Community vulnerability to elevated sea level and coastal tsunami events in Otago

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Executive summary

The Otago coastline extends 480km from Chaslands in the south to the mouth of the Waitaki River in the north. Approximately 124,000 people (64% of Otago's population) live within five kilometres of this coastline. A number of the communities situated along the coast have a level of hazard exposure to elevated sea level (or storm surge) and tsunami events. This report assesses the vulnerability (rather than the risk)[1] of these coastal communities to these hazards. The report draws on tsunami and storm surge modelling undertaken by National Institute of Water and Atmosphere (NIWA) for the Otago Regional Council (ORC) in 2007/08, coastal topography data and local knowledge of each community. This information has been used to assess how people and the communities in which they live would be affected during credible, high magnitude tsunami and elevated sea level events. It is intended that this information will:

- increase community awareness of elevated sea level and tsunami hazard
- inform decision making on the development of warning systems and evacuation plans
- assist with the selection of land-use planning and development controls
- increase the resilience of infrastructure and utilities ('lifelines').

Community vulnerability to the following three scenarios has been assessed in some detail: a 1:500-year elevated sea level event, a 1:500-year far-field (South American) tsunami event and a 1:600-year near-field (Puysegur Trench) tsunami. The vulnerability of each community to lower magnitude, higher frequency events has also been assessed. The impact of events that have a higher probability of occurring is, in many cases, only marginally smaller than the three high magnitude scenarios outlined above. Therefore, many coastal communities have a level of exposure to elevated sea level and tsunami events that are likely to occur frequently.

Several communities investigated in this report are situated on low-lying land that is afforded a degree of protection from coastal dune systems, flood banks or sea walls. Cross section profiles and topographic data show that a breach or failure of these protective features during an elevated sea level or tsunami event could lead to widespread inundation of these areas. The lower Clutha Delta and South Dunedin areas are particularly vulnerable in this respect. This report does not assess the likelihood of those protective features failing, but highlights the important part they play in mitigating the risk.

Other communities, such as Pounawea, Toko Mouth, Taieri Mouth, Long Beach, Karitane and Kakanui, also have a high degree of exposure to elevated sea level and tsunami events because of their low-lying nature and their proximity to the coast or river mouths.

The level of vulnerability for each community is dependent, in part, on the amount of warning time before a tsunami arrives. In many cases, the time between a near-field earthquake (such as the modelled event for the Puysegur Trench) occurring, and the resulting tsunami affecting the coast, may be less than two hours. Remote communities

[1] See Glossary (at back) for the definition of 'vulnerability', 'risk' and other terms used in this report.

with limited communication links may be particularly at risk from these types of event if evacuation is the primary risk mitigation measure.

In summary, this report describes the varying degrees of vulnerability to elevated sea level and tsunami hazard along the Otago coastline.

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1. Introduction

Otago's coastline stretches 480 kilometres from Chaslands in the south to the mouth of the Waitaki River in the north. Its diversity, scenic attractions, and natural harbours and anchorages have, throughout its history, attracted people to live there, with approximately 64% of Otago's population (124,000 people) now living within five kilometres of the coast.[2] The two largest centres of population on the coast are Dunedin and Oamaru, but there are also numerous small fishing and holiday communities.

This report examines the vulnerability of 22 coastal Otago communities to hazards associated with elevated sea level[3] and coastal tsunami events.[4] The locations of these communities are shown in Figure 1. The current vulnerability of each community has been assessed by considering how people and facilities may be affected during a range of modelled elevated sea level and tsunami scenarios.

The vulnerability of each community has been determined by bringing together information about the nature and extent of tsunami and elevated sea level hazards, the number of people likely to be exposed to that hazard, and the amount and type of land use within each hazardous area. The intention of this report is to help communities understand the causes and consequences of credible high magnitude events in their area. It is also intended that the information contained within this report will:

- increase community awareness of elevated sea level and tsunami hazard
- inform decision making on the development of warning systems and evacuation plans
- assist with the selection of land-use planning and development controls
- increase the resilience of infrastructure and utilities ('lifelines').[5]

1.1 Outline of report

This report begins by providing the background to the development of this assessment of community vulnerability (Section 2). Section 3 describes the methods and sources used as part of the investigation. Sections 4 and 5, respectively, explain the nature of elevated sea level and tsunami hazards, including possible causes and sources of these events. The impact of sea level rise on the vulnerability of coastal communities to these events is discussed in Section 6.

Sections 7 to 19 provide a summary of each community's vulnerability to these hazards. An accompanying document ('the map book', ORC, 2012) contains the maps and diagrams that relate to each community. The purpose of the map book is to aid understanding; ideally, the maps should be viewed alongside the information provided in the report. The maps are referred to in this text as Figure A1, A2 etc.

[2] Statistics New Zealand, 'Are New Zealanders living closer to the coast?' Accessed online at www.stats.govt.nz/browse_for_stats/population/Migration/internal-migration/are-nzs-living-closer-to-coast.aspx

[3] 'Elevated sea level' refers to the combined effect of astronomical tides, storm surge and wave action.

[4] This report does not include a vulnerability assessment of lake-side communities.

[5] Although note that this report is not to be read as a 'lifelines assessment'.

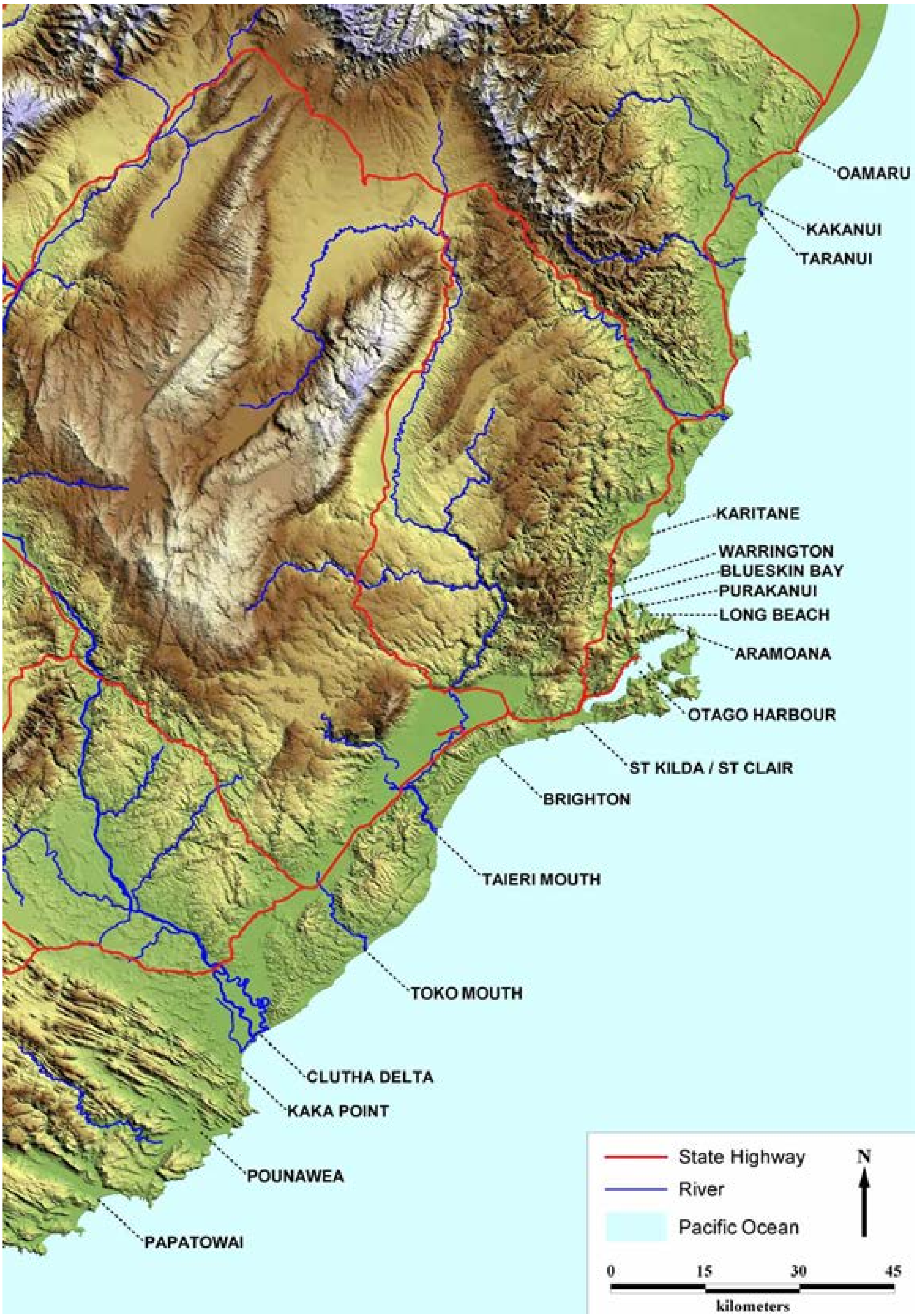


Figure 1. Coastal communities included in this report

2. Background

In November 2006, ORC contracted NIWA to carry out elevated sea level (storm surge) and tsunami inundation studies for specific communities on the Otago coastline. The aims were to identify:

- the level of inundation associated with credible elevated sea level events
- the level of inundation and water velocity associated with credible near and far-field tsunami events.

Elevated sea level modelling focused on events with a range of estimated return periods from 20 to 500 years (NIWA, 2008). Tsunami modelling analysed three different tsunami scenarios from two different potential tsunami sources: 100-year and 500-year return-period events, originating from South America (far-field events); and a 600-year return-period event, originating from the Puysegur Trench (a near-field event) (NIWA, 2007).

NIWA used comprehensive hydraulic models built specifically for their studies. The modelling also used Light Detection and Ranging (LiDAR)[6] topographic data, which the ORC had collected in 2004. The results of these two investigations were presented to Otago's territorial local authorities in 2008.

This present study has been prompted by greater public awareness of the potential consequences of large but infrequent events, increased demand for accessible natural hazards information, along with an ongoing trend of development in many coastal areas. By combining NIWA's findings with local information, this report provides an assessment of the level of vulnerability of each community in the event of elevated sea level or tsunami.

[6] See the Glossary for the definition of terms used in this report.

3. Methodology

3.1 Selection of study sites

A screening process was used to determine which communities to include within this current investigation, based on the following factors:

- exposure to elevated sea level and tsunami hazards, based on the NIWA analysis reported in 2007 and 2008[7]
- an estimate of the total population likely to be affected
- an assessment of the current level of development and potential for future development
- consultation with territorial authorities regarding their information needs.

This screening process established a total of 22 settlements where the existing population or future development has some level of hazard exposure. These communities are listed in Table 1. Settlements in close proximity have been grouped together to highlight their interdependency and combined vulnerability during tsunami or extreme sea level events.[8] There are other small settlements and unpopulated stretches of the Otago coast that are also subject to elevated sea level or tsunami hazard; however, these areas have not been included, as only a few people and facilities would be exposed to these hazards.

Table 1. Study sites, grouped by territorial authority (Refer Figure 1)

Clutha District	Dunedin City	Waitaki District
Papatowai	Brighton	Taranui, Kakanui
Catlins River mouth (including Pounawea, New Haven, Jack's Bay)	St Kilda / St Clair	Oamaru
Kaka Point, lower Clutha	Otago Harbour	
Toko Mouth	Long Beach, Aramoana, Purakanui, Harwood	
Taieri Mouth	Warrington, Blueskin Bay	
	Karitane, Waikouaiti	

It is noted that multiple study sites may be affected in some way by the same event. In other words, an event would not just affect an individual location, but would have an impact along a considerable length of the coast, including the coastline outside Otago.

3.2 Elevated sea level and tsunami scenarios

The level of vulnerability has generally been assessed under three modelled return-period events (or scenarios). While these events are unlikely to occur frequently, they may have significant consequences if they do. The scenarios include:[9]

- 1:500-year elevated sea level event

[7] NIWA modelled inundation extents for places of interest along 17 sections of the Otago coastline.
[8] For example, the Pounawea, New Haven and Jack's Bay settlements have been grouped together under the section on the Catlins.
[9] A return period was estimated by NIWA for each scenario. A 'return period' expresses the chance of an event occurring in any given year, regardless of when the last event of similar magnitude struck. For example, a 1:100-year event has a 1/100 or 1% chance of occurring in any given year.

- 1:500-year far-field (South American) tsunami
- 1:600-year near-field (Puysegur Trench) tsunami.

These scenarios are three out of the many different types of storm surge or tsunami events that could affect the Otago coastline. However, they were selected as they represent credible high magnitude (but not ‘worst case’) scenarios that could affect coastal Otago communities in the future. Smaller magnitude storm surge and tsunami events that occur more frequently may also have an impact on coastal settlements, and the report also identifies the vulnerability of communities to these types of event.

The level of vulnerability for each area has been assessed based on the extent and depth of inundation associated with the modelled elevated sea level and tsunami scenarios, and the water velocity for the modelled tsunami scenarios. This information has been overlaid onto aerial photographs and cross sections of low-lying areas. These maps and diagrams, presented in an accompanying document (ORC, 2012), show the extent and depth of inundation if elevated sea level and tsunami events do not coincide (i.e. it has been assumed that a tsunami will not occur at the same time as an elevated sea level event).

The maps and diagrams show the depth and extent of inundation at the level of current mean high water spring tide (MHWS).[10] Note that NIWA’s modelled inundation extents and water velocities assumed a situation in which no erosion of the coastline or flood protection features occurred and did not include the potential effects of debris, vegetation or structures.

3.3 Combined probability

The communities examined would be vulnerable to both elevated sea level and tsunami events. However, both types of event are independent of each other. In other words, the likelihood of one occurring is not affected by the likelihood of the other occurring. Furthermore, tsunami events that affect the Otago coast can occur from a number of independent sources.

To understand how likely it is that higher than normal sea levels will occur and affect a particular community, it is necessary to know the probability of a certain magnitude event occurring (whether due to tsunami or storm surge). For the purposes of this report, the likelihood of a water level of a certain height occurring in the next 100 years has been assessed, based on the maximum predicted levels for all the modelled tsunami and storm surge scenarios provided by NIWA (2007, 2008).[11]

Maximum water level is only one aspect of the hazard associated with tsunami and elevated sea level events.[12] Other factors, such as wave velocity and event duration, mean that a water level of a certain height resulting from a tsunami will have a different impact to the same water level resulting from storm surge.

