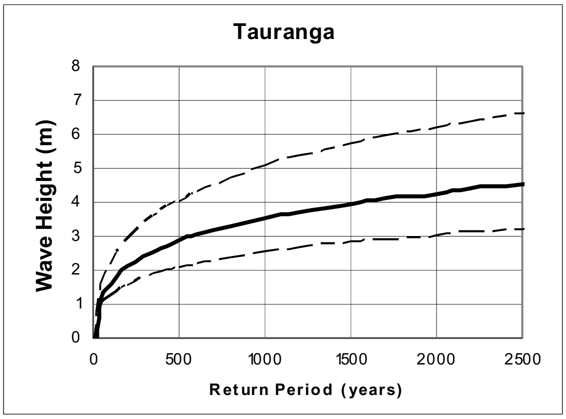
Data plotted above		50 yrs	100	200	500	1000	2500
Height (m)	84%	0.9	1.6	3.0	4.6	6.2	8.7
	50%	0.6	1.0	1.7	2.9	4.0	5.5
	16%	0	0.7	1.0	1.8	2.6	3.5
Cost ($m)	84%	0	43	270	600	890	1200
	50%	0	0	36	230	410	670
	16%	0	0	0	39	140	270
Deaths	84%	0	0	6	43	150	510
	50%	0	0	0	5	27	81
	16%	0	0	0	0	2	11
Injuries	84%	1	22	100	340	710	1400
	50%	0	3	24	100	230	450
	16%	0	0	3	30	73	150

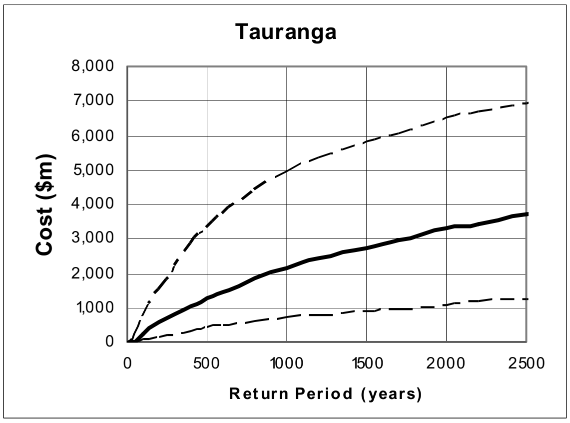
Deaggregation	1.0m (100 yrs)	2.9m (500 yrs)
Subduction zone	68%	73%
Local faults	20%	26%
S America	11%	1%
Aleutians	1%	

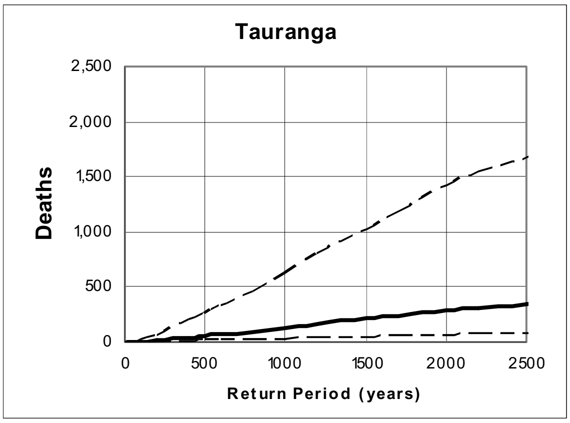
Delay	100 yrs	500 yrs
< 1 hr	88%	99%
1-3 hr	0%	0%
> 3 hr	12%	1%

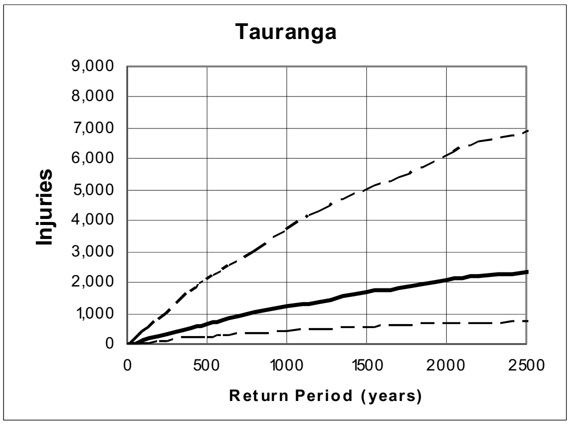
Figure 9.15. Risk curves and data for Porirua City

Tauranga









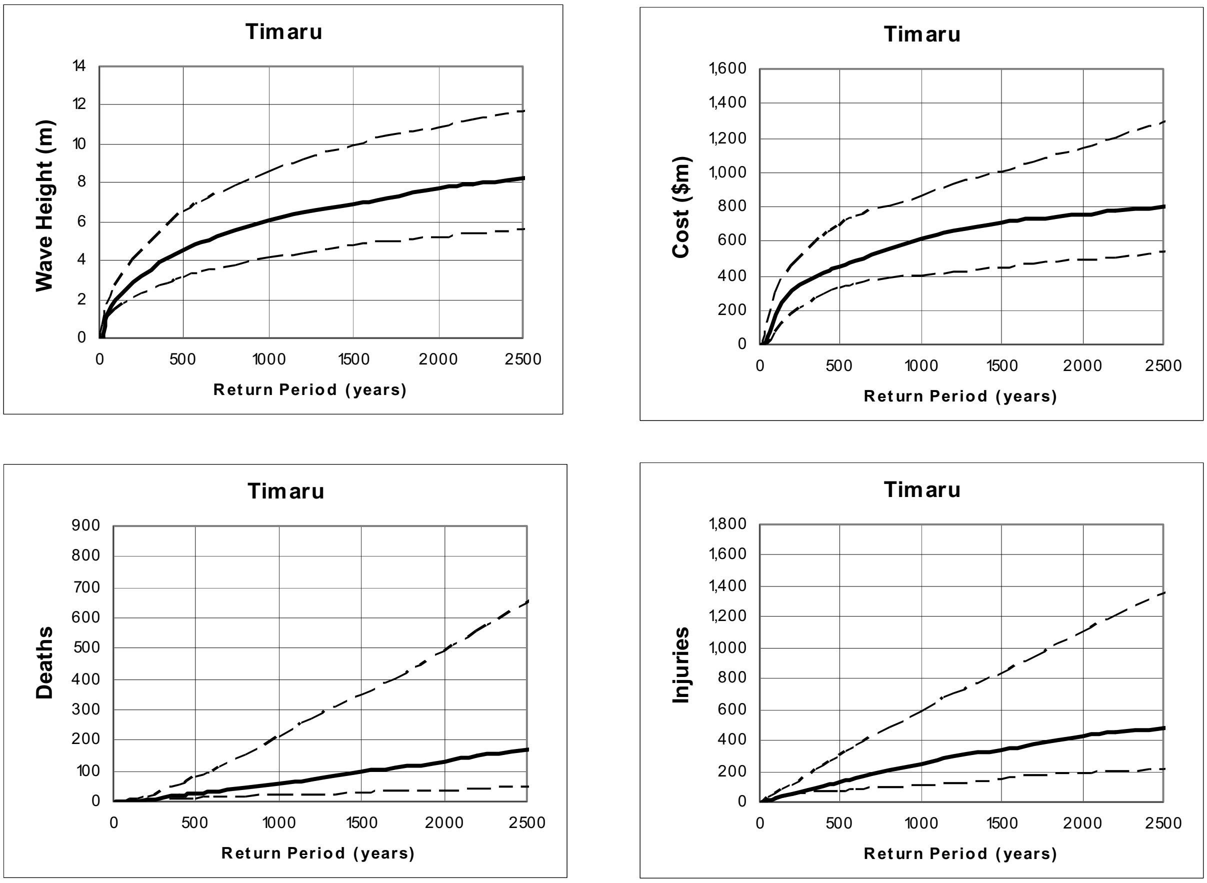
Data plotted above		50 yrs	100	200	500	1000	2500
Height (m)	84%	1.6	2.2	2.9	4.0	5.0	6.6
	50%	1.2	1.6	2.1	2.9	3.5	4.5
	16%	1.0	1.2	1.5	2.1	2.5	3.2
Cost ($m)	84%	260	730	1500	3300	4900	6900
	50%	25	240	570	1300	2100	3700
	16%	0	33	130	380	680	1200
Deaths	84%	4	15	63	260	620	1700
	50%	0	4	12	51	130	340
	16%	0	1	3	11	25	71
Injuries	84%	130	360	810	2100	3700	6900
	50%	23	130	280	670	1200	2400
	16%	0	32	88	230	390	720

Deaggregation	1.6m (100 yrs)	2.9m (500 yrs)
S America	58%	73%
Subduction zone	26%	16%
Aleutians	7%	4%
Kermadec	5%	6%
Cascadia	3%	1%
S New Hebrides	1%	

Delay	100 yrs	500 yrs
< 1 hr	5%	6%
1-3 hr	26%	16%
> 3 hr	69%	78%

Figure 9.16. Risk curves and data for Tauranga District

Timaru



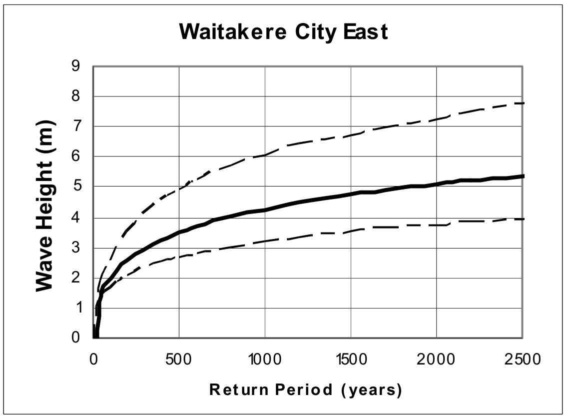
Data plotted above		**50 yrs**	**100**	**200**	**500**	**1000**	**2500**
Height (m)	84%	1.7	2.7	4.1	6.5	8.5	11.7
	50%	1.3	2.0	2.9	4.6	6.0	8.2
	16%	1.0	1.4	2.0	3.1	4.1	5.5
Cost ($m)	84%	130	310	450	690	860	1300
	50%	48	170	310	450	620	800
	16%	1	74	170	320	400	530
Deaths	84%	1	5	16	76	210	640
	50%	0	1	6	24	59	170
	16%	0	0	2	8	17	44
Injuries	84%	21	48	98	300	580	1400
	50%	9	29	55	130	250	490
	16%	2	14	34	67	110	210

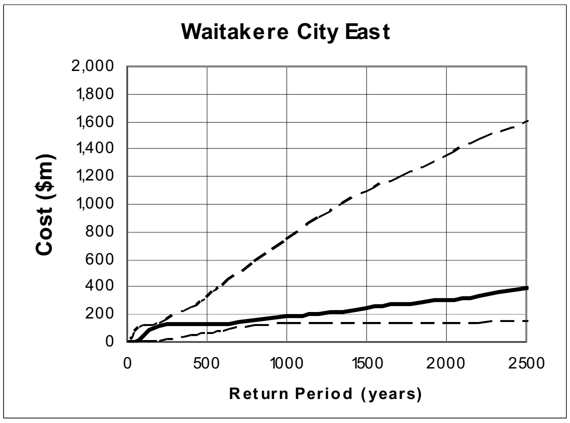
Deaggregation	**1.9m (100 yrs)**	**4.6m (500 yrs)**
S America	89%	98%
Subduction zone	8%	2%
Aleutians	3%	

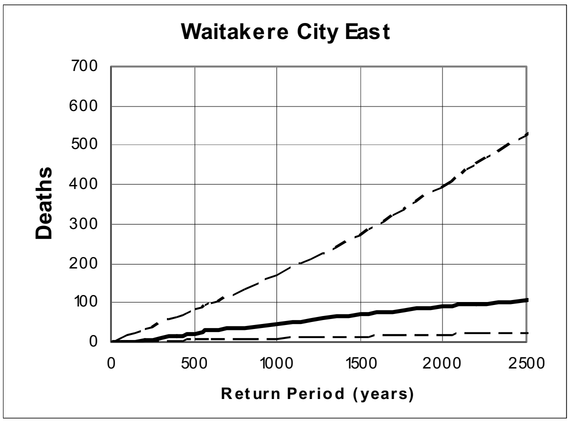
Delay	**100 yrs**	**500 yrs**
< 1 hr	0%	0%
1-3 hr	8%	2%
> 3 hr	92%	98%

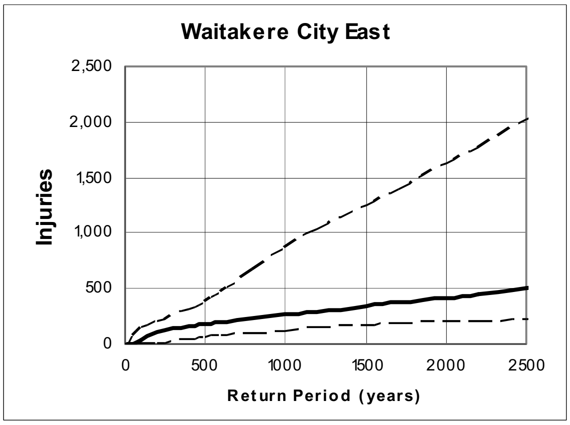
Figure 9.17. Risk curves and data for Timaru District

Waitakere City – East Coast









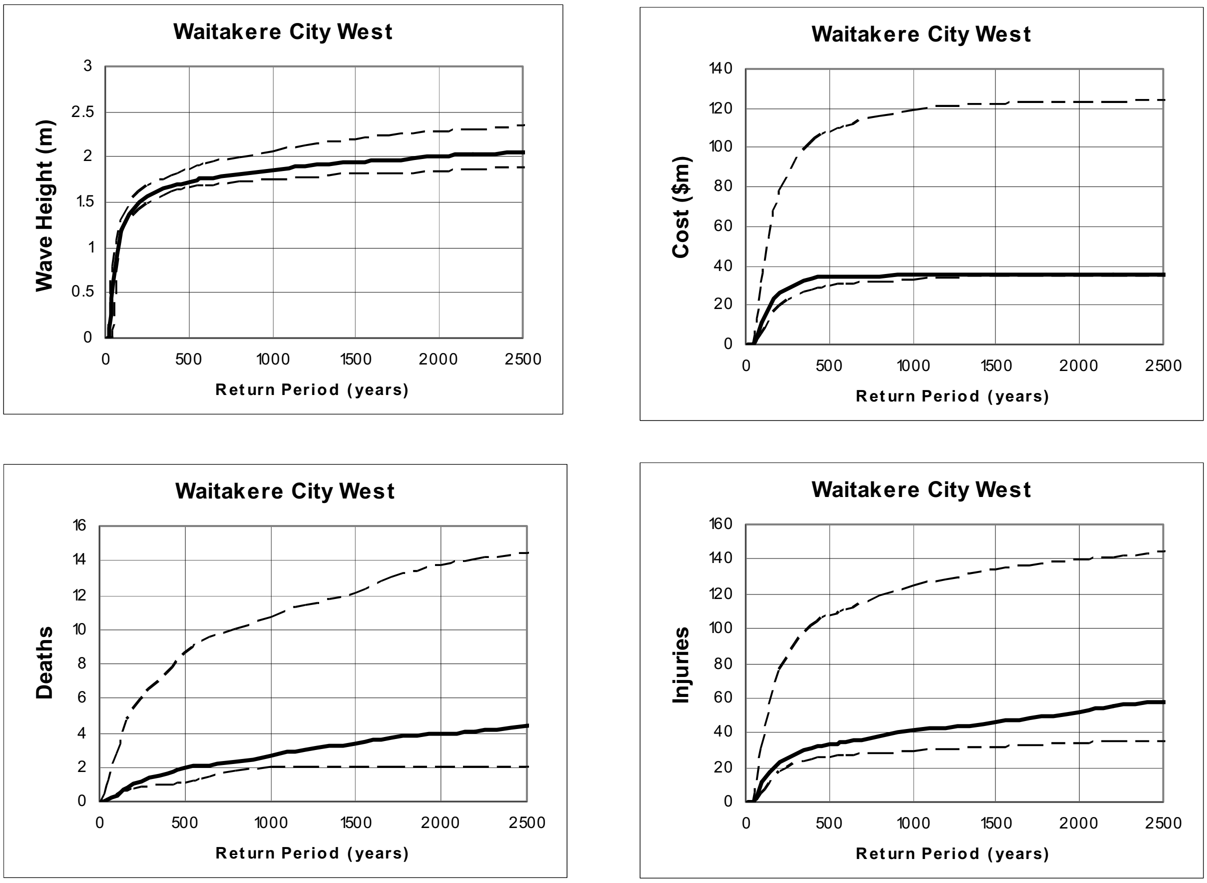
Data plotted above		50 yrs	100	200	500	1000	2500
Height (m)	84%	1.9	2.6	3.5	4.9	6.0	7.7
	50%	1.5	2.0	2.6	3.5	4.3	5.4
	16%	1.3	1.6	2.0	2.7	3.2	3.9
Cost ($m)	84%	66	120	130	320	740	1600
	50%	0	43	120	130	190	390
	16%	0	0	3	57	130	140
Deaths	84%	5	13	29	81	170	530
	50%	0	2	7	22	47	110
	16%	0	0	0	3	7	22
Injuries	84%	63	140	190	380	870	2000
	50%	0	35	110	190	260	500
	16%	0	0	8	51	110	220

