GeoEnvironmental Consultants

Wellington Regional Tsunami Hazard Scoping Project

Prepared for

Wellington Regional Council

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EXECUTIVE SUMMARY

This scoping project provides a summary of tsunami, and tsunami hazards and risk for the Wellington Region. Overall, the tsunami hazard is not as great as in some countries, but on the other hand it is similar to some regions commonly perceived to have a problem with tsunami, such as Indonesia and the islands of Hawaii. The perception that the hazard is low is probably because New Zealand has not experienced a large locally-generated tsunami since 1947AD (or 1855AD for the Wellington Region), or a large distantly-generated tsunami since the 1960AD Chilean earthquake. It is likely that a tsunami will occur soon. Further, the growing data on paleoseismicity and palaeotsunami in New Zealand indicate that the Cook Strait region, at least, is periodically subject to large magnitude events. While tsunami generated by earthquakes (possibly in association with landslides) are considered an *extreme hazard*, we know little about the submarine landslide hazards of Cook Strait and the Hikurangi Trough, and urgent work is needed to address this issue.

The estimated return period for a >5.0-10.0 m tsunami for some part of the Wellington Region coast – *based on the existing historically-documented AND prehistoric/pre-human record* is calculated to be about 84 years.

Two key assumptions are made in estimating the return periods listed in the text:

- All possible or probable historical and palaeo events recorded have been included in the calculations. Some may not have occurred, but alternatively they may all have taken place.
- It is assumed that wave heights are consistent around the Region's coast. This is not the case, but in order to establish a broad, generic understanding of the hazard, simplified Region-wide wave heights are based on the maximum wave height reported/estimated for each event at any one point on the Region's coast.

In general terms the coastline appears to be at high risk from tsunami. This ranges from the highest risk on the East Coast to a lower risk on the West Coast, where there is less exposure (but it still exists) to distantly-generated tsunami, but still with considerable risk from locally-generated events. We tentatively suggest that there is less risk from tsunami as opposed to earthquakes in the long term (100's of years) but more in the short term (ten's of years). This is primarily because large tsunami can be generated from both distant and local sources whereas damaging earthquakes are locally sourced.

There are three types of mitigation approach suggested: policy and management measures that reduce the likelihood of damage, preparedness and response planning to deal with consequences of the event, and engineering design measures that reduce vulnerability. Apart from the evacuation of people and removal of transportable assets (if possible), there are few cost-effective mitigation options available to pre-existing facilities to counteract many of these hazards in high-risk coastal areas. Therefore the limitation on the building of permanent structures in high-risk areas is a low cost mitigation measure.

Several generic information gaps exist in the available information and these have been prioritised. However, in order to emphasise the need for priority actioning to fills these gaps, the list is brief. These include the need for: i) a detailed coastal topography for the Wellington Region, ii) research to be undertaken to understand the role played by landslides in generating tsunami hazards for the Region, iii) complementary iterative modelling and palaeotsunami research to be undertaken in order to benefit from the ensuing synergies – on both landslide studies and key coastal sites such as the Kapiti and Wairarapa coasts, iv) the identification of residential and commercial shoreline facilities/structures etc. that could be damaged or could cause damage, and v) the development of mitigation plans in conjunction with key stakeholders.

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GLOSSARY

Bore:	*A wall-like wave of water, with an abrupt front, produced as an incoming tide or tsunami rushes up a shallow, narrowing estuary or bay.*
Caldera:	*A large basin-shaped volcanic depression that is more or less circular, the diameter of which is many times greater than that of the vent or vents.*
Co-seismic:	*Relating to an event that occurs at the same time as an earthquake such as the uplifting of the coastline to form an uplifted beach ridge – a "co-seismic" uplift event.*
Ground deformation:	*The changes in ground surface relating to a fault rupture (the breaking or tearing apart of rocks along a fault). The nature of the changes determines the nature of the tsunami propagated.*
Lahar:	*A landslide or mudflow of pyroclastic material on the flank of a volcano; it is also the name of the deposit.*
M_w:	*Earthquake magnitude determined from the seismic moment (measure of the magnitude of an earthquake determined by Fourier analysis of long period seismic waves. The method of analysis removes effects due to the rupture mechanism).*
Palaeotsunami:	*A tsunami that has occurred in the (geological/prehistoric) past, identified by physical evidence. Sometime associated with archaeological sites and/or oral traditions.*
Perigean-spring tide:	*These are higher than normal spring tides that occur a few days after a spring tide (full of new moon) and coincide with the Moon's perigee (i.e. when the moon is closest to the Earth in its elliptical orbit.*
Propagate:	*To transmit, as in transmitting the form of a wave.*
Pyroclastic flow:	*A turbulent blend of unsorted, mostly fine-grained material and gas ejected explosively from a fissure or crater.*

Resonance:	*The amplification of a wave when subjected to a periodic disturbance of the same frequency as the natural frequency of the system or harbour.*
Runup:	*The value of absolute inundation at the maximum horizontal extent of flooding measured perpendicular to the shoreline. The maximum elevation associated with the inundation is taken as the runup height, which is normally assumed to equal the maximum tsunami amplitude. See wave height.*
Seiching:	*An oscillation of a body of water in an enclosed or semi-enclosed basin that varies in period from a few minutes to several hours and in height from a few centimetres to a few metres, depending upon the dimensions of the basin. Caused mainly by local changes in atmospheric pressure aided by winds, tidal currents, earthquakes.*
Soliton:	*A non-dispersive solitary wave that is particularly stable in the ocean. Large distantly-generated tsunami often form these.*
strike-slip fault:	*A fault on which the movement is parallel to the fault's strike (the direction taken by the fault as it intersects the horizontal).*
Subduction earthquakes:	*This occurs in an area where one lithospheric tectonic plate (part of the Earth's crust) is descending beneath another and a movement occurs. The "subduction zone" to the east of the North Island is a long narrow trench where the Pacific Plate (eastern) is subducting beneath the Australian Plate (western).*
Volcano-meteorological tsunami:	*Tsunami generated by a pressure wave, sent out by an eruption, displacing the air in front of it.*
Wave height:	*An approximation of wave amplitude (see Figure 1), also used to represent runup height on land. In historical data this term may relate to the 'total water level variation' or the height from peak to trough (Figure 1; Table 5c).*
Wave period:	*The time taken for two successive peaks or troughs to pass a fixed point.*
Wavelength:	*The distance between successive wave crests or troughs.*
Wave train:	*A series of waves.*

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CHAPTER ONE – SUMMARY

- A summary of the key objectives of the WRC's brief is given
- The introduction includes a caveat explaining that every attempt has been made to provide as complete an interpretation of available data as possible, but there is always the possibility that some data have been missed.

1. INTRODUCTION

Wellington Regional Council (WRC) has requested a study to assess the risk that tsunami hazards pose to the Wellington Region, a Region that has over 500 km of coastline. The objectives of the brief are to:

- Define tsunami and tsunami-related hazards;
- Summarise the effects of tsunami likely to occur in the Wellington Region;
- Identify and assess the level of risk that tsunami and tsunami-related hazards pose to the Wellington Region;
- Identify potential tsunami sources for the Wellington Region;
- Identify areas at risk from tsunami hazards generated from both local and distant sources;
- Identify the effect of tsunami-related hazards on the harbours and waterways of the Region;
- Summarise current research relevant to tsunami hazards in the Wellington Region;
- Identify mitigation measures that the WRC should currently take to reduce the risks from tsunami hazards in the Region;
- Assess the uncertainties of the current information on tsunami hazards and tsunami hazards in the Wellington Region;
- Identify gaps in the available information, both scientific and historical, relating to tsunami hazards in the Wellington Region;
- List and prioritise all work needed to fill the identified gaps in knowledge;
- Identify key stakeholders who have an interest in the study and use of tsunami hazard information for the Wellington Region;
- Produce a glossary of scientific terms;
- Include maps and references.

As stated in the tender document, the overall thrust of the report will be to provide a comprehensive database of tsunami hazards in the Wellington Region and, by analysing the data, provide priorities for future work.

The methodology will closely follow the format proposed by the WRC and acknowledges the statement in the Brief that "the report should be written in a manner that can be easily understood by non-scientists. It is our intention to use the report as a basis for risk management decisions and public education".

We interpret the key aims of the report as:

- Establishing a comprehensive database of tsunami information for the Region based upon historic, prehistoric, and pre-human records.

- Providing a clear synthesis of this information to highlight: sources, effects, hazards, risk, mitigation measures, gaps, uncertainties, and key stakeholders.

1.1. Caveat

This report is written on the basis of the contemporary scientific knowledge about tsunami and tsunami hazards. We have made every attempt to provide as comprehensive an interpretation of available data as possible, although there is always the possibility that some data have been missed. In many instances much of the interpretation is based upon professional intellectual property and as such this type of information cannot be referenced. Studies of tsunami indicate that the effects along a coastline are extremely variable. Therefore, where necessary, we have adopted a conservative approach acknowledging that, for example, while runup (See *Glossary*) height is controlled by many variables, a general Region-wide runup is chosen based upon known site-specific inundations. While the prediction of tsunami hazards is not exact, the additional information provided by this report should form part of an iterative process that sees on-the-ground historic and palaeotsunami evidence incorporated into tsunami models to improve their hazard assessment capabilities. These hazard assessment capabilities can in turn be improved by on-the-ground studies of the areas believed most likely at risk from tsunami inundation. The use of one technique (modelling or historic/palaeotsunami) alone is unwise. This report is based primarily on the latter (historic/palaeotsunami) but it also assesses earlier modelling studies (Gilmour and Stanton, 1990; Barnett *et al*., 1991; Downes *et al*., 2000).

CHAPTER TWO - SUMMARY

- Tsunami, their characteristics, and tsunami-related terminology are explained.
- Tsunami generating mechanisms; earthquakes, landslides, volcanoes and bolide impacts are discussed.
- Tsunami-related hazards, such as runup and backwash, wave characteristics, and floating debris are explained.
- Of particular interest to the Wellington Region are:
  - The nature and effect of floating debris (Wellington/Porirua Harbours)
  - Seiching (the exaggerated 'sloshing': of waves inside harbours)
  - The generation of bores (see *Glossary*) in estuaries and rivers
- There is a pressing need to understand more about the impacts of saltwater contamination caused by tsunami. This is particularly important with respect to the long and short-term effects of small, more frequent and large, less frequent tsunami on buildings and structures, natural ecosystems, and agricultural land.

DEFINE TSUNAMI AND TSUNAMI-RELATED HAZARDS

2.1. Introduction

Tsunami is a Japanese word meaning '*harbour wave* or *waves*' (the word is both plural and singular). Tsunami are a series of long period waves (see *Glossary*) generated by an impulsive source. The impulse produces a sudden displacement of the water column, and thereby the water surface, which develops into a tsunami.

Tsunami *are not* 'tidal waves'. Tidal waves are primarily caused by the gravitational pull exerted by objects in the Solar System, mainly the Sun and Moon, on the Earth's surface.

The displacement causing a tsunami is normally generated by either a submarine earthquake, a landslide (into or under the water), a volcanic eruption, or a bolide impact (e.g. asteroid) (de Lange, 1998; in press). This displacement of the sea surface initiates a series of waves radiating outwards from the initial disturbance. If locally-generated, they may come onshore within minutes, but more distantly-generated ones can takes hours. For example, it can take about 14 hours for a tsunami to travel from South America to New Zealand, allowing sufficient response time to warnings from the Pacific Tsunami Warning Service (Gilmour, 1960; Downes *et al*., 2000).

Tsunami are fast-moving, and in deep ocean water the wavelength (see *Glossary*) is anywhere between about 200 to 700 kilometres, while the wave period is between 15 to 60 minutes (Figure 1). There are often several waves in a "wave train" (see *Glossary*), normally with a maximum height of about 0.5-1.0 m. Because tsunami have such a small wave height (see *Glossary*), they can be difficult to recognise without the appropriate instrumentation (de Lange, in press). Unlike wind-generated waves where the energy rapidly decreases with depth, the energy associated with a tsunami is distributed throughout the whole water column irrespective of depth, and the energy moves at the same velocity as the waves.

In shallower water (10's of metres) tsunami start to slow down and their wavelengths decrease. For example, by slowing to about 50 km an hour, the wavelengths usually decrease to about 50 km or less. While the leading (first) wave slows down in shallow water and the wavelength decreases, the wave period remains the same. To compensate for this concertina effect as the waves behind are squeezed closer together behind the first one, the wave height increases and may be up to 10's of metres high. However, while tsunami may reach several 10's of metres high at the coast, most are less than 1 m in height and come onshore as non-breaking waves acting rather like a rapidly changing tide that inundates the land.

Typically, a tsunami consists of several waves, normally appearing like a series of rapidly changing tides. These often persisting for 3-5 days, supplemented by local seiching and resonance (see *Glossary*). It is normally not the first wave that is the highest or most destructive, but rather the second or third, except perhaps in locally-generated events (Ridgway, 1984; Goldsmith *et al*., 1999; de Lange, in press).

2.2. Tsunami generation

Most tsunami are generated by earthquakes, with subduction earthquakes (see *Glossary*) being particularly effective.

n.b. The term '*earthquake*' refers to the shaking generated by a fault rupture and not the fault rupture *per se* which is normally the tsunami-generating mechanism. Shaking may generate a landslide that in turn generates a tsunami. However, since the term '*earthquake*' has more common usage it is used in this report to represent both the fault rupture and associated shaking.

There is a general tendency for the size of tsunami to increase with increasing earthquake magnitude (Iida, 1961). However this varies considerably for very large and long duration earthquakes, called *Tsunami Earthquakes*, because they produce tsunami that are significantly larger than predicted (refer to de Lange (in press) for detailed explanation).

To generate a tsunami by earthquake requires the direct displacement of the seafloor. This occurs either by a vertical, horizontal, or thrusting (combination of both horizontal and vertical) motion (Iida, 1961; Okal, 1988). Furthermore, the earthquakes need to be relatively shallow, between 20 and 100 km below the seafloor. A shallower depth provides the strongest "shove", but a deeper one distributes the "shove" over a larger area (Okal, 1988). In summary, Okal (1988) found that the parameters that best describe a *tsunami earthquake*, were when a fault ruptured as a thrust into a layer of soft sediments. The soft sediments reduce the velocity of the fault rupture, and so there is not a sudden motion, but a more drawn out one, thus giving time for the water to rise slowly, producing the required long period waves.

The Hikurangi Trough (Figure 2), the seafloor expression of the subduction zone between the Pacific and Australian Plates, is situated off the east coast of the Wellington Region, and tsunami earthquakes do occur along this zone (e.g. Kelsey *et al*., 1998). Similarly, large earthquakes occurring elsewhere in the Pacific may generate stable tsunami known as 'Solitons" (see *Glossary*). These are considered 'stable' because the earthquake occurs over a great distance and produces a non-dispersive wave (does not spread out from a central point). These can propagate (see *Glossary*) across oceans with little or no energy loss and as such represent highly destructive, distantly-generated tsunami (de Lange, in press). Small earthquakes on the other hand produce dispersive waves that spread out more from a central point.

An evaluation of tsunami risk by Okal *et al*. (1990) for the South Pacific Ocean in general indicates that there is no real tsunami risk for earthquake magnitudes less that 7.3 M_w (see *Glossary*) (de Lange, in press). However, it is interesting to note that there have been large tsunami in New Zealand associated with earthquake magnitudes of less than Magnitude 6.0 (de Lange and Hull, 1994). Unfortunately, attempting to predict tsunami risk for New Zealand has proved problematic primarily because tsunami amplitude (wave height) data are rare, and the historical database is too short to provide reliable predictions (de Lange and Healy, 1986; Fraser, 1998). Historical data are currently being supplemented by palaeotsunami (see *Glossary*) studies in an attempt to extend the record further back in time (e.g. Goff and Chagué-Goff, 2001).

In the past, the primary source of tsunami has always been considered to be earthquakes. However, there is currently some debate over the relative importance of earthquake-induced landslides (or the release of gas) as a cause of tsunami (Downes *et al*., 2000). It is possible that earthquake-induced landslides may, at least for local lengths of coastline, prove to be more common than currently believed. Equally though, it is possible that earthquake-induced landslides *in conjunction with* the generating earthquake may be the most significant (e.g. Kanamori and Kikuchi, 1993; Imamura *et al*., 1997). It is normally these co-seismic (see *Glossary*) landslides that generate tsunami, such as the landslide associated with the 1931 Napier Earthquake (de Lange and Healy, 1986; Chagué-Goff, 1999). In general, landslides act as point sources for tsunami generation and waves disperse radially away like ripples. The resultant wave train normally consists of 3-6 waves that dissipate rapidly away from the source (de Lange, in press), hence they are often only locally significant.

Most landslide-generated tsunami are reported for confined water bodies such as the Mediterranean and North Seas (e.g. Camfield, 1980; Smith and Dawson, 1990), and this clearly has implications for the semi-enclosed harbours of the Wellington Region. Large landslides can generate locally extreme tsunami (>30 m wave height), such as the 525 m high Lituya Bay tsunami in Alaska that rapidly reduced in height to 30 m at the entrance to the fjord (Miller, 1960). Landslides do not have to enter the water from above though, and it is co-seismic submarine landslides that have been the focus of much recent work. Large submarine landslides up to 5000 km^3 from the flanks of volcanoes in the Hawaiian islands have generated local tsunami 100's of metres high (Moore *et al*., 1989). Submarine landslides may equally occur off the continental shelf or submarine canyons (e.g. Dawson *et al*., 1993), such as those off the south coast of the Wellington Region in Cook Strait (e.g. Carter *et al*., 1988) (Figure 2), or the East Cape (Lewis and Collot; 2001).

Volcanic tsunami are similar to those generated by landslide in that they are generated within a limited source area, so they would normally dissipate rapidly with distance from source. While inundation by distantly-generated volcanic tsunami has been reported in the country (e.g. Krakatau, 1883AD; de Lange and Healy, 1986), New Zealand is an area of active volcanism and locally-generated ones are probably of greater concern. There are several possible methods of tsunami generation related to volcanism (de Lange and Hull, 1994), such as:

- Pyroclastic flows (see *Glossary*) impacting on water
- Earthquakes accompanying eruptions
- Landslides and avalanches of cold rock
- Submarine explosions
- Caldera (see *Glossary*) collapse
- Lahars (see *Glossary*)
- Air waves associated with large explosions
- Lava flows

Lowe and de Lange (2000) discuss a volcano-meteorological tsunami (see *Glossary*) generated by the Taupo eruption in about 200AD, and Goff and Chagué-Goff (1999a) and Goff *et al*. (2000b) report palaeotsunami deposits in the Wellington Region that date to this time. More conventional volcanic tsunami such as those generated by submarine explosions and caldera collapse are discussed by de Lange (in press), but have not, as yet, been reported in the Wellington Region.

The other significant tsunamigenic process is a bolide impact. There are at least 120 meteorite impact craters caused by asteroids and comets recorded around the World (Ahrens and Harris, 1992). We receive a constant rain of material from space, with 100 to 300 >1kg bolides impacting the Earth each year. Furthermore, there are about 2000 objects with a diameter ranging from 1 to 10 km following trajectories that will intersect with the Earth's orbit sometime in the future. An impact with an object of this size could produce tsunami heights of several kilometres (Gersonde *et al*., 1997; Poag, 1997). The only known deep ocean impact, in the South Pacific off Chile, is believed to have generated a tsunami in the shallow waters of New Zealand of between 1 and 2 kilometres high (Gersonde *et al*., 1997). However, bolides as small as 200 m in diameter could generate tsunami up to 100 m high, and these strike the Pacific Ocean about once every 24000-43000 years (Jones and Mader, 1996). This represents about a 0.002% chance of an impact each year (de Lange, in press).

2.3. Propagation of tsunami

Unless they are particularly large, tsunami produced from point sources, such as a landslide, will not be hazardous after propagating for more than 1000 km or so from the source. However, tsunami can be destructive over great distances depending upon several processes that may serve to increase the magnitude and enhance the hazard (Braddock, 1969). Large subduction earthquakes around the Pacific generally generate maximum energy either directly towards the coast or out into the middle of the Pacific (de Lange, in press). As tsunami come in to shallow water they will 'refract' or bend towards shallow water and as such these areas of shallow water can help to focus tsunami energy. For example, the 1960AD Chilean tsunami was focussed onto the East Cape region by the East Pacific Rise (Okal, 1988), and probably by the Chatham Rise onto Banks Peninsula (de Lange, in press). Nearer the shore, such refraction can cause extreme variability in wave height (Sato and Noguchi, 1998). Shallow, or shallowing areas also serve to reflect energy back away from the coast, as is the case with New Zealand's continental slope. Interestingly, when a tsunami passes by New Zealand and reaches the Great Barrier Reef, this serves to reflect energy back towards the west coast of New Zealand, while also probably focussing energy on gaps in the reef (Braddock, 1969; Nott, 1997).

Tsunami energy can also be reflected by the shoreline, but because at this point the tsunami is in shallow water it can bend and become trapped as a dispersive (spreading out from a point) wave that travels along the coast (this is called an 'edge' or 'solitary' wave). This is most likely to occur when the tsunami is generated locally on the continental shelf (Carrier, 1995; de Lange, in press).

2.4. Tsunami-related hazards

To a large extent the hazards related to each tsunami are different because they are generated differently. For example, the 1998AD Papua New Guinea tsunami varied in height from less than a metre to over 17.0 metres in the space of 10 kms, causing considerable variation in damage (Goldsmith *et al*., 1999). Therefore, the hazards created are site specific and can realistically only be dealt with in general terms.

The initial measure of potential tsunami hazard is the runup (see *Glossary*) (Figure 1). As a "rule of thumb" the runup height on land approximates the vertical wave height at the shore, although in reality this varies considerably depending upon nearshore bathymetry and onshore topography (Morgan, 1984). Therefore, the runup is the height of the tsunami above a specified datum, which is normally the tidal elevation at the time of the tsunami. The maximum potential runup provides an indication of the hazard. The higher the runup, the greater the hazard. According to de Lange (in press), any runup exceeding 1 m is considered to be potentially catastrophic. However, the maximum elevation of runup is dependent upon the sea level at the time of inundation. A small tsunami arriving at high tide may be more damaging than a large tsunami at low tide (de Lange and Hull, 1994).

When a wave comes onshore, it is normally as a non-breaking wave, or rapidly rising tide, forming bores (see *Glossary*) only within rivers and estuaries. A shallow onshore slope may encourage friction and reduce runup height, and vice versa for a steep slope (e.g. Synolakis, 1991). Tsunami sometimes come onshore as breaking waves that are turbulent and as such may have a higher runup, but because of rapid energy loss they are unlikely to penetrate as far inland (Downes *et al*., 2000).

While breaking waves and their associated turbulence are more damaging, the runup and backwash associated with non-breaking waves induces strong currents that are extremely destructive and life-threatening (Downes *et al*., 2000). Therefore, both components of tsunami inundation, runup and backwash, can be destructive. Since the energy is distributed throughout the water column, the runup is extremely destructive irrespective of the nature of the wave. Similarly, the backwash is equally or more destructive and life-threatening because the water contains an assortment of loose debris ranging from houses to small artifacts (e.g. Goff and McFadgen, 2001).

Interactions between runup and backwash are complex. Both have high velocities and as such are highly erosional. While frequently it is one of the first few waves that is considered most destructive, they may all appear to have erosional and depositional attributes (Goff *et al*., 1998b). Two classic features of tsunami deposits are that the sediments become finer (smaller) inland and that they also fine upwards (Goff *et al*., 1998b; Chagué-Goff *et al*.; in press). In other words, as the energy decreases inland, finer and finer sediments are deposited, and as the backwash retreats, while much of the material can be reworked it probably has less energy to erode all the recently deposited material. During runup, at the shore and immediately offshore, material is picked up, but almost immediately it starts to deposit material, possibly behind the eroding wave front. The high flow velocities are difficult to interpret because on-going erosion during the runup changes the onshore topography and therefore changes the response of the runup and subsequent backwash for each wave (de Lange, in press). However, the backwash generally travels down the path of least resistance, such as through low-lying topography, much of which has been recently recontoured by the incoming wave (e.g. Goldsmith *et al*., 1999).

Flow velocities of both runup and backwash can be high, varying from estimates of 10 to 70 km per hour (Shuto and Matsutomi, 1995; McSaveney *et al*., 2000). The runup is often fast-moving and sediment laden, and causes death and injury by sandblasting, crushing (against more resistant objects such as trees and buildings), and dismemberment. On the other hand, the backwash is generally associated with drowning as people are swept into deep water by the return flow, and injury by floating debris (Butcher *et al*., 1994; Goldsmith *et al*., 1999). For example, in the 1993 Hokkaido-Nansei-Oki tsunami, 71% of the deaths were due to the impact of floating debris (Butcher *et al*., 1994).

The nature and effects of floating debris have been studied in some detail (de Lange, in press). While floating debris causes numerous deaths, there are several other pertinent points:

- Floating material in tsunami bores may exert impulsive forces of more than 9 tonnes, weakening or destroying many structures it comes in to contact with (Matsutomi, (1991) in de Lange, in press).

- Hazardous debris includes:
  - Combustible material that may be ignited by sparks from electrical equipment (e.g. Lyttelton, 1960AD Chilean tsunami, several electrical failures, but no reported fires).
  - Liquid contaminants (fuels, chemicals) are a major problem for ports and marinas in New Zealand where no protection measures have been taken to protect storage and piping facilities from tsunami.
  - Small vessels are often washed inland, causing fires from leaking fuel and/or impact damage to built structures.

Much of the study of floating debris has focussed on the effects in ports. However, when a tsunami enters a harbour, estuary or river, it may well interact with the geometry and dimensions of these semi-enclosed areas to produce seiches. This excitation of the water inside a semi-enclosed area such as a harbour depends upon the time interval between the peaks of each wave, the wave period (see *Glossary*) – which is normally between 15 to 60 minutes. These wave periods can induce a sort of sympathetic (or in this case 'forced') oscillation because they interact with the natural oscillations of the area, thus enhancing the height of tsunami at some locations. For example, Wellington Harbour has several natural modes of oscillation and it therefore has the ability to resonate (amplify the waves) in response to tsunami, such as in Evans Bay (Butcher and Gilmour, 1987; Abraham, 1997). This has two effects; it serves to amplify the size of the individual waves in a tsunami, and it normally extends the effects of the tsunami by continuing to "slosh" around inside the confines of the semi-enclosed area for many hours after the arrival of the first wave. However, if the tsunami has a wave period that does not 'match' the natural modes, this may serve to dampen their height and produce no forced oscillations (Downes *et al*., 2000).

The effects of tsunami in estuaries and rivers are two-fold. Firstly, they can generate rapid changes in water level, inducing strong currents, eddies and seiches that break moorings, and scour and redeposit sediment, often necessitating the resurvey of shipping channels (de Lange, in press). Secondly, tsunami can form bores. These are particularly destructive because they are generally at their strongest at the upper limit of the tidal influence where the opposing currents of river and sea may result in the greatest steepness of wave (Tsuji *et al*., 1991), and which is also where most road and rail bridges are built (de Lange, in press). Tsunami can also form bores when they break offshore. This generates high horizontal and vertical turbulence, the latter allowing the tsunami to entrain huge objects, such as the 20 tonnes section of seawall transported 200 m inland by the 1960AD Chilean tsunami when it inundated Japan (Yeh, 1991).

Tsunami inundation introduces saltwater into the coastal area. While little work has been undertaken on the short and long term effects of this saltwater contamination, some points can be made from a review of the literature:

- "Ghost forests" of cedar trees can still be found in places up and down the Washington coast, USA, following tsunami inundation 300 years ago (Atwater and Yamaguchi, 1991).

- Regular saltwater inundation encourages greater species diversity in the longer term by providing niche microenvironments for some species (Allen and Sharitz, 1999).

- Most tree and shrub species die rapidly when flooded with saltwater concentrations of only one-third seawater (Allen and Sharitz, 1999).

- Post inundation recovery varies between species, but initially there is extensive die-off of trees and shrubs. High latitude ghost forests with limited shrub regrowth have been found 800 years after the inundation event (Minoura *et al*., 1996).