[10] In reality, storm surge and tsunami events occur over several hours. Therefore, they would occur at different stages of the tidal cycle, and the difference in inundation level would be proportional to the tidal level.

[11] The likelihood of water levels of 1.5m, 2.0m and 2.5m above the current mean level of the sea occurring was calculated. The likelihood of water levels of 3.0m occurring was also calculated for Toko Mouth.

[12] Tsunami and storm surge events involve very different processes, with different characteristics.

Appendix 1 gives the equation used to calculate the combined probability of specified water levels occurring in the next 100 years.[13] The probabilities calculated using this equation are based solely on the events modelled and discussed in this report. In reality, there are an infinite number of possible storm surge and tsunami scenarios that could affect the Otago coastline. There is also potential for much larger, rarer events to occur than those discussed here. While all of the possible scenarios could not be modelled, their inclusion in the combined probability calculations would refine the returned values and provide further certainty of the likelihood of inundation occurring in the next 100 years. The calculated probabilities are therefore lower bounds.

The scenarios discussed in this report were selected because they represent credible scenarios that could occur along the Otago coastline, based on current knowledge and understanding of storm surge and tsunami events. There may, however, be a number of sources that could contribute to an event that have yet to be identified[14], and which may remain unidentified until after that event has occurred.

The modelled peak water levels for tsunami events were based on the assumption that each scenario occurred at the current level of MHWS. If an event were to occur at a lower tidal level, it is possible that the impact would not extend as far inland (or to the same height) as if it occurred at MHWS.[15] However, sea level is predicted to rise in the future[16], which would increase the chance of a tsunami or storm surge event occurring at a higher tidal level (and therefore resulting in a peak water level higher than those used in this report).

To account for these uncertainties, the likelihood of inundation reaching a certain level has been represented as a percentage range. As further modelling is completed, techniques improve and understanding of the rate of sea level rise increases, the probability of inundation occurring in the next 100 years will be refined and probability ranges reduced.

3.4 The relationship between water depth and velocity

Water depth and velocity directly determine the destructive potential of elevated sea level or tsunami events. As water depth and/or velocity increase, the risk to people and property also increases. To understand the possible consequences of inundation due to elevated sea level or tsunami events, flood water hazard guidance, developed by the New South Wales Government (2005), has been used to assess the potential effects of the modelled scenarios. Figure 2 shows the relationship between the depth and velocity of water and the resulting hazard. It is appropriate to apply this guidance to elevated sea level and tsunami events (E. Lane, pers. comm., 6 May, 2011) as there is no other published guidance specific to coastal flood hazard. However, this guidance only gives an indication of risk to people and property because it does not take into account

[13] A period of 100 years was chosen because Policy 24 of the New Zealand Coastal Policy Statement (NZCPS, 2010) states that ‘Hazard risks, over at least 100 years, are to be assessed’, with regard to factors that include ‘(d) the potential for inundation of the coastal environment, taking into account potential sources, inundation pathways and overland extent’.

[14] Unknown tsunami sources include, for example, unidentified fault lines, undersea landslides or volcanoes.

[15] Elevated sea level and tsunami events, however, typically occur over a period of several hours; therefore, an event is likely to occur across various tidal stages.

[16] MfE (2009) recommends planning for a sea level rise of 0.5 – 0.8m by the 2090s, relative to the 1980-1999 average.

variables such as event duration, debris movement and accumulation, erosion and wave activity, all of which are relevant to elevated sea level or tsunami.

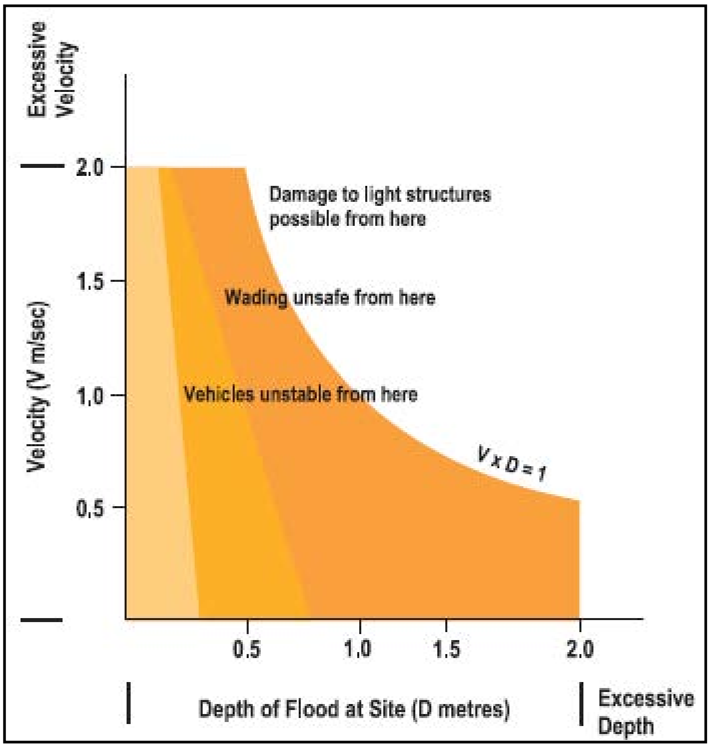


Figure 2. Hazard standard for water velocity and depth relationship (NSW Floodplain Development Manual, 2005). Note that this relationship has been derived from laboratory testing and observations of flood conditions that caused damage

Additional explanations provided in the source document (NSW Gov., 2005) include:

- At velocities in excess of 2.0 m/s, the stability of foundations and poles can be affected by scour. Also, grass and earth surfaces begin to scour and become rough and unstable.
- The velocity of water passing between buildings can produce a hazard, which may not be apparent if only average velocity is considered. For instance, the velocity of floodwaters in a model test increased from an average of 1m per second to 3m per second between houses.
- Vehicle instability is initially caused by buoyancy.
- At floodwater depths in excess of 2.0m and even at low velocities, there can be damage to light-framed buildings from water pressure, flotation and debris impact.

3.5 Sources of additional information

Census data from 2006 were used to determine the approximate resident population of each community. Inundation maps (NIWA, 2007; NIWA, 2008) were overlaid onto aerial photographs to identify areas within each community that may be subject to inundation during the modelled events.[17] ORC staff visited each community in 2011 to identify residential areas and infrastructure that may be affected by elevated sea level or

[17] Appendix 2 lists the capture date and agency responsible for the aerial photographs used in this report.

tsunami events. Consultation with territorial authorities helped to identify which communities have experienced recent population growth or development.

Combining this data has enabled an assessment of each community's vulnerability (i.e. the impact of inundation on people, buildings and infrastructure) in the event of elevated sea level and tsunami.

4. Elevated sea level

Elevated sea levels can occur as a result of a combination of tides, storm surge, wave set-up and wave run-up (Table 2).[18]

Table 2. Components of elevated sea level, including those that combine to create storm surge and those that have been combined to map inundation extents and depths for individual communities in ORC (2012)

		Component	Explanation
		Wave run-up	Additional height gained by breaking waves. Wave run-up is affected by weather, bathymetry and topography.
Extent of inundation mapped in ORC (2012)		Wave set-up	Persistent elevation of sea level through the effect of waves.
Extent of inundation mapped in ORC (2012)	Storm surge	Wind set-up	Piling-up of water against the coast by prevailing winds driving water currents towards the land.
Extent of inundation mapped in ORC (2012)	Storm surge	Inverse barometer (atmospheric pressure)	When atmospheric pressure falls, the mean level of the sea will rise by 1cm for every hectopascal decrease in pressure[19].
Extent of inundation mapped in ORC (2012)		Tide	Predicted local tidal cycle due solely to astronomical effects.

'Tide' refers to the periodic rise and fall of the waters of the ocean, caused by the attraction of the moon and sun, and occurring about every 12 hours. The tidal range along the Otago coast can be as much as 2.5m, making it an important component of elevated sea level events.

'Storm surge' occurs as a result of low atmospheric pressure and persistent wind stress (or wind set-up acting on the water surface). Low atmospheric pressure may result in sea levels higher than those caused by astronomical effects, while strong onshore winds result in the sea piling up against the coast.

'Wave set-up' and 'wave run-up' can further elevate sea levels. 'Wave set-up' is the increase in the mean level of the sea due to the effect of waves. 'Wave run-up' is the increase in sea level caused by waves breaking in the foreshore zone. The increase corresponds to each respective breaking wave. Since breaking waves are attenuated in sheltered areas such as inlets with short fetch, wave run-up is generally restricted to open coast sites.

The Figures in the map book which accompanying this report (ORC, 2012) show the extent and depth of inundation associated with elevated sea level, as a result of tide, storm surge and wave set-up, for a modelled 1:500-year event. These maps also show the maximum extent of wave run-up, which may extend beyond the inundation zone for a considerable distance, particularly on exposed stretches of coastline, and where the

[18] The combination of all these components in total is often referred to generically as 'storm surge'.
[19] A 'hectopascal' is a metric unit, equal to a millibar, which is used to measure air pressure.

land surface is relatively flat.[20] Locations within these limits are not predicted to be permanently inundated but may be susceptible to breaking surges.

4.1 Elevated sea level scenarios

NIWA carried out modelling for elevated sea level events with return periods of 20, 50, 100 and 500 years (NIWA, 2008). This report assesses the vulnerability of selected communities to the 1:500-year event in some detail, including mapping the modelled inundation depths and extents. This return period was chosen as it represents a credible high magnitude event that could conceivably occur during a person's lifetime[21], but does not represent a 'worst case' scenario. Additional information is also provided to help understand each community's vulnerability to lower magnitude events that occur more frequently.

In this report, elevated sea levels are described relative to mean sea level (MSL) (i.e. inundation depths are in displayed in metres above MSL).[22] Storm surges typically occur over a period of hours to days, and therefore will occur at different stages of the tidal cycle. Storm surge effects will usually be greater when they coincide with high tides (NIWA, 2008). Tidal range varies along the Otago coast, as demonstrated by the distribution of MHWS level, shown in Figure 3.

There are some limitations in the accuracy of the predicted elevated sea levels used in this report. These limitations are mainly due to the relatively short length and spatial extent of available data, the simplified approach used to calculate seabed and beach slope, and the neglect of complicated ocean dynamics in the surge and set-up calculations (NIWA, 2008). A further limitation is that the effects of erosion and debris accumulation were not included in NIWA's modelling process. This report identifies locations that may be susceptible to inundation if changes in coastal morphology were to occur in the future. The report does not, however, assess the likelihood of any features, such as flood banks or sand spits, which may provide a level of protection to these locations failing.

Despite the limitations outlined above, the modelled levels do provide an approximate and useful indication of the extent and depth of inundation likely to occur with each event. The use of high precision topographic data (LiDAR) means that landward extents and estimated depths of inundation are credible and relatively precise.

[20] Areas where noticeable wave run-up occurs include Toko Mouth, the upper Otago Harbour, Purakanui Inlet, Warrington sand spit, Kakanui and the Oamaru breakwater.

[21] A 1:500-year event has a 0.2% chance of occurring in any one year, and an 18% chance of occurring during the next 100 years.

[22] The levels have also been adjusted by +0.11m to account for the increase in sea level that has occurred since 1958, when the MSL datum (or Dunedin Vertical Datum 1958) was established.

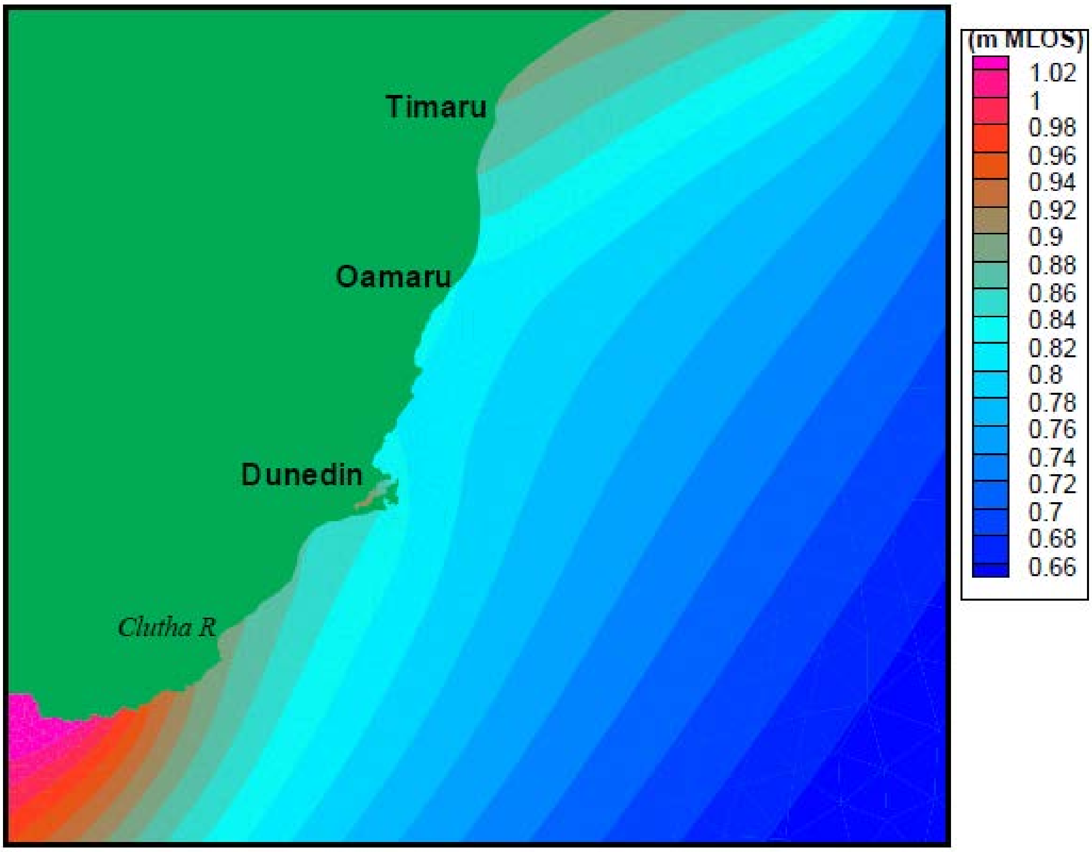


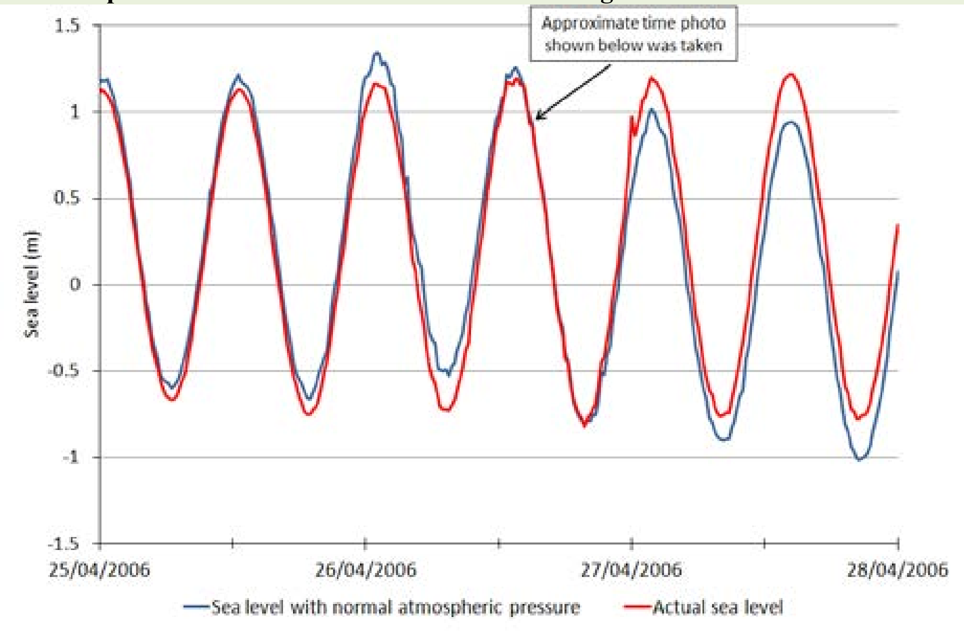
Figure 3. **Distribution of MHWS level in Otago waters. Levels are shown in metres above mean level of the sea (MLOS), based on a tidal model of New Zealand. (Image from NIWA, 2008)**