Deaggregation	2.0m (100 yrs)	3.6m (500 yrs)
S America	68%	80%
Aleutians	16%	14%
Subduction zone	10%	2%
Kermadec	4%	3%
S New Hebrides	1%	1%
Cascadia	1%	

Delay	100 yrs	500 yrs
< 1 hr	0%	0%
1-3 hr	15%	94%
> 3 hr	85%	6%

Figure 9.18. Risk curves and data for Waitakere City – East Coast

Waitakere City – West Coast



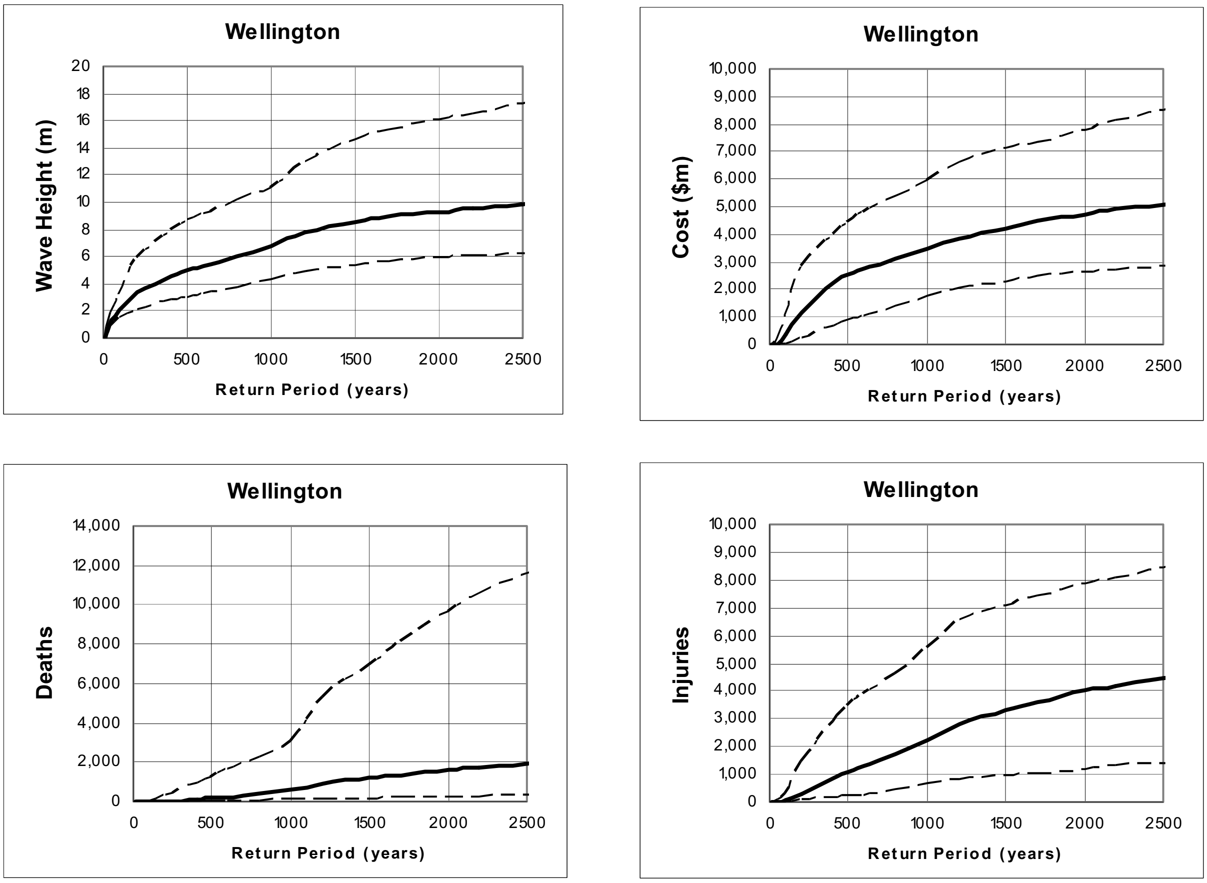
Data plotted above		50 yrs	100	200	500	1000	2500
Height (m)	84%	0.8	1.3	1.6	1.9	2.1	2.3
	50%	0.6	1.2	1.5	1.7	1.9	2.1
	16%	0	1.1	1.4	1.7	1.7	1.9
Cost ($m)	84%	0	31	78	110	120	120
	50%	0	11	26	34	36	36
	16%	0	5	19	29	32	35
Deaths	84%	0	2	6	9	11	14
	50%	0	0	1	2	3	4
	16%	0	0	1	1	2	2
Injuries	84%	0	31	76	110	120	140
	50%	0	11	23	33	41	57
	16%	0	5	17	25	29	34

Deaggregation	1.2m (100 yrs)	1.7m (500 yrs)
S America	75%	64%
Aleutians	19%	27%
S New Hebrides	3%	5%
Cascadia	3%	4%

Delay	100 yrs	500 yrs
< 1 hr	0%	0%
1-3 hr	3%	5%
> 3 hr	97%	95%

Figure 9.19. Risk curves and data for Waitakere City – West Coast

Wellington

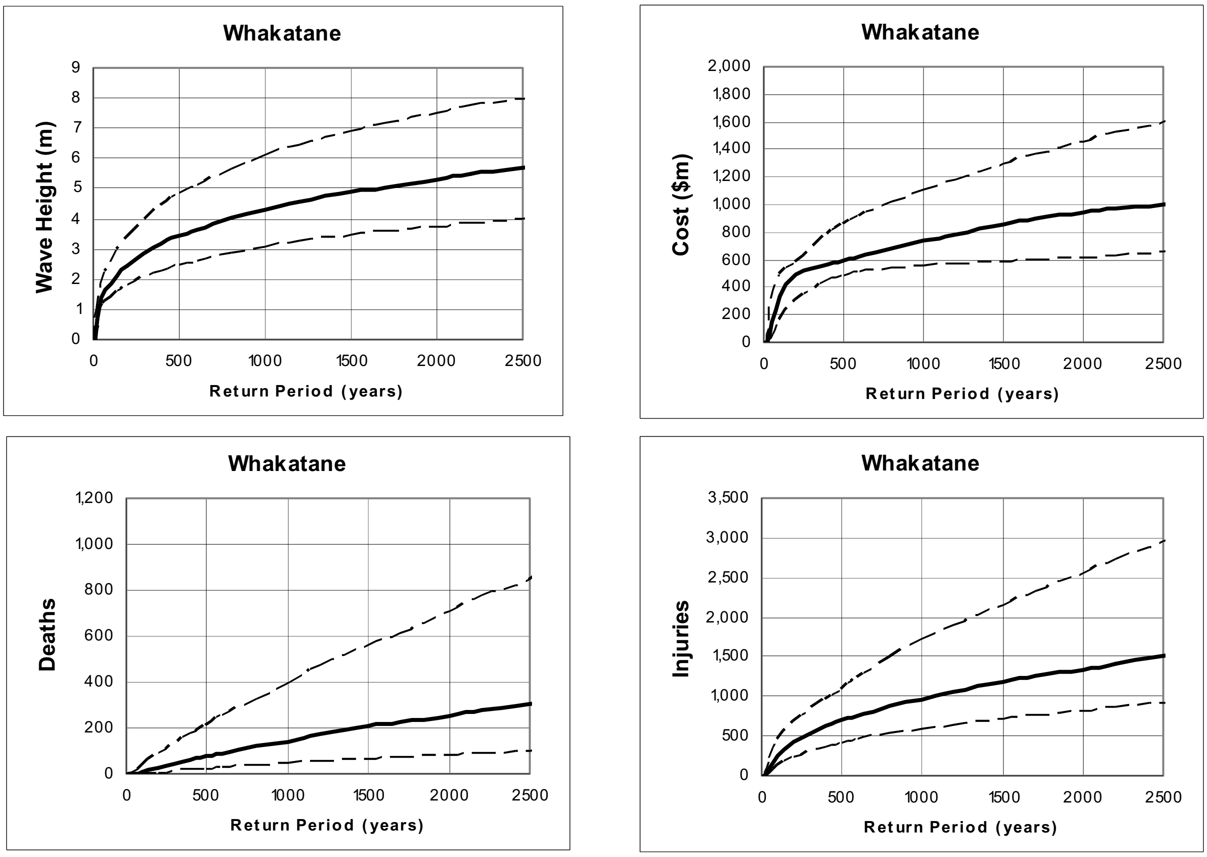


Data plotted above		50 yrs	100	200	500	1000	2500
Height (m)	84%	1.9	3.3	5.8	8.6	11.6	17.4
	50%	1.3	2.2	3.5	5.3	7.4	10.3
	16%	1.0	1.4	2.1	3.3	4.6	6.2
Cost ($m)	84%	260	1200	3000	4900	6400	9500
	50%	17	350	1200	2500	3600	5300
	16%	0	22	290	1000	1900	2900
Deaths	84%	0	26	300	1500	4100	13000
	50%	0	1	26	160	650	2300
	16%	0	0	1	17	91	320
Injuries	84%	46	330	1600	4000	6300	9900
	50%	7	68	320	1100	2400	4800
	16%	0	11	55	260	700	1500

Deaggregation	2.2m (100 yrs)	5.3m (500 yrs)		Delay	100 yrs	500 yrs
Subduction zone	41%	69%		< 1 hr	70%	88%
S America	30%	12%		1-3 hr	0%	0%
Local faults	29%	19%		> 3 hr	30%	12%

Figure 9.20. Risk curves and data for Wellington City

Whakatane



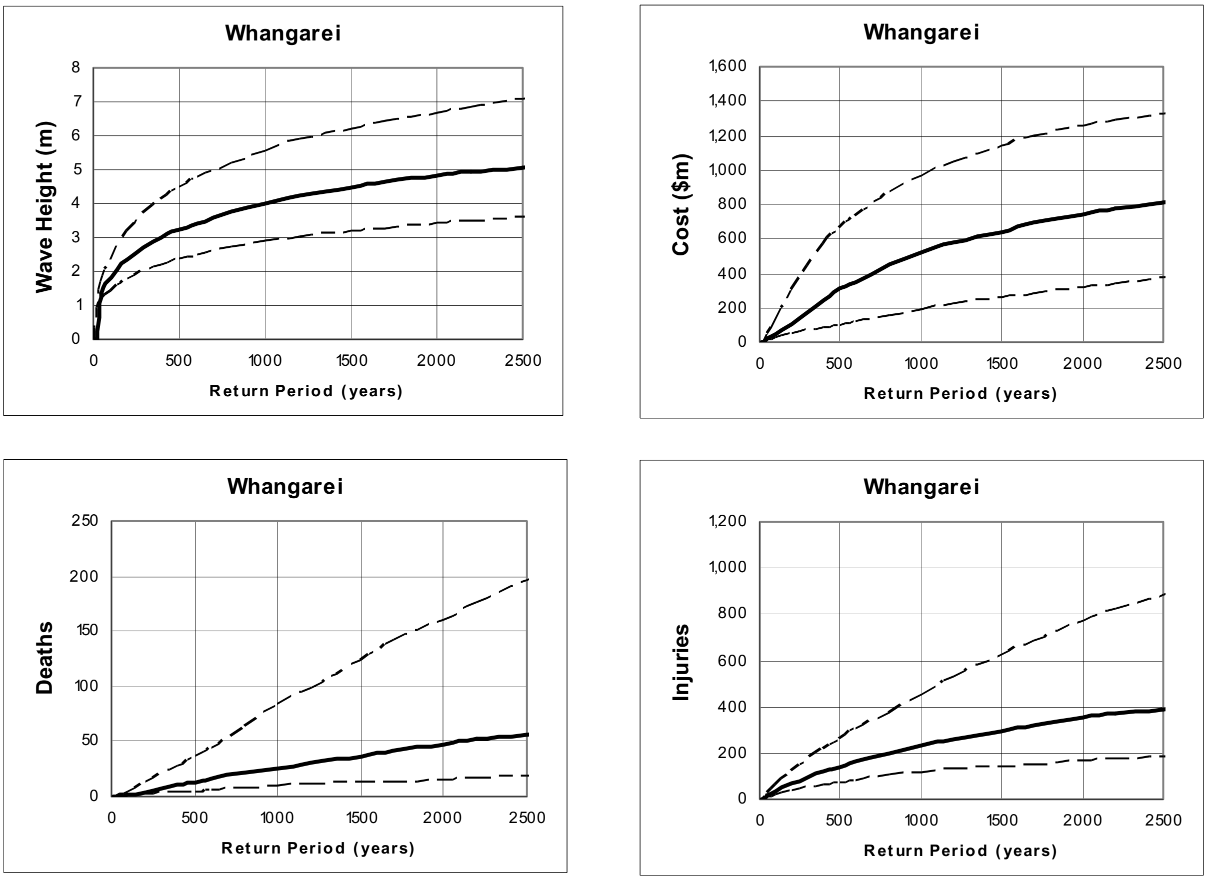
Data plotted above		50 yrs	100	200	500	1000	2500
Height (m)	84%	1.8	2.6	3.4	4.8	6.1	8.0
	50%	1.4	1.9	2.5	3.5	4.3	5.7
	16%	1.1	1.4	1.8	2.5	3.1	4.0
Cost ($m)	84%	310	490	580	850	1100	1600
	50%	150	330	490	590	740	1000
	16%	35	170	310	480	550	650
Deaths	84%	10	35	85	210	390	850
	50%	1	8	26	74	140	310
	16%	0	1	3	20	44	99
Injuries	84%	230	440	670	1100	1700	2900
	50%	110	250	420	700	970	1500
	16%	31	120	240	420	590	900

Deaggregation	1.8m (100 yrs)	3.3m (500 yrs)
S America	50%	63%
Subduction zone	28%	16%
Local faults	10%	13%
Aleutians	6%	3%
Kermadec	4%	5%
S New Hebrides	1%	
Cascadia	1%	

Delay	100 yrs	500 yrs
< 1 hr	42%	34%
1-3 hr	1%	0%
> 3 hr	57%	66%

Figure 9.21. Risk curves and data for Whakatane District

Whangarei



Data plotted above		50 yrs	100	200	500	1000	2500
Height (m)	84%	1.7	2.4	3.2	4.5	5.6	7.0
	50%	1.4	1.8	2.3	3.2	4.0	5.1
	16%	1.1	1.4	1.8	2.4	2.9	3.6
Cost ($m)	84%	43	120	300	660	960	1300
	50%	18	47	110	310	520	820
	16%	7	22	42	96	190	370
Deaths	84%	1	4	12	36	83	200
	50%	0	1	4	13	25	57
	16%	0	0	1	4	9	18
Injuries	84%	27	61	120	260	450	880
	50%	13	33	67	140	230	390
	16%	6	17	35	72	110	180

Deaggregation	1.8m (100 yrs)	3.2m (500 yrs)
S America	73%	87%
Subduction zone	11%	3%
Aleutians	7%	3%
Kermadec	4%	4%
Cascadia	4%	3%
New Hebrides	1%	

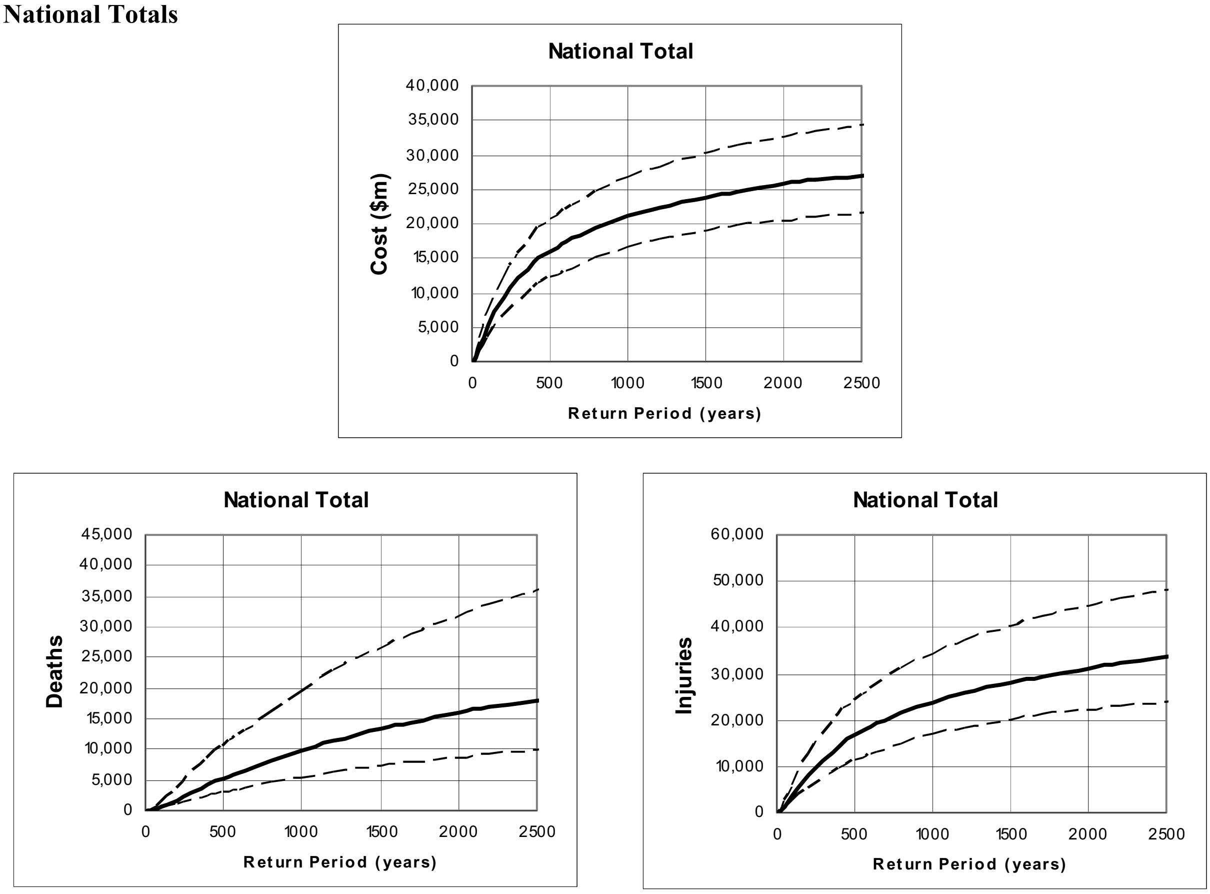
Delay	100 yrs	500 yrs
< 1 hr	0%	0%
1-3 hr	16%	7%
> 3 hr	84%	93%

Figure 9.22. Risk curves and data for Whangarei District

9.3 National Risk

National totals for costs, deaths and injuries are complicated functions of those for the individual locations, not simple totals. They are aggregated for each individual event, because a tsunami from South America, for instance, could inundate several locations along the NZ coast, and it was for this reason that the relative times of high tides were taken into account. So losses at various locations can be correlated. But the reverse can also apply; losses can be uncorrelated, i.e. where a tsunami affects only one or two locations. The effect of this is that the frequency of occurrence of these losses is aggregated in the national totals.