Two points are evident. Firstly, there is little known about the short and long term effects of saltwater contamination from tsunami. Secondly, what is known tends to suggest that saltwater contamination encourages species diversity. However, this is reported from natural forested areas. The effects on coastal farmlands and stressed natural ecosystems are unknown but they are probably dependent upon the salt tolerance of individual plants. In the case of monoculture farming or forestry, the effects could be catastrophic. For stressed natural ecosystems, there is clearly the potential for weed invasion following die-off (Goff and Chagué-Goff, 2001; GeoEnvironmental Consultants, in press).

There is a need to further understand several aspects of saltwater contamination by tsunami. What are the long and short-term effects of small, more frequent and large, less frequent tsunami:

- Buildings and structures? Are there problems with structural integrity?

- Natural ecosystems – stressed, sensitive, or apparently robust? How does one manage the ecosystems to mitigate damage?

- Agricultural land? Which crops are more susceptible than others?

There are clear long and short-term economic issues embedded in this lack of knowledge and there is a pressing need to understand more about the impacts of saltwater contamination caused by tsunami.

CHAPTER THREE – SUMMARY

- The two main source areas for tsunami are discussed – local and distant.
  - The most extreme hazard ***for New Zealand*** from a distant source is from the West Coast of South America. Waves with a height of 5.0 m have an estimated return period of about 82 years.
  - The return period for a 5.0 m tsunami for ***the Port of Wellington*** – *based on historically-documented tsunami only* is 728 years**.**
  - The return period for a >5.0-10.0 m tsunami for ***the Wellington Region*** – *based on the historically-documented AND palaeo record* is about 84 years*****.

  *****Return periods are estimated in Table 7a. Two key assumptions are made:

  i) All possible or probable historical and palaeo events recorded in the Tables have been included in the calculations. Some may not have occurred, but alternatively they may all have taken place.

  ii) It is assumed that wave heights are consistent around the Region's coast. This is not the case, but in order to establish a broad, generic understanding of the hazard, simplified Region-wide wave heights are based on the maximum wave height reported/estimated for each event at any one point on the Region's coast. A more detailed location-specific analysis is outside the parameters of this project.

- Locally-generated sources:
  - We know little about the submarine landslide hazards of Cook Strait and the Hikurangi Trough (see Figure 2). Urgent work is needed. In the absence of sufficient data they are considered a moderate to high hazard.
  - Earthquakes (possibly in association with landslides) are considered an extreme hazard, and details of local faults are given.

- Past tsunami:
  - Historical evidence is discussed. An attempt is made to estimate wave height around the Region for selected events.
  - Prehistoric and pre-human data indicate that, unlike the historic record, local earthquakes are important tsunami sources. Archaeological and physical evidence of past tsunami are used to estimate Region-wide tsunami inundations.

- The two previous models of Gilmour and Stanton (1990) and Barnett *et al.* (1991) are dated in their technology and parameters. Downes *et al*. (2000) updated some of the parameters, but new numerical modelling needs to be undertaken.

- Preliminary data indicate the following "hotspots" where incoming waves will be amplified.

  - Riversdale/Castlepoint
  - Palliser Bay, particularly the NE corner
  - Wellington Harbour
  - Porirua Harbour
  - Kapiti Coast

- The coastline is at high risk from tsunami. This ranges from the highest risk on the East Coast to a slightly lower risk however still relatively high, on the West Coast.

- Risk – for large tsunami (>5.0 – 10.0 m) as opposed to a large earthquake: we tentatively suggest that there is less risk with respect to tsunami in the long term (100's of years) but more in the short term (ten's of years), primarily because large tsunami can be generated from both distant and local sources.

3. THE LEVEL OF RISK POSED TO THE WELLINGTON REGION

Tsunami risk identification consists of several components; identification of potential tsunami sources (local and distant), a summary of the past record of events and their effects (inc. tsunami magnitude, estimated return periods, and current research relevant to tsunami hazards in the Wellington Region); identifying the effects of tsunami-related hazards on the harbours and waterways of the Region; and identifying areas at risk from tsunami hazards generated from both local and distant sources. The level of risk from tsunami is then placed qualitatively in a context against other natural and technological hazards faced by the Region.

3.1. Identification of potential tsunami sources

There are two source areas of tsunami generation that have the ability to affect the Wellington Region; distant and local (distantly-generated tsunami are also known as *teletsunami* (de Lange and Fraser, 1999)).

Distantly-generated tsunami are generated beyond the New Zealand continental shelf. Such tsunami have longer wave periods (see *Glossary*), persist for several days, and can affect most of the New Zealand coast (de Lange and Fraser, 1999).

- e.g. The 22 May 1960AD Chile earthquake produced a runup height of 0.75 m in Wellington Harbour, but produced the greatest observed height at Lyttelton (Heath 1976).

Locally-generated tsunami are generated on or from the New Zealand continental shelf. Such tsunami have shorter periods, do not last long, affect a limited section of the coast, but are likely to have localised peak runup heights well in excess of any distantly-generated tsunami (de Lange and Fraser, 1999). This interpretation relates solely to historically-documented events, whereas palaeotsunami evidence suggests that the effect of a locally-generated tsunami can be far more ubiquitous (Goff and Chagué-Goff, 2001).

- e.g. The 23 January 1855AD West Wairarapa earthquake produced an estimated runup of 3-5 m in parts of Wellington Harbour and upwards of 9-10 m in Palliser Bay (Gilmour and Stanton, 1990; Downes *et al*., 2000).
- e.g. The mid-15th Century event reported from numerous coastal sites in New Zealand, has an estimated runup of at least to 15 m (Goff *et al*., 2000a; Goff and McFadgen, 2001; Goff and Chagué-Goff, 2001).

3.1.1. Distantly-generated tsunami (Figure 3)

These are prominent in the historical record (refer to Section 3.2.1.), occurring more frequently than their locally-generated counterparts, but tending to be of lower magnitude. de Lange (in press) uses computer models and historical data to assess which earthquake zones around the Pacific Rim are likely to produce major tsunami that could affect the coast of New Zealand. He rules out certain areas because either:

- historically they have not affected New Zealand; or
- their tsunami generating mechanisms are incapable of producing one that will affect New Zealand;
- or the tsunami generated would take an indirect route, be dissipative, and be directed away from New Zealand.

- ***No hazard*** areas include: Hawaii, New Guinea, Solomon Islands, Indonesia, The Philippines, Antarctica, and Central America.
- ***Minimal hazard*** areas include: Kamchatka, Japan, Kuril Islands, South Pacific Islands, New Zealand's Exclusive Economic Zone beyond the continental shelf. In general, large (Magnitude >8.25) shallow earthquakes would be required to produce a significant tsunami (>0.25 m) because most energy is still either directed away from New Zealand, or dissipates as it passes through the Pacific Islands.
- ***Moderate to high hazard*** areas include: parts of North America. The tectonic structures between Alaska and Oregon tend to direct tsunami towards New Zealand, and the area also has a history of tsunami generated by large earthquakes (Clague *et al*., 2000). However, there has only been one historical tsunami recorded from this area (Alaska, 1964AD).
- ***Extreme hazard*** areas include: the west coast of South America. Again, based on historical data, large, shallow earthquakes have produced wave heights >5.0 m.

Annual exceedence probabilities and return periods for the New Zealand coast based upon these hazard areas have been reported (Table 1)(Fraser, 1998; de Lange, in press).

3.1.2. Locally-generated tsunami (Figures 2, 4 and 5)

Locally-generated tsunami are less common in the historical record (refer to Section 3.2.1.), but are generally of higher magnitude. However, they currently comprise all the tsunami recorded in the prehistoric and pre-human record (hereafter called the *Palaeo Record*). This highlights two key points:

- Past tsunami hazard assessments for New Zealand have been based primarily on the historic record and as such may have biased our interpretation of tsunami risk. In the historical record the distantly-generated, lower magnitude events affecting the east coast of the country predominate. In the palaeo record, larger magnitude, nationwide events are recorded (e.g. Goff and Chagué-Goff, 1999a; Goff *et al*., 2000a; 2000b).

- The palaeo record mainly preserves sedimentary evidence of ‘big’ events. Lowe and de Lange (2000) estimate that a tsunami needs to have been *at least* 5 m. high to have been recorded in the coastal sediments of Cook Strait. Therefore, whatever return period can be calculated for these larger magnitude events from the palaeo record, it can be assumed that smaller, more frequent events will have an even shorter return period.

New Zealand sits astride the boundary between two continental plates, the Pacific and Australian, and is a tectonically active country. Therefore, sources in the Wellington Region for locally-generated tsunami are numerous and include a variety of mechanisms such as volcanoes, landslides and earthquakes (Figure 4). It is difficult to adopt the same minimal to extreme rating for distant sources, but rather each mechanism will be dealt with in turn and rated accordingly.

Volcanic:

There have been no historic volcanic tsunami recorded in New Zealand, but there are possibly one or two in the palaeo record. Lowe and de Lange (2000) discuss the possibility of a volcano-meteorological tsunami (Section 2.2.) generated by the Taupo eruption, with the possible evidence being found on Kapiti Island and in Abel Tasman National Park (Goff and Chagué-Goff, 1999a; Goff *et al*., 2000b). More recently, Goff and McFadgen (2001; in press; in review) have reported nationwide tsunami (there were probably a series of tsunami, generated by a series of tsunamigenic events that affected various parts of the coastline) for which the mid 15th Century eruption of Mt. Taranaki might have been partly responsible (McFadgen, 1981).

In general, the Taupo Volcanic Zone is the most likely source for any tsunami, but unless the eruption was of the magnitude of the 200AD Taupo eruption and generated a volcano-meteorological tsunami, it seems unlikely that these represent anything more than a *minimal hazard* for the Wellington Region.

Landslide:

The Hikurangi Trough, Cook Strait Canyon system, and the adjacent continental shelf margin on both the west and east coasts contain numerous landslide scars (Carter *et al*., 1988; 1991). However, whether these are causally linked to local fault activity or are independent is inconclusive (Carter *et al*., 1988), but they do indicate that there is potential for submarine landslide-generated tsunami.

Historically, terrestrial and probably submarine landslides occurred during the 1855AD earthquake, although their precise contribution to tsunami propagation is unclear. It is possible that they served to exacerbate the 1855AD earthquake-generated tsunami (Barnett *et al*., 1991; Grapes and Downes, 1997). While there are presently few data on the age and frequency of such slope failures, Lewis (1998) presented evidence of an underwater debris avalanche (landslide) that occurred in the Kaikoura Canyon around 1833AD, possibly triggered by an earthquake along the Hope Fault. Such events could occur every couple of centuries, after enough sand and pebbles have accumulated (Lewis, 1998). A local tsunami generated from anywhere within the Hikurangi Trough or its head (Kaikoura Canyon) is likely to pose a risk to the Wairarapa coast, South Wellington coast and Wellington Harbour. However, possibly the greatest potential for a submarine landslide-generated tsunami in the Wellington-Cook Strait area is offshore along the edges of the steep submarine canyons (e.g., Cook Strait Canyon or its offshoots, Nicholson and Wairarapa Canyons) within eastern Cook Strait. There is also potential for sub-aerial rockslides along the coast (Carter *et al*., 1991; Carter and Lewis, 1995). Studies of cores from the submarine canyons of Cook Strait would serve to partially address our understanding of this hazard (L. Carter, pers. comm., 2000).

Acknowledging that we know little about the potential hazards posed by landslide-generated tsunami, we can note that the steep continental slopes of the Cook Strait Canyon system come to within about a kilometre of the region's coast (Figure 2). The rapid transfer of sediment by landsliding from the upper reaches of the canyon heads into the Cook Strait Canyon is a feature of the system and has been noted from sediment cores (L. Carter, pers. comm. 2000). Similarly, landslides, possibly in conjunction with earthquake activity, in and around the deep Hikurangi Trough, may well be responsible for recently discovered tsunami deposits off the east coast of Auckland (S. Nichol, pers. comm., 2001). It seems likely that landslide-generated tsunami pose at least a *moderate to high hazard* for the Wellington Region, although it may be some time before we are able to differentiate between earthquake and/or landslide-generated events. In the absence of a definitive answer, we will focus on the active fault structures in and around the Wellington Region as being the most likely generating mechanisms. It is recommended that further urgent work be undertaken to clarify the extent of this hazard.

Earthquake:

Earthquake-generated tsunami (possibly in association with landslides) are undoubtedly an *extreme hazard* for the Wellington Region. The Hikurangi Margin, of which the Hikurangi Trough is the most obvious geomorphological expression, represents the active plate boundary between the Australian (western) and Pacific (eastern) plates. This is a broad zone of active faulting more than 200 km wide from approximately 100 km east of the Wairarapa coast (the Hikurangi Trough) to D'Urville Island (Barnes *et al.*, 1998). Therefore, the Wellington Region possesses many active faults that have the potential to generated tsunami; some are fully submarine, others partially so (Figure 4; Table 2).

It is possible that tsunami could be sourced from any of these faults, although we currently have insufficient understanding to address this issue. However, our knowledge has reached the point where we can identify past tsunami that have probably been generated by one or more of the faults detailed in Table 2. This is discussed in the subsequent section dealing with a summary of the past record and the effects of these tsunami, leading ultimately to an assessment of the level of risk posed.

Table 2 shows that there are numerous faults in and around Cook Strait and Wellington Region's coast. It also indicates our current state of knowledge of the estimated return periods for earthquakes on some of these faults. The list is not exhaustive, and it could be argued that more distant earthquake activity may generate tsunami that affect the coastline. Of particular interest would be any faults associated with the Hikurangi Trough, about 100 km or so offshore, which runs almost parallel to the whole east coast of the North Island. Between the east coast and the Hikurangi Margin is a wide area of actively deforming ridges and basins marked by a series thrust faults (Barnes *et al*., 1993). While most of these faults may only move as a secondary event to a larger earthquake, they are still active faults. For example, in the Hawke Bay area the ridges and basins are growing at a rate of about 1.5 mm/yr. The Kidnappers Fault (not shown) has a slip rate of about 0.4 mm/yr and has a marked 1-2 m sea-floor 'cliff' associated with it (Barnes *et al*., 1993). Little research has been carried out to determine the seismic hazards posed by these faults, but it is clear that if a tsunami were generated by fault activity within the continental shelf in the Hawke Bay area, it may have implications for the Northeast coast of the Wellington Region. Some thought is given to this in the summary of past events.

The possibility of South Island faults having any bearing on tsunami hazards for the Wellington Region has generally been limited to modelling the effects of the southern segment of the Wairau Fault in southern Cook Strait (Gilmour and Stanton, 1990; Downes *et al*., 2000). However, it is now known that the Wairau Fault extends offshore from the Kapiti coast about as far as the Manawatu River (Lamarche and Nodder, 1998; E. Chalaron, pers. comm. 2000). Similarly, recent studies of palaeotsunami indicate that it was possibly the Alpine Fault in near-synchronous association with one or more other faults (a cluster of earthquakes) around the mid-15th Century that was responsible for generating tsunami that affected the whole of the New Zealand coastline (e.g. Goff and Chagué-Goff, 1999a; 2001; Goff *et al*.; 2000a; Goff and McFadgen, 2001; in press; in review). Table 2 indicates that the estimated recurrence intervals for the known major faults vary considerably, but that it is likely they will occur near-synchronously from time to time (e.g. Alpine Fault, Wellington Fault – ~1450AD). The estimated recurrence interval for clusters of large earthquakes and associated tsunami affecting the Nation's coastline was tentatively put at one every 250-500 years (Goff and Chagué-Goff, 2001).

3.2. Summarising the past record of tsunami – events and effects (inc. tsunami magnitude)

The past record of tsunami incorporates three fields of information; historic, prehistoric and pre-human. This information comes from several different sources:

- Historic: e.g. eyewitness accounts, newspapers, journal articles, wave recording devices, physical evidence (e.g. deposits).
- Prehistoric: Physical evidence (deposits), archaeological sites, oral tradition.
- Pre-human: Physical evidence only.

It is important to recognise that the nature of the evidence determines the interpretations that can be made. For example, strong conclusions about tsunami magnitude can be made where sufficient eyewitness accounts, wave measurements and physical evidence are available; in the pre-human record these various sources do not exist. In the latter case, the physical evidence of material deposited from a past tsunami can be most useful, but there are limitations to this evidence. For example, the maximum landward extent of a deposit does not mark the maximum runup height of the tsunami, the water will penetrate further inland (Dawson, 1994). Since no investigations have been carried out on the relationship between sediment and water runup heights, it is only possible to make rough estimates based on expert palaeotsunami opinion.

The record of past tsunami has been broken down into two main groups, the *historic* (from 1832AD to 1994AD) and the *palaeo* (from 6300 years Before Present [BP] to 1855AD). There is a 23 year overlap in these datasets which is based purely on the existence of a physical record for the 1855AD tsunami. This has been reported from two sites (Abel Tasman National Park and Palliser Bay; Table 3) for which contemporary tsunami magnitude data are reasonably robust (Grapes and Downes, 1997). At both sites the physical evidence is in accordance with the contemporary evidence. However, the principal author for the Palliser Bay work strongly believes now that this deposit is more likely related to a mid-15th Century tsunami (see Table 4) (Goff *et al*., 1998b).

3.2.1. The Historic record

The historical record provides considerable insight into the effects of tsunami since 1832AD (Tables 5a-d). The 1855AD tsunami was the largest event and was generated by a local source, the Wairarapa Fault (Figure 4). This is one of the few well-documented local source events in the historical record. It is clear from the data that Chile and Peru are the main distant sources of moderately large tsunami (> 1.0 m high). However, none of these events, the 1868AD, 1877AD, and 1960AD caused serious damage in the Wellington Region primarily because they arrived at or near low tide. It therefore seems appropriate to use the evidence from the 1855AD tsunami to briefly discuss the effects of historically documented events.

1855AD: Table 5b briefly summarises the main effects of the 1855AD tsunami (refer also to Appendix I), and full details can be found in Grapes and Downes (1997). Wave heights were largest in Palliser Bay (~10 m) and gradually decreased away to the west, and presumably the east, although it might have been as high as 10 m. in the eastern Wairarapa coast (estimates in Table 5d suggest otherwise). The supposition that Porirua Harbour may have had waves as high as 3 m is supported by the interpretation of the size of tsunami in harbours (Section 3.3.). Physical evidence for inundation on Kapiti Island also agrees with contemporary evidence from Otaki (Goff *et al*., 2000b). There is a complex story from inside Wellington Harbour, but it appears that Evans Bay tended to amplify waves (5.0 m as opposed to 2.0-3.0 at Lambton Harbour). This accounts for some contemporary accounts that had the tsunami in Lyall Bay flow up and across the Rongotai Isthmus, and that the tsunami inside the harbour carried a wooden boat two-thirds of the way seawards back across the Isthmus (Grapes and Downes, 1997; Downes and Grapes, 1999). The tsunami also formed a bore that ran up the Hutt River, probably moving the damaged Hutt River bridge.

While evidence for tsunami inundation is relatively detailed for Wellington Harbour, it is extremely patchy further afield. This is unfortunate because the general levels of tsunami inundation give an indication of how both locally- and distantly-generated tsunami interact with the coastline. In the absence of these data, some estimates are attempted.

Table 5d is an attempt to estimate tsunami runup heights for specific events such as the 1855AD tsunami. However, these do not take into account any resonance effects that may occur for example at Castlepoint and they also do not consider the different sources of tsunami generation. These data are simply best guesses for areas where no data are available. Further work needs to be carried out in both the search for physical evidence and modelling to clarify the Region-wide impact of specific events.

3.2.2. The Palaeo record

The interpretation of tsunami prior to the historically-documented 1855AD event is reliant upon the palaeo record (Tables 3, 4, and 6; Figure 5). This probably consists only of tsunami that are 5.0 m or higher (Lowe and de Lange, 2000). In most cases it is possible to differentiate between relative event magnitudes, at least in the broad categories of '>5.0-10.0 m (large)' and '>10.0 m (extreme)'. The latter category should be considered a catch-all for events greater than 10.0 m. At present these events range in height up to a tentative estimate of 15.0 m, although this should not be considered a maximum (Tables 3 and 4).

The palaeo record is far from complete and will continue to grow as more and better analytical techniques are developed. Therefore, the current record should be considered incomplete, and every effort should be made to expand this database. The first, well-defined tsunami, has been identified by a ubiquitous nationwide signal in both the sedimentary and archaeological record around the mid-15th Century (Tables 3, 4 and 6, Figure 5).

Sites investigated to date indicate that wave heights were probably *at least* 15 m on both the west and east coasts of the North and South Islands, with specific geological sites indicating runup as much as 3.5 km inland. In the Wellington Region, archaeological and geological evidence can be found around the whole coastline. The physical evidence for the tsunami has been dated to the same time as several large earthquakes that occurred in and around the mid-15th Century. Previous tsunami in about 1200-1220AD (this event appears to immediately pre-date Maori settlement), 950AD, 500AD, 200AD, 2500BP, and possibly 3000-3200BP and 4800-5000 BP, may possibly have been of similar nationwide impact although further research is needed to clarify this.

Archaeologically, the mid-15th Century event(s) is compelling because it appears to have affected several coastal sites around the Region. Unfortunately, it is likely that many physical records of the tsunami have been destroyed by coastal development. With this in mind, the archaeological sites detailed in Table 6 that indicate events of indeterminate age need urgent investigation (e.g. Wairarapa Coast).

While physical evidence for possible tsunami inundation *per se* has only been found for the 1200-1220AD, 200AD, 300-3200AD, and 4800-5000AD events, a suite of other signatures related to possible clusters of earthquakes (possibly one large earthquake), dated to these ages indicates the high probability of nationwide tsunami propagation (Goff and McFadgen, 2000; 2001; in prep.; Goff *et al*., 2000a). The oldest event, 6300BP, has only been found in Wairoa, northern Hawke's Bay. However, the apparent large magnitude of the event warrants inclusion because there is a distinct probability that the wave was generated by an earthquake within the continental shelf. If so, the energy may have been trapped causing the tsunami to move along the East Coast of the Wellington Region.

Most, if not all, of the possible clusters of earthquakes (possibly one large earthquake) appear to include an Alpine Fault earthquake (Yetton *et al*., 1998). The nature and extent of tsunami generated by Alpine Fault earthquakes is currently under investigation at Okarito Lagoon and this is referenced along with other past and current research relevant to tsunami hazards in the Wellington Region (Table 3: Okarito). There are two key points here. First, that the record of events in Okarito extend back to about 6500BP and there are more tsunami recorded there than are currently reported in the palaeo record. Second, there are some smaller events, perhaps >5.0m – 10.0 m (large), that have occurred more recently than the mid-15th Century tsunami. It is possible that these may have had absolutely no impact on the Wellington Region, but they are noted here as an indication of ongoing research.

Two brief notes on additional physical evidence for tsunami in the Wellington Region are worth mentioning. At Castlepoint, between Uruti Point and Mataikona, reconnaissance surveys have identified several sites that indicate tsunami inundation, but no further work has been undertaken (J. Goff, pers. observations; B. McFadgen, pers. comm., March 2001; M. Crozier, pers. comm., November 2000; E.A. Bryant, pers. comm., November 1999). These sites are additional too those discussed in Table 6. Similarly, on the south coast of the Wairarapa, to the west of Lake Ferry, possible tsunami deposits have been reported but no further work has been undertaken (J. Goff, pers observations; B. McFadgen, pers. comm., March 2001).

An attempt has been made to estimate return periods and probability based upon the detailed historic and palaeo records (Tables 7a and 7b: n.b. *These results should be treated with caution as the data used to derive these results are of limited quality*).

Interestingly, the return periods in Tables 7a and 7b are of the same magnitude as those predicted in Table 1 for distantly-generated events from areas of ***extreme hazards*** (Section 3.1.1.). They are also of similar magnitude to return periods determined from all tsunami sources for the New Zealand coast (Table 7c: n.b. *These results should be treated with caution as the data used to derive these results are of limited quality*). However, both Tables 1 and 7c are based solely upon the historical record.

Estimates from Tables 1 and 7c are for tsunami of a specific height and therefore direct comparison is difficult. Not surprisingly though, in all cases, the estimated return periods based upon *BOTH* records (historical and palaeo) are less than those based solely on the historical one. This reflects the added number of events recorded in the palaeo record, but also in the case of the Port of Wellington (Table 7c), it reflects the larger Regional picture and therefore more records of tsunami inundation. Tables 1 and 7c do not provide a return period for events greater than 10 m, but the estimate based upon a relatively more complete 2000 year record (Tables 7a and 7b) does fall within the estimate of 250-500 years suggested by Goff and Chagué-Goff (2001).

The probability estimates in Table 7b are based on a Poisson model that assumes random tsunami behaviour. As a result, elapsed time has no effect on conditional probability. Therefore, the probability of a tsunami occurring one day after the previous one is the same as for one occurring after many years. The model does not consider many issues with respect to tsunami generating mechanisms (e.g. stress accumulation in faults) and therefore it tends to overestimate probabilities soon after an event and underestimate tsunami with a considerable lapse time (Yetton *et al.*, 1998). However, there are many other variables involved in these calculations such as standard deviations in radiocarbon calibrations, and the limited data available to calculate Poisson probabilities. It seems likely that these data may underestimate the extreme events, thus producing the lowest possible probability estimates. Unfortunately, a lack of sufficient tsunami data means that alternative probability calculations (e.g. Nishenko and Buland, 1987) cannot be used.

Bearing this in mind, these lowest possible probabilities for small to large tsunami appear to vary from 81-41% in 25 years, to 100-22% in 100 years.

In summary, it seems that a locally-generated tsunami poses the greatest hazard to the overall Wellington region. Nevertheless, a sizeable distantly-generated tsunami from South America, with the appropriate wave period (Section 2.4.) for Wellington, Porirua, and/or Castlepoint Harbours, and Palliser Bay, and other possible coastal sites, poses a moderate hazard (refer to Section 3.3.).

3.3. Identifying the effects of tsunami-related hazards on the harbours and waterways of the region

Numerical modelling of tsunami impact on Wellington Harbour has previously been carried out by Gilmour and Stanton (1990), as part of a natural disaster reduction plan for the Wellington Regional Council, and by Barnett *et al.* (1991), for the Te Papa Museum Project Development Board. The scenarios modelled by these two studies were:

- Gilmour and Stanton (1990) used a model based on a 2 km grid of Cook Strait and a 250 m grid for Wellington Harbour to model the expected ground deformation (see *Glossary*) caused by:
  - A Wairau Fault (southern Cook Strait portion near Marlborough) rupture.
  - A Wellington Fault rupture.
  - An Ohariu Fault rupture.
  - A West Wairarapa Fault (based on historically observed movement of the fault and known uplift/subsidence in Wellington and Cook Strait for the 1855AD event) rupture.

- Barnett *et al.* (1991) used a model based on a 150 m grid for Wellington Harbour and the area around the Entrance to model expected ground deformation caused by:

  - A West Wairarapa Fault (based on historically observed movement of the fault and known uplift/subsidence in Wellington and Cook Strait for the 1855AD event) rupture.

Both numerical model studies concentrated on the response of Wellington Harbour to the 1855AD West Wairarapa Fault earthquake, assuming this was the worst-case scenario.

In essence, Gilmour and Stanton (1990) used a linear, hydrostatic model (making general assumptions about water motion and fluid pressures to simplify the model) Increasingly, models simulating tsunami are non-hydrostatic, as well as non-linear to better simulate the variability of water motion and changing fluid pressures and thus better model wave behaviour in shallow waters including runup and interaction with the shoreline. Barnett *et al.* (1991) used a hybrid, non-linear (but hydrostatic) model.

In reviewing these modelling attempts of a decade ago, several aspects should be considered in a revised model study:

- *Expansion of the model area to cover the whole of the Wellington Region including Porirua Harbour.*

- *These early models were simulated on relatively coarse grids or, in the case of the Barnett et al. (1991) study, with boundary conditions close to the Harbour entrance* (the edges of the model – if the edges of a model are too close to the area that is being modelled they may interfere with the results. This is a bit like the edges of a teacup – when the tea is disturbed it ripples outwards to the edges of the cup which then 'interferes' with how the disturbance would have continued unhindered).