4.2 Elevated sea level and river flooding

Elevated sea level events are relatively infrequent. However, when they do occur, they can coincide with flood events on land, as they are often borne out of the same extreme low pressure weather systems that can produce heavy rain and river flooding (Box 1). Elevated sea levels may interact with flood flows in the lower reaches of coastal rivers and in stormwater outlets, and may impede water moving downstream. This can have the effect of increasing the flood level in the lower reaches of rivers.

Wave run-up and forces associated with elevated sea levels can also deposit sand at river mouths, blocking or impeding the flow of rivers to the sea. This could occur at river mouths along the Otago coast, including the Matau and Koau branches of the Clutha River/Mata-Au, the Tokomairiro River, the Taieri River and the Waikouaiti River. Although the interaction of elevated sea level and river flooding has not been modelled as part of this study, locations where this could occur are noted.

Box 1. Example of an elevated sea level event on the Otago coastline



The Figure above shows the effect of storm surge at ORC's Green Island sea level recorder in April 2006. From approximately 8pm on the 26th April onwards, observed (or actual) sea levels at Green Island were higher than the predicted astronomical tidal pattern, following the passage of an easterly front that passed over the lower South Island. High river flows and flooding occurred in many east Otago coastal catchments as a result of the heavy rainfall associated with this front, and the return period of measured rainfall totals and river flows was estimated at >50 years (NIWA/GNS, 2006; ORC, 2006).

A number of properties in Pounawea were inundated during this event. The photo below was taken on Pounawea Road just after midday on the 26th April (i.e. not necessarily at the time of maximum inundation, and before observed sea level started to exceed predicted levels at the Green Island gauge). The photo is courtesy of Dr. Mike Hilton, Department of Geography, University of Otago. The extent of inundation at Pounawea (as represented by the photo below) was less than that modelled by NIWA for a 1:20-year return-period storm surge event.

5. Tsunami hazard

5.1 What is a tsunami?

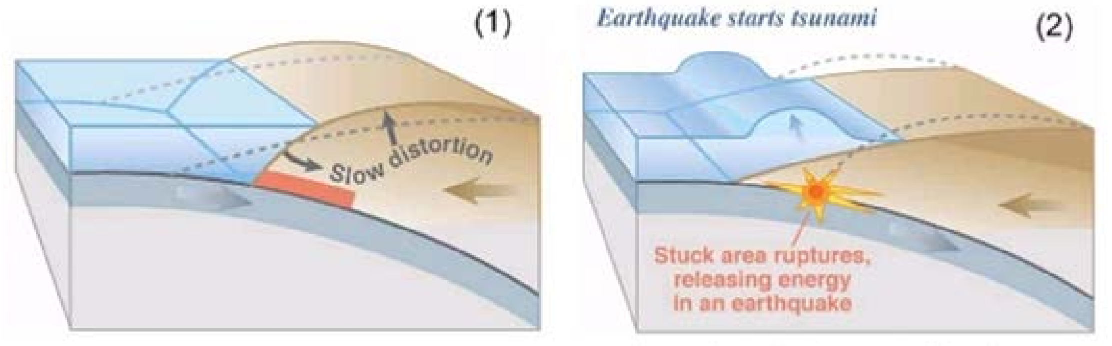
The Japanese word ‘tsunami’ translates into English as ‘harbour wave’. Despite its common usage, the term is not strictly correct, as tsunami events are not limited to harbours. A tsunami is, in fact, a natural phenomenon consisting of a series of waves caused when a large mass of earth on the bottom of the ocean drops or rises, rapidly displacing the water above it (Saunders *et al*., 2011). The most common source of damaging tsunamis worldwide are large earthquakes (M > 8)[23], which cause a vertical displacement of the seabed along a fault line. This type of displacement commonly occurs in large subduction zones, where the collision of two tectonic plates causes the oceanic plate to dip beneath the continental plate to form deep ocean trenches.[24] Other potential causes of tsunami are volcanoes or underwater landslides. Tsunami observations generally demonstrate an increase in wave height with proximity to the source (National Research Council, 2010).

A large tsunami may feature a series of waves arriving over a period of hours, with significant time between the wave crests. The first wave to reach the shore may not be the largest. Over deep water, the height of a tsunami wave above the level of the sea will probably be small and barely noticeable. When the wave enters shallow water, however, it will rise in height (Saunders *et al*., 2011). Generally, the approaching wave does not break, but instead resembles a fast-moving tidal bore, as it moves inland.

Owing to the volumes of water and the high energy involved, tsunamis can violently flood coastal regions (Saunders *et al*., 2011). In recent times, this was demonstrated during the Boxing Day tsunami, which was caused by an earthquake off the coast of northern Sumatra in 2004 (Borrero, 2005), and the earthquake and tsunami that affected the eastern coast of Japan in March, 2011 (Lekkas *et al*., 2011).

[23] M (or ‘magnitude’) characterises the amount of energy released by an earthquake. It is expressed as a numeral between 1 and 10. The scale is logarithmic (e.g. an earthquake of M5.0 has a shaking amplitude 10 times larger than one that measures M4.0).

[24] As the sea floor is abruptly deformed by a large earthquake, it vertically displaces (or moves) the overlying water from its equilibrium position. The waves formed in this way are then sustained by gravity as they propagate outwards. (See the Figure below, sourced from U.S. Geological Survey, 1999.) Movement on normal faults will also cause displacement of the seabed, but the size of the largest of such events is normally too small to give rise to a significant tsunami.



Stuck to the subducting plate, the overriding plate gets squeezed. Its leading edge is dragged down, while an area behind bulges upwards. This movement goes on for decades or centuries, slowly building up stress.

An earthquake along a subduction zone occurs when the leading edge of the over riding plate breaks free and springs seaward, raising the sea floor and the water above it. This uplift starts a tsunami.

Tsunami events are not weather related and can occur at any time of the year and at any time of the day or night. The hazard associated with tsunami waves does not necessarily diminish if they occur at low tide, as there is greater potential for people to access and use the intertidal zone at this time.

5.2 Terms associated with tsunami events

Often the first indication of a tsunami arriving is that the water retreats from the beach before the arrival of the first wave, although this does not occur in all instances. The retreat of water is referred to as the ‘trough’. Water can recede for an extended period before the arrival of the tsunami.

‘Tsunami amplitude’ refers to the height of the tsunami crest above the undisturbed level of the sea (in this case, MHWS) at the time of the event (Figure 4).

The effects of the tsunami on land can best be described by referring to the level of wave run-up. ‘Run-up’ is the vertical height above MSL that the tsunami reaches at the inland limit of inundation (Saunders *et al*., 2011) (Figure 4). Tsunami run-up is influenced by the shape of the ocean floor and coastline, and the velocity of the incoming tsunami. Areas of coastline that are orientated towards the incoming tsunami will experience higher tsunami velocities and therefore higher wave run-up. In sheltered bays and harbours that are lee to the incoming tsunami, the run-up height will be less, but will vary with each wave.

The tsunami inundation modelling assumed that the tsunami would occur at MHWS.[25] In reality, the effects of a tsunami will occur over a period of hours and will therefore be observed at different stages of the tidal cycle. The height and landward extent of the run-up associated with a tsunami wave may be influenced by the tidal level at the time that the tsunami occurs (i.e. the higher the tidal level at the time the tsunami wave arrives, the further inland the tsunami run-up may extend).

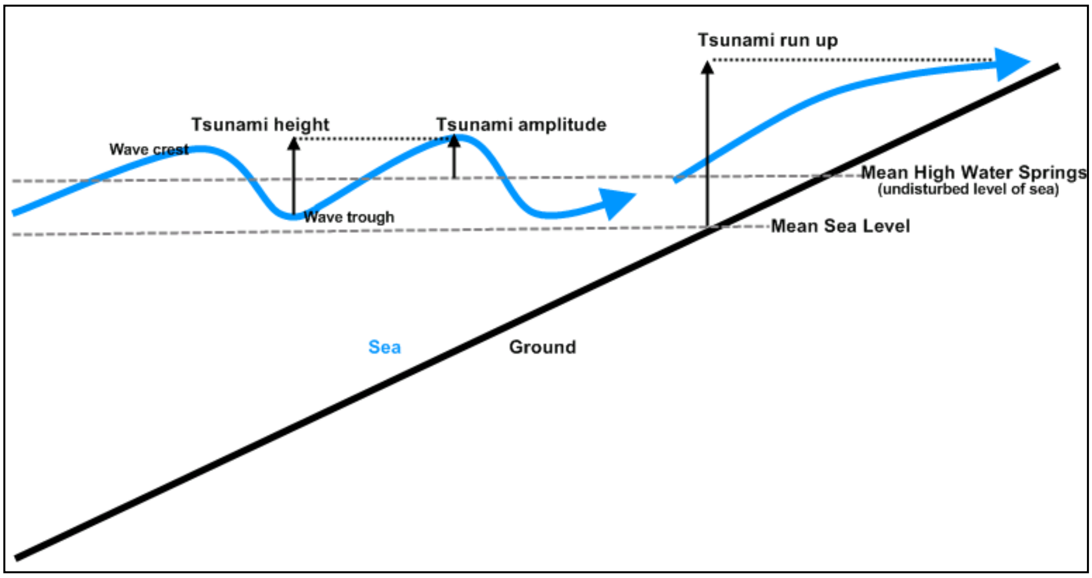
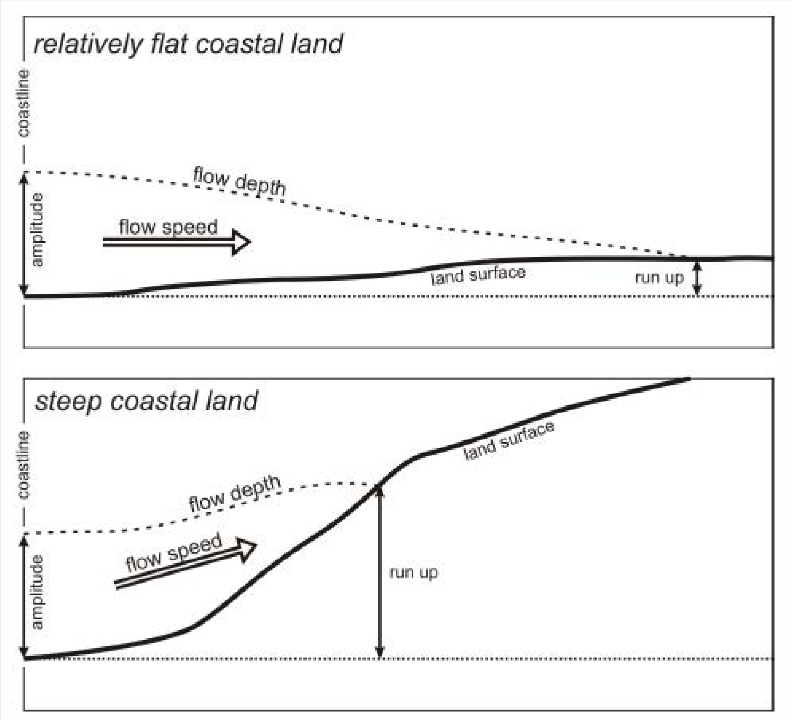


Figure 4. Diagram showing tsunami-wave amplitude and run-up. Amplitude is measured relative to the undisturbed level of the sea (which is MHWS, for the purpose of this report), while wave run-up is measured relative to MSL

[25] MHWS is variable along the Otago coast (as shown in Figure 3), but, for the purposes of NIWA’s tsunami modelling, was taken to be 0.9m above MSL (NIWA, 2007).

Box 2. Effect of coastal topography on inundation distance and run-up of tsunami events



The topography of land next to the coast will affect the distance a tsunami event will travel inland and the maximum run-up height. The diagram above shows that, for gently sloping topography, the run-up may be minimal, even though the tsunami impacts (resulting from other characteristics such as wave velocity, debris accumulation and subsequent backwash) can be huge. For steep slopes, the run-up will be greater (Figure from Saunders *et al*., 2011).

5.3 Sources of tsunami on the Otago coast

The Otago coastline could be affected by tsunamis of varying size and originating from many sources. NIWA investigated all credible sources of tsunami that could impact on the Otago coast (NIWA, 2007). These sources include a distant (far-field) source, from around the perimeter of the Pacific Ocean (often referred to as the 'Pacific Ring-of-Fire'), and local source (near-field) tsunamis, sourced from local offshore faults and nearby subduction zones, such as the Puysegur Trench to the south of New Zealand's South Island (Figure 5).