National Totals



Data plotted above		50	100	200	500	1000	2500
Cost ($m)	84%	3600	7300	12,000	21,000	27,000	34,000
	50%	2400	5000	9100	16,000	21,000	27,000
	16%	1500	3400	6400	12,000	16,000	21,000
Deaths	84%	360	1300	3800	10,000	20,000	36,000
	50%	160	620	1700	5500	10,000	19,000
	16%	62	280	890	2900	5400	10,000
Injuries	84%	2500	6400	13,000	24,000	34,000	46,000
	50%	1500	3800	8100	16,000	24,000	33,000
	16%	930	2400	5200	11,000	17,000	24,000

Figure 9.23. Risk curves and data at a national level

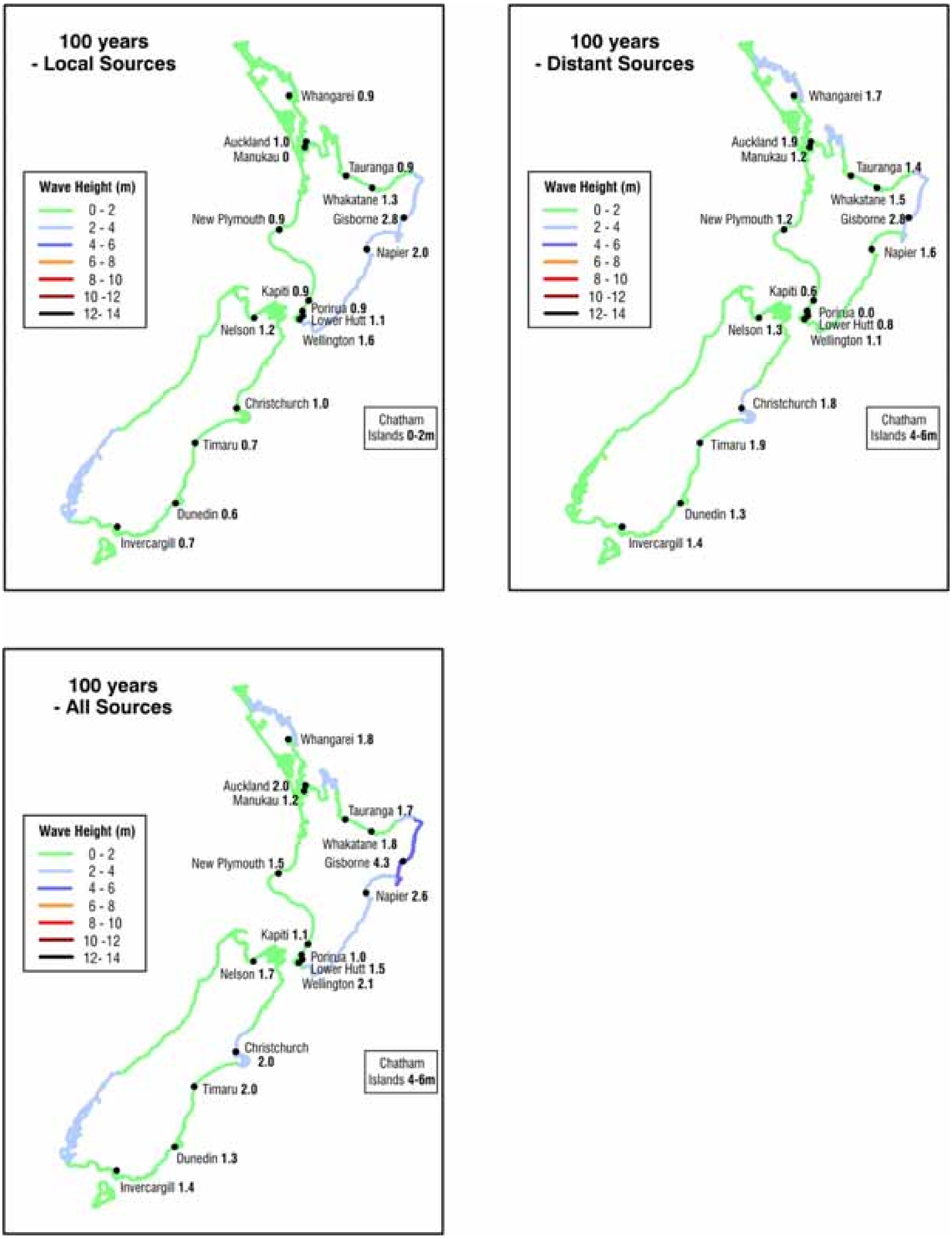


Figure 9.24a Generalised assessment of tsunami hazard in New Zealand expressed as expected mean estimate wave above mean sea level at the shore for 100 year return period. Significantly higher or lower water elevations may occur locally. These maps should not be used for site-specific assessments. Estimates made for the West Coast of the South Island are quite uncertain because a major part of the risk may come from earthquake-triggered submarine landslides off the West Coast which has proven impossible to quantify with existing information for this review.

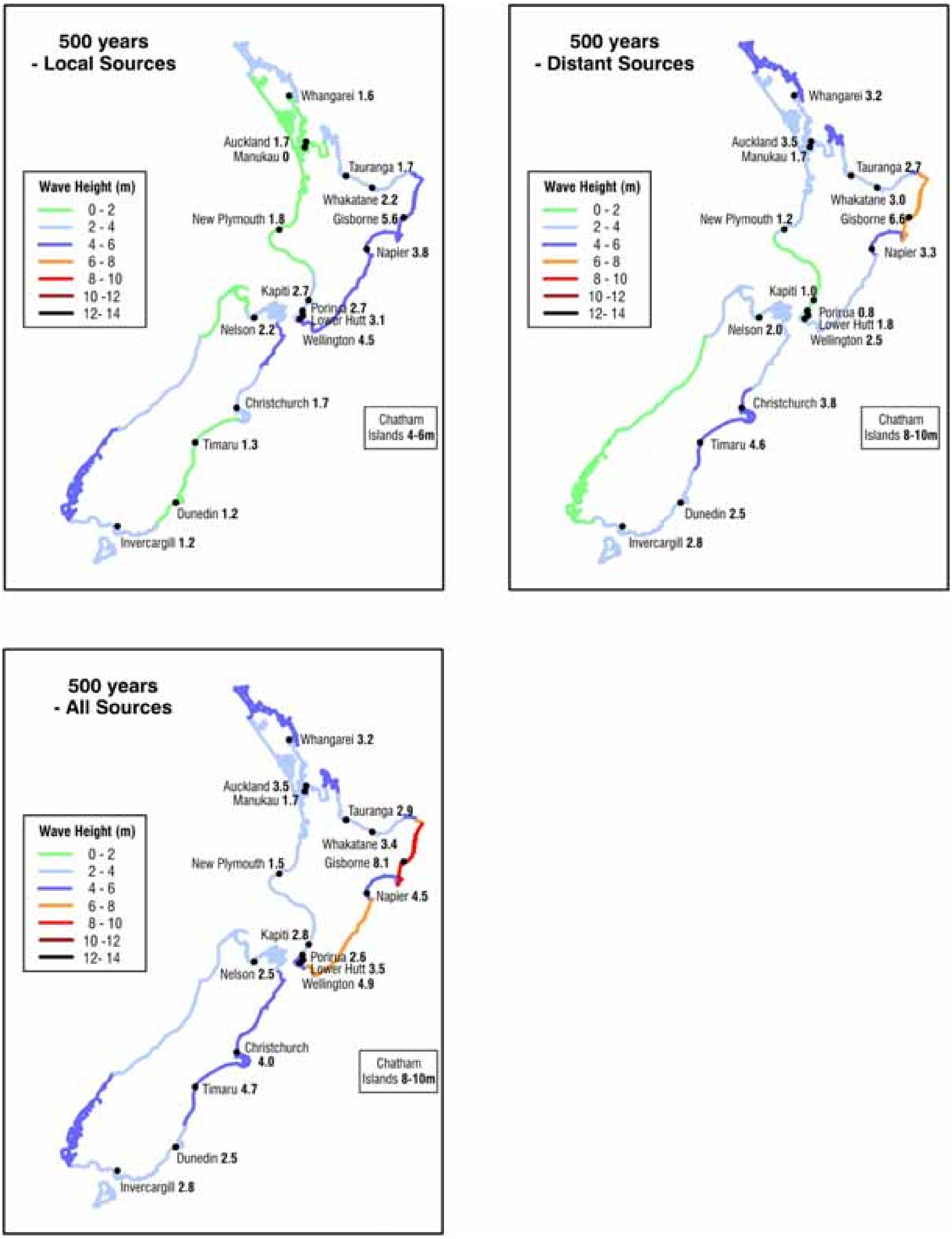


Figure 9.24b Generalised assessment of tsunami hazard in New Zealand expressed as expected mean estimate wave above mean sea level at the shore for 500 year return period. Significantly higher or lower water elevations may occur locally. These maps should not be used for site-specific assessments. Estimates made for the West Coast of the South Island are quite uncertain because a major part of the risk may come from earthquake-triggered submarine landslides off the West Coast which has proven impossible to quantify with existing information for this review.

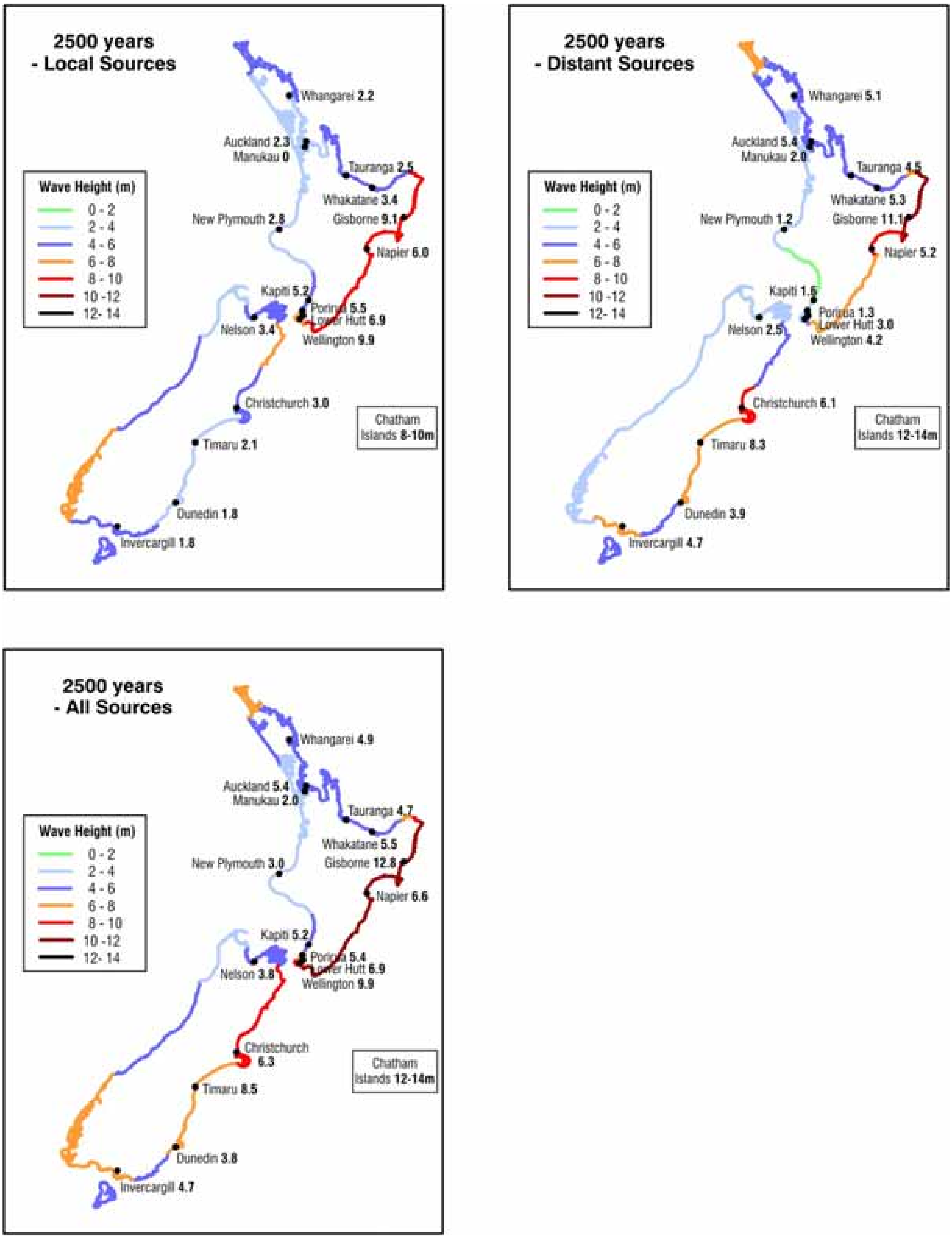


Figure 9.24c Generalised assessment of tsunami hazard in New Zealand expressed as expected mean estimate wave above mean sea level at the shore for 2500 year return period. Significantly higher or lower water elevations may occur locally. These maps should not be used for site-specific assessments. Estimates made for the West Coast of the South Island are quite uncertain because a major part of the risk may come from earthquake-triggered submarine landslides off the West Coast which has proven impossible to quantify with existing information for this review.

9.4 Individual Risk

In addition to the risks to communities and the nation as a whole, we have estimated the risk to individuals who live at low elevations close to the coast, at the same list of localities. In Table 9.1 we present the estimated annual risk of death for individuals who reside at 2m and 4m above mean sea level. The assumptions inherent in this are the same as for the casualties estimates earlier, i.e. that there is no warning. We make the further assumption here that an individual who lives at such locations will be at home for about half the time (and away elsewhere, and thus safe, for the remainder of the time). As with the estimates of wave height, cost, etc, we present the 16th and 84th percentiles as well as the median. In Table 9.2 we relate these to some commonly held criteria for personal risk with respect to other natural and technological hazards, especially with respect to rail accidents in Britain (Taig, pers. comm., 2004). The entries in Table 9.1 have been colour coded according to Taig's risk ranges in Table 9.2.

Table 9.1 The estimated annual risk of death from tsunami for individuals who reside at the coast at 2m and 4m above mean sea level.