  Modern numerical models are considerably faster, include non-linear and non-hydrostatic terms, and can cover larger regions. The focus has understandably been on Wellington Harbour, where much of the CBD and urban infrastructure such as ports and motorways are potentially at risk. However, a preliminary model study should be completed as soon as possible to investigate the risk to urban areas around Porirua Harbour and coastal communities along the Kapiti coast. This should be carried out in conjunction with a reconnaissance study of the physical evidence in order to provide direction for future work.

- *The two former models were run assuming that the water was initially still and the tides were also not included.* While tidal currents are very weak within the Harbour, strong tidal currents in Cook Strait should have been included in the model to test the sensitivity of the results to non-linear interactions of the tsunami with the prevailing tidal current (also a long period wave). The 1855AD earthquake coincided with a high perigean-spring tide (see *Glossary*), which would have generated strong tidal currents in Cook Strait. The behaviour of a tsunami in shallow areas will also be different depending on whether its peak activity coincides with a low or high tide. Therefore future modelling should take into account the interactions with tides.

- *Since the two former model studies were developed, new information has become available about the ground deformation of the 1855AD earthquake, and more refined information is also available for other faults in the Wellington Region.* Downes *et al.* (2000) addressed some of these changes but used Gilmour and Stanton's (1990) old model. In particular, possible scenarios for the other three main faults (Wellington, Ohariu, Wairau) plus other offshore faults (Kapiti-Manawatu and Cape Palliser areas) should be reconsidered. As discussed in

Section 3.1.2. The possibility of South Island faults having any bearing on tsunami hazards for the Wellington Region has generally been limited to modelling the effects of the southern segment of the Wairau Fault in southern Cook Strait. However, it is now known that the Wairau Fault extends offshore from the Kapiti coast about as far as the Manawatu River (Lamarche and Nodder, 1998; E. Chalaron, pers. comm. 2000). Where possible, scenarios should also be run for those submarine faults for which sufficient information is available (see Table 2), and possibly the Alpine Fault.

- *Tsunami runup modelling should only be considered when good spatial topography data is available for the coastline and immediate hinterland.* These data are of limited availability at present.

- *To date, the focus has been entirely centred on the impact of a local tsunami generated by seabed deformation during an earthquake.* Consideration should be given to modelling, or at least investigating, the impacts of likely scenarios for a submarine debris flow from the walls of the canyons in Cook Strait (both to the east and west), a similar event in the Kaikoura Canyon, and sub-aerial landslides from coastal cliffs around the Wellington region.
- Present tsunami modelling being undertaken by the National Institute of Water and Atmospheric Research Ltd. for the whole of New Zealand should provide sufficient accuracy for an assessment to be made of the distantly-generated tsunami hazard for the “open” coastline of Wellington region. However, further grid resolution is required for the harbours (Appendix III – an example of a preliminary model for the Wellington Region).

Some *preliminary* modelling results from a National Institute of Water and Atmospheric Research Ltd. study of distantly-generated tsunami amplification around New Zealand are shown in Appendix III. For an example of an incoming tsunami wave train from the east at a selected wave periods of 15, 30, 60 and 120 minutes.

These results are only a preliminary screening test for resonance along the coast and ONLY apply to the “open” coastline, rather than the harbours. Further work is required to resolve the nearshore and harbour seabed bathymetry in *greater detail* before any conclusions can be reached on tsunami amplification in any of the harbours or the nearshore behaviour and runup of actual tsunami events such as the one generated by the 1855AD West Wairarapa earthquake.

The resulting tsunami wave train from the 1855AD event exhibited wave periods in the range 15–30 minutes, with high amplitudes in Palliser Bay. The results from the resonance screening test for 15 and 30 minute periods (Figure III.A. and III.B.) show large amplification in the eastern side of Palliser Bay. This matches with the highest observed tsunami run-up height for the 1855AD event of ~9–10 m at Te Kopi in eastern Palliser Bay. Therefore, there appears to be a reasonable linkage between amplitude and runup.

Coastal resonance of an incoming tsunami wave train is determined by a number of factors including period (or wave length) of the waves, water depth on the continental shelf and shoreface, and the shoreline planform shape. This is in a similar way that different resonant sounds are generated by different shapes and sizes of drums.

At first glance, the high resonance on the west coast for a 120-minute wave train from the east seems counter-intuitive (Figure III.D). However the wave train can easily propagate through Cook Strait, and at that period of 120 minutes, the basin shape between Taranaki and the Marlborough Sounds is conducive to resonant wave sloshing to and fro at that wavelength. However, at that period on the east coast, there is no major coastline features to cause resonance, except down the east coast of South Island, where a resonance is set up between Banks Peninsula and Marlborough. However the east Wairarapa coastline is subject to resonance at the shorter 15–60 minute periods that encompass most tsunami frequencies.

The main message is that different areas around the “open” Wellington coastline resonate at different frequencies, so the impact of any particular tsunami wave train (which is usually a mix of different wave periods) is highly dependent on the frequency of the incoming wave train, its direction and the shape and seabed profile around the coastline. Knowledge of various resonant “hotspots” will enable future studies to be focused on those areas. It should be noted that for any one of the maps shown in Appendix III, the wave amplitude at any one point is relative to any other point on the same map. The following “hotspots” can be identified (the wave periods that these areas would amplify are given in brackets.)

- Riversdale/Castlepoint (15, 30, 60 minutes)
- Palliser Bay, particularly the NE corner (15, 30 minutes)
- Wellington Harbour (15, 30 minutes – more work is needed to assess localised in-harbour effects)
- Porirua Harbour (15?, 30, 120 minutes – more work is needed to assess localised in-harbour effects)
- Kapiti Coast (30, 120 minutes)

In summary, the preliminary results from Appendix III show that the East and South coasts of the Wellington Region are susceptible to short to medium period tsunami (15–60 minutes) from the east, along with Porirua Harbour(?), while the West Coast would be impacted if an easterly, distantly-generated tsunami arrived with short (30 minute) or long-period (120 minute) wave trains. The response would be different for different approach directions.

3.4. Identifying areas at risk from tsunami hazards

A hazard is a potentially perilous event, such as a tsunami, while risk is the probability that the hazard will occur repeatedly and affect a specified population. Risk includes the frequency of occurrence, exposure, and magnitude (Curtis and Pelinovsky, 1999).

Figure 6 gives a general Region-wide summary of areas at risk from tsunami hazards, and, for reference purposes, an approximate 10 m tsunami inundation contour is given in Appendix II, and preliminary modelling results in Appendix III. The region has been divided up into three broad areas of coastline, West, South, and East:

- ***West Coast:***

An estimated return period of ~250-400 years is suggested. This is based on a lack of recorded distantly-generated tsunami and what is probably an incomplete record of locally-generated ones.

Contrary to general thinking, the West Coast of the region is a relatively high risk area. Off the Horowhenua coast, prominent faults associated with a zone of faulting that extends from offshore of Kapiti Island to onshore Manawatu have been identified (e.g., Anderton, 1981). Faults here are typically strike-slip (see *Glossary*) in character (Hull *et al.*, 1993) and the area should be regarded as being susceptible to significant fault ruptures occurring during strong earthquake activity. Therefore, the West Coast is would appear to be exposed primarily to locally-generated tsunami, because the most hazardous distant tsunami sources lie to the east of New Zealand. Distant sources to the west are blocked by islands, Australia and shallow seas. Tsunami waves from the eastern Pacific Ocean do reach the west coast of New Zealand, mostly by reflection off the Great Barrier Reef of Australia (Braddock, 1969) or via diffraction around the ends of the two main islands e.g. through Cook Strait into the South Taranaki Bight (Appendix III). Reflected waves from the Great Barrier Reef are smaller, and arrive later than the direct waves reaching the East Coast of New Zealand.

So far, most events recorded on the West Coast have been local, with a return period of about one every 400 years for waves higher than 10 m (11-15 m, Tables 3, 7a,and 7b) based upon a 2000 year record, although there were three recorded in the last millennium (inc. the 1.0-2.0 m 1855AD event). This record is undoubtedly incomplete, and requires higher resolution studies of suitable sites.

n.b. Tsunami waves have a tendency to flow oblique or parallel to the coast (Dawson, 1996), penetrating inland along river channels, or merely inundating coastlines lower than wave height by overtopping. This means that while Kapiti and Mana Islands may be perceived as providing protection for some parts of the coastline from such events, in reality this is unlikely. There is also the possibility that if the tsunami becomes trapped between the mainland and an offshore island, it may “bounce” to and fro between them. Furthermore, if a tsunami approached either perpendicular or oblique to the coast it would ‘refract’ or bend around offshore islands. Any associated shallowing water would also serve to refract the wave towards shallow water. As such these areas of shallow water can help to focus tsunami energy.

These interpretations have serious implications for coastal development. In short, all urban areas along the West Coast are at a relatively high risk from inundation and coastal development must be undertaken with caution. Reference to Appendix II provides an indication of the extent of urban and non-urban areas at risk below the 10 m contour, including all coastal urban areas from Foxton through to Makara. Most likely affected will be the low-lying areas from Paekakariki northwards, and those in and around Porirua Harbour.

Furthermore, the preliminary modelling of distantly-generated tsunami from the east have the potential to be amplified, so the hazard and risk from these sources may well be underestimated.

- ***South Coast***

An estimated return period of ~100-250 years is suggested. This is based on a history of moderately small, distantly-generated tsunami and what is probably an incomplete record of numerous locally-generated ones.

Two regions tend to have a higher than average response to distantly-generated tsunami: Banks Peninsula; and Poverty Bay/Hawke Bay. This group is then followed by Wellington Harbour. A lack of measured records precludes comment on most other sections of the area. The largest recorded or observed distantly-generated tsunami in Wellington Harbour occurred after the 1868AD Chilean earthquake (15-Aug), followed 9 years later by another large earthquake in Chile in 1877 (11-May) (Table 5c). All three Chilean tsunami (including the 1960AD event) fortuitously arrived in the Wellington Region near low tide, thus averting major damage. Furthermore, the 1868AD tsunami was observed to have wave periods around 45 minutes, well off that necessary to cause amplification inside the Harbour, which explains the relatively muted response in Wellington compared to the havoc created elsewhere in New Zealand. However, seiching may occur both within the harbour (e.g. in 1855AD) or on a larger scale in Cook Strait as indicated by the after-effects of the 1855AD tsunami (Appendix I).

The proximity of the South Coast to Cook Strait and its numerous faults and submarine canyons puts this area at a higher risk from locally-generated events than the West Coast (Figure 2). Unfortunately, we currently have insufficient information about the magnitude and frequency of submarine landslides in Cook Strait, be they generated by earthquakes or not, and this is a cause for concern. On the south coast of the City, Breaker, Lyall, Island and Owhiro Bays appear to be the most at risk, although Seatoun and the eastern bays should be considered if Gilmour and Stanton's (1990) model simulation suitably approximates the effects of the 1855AD tsunami. Based upon the effects of the 1855AD tsunami, the coastline from Ocean Beach to Ngawhi appears to be similarly high risk, at least from locally-generated events. Fortunately, much of the South Coast of the region is cliffed and only sparsely populated, although infrastructural and service industries are numerous such as the Port, Ferries, Sewerage, International Airport, Roads, and the Cook Strait cable at Oteranga Bay.

The recommended design runup heights for locally-generated tsunami (based on modelling of the 1855AD event) of 2.8 m above high tide was considered a prudent design level for the central city area by Barnett *et al.* (1991). Obviously a much higher design value should be applied to shorelines around Evans Bay, Lyall Bay and the Entrance area of around 5.0 m above mean high tide. These values appear to be reasonable, based on existing information, until further investigations are carried out.

- ***East Coast***

An estimated return period of ~100-150 years is suggested. This is based on a history of several moderately small distantly-generated tsunami and what is probably an incomplete record of numerous locally-generated ones, and some reported in the archaeological and geological record that are yet to be investigated.

The East Coast appears to be the highest risk area of the Region's coast.

There is a tectonically-active region immediately offshore to the east of Cape Palliser and the Wairarapa coast (Figure 3). The potential for tsunami-generation is still largely unknown and requires further investigation, but the exposure of the coast to locally- and distantly-generated tsunami is apparent from the historic and palaeo records. Unlike the West Coast, the Hikurangi Trough extends the full length of the North Island's East Coast, exposing the East Coast of the Region to tsunami generated in Hawke Bay and beyond. While the area is sparsely populated, the urban centres of Riversdale and Castlepoint are at most risk. There is also a considerable amount of reconnaissance evidence to indicate that one or more large tsunami has inundated the area. Much of the Wairarapa coast consists of flat, raised beaches (e.g. Flat Point) that are the result of co-seismic (see *Glossary*) uplift events generated by local faults. It is probable that many of these were submarine events that generated tsunami, although this has yet to be determined in any great detail. However, this combination of active uplift and exposure to distantly-generated events puts many of the low-lying areas of the East Coast at great risk from tsunami. Urgent work needs to be undertaken to determine the full extent of the risk. As a "rule of thumb" the approximate 10 m inundation contour should be applied since this relates to maximum tsunami wave heights with an estimated return period of less than 84 years for the Region and maybe as low as 100-150 years for the East Coast.

In summary, the Region's coastline is an area of high tsunami risk. It ranges from what we believe to be the highest risk on the East Coast to a high risk on the South Coast, and a moderately high risk on the West Coast. While probably at the lowest level of risk, the West Coast situation needs to be highlighted because it has not been perceived as a problem in the past.

3.5. The level of risk from tsunami compared qualitatively against other hazards (Tables 8-10)

The database for other natural and technological hazards is reasonably limited, but a summary of the return periods for tsunami, earthquakes, extreme rainfall (Wairarapa), windstorms (Wairarapa coast), petroleum-related events, and river floods is given in Table 8. The most comparable data would appear to be between tsunami (large: >5.0-10.0 m) and extreme: >10.0 m) and earthquakes (7.0 MM and 7.2-7.8 MM: Davey and Sheppard, 1995a-e).

In attempting to put a value to the possible damage associated with large and extreme tsunami the estimated costs for repair were calculated for a series of commercial and residential items. *It should be noted that this is still a qualitative comparison since a true estimate of costs for coastal property and infrastructure is outside the parameters of this study*. At best the figures can be seen as internally consistent for different areas of coastline and tsunami runup. A tentative suggestion is made that for large tsunami the risk (and costs) are greater than for a large earthquake (return periods of ~80 years), as opposed to extreme events (return period ~600 year) where the costs for earthquake damage are considerably higher. The relative difference between large and extreme tsunami would appear to be less than those for earthquakes. Based upon the guesstimates used, tsunami would appear to be a higher level of risk than most other hazards for which details were available. Not surprisingly, the South Coast area of the Region seems to be most badly affected, followed by the West and East Coasts.

It is recommended that a robust costing exercise be undertaken to assess the value of threatened properties and infrastructural facilities.

CHAPTER FOUR – SUMMARY

- Three types of mitigation approach can be used:
  - Policy and management measures that reduce the likelihood of damage.
  - Preparedness and response planning to deal with consequences of the event.
  - Engineering design measures that reduce vulnerability.

- Some mitigation measures identified fall within the Regional Council's jurisdiction; others rely on outside agencies. Within this constraint, there may be opportunities for the Regional Council input or involvement in joint ventures.

- Available policy options include:
  - Include hazard information about identified hazards in public documents
  - Tsunami hazards should be considered when planning development in coastal areas to either avoid the hazard or reduce the level of risk.
  - Using both the RMA (placement of buildings) and the Building Act (construction of buildings) to achieve the aim of mitigating against natural hazards.

- Any plan for dealing with tsunami hazards requires a comprehensive emergency management approach, linking mitigation, preparedness, response and recovery.

- Dissemination of information about tsunami hazards is important in encouraging an appropriate public response. Risk communication is a social process, not an act, and should seek to start a conversion within the community.

- Apart from the evacuation of people and removal of transportable assets (if possible), there are few cost-effective mitigation options available to pre-existing facilities to counteract many of these hazards in high-risk coastal areas. Therefore the limitation on the building of permanent structures in high-risk areas is a low cost mitigation measure.

- A list of the probable stakeholders is included.

- Recommendations

  - South Coast: This area appears to have the highest costs for repair based upon our perception of land users. It would seem logical to prioritise any actions in this area.

  - East Coast: This area appears to have the lowest residential and commercial coastal land use, but it may be subject to development pressure in the future. If this is the case, it would be useful to ensure that any developments are subject to consideration of the latest hazard and risk information.

- West Coast: This is a rapidly growing residential area and caution should be taken to ensure that residential and commercial developments are subject to consideration of the latest hazard and risk information. This would also seem to be the area least aware of the tsunami risk.

- That the council conduct a series of focus group interviews with stakeholders.

* Wellington Regional Council should give some thought to the development of a tsunami hazard website for stakeholders.

4. MITIGATION AND STAKEHOLDERS

4.1. Identifying mitigation measures

Once tsunami hazard identification has taken place and the vulnerability of potentially affected areas and populations have been assessed, mitigation strategies can be developed. Three types of approaches can be used:

- Policy and management measures that reduce the likelihood of damage.
- Preparedness and response planning to deal with consequences of the event.
- Engineering design measures that reduce vulnerability.

Some mitigation measures identified fall within the Regional Council's jurisdiction; others rely on outside agencies. Within this constraint, there may be opportunities for the Regional Council input or involvement in joint ventures. Mitigation options should be evaluated in terms of risk reduction and the benefits or opportunities created (Australia/New Zealand Standard, 1999).

4.1.1. Policy and management measures

<u>Resource Management Act 1991 (and amendments)</u>

The requirement to mitigate natural hazards in New Zealand is covered by the Resource Management Act (1991) (RMA) which seeks to provide a structure for natural hazard management that focuses responsibilities and requires effective means of control to be adopted. Implementation of this regime is carried out by regional and territorial authorities through regional policy statements, regional plans, district plans and resource consents. Regional Policy Statements and regional/district plans should recognise *explicitly* that coastal areas are susceptible to tsunami hazards and need to be identified in plans and on planning maps. Tsunami hazard information should also be included in Land Information Memorandums (LIMs), Project Information Memorandums (PIMs), hazard maps and educational material. In order to ensure an integrated approach, tsunami hazards should also be acknowledged and accounted for in other relevant council documents (e.g. funding for tsunami mitigation should be accounted for and identified in financial documents/annual plan).

Tsunami hazards should be considered when planning for development in coastal areas in order to either avoid the hazard or reduce the level of risk. This may include the consideration of appropriate land use, placement of restrictions on land use if necessary, the creation of esplanades in tsunami hazard areas, implementation and monitoring of building codes, the location of community gathering places (eg. churches, schools) and critical facilities away from the coastline, tsunami contingency planning, etc. Non-regulatory methods can be used as an alternative to regulatory methods to mitigate against tsunami hazard and a selection of these are listed in Table 11.

Objectives and polices for natural hazards and tsunami have been incorporated into the Wellington Regional Policy Statement. With respect to hazards, the Regional Council considers it is primarily responsible for developing objectives and policies, while territorial authorities are primarily responsible for developing rules. The Regional Council will not write rules unless the relevant required objective or policy is not able to be achieved through rules in district plans (Regional Policy Statement for the Wellington Region, 1995). Therefore, the Regional Council has some influence on hazard objectives and policies, but many of the land use mitigation options such as setting of rules, zoning, creating esplanades, implementation and monitoring of building codes, the location of community gathering places and use of hazard information in PIMs and LIMs are options that are primarily available to territorial authorities (TAs). Regional council input into territorial activities can still can be given as part of the normal consultation and/or submission process and in this way it may be possible to have an influence on tsunami mitigation.

Under the RMA, the Regional Council is required to monitor the effectiveness of the Regional Policy Statement, while territorial authorities also required to monitor their district plans. As a result of the monitoring process it should be possible to identify the effectiveness of planning for tsunami and other hazards, and therefore adjust mitigation measures accordingly.

In terms of mitigation, the Regional Council can also contribute to other initiatives either individually or in conjunction with other organisations (for example, coastal planting initiatives, the erection of tsunami signage on beaches, community education initiatives, etc). The exact measures to be undertaken will need to be decided in consultation with other involved parties and the community.

Building Act 1991 (and amendments)

While the RMA is concerned with the placement of buildings, the Building Act 1991 primarily relates to the construction and subsequent use of buildings (although some provisions do exist to restrict development on land affected by certain hazards including erosion, avulsion, falling debris, subsidence, inundation and slippage). Tsunami are not mentioned specifically as a hazard in the Building Act, but inundation of land is, and would therefore be covered by this interpretation.

Under the Building Act 1991 all building work must comply with the Building Code 1992. Natural hazards known to local authorities but not apparent in the district plan, must be noted on the relevant Project Information Memorandum (PIM). Section 36 of the Building Act prevents the issue of a building consent for building on land which is affected by certain (site specific) natural hazards, unless the hazards have been avoided or mitigated. Under section 36(2) a building consent can be issued in certain circumstances, and a section 36(2) notice is then registered on the title.

In a recent study on earthquake hazards (Becker and Johnston, 2000) it was found that a number of councils have a tendency to place reliance on the Building Act alone in an attempt to mitigate hazards and often did not make linkages between the RMA and Building Act. As both pieces of legislation deal with separate issues it is essential that councils consider the best use of both pieces of legislation to achieve the aim of mitigating natural hazards. This issue is relevant to tsunami hazards as the placement and construction of buildings will be an important consideration when planning for tsunami in the coastal zone.

Building Standards

The Building Code is supported by a series of Approved Documents (approved and issued by the Building Industry Authority), which set out means of complying with the Building Code. Approved Document B1 cites the New Zealand Standard 4203 *Code of Practice For General Structural Design and Design Loadings For Buildings* (NZS 4203). The provisions in this document relate to how buildings are to be designed and constructed rather than where they are able to be located. However, the Building Act can influence the location of a building, if the building does not meet the structural performance criteria of the Act. Earthquakes are addressed in the document with requirements that a building be designed to resist a 450 year return period earthquake. This requirement has relevance as tsunami may be induced by earthquake events (Parliamentary Commissioner for the Environment, 2001).

The following two extracts are of use:

> "Neither of the [above] NZS 4203 Standards addresses the problem of localised site effects *such as enhanced earthquake ground motions due to unfavourable ground conditions or proximity to a fault*. Where these are identified they shall be the subject of a special study."
>
> (Building Industry Authority Approved Document B1: Structure, Verification Method B1/VM1 General, clause 1.4.3. This legal instrument was prepared in accordance with section 49 of the Building Act 1991 and directly refers to the New Zealand Loadings Standard).
>
> and:
>
> "As a guide for special studies, the aim of the designer should be that for the ultimate limit state loads there is not greater than a 5 % probability of exceedence in a 50 year period (975 year return period) or in the assumed life of the structure.
>
> The probability of exceedence may be increased to 10 % for the ultimate limit state earthquake forces (approximately 450 year return period).
>
> In this Standard, the uniform risk spectra, resulting from a risk analysis utilising the attenuation of peak response values, have been reduced by a 'structural performance factor' to provide the design values. ... The value of the 'structural performance factor' adopted in this standard (i.e. 0.67) is considered appropriate for structures 'on average'.

> The choice of an appropriate 'structural performance factor' for special cases will rely on the designer's judgement and therefore should be approached with caution. This is especially the case for systems that respond in an inherently brittle manner. In such cases a value of the 'structural performance factor' approaching 1.0 may be appropriate."
>
> (NZS 4203:1992 Loadings Standard volume 2, clause C2.2.2, i.e. page 9 of the commentary volume of the New Zealand Loadings Standard).
>
> In short the formula is return period *structural factor.

The Building Act is administered by the Department for Internal Affairs (DIA), while the Building Code is overseen by the Building Industry Authority (BIA). Both the Building Act and Code have most influence at a territorial authority level, where buildings are approved and built. The Regional Council therefore has limited input into the process of approving suitably built or located buildings, aside from the normal consultation and/or submission process. Only by using this process will it be possible for the Regional Council to have an influence on buildings with regard to tsunami mitigation.

New Zealand Coastal Policy Statement

While there is no national policy statement that addresses tsunami hazards or natural hazards in general, the New Zealand Coastal Policy Statement has provisions for coastal hazards. Some of the policies in this document include:

- Local authority policy statements and plans should identify areas in the coastal environment where natural hazards exist.
- Policy statements and plans should recognise changes in sea level, and areas subject to possible inundation or erosion.
- New subdivision, use and development should be so located and designed that the need for hazard protection works is avoided.
- Where existing subdivision, use or development is threatened by a coastal hazard, coastal protection works should be permitted only where they are the best practicable option for the future. The abandonment or relocation of existing structures should be considered among the options. Where coastal protection works are the best practicable option, they should be located and designed so as to avoid adverse environmental effects to the extent practicable.

Summary of Policies

With regards to tsunami mitigation, the first two policies listed above identify the need to include coastal hazards (which would include tsunami) in policy or plan documents. The policy regarding subdivision would be primarily used by territorial authorities that deal with land use. However, some overlap may occur with the fourth policy depending on where the coastal protection works are currently, or may be, placed in the future. For example, if the work falls in the coastal marine area, the Regional Council is primarily responsible, but if it were to be placed on land then the territorial authorities would be primarily responsible. Coordination between authorities would be essential to ensure a suitable outcome.

Civil Defence Emergency Management

The Civil Defence Emergency Management (CDEM) Bill currently in parliament requires that regional and territorial authorities form Civil Defence Emergency Management Groups in order to address planning for the consequences of hazards. The CDEM Group will be responsible for deciding on the planning processes as a whole, the direction the group will follow, roles and responsibilities, and other initiatives. One of the roles of CDEM Groups is to develop a plan to deal with the 4 R's of reduction, readiness, response and recovery (Table 12). Currently, civil defence plans deal primarily with readiness, response, and recovery activities. Reduction activities are dealt with through other mechanisms such as annual plans, regional and district plans and enforcement of the Building Code. Under the new arrangements, the CDEM Group plan will have a strategic component that binds together the elements of the 4 R's (Ministry for Emergency Management, 2000).

The CDEM Bill also places a number of duties on lifeline utilities. Every lifeline utility must:

- Ensure that it is able to function to the fullest possible extent, even though this may be at a reduced level, during and after an emergency.
- Make its plan for functioning during an after an emergency available to the Director of Civil Defence and Emergency Management upon request.
- Participate in the development of the national CDEM strategy and CDEM Group plans.
- Provide technical advice to the CDEM Groups or the Director of Civil Defence and Emergency Management.

The new CDEM regime will provide opportunities for the Regional Council (as well as lifeline utilities, territorial authorities and other agencies) to address tsunami hazards through the CDEM Group planning process and other activities.

4.1.2. Preparedness and response planning

Preparedness and response planning measures are discussed in three groupings, all of which can be used collectively. They are:

- Contingency plans
- Education
- Warnings

4.1.2.1. Contingency plans

Any plan for dealing with tsunami hazards requires a comprehensive emergency management approach, linking the 4 R's of reduction, readiness, response and recovery. However, there needs to be sufficient flexibility to accommodate and target the different hazards and corresponding degrees of risk. Emergency management in contingency planning must be linked with broader provisions of land-use management generated by the Resource Management Act (1991) and contained in district and coastal plans.

Contingency plans must remain simple and flexible, and focus on principles rather than details. Their purpose is to facilitate an effective and appropriate response. The contingency planning process is a continuous and evolutionary one (i.e. the plan is never complete). It seeks to form and maintain a clear and accurate understanding of the roles and responsibilities of all the organisations involved in the management of a tsunami. However, a number of researchers have documented that emergency planning in New Zealand and overseas is often based on false assumptions and inappropriate analogues (e.g. Perry, 1985; Britton, 1986, 1995; Dynes, 1994). These may include perceptions of human reactions and response (e.g. panic vs. effective coping), planning assumptions (e.g. focus on hazards vs. general principles) and effectiveness assumptions (e.g. safety devices, warnings etc). Other obstacles to good planning practices include the lack of experience with past events and the lack of an effective planning process (Kartez and Lindell, 1987).