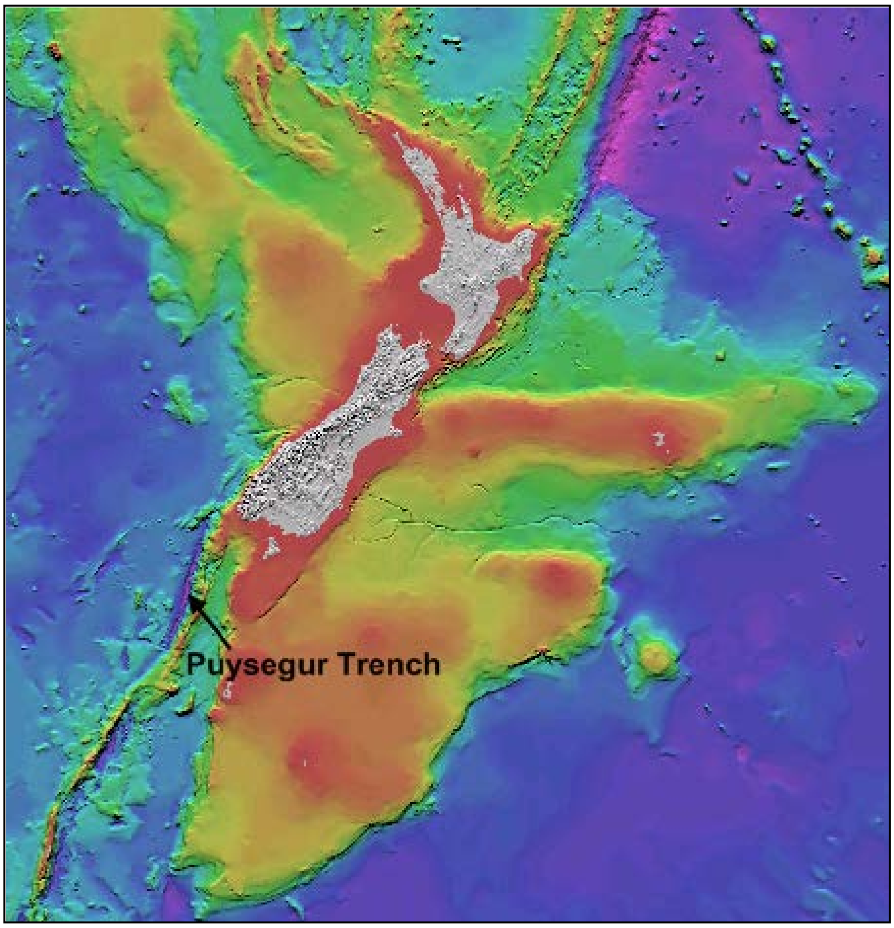


Figure 5. Bathymetric image of the area surrounding New Zealand. The location of the Puysegur Trench is also shown (source: www.niwa.co.nz)

NIWA concluded that both near and far-field earthquakes can generate tsunamis that could affect the Otago coast. The northern stretch of the Otago coastline (north of the Otago Peninsula) generally has a greater level of exposure to tsunami generated from South America, while the southern stretch of coastline (south of the Otago Peninsula) generally has a greater level of exposure from near-field subduction zone events in the Puysegur Trench (Figure 5). This difference is mainly due to the local geography and aspect of these two sections of coast. The coastline north of the Otago Peninsula has a more easterly aspect and is therefore more exposed to tsunami waves approaching from South America. The Otago Peninsula may also have a moderating effect during a Puysegur Trench tsunami, with refraction of waves occurring along the coastline to the north of this feature. Communities to the south of the Otago Peninsula are also closer to the Puysegur Trench.

NIWA identified that the largest tsunami faced by the Otago region is likely to be associated with a large subduction zone earthquake on the Puysegur Fault. This is due to the proximity of this potential tsunami source and its potential to generate large earthquakes. The impact of a tsunami generated from the Puysegur Trench is likely to be considerable for the southern part of the coast (NIWA, 2007).

Other sources of tsunami include offshore local faults, such as the Castle Hill, Akatore, Takapu and Waihemo fault systems (Figure 6) and continental shelf submarine landslides. NIWA (2007) concluded that the effects of tsunamis generated by offshore local faults are likely to create 'small' tsunamis with water-surface displacement of up to two metres. Modelling of a continental shelf submarine landslide scenario showed that maximum water levels of up to two metres at some coastal locations may be generated. However, the effect of landslide events may be moderated because they have far smaller wavelengths that are attenuated as they travel across the continental shelf towards the coast. NIWA found that locally generated tsunamis may have a significant impact on part of the Otago coastline only, due to their location or the orientation of the fault or submarine landslide.

While the impacts of locally generated tsunamis are not investigated in any detail in this report, they are identified within the relevant community sections below.

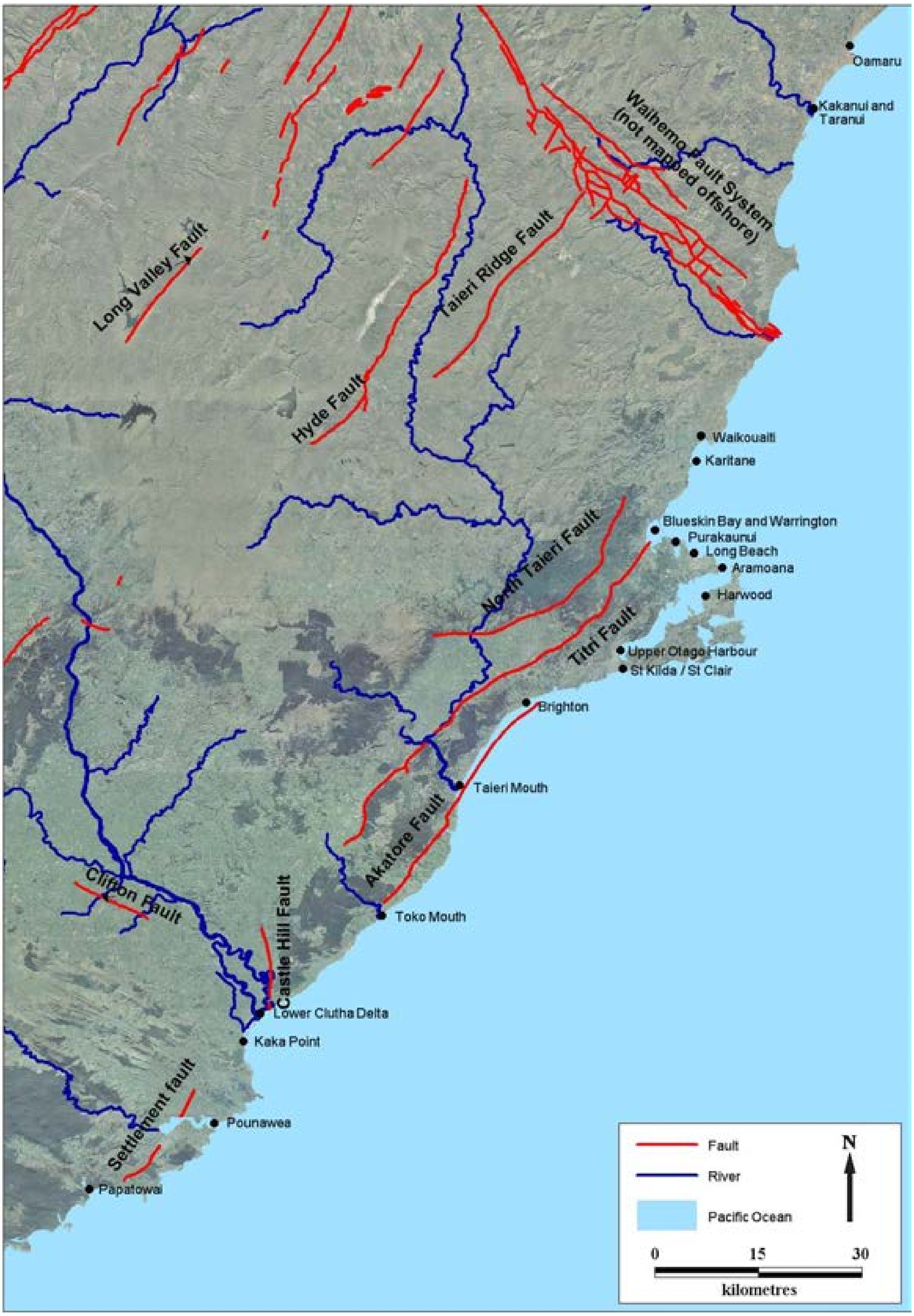


Figure 6. **Location of mapped active faults in eastern Otago[26] and the location of coastal communities included in this report**

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[26] Note that this map excludes offshore faults, including the Takapu Fault, which runs approximately parallel with the Akatore Fault (Norris & Litchfield, 1996). The location of offshore faults is often difficult to determine precisely.

5.4 Modelled tsunami scenarios

NIWA (2007) modelled three credible near and far-field sources of tsunami that could threaten the Otago coastline. The results of the modelling for two of these scenarios have been used in this assessment of community vulnerability:[27]

- the near-field (Puysegur Trench) 1:600-year tsunami, occurring at MHWS
- the far-field (South American) 1:500-year tsunami, occurring at MHWS.

Near-field (Puysegur Trench) earthquake

The Puysegur Trench is a continuation of the same tectonic plate margin as the Alpine Fault and is formed as the Australian continental plate is being subducted beneath the Pacific Oceanic plate (Figure 5). Earthquakes greater than magnitude 7 are known to have occurred in the Puysegur Trench area (Table 3).

Table 3. Recorded earthquakes in the Puysegur Trench region

Location	Date	Magnitude	Depth (km)
Puysegur Bank	3rd November 1918	6.7	8 ± 5
Puysegur Bank	1st September 1945	7.4 - 7.7	28 ± 5
Solander Trough	25th September 1968	6.3	4
Puysegur Bank	12th October 1979	7.2	12
Resolution Ridge	31st January 1985	6.2	27
Puysegur Trench	23rd November 2004	7.1	10

When a large earthquake occurs in the Puysegur Trench area, it is likely to cause vertical displacement along the fault. This type of fault motion has the greatest potential to cause a tsunami as it affects the whole water column (see Section 5.1). The devastating tsunami that struck the east coast of Japan in March 2011 was caused by a magnitude 9 earthquake occurring on a subduction zone (Lekkas *et al.*, 2011).

Large (M > 8.1) earthquakes have occurred further south of the Puysegur Trench, near the Macquarie Ridge and Balleny Islands. However, these have been strike/slip earthquakes that typically involve horizontal motion along the fault and therefore have low potential to generate a tsunami as large amounts of water are not displaced. NIWA (2007) found that the most likely source of a near-field tsunami for the Otago coast was a subduction earthquake event on the Puysegur Fault.

Anecdotal evidence suggests that several tsunamis in pre-European times caused a large number of deaths. These include a tsunami reported to be 10m high that killed several Maori walking along the beach at Orepuki in Southland in 1820.[28] Such a tsunami could have originated in the Puysegur Trench area and would also have affected the Otago coastline.

[27] The extent of inundation under a third modelled scenario (a 1:100-year far-field tsunami) on coastal communities has not been mapped. However, where such an event (which has a higher likelihood of occurrence and a lower magnitude) is likely to have a substantial impact on a particular community, its possible effects have been described.

[28] http://www.eqiq.co.nz/riskmaps/south-si.aspx

Far-field (South American) tsunami

Earthquakes with magnitude greater than 8 are the most common source of damaging tsunamis worldwide (NIWA, 2007). Approximately 80% of these earthquakes occur around the perimeter of the Pacific Ocean. For a far-field tsunami to have a significant impact on the Otago coastline, the outgoing wave needs to be orientated towards the Otago coast. NIWA identified South America as being the most likely source of a far-field tsunami with the potential to affect the Otago coast. This is because tsunamis generated by fault rupture sources in South America are:

- highly likely to be orientated towards New Zealand
- uninhibited by other landmasses that may disperse the wave
- of a magnitude to produce significant wave heights on arrival at the New Zealand coast.

Large earthquakes with the potential to generate a tsunami typically occur off the coast of South America approximately every 45 to 50 years (NIWA, 2007). The impact on New Zealand would vary depending on where the earthquake was located. Generally, the effects from a far-field tsunami originating off the South American coast would be greater north of the Otago Peninsula, due to the orientation of the coastline, tsunami wave and the shape of New Zealand's offshore continental shelf. Tsunamis of South American origin would take approximately 15 hours to reach the Otago coastline. Modern-day monitoring and communication networks would allow the physical characteristics and time of arrival of such a tsunami to be understood well before it reached the Otago coastline.

5.5 Uncertainty of tsunami modelling

The historical record of tsunamis in New Zealand is short, going back about 165 years (Saunders *et al*., 2011). Therefore, the full range of possible tsunami events that could affect the Otago coastline might not have yet been experienced, as the recurrence intervals of large earthquakes capable of producing tsunamis can be in the realm of hundreds to thousands of years. Consequently, complex models were used to determine the likely behaviour of tsunamis; even so, such modelled data will always have an inherent level of uncertainty.

Saunders *et al*. (2011) describe four levels of tsunami modelling:

- a simple 'bathtub' model that projects the level of maximum wave height inland (level 1)
- a rule-based wave height attenuation inland from the coast (level 2)
- a computer-derived simulation model that allows for added complexities such as surface roughness and refraction (level 3)
- an envelope of inundation extents from multiple computer models covering all credible scenarios (level 4).

The modelling undertaken by NIWA (2007) used to inform this investigation sits at level 3 within this scale as it provides one set of computer-derived modelling results. These results do incorporate the complex effects of the ocean floor and coastline on tsunami waves. Saunders *et al*. (2011) recommend that level 3 and 4 modelling is suitable for inclusion in Land Information Memoranda (LIMs) and can be used to inform evacuation planning and other emergency management requirements, and for land-use planning purposes.