		2m	4m
Auckland East	84%	1.4×10^{-4}	4.3×10^{-5}
	50%	3.9×10^{-5}	7.7×10^{-6}
	16%	9.6×10^{-6}	9.1×10^{-7}
Auckland West	84%	3.1×10^{-7}	0
	50%	4.3×10^{-8}	0
	16%	2.0×10^{-9}	0
Christchurch	84%	2.2×10^{-4}	8.3×10^{-5}
	50%	6.1×10^{-5}	1.5×10^{-5}
	16%	1.7×10^{-5}	2.4×10^{-6}
Dunedin	84%	3.2×10^{-5}	4.6×10^{-6}
	50%	7.4×10^{-6}	3.3×10^{-7}
	16%	1.2×10^{-6}	0
Gisborne	84%	1.7×10^{-3}	9.7×10^{-4}
	50%	6.0×10^{-4}	2.8×10^{-4}
	16%	2.0×10^{-4}	6.4×10^{-5}
Invercargill	84%	7.2×10^{-5}	2.3×10^{-5}
	50%	2.2×10^{-5}	4.4×10^{-6}
	16%	4.8×10^{-6}	5.1×10^{-7}
Kapiti Coast	84%	1.4×10^{-4}	6.0×10^{-5}
	50%	3.2×10^{-5}	7.4×10^{-6}
	16%	4.4×10^{-6}	2.7×10^{-7}
Lower Hutt	84%	3.0×10^{-4}	1.6×10^{-4}
	50%	8.5×10^{-5}	2.5×10^{-5}
	16%	1.4×10^{-5}	1.7×10^{-6}
Manukau East	84%	1.4×10^{-4}	4.3×10^{-5}
	50%	3.9×10^{-5}	7.7×10^{-6}

	16%	9.6×10^{-6}	9.1×10^{-7}
Manukau West	84%	3.1×10^{-7}	0
	50%	4.3×10^{-8}	0
	16%	2.0×10^{-9}	0
Napier	84%	3.1×10^{-4}	1.1×10^{-4}
	50%	9.0×10^{-5}	1.8×10^{-5}
	16%	1.6×10^{-5}	1.2×10^{-6}
Nelson	84%	2.9×10^{-5}	6.8×10^{-6}
	50%	6.9×10^{-6}	4.7×10^{-7}
	16%	1.3×10^{-6}	7.6×10^{-9}
New Plymouth	84%	2.2×10^{-5}	9.4×10^{-6}
	50%	5.4×10^{-6}	1.3×10^{-6}
	16%	7.4×10^{-7}	2.4×10^{-8}
North Shore	84%	1.4×10^{-4}	4.3×10^{-5}
	50%	3.9×10^{-5}	7.7×10^{-6}
	16%	9.6×10^{-6}	9.1×10^{-7}
Porirua	84%	1.6×10^{-4}	7.1×10^{-5}
	50%	3.7×10^{-5}	8.2×10^{-6}
	16%	4.9×10^{-6}	1.8×10^{-7}
Tauranga	84%	7.1×10^{-5}	2.1×10^{-5}
	50%	1.9×10^{-5}	3.7×10^{-6}
	16%	4.5×10^{-6}	4.1×10^{-7}
Timaru	84%	3.7×10^{-4}	2.0×10^{-4}
	50%	1.5×10^{-4}	6.6×10^{-5}
	16%	4.8×10^{-5}	1.7×10^{-5}
Waitakere East	84%	1.4×10^{-4}	4.3×10^{-5}
	50%	3.9×10^{-5}	7.7×10^{-6}
	16%	9.6×10^{-6}	9.1×10^{-7}
Waitakere West	84%	3.1×10^{-7}	0
	50%	4.3×10^{-8}	0
	16%	2.0×10^{-9}	0
Wellington	84%	6.9×10^{-4}	4.5×10^{-4}
	50%	2.5×10^{-4}	1.2×10^{-4}
	16%	6.0×10^{-5}	1.5×10^{-5}
Whakatane	84%	1.5×10^{-4}	5.6×10^{-5}
	50%	4.5×10^{-5}	1.3×10^{-5}
	16%	1.2×10^{-5}	2.7×10^{-6}
Whangarei	84%	9.8×10^{-5}	2.9×10^{-5}
	50%	2.8×10^{-5}	4.8×10^{-6}
	16%	6.2×10^{-6}	4.8×10^{-7}

Table 9.2 Guidelines to acceptable levels of personal risk (T.Taig, pers. comm.) Colour codes refer to Table 9.1.

Risk level (individual annual fatality risk)	**Significance**
10^{-6} to 10^{-7}/year or lower	Unlikely to be nationally significant unless there are some very special features at risk
~10^{-5} to 10^{-6} per year	Many New Zealanders probably already face natural risks at home and at work of this scale. Might want to avoid new consents to add to the numbers where possible. Government needs to note that if it helps one group of people at these sorts of risk level "on safety grounds" then it might face large numbers of equally valid claims for help in future.
~10^{-4} to 10^{-5} per year	Some New Zealanders probably already face natural hazard risks at home/work of this scale. Definitely avoid new consents to add to the numbers. Government helping out at these sorts of levels on safety grounds might open up further claims (not sure how many).
~10^{-3} to 10^{-4} per year	Getting up to the sort of levels regarded as intolerable for non-beneficiaries in regulatory regimes focused on man-made hazards. Government should not be comfortable if risks at this level are being imposed on people without their consent, or with people being induced to accept risks at this level.
~10^{-2} to 10^{-3} per year	Widely regarded as intolerable even for beneficiaries of an activity with a degree of control over the risk (e.g. employees in hazardous industries). There need to be special reasons to tolerate any kind of individual risks at this scale from pretty much any cause.
Above ~10^{-2} per year	Getting beyond the pale for almost any accidental cause in any developed country. Even if the risk is entirely for the benefit of the exposed person (e.g. a patient seeking a risky treatment for a serious medical condition) special care is warranted to ensure the recipient really understands and accepts the risk.

9.5 Comparison with earthquake risk

Casualties and damage costs due to earthquakes affecting all buildings and people in New Zealand were estimated by applying the Monte Carlo method of Smith (2003) to a first-order earthquake loss model developed by Cousins (2004). The Smith method involves generating a synthetic catalogue of earthquakes, in this case 100,000 years long, that represents the current seismicity model for New Zealand (Stirling and McVerry, 2002). Buildings and population assets models for New Zealand were subjected to each of the approximately 500,000 earthquakes in the synthetic catalogue, with damage (then losses) and collapse (then casualties) being estimated for each earthquake. Exceedance rates for various levels of casualties and losses were estimated from the accumulated results.

Figure 9.25 shows the median estimates, from the above results in Section 9.2, together with the corresponding estimates for direct earthquake losses. Note that on this scale the earthquake-related deaths and injuries are almost insignificant.

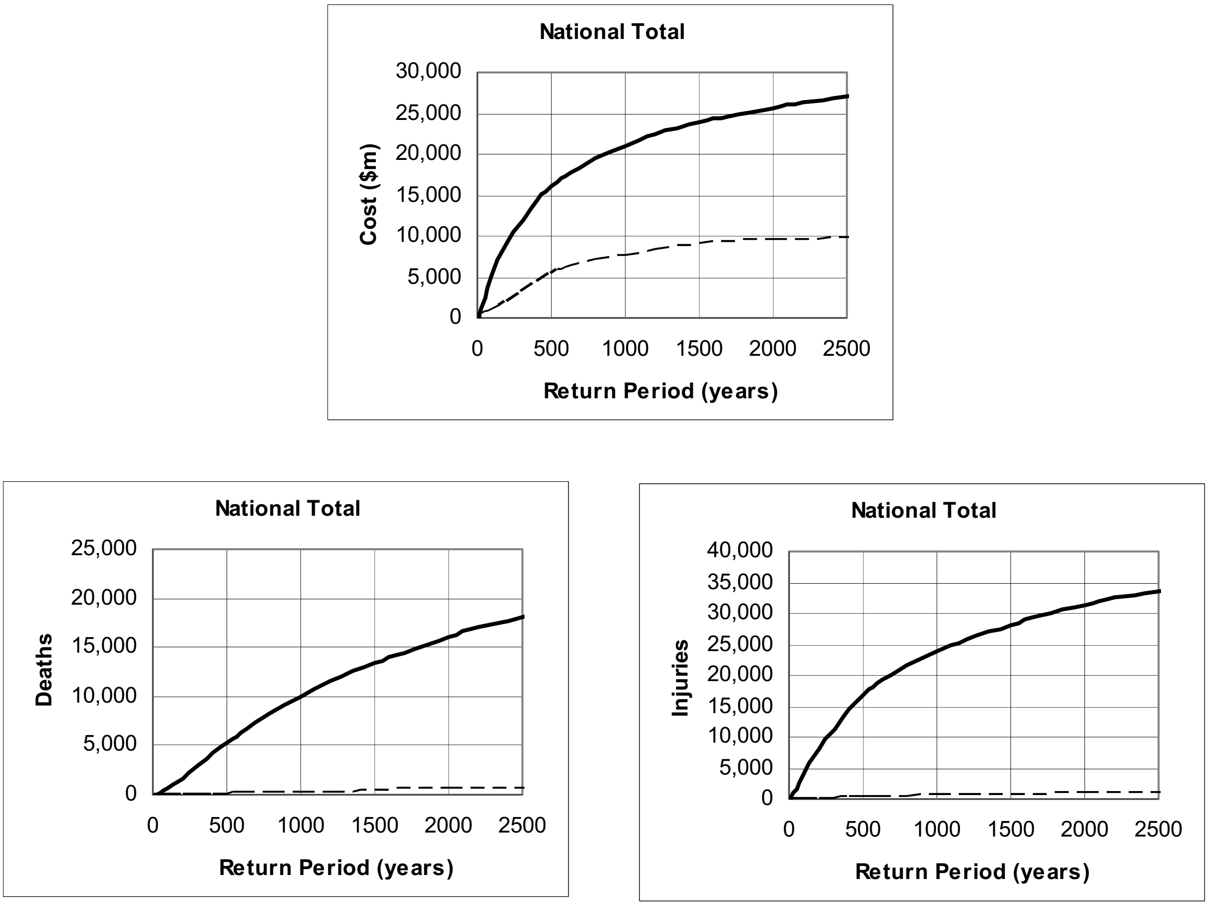


Figure 9.25. Mean national losses from tsunami (bold curves) and earthquake (broken curves).

It is apparent that the expected losses from tsunami, on a nationwide basis, are approximately twice those from earthquakes, and that the expected deaths and injuries are many more than from earthquakes. These tsunami loss estimates assume no effective warning, even for distant tsunami. From Figures 9.1 to 9.24 it is apparent that much of the risk is due to distant tsunami, particularly from South American sources, and from these sources a high level of effective warning should be readily achieved. Thus, loss of life and injuries presented in Fig. 9.25 may well be extremely pessimistic. The Preparedness Report will address the effectiveness of warning, and options for achieving effective warning to mitigate losses due to deaths and injuries.

10.0 CONCLUSIONS

In this report we have examined all the likely sources of tsunami that can affect New Zealand, evaluating their potential to generate tsunami, the likely waves produced, and their impact on the principal urban centres around the New Zealand coastline. This review has been completed to the best possible standard noting the short timeframe available, and the requirement to use existing information. A probabilistic methodology has been developed to achieve these objectives. The report is thus the first probabilistic tsunami risk study undertaken in New Zealand. In fact we are not aware of any comparable study anywhere else in the world. Our decision to embark on a probabilistic approach was primarily to capture uncertainty in the calculations. Identifying and amalgamating a range of viable alternate parameters and models is the most useful approach when attempting a hazard and risk estimate with weakly constrained data.

We have provided estimates of the tsunami hazard and risk, i.e. the probability that various localities will experience tsunami, and the likely losses in terms of cost of damage, lives lost and injuries caused.

Identification of the sources of possible earthquake-generated tsunami has been careful and exhaustive, and every effort has been made to assign appropriate parameters to them in terms of magnitudes and recurrence intervals. But the seismological and geological data are limited and so there are large uncertainties. Where possible, we have used historical and paleotsunami data to validate source models.

Landslide-generated tsunami have also been given close consideration in terms of possible sources and their recurrence intervals. The contribution from earthquake-induced landsliding to tsunami risk is already incorporated within the Japanese data we used to derive the tsunami propagation relationship, but there may be rare cases of landslide-generated tsunami without an earthquake trigger.

Volcano sources have also been considered in this report, but are not included in the risk calculations. This is for two reasons: firstly, volcano sources that are large enough to cause damaging tsunami have recurrence intervals that are too long to be of concern in terms of the 2500 year timeframe that we are considering and, secondly, more frequent volcano sources, including sector collapse, are considered too small to produce a 2 m wave at an adjacent coast.

Tsunami propagation characteristics are also quite uncertain; directivity of the source, propagation across oceanic distances, and propagation to short distances from local sources cannot be known with great confidence. But we have implemented the best available empirical data to model these characteristics in the interim, before more appropriate numerical simulations are completed in the coming years.

There is very significant uncertainty also in the level to which land is inundated. Models of tsunami run-up and the effect to which buildings and other roughness of the landscape attenuate the wave are by no means precise, and as a result the uncertainties in our estimates are quite high. This reflects the shortcoming of empirical approaches to this complex question, but we are confident that the range of models we use in the risk estimation suitably bound the range of viable models.

Damage to buildings is modelled for all residential and non-residential buildings. While there is uncertainty about the level of damage when a building is subjected to tsunami inundation of any given depth, it has turned out that the total cost of damage is not very sensitive to the particular fragility model that was chosen. We are therefore confident that the fragility aspects of our modelling are relatively robust.

The limitations of this study are spelt out in more detail in Appendix 5. In spite of these limitations, however, we believe that we have been able to derive meaningful numbers that will inform decisions about prioritising future research efforts to improve the confidence of the hazard and risk estimates, and inform thinking on the adequacy of warning systems and other mitigation measures. The large uncertainties that we have had to contend with will tend to wide bounds on loss estimates, and it is important that these uncertainties be reduced in future through continued research.

Limitations aside, the study shows that the ongoing risk from tsunami in New Zealand is significant, possibly rather higher than many people may realise. New Zealand has some experience of tsunami in the historical past, but few lives have been lost and damage to property to infrastructure has been modest. However, the large historical tsunami events that threatened New Zealand occurred when shoreline development was very modest by comparison with present, so the fragility is now much, much greater.

Our study has not allowed for the possibility that there may be an effective warning before the arrival of a tsunami, especially from a distant source, because this issue will be addressed in the Preparedness Report. But while an effective warning system will no doubt reduce deaths and injuries, taking this into account in the modelling will of course not change the estimated amount of damage.

Another issue that is addressed in the Preparedness Report is that some localities are more prone to inundation from tsunamis that originate at great distances, while others are locally generated. This has very important consequences for the feasibility of an effective warning system.

As well as examining the risks that individual localities face, we have assessed risks on a national basis because of the possibility that a tsunami might inundate a number of localities. In doing that we took account of the variation in the times of tides around the country.

On a national basis we were also able to make a comparison with direct losses from earthquakes, which we have modelled previously. In summary, the damage to property from tsunami is about twice what we expect from earthquakes with similar return period, and the deaths and injuries are many times more. A caveat here is that the projected deaths and injuries numbers will drop if it is felt appropriate to assume an effective warning system exists for tsunami of distant origin, but they will still be substantially greater than for earthquakes in places such as Wellington where the major threat is from locally generated tsunami.

11.0 RESEARCH REQUIREMENTS FOR IMPROVED HAZARD & RISK ASSESSMENT

11.1 Historical and pre-historical record

- Paleotsunami research is in its infancy both internationally and in New Zealand. This field of study can make a valuable contribution to calibration of hazard models and has the great merit of extending the record of large but infrequent tsunami inundations. To obtain high quality, robust data requires careful and time-consuming work.
- While the historical record is good by international standards, new events and new data are still being uncovered and added — effort that is significantly improving the value of this database as a calibration for numerical models.

11.2 Numerical Modelling

Numerical modelling of tsunami serves a double purpose, it allows us to predict the behaviour of events which have yet to happen, and it enables us to test and confirm our understanding of past tsunami. Very few sources of tsunami in New Zealand have been modelled in a comprehensive manner as yet. To have a full understanding of the hazards and risks of tsunami in New Zealand considerably more modelling is required. There are three components to numerical modelling, each having their critical success factors, described below.

11.2.1 Source Characterisation

- Better identification and characterisation of faults — slip rate, recurrence interval, maximum magnitude and better modelling and characterisation of landslide source models and volcano eruption/caldera collapse models. The largest and most important gaps in knowledge appear to be associated with the recurrence and size of earthquakes in the Hikurangi subduction margin, landslide frequency and magnitude at local source distances.
- Inclusion of all potential sources of tsunami for all populated coastlines in New Zealand.
- Inclusion of variable slip fault models. In the numerically modelled earthquake scenarios used for this review, averaged fault displacements on a fault plane are used, that is, the displacement is taken to be the same along the length of the fault. In reality, the vertical deformation at the seabed (the main cause of a tsunami) may vary considerably from one part of the fault to another in response to variations in slip. This is particularly important for local source earthquakes, one possible consequence being that the coast adjacent to the areas of high deformation may experience higher waves than in the averaged model.

11.2.2 Propagation & Inundation Modeling

- A critical input to propagation models is the bathymetry of the seafloor. This is because the speed, and ultimately the direction, of the tsunami are controlled by the depth of water. Consequently the model results are only as good as the bathymetry data allow. In water depths of <50 m a seafloor bathymetry with accuracy to better than ±1 m is required for accurate tsunami modelling across the water-land interface. Much good bathymetry data exists, but the processes of combining different sources of bathymetry and processing it into the required form is one of the most labour-intensive aspects of tsunami modelling. The proprietary nature of many bathymetry databases is also an obstacle to the preparation and use of bathymetry grids for tsunami modelling.
- A critical input to inundation modelling is detailed data on the topography of the areas being considered, ideally with a vertical resolution of less than 0.5 m. Currently there are very few areas of New Zealand which have topography mapped to this resolution. High-resolution inundation modelling also benefits from data on the size and shape of buildings and on land use, i.e. whether forested, cultivated, urban, etc.
- Many of New Zealand's urban centres are situated on natural harbours and estuaries, and the dynamics of tsunami as they propagate from the ocean coast across these estuaries is poorly understood. Bottom-friction causes tsunami to slow and attenuate, especially over mud flats. In addition, harbours and estuaries have natural resonance frequencies which can cause amplification (or de-amplification) depending on the frequencies present in the tsunami. At present there is insufficient information to disentangle the multiple effects that occur in such a way as to establish simple procedures which can be applied to a range of locations using GIS. It is recommended that the current analysis be used as a 'first-approximation' to establish the most at-risk locations where estuaries play a significant role, and that detailed physics-based numerical models be applied there. Information from such numerical modelling, combined with data gathered from the 26 December 2005 and other historical tsunami, could then be used to establish the most appropriate approximations for application by GIS.
- Topography, land-use, the frequency and type of waves in the tsunami wave train (fast rising and falling water levels, or as turbulent walls of water) determine how far inland and how fast the water travels, and hence, how destructive it is. There is very limited literature on the following relationships:
  - between the height of the incoming waves at the shoreline and on-land water depths and currents
  - between on-land water depths and currents and the damage of the built environment inland
  - between on-land water depths and damage and casualties.