Perry (1985) notes:

> *Too often emergency plans which are administratively derived turn out to be based on misconceptions of how people react and therefore potentially create more problems than they solve.*

Any contingency plan should contain the following elements:

- Presentation of hazard analysis results and mapping of hazard zones;
- Definition of the roles and responsibilities that all responding agencies will have, from pre-planning to recovery.
- Definition of procedures for communication of public warnings.
- Clarification of response procedures and responsibilities for evacuations.

- Consideration of appropriate public education activities before an event.
- Provisions for revising and updating the plan at regular intervals.

Contingency plans can be developed at many levels including central government (eg. National Civil Defence Plan), CDEM Groups, regional/territorial authorities, lifeline utilities, businesses and individuals. The CDEM group will be responsible for deciding how regional and local tsunami contingency planning will take place.

The CDEM Plan itself would be a suitable mechanism for including either functional or contingency based planning for tsunami as it provides an integrated approach which brings together strategic, operational and administrative considerations. Tsunami hazards could either be included as part of a wider (perhaps more functional) plan that takes into account other hazards as well and outlines the functions and management arrangements, or could be considered independently at a more detailed level in a separate tsunami contingency plan. Functional planning has some benefits because such plans are applicable irrespective of what event may occur, reducing duplication and potential inconsistencies. It would be for the CDEM Group to decide what would best suit the situation regarding tsunami.

4.1.2.2. Education

Dissemination of information about tsunami hazards is important in encouraging an appropriate public response. Risk communication is a social process, not an act, and should seek to start a conversion within the community (Mileti, 1996). By developing an education programme it is critical that key steps be taken to maximise its effectiveness.

Rohrmann (2000) suggested the following:

- Ensure valid understanding of how people process and evaluate risk information.
- Identify existing knowledge and pertinent “mental models” of the hazard.
- Define and explain a program’s objectives before designing campaigns and materials.
- Focus risk communication on change in behaviour (not just knowledge advancement).
- Check materials/advice for comprehensibility, credibility, feasibility, capacity to motivate.
- Acknowledge apathy/inertia and information overload when suggesting activities.
- Adapt materials to core characteristics of specified target groups (including ethnicity).
- Provide interactive communication and pathways for information requests and compliance.

- Strengthen personal involvement and responsibility.

A range of methods for disseminating public information are available including signage, brochures, newspaper articles and public talks. Signage is becoming increasing common in the west coast of the United States and even in parts of New Zealand (Figures 7 and 8).

Schools can play a vital role in tsunami hazard education as natural hazards can be included in the science and geography curricula. The current school curriculum in New Zealand affords the perfect opportunity to teach children about tsunami. The school curriculum itself cannot be directly influenced by the Regional Council but it is flexible enough to allow the Regional Council to have some input into education measures undertaken in schools if desired. Auckland Regional Council provides an example of this with its volcanic hazards website for the “GIS in Schools” project (www.arc.govt.nz/volcanic/index.htm). This project uses educational material about volcanic hazards to assist pupils and teachers to start using Geographic Information Systems in the school curriculum.

For buildings in hazardous zones, a public relations campaign may be necessary to inform residents and businesses about emergency planning. The ‘Yellow Pages’ should continue to be used, but the Regional Council may wish to consider other innovative ways to deliver their message. To our knowledge, no one has ever created an incentive for residents to develop an emergency plan. Whatever methods are selected for educating the public about tsunami risk, programmes must be backed up with a systematic empirical evaluation to assess their effectiveness.

The Regional Council can be involved with tsunami educational activities either independently or in conjunction with other authorities, organisations or community groups.

4.1.2.3.Warnings

The procedures for the issue of warnings are covered by Part 3 of the current National Civil Defence Plan and all responding agencies must understand their responsibilities as per that plan. Details of the National Tsunami Warning System are outlined by Finnimore (1999). It is important that responding agencies also separate "information notices" from warnings.

Warning messages are usually given to a specific community or communities when a direct response to a threat is required. The response to warnings by individuals has been found to relate to:

- Individual risk perception (understanding, belief and personalisation);
- The nature of the warning information (specificity, consistency, certainty, accuracy, clarity, media, frequency etc);

- The personal characteristics of the recipient (demographics, knowledge, experience of the hazard, social network and so on).

 (Mileti and O'Brien, 1993)

A consistent and clear conclusion of social science research is that the warning message itself is one of the most important factors that influences the effectiveness of the warning system (Mileti and Sorensen, 1990). Five topics are important when constructing a warning message: the hazard or risk, guidance, location, time and source.

The warning message must contain information about the impending hazard with sufficient simple detail that the public can understand the characteristics of the hazard that they need to protect themselves from. The message should include guidance about what they should do to maximise their safety. The warning message must describe the exact location that is at risk and address the "when" aspect of the required response. A worldwide concern is the common phenomena of people moving to coastal areas to observe the tsunami following tsunami warnings (e.g. Figure 9). This highlights the need for the public to develop a better understanding of the risk tsunami pose to their personal safety.

Central government (Ministry for Civil Defence and Emergency Management - MCDEM) are responsible for the National Tsunami Warning System and if a tsunami is approaching, regional councils will receive a warning message from MCDEM. Once they have received this warning, regional councils are then required to check with their respective territorial authorities that they too have received the warning. While MCDEM is also responsible for issuing warnings to the public, the Regional Council will still have a role in the processes that occur after the warnings have been issued. In addition, if a problem occurs, and communications fail, the Regional Council may be required to step in and disseminate warnings itself. It is essential that the consideration of roles, responsibilities and possible processes occurs during planning prior to a tsunami to ensure adequate mitigation.

4.1.3. Engineering design protective measures

Apart from the evacuation of people and removal of transportable assets (if possible), there are few cost-effective mitigation options available to pre-existing facilities to counteract many of these hazards in high-risk coastal areas. Therefore the limitation on the building of permanent structures in high-risk areas is a low cost mitigation measure. However, in selecting any appropriate option or options the cost must be balanced against the benefits derived from it. Funds spent on engineering solutions to control hazards may draw resources away from equally effective, less costly social solutions.

de Lange (1998) outlines a number of protective measures that have been undertaken in different countries. These measures have had varying degrees of success and include:

- Protective measures such as barriers may be used in areas subject to frequent tsunami inundation or areas that contain essential infrastructure. Coastal barriers (e.g. tidal barriers across river mouths) are very expensive and may adversely affect the environment. In addition, they have been utilised in countries such as Japan with limited success as tsunami wave heights were not accurately predicted and subsequent waves overtopped the barriers.
- Tsunami forests are coastal tree plantations that may absorb tsunami energy and reduce the distance the wave travels inland, but do not eliminate the impacts of the tsunami completely. It is necessary to investigate exactly what trees may be of use however, as some trees may snap off or be ripped up and actually increase the impact (Section 2.4.).
- Building tsunami resistant buildings, eg. Te Papa.
- Incorporating appropriate building design, so that lower floor levels can cope with low levels of tsunami inundation (i.e. be designed to sustain flooding) (e.g. Hilo, Hawaii).

4.2. Identifying key stakeholders

There are numerous stakeholder groups in the Wellington Region with an interest in tsunami hazards. Identification of these groups is critical to understanding how messages are to be delivered to these groups and the language in which the messages are presented. Groups are diverse and therefore careful consideration is needed regarding the format and delivery of information about tsunami hazards to different parts of the community.

A list of the stakeholders may include:

- Wellington Regional Council: Assets and governance.

- City and district councils: Particularly Wellington City, Hutt City, Porirua City, Kapiti Coast District, Masterton District and South Wairarapa District. Their emergency management offices are critical to overseeing the task of response and recovery.

- Central Government: Depending upon the severity of the event, the central government headquartered in Wellington may be physically affected.

- Lifelines (power, gas, water supply, rail, road, sewerage, etc.): Each of these industries needs to know the priorities and their dependencies upon each other.

- Local Tangata Whenua. Local Tangata Whenua should be aware of the actions that need to be taken in the event of tsunami inundation.

- Port Authority: CentrePort New Zealand. Major infrastructure within Wellington Harbour will most likely be affected. CentrePort is also responsible for wharf facilities at Burnham and Seaview wharves (see below).

- Tranz Rail (ferry and rail): As with the port, it is likely that the ferry facilities may be severely damaged. This also applies to the Eastbourne Ferry.

- Emergency services (police, fire, ambulance): It is critical that these services be prepared.

- Hospitals: Without water and power, these facilities will be heavily stressed, whether or not they suffer damage.

- Schools: Should be considered critical facilities with the density of young people that occupy these buildings. Preparedness is critical in low-lying coastal areas e.g. Kilbirnie.

- Lawyers: Litigation is always an issue when it comes to preparedness. Businesses that do not practice business continuity preparedness may be liable for damages in the future.

- Department of Conservation: Erosion and access to Department of Conservation estate, protection of native species and coastal land. The Department manages about 100 km of Region's coastline.

- Lighthouses: Highly vulnerable features, vital to re-establishing communication links.

- Quarries: Aggregate and building material supplies may be affected – transport companies and facilities will be affected.

- Insurance: A tsunami coupled with an earthquake will most likely exceed the capacity of most local insurance companies, both in terms of resources to meet the large number of claims as well as financial payments. Insurance companies rely on accurate hazard assessments in order to carry out risk assessment and actuarial calculations.

- Airport: Flights in/out of Wellington will most likely be interrupted. Again, a functioning airport is vital to re-establishing communication links.

- Tourism (flights, cruise ships, bus tours, fishing tours, helicopter rides, etc.): Any severe event like this will have adverse effects on local tourism.

- Marinas and sailing clubs: Damage could be severe to all boats, but particularly small, private vessels.

- Coastal residents: Many will be homeless, homes may be beyond repair, contingency plans need to be made for such an event.

- Farming communities: Many will be either temporarily or permanently unable to operate. Again, contingency plans need to be made for such an event. A particular problem would be saltwater contamination, but also damage to or loss of buildings and structures. Groups particularly affected would be agroforestry, dairy, and seafood industries.

- Hazardous substances storage facilities and companies: Each company should take steps to ensure that reasonable precautions have been made. Contingency plans must be in place for events such as contamination clean up and fire. Included here are LPG bulk storage tanks, companies using, manufacturing and/or storing hazardous substances, large fuel storage depots, above ground fuel tanks, and wharf areas used by fishing vessel (ammonia refrigerant). e.g.

  - Seaview and the Seaview wharf area in Wellington Harbour contains storage facilities for bulk petroleum: Mobil, BP, Challenge.
  - Burnham Wharf contains storage facilities for bulk bitumen: Shell New Zealand Ltd.

- Transport operators (exc. Ferries): e.g. Stagecoach (buses), Roadfreighters. Information can be found under: http://www.nztrades.com/transportation/Wellington.htm

- Other coastal businesses with structures at or near the coast: Any industry with facilities at or near the coast needs to have established contingency plans.

It is valuable to note the interest in reliable and timely tsunami information by different stakeholders. Interviews carried out with a sample of three different stakeholders revealed just how variable these needs are, and how they may fall into one or more of the 4 R's of emergency management. For example:

- *City Government*: Local government agencies are charged with a diversity of responsibilities that include infrastructure planning and asset management (roads, parks, public facilities and open spaces), district planning (hazard areas, policies, rules), emergency management (community preparedness, warning systems, response capability), recovery capability (emergency funds), in-house business continuity planning, community development (vulnerable populations, links with emergency management). Thus, hazard information will need to span this spectrum of needs. While tsunami (or any hazard) information will need to be presented in a form that covers the probability of events over a long time frame (for policy making or planning), other information will need to be disseminated as soon as it becomes available in the case of an imminent hazard or disaster. For rapid response officials have a network of emergency managers that can be immediately activated into a response mode and rely on these real-time warnings to mobilise their people for preparing infrastructure and communities for the event.

- *Insurance*: Insurers are interested in real-time information for two main purposes: First, to warn their clients of the immediate danger in order to minimise the number of claims, and second, to mobilise their own teams to prepare for incoming claims. Real-time information for redistributing their financial assets is not of time-critical importance at this stage.

  Insurers are also interested in hazard information for long term planning. Premiums are based on the statistical occurrence of an event as well as the financial market forces. Thus, from a hazard point of view, the better the understanding of a particular hazard, in terms of the frequency of occurrence, the better the underwriters can optimise the price of insurance.

- *Lawyers*: This stakeholder group is often overlooked. Generally, they do not require real-time information (although this may change in the future), but in terms of preparedness it could mean “everything”. Liability litigation is not commonplace in New Zealand (as it is in other countries), however this trend may change in the future. As the cost of damage escalates more questions will be raised regarding whether sufficient preparation was made by individuals, companies, or government to mitigate the risk of natural disasters. In any natural disaster lawyers and their clients will be looking for the probable cause of harm or damage, and it is most likely that the responsible parties will be those with the deepest pockets. Litigation may come about for either withholding information or not acting on known information. In law, one person’s disaster is another person’s opportunity (Hodge, 1998). Lawyers will use the Fair Trading Act (1986), the Consumer Guarantees Act (1993), LIM reports, the Building Act (1991), the Resource Management Act (1991) or any other mechanism to defend their clients in order to minimise the risk (either financial or natural hazard) to their enterprise or livelihood.

  A 1998 conference on “Best Practice in Disaster Management” highlighted the fact that litigation is an outcome that needs to be considered since the lawyers of tomorrow are being trained to look at probable cause in natural disasters. Businesses that do not practice business continuity preparedness may be liable for damages in the future.

4.3. Recommendations

A tsunami will affect each of the stakeholders identified in the previous section differently. Even if stakeholders do not occupy tsunami prone coastal areas, they still face the consequences of the impact indirectly. Based on the variety of responses to the question of how quickly stakeholders need information, it is likely that their concerns also vary widely regarding policy, preparedness, and other issues. Thus our first recommendation is:

- That the council conduct a series of focus group interviews. These surveys should explore the various issues in more detail with the stakeholder groups. It should also seek to determine from the interviews what the stakeholders think should be done in each of the categories, thus creating ownership in the solution. It is difficult, if not impossible, to direct a group of vulnerable stakeholders into a mitigation plan if one comes from outside the group and is not in the same position of vulnerability. Issues to be explored might include incentives to enable people to create and act on a plan.

In the absence of a comprehensive assessment of the potentially affected residential and commercial coastal land user it is difficult to prioritise actions pertinent to the appropriate level of risk discussed in Sections 3.4. and 3.5. However, some points can be made and these are presented as recommendations:

- South Coast: This area appears to have the highest costs for repair based upon our perception of land users. It would seem logical to prioritise any actions in this area.
- East Coast: This area appears to have the lowest residential and commercial coastal land use, but it may be subject to development pressure in the future. If this is the case, it would be useful to ensure that any developments are subject to consideration of the latest hazard and risk information.
- West Coast: This is a rapidly growing residential area and caution should be taken to ensure that residential and commercial developments are subject to consideration of the latest hazard and risk information. This would also seem to be the area least aware of the tsunami risk.

There is no easy quick-fix solution to the issues identified in the previous sections on mitigation. It is well known that people take a long time to respond to advertising. It can take years (and a great deal of investment) before individuals respond to a message coming from a variety of mediums. Mitigation measures (planning, preparedness, and response) must be a long-term investment.

The Regional Council should give some thought to the development of a tsunami hazard website for stakeholders. This could include clickable sections of 1:25000 or 1:50000 maps of the coastline, enabling stakeholders to ascertain data pertinent to the section in which they interested. Data could include; historical and palaeo-tsunami information, modelled tsunami information, current stakeholder initiatives, legislation of relevance to the public, and so on. The site would develop over time, but could serve as a primary source for an increasingly computer literate community.

CHAPTER FIVE - SUMMARY

- Uncertainties in the current information include:
  - Historical data – problems with contemporary accounts/early historical records
  - Palaeo data – identifying tsunami sources/incomplete records/difficulties in estimating wave height and runup.
  - Modelling data - interactions between a tsunami the bathymetry of the coastline, and land near the coast are poorly understood/each tsunami behaves differently even if it comes from the same source area. As a result, a generic model cannot be produced/the outcomes of a model are dependent upon the boundary conditions set.
  - Determining the risk - Developing return period and probability information to assess risk from a mixture of historic, palaeo, and model data requires comparison of different data sets each with their own degrees of uncertainty.
  - Mitigation - While the mitigation information given is appropriate, there is uncertainty in prioritising actions.

- Generic gaps in the available information include:
  - A lack of a detailed coastal topography for the Wellington Region.
  - The need to determine the significance of landslides to tsunami generation needs to be determined.
  - The need for complementary iterative research between modellers and palaeotsunami researchers.
  - The need to identify residential and commercial shoreline facilities/structures etc. that could be damaged or could cause damage is needed. Interviews of stakeholder groups could be undertaken to discuss the issues.

- Identifying and prioritising work to fill gaps:
  - Carry out a detailed coastal topography for the Wellington Region.
  - Identify residential and commercial shoreline facilities/structures etc. that could be damaged or could cause damage.
  - Fund key research to assess the significance of landslides (coastal and submarine) to tsunami generation needs to be determined.
  - Fund key site-specific studies to assess the hazards of tsunami inundation to people, lifelines and structures (e.g. Kapiti and Wairarapa coastal sites).
  - Formulate an approach to key stakeholders to consider business preparedness, support of on-going studies, public awareness, etc. Development of public education and mitigation plan. Interviews of stakeholder groups could be undertaken to discuss the issues. The council should consider the development of a tsunami hazard website for stakeholders.
  - Complete the historical database.

5. ASSESS UNCERTAINTIES OF THE CURRENT INFORMATION

Uncertainties in the current information include:

- *Historical data:*
  - Contemporary accounts can be misleading and in many cases there is no corroborating evidence.
  - Many pre-'wave recording technology' events are missed, particularly the relatively small ones.
  - In the early historical records, there may well have been some events missed because the coastline was unpopulated. Similarly, for some events there is only one account and the reliability must be questioned. As the historical records become more distant with time, the ability to identify, and differentiate between events become more difficult, and the number of documents decreases.

- *Palaeo data:*
  - The precise local tsunami source is uncertain in most cases and is based on the most probable event recorded in the record of past earthquakes, eruptions, and landslides.
  - The palaeo record is incomplete because;
    - i) Few sites have been studied,
    - ii) Current funding levels realistically allows only low resolution analyses to be carried out and so only tsunami with wave heights of around 5 m or more are generally identified, but it is probable that some 5-10 m events are missed. Therefore, there is much uncertainty about the return period of large events in particular.
  - Dating control means that we do not know exact ages of events, and we may assign a tsunami to the incorrect generating mechanism. The nature of tsunami inundation makes dating control difficult.
  - Wave height and runup estimates – tsunami magnitudes - are probably minimum figures because a tsunami does not deposit sediment as far as the water penetrates inland.
  - In some cases it can be difficult to differentiate between a tsunami and a storm surge. However, the ability to differentiate is improving (e.g. Nanayama *et al*., 2000) and is largely cost-dependant. However, the palaeotsunami currently reported for the Wellington Region as less problematic than others.

- *Modelling data:*

  - The interactions between a tsunami and the bathymetry of the continental shelf, the nearshore environment (bathymetry, islands, etc.), the coastline, and the land near the coast are poorly understood. Thus, runup heights and other parameters are difficult to model.

    This report recognises that, while the models of Gilmour and Stanton (1990) and Barnett *et al.* (1991) adequately match observed effects within the Harbour, Gilmour and Stanton's (1990) model severely under-predicts the effects in Cook Strait and by inference, areas beyond it. Barnett *et al*.'s (1991) model only considers Wellington Harbour.

  - Each tsunami behaves differently even if it comes from the same source area. There are many variables, and hence one relies upon running scenarios closely approximating known historic events. This creates two key uncertainties;

    i) A generic model cannot be produced, and therefore our understanding of tsunami hazard is limited by the number of scenarios that can be modelled.
    ii) When a model does not fit the historic data, it is often reworked to the nearest approximation. This relies heavily on the reliability of the historic data, but also means that some of the modelling parameters are incorrect.

  - The outcomes of a model are dependent upon the boundary conditions set. In essence, imagine it like generating a wave in bath, the wave is confined by the edges of the bath and therefore will respond accordingly depending upon how big the bath is, the same applies to tsunami models.

- *Determining the risk:*

  - Developing return period and probability information to assess risk from a mixture of historic, palaeo, and model data requires comparison of different data sets each with their own degrees of uncertainty. The return periods for particular magnitudes in this report have been developed from an imperfect data set and rely heavily upon expert interpretation of the data. This generates a high level of uncertainty since nearly all experts will disagree. Similarly, the relative exposure of any one site, be it Castlepoint, or Porirua Harbour or wherever within the Region, comes from an analysis and expert interpretation of the available data. In some cases there is a significant amount of data, in other cases not, and it is often necessary to extrapolate and infer. Therefore, risk information is produced from the information available at the time, and as such it is in need of constant updating and review.

- We are uncertain about the long and short-term effects of saltwater contamination caused by tsunami inundation. There are clear long and short-term economic issues related to buildings and structures, natural ecosystems, and agricultural land.

- *Mitigation:*

  - While the mitigation information given is appropriate, there is uncertainty in prioritising actions. Actions will vary depending upon knowledge of the extent and value of potentially affected residential and commercial coastal land users (inc. properties and infrastructure). Furthermore, it may be necessary to prioritise based upon on-going, future, or proposed developments of section of coastline and both council and public perceptions of the risk.

5.1. Identifying gaps in the available information

The gaps develop out of the uncertainties to the extent that to become more certain about the data we have presented there are key gaps that need to be filled. To retain continuity, the gaps detailed below are listed in the same order as the uncertainties identified above. Some gaps are repeated under different headings (marked *). The fundamental uncertainties are being address by researchers both in New Zealand and around the World and as progress is made the advances should automatically form part of any ongoing work contracted by the Wellington Regional Council. It is not proposed to identify these fundamental gaps for the purpose of this report, unless they directly relate to key sites.

- *Historical data:*

  - *A detailed coastal topography for the Wellington Region is needed, at 1.0 m intervals up to 30 masl. Tidal limits should be indicated.
  - The historical database still needs completion. Undoubtedly several small events are missing, and possible one or two larger ones.
  - With all sources, the historical record is too short to be able to realistically determine tsunami return periods and probability. It must be used *in conjunction with* the palaeo record to improve these data.
  - *The significance of submarine, and to a lesser extent coastal, landslides (in Cook Strait in particular, but all around the Region) with respect to

tsunami generation needs to be determined, both in conjunction with earthquakes and on their own.

- *Palaeo data:*
  - *A detailed coastal topography for the Wellington Region is needed, at 1.0 m intervals up to 30 masl. Tidal limits should be indicated.
  - *The significance of submarine, and to a lesser extent coastal, landslides (in Cook Strait in particular, but all around the Region) with respect to tsunami generation needs to be determined, both in conjunction with earthquakes and on their own.
  - More palaeotsunami studies need to be carried around the coast, preferably in conjunction with studies of past landslides in Cook Strait and other pertinent canyon systems (this links with previous point – it will help identify match-ups between submarine landslides and tsunami inundations). This will improve our understanding of the landslide-generated tsunami hazard, and also general region-wide runup, hazard and risk. Known coastal sites should be studied first (n.b. Several known sites are archaeological and are at risk of coastal erosion).
  - *Complementary iterative research should be undertaken between modellers and palaeotsunami researchers. By improving knowledge of past tsunami, runup, return periods, areas inundated, etc., the models can be improved and used to identify areas at greater risk, which in turn provides sites for targeted palaeotsunami research to verify the modelling, and so on. The historic record is far more complete and therefore most significant advances will be made in palaeotsunami and modelling research.

- *Modelling data:*
  - *A detailed coastal topography for the Wellington Region is needed, at 1.0 m intervals up to 30 masl. Tidal limits should be indicated.
  - *The significance of submarine, and to a lesser extent coastal, landslides (in Cook Strait in particular, but all around the Region) with respect to tsunami generation needs to be determined, both in conjunction with earthquakes and on their own.
  - *Complementary iterative research should be undertaken between modellers and palaeotsunami researchers. By improving knowledge of past tsunami, runup, return periods, areas inundated, etc., the models can be improved and used to identify areas at greater risk, which in turn provides sites for targeted palaeotsunami research to verify the modelling, and so on. The historic record is far more complete and therefore most significant advances will be made in palaeotsunami and modelling research.

- To assist tsunami modelling there needs to be more observational data available from the open coasts, where the record is not contaminated by harbour resonance modes.

- *Determining the risk:*
  - *A detailed coastal topography for the Wellington Region is needed, at 1.0 m intervals up to 30 masl. Tidal limits should be indicated.
  - *Identification of residential and commercial shoreline facilities/structures etc. that could be damaged or could cause damage, is needed. This would preferably be carried out in conjunction with the preparation of a detailed coastal topography to assist with development of policy measures and in guiding development considerations.
  - An understanding is needed of the long and short-term effects of saltwater contamination caused by tsunami inundation.

- *Mitigation:*
  - *(as per *Determination of Risk*) A study of the extent and value of potentially affected residential and commercial coastal land users (inc. properties and infrastructure) is needed.
  - A subsequent analysis of possible future coastal development needs to be undertaken prior to any policy formulation for tsunami hazard mitigation.
  - Public perception of tsunami risk is poor with the possible exception of Castlepoint, although signage may do little to raise perceptions without education in some form. Bearing in mind the high risk for the regional coastline, there is a distinct education gap. The council could conduct a series of focus group interviews.

5.2. Identifying and prioritising implementation of work to fill gaps

The work identified below is all high priority, with the exception of the last point that is of moderate priority. It is difficult to differentiate between the points listed but there are two main themes. Understanding more about tsunami through palaeo and modelling pathways, and formulating approaches to stakeholders and establishing the true risk. With this in mind, the first point is probably the highest in that it provides a template for progressing the two main themes.

- A detailed coastal topography for the Wellington Region is needed, at 1.0 m intervals up to 30 masl. Tidal limits should be indicated (*Internal or External? – LINZ?*).

- Identification of residential and commercial shoreline facilities/structures etc. that could be damaged or could cause damage, is needed. This would preferably be carried out in conjunction with the preparation of a detailed coastal topography to assist with development of policy measures and in guiding development considerations. A study of the extent and value of potentially affected residential and commercial coastal land users (inc. properties and infrastructure) is needed. (*External/Internal collaboration*?).

- The significance of landslides (coastal and submarine) to tsunami generation needs to be determined, both in conjunction with earthquakes and on their own. Return periods and probabilities need to be investigated using a combination of modelling and palaeotsunami studies around Cook Strait. The 1855AD earthquake needs to be remodelled if only to indicate that landsliding may have contributed to the tsunami, and thus may be a factor in future large earthquakes (*External – NIWA/ GeoEnvironmental Consultants*).

- Fund key site-specific studies to assess the hazards of tsunami inundation to people, lifelines and structures (e.g. Kapiti and Wairarapa coastal sites)– an iterative palaeotsunami and modelling exercise (*External – NIWA/ GeoEnvironmental Consultants*).

  e.g. To assist tsunami modelling there needs to be more observational data available from the open coasts, where the record is not contaminated by harbour resonance modes. Until recently, there had been only one open-coast water level recorder installed temporarily for a few years at Castlepoint by the then Dept. of Survey and Land Information (now LINZ). NIWA recently installed two more, one on Kapiti Island (opened July 1997) and the other at Riversdale (opened August 1997). While these gauges sample at 5 minutes, a priority for the future is to improve the quality of the data stored by these open coast monitoring stations. The Port of Wellington sea-level gauge is also strategically important to capture the behaviour of any incoming tsunami within the confines of the Harbour. The sampling rate of the Wellington gauge should be reviewed to see if it could be extended to cover a faster rate of sampling and data storage. To aid the preliminary identification of seiching modes of Porirua Harbour (which are unknown), it would be advisable to temporarily install a sea-level gauge well inside Porirua Harbour. The installation need only be over a two- to three-month period, long enough to capture some storm events, during which seiching can be amplified within a harbour in a similar way to tsunami. To further resolve potential hotspots within Porirua Harbour, a model study is advised to obtain full spatial coverage of tsunami behaviour, which cannot be achieved by sea-level gauge installations at one or two sites. Physical evidence from sites such as Paramata, Pauatahanui Inlet, and Te Onepoto Bay can be used to groundtruth and complement the model.