6. The impact of future sea level rise

The NIWA studies also modelled the impacts of 0.3m and 0.5m of sea level rise on elevated sea level (storm surge) and tsunami scenarios. When the modelling was undertaken in 2006-2007, this range of sea level rise had been adopted as a realistic range of predicted increase in sea level by the end of the 21st century (IPCC, 2001).[29]

In general, the depth and extent of inundation were shown to increase with sea level rise for both storm surges and tsunami. Maximum water speed associated with tsunami events was also shown to increase with sea level rise for any given tide. It is worth noting that sea level rise may result in erosion and other morphological changes on the coastline. The extent or nature of these changes is as yet unknown, but they are likely to have an additional influence on the extent of inundation caused by elevated sea level and tsunami events.

For the purpose of this study, the present sea level is seen as the most relevant when assessing the vulnerability of coastal communities. The NIWA modelling that incorporated sea level rise may be used for future planning, and this information is available from ORC on request. The two supporting NIWA reports also provide further details about the effects of sea level rise.

[29] MfE (2009) recommends planning for a sea level rise of 0.5 - 0.8m by the 2090s, relative to the 1980-1999 average.

7. Papatowai

7.1 Community description

The settlements of Papatowai and Maclennan are located in South East Otago, near the mouth of the Tahakopa and Maclennan rivers (Figure 1 and Figure A1).[30] In 2006, the resident population in the wider area was 78 (from census data), although this number can be significantly higher at times, due to tourists visiting the area. Many residents live in the rural area outside Papatowai and Maclennan, but there are also a number of permanent residents who live in these settlements, which are situated beside the Tahakopa and Maclennan rivers. Papatowai Township is the larger of the two communities and is a mix of permanent residences and cribs, with a number of tourism-based activities and accommodation options.

Development is able to occur on empty sections as of right within the Papatowai Township, which is zoned 'Rural Settlement Resource Area' (CDC, 1998). However, infrastructure constraints (such as wastewater capacity) would limit this in some cases. Beyond the rural settlement zone, consent authority approval is required for development in land zoned 'Coastal Resource Area', with natural hazards a relevant matter to be considered by the consent authority.

Figure 7. Bridge across the Tahakopa River, and low-lying land at the northern entrance to Papatowai (June 2011)

7.2 Effect of elevated sea level and tsunami events

Elevated sea level

The maximum elevated sea level for the modelled 1:500-year event would be 1.1m above MHWS at Papatowai (Table 4). This would result in both sides of the Tahakopa River being inundated to a depth of more than 0.5m for up to 5.5km inland. Both sides of the Maclennan River would also be inundated to a similar depth for up to 2km above the confluence with the Tahakopa River. A more frequent event with an estimated 1:20-year return period would also inundate much of the low-lying, flat land alongside these rivers, as the difference in water level between this and a 1:500-year event is only 0.2m (Table 4). Flooding in the Tahakopa and Maclennan rivers may occur in conjunction

[30] Refer to the map book (ORC, 2012) for all Figures beginning with 'A'.

with elevated sea level events, although the interaction of these two hazards has not been modelled as part of this study. (See Section 4.2.)

Table 4. The level of the sea (relative to MSL) at MHWS and for a range of modelled elevated sea level events at Papatowai. The percentage chance of a particular elevated sea level event occurring in any 100-year period is shown in brackets

Return period in years (chance of occurring in any 100-year period)	MHWS	20 (99%)	50 (87%)	100 (63%)	500 (18%)
Water level (m above MSL)	1.0	1.9	1.95	2.00	2.1
Existing houses affected?	No	Possible	Possible	Likely	Likely

Far-field tsunami

The times series modelling (Figure A5) undertaken for the 1:500-year far-field tsunami shows that a series of waves would reach Papatowai about 15½ hours after the earthquake. The third wave would be the biggest and would arrive about 4 hours after the first wave, with many smaller waves likely to occur for up to 10 hours after this. The maximum wave run-up observed at Papatowai from this scenario was 2.6m above MSL (Table 5). This amount of run-up would result in 0.5 to 1.0m of inundation along the eastern side of the Tahakopa River to the north of the Papatowai Bridge (Figure A3).

The depth and extent of inundation associated with a 1:100-year far-field tsunami would be considerably less than for a 1:500-year event, although some land on the eastern side of the Tahakopa River between Papatowai and Maclennan would be inundated by up to 0.5m. Inundation of greater than 1m would be restricted to the sand spit on the north side of the Tahakopa River mouth.

Near-field tsunami

Inundation and water velocities associated with a Puysegur Trench tsunami (Figure A2) were significantly greater than that caused by far-field tsunamis. Table 5 shows that the Puysegur Trench tsunami would produce waves of up to 3.7m amplitude, with a maximum vertical run-up of 4.5m above MSL on land. This would result in land on both sides of the Tahakopa and Maclennan rivers being inundated up to 1.5m for up to 3km above their confluence. Modelling shows that tsunami waves may result in water velocities of over 5m per second at the river mouth, decreasing to 3-4m per second near the Papatowai Bridge.

Figure A4 shows a time series of changes in water level during the modelled 1:600-year Puysegur Trench event. The time series shows that sea would begin to retreat 1½ hours after the earthquake, with the first (and biggest) wave arriving approximately 40 minutes later. The water level would rise to a maximum of 4.5m above MSL and then retreat to 1m below MSL over a period of 10 minutes. Waves and strong currents would continue to affect the area for at least 6 hours after the earthquake.

Other near-field sources of tsunami may include the Castle Hill Fault (Figure 6) and submarine landslides. The Castle Hill Fault runs offshore for approximately 35km in a NW-SE direction from the Clutha River/Mata-Au mouth area. Norris and Litchfield (1996) make an ‘educated guess’ that an earthquake of magnitude 6.5-7 could result in reverse uplift on the NE side of this fault of about 1m, with a frequency of approximately 10,000 years.

Table 5. Characteristics of tsunami events at Papatowai (as modelled by NIWA 2007)

Characteristic	1:600-year Puysegur Trench tsunami	1:500-year South American tsunami
Tsunami arrival time (after fault rupture)	1 hour 30 min	15 hours 30 min
Maximum wave amplitude above the undisturbed level of the sea	3.7m	1.6m
Predominant period of wave arrivals	30 min	1 hour 30 min
Maximum wave run-up above MSL	4.5m	2.6m

Probability of inundation

The probability of maximum water levels of 1.5, 2.0 and 2.5m above MSL occurring as a result of any of the tsunami or elevated sea level scenarios modelled by NIWA is shown in Table 6. The table also provides a generalised explanation of the likely extent of inundation if a tsunami or elevated sea level event that reached 1.5, 2.0 or 2.5m were to occur.[31]

Table 6. Likelihood and possible consequences of peak water level due to the modelled storm surge and tsunami scenarios at Papatowai (with current sea level)

Maximum water level (m above MSL)	Probability of occurrence during any 100-year period (%)	Likely extent of inundation
1.5	>99	Tahakopa and Maclennan river channels inundated, extending into adjacent low-lying areas. Potential overtopping of the Papatowai Highway between Papatowai and Maclennan.
2.0	75-85	Extensive inundation of low-lying areas beside both rivers, particularly on the western bank near the confluence with the Maclennan River and both banks upstream of the Maclennan Bridge. Inundation of the Papatowai highway.
2.5	25-35	Extensive inundation of low-lying areas surrounding both rivers.

The probability of maximum water levels reaching any of these three heights will increase if sea level rises in the future. Table 7 shows the probability of maximum water level reaching 1.5, 2.0 or 2.5m above MSL as a result of tsunami or elevated sea level scenarios if 0.5m of sea level rise were to occur.

Table 7. Likelihood of peak water level due to the modelled storm surge and tsunami scenarios at Papatowai (if the average sea level were 0.5m higher than at present)

Maximum water level (m above MSL)	Probability of occurrence during any 100-year period (%)
1.5	>99
2.0	>99
2.5	75-85

[31] The extent of inundation has been estimated through a simple assessment of coastal topography and elevation. Note that other factors associated with tsunami and elevated sea level events, such as wave velocity and duration of inundation, would also have an impact on particular communities.

7.3 Community vulnerability

Most residential properties within Papatowai and Maclennan are outside the area inundated under the modelled elevated sea level and tsunami scenarios. However, a number of houses are located on low-lying land alongside the river. Properties on either side of the Papatowai Bridge, and along the Papatowai Highway towards Maclennan, are most likely to be affected (Figure A1 to A3). As well as the modelled scenarios shown in these Figures, properties in this area are also vulnerable to lower magnitude events that occur more frequently.

Tsunami and elevated sea level events may affect road access between Papatowai, Maclennan and other nearby settlements, due to inundation and erosion of local roads and bridges. The electricity distribution network (power poles and lines) in this area may also be damaged. The modelling undertaken by NIWA (2007) for a Puysegur Trench tsunami shows that water velocities of more than 5m per second would occur at the mouth of the Tahakopa River. The piles that support the bridge across this river[32] (Figure 7) would need to be able to withstand these high water velocities and elevated water levels to avoid being damaged during such an event.

The greatest risk to these communities is presented by a near-field Puysegur tsunami. Tahakopa Bay and the Tahakopa River mouth face to the south-east, so they are especially exposed to an event originating from the Puysegur Trench. The time (1½ hours) between earthquake and tsunami arrival and the greater levels of inundation also mean that community vulnerability is higher for this type of event. People in low-lying areas and close to the shoreline[33] would need prompt warning of an approaching tsunami if that warning were to be effective. There is currently no mobile phone coverage at Papatowai (as of March 2011), which would make this difficult. People in these areas would also need to be aware of the quickest route to a safe area.

Figure 8. Tahakopa River Estuary, looking west towards Papatowai (June 2011)

The best warning of an approaching Puysegur Trench tsunami may be the ground shaking associated with the earthquake that triggers the tsunami or a retreat in sea level before the tsunami wave approaches. This shaking may not be felt by everyone however, and even those who do feel it may not immediately associate it with the potential occurrence of a large tsunami.

[32] Along with any critical services that use the bridge to cross the river
[33] Including in and around the Papatowai Estuary and Tahakopa beach (See Figure 8.)

7.4 Summary

- People in the area between the Papatowai and Maclennan bridges, on or near the Papatowai Estuary and on the Tahakopa beach are vulnerable to elevated sea level and tsunami events.
- Residential properties, roads and other infrastructure in the area between the Papatowai and Maclennan bridges may be inundated by waves up to 1m deep, and travelling at up to 3m per second during a near-field Puysegur Trench tsunami.
- Changes in sea level of more than 5m may occur along this stretch of coast over a 10-minute period during a near-field Puysegur Trench tsunami.
- Any warning prior to the arrival of a Puysegur Trench tsunami is likely to be minimal at best. People would therefore need to be aware of the quickest and safest way to evacuate to an identified safe area.

8. The Catlins

8.1 Community description

The settlements of Pounawea, New Haven and Jack's Bay are located near the mouth of the Catlins River in South East Otago. This area is popular for tourism, with a number of scenic walks, activities and accommodation facilities available.

Pounawea and New Haven

The Pounawea and New Haven settlements are located on the northern side of the Catlins River and separated by the Owaka River (Figure 9). Much of the Pounawea Township is very low lying, being less than 2m above MSL.[34] These low-lying areas consist of sand and gravel deposits, formed into a terrace by fluvial, estuarine and coastal processes. New Haven is located on a slightly higher terrace (4-6m above MSL), near the mouth of the Catlins River.

According to data from the 2006 census, Pounawea and New Haven had resident populations of approximately 70 and 20 respectively. This number can be higher at times due to tourists visiting the area. Land use in the two settlements is residential, and the surrounding areas are mainly farmland and bush.

Infill development can occur as of right on empty sections within the existing Pounawea and New Haven townships, which are both zoned 'Rural Settlement Resource Area'. However, infrastructure constraints (such as wastewater capacity) would limit this in some cases. Other parcels of land close to the shoreline are zoned 'Coastal Resource Area', and consent authority approval is required for additional development in this area, with natural hazards a relevant matter to be considered by the consenting authority.

Figure 9. Pounawea and New Haven from Settlement Road (June 2011)

[34] As such, the hazard associated with elevated sea level and tsunami events for these communities will be particularly sensitive to future sea level rise (NIWA, 2007; NIWA, 2008).

Figure 10. View of the Catlins River and Pounawea from New Haven Road (June 2011)

Jack's Bay

The Jack's Bay settlement is located on an old beach ridge, formed when the sea was at a higher level, and elevated 3-5m above where the beach is at present. The ground rises steeply in a 5-10m high bank behind the settlement, and then rises more gradually towards the west (Figure 11). Jack's Bay faces east and is flanked by Tuhawaiki Island to the south and Catlins Heads to the north. The bay is somewhat isolated, with one gravel access road, which follows the southern edge of the Catlins River before crossing at Hinahina, or further west at Ratanui.

The settlement consists of about 25 houses. These are mainly cribs, although a number of buildings appear to be occupied permanently, with a resident population of about 15, according to the 2006 Census. The densest grouping of buildings is in an area to the north of Jack's Bay Road, which is zoned 'Rural Settlement Resource Area' (Figure 13). Development can occur on any available sections as of right within this area.

Land to the south of Jack's Bay Road is zoned 'Coastal Resource Area', and consent authority approval is required for development. There is a group of older houses within this zone towards the southern end of the bay (Figure 11). A recent subdivision has also created seven new sections within this 'Coastal Resource Area' in the centre of the bay, and two of these have had houses built on them (as at June 2011).

Figure 11. Jack's Bay looking south from the centre of the beach (June 2011)

8.2 Effect of elevated sea level and tsunami events

Elevated sea level

NIWA's (2008) modelling showed that a 1:500-year event would result in an elevated sea level of more than 2m above MSL and more than 1m above MHWS in the Catlins area (Table 8), which would cause inundation of low-lying parts of Pounawea of up to 0.5m (Figure A7).[35] Land on either side of the Owaka River would be inundated as far upstream as the golf course, and extensive areas on the south side of the Catlins River would be inundated to a depth of up to 2m (Figure A6). A more frequent event, with an estimated 1:20-year return period, would also inundate a similar extent of the low-lying land alongside these rivers, as the difference in water level between this and a 1:500-year event is only 0.2m.