The many limitations in the current understanding can only be remedied with better physics-based numerical models, but they are challenging both from the technical and time requirements involved. This is an area of rapid international development also, and New Zealand must participate in this advancement.

11.3 Fragility, Casualty & Loss Modelling

Fragility

- Conduct extensive literature search for data to calibrate building fragility models
- Develop improved estimates of forces needed to (a) displace, and (b) collapse, typical New Zealand buildings
- Assess the effectiveness of typical New Zealand natural barriers, such as dunes and vegetation, to reducing tsunami forces, and fragility

Casualty

- Conduct extensive literature search for data to calibrate casualty models
- Improve the inundation modelling to more accurately assess both inundation depth and inundation velocity
- Develop better estimates of injury types and numbers as a percentage of the population at risk
- Develop casualty models for day-time conditions, and for seasonal fluctuations

Loss/Risk

- Examine the uncertainty treatment in the probabilistic methodology making sure that knowledge and statistical uncertainties are appropriately assigned.
- Extend the models to include all coastal communities to obtain a better estimate of national risk
- Complete a series of sensitivity tests of the probabilistic risk result to identify the principal components of the model contributing to uncertainty as an aid to prioritising future research

11.4 Preliminary Recommendations for Prioritising Future Research

Preliminary analysis of the risk results suggest that the following research (in approximate priority order) would make best use of resources to improve risk estimates and to inform the hazard mitigation community as to sensible steps in tsunami preparedness, including the type and extent of warning systems:

1. The capacity of the Hikurangi subduction margin along the East Coast of the North Island shows out as the most important, poorly constrained, tsunami source apparently affecting

New Zealand. Both the size and frequency of tsunami from this source are poorly known, and, because the source is local, it has major implications to preparedness. Current levels of funding are inadequate to make rapid progress on this challenging topic. A wide range of disciplines are required to evaluate this problem, ranging across seismology, seismic reflection geophysics, geodesy, earthquake geology, numerical water modelling and paleotsunami.

2. Detailed bathymetry and topography should be obtained from one or two case study areas where the risk appears to be very high (e.g. Gisborne, Napier, or Wellington) as a preamble to developing a fully integrated numerical model of tsunami propagation and inundation. Some significant investment in data acquisition is required before full-scale numerical modelling is warranted.

3. A series of numerical models of tsunami generated from a range of credible volcano and landslide sources is warranted. This will provide insight into their viability as sources of damaging tsunami in New Zealand. The Kermadec and Auckland field volcanoes, and Cook Strait and West Coast (South Island) landslides would seem to be the highest priority.

4. Make as many improvements to fragility and casualty models as is possible from literature review, and from field studies of future tsunami when they occur around the world. Improvements in these models are critical to better assessment of risk and therefore to developing most-effective risk mitigation strategies.

In addition to the above risk-oriented studies, work on quantifying the sources and modelling the propagation of pan-ocean tsunami needs to be accelerated. This will help to inform risk from distant-source tsunami, provide essential input for numerical inundation models, but in addition will, in time, allow far more accurate wave-height prediction for the early warning system, as recommended in the Preparedness Report.

12.0 ACKNOWLEDGEMENTS

A great number of people contributed to this report. The principal contributors are listed in Section 1.2.

The overall direction of the project was guided by the Ministry of Civil Defence and Emergency Management Steering Committee whose membership comprised John Norton, and Mike O'Leary (MCDEM); Pat Helm (DPMC); Lesley Middleton and Andrew Watson (MoRST). The direction provided by this group is gratefully acknowledged. The report has benefited significantly from thoughtful review comments from Prof Lori Dengler (Humbolt State University) and Dr Phil Cummins (GeoScience Australia).

13.0 REFERENCES

Abe, K. (1975). Reliable estimation of the seismic moment of large earthquakes. *Journal of Physics of the Earth* **23**, 381-390.

Abe, K., K (1979). Estimate of tsunami run-up heights from earthquake magnitudes". In: Tsuchiya, Y., Shuto, N., (eds.), Tsunami: Progress in prediction, disaster prevention and warning, Dordrecht: Kluwer Academic Publishers, p21-35.

Agriculture and Resource Management Council of Australia and New Zealand (2000). Floodplain management in Australia. Best practice principles and guidelines.

ANCOLD (2003). Guidelines on risk assessment. Australian National Committee on Large Dams Incorporated. 204pp.

Barnes, P.M., Mercier de Lépinay, B., Collot, J-Y., Delteil, J., Audru, J-C. (1998). Strain partitioning in the transition area between oblique subduction and continental collision: Hikurangi margin, New Zealand. *Tectonics* **17,** 534-557.

Barnes, P.M., Nicol, A., Harrison, T. (2002). Neogene deformation history and seismic potential of Lachlan Ridge: a major active thrust complex, Hikurangi subduction margin, New Zealand. *Geological Society of America Bulletin* **114,** 1379-1405.

Barnett, A. (2005). Christchurch Tsunami Hazard: Scenario 1. Barnett & MacMurray Ltd. Client Report for the Institute of Geological and Nuclear Sciences Ltd., 8pp.

Berryman, K.R. (1993). Age, height, and deformation of Holocene marine terraces at Mahia Peninsula, Hikurangi subduction margin, New Zealand. *Tectonics* **12,** 1347-1364

Berryman, K.R., Ota, Y., Hull, A.G. (1989). Holocene paleoseismicity in the fold and thrust belt of the Hikurangi subduction zone, eastern North Island, New Zealand. *Tectonophysics* **163,** 185-195.

Brown, P., Spalding, R.E., ReVelle, D.O., Tagliaferri, E.,Worden, S.P (2002). The flux of small near-Earth objects colliding with the Earth. *Nature* **420**, 294–296.

Camfield, F.E. (1980). Tsunami Engineering. Special Report No. 6, February 1980. Coastal Engineering Research Centre, Corps of Engineers, U.S. Army.

Carter, L., Carter, R.M. (1993). Sedimentary Evolution of the Bounty Trough: A Cretaceous Rift basin, Southwestern Pacific Ocean, in *South Pacific Sedimentary Basins*, vol. 2, Sedimentary Basins of the World, edited by P.F. Ballance, pp. 225-250, Elsevier Science, New York..

Chague-Goff, C., Dawson, S., Goff, J. R., Zachariasen, J., Berryman, K. R., Garnett, D. L., Waldron, H. M., Mildenhall, D. C. (2002). A tsunami (ca. 6300 years BP) and other Holocene environmental changes, northern Hawke's Bay, New Zealand. *Sedimentary Geology* **150,** 89-102.

Clague, J. J. (1997). Evidence for large earthquakes at the Cascadia subduction zone. *Reviews of Geophysics* **35,** 439-460.

Cochran, U. A., Berryman, K. R., Mildenhall, D. C., Hayward, B. W., Southall, K., Hollis, C. J. (in press). Towards a record of Holocene tsunami and storms for Northern Hawke's Bay, New Zealand. *New Zealand Journal of Geology and Geophysics* **48.**

Collot, J-Y., Lewis, K.B., Lamarche, G., Lallemand, S. (2001). The giant Ruatoria avalanche on the northern Hikurangi margin, New Zealand: Result of oblique seamount subduction. *Journal of Geophysical Research* **106**, 19,271-19,297.

Cornell, C.A. (1968). Engineering seismic risk analysis. *Bulletin of the Seismological Society of America* **58,** 1583-1606.

Cousins, W.J. (2004). Towards a first-order earthquake loss model for New Zealand. Proceedings, *2004 Conference of the New Zealand Society for Earthquake Engineering*, 19-21 March 2004, Rotorua. New Zealand Society for Earthquake Engineering, Paper No. 029.

de Lange, W.P. (1997). Tsunami and storm surge scenarios for the Auckland Region. Carson Group and Auckland Regional Council, July 1997. Auckland

de Lange, W.P., Healy, T.R. (1986). Tsunami hazards in the Bay of Plenty, New Zealand: an example of hazard analysis using numerical models. *Journal of Shoreline Management* **2**, 177-197.

de Lange, W.P., Moon, V.G. (2004). Estimating earthquake and landslide tsunami hazard for the New Zealand coast. *Bulletin of the N.Z. Society for Earthquake Engineering* **37,** 62-69.

de Lange, W.P., Prasetya, G. (1997). Volcanoes and tsunami hazard – implications for New Zealand. *Tephra* **17,** 30-35.

Dengler, L., Preuss, J. (2003). Mitigation lessons from the July 17, 1998 Papua New Guinea tsunami. *Pure and Applied Geophysics* **160**, 2001-2031.

Downes, G.L., Webb, T.H., McSaveney, M.J., Darby, D.J., Doser, D., Chague-Goff, C., Barnett, A. (2000). The 26 March and 17 May 1947 Gisborne earthquakes and tsunami : implication for tsunami hazard for East Coast, North Island, New Zealand. p. 21 In: The International Workshop : tsunami risk assessment beyond 2000 : theory, practice and plans : in memory of Professor Sergey L. Soloviev, June 14-16, 2000, Russia, Moscow.

Dunbar, D., LeBlond, P.H., Murty, T.S. (1989). Maximum Tsunami Amplitudes and Associated Currents on the Coast of British Columbia. *Science of Tsunami Hazards* **7**, 1, 3-44.

Fryer G.J., Watts, P., Pratson, L.F. (2004). Source of the great tsunami of 1 April 1946: a landslide in the upper Aleutian forearc. *Marine Geology* **203**: 201-218

Gamble, J.A., Wright, I.C., Baker, J.A. (1993). Seafloor geology and petrology of the oceanic to continental transition zone of the Kermadec - Havre - Taupo Volcanic Zone arc system, New Zealand. *New Zealand Journal of Geology and Geophysics* **36**, 417-435.

Goff, J. R., Chague-Goff, C. (1999). A late Holocene record of environmental changes from coastal wetlands: Abel Tasman National Park, New Zealand. *Quaternary International* **56,** 39-51.

Goff, J. R., Crozier, M., Sutherland, V., Cochran, U., Shane, P. (1998). Possible tsunami deposits from the 1855 earthquake, North Island, New Zealand. *In* "Coastal Tectonics." (I. S. Stewart, and C. Vita-Finzi, Eds.), pp. 353-374. Geological Society, London, Special Publications, London.

Goff, J. R., McFadgen, B. G. (2001). Catastrophic seismic-related events and their impact on prehistoric human occupation, coastal New Zealand. *Antiquity* **75,** 155-162.

Goff, J. R., McFadgen, B. G. (2002). Seismic driving of nationwide changes in geomorphology and prehistoric settlement – a 15th Century New Zealand example. *Quaternary Science Reviews* **21,** 2229-2236.

Goff, J. R., McFadgen, B. G. (2003). Large earthquakes and the abandonment of prehistoric coastal settlements in 15th century New Zealand. *Geoarchaeology* **18,** 609-623.

Goff, J. R., Rouse, H. L., Jones, S. L., Hayward, B. W., Cochran, U., McLea, W., Dickinson, W. W., Morley, M. S. (2000). Evidence for an earthquake and tsunami about 3100-3400 yr ago, and other catastrophic saltwater inundations recorded in a coastal lagoon, New Zealand. *Marine Geology* **170,** 231-249.

Goff, J. R., Wells, A., Chague-Goff, C., Nichol, S. L., Devoy, R. J. N. (2004b). The elusive AD 1826 tsunami, south Westland, New Zealand. *New Zealand Geographer* **60,** 28-39.

Goff, J., McFadgen, B., Chague-Goff, C. (2004a). Sedimentary differences between the 2002 Easter storm and the 15th-century Okoropunga tsunami, southeastern North Island, New Zealand. *Marine Geology* **204,** 235-250.

Gusiakov, V.K. (2001). Basic Pacific tsunami catalog and database 47 BC–2000 AD: Results of the first stage of the project. *ITS 2001 Proceedings* 263–272.

Hancox, G.T., Cox, S.C., Turnbull, I.M., Crozier, M.J. (2003). Reconnaissance studies of landslides and other ground damage caused by the M_W7.2 Fiordland earthquake of 22 August 2003. *Institute of Geological & Nuclear Sciences science report 2003/30.* 32 p.

Houghton, B.F., Weaver, S.D., Wilson, C.J.N., Lanphere, M.A. (1992). Evolution of a Quaternary peralkaline volcano: Mayor Island, New Zealand. *Journal of Volcanology and Geothermal Research* **51,** 217-236.

Imamura, F., Synolakis, C.E., Gica, E., Titov, V., Listanco, E. & Jun Lee, H. (1995). Field survey of the 1994 Mindoro Island, Philippines tsunami. *Pure and Applied Geophysics* **145(3/4),** 875-890.

Koshimura, S., Imamura, F., Shuto, N. (2001). Characteristics of Tsunamis Propagating over Oceanic Ridges: Numerical Simulation of the 1996 Irian Jaya Earthquake Tsunami. *Natural Hazards* **24**, 213-229.

Lamarche, G., Barnes, P., Lewis, K., Wright, I., Collot, J.-Y. (2003). "Submarine landslide hazards on the New Zealand continental margin." Presented at the International Tsunami Workshop: Tsunamis in the South Pacific – research towards preparedness and mitigation, Wellington, September 2003.

Lamarche, G., Proust, J-N., Nodder, S.D. (2005). Long-term slip rates and fault interactions under low contractional strain, Wanganui Basin, New Zealand. *Tectonics* **24,**

Latter, J.H., Lloyd, E.F., Smith, I.E.M., Nathan, S. (1992). Volcanic hazards in the Kermadec Islands, and at submarine volcanoes between southern Tonga and New Zealand. *Hazards Information Series No. 4*. Ministry of Civil Defence. 44p.

Lay, T., Kanamori, H., Ammon, C.J., Nettles, M., Ward, S.N., Aster, R.C., Beck, S.L., Bilek, S.L., Brudzinski, M.R., Butler, R., DeShon, H.R., Ekstrőm, G., Satake, K., Sipkin, S. (2005). The great Sumatra-Andaman earthquake of 26 December 2004. *Science* **308**, 1127-1133.

Lewis, K., Pantin, H.M. (2002). Channel-axis, overbank and drift sediment waves in the southern Hikurangi Trough, New Zealand. *Marine Geology* **192**, 123-151.

Lewis, K.B., Barnes, P.M. (1999). Kaikoura Canyon, New Zealand: active sediment conduit from near-shore sediment zones to trench-axis channel. *Marine Geology* **162,** 39-69.

Lewis, K.B., Collot, J-Y., Lallemand, S.E. (1998). The dammed Hikurangi Trough: a channel-fed trench blocked by subducting seamounts and their wake avalanches (New Zealand –France GeodyNZ). *Basin Research* **10**, 441-468.

Lewis, K.B., Lallemand, S.E., Carter, L. (2004). Collapse in a Quaternary shelf basin off East Cape, New Zealand: evidence for passage of a subducted seamount inboard of the Ruatoria giant avalanche. *N. Z. Journal of Geology and Geophysics* **47**, 415-429.

Lloyd, E.F., Nathan, S., Smith, I.E.M., Stewart, R.B. (1996). Volcanic history of Macauley Island, Kermadec Ridge, New Zealand. *New Zealand Journal of Geology and Geophysics* **39,** 295-308.

Lynett, P.J., Borrero, J.C., Liu, P.L.-F., and Synolakis, C.E. (2003). Field survey and numerical simulations: a review of the 1998 Papua New Guinea tsunami. *Pure and Applied Geophysics* **160**, 2119-2146.

Magill, C.R. (2001). Numerical modelling of tsunami generated by mass movement. M.Sc thesis, University of Waikato, 198 pp.

McAdoo, B.G., Pratson, L.F., Orange, D.L. (2000). Submarine landslide geomorphology, US continental slope. *Marine Geology* **169,** 103-136.

McAdoo, B.G., Watts, P. (2004). Tsunami hazard from submarine landslides on the Oregon continental slope. *Marine Geology* **203**, 235-245.

McCann, W. R., Nishenko, S. P., Sykes, L. R., Krause, J. (1979). Seismic gaps and plate tectonics: seismic potential for major boundaries. *Pure and Applied Geophysics* **117,** 1082-1147.

McFadgen, B. G., Goff, J. R. (2005). An earth systems approach to understanding the tectonic and cultural landscapes of linked marine embayments: Avon-Heathcote Estuary (Ihutai) and Lake Ellesmere (Waihora), New Zealand. *Journal of Quaternary Science* **20,** 227-237.