- Formulate an approach to key stakeholders to consider business preparedness, support of on-going studies, public awareness, etc. Development of public education and mitigation plan (inc. an analysis of possible future demands for coastal development). Interviews of stakeholder groups could be undertaken to discuss the issues. The council should consider the development of a tsunami hazard website for stakeholders (*Internal/External collaboration – GNS/GeoEnvironmental Consultants*).

- There is a real need to understand the long and short-term effects of saltwater contamination caused by tsunami inundation. The Council should be proactive in seeking out research funding for this work, whether as a sponsor or co-funding agency (*External - GeoEnvironmental Consultants/NIWA*).

- The historical database needs to be completed (this is estimated as 90% complete for events over 1m in the Wellington Region) (*External – GNS*).

6. CONCLUSIONS

- Overall, the hazard represented by tsunami is not as great as some other countries. However, the frequency of hazardous tsunami in New Zealand is similar to some regions commonly perceived to have a problem with tsunami, such as Indonesia and the islands of Hawaii. The hazard appears to be less because New Zealand has not experienced a large locally-generated tsunami since 1947AD (1855AD for the Wellington Region), and a large distantly-generated tsunami since 1964AD Alaskan earthquake. It is likely that this period of relative inactivity will not continue for long. Further, the growing data on paleoseismicity and palaeotsunami in New Zealand indicates that the Cook Strait region, at least, is subject to large magnitude events that could be catastrophic.

  - The most extreme hazard from a distant source is from the West Coast of South America. Waves with a height of 5.0 m have an estimated return period of about 82 years for New Zealand.
  - The return period for a 5.0 m tsunami for the Port of Wellington – *based on historically-documented tsunami only* is 728 years.
  - The return period for a >5.0-10.0 m tsunami for the Wellington Region – *based on the historically-documented AND palaeo record* is about 84 years.

- Locally-generated sources: We know little about the submarine landslide hazards of Cook Strait and the Hikurangi Trough and urgent work is needed to address this issue. In the absence of sufficient data they are considered a *moderate to high hazard*. Earthquakes (possibly in association with landslides) are considered an *extreme hazard*.

- The two previous models of Gilmour and Stanton (1990) and Barnett *et al.* (1991) are dated in their technology and parameters. New numerical models need to be developed using non-linear and non-hydrostatic terms covering larger areas.

- The coastline is at high risk from tsunami. This ranges from the highest risk on the East Coast to a slightly lower risk on the West Coast.

- Risk – for large tsunami as opposed to a large earthquake: we tentatively suggest that there is less risk in the long term (100's of years) but more in the short term (ten's of years), primarily because large tsunami can be generated from both distant and local sources.

- There are three types of mitigation approach: Policy and management measures that reduce the likelihood of damage, preparedness and response planning to deal with consequences of the event, and engineering design measures that reduce vulnerability.

- Available policy options include: The inclusion of hazard information about identified hazards in public documents; the consideration of tsunami hazards when planning development in coastal areas to either avoid the hazard or reduce the level of risk; and the use of *both* the RMA (placement of buildings) and the Building Act (construction of buildings) to achieve the aim of mitigating against natural hazards.

- Any plan for dealing with tsunami hazards requires a comprehensive emergency management approach, linking mitigation, preparedness, response and recovery. The dissemination of information about tsunami hazards is important in encouraging an appropriate public response. Risk communication is a social process, not an act, and should seek to start a conversion within the community.

- Apart from the evacuation of people and removal of transportable assets (if possible), there are few cost-effective mitigation options available to pre-existing facilities to counteract many of these hazards in high-risk coastal areas. Therefore the limitation on the building of permanent structures in high-risk areas is a low cost mitigation measure.

- In the absence of a comprehensive assessment of the potentially affected residential and commercial coastal land user it is difficult to prioritise actions pertinent to the appropriate level of risk discussed in Sections 3.4. and 3.5.

- There are several uncertainties in the current information pertaining to historical, palaeo and modelling data that primarily relate the form of record obtained. In determining the risk these varying levels of uncertainly all contribute to the uncertainty of the results.

- There are several generic information gaps including the lack of detailed coastal topography for the Wellington Region and insufficient information about role played by landslides in generating tsunami hazards for the Region. Furthermore, there is a need to undertake complementary iterative modelling and palaeotsunami research to benefit from the ensuing synergies. The need to identify residential and commercial shoreline facilities/structures etc. that could be damaged or could cause damage, is also a key gap.

7. RECOMMENDATIONS

A priority listing of the work needed to fill the gaps is outlined below (and in Section 5.2.). The undertaking of these tasks will highlight further information gaps and quite possibly give cause to reprioritise the work needed. We have been brief in out recommendations in order to underpin the priority status of those listed below.

- A detailed coastal topography for the Wellington Region is needed, at 1.0 m intervals up to 30 masl. Tidal limits should be indicated (*Internal or External? – LINZ?*).

- Identification of residential and commercial shoreline facilities/structures etc. that could be damaged or could cause damage, is needed. This would preferably be carried out in conjunction with the preparation of a detailed coastal topography to assist with development of policy measures and in guiding development considerations. A study of the extent and value of potentially affected residential and commercial coastal land users (inc. properties and infrastructure) is needed. (*External/Internal collaboration*?).

- The significance of landslides (coastal and submarine) to tsunami generation needs to be determined, both in conjunction with earthquakes and on their own. Return periods and probabilities need to be investigated using a combination of modelling and palaeotsunami studies around Cook Strait. The 1855AD earthquake needs to be remodelled if only to indicate that landsliding may have contributed to the tsunami, and thus may be a factor in future large earthquakes (*External – NIWA/ GeoEnvironmental Consultants*).

  Fund key site-specific studies to assess the hazards of tsunami inundation to people, lifelines and structures (e.g. Kapiti and Wairarapa coastal sites)– an iterative palaeotsunami and modelling exercise (*External – NIWA/ GeoEnvironmental Consultants*).

- Formulate an approach to key stakeholders to consider business preparedness, support of on-going studies, public awareness, etc. Development of public education and mitigation plan (inc. analysis of possible future coastal development). Interviews of stakeholder groups could be undertaken to discuss the issues. The council should consider the development of a tsunami hazard website for stakeholders (*Internal/External – GNS/GeoEnvironmental Consultants*).

- There is a real need to understand the long and short-term effects of saltwater contamination caused by tsunami. The Council should be proactive in seeking out research funding for this work, whether as a sponsor or co-funding agency (*External - GeoEnvironmental Consultants/NIWA*).

- The historical database needs to be completed (this is estimated as 90% complete for events over 1m in the Wellington Region) (*External – GNS*).

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FIGURES

Figure 1: General terms relating to tsunami (after Downes *et al*., 2000)

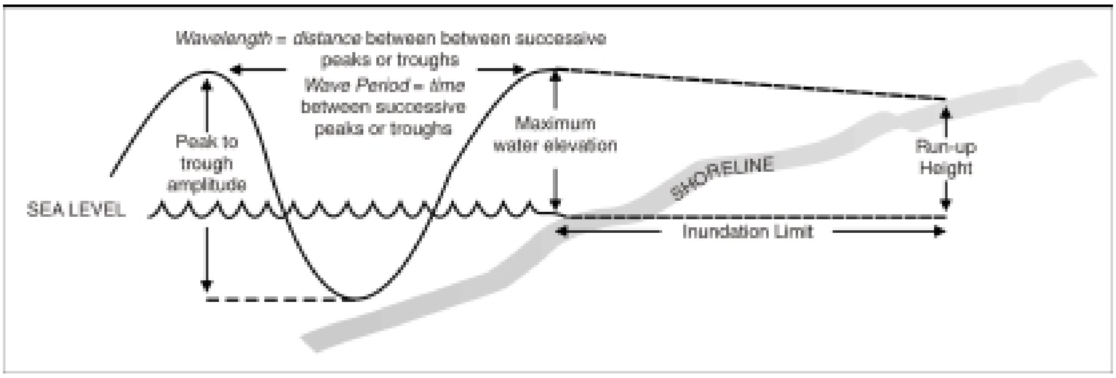


Figure 2: Cook Strait Canyon System (after Carter *et al*., 1988). Note Hikurangi Trough to the southeast of Cook Strait – the trough extends northeast parallel to the east coast of the North Island. (Bathymetry in metres)

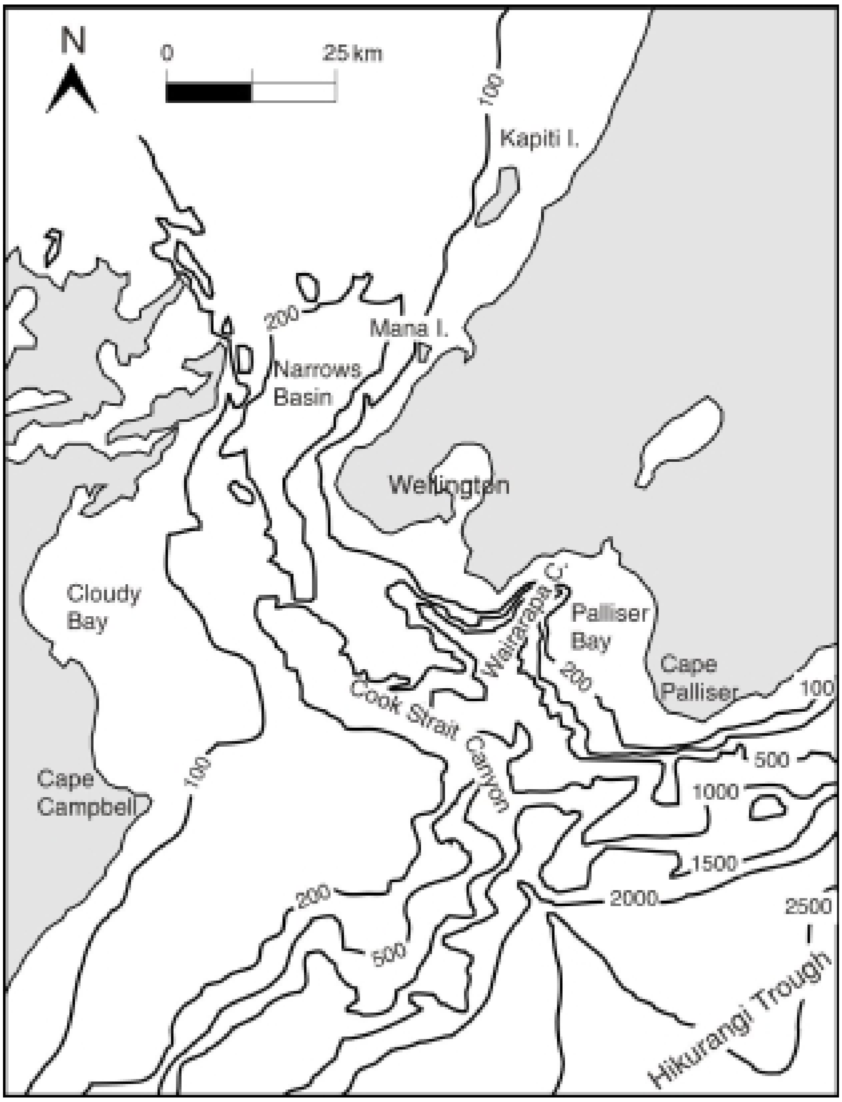


Figure 3: Major source regions for distantly-generated tsunami affecting the Wellington Region. Arrows indicate the principal directions of wave energy (after de Lange and Hull, 1994)

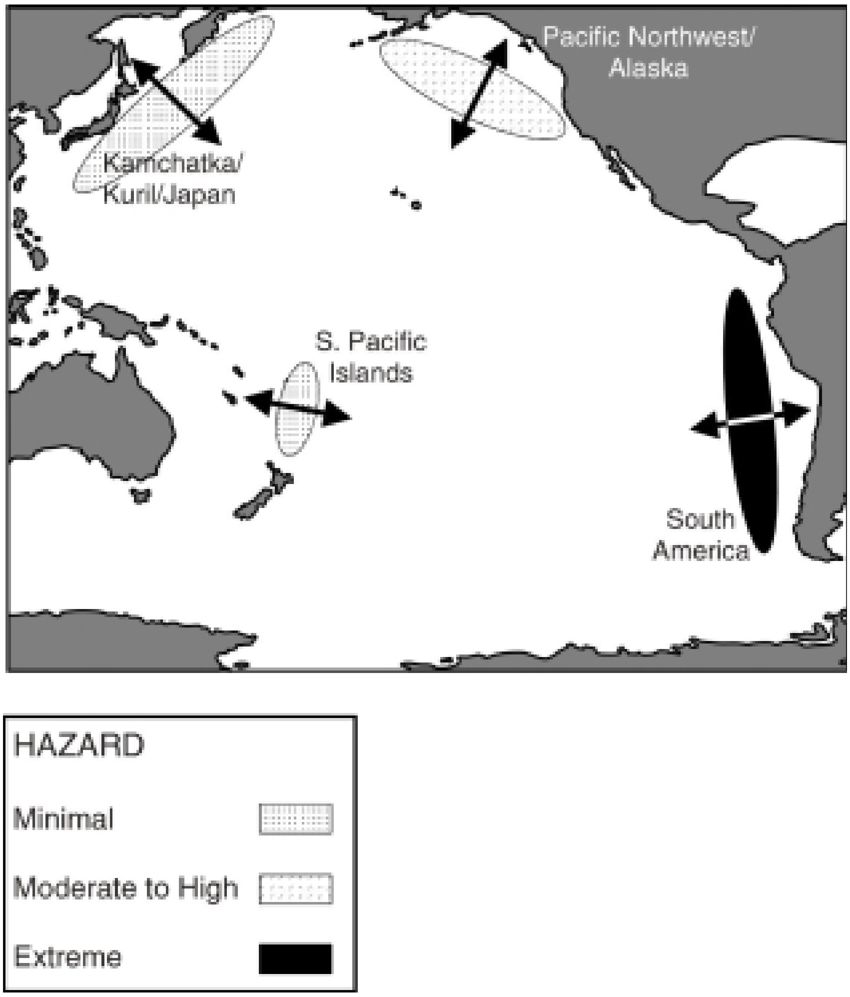
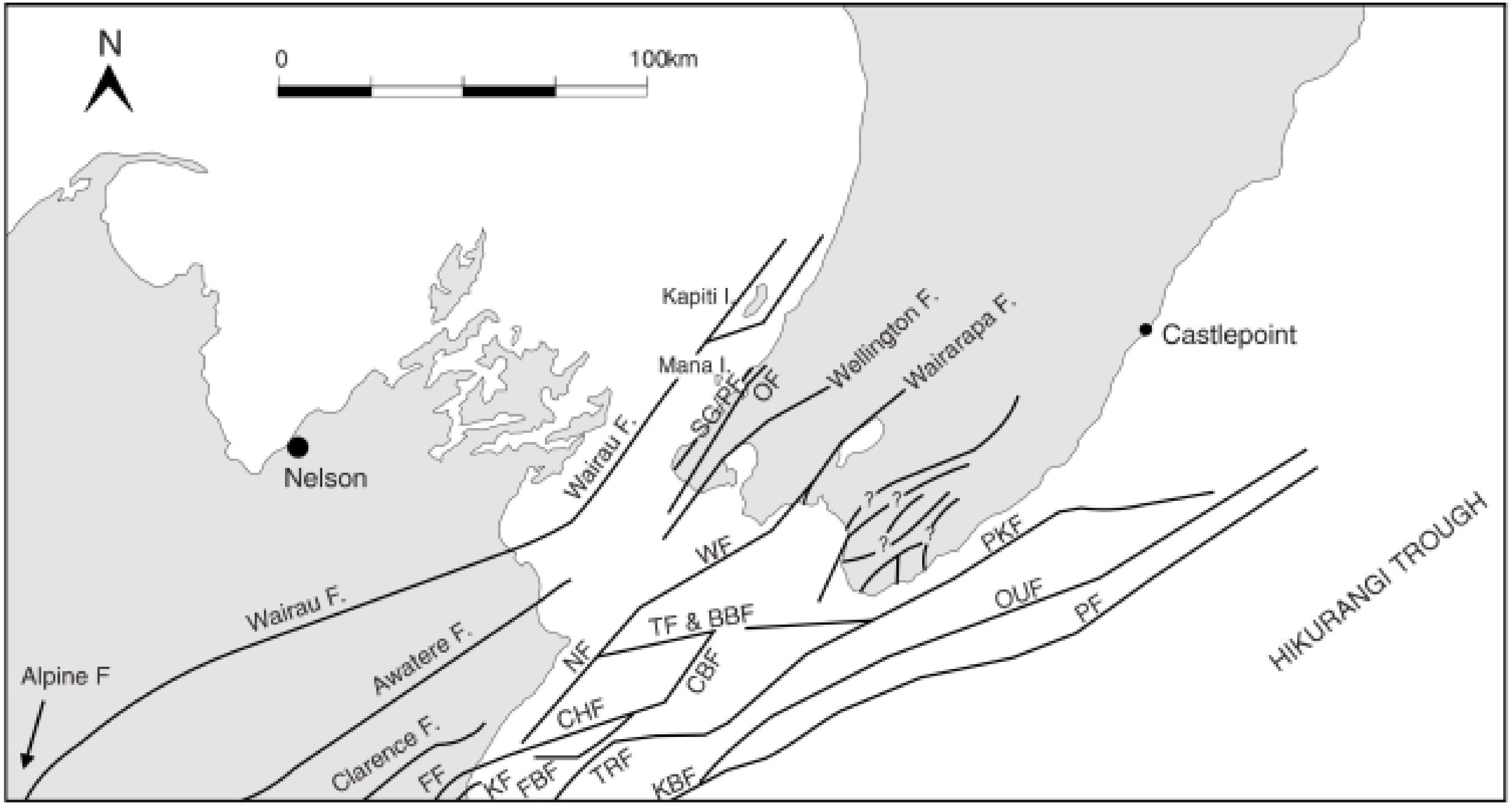


Figure 4: Schematic interpretation of known major faults in and around the Wellington Region (Te Rapa Fault is the extension of the Hope Fault), after Barnes and Audru (1999a; 1999b) and Goff and McFadgen (2001)



BBF - Boo Boo Fault; CBF - Campbell Bank Fault; CHF - Chancet Fault; FBF - Flaxbourne Fault; FF - Fidget Fault; KF - Kekerengu Fault; KBF - Kekerengu Bank Fault; NF - Needles Fault; OF - Ohariu Fault; OUF - Opouawe-Uruti Fault; PF - Pahaua Fault; PKF - Palliser-Kaiwhata Fault; SG/PF - Shepherds Gully/Pukerua Fault; TF - Tako Fault; TRF - Te Rapa Fault; WF - Wairarapa Fault

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Figure 5: Palaeotsunami studies of relevance to the Wellington Region (dates are approximations – prior to 2000 years ago, dates are recorded as 'BP')

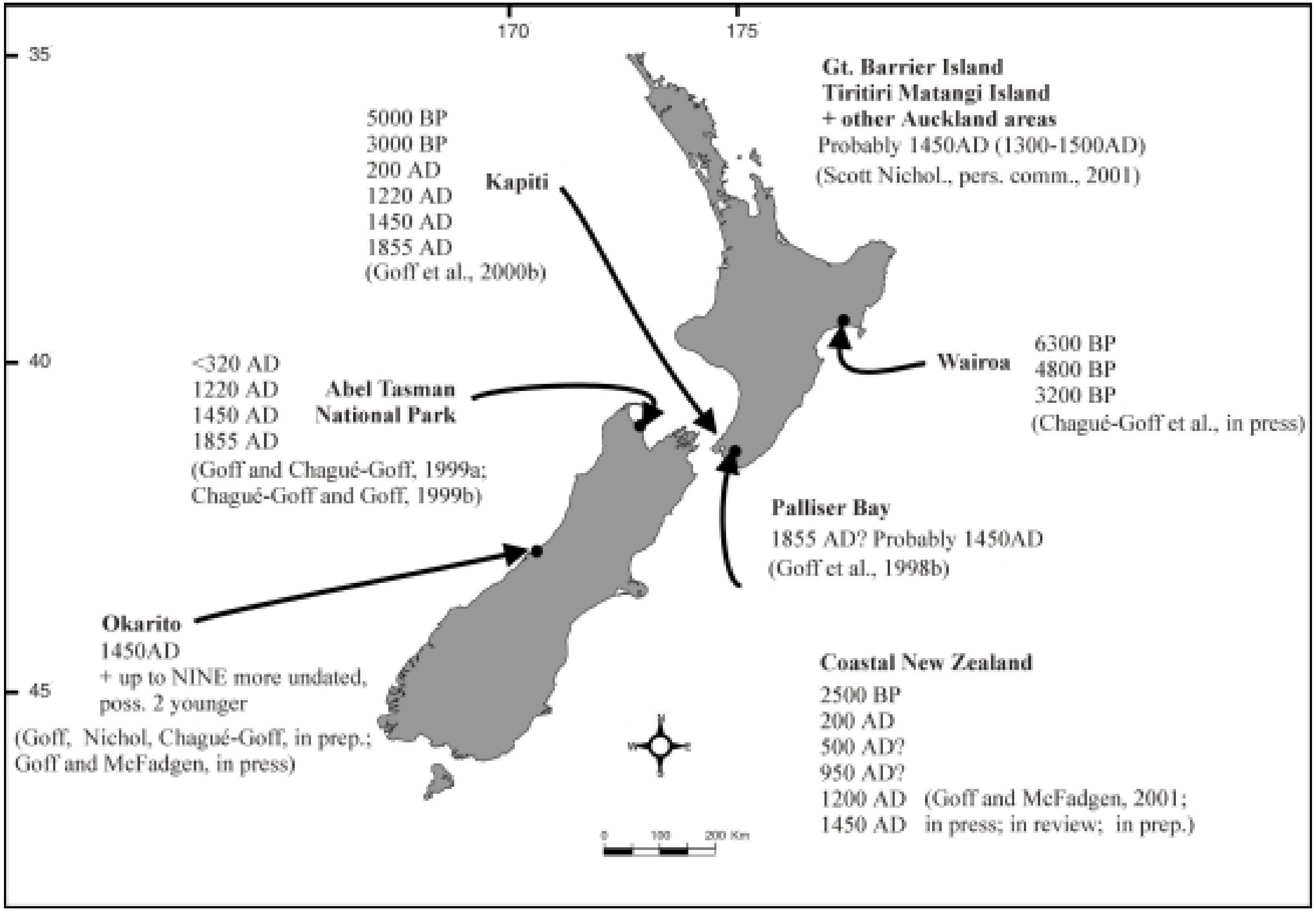

Figure 6: Summary of areas at risk from tsunami hazards

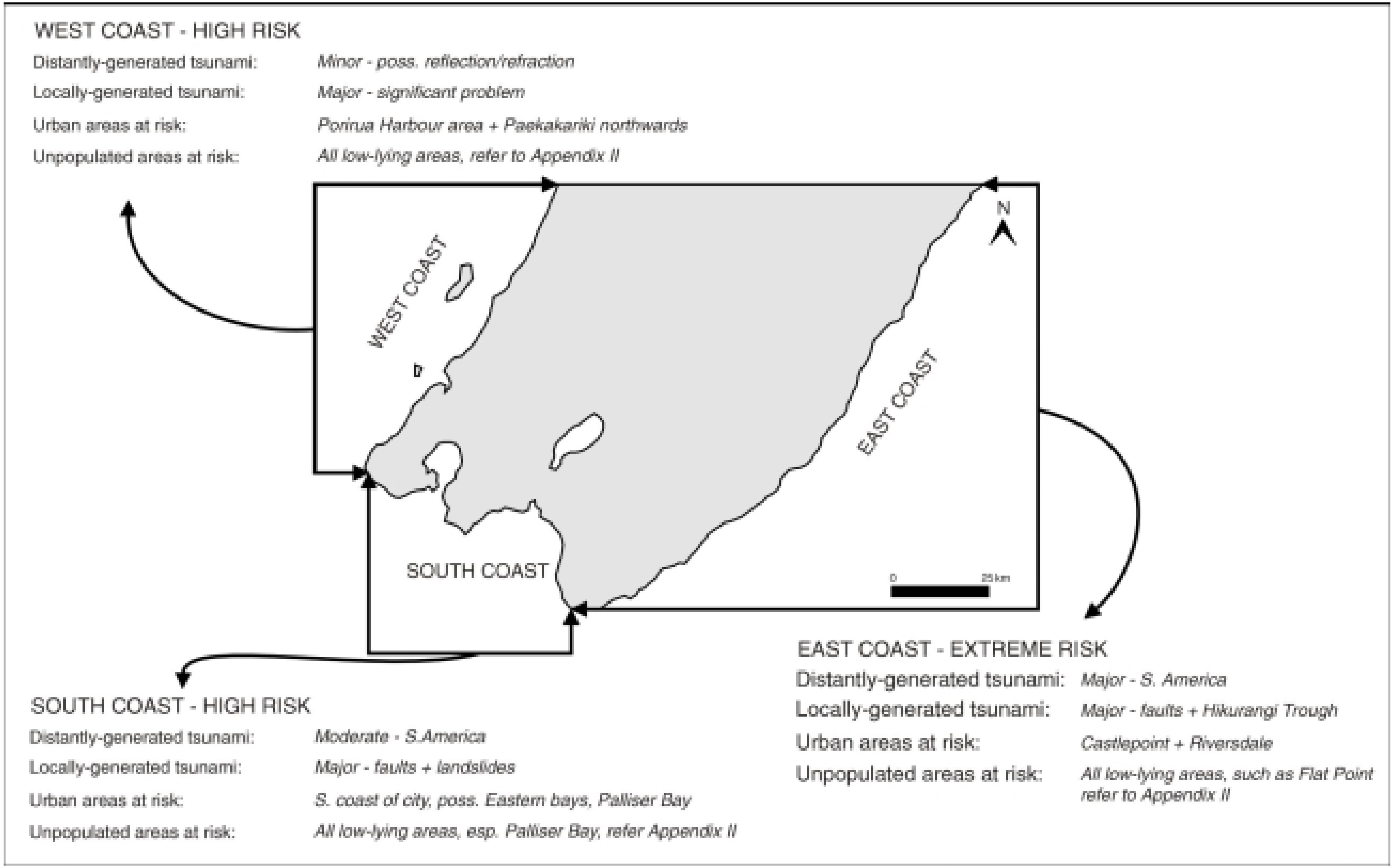

Figure 7: Warning signs used in Washington State, USA

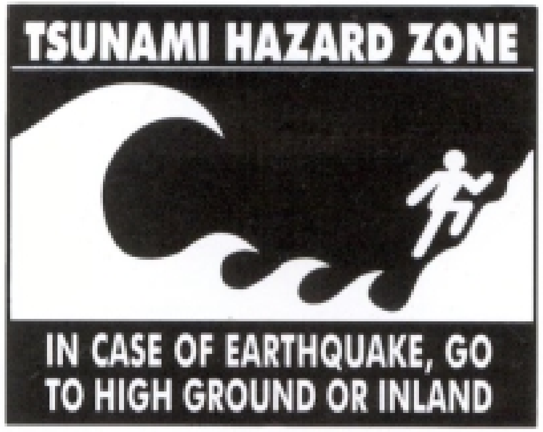

Figure 8: Warning sign from Castlepoint on the Wairarapa coast

Figure 9: Crowds gather to observe the arrival of the 1960 Chilean tsunami at Gisborne Harbour

TABLES

Table 1: Predicted tsunami annual exceedence probabilities and return periods for distantly-generated tsunami from Minimal to Extreme Hazard sources determined for the New Zealand coast (after Fraser, 1998; de Lange, in press)

Height (m)	Annual Exceedence Probabilities	Return Period (yrs.)
1.0	Min.: 2.87×10^{-3}	349
	High: 5.63×10^{-3}	178
	Extreme: 0.22	**46**
2.5	Min.: 8.65×10^{-5}	11,560
	High: 1.77×10^{-3}	564
	Extreme: 0.018	**57**
5.0	Min.: 2.5×10^{-7}	3.9 million
	High: 2.59×10^{-4}	3,866
	Extreme: 0.012	**82**
10.0	Min.: 2.16×10^{-12}	462.5 billion
	High: 5.5×10^{-6}	181,700
	Extreme: 0.006	**169**

Table 2: Summary of known major, local fault ruptures in the Wellington Region inc. pertinent South Island faults (see Figure 4). Events are simplified to assume rupture along the whole fault (after Goff and McFadgen, 2001)

Fault	**Approx. date of last event(s) (yr AD)**	**Est. Return Period (yrs)**	**Est. magnitude (M_w)**	**Reference**
Alpine	1220, 1450, 1620, 1717	250	~8.0, ~8.0, ~8.0, ~8.0	Bull, 1996; Yetton *et al.*, 1998
Awatere	1848	>1000	~7.5	Grapes *et al.*, 1998
Hope	1888	81-200	7.0-7.3	Cowan and McGlone, 1991
Ohariu	1290	1500-5000	7.6 $\pm$ 0.3	Van Dissen and Berryman, 1996
Palliser-Kaiwhata	~1450?	unknown	unknown	Ota *et al.*, 1987; McFadgen pers. comm., 2001
Shepherd's Gully/Pukerua	unknown >1290	2500-5000	7.6 $\pm$ 0.3	Van Dissen and Berryman, 1996
Wairarapa	1855	1160 – 1880	8.0 – 8.3	Van Dissen and Berryman, 1996
Wairau	>800 years (~1400BC?)	1000-2300	7.6 $\pm$ 0.3	Van Dissen and Berryman, 1996; Goff *et al.*, 2000b
Wellington	1250, 1450	500-770	?, 7.6 $\pm$ 0.3	Van Dissen and Berryman, 1996
		Est. Slip/Growth Rate (mm/yr)		
Boo Boo	These have all been active during the Quaternary and have mostly been identified by seismic profiling from boats. Therefore, their activeness has been determined by measuring the overall amount of fault movement and sediment displaced. Refer to references for full details.	~3.0	unknown	Barnes and Audru, 1999b
Campbell Bank		unknown	unknown	Barnes *et al.*, 1998; Barnes and Audru, 1999a; b
Chancet		unknown	unknown	Barnes *et al.*, 1998; Barnes and Audru, 1999a; b
Flaxbourne		unknown	unknown	Barnes *et al.*, 1998; Barnes and Audru, 1999a; b
Fidget		unknown	unknown	Barnes *et al.*, 1998; Barnes and Audru, 1999a; b
Kaikoura (not shown Fig. 4)		~1.0	unknown	Barnes and Audru, 1999a
Kekerengu		5-22	unknown	Barnes and Audru, 1999a
Kekerengu Bank		unknown	unknown	Barnes *et al.*, 1998; Barnes and Audru, 1999a; b
Needles		~1.1	unknown	Barnes and Audru, 1999a
Opouawe-Uruti		unknown	unknown	Barnes *et al.*, 1998; Barnes and Audru, 1999a; b
Pahaua		unknown	unknown	Barnes *et al.*, 1998; Barnes and Audru, 1999a; b
Tako		unknown	unknown	Barnes *et al.*, 1998; Barnes and Audru, 1999a; b
Te Rapa		unknown	unknown	Barnes *et al.*, 1998; Barnes and Audru, 1999a; b

Table 3: List and summary of past and current research relevant to tsunami hazards in the Wellington Region (see Figure 5).
*Wave height/runup estimates by J. Goff – based on available data. For the sake of this exercise, wave height and runup are assumed to be the same. In the absence of additional data (excl. 1855AD), estimated heights/runups are also assumed to be representative of a region-wide inundation height, although this is known to vary. Possible matching events are in bold with superscripted number.