Table 8. The level of the sea (relative to MSL) at MHWS and for a range of modelled elevated sea level events in the Catlins. The percentage chance of a particular event occurring in any 100-year period is shown in brackets

Return period in years (chance of occurring in any 100-year period)	MHWS	20 (99%)	50 (87%)	100 (63%)	500 (18%)
Water level (m above MSL)	1.0	1.9	1.95	2.0	2.10
Existing houses affected?					
- Pounawea	No	Yes	Yes	Yes	Yes
- New Haven	No	No	No	No	Possible
- Jack's Bay	No	No	No	No	Possible

Far-field tsunami

The times series of changes in water level in Figure A13 shows that the modelled 1:500-year South American tsunami would reach the Catlins about 15½ hours after the earthquake. The biggest wave would arrive approximately 4½ hours after the first wave, with many smaller waves occurring for over 10 hours after this. The maximum run-up observed at the Catlins from this scenario would be 2.2m above MSL. This would result in a tsunami wave up to 1.5m deep, and travelling at 1m per second in parts of Pounawea (Figure A11). The southern margins of the Catlins River and Catlins Lake would also be inundated by up to 1m, while only minimal inundation at the New Haven and Jack's Bay settlements would occur as a result of this scenario (Figure A10).[36]

A lower magnitude, higher frequency far-field tsunami with a 1:100-year return period would result in a tsunami wave up to 1m deep, with a maximum speed of 1m per second. The wave would affect the first row of properties along the Pounawea waterfront (Park Lane), as well as those properties alongside the Owaka River (Devil's Elbow).

Near-field tsunami

Inundation and water velocities associated with a Puysegur Trench tsunami (Figures A8 and A9) are significantly greater than those caused by either of the modelled South American tsunami scenarios. Table 9 shows that the modelled Puysegur Fault tsunami may produce waves of up to 2.6m amplitude at sea, with vertical wave run-up on land up to 4m above MSL. Water velocity through low-lying parts of Pounawea could be as

[35] Refer to the map book (ORC, 2012) for all Figures beginning with 'A'.
[36] The modelling undertaken by NIWA for the tsunami scenarios only covers the northern end of Jack's Bay.

fast as 4m per second. The depth of inundation would range from 2.5m at properties along the waterfront to 1m along Pounawea Road (Figure A9). At New Haven (Figure A9) and Jack's Bay (Figure A8), water velocities of 1m per second and depths of 1m are possible in areas beside the shoreline.

Table 9. Characteristics of tsunami events in the Catlins River mouth area (as modelled by NIWA 2007)

Characteristic	Puysegur Trench tsunami	1:500-year South American tsunami
Tsunami arrival time (after fault rupture)	1 hour 45 min	15 hours 30 min
Maximum wave amplitude above the undisturbed level of the sea	2.6m	1.6m
Predominant period of wave arrivals	20 min	1 hour 30 min
Maximum wave run-up above MSL	4m	2.2m

Local variations in micro-topography (such as roads, houses and fences) may focus tsunami wave energy into certain areas, which could influence inundation depths and water velocity. For example, Pounawea Road runs directly through the town from the Catlins River Estuary towards the Owaka River (Figure 12). Tsunami waves would be unimpeded as they moved along this road, which could cause an increase in water velocity along this corridor.

Other near-field sources of tsunami may include the Castle Hill Fault (Figure 6) and submarine landslides. The Castle Hill Fault runs offshore for approximately 35km in a NW-SE direction from the Clutha River/Mata-Au mouth area. Norris and Litchfield (1996) make an 'educated guess' that an earthquake of magnitude 6.5-7 could result in reverse uplift on the north-eastern side of this fault of about 1m, with a frequency of approximately 10,000 years.

Figure 12. Pounawea Road, which forms a corridor between the Catlins River Estuary and the lower Owaka River (June 2011)

Figure A12 shows a time series of changes in water level during the modelled Puysegur Trench tsunami. Initially, the sea would retreat slightly at Jack's Bay and the mouth of the Catlins River, approximately 1 hour 45 minutes after the earthquake. The first wave would arrive 35 minutes later. The biggest wave would impact the coast approximately 4 hours after the earthquake, with waves continuing to affect the Catlins area for another 2 hours.

Probability of inundation

The probability of maximum water levels of 1.5, 2.0 and 2.5m above MSL occurring as a result of any of the modelled tsunami or elevated sea level scenarios modelled by NIWA is shown in Table 10. The table also provides a generalised explanation of the likely extent of inundation if a tsunami or elevated sea level event that reached 1.5, 2.0 or 2.5m were to occur.[37]

Table 10. Likelihood and possible consequences of peak water level due to the modelled storm surge and tsunami scenarios at the Catlins (with current sea level)

Maximum water level (m above MSL)	Probability of occurrence during any 100-year period (%)	Likely extent of inundation
1.5	>99	Wave run-up may push water into low-lying parts of Pounawea, particularly along Park Lane and other areas close to the shoreline.
2.0	40-50	Extensive inundation of low-lying parts of Pounawea, particularly properties on the north-east side of Pounawea Road.
2.5	10-20	Extensive inundation across the coastal terrace, upon which most of Pounawea has been built. Wave run-up may also cause temporary inundation around some Jack's Bay and New Haven properties.

The probability of maximum water levels reaching any of these three heights will increase if sea level rises in the future. Table 11 shows the probability of maximum water level reaching 1.5, 2.0 or 2.5m above MSL as a result of tsunami or elevated sea level scenarios, if 0.5m of sea level rise were to occur.

Table 11. Likelihood of peak water level due to the modelled storm surge and tsunami scenarios at the Catlins (if average sea level were 0.5m higher than at present)

Maximum water level (m above MSL)	Probability of occurrence during any 100-year period (%)
1.5	>99
2.0	>99
2.5	40-50

[37] The extent of inundation has been estimated through a simple assessment of coastal topography and elevation. Note that other factors associated with tsunami and elevated sea level events, such as wave velocity and duration of inundation, would also have an impact on particular communities.

8.3 Community vulnerability

Pounawea and New Haven

Despite its reasonably sheltered location, Pounawea is highly vulnerable to elevated sea level and tsunami events, as much of the township is less than 2m above MSL (Box 1). Both the modelled 1:500-year elevated sea level event and the modelled 1:500-year far-field (South American) tsunami would cause inundation of low-lying parts of Pounawea up to a depth of 1.5m.

Water velocity associated with a 1:500-year far-field tsunami would be up to 2m per second. This may cause scour and erosion along the waterfront and riverbanks. Such an event would result in considerable inundation along the banks of the Owaka River and the south side of Catlins Lake. Road access to Pounawea and New Haven is likely to be cut off due to inundated and damaged roads. The electricity distribution network (power poles, lines and power transformers) would need to withstand high water velocities and elevated water levels to avoid being damaged during tsunami events.

The inundation associated with the modelled Puysegur Trench tsunami would be more extensive than that caused by a tsunami of South American origin. A number of houses and buildings in Pounawea would be inundated during such an event, with the worst affected area likely to be the low-lying land to the north of Pounawea Road (Figure A9). High water velocities of up to 4m per second, combined with water depths of up to 2.5m, would be sufficient to carry vehicles away and destroy buildings, as shown in Figure 2**.** The roads linking Pounawea and New Haven with Owaka would be inundated and damaged. Land bordering the Owaka River may be inundated as far upstream as the golf course.

The modelled Puysegur Trench tsunami showed that up to ten houses at New Haven could be inundated by up to 1m (Figure A9), and maximum water speeds of up to 1m per second could occur. These conditions could cause vehicles to be carried away and buildings to be damaged (Figure 2). The worst affected area in New Haven during such an event appears to be the southern end of Surat Bay Road and properties at the western end of the settlement. Modelling shows only minimal (0-0.5m) inundation of New Haven as a result of far-field (South American) tsunami or elevated sea level events, although additional scouring and erosion may occur along riverbanks.

Jack’s Bay

The Jack’s Bay community is vulnerable to the effects of a near-field Puysegur Trench tsunami.[38] High water velocities could cause scouring and erosion of the strip of land between the beach and buildings. Maximum inundation depths of up to 1m may occur around the first row of houses (closest to the ocean) at the northern end of the beach (Figure 13). Maximum water speeds of 1m per second may also occur in this area. These conditions could cause vehicles to be carried away and buildings to be damaged.

[38] NIWA’s modelling shows no direct inundation of existing houses at Jack’s Bay as a result of a far-field (South American) tsunami or an elevated sea level event.

Figure 13. Northern end of Jack's Bay, looking towards Catlins Heads (June 2011)

Properties at the southern end of the bay are also low lying and close to the water's edge (Figure 14). These properties could be vulnerable during this type of event, although modelling results for this scenario are not available to confirm this.

Figure 14. Cribs at the southern end of Jack's Bay. Tuhawaiki Island is in the background (June 2011)

Warning signals of an approaching tsunami in the Catlins area

Providing sufficient warning of approaching tsunami events in the Catlins area would be vital so that people could evacuate to higher ground. People in these areas would need to be aware of the quickest route to a safe area if such a warning were to be effective, particularly during near-field tsunamis, as the impacts may be felt less than 2 hours after a large earthquake. Distribution of warnings may be hampered by the currently patchy mobile phone coverage in some parts of the Catlins area.

The best warning of an approaching Puysegur Trench tsunami may be the ground shaking associated with the earthquake that triggers the tsunami. Not everyone may feel this shaking, however, and those who do may not immediately associate it with the potential occurrence of a large tsunami. Retreat of the ocean before such an event may also be minimal, particularly at Pounawea, and the first indication of an approaching tsunami may be the onset of the first wave 2 hours and 22 minutes after the fault rupture (Figure A12, map 3).

8.4 Summary

- People living in or visiting Pounawea are vulnerable to elevated sea level and tsunami events, including lower magnitude events that occur more frequently.
- People living in or visiting New Haven and Jack's Bay are also vulnerable to these events, although in most cases the effects would not be felt in residential areas, but rather in areas that people use for recreation, such as the Catlins River Estuary, coastal walks and beaches. In this case, the level of vulnerability may increase at low tide, when these areas are more accessible (particularly for near-field tsunami events).
- Residential properties and roads in Pounawea and alongside the Owaka and Catlins rivers may be inundated by waves up to 2.5m deep and travelling at up to 4m per second during a near-field Puysegur Trench tsunami.
- Changes in sea level of several metres may occur along this stretch of coast over very short periods during tsunami events.
- Any warning before the arrival of a Puysegur Trench tsunami is likely to be minimal at best. People would therefore need to be aware of the quickest and safest way to evacuate to an identified safe area.

9. Kaka Point and Lower Clutha

9.1 Community description

This area includes the stretch of coastline between Kaka Point and the northern (Matau Branch) mouth of the Clutha River/Mata-Au. It also extends inland to include Kaitangata, Inch Clutha Island and Paretai (Figure A17).[39] This area is mainly rural, with scattered farm buildings and houses. Kaka Point and Kaitangata are the two main settlements; Figure A24 shows the resident population in this area in 2006 (from census data). Although Kaka Point has a smaller population, the township has increased in popularity for visitors and residents alike in recent years.

Kaitangata has a population of approximately 770, with a lower population density in the surrounding rural area. Much of this area is offered an element of protection by an extensive network of flood banks designed to protect against Clutha River/Mata-Au floods of up to 4,000m^3/s (ORC, 2000). Generally, the flood bank crest in the lower Clutha area is 3m higher than the surrounding land. These flood banks also offer a level of protection against tsunami and storm surge events. However, a higher magnitude event may result in sections of flood bank being overtopped, weakened or breached.

The potential for development within the Kaka Point and lower Clutha area was assessed through consultation with the Clutha District Council. Development is able to occur on empty sections as of right on land that is zoned ‘Urban Resource Area’ in Kaka Point and Kaitangata (CDC, 1998).[40] The remainder of the lower Clutha area is zoned ‘Rural Resource Area’, and consent authority approval is generally required for development in this area.

9.2 Effect of elevated sea level and tsunami events

Elevated sea level

NIWA’s (2008) modelling showed that a 1:500-year event would result in an elevated sea level of 1.1m and 1.35m above MHWS for Kaka Point and the lower Clutha, respectively (Table 12 and Table 13). Such an event would largely be contained within the flood banks of the lower Clutha (Figure A17). However, areas of farmland alongside the Puerua River would be inundated as far inland as the Owaka Highway. Kaka Point Road may be inundated on either side of Kaka Point, which may restrict access to the town. The extent of inundation associated with smaller, but more frequent events would be similar, as the difference in water level between a modelled 1:20-year and a modelled 1:500-year event is only 0.25m for both Kaka Point and the lower Clutha.

There is a reliance on the lower Clutha flood banks to protect the lower Clutha area. Failure of these banks could result in inundation of large areas because of the low-lying nature of the delta. It is noted that flood bank breach scenarios were reported in NIWA (2005).

[39] Refer to the map book (ORC, 2012) for all Figures beginning with ‘A’.
[40] Note that much of the lower-lying residential land in Kaitangata between Eddystone Street and Water Street is also zoned ‘Urban Resource Area’.

Table 12. The level of the sea (relative to MSL) at MHWS and for a range of modelled elevated sea level events at Kaka Point. The percentage chance of a particular event occurring in any given 100-year period is shown in brackets

Return period in years (chance of occurring in any 100-year period)	MHWS	20 (99%)	50 (87%)	100 (63%)	500 (18%)
Water level (m above MSL)	1.0	1.85	1.9	2.0	2.1
Existing houses affected?	No	No	No	No	No

Table 13. The level of the sea (relative to MSL) at MHWS and for a range of modelled elevated sea level events in the lower Clutha. The percentage chance of a particular event occurring in any given 100-year period is shown in brackets

Return period in years (chance of occurring in any 100-year period)	MHWS	20 (99%)	50 (87%)	100 (63%)	500 (18%)
Water level (m above MSL)	1.0	2.1	2.2	2.25	2.35
Existing houses affected?	No	No	No	No	No

Far-field tsunami

The modelling undertaken for the 1:500-year South American tsunami (Figure A20) shows that a series of waves would begin to reach Kaka Point and Clutha approximately 15½ hours after an earthquake. The largest wave would arrive about 4 hours later. Many smaller waves would continue for another 15 hours after this. The maximum run-up observed at Kaka Point/lower Clutha from this scenario would be 2.7m above MSL (Table 14). Modelling shows that this event would inundate land next to the Puerua Estuary up to a depth of 0.5m, and near the mouth of the Matau branch of the Clutha to a depth of 1.5m. Inundation associated with this scenario at Kaka Point would be restricted to the dunes and reserve on the seaward side of Esplanade Road.