McMurtry, G.M., Watts, P., Fryer, G.J., Smith, J.R., Imamura, F. (2004). Giant landslides, mega-tsunamis, and paleo-sea level in the Hawaiian Islands. *Marine Geology* **203***,* 219-233.

McSaveney, M., Rattenbury, M. (2000). Tsunami impact in Hawke's Bay. *Institute of Geological and Nuclear Sciences Client Report 2000/77.*

Meckel, T.A., Coffin, M.F., Mosher, S., Symonds, P., Bernadel, G., Mann, P. (2003). Underthrusting at the Hjort Trench, Australian-Pacific plate boundary: Incipient subduction? *Geochemistry, Geophysics Geosystems* **4(12),** 1099.

Nichol, S. L., Lian, O. B., Carter, C. H. (2003). Sheet-gravel evidence for a late Holocene tsunami run-up on beach dunes, Great Barrier Island, New Zealand. *Sedimentary Geology* **155,** 129-145.

Nichol, S. L., Lian, O. B., Horrocks, M., Goff, J. R. (in press). Holocene record of gradual, catastrophic and human-influenced sedimentation from a backbarrier wetland, northern New Zealand. *Journal of Coastal Research*.

Nichol, S. L., Regnauld, H., Goff, J. R. (2004). Sedimentary evidence for tsunami on the northeast coast of New Zealand. *Geomorphologie: relief, processus, environnement* **1,** 35-44.

Power, W.L., Downes, G.L., Stirling, M.W. (2004). Progress towards a probabilistic tsunami hazard map for New Zealand. *Eos Transactions AGU* **85(47)**, Fall Meeting Supplement, Abstract OS22B-07

Ramsbottom, D., Floyd, P. & Penning-Roswell, E. (2003). Flood risks to people. Phase 1. DEFRA/Environment Agency Flood and Coastal Defence R & D Programme. R&D Technical Report FD2317. July 2003.

Reyners, M.E. (1998). Plate coupling and the hazard of large subduction thrust earthquakes at the Hikurangi subduction zone, New Zealand. *New Zealand Journal of Geology and Geophysics* **41(4)**, 343-354.

Shimamoto, T., Tsutsumi, A., Kawamoto, E., Miyawaki, M. & Sato, H. (1995). Field survey report on tsunami disasters caused by the 1993 Southwest Hokkaido Earthquake. *Pure and Applied Geophysics* **145(3/4)**, 665-691.

Smith, W.D. (2003). Earthquake hazard and risk assessment in New Zealand by Monte Carlo methods. *Seismological Research Letters* **74(3)**, 298-304.

Spence, R.J.S., Pomonis, A., Dowrick, D.J., Cousins, W.J. (1998). Estimating human casualties in earthquakes: the case of Wellington. *Proceedings, Sixth SECED (Society for Earthquake and Civil Engineering Dynamics) conference: Seismic Design Practice into the Next Century*, Oxford, UK, March 26-27: pages 277-286.

Standards New Zealand (1999). NZ Standard 3604:1999, Timber Framed buildings, Sections 6.4.1.1, 6.11.2.1, 6.14.4 and 7.5.2.1.

Statistics New Zealand (2003). 2001 census data and population projections. www.stats.govt.nz.

Stirling M.W., McVerry G.H. & Berryman K.R. (2002). A new seismic hazard model for New Zealand. *Bulletin of the Seismological Society of America* **92**,1878-1903.

Sugimoto, T., Murakami, H., Kozuki, Y., and Nishikawa, K. (2003). *Natural Hazards* **29**, 585-600.

Tanioka Y., Seno, T. (2001). Detailed analysis of tsunami waveforms generated by the 1946 Aleutian tsunami earthquake. *Natural Hazards & Earth System Science* **1,** 171-175.

Thurston, S.J., King, A.B. (2003). Full sized house cyclic racking test. Proceedings 2003 Pacific Conference on Earthquake Engineering, 13-15 February 2003, Christchurch. New Zealand Society for Earthquake Engineering. Paper No. 029

Tsuji, Y., Imamura, F., Matsutomi, H., Imamura, F., Takeo, M., Kawata, Y., Matsuyama, F., Takahashi, T., Sunarjo, & Harjadi, P. (1995a). Damage to coastal villages due to the 1992 Flores Island earthquake tsunami. *Pure and Applied Geophysics* **145(3/4)**, 481-524.

Tsuji, Y., Imamura, F., Matsutomi, H., Synolakis, C.E., Nanang, P.T., Jumadi, Harada, S., Sub Han, S. Arai, K. & Cook, B. (1995b). Field survey of the East Java earthquake and tsunami of June 3, 1994. *Pure and Applied Geophysics* **145(3/4)**, 839-854.

Walters, R. A., Barnes, P.M., Lewis, K.B., Goff, J., Fleming, J. (submitted 2005). Locally Generated Tsunami along the Kaikoura Coastal Margin: Part 2. Submarine landslides. *N.Z. Journal of Marine and Freshwater Research.*

Walters, R.A. (2003). Submarine landslides: model development and Kaikoura study (Abstract). in Cochran, U. (comp.) Programme & abstracts: the International Workshop, Tsunamis in the South Pacific: research towards preparedness and mitigation, 25-27 September, 2003. Wellington, New Zealand. *Institute of Geological & Nuclear Sciences information series* **58**. 86 p.

Walters, R.A., Goff, J. (2003). Assessing tsunami hazard along the New Zealand coast. *Science of Tsunami Hazards* **21(3)**, 137.

Ward, S.N. (2001). Landslide tsunami. *Journal of Geophysical Research* **106,** 11201-11215.

Watts, P. (2004). Probabilistic predictions of landslide tsunamis off Southern California. *Marine Geology* **203**, 281-302.

Watts, P., Grilli, S.T., Kirby, J.T., Fryer, G.J., Tappin, D.R. (2003). Landslide tsunami case studies using a Boussinesq model and a fully nonlinear tsunami generation model. *Natural Hazards and Earth System Sciences* **3**, 391-402.

Wellman, H. W. (1962). Holocene of the North Island of New Zealand: a coastal reconnaissance. *Transactions of the Royal Society of New Zealand* **1,** 29-99.

Witter, R. C., Kelsey, H. M., Hemphill-Haley, E. (2003). Great Cascadia earthquakes and tsunamis of the past 6700 years, Coquille River estuary, southern coastal Oregon. *Geological Society of America Bulletin* **115,** 1289-1306.

Wright, I.C., Gamble, J.A. (1999). Southern Kermadec submarine caldera arc volcanoes (SW Pacific): caldera formation by effusive and pyroclastic eruption. *Marine Geology* **161***,* 207-227.

Wright, I.C., Gamble, J.A., Shane, P.A.R. (2003). Submarine silicic volcanism of the Healy caldera, southern Kermadec arc (SW Pacific): I - volcanology and eruptive mechanisms. *Bulletin of Volcanology* **65***,* 15-29.

Wright, I.C., Garlick, R.D., Rowden, A., Mackay, E. (2004). New Zealand's Undersea Volcanoes*. NIWA Chart, Miscellaneous Series No.81*, Wellington, NIWA.

Wright, I.C., Worthington, T.J., Gamble, J.A. (in press). New multibeam mapping and geochemistry of the 30° - 35°S sector, and overview, of southern Kermadec arc volcanism. *Journal of Volcanology and Geothermal Research*.

APPENDICES

APPENDIX 1 — List of New Zealand paleotsunami deposits that have been formally published in the scientific literature

- **with details as outlined in the relevant publication (for references see main report).**

Location	Age ‡		Sedimentology	Deposit Thickness	Maximum Height	Lateral Extent		Source Suggested in publication	Reference
(NZMS 260 grid reference)	(calibrated years before 1950 AD)	(calibrated calendar years)		(max. in m)	(m above present msl)	(m inland of present mean high tide line)	(km along coast) *		
Henderson Bay, Northland	c. 660-510 (Loisels pumice)		Gravel sheet on sand dunes tapering inland to a sand unit within wetland peat.	0.08	32	1000	>250	Healy caldera collapse	Nichol et al., 2004
Whangapoua Bay, Great Barrier Island (S08 527709)		Post 1390AD-1670AD (C14: 1 sigma on reworked midden material)	Cobble to granule sheet on dunes		14.3	200	>250	Kermadec arc volcanism	Nichol et al., 2003
Harataonga Bay, Great Barrier Island	c. 3000 (bracketing by C14 and OSL)		Coarse sand and gravel units, erosional base with gravel and rip-up clasts within backbarrier wetland	0.77	c. 4	100	0.4		Nichol et al., in press
Cooks Cove, Tolaga Bay	Post 660-510 (above Loisels pumice)		Shelly sand with many whole shells	0.40	c. 2.3	<50	0.1		Wellman, 1962
Opoho, Hawke's Bay (X19 110296)	c. 5500 (Whakatane tephra)		Fine sand with wood, clay clasts and dinoflagellates within lagoonal silt	0.16	-2.1	750		Fault rupture: Hikurangi interface or upper plate (local subsidence)	Cochran et al., in press
"	c. 7100 (C14 and accumulation rates)		Chaotically mixed sand and silt with shells and wood within lagoonal silt	0.18	-5.1	750	10	Fault rupture: Hikurangi interface or upper plate (local subsidence)	"
Te Paeroa Lagoon, Hawke's Bay (X19 007300)	7400-7000 (C14: 2 sigma)		Gravel to sand unit within estuarine silt	0.23	-3.0	2000	10		Chagué-Goff et al., 2002

Location	Age [‡]		Sedimentology	Deposit Thickness	Maximum Height	Lateral Extent		Source Suggested in publication	Reference
Okoropunga, Wairarapa	Post 500 (overlies Maori gardens) and pre 300 (soil profile)		Sand sheet on raised gravel beach ridges	0.7	10.5	250	2	Fault rupture: Cook Strait	Goff et al., 2004a
Okourewa Stream, Wairarapa		Post 180AD (Taupo pumice) and pre 1890AD (pine appearance)	Cobble to sand units overlying lagoonal silts	1.4	7	1400	>220	Fault rupture: Wairarapa 1855?	Goff et al., 1998
Te Ika A Maru Bay, Wellington (Q27 493940)		Post Maori occupation and pre 1855AD	Pebbles and coarse sand overlying alluvial deposits	0.15	1.5	200	>160	Fault rupture: Cook Strait	Goff and McFadgen, 2001; 2003
Okupe Lagoon, Kapiti Island		1296-1451AD (C14: 1sigma)	Sand unit with large wood fragments	0.15	1.5	150	>160	Fault rupture: Cook Strait	Goff et al., 2000
“		1224-1329AD (C14: 1sigma)	Pebbles in fining upwards sand unit with erosional base	0.05	1.3	300	>160	Fault rupture: Cook Strait	“
“		1436-1101BC (C14: 1sigma)	Fining upwards sand unit with pebbles, shells and erosional base	0.15	0.5	300		Local source (associated uplift)	“
Totaranui Inlet, Northwest Nelson		Post 1965AD (Cs137) and pre 1850AD (European arrival)	Increases in silt/clay (vs sand), organics, Fe and/or S; decrease in contaminants	0.12	<2.0	200	>220	Fault rupture: Wairarapa 1855AD	Goff and Chagué-Goff, 1999
“		1390AD-1472AD (C14: 1 sigma)	“	0.12	<2.0	200	>160	Fault rupture: Wellington or Wairarapa	“
“		1196AD-1232AD (C14 and accumulation rates)	“	0.1	<2..0	200	>160	Fault rupture: Wellington or Wairarapa	“

Location	Age ŧ		Sedimentology	Deposit Thickness	Maximum Height	Lateral Extent		Source Suggested in publication	Reference
Wainui Inlet, Northwest Nelson		Post 1965AD (Cs137) and pre 1678-1789AD (C14: 1 sigma)	"	0.08	<2.0	160	>220	Fault rupture: Wairarapa 1855AD	"
"		1338AD-1478AD (C14 and accumulation rates)	"	0.1	<2.0	160	>160	Fault rupture: Wellington or Wairarapa	"
Awaroa Inlet, Northwest Nelson		Post 1965AD (Cs137) and pre 1850AD (European arrival)	"	0.05		200	>220	Fault rupture: Wairarapa 1855AD	"
"		1368AD-1551AD (C14 and accumulation rates)	"	0.1	<2.0	200	>160	Fault rupture: Wellington or Wairarapa	"
"		856AD-1225AD (C14 and accumulation rates)	"	0.14	<2.0	200	>160	Fault rupture: Wellington or Wairarapa	"
Okarito Lagoon, Westland		Pre 1837AD (Pb210) 1700-1870AD (C14 and accumulation rates) 1820s (tree rings)	Fining upwards sand unit with basal shell hash overlying silt	0.3	<2.0	100		Fiordland earthquake 1826AD	Goff et al., 2004b
"		Post 1318-1495AD (C14: 2 sigma)	Fining upwards sand unit	0.35	<2.0	100			"
Long Beach, Otago		c. 1400-1500AD (archaeological site)	Archaeological site washed by sea			750			Goff and McFadgen, 2002
Avon-Heathcote Estuary, Canterbury	Pre 635-545 (C14: 2 sigma)		Driftwood, sand and rounded pebbles	0.1	<2.0	200			McFadgen and Goff, 2005
"	4400-4100 (C14: 2 sigma)		Shells embedded in cave roof	N/A	c. 6.0	250			

ŧ Dating methods or controls are listed in brackets with abbreviations as follows: C14 = carbon 14 isotopic dating; OSL = optically stimulated luminescence dating; Cs137 = Caesium 137 isotopic dating; Pb210 = Lead 210 isotopic dating.

* Defined as the distance along the coast between sites thought to contain deposits of the same paleotsunami. These are best-guess correlations based on deposit age and characteristics (colour-coding illustrates inferred correlations).

APPENDIX 2 — PROBABILISTIC METHODOLOGY

The procedure for combining all the source, propagation, inundation, asset and vulnerability models has been a Monte Carlo one. This involved the following steps.

1. Appendix 3 gives the parameters for all the sources. For each source, we simulated 100,000 years of seismic activity by noting the recurrence interval and the likely magnitudes of large events. The recurrence interval enabled us to calculate how many events there will be in 100,000 years.
   Characteristic magnitude sources. We allowed up to three possible pairs of recurrence interval and magnitude, with associated probabilities. The Monte Carlo procedure selected one pair, and randomised the magnitude by selecting from a Normal distribution of specified standard deviation, but limiting the excursion to two standard deviations because it was important to avoid the tails in the distribution.
   Gutenberg-Richter sources. We chose the magnitude from a truncated exponential distribution, with specified maximum magnitude. This maximum could likewise be specified as up to three alternatives, and the Monte Carlo procedure selected one according to the specified probabilities. We applied a Normal distribution with specified standard error to the b-value.
2. For each event, wave heights were calculated at each of the locations. For distant sources we applied the uncertainties in B parameter as Normal distributions truncated at three standard deviations. A local amplification factor was applied for distant events (Appendix 5).
3. We then added a local tide height, determined as follows. From the tidal range at each location we applied a sinusoidal variation with period 12.5 hours, modulated by a monthly sinusoid to take account of spring tides. In addition we added a tidal phase in hours with respect to Gisborne, together with the propagation time lag between Gisborne and each other location. This last parameter had to be evaluated for each source region. Because of the Monte Carlo modelling, i.e. the events were modelled as occurring at no particular phase of the tide, this tidal variation was important only for estimating the national losses. That is, it had no effect on the statistics of losses at any particular location but for assessing national losses it was important to take into account the possibility that the waves might hit more than one location at high tide.

The following table gives the tidal ranges (metres) for spring and neap tides, and also the phase in hours with respect to Gisborne. Data are from the LINZ website http://www.hydro.linz.govt.nz/tides/info/tideinfo5.asp

	Spring	Neap	Phase
Auckland	2.64	1.93	+1.0
Christchurch	1.87	1.62	-1.1
Dunedin	1.81	1.43	-1.4
Gisborne	1.38	1.19	0.0
Invercargill	2.03	1.40	-3.5
Kapiti	1.30	0.30	+3.4
Manukau	3.33	1.97	+4.1
Napier	1.46	1.30	-0.2
Nelson	3.58	1.88	-2.4
New Plymouth	3.04	1.70	+3.5
Porirua	1.00	0.20	+3.4
Tauranga	1.59	1.23	+1.3
Timaru	1.75	1.38	-2.1
Wellington	1.03	0.93	-0.5
Whakatane	1.70	1.20	+0.6
Whangarei	2.29	1.69	+1.3

1. Wave height statistics were accumulated for all locations, and expressed as the heights corresponding to a set of selected mean return periods.
2. Costs of damage, casualties and injuries were determined by using three separate inundation models (see Section 7.0).
3. It was assumed that no effective warnings would be given. This is an issue to be addressed in the Preparedness Report, because it is clear that substantial warning time should be available for tsunami from distant sources, though not for local sources. The effectiveness of such warning will of course be the point at issue.
4. Statistics for costs ($millions), casualties and injuries were accumulated over the 100,000 year run.