Location	Estimated Age of Tsunami	Estimated Height/ Runup* (m)	Comments	Reference/Authors
Abel Tasman National Park	**1855AD[1]** **~1450AD[2]** **~1220AD[3]** **<320AD[4]**	>5 >10 >10 >5?	Synchronous events were found in cores from three different wetlands. Based upon these data and those from Kapiti Is. Lowe and de Lange (2000) suggested a min. wave height of 5.0 m was needed for tsunami to leave 'recognisable' deposits in coastal Cook Strait.	Chagué-Goff and Goff, 1999b; Goff and Chagué-Goff, 1999a
Archaeological sites: Canterbury Coast, D'Urville Is., Palliser Bay, Wairarapa Coast, Mana Is., Otago Coast, Paramata, Te ika amaru Bay	**~1450AD[2]** **13th Century (~1220AD)[3]** **2400BP[5]** to date **5000-6000BP[7]**	5.0-10.0?	Refer to Table 6.	Refer to Table 6
Great Barrier Island/ Northland	**~1450AD[2]**	>13	Found as a pebble unit overlying dune sands. This has reworked Maori midden sites. Probably related to a fault near the Hikurangi Trough, so relevant to Wellington Region.	Nichol *et al.*, 2000; S. Nichol, pers. comm., 2001
Kapiti Is., Pencarrow Lakes, Taupo Swamp	unknown	unknown	VUW – Geology PhD project studying diatoms in coastal wetlands with an aim to identifying catastrophic events, not just tsunami. Kapiti Is. results support those of Goff *et al* (2000b) below, there is evidence for an uplift event in Taupo Swamp about 2500 years BP – unknown if a tsunami was generated.	Cochran, in review; Cochran *et al.*, 1999
Kapiti Island (+ Mana Is. – 1450AD)	**1855AD[1]** **~1450AD[2]** **~1220AD[3]** **200AD[4]** **3000BP[6]** **5000BP[7]**	2-3 11-15 (min.) 11-15 (min.) 11-15 (min.) 11-15 (min.) 6-10 (min.)	Deposits were found in cores from Okupe Lagoon at the northern end of Kapiti Island. The lagoon is surrounded by an extensive boulder bank. Most likely more events preserved but results were limited by level of funding support. The island DOES NOT protect coast from tsunami inundation. No further work is planned at present. Evidence for the 1855AD tsunami was found on an adjacent beach, not as sediment, but shells lodged under rocks.	Goff *et al.*, 2000b
Nationwide	**~1450AD[2]** **~1200AD[3]** 950AD 500AD **200AD[4]** **2500BP[5]**	11-15 (max?) 11-15 (max?) 11-15 (max?) 11-15 (max?) 11-15 (max?) 11-15 (max?)	Using the 1450AD tsunami as a template for the earlier ones, these might possibly be linked to clusters of large earthquakes. These near-synchronous earthquakes may generate tsunami that inundate most, if not all, of the country's coast. Evidence for the 1450AD tsunami comes from numerous sources, earlier events are based primarily upon previous research cited in the literature.	Goff and McFadgen, 2001; in press; in review; in prep.
Okarito	**~1450AD[2]** Nine others (max)	>10	Found in sediment cores and trenches. The 1450AD event appears to be a suitable template for at least three other events in the cores. Up to six smaller, possibly >5 m events may be present. This is further supporting evidence for ubiquitous nationwide events that affect Wellington and the rest of the country.	J. Goff, S. Nichol, C. Chagué-Goff, in prep.; Goff and McFadgen, in press
Palliser Bay	**1855[1]?** Probably **1450AD[2]**	>10	Originally interpreted as being related to the 1855AD tsunami. While this may still be the case, dates suggest that an age of 1450AD is more reasonable. The deposit consists of	Goff *et al.*, 1988

Location	Estimated Age of Tsunami	Estimated Height/ Runup* (m)	Comments	Reference/Authors
			evidence for three waves.	
Wairoa	**3200BP**[6] **4800BP**[7] 6300BP	>5 >5 >10	Cores taken from lagoon behind high barrier. The oldest deposit was the most recognisable and probably the largest, the others are less well defined, and may in fact not be tsunami although the dates match those for Kapiti Island. For the purposes of this report they are assumed to be tsunami deposits. Possibly generated by a local Hawke Bay fault and may propagate tsunami along the coast to the Wairarapa.	Chagué-Goff *et al.*, in press

Table 4: Summary of prehistoric and pre-human tsunami, and their effects

Estimated Age of Tsunami	Location	Comments on effects (see references in Tables 3 and 6)
1450AD	Nationwide	*Abel Tasman National Park* – up to 3.5 km inland, probably over 10 m high. Smothering of underlying vegetation. *Archaeological sites* – almost ubiquitous signal found throughout the country. Found at many sites around the Region's coastline. *Great Barrier Island/Northland* – up to at least 350 m inland, probably over 13 m high, reworking of Maori ovens/midden sites. *Kapiti Is*. – over 200 m inland, probably close to 15 m high, saltwater inundation of environment. *Okarito* – over 2.5 km inland, possibly up to 10 m high, destruction of nearshore vegetation. *Palliser Bay* –over 3.5 km inland, probably over 10 m high, erosion of coast for about 1.5 km landward. The 1450AD 'event' is most likely related to tsunami (plural) generated by a cluster of large earthquakes that occurred within a short time period in the 15th Century (see Goff and McFadgen, 2001).
1220AD	Nationwide	Effects were similar in Abel Tasman National Park and on Kapiti Is. Using the 1450AD as a template, it is likely that the event is not preserved in Palliser Bay because this is an exposed section of coastline and the last large event (1450AD) removed evidence of previous ones - this may apply to much of the Wairarapa coast. Hence the need to study protected coastal wetlands such as Kapiti Is. in order to establish some form of return period. Identification of this event in association with archaeological sites on the Region's east coast (see Table 6 – Te Oroi) suggest that this was also nationwide in extent.
950AD	Nationwide	As per 1450AD, although perhaps relatively smaller, possibly 10-11 m. However, no field evidence has been found so this should be considered as a possible event. It is possible that evidence was destroyed by later events in sites already studied, or that the deposit is present but not picked up by the broad brush, low resolution, analyses of Abel Tasman National Park and Kapiti Is.
500AD	Nationwide	As per 950AD.
200AD	Nationwide	Probably related to a volcano-meteorological tsunami generated by the Taupo eruption (Lowe and de Lange, 2000), although seems to have occurred with some earthquake clustering. Similar to the 1450AD event.
2500BP	Nationwide	Probably smaller than the 1450AD event, but larger than the possible 950AD and 500AD events. It has been recorded in sediments in both Abel Tasman National Park and Kapiti, and the effects would have been similar to those reported for the 1450AD above, also appears to have affected Chatham Is.
3000BP	Wairoa, Kapiti	If these events are synchronous or near-synchronous, then it seems likely that this would be of nationwide coverage. It is suggested that this is similar to the 1450AD template. At Wairoa the deposit is poorly preserved, but for the purposes of this report it is considered to represent a tsunami It would probably have been a smaller event than that of the 6300BP.
5000BP	Wairoa, Kapiti	As per 3000BP, but also found on Chatham Island.
6300BP	Wairoa	This was a large event at Wairoa, penetrating at least 2 km inland, the runup height is unknown because some subsidence has taken place. Possibly only of local (east coast of the lower North Island) significance, but if it extended along the coast to the south it would probably have been an extreme event on the eastern Wairarapa coast.

Table 5a. Tsunami events that may have affected the Wellington Region: pre 1840AD (see Appendix I for additional notes)

Year (AD)	Date noted	Source	Location of tsunami observation	Est. runup or est. tsunami height at shore (m)	Comments
1832	?	Earthquake at unknown location, possibly the Wairarapa	Wellington Region	Possibly as large as the 1855AD tsunami	Lyell (in Downes & Grapes 1999) refers to an event (no location given) in which "alterations in the relative level of the sea and land occurred", and that the shaking forced whalers to take refuge in their boats for four months. Two other historical references refer to a large earthquake in the Wairarapa in 1832AD. However, at least some factors in these accounts indicate confusion with the 1855AD Wairarapa earthquake. If real, this event could have produced a tsunami of a similar size to the 1855AD Wairarapa earthquake tsunami, i.e. a maximum 9-10 m tsunami wave height with extensive areas of up to 5 m and 1-2 m on outer fringes. This event may be the same as the 1832-38AD earthquake and probable tsunami below.
1832-1838	?	Earthquake at unknown location, but probably offshore Poverty Bay	Wellington Region	If centred in Poverty Bay, in the order of 1.0-3.0 m in the eastern Wairarapa, <1.0 m in Wellington Harbour	This event that caused an "immense" swell of the sea in Poverty Bay after an "powerful earthquake" may be the same as the 1832AD earthquake referred to above.

Table 5b. Locally-generated tsunami known to have affected the Wellington Region: 1840AD-present (see Appendix I for additional notes)

Year (AD)	Date effects noted	Source	Location of tsunami observation	Est. runup or est. tsunami height at shore (m)	Comments
1848	Oct. 16-19	M7.4 Marlborough earthquake and aftershocks. Epicentre: Awatere Valley Surface rupture: Awatere Fault	Lambton Quay	**0.5**	A high tide, with minor flooding of Lambton Quay, was noticed in Wellington 12 hours after the large aftershock on Oct 17. An extra high tide was also noted in Taranaki, time unknown, suggesting that the higher than normal tides may have been the result of storm surge rather than tsunami. On October 19, at the time of another large aftershock, the Hutt River was agitated, but no change in level was noted. Probably a seiche (in response to shaking, rather than sea-floor deformation). It is interesting, however, that the European population was aware enough of the association of earthquakes and tsunami to look for changes in the sea. Had there been previous experience in NZ prior to 1840AD or were people aware of the tsunami that had occurred in South America 13 years previously? Or, had the Maori noted the association from past events and passed their knowledge on. One account of the 1855AD earthquake written a few years after the earthquake and based on personal accounts of those who had experienced it, suggest the Maori took to the hills as the safest place to go. Equally, they may have been aware that the flat ground of the Hutt Valley was subject to ground cracks and liquefaction.
1855	Jan. 23	M8.2 Wairarapa earthquake Epicentre: Prob. beneath Wellington Surface rupture: Wairarapa Fault	Wellington Region		The tsunami associated with this event affected the whole Cook Strait area, the Kapiti coast and northeast coast of the South Island. It is not known whether the east Wairarapa coast was affected, but it would be surprising if there was not at least a metre or two of runup to the north of Palliser Bay. Although one historical account suggests 9m on the east coast, this has been thought to refer to Palliser Bay. However, the tsunami may have still been considerable at Ngawi and at Cape Palliser (4-5 m). On the west coast, the tsunami is known to have reached about 2 m, possibly higher, at Otaki. It is also not known how much further north of Otaki the tsunami reached. Accounts of flooded beaches about the Manawatu may be the result of tsunami, or of liquefaction. The waters of Cook Strait and in Wellington Harbour, were disturbed for 8-12 hours. At any location, the largest waves were not necessarily the first waves to arrive. For example, the largest waves at Lyall and Evans Bays probably occurred within an hour or two of the main earthquake, not within minutes. Several waves, not necessarily successive, may have had the same runup. It is possible that submarine landsliding contributed to the tsunami. This is supported by the fact that tides were irregular in Cook Strait for a week after the mainshock, some of the irregularity being directly associated with specific large aftershocks in which further large scale faulting would be unlikely.

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Year (AD)	Date effects noted	Source	Location of tsunami observation	Est. runup or est. tsunami height at shore (m)	Comments
1855 (cont.)			Otaki	**≥1.0**	Almost reached to houses, fish stranded well above high tide mark.
			Porirua Harbour	**2.0-4.0**	Tsunami said to be greater here than in Wellington. Possibly as great as 2-3m. Lack of reported damage may be due to low tide at Porirua at the time the tsunami arrived (about 2-3 hrs after the main earthquake).
			Lyall Bay	**4.0-6.0**	Water rushed into Burnham Water, an area that is now part of Miramar, depositing fish. Waters of Lyall and Evans Bay were said to have met and reached 1m depth at some time within 8 hours of mainshock
			Evans Bay	**3.5-5.0**	See Lyall Bay. A boat was washed 2/3 way across the isthmus to Lyall Bay
			Lambton Quay	**2.5-3.0**	Shops flooded along low part of Lambton Quay
			Hutt River	**≥2.0**	Bore in river may have shifted already damaged bridge
			Te Kopi, Palliser Bay	**9.0-10.0**	A shed 9m above sea and four houses said to be washed away.
	Jan. 23-30	Aftershocks of Jan 23 earthquake	Cook Strait		Tides were irregular for a week after the first large earthquake. Some water level fluctuations seem to be associated with large aftershocks
1870	April 7	Unknown	Wellington	**<0.5?**	Tide rushed in and out all day, irregularly and rapidly. Attributed at the time to a southerly swell at the heads, although the harbour itself was smooth.
1882	April 13	Probable offshore Wairarapa earthquake, but its occurrence and location yet to be confirmed	Glenburn (east Wairarapa coast)		Reference for this is catalogue card in the Masterton Library, referring to a newspaper account, the original of which is no longer available.

Table 5c. Distantly-generated tsunami known to have affected the Wellington Region: 1840AD-present (see Appendix I for additional notes)

Year (AD)	Date effects noted (NZ Time)	Source	Location of tsunami observation	Est. runup or est. tsunami height at shore (m)	Comments
1840	August	Unknown. Possibly to NE of New Zealand. No distant source listed in Pacific Tsunami Database			Known to have caused damage to shipping at Whitianga and thrown fish on shore along East Coast near Hicks Bay. It is not known whether the Wellington region was affected, as accounts of tsunami have not been searched in this period.
1868	August 15	M8.5, northern Chile	Wellington Region Castlepoint Wellington	 **About 1.0?** **1.4**	The most damaging historical tsunami from a distant source. The whole of the east coast of NZ was affected, some locations considerably more so than others. This was dependent on the timing of the maximum waves and on bathymetry and harbour/inlet/bay dimensions. A village in the Chatham Islands was destroyed, while on the mainland, Lyttelton experienced the largest waves (7.6m). An extra high tide reported The highest waves arrived at low tide, and were measured at 1.5 m. Today, this wave would cause minor flooding of low areas around the harbour. Variations in level would be expected in the harbour, but were not reported (possibly because none was high enough to be a problem because it occurred at low tide).
1877	May 11	M8.3, southern Peru/northern Chile	Wellington Region Castlepoint Wellington	 **≥1.2** **About 1.2**	This tsunami was as extensive, but not as damaging as the 1868AD tsunami. Again the whole east coast was affected, but the highest waves probably arrived at most places at near low tide. Tide rose 1.2m at 0930, rising again at 1430 much above high water mark. The highest waves at the beginning of the tsunami occurred at near low tide. Later waves were considerably smaller (0.3m about 2 hours after the first waves), those occurring at high tide apparently causing no problem. Oscillations continued for about 24 hours. A bore occurred in a narrow channel.
1883	August 27	Explosive eruption of Krakatau	Wellington Region		Many places in New Zealand reported tidal oscillations that have been attributed to atmospheric pressure/ocean surface interaction (called a Rissaga). Maximum effect was at Lyttelton with 1.8m waves. Effect at Wellington unknown.

Year (AD)	Date effects noted (NZ Time)	Source	Location of tsunami observation	Est. runup or est. tsunami height at shore (m)	Comments
1897	Sept. 21	Unknown	Wellington	**1.0**	Unusual wave noticed, which was not reported elsewhere. Tsunami possible, but unlikely.
1922	Nov. 12	M8.3, central Chile	Wellington	**Presumed <0.5**	Tsunami noticed at the Chatham Islands, and along the east coast, the maximum height (about 1.2m) being reached at the Chathams. No damage reported.
1923	Sept. 04	M8.3, Japan	Wellington	**0.1**	
1946	April 2	M8.5, Aleutian Islands	Wellington	**Small, <0.5**	Unusual tidal variations noted, but no amplitude given.
1952	Nov. 06	M8.3, Aleutian Islands	Wellington	**0.2**	Regular series of fluctuations with a variation from 0.18-0.20m.
1960	May 24-25	M8.5, Southern Chile	Wellington Region Riversdale Ngawi Wellington	 **1.5** **1.5** **0.95**	One of the largest and most well recorded tsunami in recent times, but not as large as the 1868AD tsunami. Three 20 foot whales were washed up to shore due to surges.
1964	March 29	M9.5, Alaska	Wellington	**0.35**	
1994	October 15	M8.3, Kuril Islands	Wellington	**<0.1**	

Table 5d. Estimated (italicised) or observed (bold) maximum tsunami height (m) at the shore at sites within the Wellington Region from specified events (Some heights are derived (and hence may be estimates in some cases) from historical accounts - Note that these are best guesses and may considerably under- or over-estimate actual tsunami height)

Location	**Tsunami date (AD)**					
	1855	**1868**	**1877**	**1922**	**1946**	**1960**
Castlepoint	*1-2*	**~1**	**1.2**	*<0.5*	*<0.5*	*1.5*
Flat Point	*1-2*	*<1*	*1.2*	*<0.5*	*<0.5*	*1.5*
Palliser Bay (Lake Ferry)	*5-10*	*1-2*	*1.2*	*<0.5*	*<0.5*	*1.5*
Lyall Bay	**4-6**	*2.0*	*1.8*	*<0.5*	*<0.5*	*1.5*
Evans Bay	**3.5-5**	*2.0*	*1.8*	*<0.5*	*<0.5*	*1.2*
Queen's Wharf	**2.5-3**	**1.4**	**1.2**	*<0.5*	*<0.5*	**0.95**
Petone	*2-3*	*1.4*	*1.2*	*<0.5*	*<0.5*	*0.95*
Eastbourne	*2-3*	*1.4*	*1.2*	*<0.5*	*<0.5*	*0.95*
Porirua Harbour	*2-4*	*<1*	*<1*	*<0.3*	*<0.3*	*<1*
Waikanae	*2*	*<0.5*	*<0.5*	*<0.3*	*<0.3*	*<0.5*
Otaki	**>1**	*<0.5*	*<0.5*	*<0.3*	*<0.3*	*<0.5*

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Table 6. Observations of stratigraphic features found during archaeological studies, and evidence for tsunami events in the Cook Strait region during the New Zealand prehistoric period (*c*.1250AD to 1800AD). Estimated wave heights are based on elevation of deposit above sea level. However, according to Lowe and de Lange (2000) a tsunami needs to be at least 5.0 m high to leave a recognisable deposit. Wave heights in brackets indicate reference to this or other evidence (cited accordingly)

1. WELLINGTON REGION AND COOK STRAIT COAST – KAPITI ISLAND TO WHAKATAKI RIVER					
Locality	**Observation**	**Interpretation and age**	**Est. wave height (m)**	**Comment**	**Reference**
Paremata, Ngati Toa Domain. Entrance to Pauatahanui Inlet	Marine gravel layer thinning inland from sea shore, overlying Moahunter occupation layer	Possibly a tsunami *c.* mid 15th Century AD	**>1.0 (min. 5.0)**	Gravel layer interpreted by McFadgen (1980) as resulting from an eustatic sea level rise. Gravels correlated with shoreline deposits on the north shore of the Pauatahanui Inlet east of the Ohariu Fault. Insufficient data to rule out catastrophic saltwater inundation. Needs re-examination	McFadgen, 1980c; pers. obs.; Davidson, 1978
Mana Island	Marine gravels in back beach wetland	Possibly a catastrophic saltwater inundation, younger than 1000 AD	**>2 (11-15?)**	Fine, rounded gravels merge with wetland silt 50m to 60m inland from shoreline. Gravel possibly wind blown. Needs re-examination. Goff *et al*. (2000) report a mid 15th Century tsunami on Mana Is. and Kapiti Is. These are most likely the same event, in which case wave height was 11-15 m.	McFadgen pers. obs., (*c.* 1990)
Te Ika amaru Bay. West Wellington coast	A poorly stratified unit of marine pebbles and coarse sand overlying alluvial deposits and Maori occupation remains up to 200 m inland	Tsunami event, *c.* mid 15th Century AD	**>3.0 (min. 5.0)**	Originally attributed to Maori gardening. The distance the unit extends inland and the gradually reducing thickness inland makes transport by Maori an unlikely explanation for its origin. Samples of the layer have not been fully examined.	Goff and McFadgen, 2001
Greville Harbour, D'Urville Island	Layer of coarse gravel/sand on top of a buried soil, underlying lower occupation layer	Possibly a tsunami event, *c.* mid 15th Century AD	**>1.0 (min. 5.0)**	Originally attributed to Maori gardening. Needs re-examination	Wellman, 1962
Wellington Harbour	Maori tradition of seismic event called Hao-whenua. Uplifted what is now the Rongotai Isthmus turning Miramar from an island into a peninsula	Seismic event c. 15th Century AD, earthquake and possibly concurrent tsunami	**Poss. 10.0 see Table 3**	Known as the Haowhenua earthquake (Best 1918, 1923). Haowhenua may also be an illusion to a tsunami as, according to Williams (1957), Hao can also mean "make a clean sweep of anything". Haowhenua was recently translated as "sweeping the land clean" (I. James, pers. comm., 2001)	Best, 1918; 1923; Williams, 1957; Goff, 1997
Locality	**Observation**	**Interpretation and age**	**Est. wave height (m)**	**Comment**	**Reference**
Eastern Palliser Bay	Abandonment of coastal archaeological sites	Tsunami and earthquake event, *c.* mid 15th Century	**>5.0**	Archaeological observations include silting up of streams, changes to shoreline, slips, changes to shellfish populations. Earthquake uplift is evident from uplifted shorelines, a tsunami	Goff and McFadgen, 2001

		AD		event is inferred and needs field investigation to confirm	
Te Oroi stream,. SE Wairarapa coast	Two units of rounded and sub-rounded (marine?) gravels overlying fluvial deposits in stream fan. Gravels extend inland for a distance of more than 50m from present coast. One unit pre-dates, the other post-dates Loisels Pumice	Possibly two tsunami: *Older unit:* 13th to 14th Century AD or possibly a little older. *younger unit*: correlated with Ohuan deposits and probably 15th Century AD	**>3.0 (min. 5.0)**	Exposed in stream bank section and noted 25 years ago. Needs re-examination. Both deposits contain shell	McFadgen pers. obs., (*c.* 1975)
Okoropunga. Wairarapa coast	Sand layer, partly buried stone rows of Maori stone row system, and partly infilled Maori borrow pit on Holocene coastal platform	Possibly a tsunami event, *c.* mid 15th Century AD	**5.0-6.0**	Water runup and withdrawal are inferred from surface features evident on an oblique photograph of a Maori Stone Row System. A sand sheet, identified and mapped but not explained by McFadgen (1980a,b), is possibly a tsunami deposit. Runup height would be at least 5-6m. Needs field examination	McFadgen, 1980a; b; Goff and McFadgen, in review
Uruti Point. Wairarapa coast	Well-rounded pebbles of igneous rock among sand dunes	Possibly a tsunami event, no date	**?? (min. 5.0)**	No igneous rocks known from locality. Needs re-examination	King, 1932
c. 3 km north of Whakataki River. Wairarapa coast.	Scattered shells and beach boulders throughout sand dunes	Possibly a tsunami event, no date	**?? (min. 5.0)**	Davis (1957) did not consider shells and boulders to be of human origin. Needs re-examination	Davis, 1957
2. New Zealand coast including Chatham Island (sites considered to be of relevance to Wellington Region)					
North Island, South Island, and Chatham Island	Coastal sand dune advance: Ohuan (N. + S. Islands), Kekerionean (Chatham Is.)	Possibly initiated by tsunami in the mid 15th century AD	**??**	Short-lived sand dune building phase, originally attributed to climate change and/or human interference with vegetation. The brief timespan of the phase suggests a short-lived initiating event. Needs further examination	McFadgen, 1985
Locality	**Observation**	**Interpretation and age**	**Est. wave height (m)**	**Comment**	**Reference**
Martins Bay, Fiordland	Coastal sand dune advances (probably correlate with McFadgen's (1985) dune building phases)	Two of three advances post-date human settlement. Middle event possibly initiated by tsunami in mid 15th Century AD	**??**	Sand dune advances originally attributed to climate change. Needs further examination	Wellman and Wilson, 1964

Chatham Island, north and east coasts	Rounded pebbles and stones in deflated sand dunes, and in buried soils in sand dunes	Possibly multiple tsunami events between 2400 years BP and present day	**>5.0**	Originally interpreted as sea lion gastroliths. Needs re-examination	McFadgen, 1994
Te Awa Patiki, Chatham Island	Tuatua shells dated at 15000 to 16000 years BP in peat probably deposited at present high water mark *c*. 5000 to 6000 years BP	Tsunami event between about 5000 and 6000 years BP	**>1.0 (poss. far larger)**	From their radiocarbon age the shells would have been living when sea level was between 56m and 75m below present sea level. McFadgen (1994) inferred that the shells were reworked from earlier offshore deposits but no mechanism was proposed. A tsunami is a strong possibility. Needs re-examination	McFadgen, 1994
Long Beach, Otago	Archaeological shell midden layer disturbed by wave action	Possibly tsunami event or storm surge *c*. 13th to 15th Century AD	**??**		Leach and Hamel, 1981
Canterbury coast, South Island	Apparent gap in occupation of dated coastal Maori sites	Possibly a result of a major coastal catastrophe in or about the 15th century AD	**??**	The apparent gap is possibly due to calibration stochastic distortion (McFadgen, *et al.* , 1994) of the radiocarbon dates. Further research is needed to clarify the issue	Challis, 1995

Table 7a. Estimated return periods for tsunami in the Wellington Region based upon a combination of historic and palaeo records (see Tables 3 and 5a-c)

Estimated Height[1,2] (m)	Est. Average Return Period (yrs)	Comments
0 - 1.0 (Small)	<15	11 out of 18 events in historical record since 1832AD. Likely many more not recorded. Too small for palaeo record.
>1.0 – 5.0 (Medium)	<34	5 out of 18 historical record since 1832AD (estimated 90% complete). Mostly too small for palaeo record.
>5.0 – 10.0 (Large)*	<84	2 out of 18 historical record since 1832AD (estimated 90% complete). *Rule of thumb – to be noted in palaeo record, waves probably need to be greater than 5 m high (Lowe and de Lange, 2000). In palaeo record: 1855AD duplicated, taking max. wave heights, there are no single events where the max. wave height was less than 10 m in the Wellington Region. The palaeo record is far from complete though and it is highly likely that more deposits remain to be found.
>10.0 (Extreme)	400 (2000 yr)[a] 700 (6300 yr)[b]	No tsunami in the historical record. It should be noted that because of several factors there is most likely a loss of record with time in the sedimentary sequences studied, so the return period estimates should be seen as a minimum (Goff *et al*., 2000b). [a, b] With this in mind two estimates are made, one based on the past 2000 years, another on 6300 years.