Maximum wave run-up associated with a lower magnitude, more frequent (1:100-year) South American tsunami would be 2.1m, with inundation limited to the coastal strip and within flood banks on the lower Clutha.[41]

Table 14. Characteristics of tsunami events in the Kaka Point/lower Clutha area (as modelled by NIWA 2007)

Characteristic	Puysegur Trench tsunami	1:500-year South American tsunami
Tsunami arrival time (after fault rupture)	1 hour 45 min	15 hours 30 min
Maximum wave amplitude above the undisturbed level of the sea	2.7m	1.7m
Predominant period of wave arrivals	35 min	1 hour 30 min
Maximum wave run-up above MSL	5m	2.7m

Near-field tsunami

The south-westerly aspect of the lower Clutha area means that maximum wave run-up, inundation and water velocities associated with the modelled 1:600-year Puysegur Trench tsunami would be greater than that caused by a South American tsunami. Table

[41] Note that inundation extents associated with far-field tsunamis are not shown in the map book (ORC, 2012) for the Lower Clutha, as they are less extensive than those associated with a Puysegur Trench tsunami.

14 shows that the modelled Puysegur Trench tsunami may produce waves with run-up on land of up to 5m above MSL.

Time series of modelled changes in water level for Kaka Point and lower Clutha are shown in Figures A19 and A22. Modelling undertaken to show the effects of a Puysegur Trench tsunami (NIWA, 2007) shows that water would retreat from the beach approximately 1 hour 45 minutes after an earthquake. The first wave would arrive about 35 minutes later. Two large waves would strike the coastline about 3 hours 45 minutes and 4 hours 15 minutes after an earthquake. Large waves and strong currents could continue to have an impact on the area for nearly 7 hours.

Tsunami waves with water velocities of up to 5m per second may cause erosion or undermining of the sand dunes and flood banks that protect low-lying land on the delta. The modelling used in the NIWA study assumed that the land is static and did not account for possible erosion of flood banks or sand dunes. Inundation could therefore be greater than that shown in Figure A18. Figure A31 shows the maximum water velocity associated with a 1:600-year Puysegur Trench tsunami in the lower Clutha area. The Figure shows that the highest water velocities would occur at the Matau and Koau mouths of the Clutha River/Mata-Au and at the southern end of Molyneux Bay, near the outlet of the Puerua River. Increased wave velocity means that there is greater potential for erosion in these areas, both on the incoming wave surge, and when the wave retreats back out to sea.

Other near-field sources of tsunami may include the Castle Hill Fault (Figure 6) and submarine landslides, as described in the sections on Papatowai (Section 7) and Pounawea (Section 8).

Probability of inundation

The probability of maximum water levels of 1.5, 2.0 and 2.5m above MSL occurring as a result of any of the tsunami or elevated sea level scenarios modelled by NIWA is shown in Table 15. This table also provides a generalised explanation of the likely extent of inundation if a tsunami or elevated sea level event that reached 1.5, 2.0 or 2.5m were to occur.[42]

Table 15. Likelihood and possible consequences of peak water level due to the modelled storm surge and tsunami scenarios for the lower Clutha and Kaka Point (with current sea level)

Maximum water level (m above MSL)	Probability of occurrence during any 100-year period (%)	Likely extent of inundation
1.5	>99	Extensive inundation of low-lying river flats and farm land next to the Puerua River and Clutha River/Mata-Au mouth.
2.0	>99	Inundation extending further inland, including farmland and sections of Kaka Point Road.
2.5	25-35	Extensive inundation of low-lying farmland and Kaka Point Road.

[42]The extent of inundation has been estimated through a simple assessment of coastal topography and elevation. Note that other factors associated with tsunami and elevated sea level events, such as wave velocity and duration of inundation, would also have an impact on particular communities.

The probability of maximum water levels reaching any of these three heights will increase if sea level rises in the future. Table 16 shows the probability of the maximum water level reaching 1.5, 2.0 or 2.5m above MSL as a result of tsunami or elevated sea level scenarios if 0.5m of sea level rise were to occur.

Table 16. Likelihood of peak water level due to the modelled storm surge and tsunami scenarios for the lower Clutha (if average sea level were 0.5m higher than at present)

Maximum water level (m above MSL)	Probability of occurrence during any 100-year period (%)
1.5	>99
2.0	>99
2.5	>99

Cross section profiles

Figures A15 and A16 show a cross section profile through the Kaka Point Township from south to north. Maximum water levels associated with the modelled 1:600-year Puysegur Trench tsunami, 1:500-year South American tsunami and 1:500-year elevated sea level events have been superimposed on the cross section to show the level of inundation in relation to the ground level. The profile shows that Kaka Point would be largely unaffected during any of the three modelled scenarios, apart from some minor inundation of properties fronting the beach during the modelled 1:600-year Puysegur Trench tsunami event.

Figures A25 and A26 show a cross section profile extending from Molyneux Bay across the Inch Clutha Island and finishing near Stirling. The cross section shows that the Inch Clutha area is very low lying and that the modelled tsunami or storm surge events could extend well inland if they were to breach or overtop the dunes or flood banks that surround the area. As a result, a large area could be inundated.[43]

Figures A27 to A30 show cross sections through the coastal margin in greater detail. These sections extend from the beach to the low-lying areas inland of the coastal dunes, and they show the heights of the sand dunes and flood bank crest levels at three locations along the beach. The maximum run-up level of the Puysegur Trench tsunami has been overlaid on the cross sections.[44] This level is higher than the sand dunes at cross sections 1 and 2 and only slightly below the dune crest level at cross section 3.

The modelling undertaken by NIWA (2007, 2008) does not show significant inundation beyond the coastal sand dunes or lower Clutha flood banks, but assumes that the protection offered by these features remains in place (i.e. no allowance has been made for possible erosion of these defences). The cross sections described above show that the coastal sand dunes and flood banks are a relatively thin barrier. Erosion of these defences may lead to more widespread inundation than the modelled results shown in Figures A17 and A18.

[43] Box 2 in Section 5.2 demonstrates how topography can influence the inundation distance and run-up of tsunami events.

[44] Note that this level is the maximum modelled run-up level for the whole lower Clutha area, and that the actual run-up level at each cross section location may be lower.

Figure 15. **View across the mouth of the Matau branch of the Clutha River/Mata-Au, looking west towards Inch Clutha Island. The approximate location of cross section 3 (Figure A30) is shown as a red line (Sept 2007)**

9.3 Community vulnerability

Kaka Point

During a 1:600-year Puysegur Trench tsunami, some of the properties close to the sea in Kaka Point may be inundated up to a depth of 0.5m (Figure A14). Some sections of Kaka Point Road may also be inundated by a similar depth of water. This may restrict road access to Kaka Point from both the north and south.

Lower Clutha

Flood banks and sand dunes in the lower Clutha area offer a level of protection against tsunami and storm surge events. (An example is shown in Figure 16.) However, a series of large waves, along with high water velocities, may erode or weaken these features. This could cause a breach and result in widespread inundation. The extent of inundation would depend on:

- the physical characteristics of the storm surge or tsunami event
- the nature, location and timing of the breach
- the river flow conditions at the time (e.g. a flood event occurring simultaneously).

People living or working on the lower Clutha Delta are particularly vulnerable, as much of this area could be inundated if such a breach were to occur during a high magnitude storm surge or tsunami event. This is especially true for those on the Inch Clutha Island, as there are only two bridges leading off the island to higher ground (at Stirling and

Kaitangata). The resident population of the lower Clutha area closest to the ocean was 141 in 2006; while a further 210 people lived in the area 3 to 5km back from the coast (Figure A24).

Figure 16. Flood bank and residence on the true right (southern) side of the Koau branch of the Clutha River/Mata-Au (July 2007)

Kaitangata

Kaitangata has the greatest population density in this area and is located next to the Matau branch of the lower Clutha. Although it is located about 5km from the coast, parts of Kaitangata are still low lying. Many of the properties on Clyde Street and in the area between Water Street and Eddystone Street are less than 3m above MSL. People in this area are vulnerable due to the possibility of widespread inundation if the flood banks were breached or overtopped during a high magnitude tsunami or storm surge event.

The limited warning time associated with a Puysegur Trench tsunami makes this area particularly vulnerable if overtopping or a breach of the flood bank were to occur as a result of such an event. Parts of Kaitangata would also be vulnerable to inundation associated with a high magnitude storm surge event if this were to coincide with a flood event in the lower Clutha. Figure 17 and Figure 18 show the extent of inundation that has occurred around Kaitangata in previous flood events. The November 1999 flood resulted from heavy rainfall in the upper catchment, which took several days to reach the lower Clutha. It is therefore unlikely that sea level was elevated due to storm surge when this flood peaked in the lower reaches of the Clutha River/Mata-Au. These Figures highlight the vulnerability of the low-lying section of Kaitangata alongside the river.

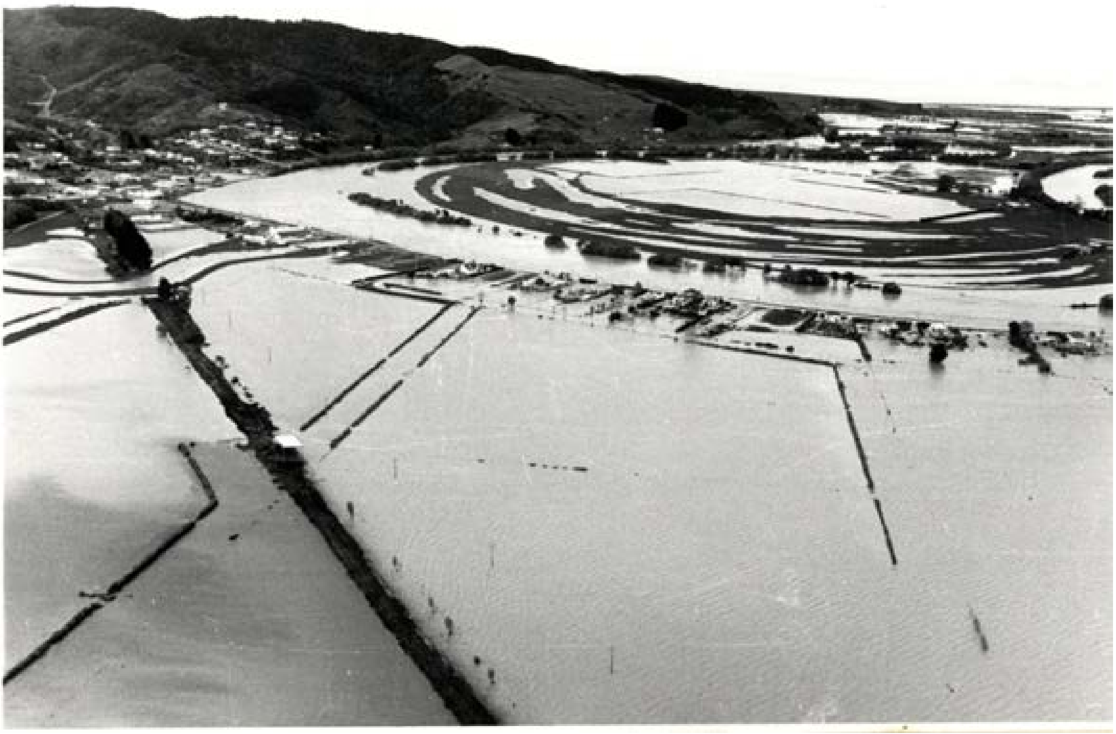

Figure 17. Aerial view overlooking Clyde Terrace in Kaitangata and the Matau branch of the lower Clutha. Photo taken on 15 October 1978 at 8:30am

Figure 18. Aerial view overlooking the Matau branch of the lower Clutha and Kaitangata. Photo taken 18 November 1999

9.4 Summary

- Inundation is likely to occur across the dunes, estuary and river mouth areas near the lower Clutha Delta coastline during extreme sea level and tsunami events. Minor inundation of coastal property is likely to occur at Kaka Point during a near-field tsunami.
- Tsunami or extreme sea level events could inundate parts of the delta if they were to breach or overtop sand dunes and flood banks. People and property on the lower Clutha Delta would be vulnerable due to the low-lying nature of this area and the distance to high ground, which would include crossing the Clutha River/Mata-Au.
- Lower magnitude events that occur more frequently may also have the ability to breach or overtop these protective features and inundate parts of the delta.
- Localities on the delta likely to be worst affected by inundation include Paretai, Matau and Port Molyneux, due to their physical setting and proximity to the coast. Low-lying parts of Kaitangata alongside the Matau branch of the Clutha River/Mata-Au also have a level of vulnerability.
- Any warning before the arrival of a Puysegur Trench tsunami is likely to be minimal at best. People would therefore need to be aware of the quickest and safest way to evacuate to an identified safe area.
- Changes in sea level of several metres may occur very quickly along this stretch of coast during tsunami events.

10. Toko Mouth

10.1 Community description

The Toko Mouth settlement is located on the east coast of Otago, at the mouth of the Tokomairiro River (Figure A32).[45] The shoreline in this area runs from south-west to north-east, and Toko Mouth is located on a slight promontory at the north-eastern end of Measly Beach. The township is located on an old beach ridge, which is elevated 2-5m above MSL and was formed when the sea was at a higher level. Behind the settlement, the ground rises up a 10m bank to a terrace overlooking the township.

Toko Mouth is a popular holiday area, with approximately 80 houses and cribs, some of which are shown in Figure 19. The resident population of Toko Mouth and the lower Tokomairiro Gorge area was 21 in 2006 (from census data). This number is likely to increase during the weekend and holiday periods. Access to the township is via Toko Mouth Road, which runs alongside the Tokomairiro River, or by Coast Road, which runs along the coast to Kaitangata. Both of these roads would be prone to damage or inundation during elevated sea level or tsunami events. There are power lines and poles that supply electricity to Toko Mouth alongside these roads.

The potential for development within the Toko Mouth settlement was assessed through consultation with the Clutha District Council. Areas where houses are located are zoned 'Rural Settlement Resource Area', and there is some potential for infill building, but this is largely limited by parcel size and effluent disposal restrictions. Other (empty) parcels of land within the settlement are zoned 'Coastal Resource Area', and consent authority approval is required for development in these areas, with natural hazards a relevant matter to be considered by the consent authority. Infrastructure constraints (such as wastewater capacity) may also limit development on these sections.