A2.1 Epistemic uncertainty and aleatory variability

These two factors were analysed very carefully. Uncertainty describes the lack of knowledge of parameters, such as the characteristic magnitude and recurrence interval for a given fault source. Variability refers to the inherent nature of the process, i.e. that subsequent occurrences will not be identical. An example is the magnitudes of subsequent earthquakes originating in a Gutenberg-Richter source zone (magnitude takes any value from the threshold to the maximum) or tsunami that originate from different parts of a distant source region such as South America; their propagation characteristics will depend on source geometry.

A2.2 Parameters with epistemic uncertainty

- Abe correction parameter for distant tsunami (0.0 or 0.2) (Appendix 5)
- Site amplification, including factor for local events (Normal to 3σ) (Appendix 5)
- Characteristic magnitude for earthquake source (choice of up to 3, given probabilities) (Appendix 4)
- Maximum magnitude for Gutenberg-Richter sources (up to 3, given probabilities) (Appendix 4)
- b-value for Gutenberg-Richter sources (Normal to 2σ) (Appendix 4)
- Inundation model (choice of 3 models)

A2.3 Parameters with aleatory variability

- Selected Abe correction parameter (Normal to 3σ) (Appendix 5)
- Magnitude for Gutenberg-Richter sources (truncated exponential) (Appendix 4)
- Daily tidal phase (See above)
- Monthly tidal phase (See above)
- B parameter for distant tsunami propagation ((Normal to 3σ) (Appendix 5)

We also noted that assuming an uncertainty in the value of a characteristic magnitude implies a bias in the recurrence interval, in order to ensure the same average moment rate of that source. Integration shows that a standard error of σ in the magnitude corresponds to a bias in the distribution for earthquake moment. We therefore adjusted the recurrence interval by this factor.

The procedure was to sample from all the variability distributions for each event in the 100,000 year run. We then repeated this 1000 times, sampling parameters on each occasion from all the uncertainty distributions and maintaining those parameters constant throughout the 100,000 year run. In this way we obtained 1000 curves for each location, for wave height, costs, casualties and injuries. The best estimate is the mean of these curves, but we also show the 16th and 84th percentiles in order to represent the uncertainty.

A2.4 Individual Risk

The Monte Carlo procedure also allowed us to calculate individual risk. For each event we calculated the wave height at the coast. The relationship for likelihood of death as a function of inundation depth gave us the probability that an individual will be killed, according to the height above sea level. By accumulating these probabilities over the 100,000 year modelling period, we were able to extract the annual probability of death, which is a parameter that is often used in individual risk assessments.

A2.5 Deaggregation of Sources

The detailed results in Section 9 also show the deaggregation of the risk to identify those sources most responsible for high waves at each location. This analysis is done in the Monte Carlo procedure by examining the sources of events that cause waves more than 2 metres in height. It is a simple procedure to count the number of times each source contributes such waves, over the 100,000 years modelling period, and to convert these to percentages.

APPENDIX 3 — BOLIDE FREQUENCY AND MAGNITUDE

The flux of small near-Earth objects colliding with the Earth follows a power-law distribution (Brown et al. 2002). The cumulative number N of objects colliding with the Earth each year with diameters exceeding D is given by:

$$\log N = 1.57(\pm 0.03) - 2.70(\pm 0.08) \cdot \log D \qquad \text{A3.1}$$

or in terms of energy, E (in kilotons):

$$\log N = 0.568(\pm 0.015) - 0.90(\pm 0.03) \cdot \log E \qquad \text{A3.2}$$

(One kiloton TNT equivalent is 4.185×10^{12} Joules).

The flux is more-or-less uniformly distributed over Earth's surface, and so the proportion falling on any smaller area is approximately in direct proportion to the ratio of areas. The area within a 1000 km radius of Wellington is ~0.62% of the Earth's surface, and the area within a 3000 km radius is ~5.54% (we choose these two distances arbitrarily for the purpose of illustration). A larger bolide could cause a dangerous tsunami from a more distant ocean impact than a smaller bolide.

To estimate the potential of these bolides to generate tsunami, we use the relationship between kinetic energy, mass and velocity ($E = \frac{1}{2}mv^2$), and assume that they transfer 50% of their energy to create a water wave (much water is heated and some is vaporised). Hence the mass of water (M kg) displaced is given by:

$$M = 4.185 \times 10^{12} V^{-2} \cdot 10^{0.63(\pm 0.04) - 1.11(\pm 0.04)\log N} \qquad \text{A3.3}$$

In deep water, the wave speed (V) is ~200 m/s. It is unlikely that the efficiency of transfer of kinetic energy on impact with water is as great as 50%. A portion of the energy of the bolide is lost in its passage through the atmosphere; this is 100% for smaller than fist-sized bolides. Above a few tens of metres in diameter, energy is also consumed in forming a crater in the sea floor. Hence the estimation of the probability of displacement of a given volume of water is conservative with respect of public safety. Again to be conservative, we ignore the salt content of sea water to estimate the volume of displaced sea water (Figure A3.1).

Within the probability horizon of our calculation of risk, out to a probability of once in a few thousand years, bolide-impact tsunami do not feature as a significant risk; they are lost in the background noise below other large and more probable events. But at longer event horizons, bolide tsunami are the largest tsunami waves that can hit large areas of the New Zealand coast. There is, however, a bolide size at which a tsunami is not the most significant effect of the collision. Such large events are not only conceivable, they are known to have occurred a number of times in Earth's history.

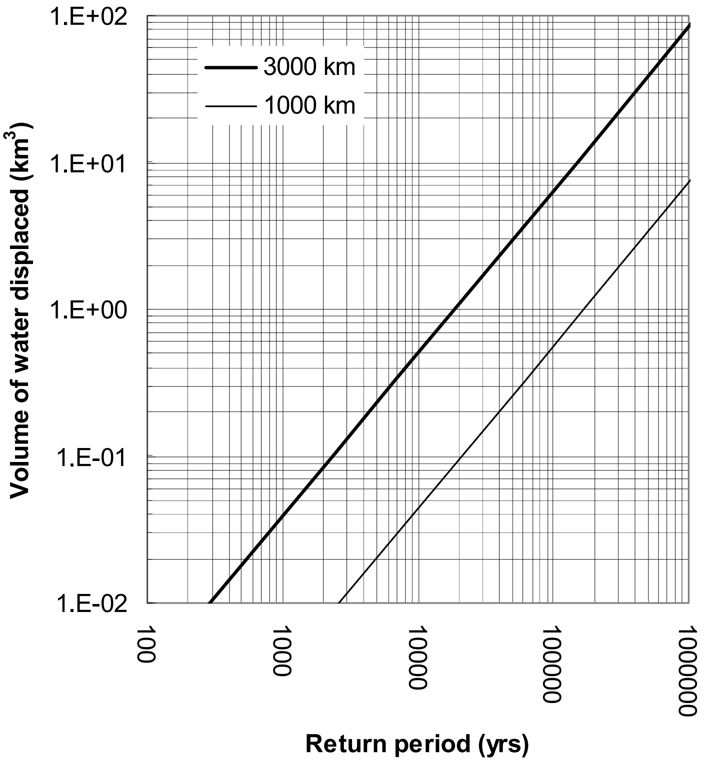


Figure A3.1 Estimated volume of water displaced by a bolide hitting ocean within 1000 and within 3000km of Wellington for various return periods. A displaced volume of less than 0.1 cubic kilometres is not likely to produce a damaging tsunami, and hence bolides are not a factor warranting concern in New Zealand's tsunami risk. In the rare event of a large Near Earth Object colliding with the Earth, a warning time of weeks to months is available with current technology.

Because all larger Near Earth Objects are identified and tracked, warnings can be issued. Hence, unlike any other tsunami, the possibility exists to know of the likelihood of generation of a specific bolide tsunami weeks or months in advance of the event.

APPENDIX 4 — SOURCE DATA

A. Gutenberg-Richter Sources - Distant

Source	Recurrence Interval[1]	Threshold	Maximum[2]	b-value	σ[3]
S America 1	43 (0.25), 32 (0.5), 26 (0.25)	8.5	9.51	1.0	0.05
S America 2	146 (0.25), 110 (0.5), 88 (0.25)	8.5	9.51	1.0	0.05
Aleutians	126	8.5	9.3	1.0	0.05

B. Gutenberg-Richter Sources - Regional

Source	Recurrence Interval[1]	Threshold	Maximum[2]	b-value	σ[3]
Kermadec 1	1440	8.0	8.6,	1.0	0.05
Kermadec 2	1440	8.0	8.6	1.0	0.05
Kermadec 3	1440	8.0	8.6	1.0	0.05

C. Characteristic Sources - Distant

Source	Recurrence Interval	Magnitude	σ
Cascadia	800	9.1	0.05
S New Hebrides	2100 (0.3), 610 (0.7)	8.5	0.1

D. Characteristic Sources – Bay of Plenty

Source	Recurrence Interval	Magnitude	σ
Whakatane	429	6.26	0.3
Waimana	2238	6.99	0.3
Waiotahi	2238	6.99	0.3
Rangitaikei	614	6.43	0.3
White Is	515	6.67	0.3
Matata offshore	344	6.3	0.3
Braemar offshore	688	6.3	0.3
Rurima	358	6.56	0.3
Pukehoko	646	6.27	0.3
Awaite offshore	646	6.27	0.3

E. Characteristic Sources – West Coast

Source	Recurrence Interval	Magnitude	σ
Cape EgmontALL	53313	7.81	0.1
Cape EgmontMOST	11261	7.63	0.1
Cape EgmontNS	5749	7.24	0.1
Cape EgmontSS	5569	7.22	0.1
Turi	13424	7.76	0.1
WavOkaia1	68006	7.41	0.1
Waitot1011	18643	7.46	0.1
NukWaitot1to6	43551	7.47	0.1
Waito8to9	21560	7.53	0.1
RidgeROkaia2	24951	7.41	0.1

MoumahOkaia4	13068	7.35	0.1
Okaia3	11809	6.48	0.1
Okaia5	44772	6.96	0.1
Wairaka	10861	6.99	0.1
TeHoro	4704	6.59	0.1
OtahekeC	5070	6.73	0.1
OtahekeN	4795	7.35	0.1
Kapiti	4061	7.20	0.1
Rangitikei	1463	6.94	0.1
Onepoto	2073	7.34	0.1
Waitarere	6238	7.30	0.1
MascarinBIG	2158	7.42	0.1
Moana	6929	6.90	0.1

F. Characteristic Sources – East Coast North Island

Source	**Recurrence Interval**	**Magnitude**	**σ**
Palliser-Kaiwhata	1121	7.49	0.1
Riversdale	1984	7.21	0.1
Pukeroro Ridge 1	5304	7.34	0.1
Pahaua Fault	4966	7.79	0.1
Opouawe-Uruti	4983	7.80	0.1
Otahome	2679	7.04	0.1
Mataikona	1875	7.04	0.1
Madden Bank (total)	5267	7.49	0.1
Porangahau Ridge 1	5100	7.66	0.1
Paoanui Ridge 1	3591	7.76	0.1
Pourerere/Kairakau	3215	7.20	0.1
Motukura Ridge 1	3661	7.43	0.1
Motukura Ridge 2	3366	7.10	0.1
Omakere Ridge 3	6094	7.46	0.1
Ritchie Banks 4	2852	7.21	0.1
Kidnappers East	2312	7.22	0.1
Lachlan (total)	1044	7.62	0.1
Hawkes Bay 3	2652	7.15	0.1
Hawkes Bay6-Kid	3594	7.30	0.1
Hawkes Bay 10	1765	6.85	0.1
Ariel Bank	1061	6.90	0.1
Poverty Channel	1193	7.33	0.1
Poverty Margin 1	2516	7.30	0.1
Pakarae 1	1124	7.00	0.1
Pakarae 2	1837	7.02	0.1
Raukumara	2406	7.52	0.1
GR1 + KB1	6231	7.48	0.1
Ranfurly 2	1837	7.02	0.1
Ranfurly 4	1759	6.98	0.1
Wairarapa	1600 (0.5), 1900 (0.5)	7.70	0.1

G. Characteristic Sources – Subduction zone

Source	Recurrence Interval	Magnitude	σ
Hik-Wgtn	1008 (0.5), 155 (0.5)	8.36, 8.06	0.1
Hik-S.HBay	992 (0.5), 83 (0.5)	8.10, 7.67	0.1
Hik-C.HBay	980 (0.5), 114 (0.5)	8.31, 7.99	0.1
Hik-S.Rauk	1246 (0.5), 79 (0.5)	8.14, 7.73	0.1
Hik-N.Rauk	911 (0.5), 76 (0.5)	8.14, 7.73	0.1

H. Characteristic Sources – East Coast South Island

Source	Recurrence Interval	Magnitude	σ
Pegasus1nw	5949	6.96	0.1
NorthCant1	11380	6.92	0.1
NorthCant2	10301	6.72	0.1
NorthCant4	8888	6.51	0.1
NorthCant11	15938	6.88	0.1
NorthCant8	18951	7.03	0.1
NorthCant10	604	6.78	0.1
NorthCant13	1068	6.87	0.1
NMFZB	81524	7.82	0.1
NMFZ4647	17790	7.21	0.1
NMFZE	20376	7.57	0.1
NMFZF	19804	7.47	0.1
NMFZ1819	34446	7.19	0.1
NMFZK	30620	7.70	0.1
NMFZM	27440	7.32	0.1
MS09	18237	6.54	0.1
MS04	6290	7.01	0.1
MS08	4250	6.67	0.1
MS02	1040	6.51	0.1
MS01	4208	6.66	0.1
MS05	10603	6.89	0.1
KekerenguBF	2200	7.30	0.1
UpperSlope	1517	6.98	0.1
MS06	3635	6.53	0.1
TeRapa1n2	445	6.40	0.1
KekeChancet	177	6.86	0.1
WharaToCampB	7547	6.78	0.1
KekeToCamp	618951	6.99	0.1
NeeToWai1855	877	7.33	0.1
Needles1and2	563	6.82	0.1
Needles3	522	7.07	0.1
BooBoo	366	7.01	0.1

I. Characteristic Source – South of South Island

Source	**Recurrence Interval**	**Magnitude**	**σ**
Puysegur	300 (0.25), 600 (0.5), 1500 (0.25)	8.7	0.1

Notes

1. The Recurrence Interval shown applies to the threshold magnitude, for Gutenberg-Richter sources, or to the characteristic magnitude, for characteristic sources. Where multiple values are given, they are assigned the weights shown in brackets.
2. Where multiple values are given, these are paired with the corresponding recurrence intervals, and given the same weights. If only one magnitude is given, but there is more than one recurrence interval, the same value of magnitude is used with each recurrence interval.
3. For Gutenberg-Richter sources, the b-value is assumed to have Normal distribution with standard error σ as shown. The distribution is assumed to extend only to 2σ.

APPENDIX 5 — MODELLING TSUNAMI PROPAGATION

A5.1 Summary of modelling projects relevant to New Zealand

Author(s)	Location	Reference	Source
R.A. Walters, J. Goff	All New Zealand	*Assessing Tsunami Hazard Along the New Zealand Coast,* Science of Tsunami Hazards, Volume 21, Number 3, (2003). R.A. Walters, *Long wave resonance on the New Zealand coast.* NIWA Technical Report 109, 32 p, (2002).	Amplification estimates for distant source tsunami approaching from the east.
W. Power, G. Downes, M. Stirling	All New Zealand	*Progress towards a Probabilistic tsunami hazard map for New Zealand.* Eos Trans. AGU, 85(47), Fall Meet. Suppl., Abstract OS22B-07	South American earthquakes
W. Power	All New Zealand	Display for Te Papa, Wellington (2005).	26 December 2004 Sumatra earthquake
W. Power	All New Zealand	Display for the National Aquarium, Hawkes Bay (2004).	1868 Peru earthquake
A.E. Gilmour	All New Zealand	*Tsunami travel times to New Zealand. 1:37,090,000.* New Zealand Oceanographic Institute, Wellington. Gilmour, A.E., (1964). *Tsunami travel times to New Zealand.* New Zealand Journal of Marine and Freshwater Research, 1(2): 139-142 (1967)	Locations around the Pacific Ocean
W.P. de Lange, T. Healy	Auckland	*Tsunami hazard for the Auckland region and Hauraki Gulf, New Zealand.* Natural hazards, 24(3), 267-284. (2001)	Kerepehi fault, South America, Auckland Volcanic Field
G.S. Prasetya	Auckland area	*Modelling volcanic tsunamis*. MSc Thesis, The University of Waikato, Hamilton, 299 pp. (1998)	Volcanic events in the Auckland Volcanic Field
J. Chittleborough	Australia (Southeast)	*Tsunami waves caused by Fiordland, NZ earthquake of August 2003*: National Tidal Facility Australia.	2003 Fiordland earthquake
W.P. de Lange	Bay of Plenty, East Cape	*Tsunami hazard: an investigation into the potential tsunami hazards of the Bay of Plenty Region using numerical models*. M.Sc. Thesis, University of Waikato, Hamilton, 250 pp. (1983)	Earthquakes and pyroclastic flows at Mayor Island and White Island
W.P. de Lange, T. Healy	Bay of Plenty	*Tsunami hazards in the Bay of Plenty, New Zealand: an example of hazard analysis using numerical models.* Journal of shoreline management, 2, 177-197 (1986)	South America
W.P. de Lange, G.S. Prasetya, T. Healy	Bay of Plenty	*Modelling of Tsunamis Generated by Phyroclastic Flows (Ignimbrites).* Natural Hazards, 24, 251-266, 2001.	Mayor Island
D.D.J. McKenzie	Bay of Plenty	*Numerical modelling of tsunamis in the Bay of Plenty.* MSc Thesis, University of Waikato, Hamilton, 88 pp. (1993)	Earthquakes associated with Whakatane graben, and Taupo volcanic zone faults