[1]Estimated height – based on all available data. In the case of the palaeo record this is based on all available physical evidence including the palaeoenvironmental context for the site. See Tables 3-6.
[2]Maximum wave height – divided into 0-1.0 (small), >1.0-5.0 (medium), >5.0-10.0 (large) and >10.0 (extreme). These refer to the maximum wave height for any one site in the Region, not all sites. At present the largest estimated wave height is about 15 m. While this is most likely not the maximum, it represents the best estimate based upon current information. The >10.0 m category includes any wave heights in excess of this, but when further research is forthcoming it may be necessary to change the categories to reflect an increasing maximum wave height.

Table 7b: Simple Poisson probability for tsunami inundation in the wellington region for waves of different height

Tsunami wave height (m)	No. of events (refer Table 7)	Av. Return Period (yrs)	*Probability (% in brackets)			
			25 yr	50 yr	75 yr	100 yr
0-1.0	11[a]	15	0.81 (81)	0.96 (96)	0.99 (99)	1.00 (100)
>1.0-5.0	5[b]	34	0.52 (52)	0.77 (77)	0.89 (89)	0.95 (95)
>5.0-10.0	2[c]	84	0.26 (26)	0.45 (45)	0.59 (59)	0.70 (70)
>10.0	5[d] 9[e]	400 700	0.06 (6) 0.04 (4)	0.12 (12) 0.07 (7)	0.17 (17) 0.10 (10)	0.22 (22) 0.13 (13)

a. since 1832AD; b. since 1832AD; c. since 1832AD; d. since 200AD; e. since 6300BP

*Probability calculated by: $P_N = 1 – \exp^{(-t/tr)}$ (after Yetton *et al*., 1998)
Where P_N = The probability over N years; t = time period in years, tr = average recurrence interval.

Table 7c. Return periods for specified tsunami heights determined for New Zealand and the Port of Wellington – *Based on Historically-documented tsunami only* (after Fraser, 1998; de Lange, in press)

Location	**Tsunami height (m)**			
	1.0	**2.5**	**5.0**	**10.0**
New Zealand	35	52	101	376
Wellington	40	119	728	27,200

Table 8: Comparison of return periods for large and extreme tsunami compared against other natural and technological hazards for the Wellington Region

Tsunami[1]		**Earthquakes**[2]			**Extreme rainfall**[3] **(Wairarapa)**		**Windstorms**[4] **Wairarapa coast**		**Petroleum**[5]	
Est. Height (m)	Est. Return Period (yrs)	Est. Mag. (MM)	Location	Est. Return Period (yrs)	Est. 24 hour rainfall (mm)	Est. Return Period (yrs)	Speed (km/h)	Return Period (yrs)	Event	Est. Return Period (yrs)
>5.0 – 10.0	**<84**	7.0	Marlborough	**20-80**	132	**142**	198	**142**	Storage spill (Seaview)	**8500?**
>10.0	**400-700**	7.2-7.8	Wellington	**600**	153	**475**	216	**475**	Storage spill (Kaiwharawhara)	**4000?**

River floods[6]				
Hutt R. Flood flows (m^3/s)	Otaki R. Flood flows (m^3/s)	Ruamahanga Flood flows (m^3/s)	Waikanae R. Flood flows (m^3/s)	Return Period (yrs)
1710	1710	1513	333	**50**
1900	1860	1699	371	**100**

[1]See Table 7a for details
[2]Scenarios used for earthquake risk assessment study by Davey and Sheppard (1995a-e)
[3]From NIWA (1999)
[4]From NIWA (1999)
[5]Based on Opus (1999; 2000)
[6]From The Upper Ruamahanga River and Floodplain Investigation, McKercher (1991), WRC (1994; 1996; 1999)

Table 9: Estimated* value for property/infrastructure damage from large (<84 yr return period) and extreme (400-700 year return period) tsunami (Based partly on WRC, 1990). (*This is a qualitative study and does not purport to have detailed knowledge of coastal property and infrastructural. Costs are at best 'guess-timates', but are attempted in order to highlight the potential areas of risk. More work is needed – these data may possibly be internally consistent)

Cost for repair ($ Million)	**REGION**					
	West Coast[1]		South Coast[2]		East Coast[3]	
	<84	400-700	<84	400-700	<84	400-700
Residential	25	40	60	100	10	25
Commercial						
Farms + Buildings	10	25	10	25	15	30
Transport/Communications:						
Roads	20	40	30	50	5	10
Bus depots	0.25	0.5	5.0	10	0.0	0.0
Railway	20	40	5.0	10	0.0	0.0
Airports	0.5	1.0	30	60	0.0	0.0
Telecommunications	5.0	7.5	10	20	2.5	2.5
Schools	15	20	20	50	2.5	5.0
Industry	50	75	200	500	5.0	10
Police	10	20	20	40	0.0	0.0
Fire Authority	10	20	10	20	0.0	0.0
Min. of Defence:						
Airport facilities/Other?	10	10	10	10	0.0	0.0
University (e.g. Marine lab)	0.0	0.0	1.5	2.5	0.0	0.0
Care Facilities (e.g. hospitals, child care)	20	40	25	50	2.5	5.0
Sewage facilities	15	30	25	50	1.0	2.0
Water supply	25	50	50	100	2.5	5.0
Electricity	25	50	50	100	2.5	5.0
Gas	15	25	25	50	0.0	0.0
Port Facilities	0.0	0.0	25	50	0.0	0.0
Wharves	0.0	0.0	25	50	0.25	0.5
Overseas Passenger Terminal	0.0	0.0	5.0	10.0	0.0	0.0
Seaview Industrial Area	0.0	0.0	25	50	0.0	0.0
Petroleum Storage areas	5.0	10	25	50	0.25	0.5
Marinas	2.0	3.0	15	20	0.25	0.5
Retail Centres	15	30	25	50	0.2	0.4
Council facilities/offices (WRC, WCC, PCC)	2.0	2.0	15	30	0.0	0.0
Navigation facilities (e.g. lighthouses)	2.0	5.0	5.0	10	2.5	5.0
Cultural facilities (e.g. Marae)	2.5	5.0	5.0	10	2.5	2.5
Recreational facilities (e.g. parks)	2.5	5.0	10	20	2.5	2.5
TOTAL:	**311.75**	**531.50**	**766.5**	**1507.5**	**56.95**	**111.4**

[1]West Coast: From the northwest WRC boundary to Oteranga Bay; [2]South Coast: Oteranga Bay to Cape Palliser; [3]East Coast: Cape Palliser to northeast boundary

Table 10: Estimated values for property/infrastructure damage from various return period events: Less than 100 year and c. 600 year return periods for tsunami and earthquakes are comparable; Large (<84 yr return period) *tsunami*, 7.0 MM Marlborough *earthquake* (20-80 years); Extreme (400-700 yr return period) *tsunami*, 7.2-7.8 MM Wellington *earthquake* (600 years); (from Tables 8 and 9). Data for Extreme rainfall, windstorms, petroleum-related events not available, those for river floods are for 50 and 100 year return period only. *Caution*: We are not aware how each cost estimate was calculated – the tsunami data are guesstimates and may either over- or under-estimate the true costs.

Tsunami		**Earthquakes**[2]		**River floods**[3] **-** Cost (NZ$ Million)			
Cost (NZ$ Million)	Est. Return Period (yrs)[1]	Cost (NZ$ Million)	Est. Return Period (yrs)	Hutt	Otaki	Waikanae	Est. Return Period (yrs)
1135.2	**<84**	356.9	**20-80**	?	13.3	10.8	**50**
2150.4	**400-700**	3997.1	**600**	146.0	16.0	30.8	**100**

[1]See Table 7a for details
[2]Scenarios used for earthquake risk assessment study by Davey and Sheppard (1995a-e)
[3]McKercher (1991), WRC (1994; 1996; 1999)

Table 11: Methods for Natural Hazard Management (with particular reference to tsunami hazards)

Local Government		**Landowners/Developers**
Regulatory Methods	Non-regulatory Methods	Market Methods
• ss.30, 31,106,108,220 RMA • s.36 Building Act • District plans (land use and subdivision rules) • Regional coastal plan • Development impact fees (DIFs) eg. For constructing or upgrading stormwater to reduce flooding hazard • Creation of esplanade reserves (hazard buffers) • Code of Development Practise • Covenants, consent notices on property title	• Coast-Care initiatives; eg. replanting dunes thereby reducing coastal erosion potential • Education about natural hazards • Research and Hazard identification (scientific/technical reports) • Monitoring eg. Monitoring of development in tsunami hazard areas • Reserve management • LIM reports • Site specific hazard mitigation eg. Erecting signage along the beach	• Insurance (EQC, individual members) • Risk Implications • Desirability and affordability of a site or area • Physical works to avoid or mitigate natural hazards eg. constructing barriers to reduce tsunami impact • Site specific hazard identification

(Phizacklea, 2001)

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Table 12: CDEM Group Plan: Suggested Structure (Ministry for Emergency Management, 2000)

Strategic		Operational		Administrative
• Context • Hazards & Risks • Assess management mechanisms • Objectives, targets, actions		• Principles • Readiness arrangements • Response arrangements • Recovery arrangements		• Make-up of group • Procedural arrangements for meetings • Appointments • Funding

APPENDICES

APPENDIX I

ADDITIONAL HISTORICAL NOTES

1832AD tsunami:

Lyell (1856c; 1856d; in Downes and Grapes, 1999) refers to an event in 1832AD in which “alterations in the relative level of the sea and land occurred”, and in which whalers were forced to take refuge in their boats for four months because of the shaking. The location of this event is not given, nor the source of the information. That the earthquake to which Lyell refers was possibly in the Wairarapa, is suggested by two other historical references, Iorns (1932) and Bannister (1940) (appropriate extracts being found in Downes and Grapes, 1999). Iorns (1932) refers to a large earthquake in the Wairarapa in 1832AD, while Bannister (1940) refers to one in about 1838AD. However, at least some factors in these accounts strongly indicate confusion with the 1855AD Wairarapa earthquake. There are also arguments against a large earthquake occurring in the Wellington area immediately prior to European settlement in 1840AD. According to Florance (1858; in Downes and Grapes (1999)), “The Maories [in the Wellington area] have often been heard to remark that the earthquakes prior to the two last great shakes [1848AD and 1855AD] were never thought anything of by them, they were so slight and never injurious”. The other possibility is that Lyell is referring to an earthquake 1832-1838AD, which was strongly felt in Poverty Bay and which was almost certainly accompanied by a tsunami. While this event cannot be dismissed, its occurrence and its location are very doubtful. However, if changes of the relative of land and sea were observed, these would almost certainly be accompanied by a tsunami, possibly comparable with the 1855AD earthquake tsunami.

1832-38AD tsunami:

This event caused an “immense” swell of the sea in Poverty Bay after a “powerful earthquake” (may be the same as the 1832AD earthquake referred to above). If centred at Poverty Bay, probably only the eastern Wairarapa would be affected, with the tsunami waves that might of the order of 1-3 m.

1840AD tsunami:

This event was almost certainly a tsunami, but its source is not known. There are no reports of a tsunami in the Historical Tsunami Database for the Pacific 47BC-2000AD (tsun.sscc.ru/htdbpac), so it assumed to have an origin near New Zealand, perhaps to the northeast. It is not known whether the Wellington Region was affected. Needs investigation of Auckland and Wellington papers.

1848AD M7.4 Marlborough earthquake:

The 1848AD M7.4 Marlborough earthquake ruptured the Awatere Fault in the Awatere valley in the South Island (Grapes *et al.*, 1998). The first earthquake on October 16 was followed by large aftershocks on October 17 and October 19. The sequence severely damaged brick buildings in the infant town of Wellington (Eiby, 1980). de Lange and Healy (1986) report that Wellington experienced unusually high tides on several occasions after the first shock. On one occasion, the lower parts of shops, probably in Lambton Quay, which was the shoreline in 1848AD, were flooded. On October 19, at the time of one of the large aftershocks, the Hutt River was agitated, but no change in level was noted. de Lange and Healy (1986) suggest that not all the higher than expected tides can be attributed to the storm that occurred over several days during the sequence, and that a tsunami could have occurred in association with the mainshock or one of the aftershocks.

It is interesting, however, that the European population was aware enough of the association of earthquakes and tsunami to look for changes in the sea. Had there been previous experience in NZ prior to 1840AD or were people aware of the large tsunami that had occurred in South America 13 years previously? Or, had the Maori noted the association of earthquakes with tsunami from past events and passed their knowledge on? One account of the 1855AD earthquake written a few years after the earthquake and based on personal accounts of those who had experienced it, suggest the Maori took to the hills during earthquakes as the safest place to go. The Maori may have been afraid of tsunami, or equally, aware that the flat ground of the Hutt Valley was subject to ground cracks, settlement and liquefaction?

1855AD M8.1-8.2 Wairarapa earthquake:

(Unless indicated, information is from Grapes and Downes, 1997).
The 1855AD M8.1-8.2 Wairarapa earthquake is the largest earthquake in New Zealand's historical record. Up to 12 m horizontal and 2 m vertical movement was recorded at the surface trace of the Wairarapa Fault, which ruptured for a distance of 90-140 km on land and probably continued for a further 20-30 km beneath Cook Strait. Regional uplift extended west from the fault decreasing to near zero at Paekakariki. The maximum of about 6 m occurred near Cape Turakirae. These large horizontal and vertical movements, accompanied by coastal landslides, and possibly by submarine landslides, were responsible for a tsunami that propagated throughout Cook Strait, along the Kapiti coast, the northeast coast of the South Island and probably along the east Wairarapa coast. The small, sparsely distributed population meant that little structural damage was caused by the tsunami, and there was no loss of life.

The tsunami, which was generated at almost high tide, strongly affected the waters of Cook Strait and Wellington Harbour for 8-12 hours, while disturbances of water levels, some in close association with aftershocks continued for about a week. Only the tsunami associated with mainshock was reported to have caused damage. While the first disturbance at Lambton Quay reached higher than subsequent waves, elsewhere the first waves were not necessarily the largest. Modelling (Gilmour and Stanton, 1990) indicates that waves at Evans Bay 2-3 hours after the mainshock were larger than those that occurred within the first hour. Several waves were the same height.

The tsunami within the Wellington Harbour area was generated in three ways:

- sudden horizontal movement of the harbour perimeter, causing "sloshing", as in a suddenly moved bowl of water (immediate)

- sudden vertical uplift of the harbour, about 1m more on the east side than on the west side (immediate, but taking 10 minutes for water to move form one side of the harbour to the other)
- sudden horizontal and vertical sea-floor deformation in Cook Strait (taking about 20 minutes for the highest waves to reach the harbour entrance)

Summary of observed effects and estimates of tsunami height at locations where there were no observations:

In the Wairarapa: The highest recorded runup occurred at Te Kopi in Palliser Bay. Here, sheds on a shelf 9 m above the sea were washed away. Nearby, people observed the waves arriving, recognised their significance, and escaped to high ground. Only one known historical account refers to effects on the eastern Wairarapa coast. This account suggests that the wave reached 9 m, but this has been thought to refer to the Te Kopi site. However, it would be surprising if there was not at least a metre or two of runup even as far north as Castlepoint, while between Te Kopi and Cape Palliser, the tsunami may have been considerable, probably 4-7 m, possibly higher.

Within Wellington Harbour: Immediately following or during the earthquake, buildings along this part of Lambton Quay (the shoreline in 1855AD) were inundated to at least 30cm and possibly as much as a metre in depth. Accounts of the inundation suggest runup of at least 1.2m to possibly 2.4-3.0m. Only the first waves reached to the shops. Fish were deposited at many places along the harbour shoreline. The road to the Hutt Valley was inundated. At Evans Bay a boat moored near the beach was found two-thirds of the way across the isthmus to Lyall Bay, suggesting 3.5-5.0 m maximum height for the tsunami there. Several accounts suggest that at some time after the mainshock water from the two bays met. A bore was probably formed in the Hutt River, possibly being responsible for moving an already damaged bridge.

South Wellington: The greatest reported impact of the tsunami here was at Lyall Bay, where water penetrated as far inland as the hills at the north end of Miramar, and probably for a large part of the distance across to Evans Bay. Fish were also deposited well above high tide mark along the southern coast to Terawhiti. Gilmour and Stanton's (1990) modelling indicates that several places around the harbour entrance would have experienced waves nearly as high as those at Lyall Bay.

Porirua: According to one historical account, Porirua was more affected by the tsunami than Wellington. There is no other information. It is probable that the runup was 2-4 m.

Kapiti coast: The tsunami is known to have deposited fish well above high water mark at Otaki. It is not known how much further north of Otaki the tsunami reached high enough levels to be noticeable. There are accounts of flooded beaches along the Manawatu coast, but these may have been caused by liquefaction, rather than tsunami.

1868AD Chilean earthquake and tsunami:

This tsunami, from a very large earthquake off the northern Chile coast, propagated throughout the Pacific. It caused one death and destroyed a Maori village on the Chatham Islands, and was observed at many locations along the east coast of the North and South Islands, including Bay of Plenty and North Auckland, and at a few locations on the west coast. Some locations, particularly on Banks Peninsula and the Chatham Islands, were considerably more affected than others dependent on timing of the highest waves, bathymetry, and harbour/inlet/bay dimensions. For many places, the highest waves seem to have arrived within an hour or two of low tide. On Banks Peninsula, fences, bridges, and jetties were damaged or destroyed and water overflowed onto the land at the shore, and beside rivers and streams for several kilometres upstream, reaching houses in some cases. At the time of high tide 6-8 hours after the arrival of the first large waves, waves in some places were still high enough to cause concern. Water levels oscillated for 24 hours or more.

In the Wellington Region, Castlepoint reported water reached to a little beyond normal high tide level at low tide, while at a wharf near the present Queen's Wharf, water levels were measured for several hours, the maximum height above normal tidal level of 1.4 m occurring near low tide. Because of the resonance properties of the harbour, the height of the tsunami would be expected to vary around the harbour, but there are no reports of this happening.

It is of interest here to include a descriptive summary of the effects in Wellington as an illustration of what might be expected in the future:

Shortly before 7 am (3/4 ebb tide), tide rose to above HWM in about 15 minutes, receded in 15 minutes to LWM. Ebb and flow at intervals decreasing from 15 minutes at 8 am to 10 min at 10 am, the rise and fall diminishing also. At 8 am, difference was nearly 1.5 m; at 10 am, 0.6 m.. At midday intervals of ebb and flow were reduced to 7 min and the rise about 0.3 m. At corner of old reclaimed land near the rear of Lion Foundry, water raced and out of a gap in the sea wall under construction as a bore running at a rate estimated as 7-8 knots. Current was noticeable far beyond Queen's Wharf, a series of whirlpools and eddies forming in the harbour. Disturbances continued all day, high and low water occurring about 20 times between 7 am and 3 pm. Boats were caught up in currents but no accidents occurred. (Evening Post May 11) [Later report] Tidal disturbances continuing ebbs and flows every 20 min, rise and fall at wharf being nearly 1.2 m. Outer signalman at Heads reported moderate sea with a "long run on the beach". (Evening Post May 11) Disturbances continued in evening as long as observations were maintained. Tide ebbed and flowed generally once in 20 min, and the rise and fall varied from 0.6-1.2 m, sometimes more, sometimes less. Still disturbed on morning of May 12, but much less, the rise and fall being 5-15 cm. Ordinary tides dominant by this time. At Wellington Heads: high tide at about 3.10 pm, heavy sea on beach but not much more than after a SE gale when there has been a heavy sea at Heads (Evening Post May 12).

1877AD M8.3 southern Peru earthquake and tsunami:

This tsunami was as extensive, but not as damaging in New Zealand, as the 1868AD tsunami. It was generated by s a large earthquake off southern Peru, just north of the source of the 1868AD tsunami. The whole east coast of the North and South Islands was affected, the waves being amplified in many of the places that experienced high waves in 1868AD. Damage occurred in Northland, Coromandel, Gisborne, Banks Peninsula, and Oamaru. As in 1868AD, damage would almost certainly have been greater, had the highest waves coincided with high tide. Strong tidal currents on ports and harbours are commented upon in several historical accounts, this feature of the tsunami clearly causing concern to port authorities of the era.

1882AD earthquake:

One reference only describes this earthquake and apparent tsunami event. The reference is in the card index at Masterton Library. It refers to a newspaper article in a newspaper, of which copies are no longer available. The earthquake catalogue for the period 1855-1900AD is not complete for small and moderate earthquakes and an earthquake is not known for the date indicated. Further research is needed on this event.

1960AD M8.5 southern Chile earthquake and tsunami:

One of the largest and best recorded tsunami in New Zealand in recent times. As in 1868AD and 1877AD, the whole east coast was affected, with mostly minor damage reported in Northland, Coromandel, Tolaga and Tokomaru Bays, Gisborne, Napier, Banks Peninsula and near Brighton (Dunedin). However, no damage seems to have occurred within the Wellington region.

APPENDIX II

EXAMPLES OF APPROXIMATE 10 m INUNDATION CONTOUR

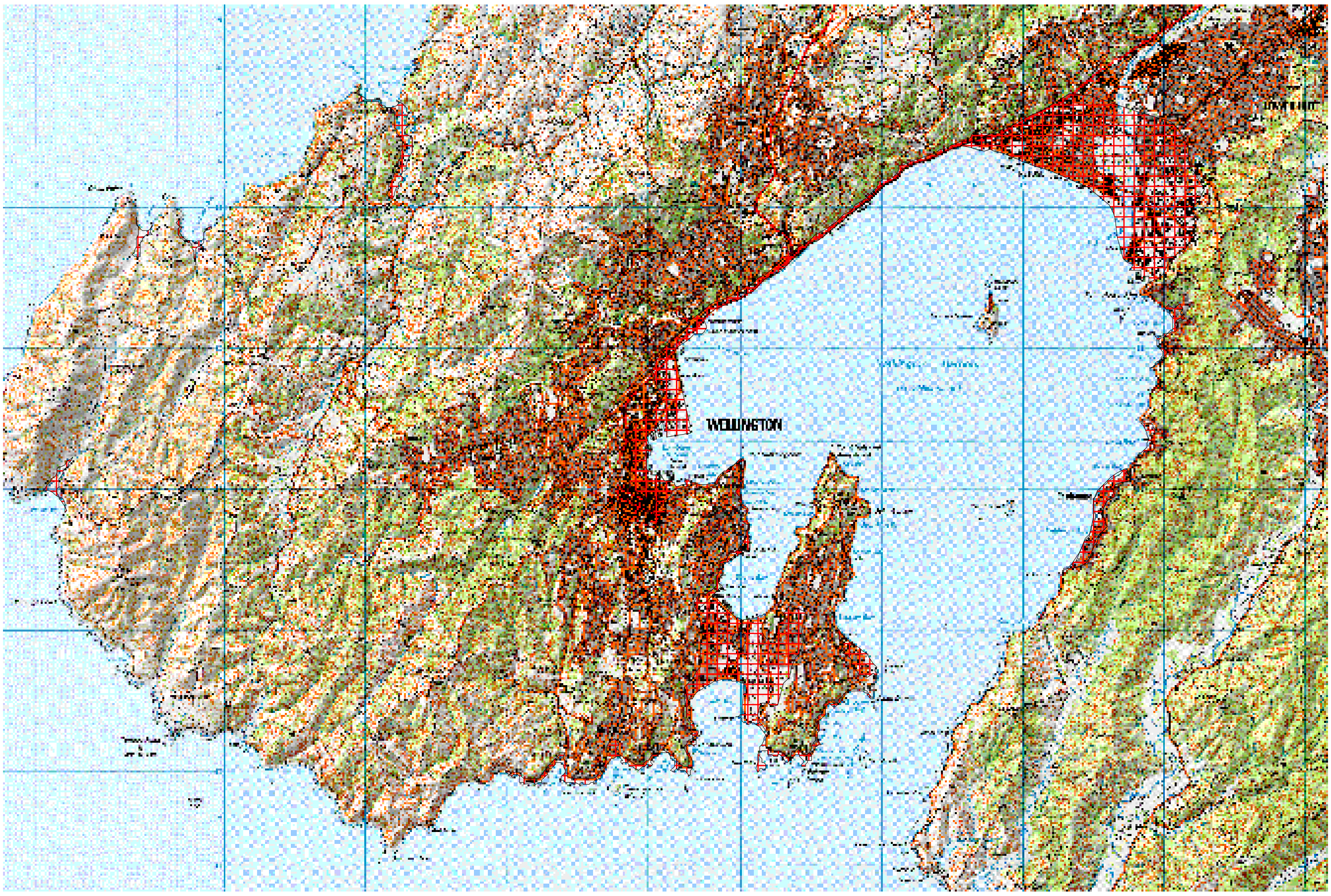

Figure II.A: Wellington harbour and Oteranga Bay area

Figure II.B: Porirua Harbour, Pauatahanui Inlet and coast

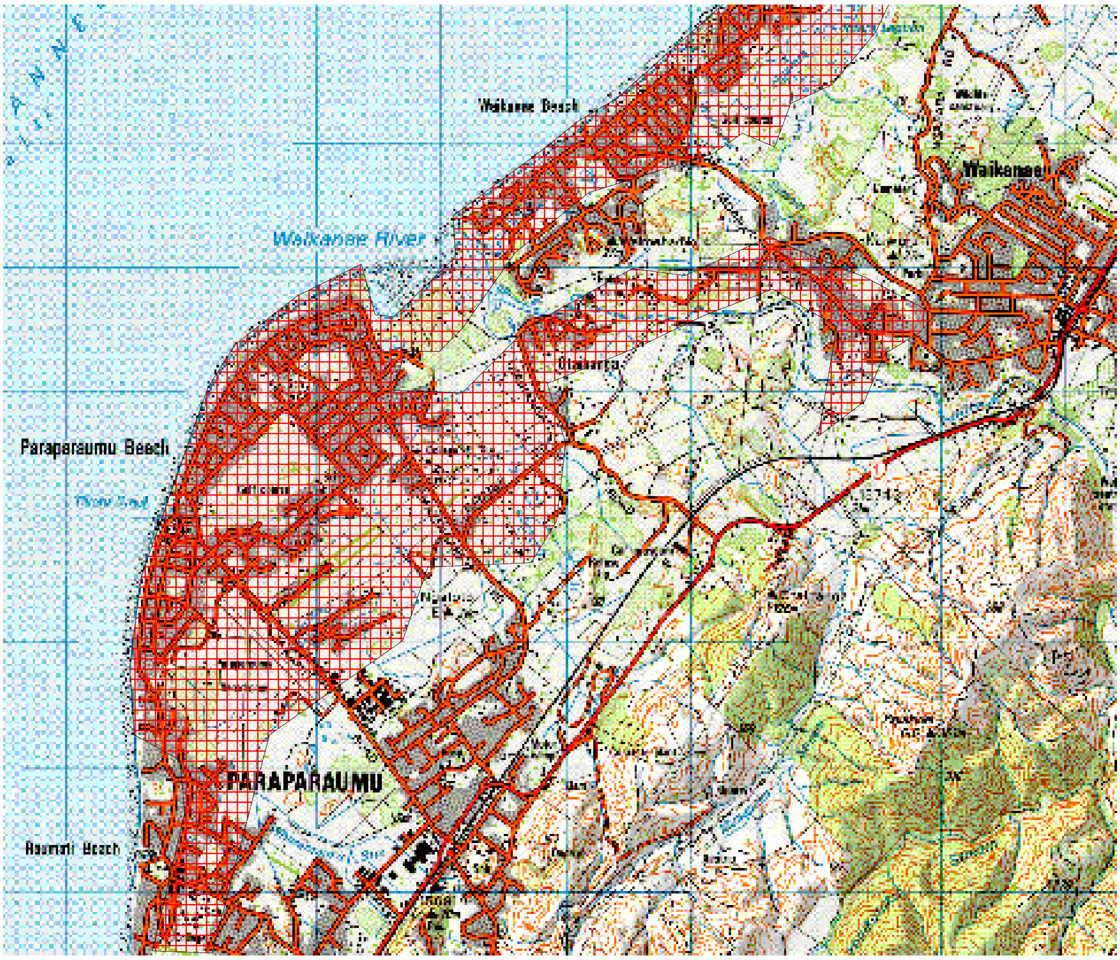

Figure II.C: Paraparaumu area

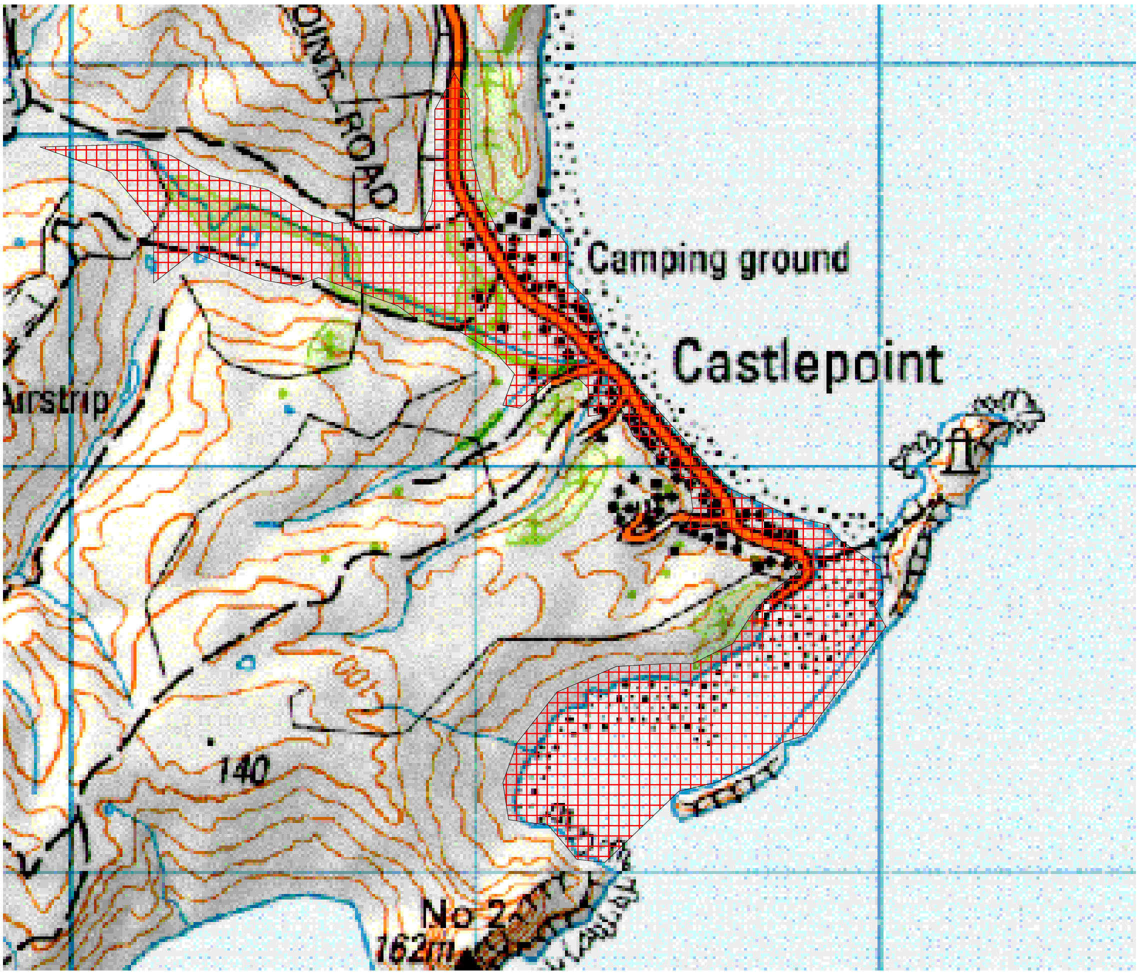

Figure II.D: Castlepoint area

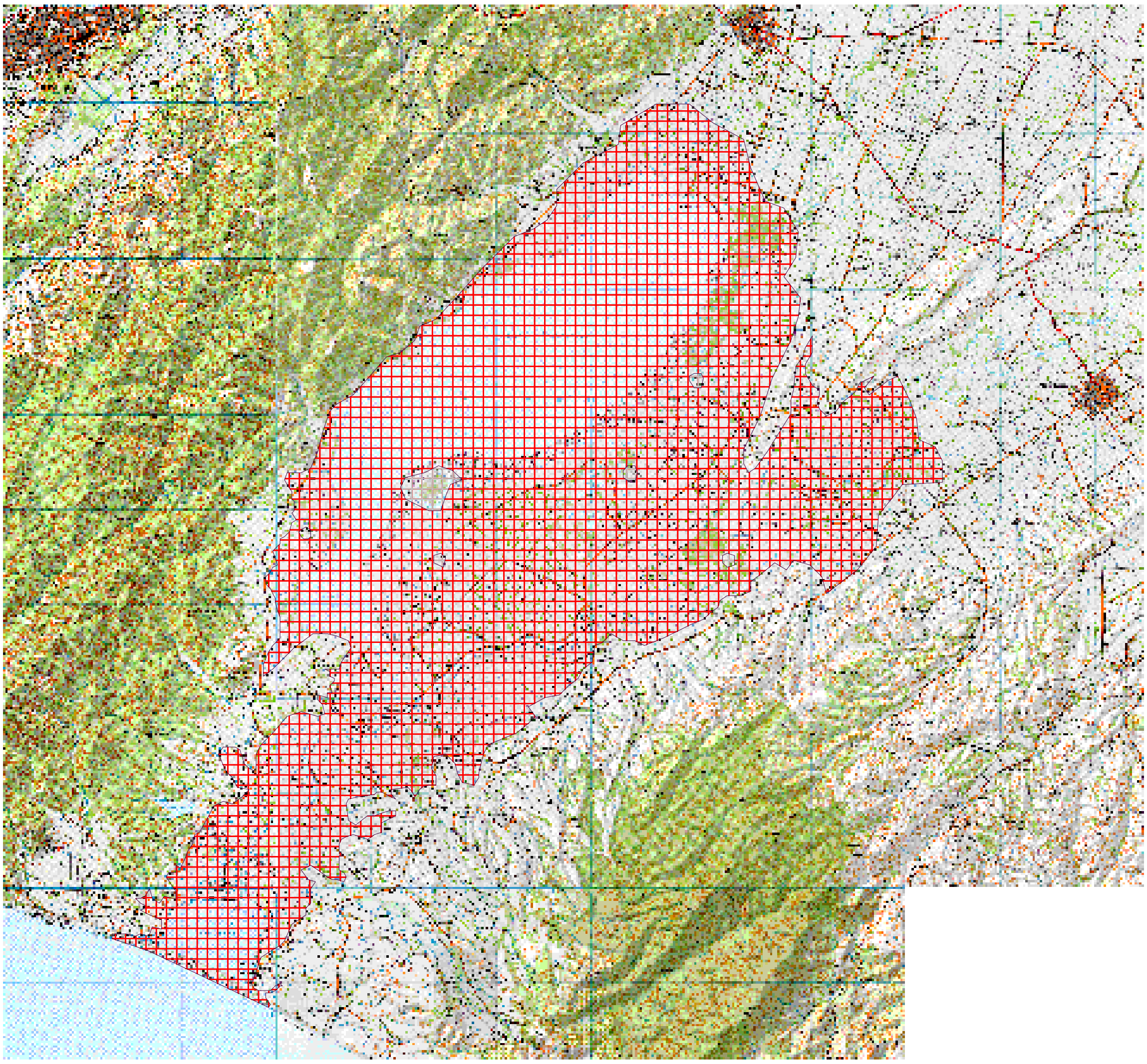

Figure II.E: Palliser Bay – L. Wairarapa area

APPENDIX III

EXAMPLES OF PRELIMINARY MODEL SIMULATIONS PERFORMING A RESONANCE SCREENING TEST TO DETERMINE HOTSPOTS FOR A "CONTINUOUS" WAVE TRAIN FROM THE EAST

Roy Walters & Rob Bell (NIWA)

The following diagrams illustrate the type of larger-scale modelling that can be utilised to initially identify "hotspots" that resonate at various selected wave periods. In this example, we have selected 15, 30, 60 and 120 minutes, which covers the frequency band characteristic of most tsunami. The finite-element model TIDE2D of the NZ region (Walters et al., in press) has been run with a continuous wave train with an arbitrary wave amplitude of 0.01 m along the far eastern boundary of the model along the 150° W meridian. Each diagram displays the amplification factor at any location. For example, 10 X is where wave amplitude is amplified ten times higher than the incident offshore wave from the east.

These results are only preliminary screening test for resonance along the coast and ONLY apply to the "open" coastline, rather than the harbours. Further work is required to resolve the nearshore and harbour seabed bathymetry in greater detail before any conclusions can be reached on tsunami amplification in any of the harbours or the nearshore behaviour and runup of actual tsunami events such as the one generated by the 1855 West Wairarapa earthquake.

The resulting tsunami wave train from the 1855 event exhibited wave periods in the range 15–30 minutes, with high amplitudes in Palliser Bay. The results from the resonance screening test for 15 and 30 minute periods (Fig. A.1 & A.2) show large amplification in the eastern side of Palliser Bay. This matches with the highest observed tsunami run-up height for the 1855 event of ~9–10 m at Te Kopi in eastern Palliser Bay.

Coastal resonance of an incoming tsunami wave train is determined by a number of factors including period (or wave length) of the waves, water depth on the continental shelf and shoreface and the shoreline planform shape (in a similar way that different resonant sounds are generated by different shapes and sizes of drums). At first glance, the high resonance on the west coast for a 120-minute wave train from the east seems counter-intuitive (Fig. A.4). However the wave train can easily propagate through Cook Strait, and at that period of 120 minutes, the basin shape between Taranaki and the Marlborough Sounds is conducive to resonant wave sloshing to and fro at that wavelength. However, at that period on the east coast, there is no major coastline features to cause resonance, except down the east coast of South island, where a resonance is set up between Banks Peninsula and Marlborough. However the east Wairarapa coastline is subject to resonance at the shorter 15–60 minute periods that encompass most tsunami frequencies.

The main message is that different areas around the "open" Wellington coastline resonate at different frequencies, so the impact of any particular tsunami wave train (which is usually a mix of different wave periods) is highly dependent on the frequency of the incoming wave train, its direction and the shape and seabed profile around the coastline. Knowledge of various resonant "hotspots" will enable future studies to be focused on those areas.

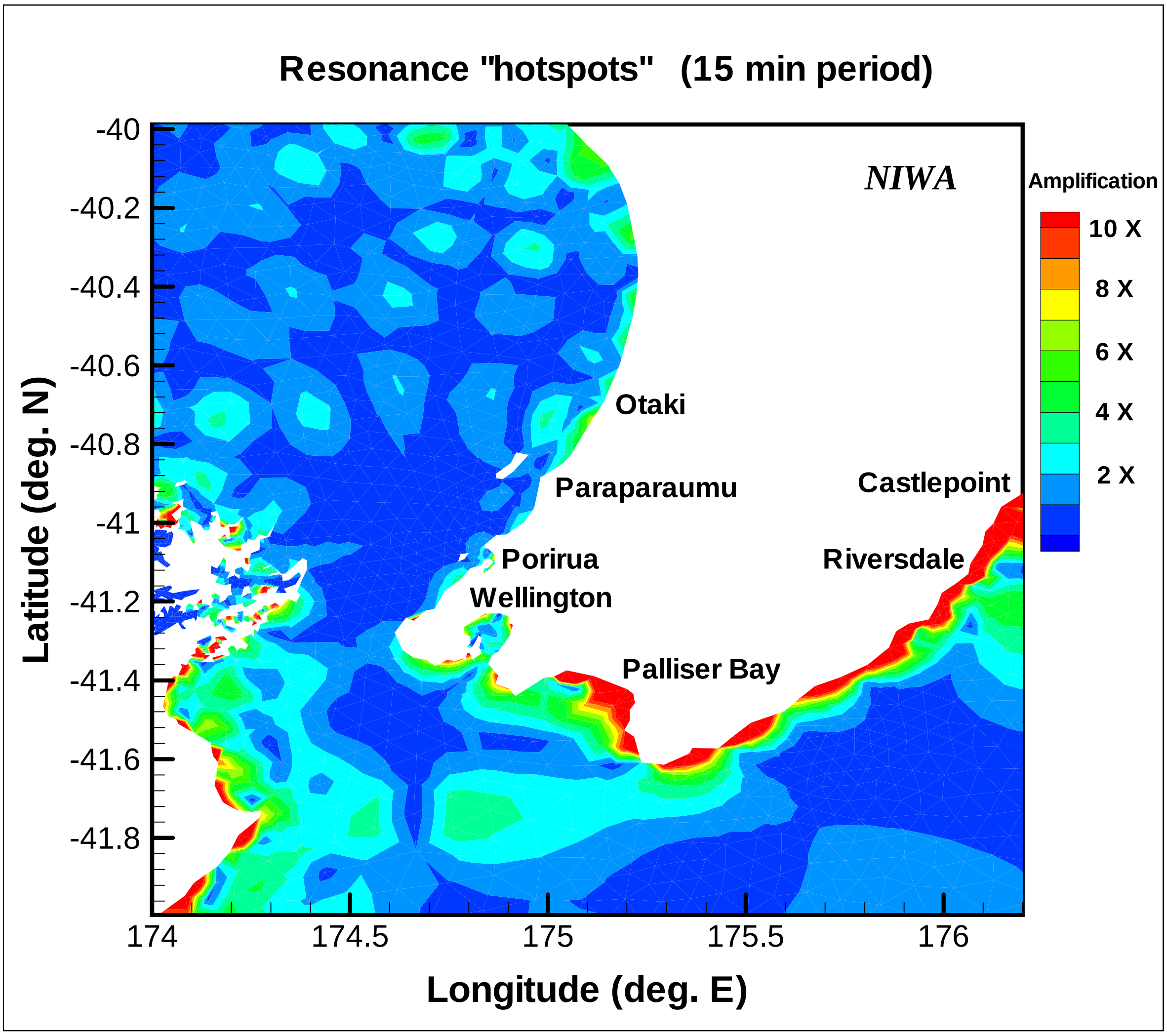

Figure III.A: Resonance "hotspots" in terms of amplification for an offshore wave train from the east at 15-minute periods. Red colour shows areas where the offshore wave height has been amplified by 10 times or more.

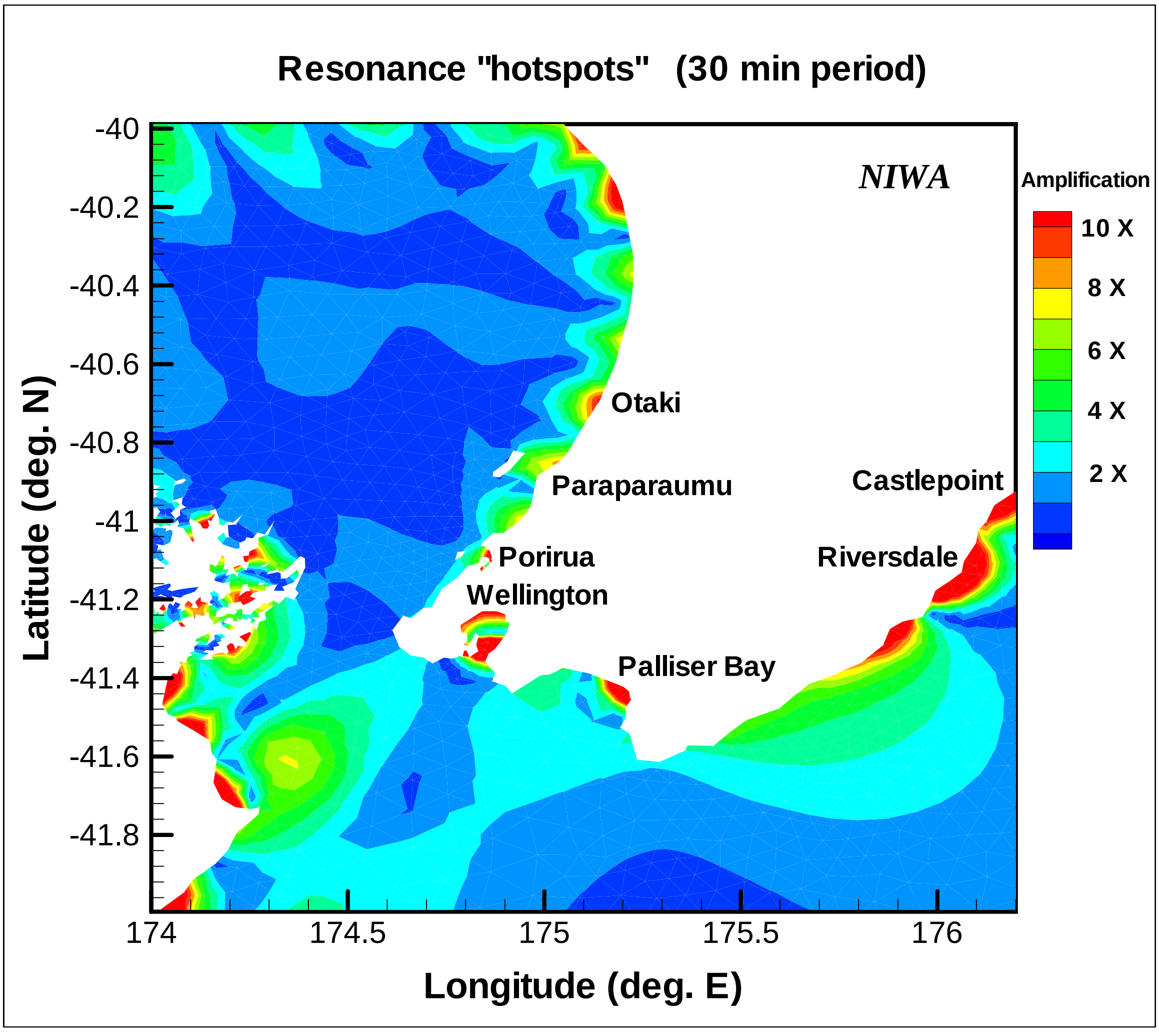

Figure III.B: Resonance "hotspots" in terms of amplification for an offshore wave train from the east at 30-minute periods. Red colour shows areas where the offshore wave height has been amplified by 10 times or more.

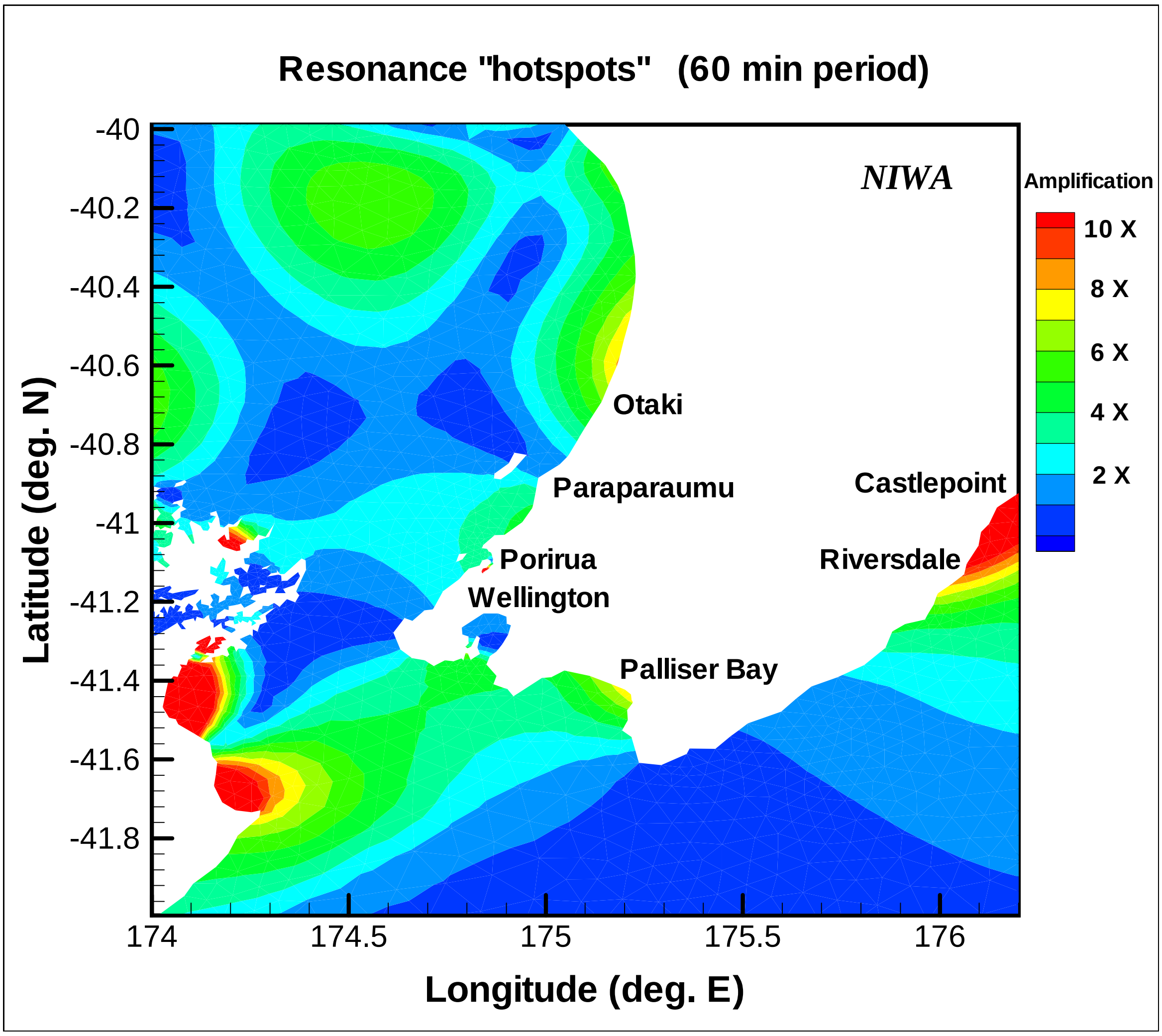

Figure III.C: Resonance “hotspots” in terms of amplification for an offshore wave train from the east at 60-minute periods. Red colour shows areas where the offshore wave height has been amplified by 10 times or more.

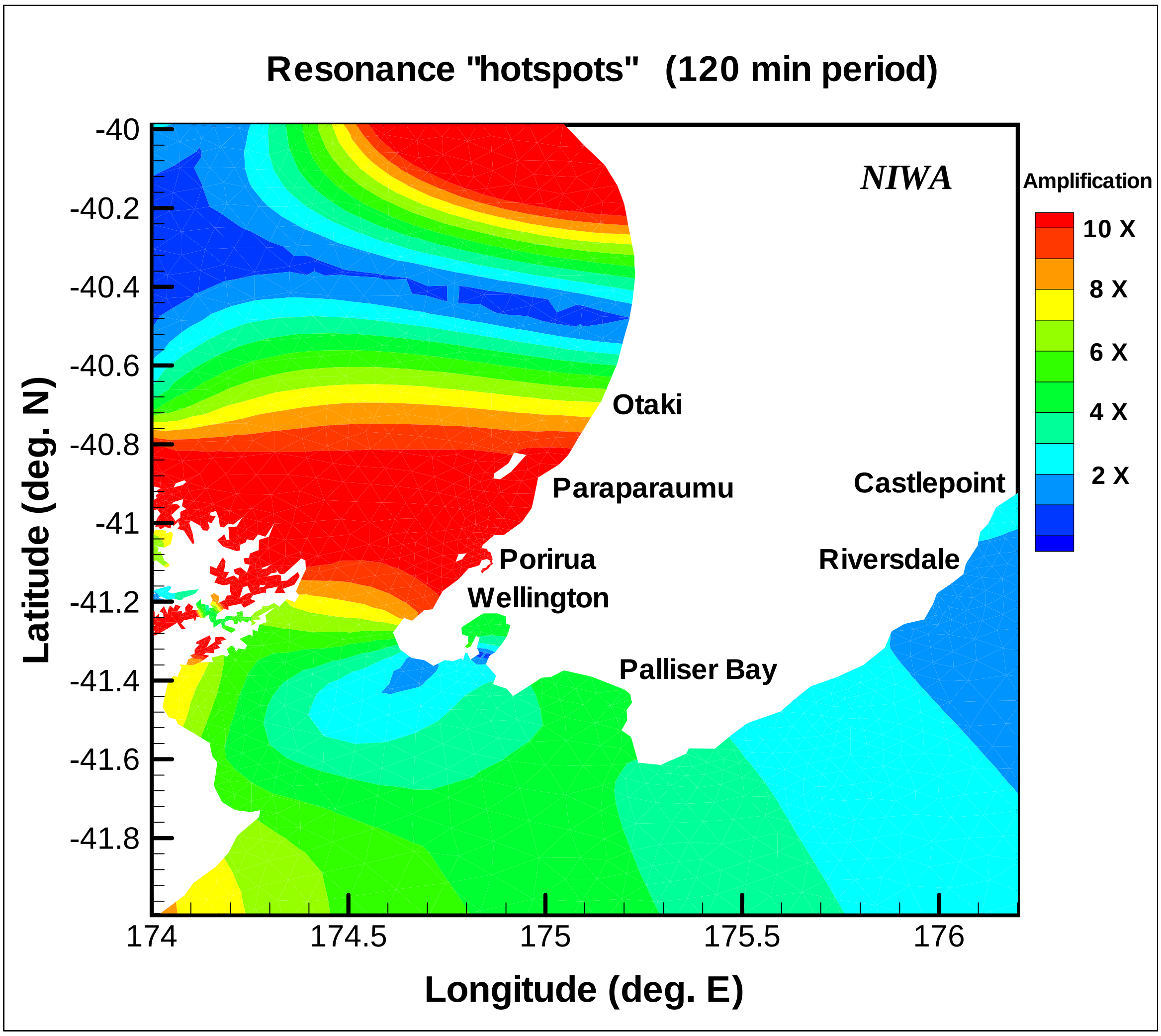

Figure III.D: Resonance "hotspots" in terms of amplification for an offshore wave train from the east at 120-minute periods. Red colour shows areas where the offshore wave height has been amplified by 10 times or more.