G.J. Weir, S. P. White	Bay of Plenty	*Mathematical modelling of volcanic tsunamis,* New Zealand Journal of Marine and Freshwater Research, Vol. 16, p. 373, 1982.	White Island volcanic events
D. Todd	Canterbury and Otago	*Regional tsunami studies: Canterbury and Otago,* Tephra, October: 56-58 (1999)	South America
R.A. Walters, P. Barnes, K. Lewis, J. Goff, and J. Fleming	Kaikoura	*Locally generated tsunami along the Kaikoura coastal margin: Part 1. Submarine landslides*. New Zealand Journal of Marine and Freshwater Research (in review) (2005). R.A. Walters, *Tsunami generation, propagation, and runup.* Estuarine and Coastal Modelling: Proc. of the 8th International Conference, edited by M.L.Spaulding, ASCE, p423-438 (2004). R.A. Walters, *Coastal Ocean models: Two useful finite element methods.* Continental Shelf Research 25: 775-793 (2005).	Submarine landslides
R.A. Walters, P. Barnes, and J. Goff	Kaikoura	*Locally generated tsunami along the Kaikoura coastal margin: Part 1. Fault ruptures*. New Zealand Journal of Marine and Freshwater Research (in review) (2005). R.A. Walters, *A semi-implicit finite element model for non-hydrostatic (dispersive) surface waves*. International Journal for Numerical Methods in Fluids (in press) (2005).	Kaikoura thrust fault
R.A. Walters	Hawkes Bay	Display for the National Aquarium, Hawkes Bay (2004).	Earthquakes on the Lachlan fault
W.P. de Lange	Poverty Bay	*Tsunami hazard associated with marl diapirism off Poverty Bay, New Zealand.* In: D.N.B. Skinner (Editor), Geological Society of New Zealand 1997 Annual Conference. Geological Society of New Zealand, Wellington, pp. 49. (1997)	Mud volcanism
W.P. de Lange, T. Healy	Poverty Bay	*Numerical modelling of tsunamis associated with marl diapirism off Poverty Bay, New Zealand*, Combined Australasian Coastal Engineering and Ports Conference, Christchurch, pp. 1043-1047. (1997)	Mud volcanism
C. Magill	Poverty Bay	*Numerical modelling of tsunami generated by mass movement.* MSc thesis, University of Waikato, 198, 2001.	Landslides
U. Cochran, G. Downes, R. Walters et al.	Southland	EQC report (in preparation)	Earthquakes on the southern portion of the alpine fault and within the Puysegur trench.
Magill, C.R.	Lake Tarawera, Poverty Bay	Numerical modelling of tsunami generated by mass movement. MSc Thesis, University of Waikato, Hamilton, 198 pp. (2001)	Pyroclastic flow (Tarawera), Landslide (Poverty Bay).

W.P. de Lange, C.R. Magill, I.A. Nairn, K. Hodgson	Lake Tarawera	*Tsunami generation by pyroclastic flows entering Lake Tarawera,* Eos, 83(22:supplement): WP54, 2002	Tarawera volcano
W.P. de Lange, L. Chicks, T. Healy	Firth of Thames	*Potential Tsunami hazard associated with the Kerepehi Fault, Firth of Thames, New Zealand.* Natural Hazards, 24, 309-318. *Tsunami hazard and inundation modelling for the Firth of Thames,* Tephra, October: 51-55 (1999)	Kerepehi fault, South America, Auckland Volcanic Field
L.M. Chick	Firth of Thames, Hauraki Gulf	*Potential tsunami hazard associated with the Kerepehi Fault, Hauraki Gulf, New Zealand.* MSc Thesis, The University of Waikato, Hamilton, 284 pp. (1999)	Earthquakes on Kerepehi fault
C.N. Butcher, A.E. Gilmour	Wellington and Lyttleton Harbours	*Free oscillations in Wellington and Lyttelton Harbours*. DFMS Reports, 1: 3-10. (1987)	Chile 1960 and Alaska 1964 earthquakes
E.R.C. Abraham	Wellington Harbour	*Seiche modes of Wellington Harbour, New Zealand.* New Zealand Journal of Marine and Freshwater Research, 31(2): 191-200 (1997)	
A. Barnett, S. Beanland, R. G. Taylor	Wellington Harbour (Te Papa)	*Tsunami and Seiche Computation for Wellington Harbour,* Proceedings of Pacific Conference on Earthquake Engineering, Vol. 2, Auckland, 1991.	Crustal earthquakes in Cook Strait and South American earthquakes.
A. Gilmour, B. Stanton	Wellington Region	*Tsunami Hazards in the Wellington Region,* Report for Wellington Regional Council, by DSIR 1990.	Crustal earthquakes in Cook Strait and South American earthquakes.
W. Power, G. Downes, M. Mc Saveney, J. Beavan, G. Hancox	West Coast	*The Fiordland earthquake and tsunami, New Zealand, 21 August 2003,* Proceedings of the IUGG Tsunami Workshop 2003 and the International Workshop, Tsunamis in the South Pacific, Kluwer, 2003.	2003 Fiordland earthquake

A5.2 Source to site functions

In order to model the relationship between earthquake magnitude at source and wave elevation at the site of interest we have adapted Abe's empirical expressions for tsunami height due to distant and local sources (Abe 1979).

The adaptations to this method are intended to allow for the Monte-Carlo modelling of both aleatory variability and epistemic uncertainty.

We assume that the tsunami height at the point where the tsunami comes ashore is equal to the peak-to-trough wave height, as would be measured by a tide gauge on the same coast, apart from a log normally-distributed site amplification factor.

Wave elevation for Lower Hutt was assumed to be 70% of the wave height for Wellington harbour entrance. Due to the amplifying nature of Lambton Harbour and Evans Bay (Barnett, 1991) the wave height for inner Wellington harbour was assumed equal to that of the harbour entrance.

A5.2.1 Distant sources:

The tsunami height H_{ij} at shore *i*, due to an earthquake of magnitude M_w in source region *j* is estimated by:

$$H_{ij} = 10^{S_i} 10^{(M_w - B_{ij})} \quad \text{A5.1}$$

where:

$$B_{ij} = Mean(B_{ij}) + \sigma_{B\,ij} N(0,1) \quad \text{A5.2}$$

in which $\sigma_{B\,ij}$ is the *variability* due to location[8], and

$$S_i = \sigma_{S_i} N(0,1) \quad \text{A5.3}$$

describes the *uncertainty* in site amplification. The suggested value[9] for $\sigma_{S_i} = 0.16$

A5.2.2 Local sources:

$$H_{ij} = 10^{U_{ij}} 10^{S_i} 10^{M_w - \log R_{ij} + 5.55 + C + \delta C_j} \quad \text{A5.4}$$

where the *uncertain* parameter C:

C=0.0 with 50% probability

C=0.2 with 50% probability

And δC_j has *variability* given by:

$$\delta C_j = \sigma_C N(0,1) \quad \text{A5.5}$$

the suggested value[10] for $\sigma_C = 0.15$. Site amplification is parameterised by the same

$$S_i = \sigma_{S_i} N(0,1) \quad \text{A5.6}$$

which describes the *uncertainty* in site amplification for distant sources.

U_{ij} describes the *uncertainty* for each site-source pair:

$$U_{ij} = \sigma_{U_{ij}} N(0,1) \quad \text{A5.7}$$

The suggested value[11] for $\sigma_{U_{ij}} = 0.18$

---

[8] $Mean(B_{ij})$ and $\sigma_{B\,ij}$ are estimated for each site-source pair by the empirical analysis described in Appendix YY.

[9] This is the mean logarithmic standard deviation in runup heights as measured within 40km segments over 1500km of the Japan Sea coast following the Nihonkai-Chuba earthquake in 1983 (Kajiura, 1986).

[10] This is the standard deviation in the difference between M_w and M_T for the events studied by Abe (1995).

[11] This value is deduced from the estimate in Kajiura (1986) of the combined site-amplification uncertainty and site-to-source uncertainty for six Pacific earthquakes. $\sigma_U = \sqrt{0.24^2 - 0.16^2} = 0.18$

Throughout N(0,1) stands for a normally distributed random variable of unit variance, and the subscripts *i* and *j* stand for the individual sites and sources respectively.

The local source expression is modified at short range in such a way that the wave heights reach a limiting value in the near vicinity of the source (Abe 1979), but similarly adapted to include the same uncertainties and variabilities described above.

A5.3 Estimation of parameters for Abe's equation for far-field tsunami

Abe (1979) proposed the following equation for estimating the height of a tsunami at a given site (labelled by the subscript *i*) due to earthquakes from a particular source region (labelled by subscript *j*).

$$H_{ij} = 10^{(M_w - B_{ij})} \qquad \text{A5.8}$$

For a given site-source pair we can estimate B_{ij} with data from one particular earthquake by:

$$\widetilde{B}_{ij} = \log(H_{ij}) - M_w \qquad \text{A5.9}$$

By compiling data from several earthquakes we can estimate a mean value for B_{ij} and a standard deviation around this mean σ_{Bij}.

The tsunami height H_{ij} is measured either as a maximum peak-to-trough tide gauge reading, or as a run-up height, these are treated as being approximately equivalent (Abe, 1979, Kajiura, 1986).

Five distant source regions were identified in this study:

- Region 1: South America between 45-19S and 8-0S
- Region 2: South America between 19S and 8S
- Region 3: Cascadia (NW USA and Vancouver Island, Canada)
- Region 4: West Aleutians / Rat Island
- Region 5: Southern New Hebrides

Region 5 is strictly speaking a regional source, as the travel time to NZ is just under 3 hours, however it was convenient to include treat this source as distant.

Of these regions the historical evidence suggests that the South American sources are the most important. Historical data for Region 1 comes from the tsunami of 1877 and 1960, and data for Region 2 comes from the tsunami of 1868 and 2001. Some sites did not record historical data for these events, in these cases numerical model results were compared to select a 'best-fit' model to the data at sites where observations were recorded, and the output from these models were then used to estimate the heights at those points for which no data was available.

The historical data, and models of historical events, were not themselves sufficient to accurately quantify the B_{ij} parameters, so additional synthetic (non-historical) scenarios were used. Two scenarios each were modelled for Regions 1 and 2, and one scenario each for the other Regions. Within Regions 1 and 2 the locations for the synthetic earthquakes were chosen to represent the geographical spread of possible event within the regions.

This combination of tsunami height information from historical observations, reconstructions of historical events, and synthetic models, was then used to estimate the mean and standard deviation of B_{ij} for each site and source region.

Since only one synthetic model was used for Regions 3-5 the standard deviation was estimated from the average standard deviation for Region 2 (this was chosen ahead of Region 1 because it was a more similar length to the other source regions).

The numerical models were developed at GNS through FRST funded research programmes for tsunami modelling and hazard assessment. The modelling software used was the MOST software developed by NOAA (Titov and Gonzalez, 1997), and the bathymetry data is a combination of the 1 minute Smith & Sandwell - GEBCO blend created by Walter Smith (Smith 2004) (NB: New Zealand bathymetry was contributed to GEBCO by NIWA), and data from the CMAP dataset from Seabed Mapping Inc. A run-up factor of 2 was used to estimate the tsunami height at shore, as the numerical models are limited to estimating wave-heights in depths greater than 10m.

Estimated values of the Abe B-parameter for distant tsunami

	Region 1: 45-19 S and 8-0 S 1877, 1960, syn2, syn3		Region 2: 19 S to 8 S 1868, 2001, syn1, syn4		Region 3: Cascadia syn5		Region 4: West Aleutians syn6		Region. 5: S. New Hebrides syn7	
	Mean B	Sigma B	Mean B	Sigma B	Mean B	Sigma B	Mean B	Sigma B	Mean B	Sigma B
Auckland	8.908087	0.199127	8.98366	0.168269	9.170616	n/a	8.790067	n/a	8.554677	n/a
Wellington	9.148686	0.27822	8.850631	0.0652	9.69485	n/a	9.245757	n/a	8.987216	n/a
Christchurch	8.864419	0.203804	8.764149	0.12787	9.444125	n/a	9.2	n/a	9.09485	n/a
Dunedin	9.066894	0.144913	8.845986	0.08245	9.655932	n/a	9.400659	n/a	9.29897	n/a
Tauranga	9.033703	0.230413	9.002176	0.180649	9.063279	n/a	9.018156	n/a	8.640959	n/a
Napier	8.917961	0.039294	8.666033	0.077418	9.380456	n/a	9.09279	n/a	9.068521	n/a
Invercargill	9.100772	0.270044	8.827647	0.12116	9.631798	n/a	9.429148	n/a	9.520819	n/a
Whangarei	8.927295	0.192467	8.942577	0.145775	8.959451	n/a	9.029738	n/a	8.636212	n/a
Whakatane	9.074981	0.30771	8.888868	0.116221	9.260481	n/a	8.987812	n/a	8.570616	n/a
Gisborne	8.609045	0.202982	8.562442	0.206395	9.231517	n/a	8.956962	n/a	8.713509	n/a
Timaru	8.93283	0.344297	8.652915	0.119734	9.280922	n/a	9.076148	n/a	9.008935	n/a
Manukau	9.769753	0.276844	9.561635	0.032155	9.576751	n/a	9.348742	n/a	8.361954	n/a
Porirua	9.715264	0.258652	9.428391	0.212004	9.921246	n/a	9.587216	n/a	8.937242	n/a
New Plymouth	9.685923	0.205042	9.37942	0.045932	9.59794	n/a	9.286186	n/a	8.499629	n/a
Wanganui	9.442123	0.246528	9.193609	0.174509	9.313509	n/a	9.421849	n/a	8.780456	n/a
Kapiti	9.68907	0.288415	9.316143	0.184665	9.838272	n/a	9.546787	n/a	8.909804	n/a
Nelson	9.560089	0.216511	9.27443	0.245533	9.50103	n/a	9.407608	n/a	8.976751	n/a
	8.962243	0.219388	8.817008	0.128285	9.343039	[0.13]	9.111567	[0.13]	8.917753	[0.13]

Notes
The models for Regions 3 and 4 are limited to 24 hours since the time of the source. It is possible that some locations may not have experienced their maximum possible wave height in this time.
The model for region 5 does not allow for the possibility of reflection of the tsunami from Australia.
Coefficients are calculated to provide estimates of wave height at the open ocean coast.

APPENDIX 6 — LIMITATIONS OF THE RISK ASSESSMENT

A6.1 General Points

- Risk estimates have only been made at the 19 largest coastal population centres (some are divided into sub-regions, for example, Manukau City east and Manukau City West).
- A night-time only scenario has been considered and there has been no consideration of the increase in summertime coastal populations or to tourists visiting New Zealand.
- Damage estimates apply to domestic and some commercial buildings, not to lifelines, shipping, etc., nor to long-term economic and environment effects.
- Only sources of tsunami judged to cause water elevations at the shore of 2 m or more at the 18 locations have been included. A 2 m threshold was chosen because significant damage begins to occur at this level. For the purposes of a tsunami warning system, a lower threshold may be more appropriate.
- The risk assessment assumes no effective response to natural or broadcast tsunami warnings.
- Only earthquake sources have been considered in the quantitative risk calculations. This is primarily due to limited knowledge of many aspects of tsunami generation and propagation from landslide sources and the lack of a reliable empirical relationship. Volcano sources are, given current knowledge, too infrequent or too small to be considered.
- In regard to tsunami caused by earthquakes, the use of empirical relationships developed internationally (but primarily using Japanese data) is a major limitation on the accuracy with which tsunami height at the shore can be assessed. These equations were used because of limited research on/modelling of, tsunami in New Zealand, but have been calibrated for New Zealand using what historical data, and numerical modeling results that are available.
- Inundation, damage and casualty modelling are also limited by the paucity of information and relationships in international literature.
- The uncertainty in the risk assessments are reflected in the large range of values for casualties and damage given in the tables and figures in Section 9.
- Not all aspects of uncertainty in the casualty model are reflected in the range of risk estimates
- The New Zealand-wide loss estimates do not include many smaller coastal communities, some of which almost certainly have higher risk exposure than nearby larger urban centres (e.g. Lyttelton compared with Christchurch, or Coromandel towns compared with Tauranga).

Institute of Geological & Nuclear Sciences Limited

Gracefield Research Centre
69 Gracefield Road
PO Box 30 368
Lower Hutt
New Zealand
Phone +64-4-570 1444
Fax +64-4-570 4600

Rafter Research Centre
30 Gracefield Road
PO Box 31 312
Lower Hutt
New Zealand
Phone +64-4-570 4637
Fax +64-4-570 4657

Dunedin Research Centre
764 Cumberland Street
Private Bag 1930
Dunedin
New Zealand
Phone +64-3-477 4050
Fax +64-3-477 5232

Wairakei Research Centre
State Highway 1, Wairakei
Private Bag 2000
Taupo
New Zealand
Phone +64-7-374 8211
Fax +64-7-374 8199

For more information visit the GNS website
http://www.gns.cri.nz