Figure 19. View to the east over the Toko Mouth settlement. The mouth of the Tokomairiro River is on the left (August 2011)

10.2 Effect of elevated sea level and tsunami events

Elevated sea level

NIWA's (2008) modelling showed that a 1:500-year event would result in an elevated sea level of 1.75m above MHWS at Toko Mouth (Table 17). The extent of inundation associated with this event is shown in Figure A32. The Toko Mouth area showed the highest increase in elevation of sea level due to storm surge of all the coastal

[45] Refer to the map book (ORC, 2012) for all Figures beginning with 'A'.

communities in Otago modelled in the study. This increase is due to site-specific conditions, such as beach topography and its effect on wave set-up during an extreme sea level event. Toko Mouth is also susceptible to inundation during more frequent low magnitude events, and Table 17 shows that the difference in water level between the modelled 1:20-year and 1:500-year events is just 0.3m. The extent of inundation associated with a 1:20-year event is shown in Figure A33.

Table 17. The level of the sea (relative to MSL) at MHWS and for a range of modelled elevated sea level events, at Toko Mouth. The percentage chance of a particular event occurring in any given 100-year period is shown in brackets

Return period in years (chance of occurring in any 100-year period)	MHWS	20 (99%)	50 (87%)	100 (63%)	500 (18%)
Water level (m above MSL)	1.0	2.45	2.55	2.6	2.75
Existing houses affected?	No	Yes	Yes	Yes	Yes

Far-field tsunami

Figure A37 shows that the modelled 1:500-year South American tsunami would reach Toko Mouth about 15½ hours after the earthquake. The largest wave would strike the coast 4 hours later. Many smaller waves would continue for another 15 hours. The maximum wave run-up observed at Toko Mouth from this scenario is 2.8m above MSL (Table 18). This would inundate low-lying land next to the Tokomairiro River for up to 4km upstream of the river mouth. Estuarine areas that are exposed at low tide may be inundated to a depth of more than 2.5m, and a number of properties along the bank of the river would be inundated to a depth of up to 1m (Figure A35). Water velocities of up to 3m per second would occur through the river mouth, declining to 1m per second further up the river. This could cause erosion of the riverbed and banks.

Maximum wave run-up associated with a more frequent (1:100-year) South American tsunami would be just only 0.2m less than for a 1:500-year event, and would result in a similar extent of inundation of properties alongside the river.

Near-field tsunami

Table 18 shows that the modelled 1:600-year Puysegur Trench tsunami may cause wave run-up of up to 3.5m above MSL. The maximum water depth for inundated land during a Puysegur Trench tsunami is shown in Figure A34. This type of event could produce water velocities of up to 5m per second through the Toko Mouth area, with the greatest velocities experienced at the river mouth. Low-lying land on either side of the Tokomairiro River would be inundated for up to 4km up the gorge.

Figure A36 shows a time series of modelled water levels as a result of this event. Water is shown to retreat from the beach 1 hour 45 minutes after the earthquake. The first wave would be the biggest and arrive 35 minutes later. Another large wave would strike Toko Mouth 3 hours 35 minutes after the earthquake. Large waves and strong currents would continue to affect the area for another 3 hours.

Table 18. Characteristics of tsunami events at Toko Mouth (as modelled by NIWA 2007)

Characteristic	Puysegur Trench tsunami	1:500-year South American tsunami
Tsunami arrival time (after fault rupture)	1 hour 45 min	15 hours 30 min
Maximum wave amplitude above the undisturbed level of the sea	1.9m	1.6m
Predominant period of wave arrivals	35 min	1 hour 30 min
Maximum wave run-up above MSL	3.5m	2.8m

Probability of inundation

The probability of maximum water levels of 1.5, 2.0, 2.5, and 3.0m above MSL occurring as a result of the tsunami or elevated sea level scenarios modelled by NIWA is shown in Table 19. The table also provides a generalised explanation of the likely extent of inundation if a tsunami or elevated sea level event that reached 1.5, 2.0, 2.5 or 3.0m were to occur.[46]

Table 19. Likelihood and possible consequences of peak water level due to the modelled storm surge and tsunami scenarios at Toko Mouth (with current sea level)

Maximum water level (m above MSL)	Probability of occurrence during any 100-year period (%)	Likely extent of inundation
1.5	>99	Tokomairiro River channel and sections of river flat inundated, extending upstream into the gorge. Inundation of Toko Mouth Domain Road alongside the river.
2.0	>99	Parts of Toko Mouth settlement inundated, including the reserve and swampy area beside Toko Mouth Domain Road. Low-lying sections of Toko Mouth Road also inundated.
2.5	>95	More extensive flooding of Toko Mouth settlement, including up to 15 residential sections on Toko Mouth and Toko Mouth Domain roads.
3.0	10-20	Inundation of most of the residential sections in Toko Mouth. Extensive inundation of low-lying land alongside the Tokomairiro River for several kilometres upstream of the mouth.

The probability of maximum water levels reaching any of these four heights will increase if sea level rises in the future. Table 20 shows the probability of maximum water level reaching 1.5, 2.0, 2.5 or 3.0m above MSL as a result of the tsunami or elevated sea level scenarios if 0.5m of sea level rise were to occur.

[46]The extent of inundation has been estimated through a simple assessment of coastal topography and elevation. Note that other factors associated with tsunami and elevated sea level events, such as wave velocity and duration of inundation, would also have an impact on particular communities.

Table 20. Likelihood of peak water level due to the modelled storm surge and tsunami scenarios at Toko Mouth (if average sea level were 0.5m higher than at present)

Maximum water level (m above MSL)	Probability of occurrence during any 100-year period (%)
1.5	>99
2.0	>99
2.5	>99
3.0	>95

Cross section profile

Figures A38 and A39 show a cross section profile through the Toko Mouth area. The cross section shows that the Toko Mouth residential area is relatively low lying, with many houses less than 3m above MSL.

10.3 Community vulnerability

Toko Mouth is vulnerable to inundation during extreme sea level and tsunami events, as the residential area is close to the coast and river, and at low elevation. The modelled 1:500-year extreme sea level event would inundate parts of the Toko Mouth settlement by up to 1.5m, with wave run-up extending the area of inundation significantly on flatter areas (Figure A32).

The effects of tsunami events would generally be limited to properties along Toko Mouth Road and next to the river. The 1:500-year South American and 1:600-year Puysegur Trench tsunami events would both result in up to 2.5 metres of inundation close to the river, dropping away to 0.5m on the Toko Mouth reserve and on Toko Mouth Road. Maximum water speed would be greater for the Puysegur Trench tsunami, although either event could carry away vehicles and damage buildings. High water velocities through the river mouth would also be hazardous to any boats or people in the water and may cause erosion of the riverbanks and damage to the road. Tsunami waves may also damage power and telephone lines.

Houses and property in Toko Mouth would also be affected during lower magnitude, higher frequency extreme sea level and tsunami events. For example, the extent and depth of inundation associated with a 1:20-year extreme sea level event would only be slightly less than that emanating from a 1:500-year event (Figures A32 and A33). Access to the settlement, even during minor events, is likely to be affected; in fact, the main access road to the west (Toko Mouth Road) already becomes inundated during high perigean-spring or ‘king’ tides. The electricity distribution network (power poles and lines) is located on low-lying land alongside Toko Mouth Road and may also be damaged or require inspection.

Residents and visitors to the Toko Mouth area would be most vulnerable to a Puysegur Trench tsunami, due to the time (less than 2 hours) between the earthquake and tsunami arrival. Storm surge levels build up over hours, whereas a tsunami can arrive almost immediately. Therefore, warning times for an elevated sea level event would probably be longer, although a combination of river flooding and storm surge may cause water to rise rapidly at Toko Mouth. If this occurred at night, then people may be less aware of the hazard. The Toko Mouth area is also reasonably isolated, with limited mobile phone reception. People would need to be aware of the quickest and safest route from the settlement to higher ground. Furthermore, the only access road is low lying and prone to inundation, while the elevated bank behind the town is steep and difficult to climb.

Figure 20. Looking west towards buildings alongside the true right of the Tokomairiro River near the mouth (August 2011)

10.4 Summary

- People living in or visiting Toko Mouth are vulnerable to elevated sea level and tsunami events, including lower magnitude events that occur more frequently.
- Tsunami events are shown to inundate properties alongside the true right bank of the Tokomairiro River for some distance upstream from the mouth, while extreme sea level events may also inundate properties further south within the main settlement.
- Road access to Toko Mouth from the west (Toko Mouth Road) or south (Coast Road) may be restricted or cut.
- The beach and estuary, which are used regularly for recreation, would experience higher levels of inundation (and maximum water speed during tsunami events). People in these areas would therefore be particularly vulnerable, especially at low tide, when these areas are more accessible.
- Any warning before the arrival of a Puysegur Trench tsunami is likely to be minimal at best. Therefore, people would need to be aware of the quickest and safest way to evacuate to an identified safe area.
- Changes in sea level of several metres may occur quickly along this stretch of coast during tsunami events.

11. Taieri Mouth

11.1 Community description

The Taieri Mouth settlement is located where the Taieri River exits the Lower Taieri Gorge and enters the sea (Figure A40).[47] There are about 300 permanent residents living in the Taieri Mouth area (2006 Census), and the area is also popular during the summer and holiday periods. The community is spread out along a 4.5km stretch of the coastal road, from the north bank of the Taieri River to Livingstonia Park. A number of houses are also located close to the river, upstream of the Taieri Mouth Bridge on Riverside Road (Figure 22). There is a primary school and a holiday camp on the south side of the river. A number of commercial fishing boats have their base at Taieri Mouth, and the public also use the area to moor and launch boats (Figure 21).

The potential for development within the Taieri Mouth settlement was assessed through consultation with the Clutha District Council. Development is able to occur on empty sections as of right within the existing settled area, which is zoned 'Urban Resource Area'. However, infrastructure constraints (such as wastewater capacity) would limit this in some cases. Other parcels of land between the main road and the ocean are zoned 'Coastal Resource Area', and consent authority approval is needed for development, with natural hazards a relevant matter to be considered by the consent authority. A field visit in August 2011 indicated that there have been a number of new houses built and renovations of existing houses in recent years in Taieri Mouth, although this has generally occurred on elevated land.

Figure 21. View of Taieri Mouth, showing moored fishing boats, the bridge over the Taieri River and other buildings (October 2007)

11.2 Effect of elevated sea level and tsunami events

Elevated sea level

NIWA's (2008) modelling showed that a 1:500-year event would result in an elevated sea level of about 1.15m above MHWS at Taieri Mouth (Table 21). This event would result in inundation of up to 1m along the near-shore strip on the north and south side of the Taieri River, downstream of the bridge (Figure A40). Residential sections within this area and the low-lying area next to Sawmill Creek may be inundated to a depth of 0.5m. Modelled inundation extents do not extend beyond the Taieri Mouth Bridge.

[47] Refer to the map book (ORC, 2012) for all Figures beginning with 'A'.

However, a number of houses located close to the intertidal zone on Riverside Road upstream of the bridge could also be vulnerable to elevated sea level, as they lie less than 2m above MSL (Figure 22).

Figure 22. Houses on Riverside Road on the south bank of the Taieri River, upstream of the bridge (August 2011)

Low-lying parts of Taieri Mouth are also susceptible to inundation during more frequently occurring elevated sea level events. Table 21 shows that the difference in maximum water level between the 1:20-year storm surge and 1:500-year storm surge is just 0.2m.

Table 21. The level of the sea (relative to MSL) at MHWS and for a range of modelled elevated sea level events at Taieri Mouth. The percentage chance of a particular event occurring in any given 100-year period is shown in brackets

Return period in years (chance of occurring in any 100-year period)	MHWS	20 (99%)	50 (87%)	100 (63%)	500 (18%)
Water level (m above MSL)	0.95	1.90	1.95	2.0	2.1
Existing houses affected?	No	Yes	Yes	Yes	Yes

Far-field tsunami

Figure A46 shows that the modelled 1:500-year South American tsunami would reach Taieri Mouth about 15 hours 25 minutes after the earthquake. The first wave would peak about 35 minutes later, with the largest modelled wave striking the coast 19 hours 45 minutes after an earthquake. Many smaller waves would continue for another 15 hours afterwards.

The maximum run-up observed at Taieri Mouth from this scenario is 2.7m above MSL (Table 22). This would inundate low-lying land next to the river as far upstream as Henley Ferry (in the vicinity of the Taieri River/Waipori River confluence) to a depth of up to 1m (Figure A44). Water velocities of up to 3m per second would occur through the river mouth and under the Taieri Mouth Bridge. The bridge and its approaches would therefore need to withstand the combined effect of this increased velocity and depth to avoid being damaged. Residential sections upstream of the bridge on Riverside

Road would be inundated by up to 1m, and maximum water speeds of up to 1m per second.

Maximum wave run-up associated with a more frequent (1:100-year) South American tsunami would be 2.1m above MSL, which is 0.6m less than for a 1:500-year event. Such an event would cause inundation of properties along the south bank (from the river mouth up to Riverside Road) of up to 0.5m.

Table 22. Characteristics of tsunami events at Taieri Mouth (as modelled by NIWA 2007)

Characteristic	Puysegur Trench tsunami	1:500-year South American tsunami
Tsunami arrival time (after fault rupture)	1 hour 30 min	15 hours 30 min
Maximum wave amplitude above the undisturbed level of the sea	3.2m	1.6m
Predominant period of wave arrivals	30 min	1 hour 30 min
Maximum wave run-up above MSL	3.5m	2.7m

Near-field tsunami

The modelled 1:600-year Puysegur Trench tsunami would result in maximum wave run-up of up to 3.5m above MSL on land (Table 22), and Figure A41 shows the extent and depth of inundation around Taieri Mouth associated with this event. The banks of the Taieri River near the mouth would be inundated up to a depth of 2.5m, while residential sections on Riverside Road upstream of the bridge would be inundated by up to 2m. Low-lying land next to Sawmill Creek would be inundated up to a depth of 1.5m. A Puysegur Trench tsunami would impact as far upstream as Henley Ferry (in the vicinity of the Taieri River/Waipori River confluence), with water depths of up to 1m in low-lying areas next to the river (Figure A43).

This type of event could produce water velocities of 2-5m per second in the Taieri Mouth area, with the greatest velocities experienced near the bridge. As for a far-field tsunami, the bridge would need to be able to withstand the combined effect of increased velocity and depth to avoid being damaged.

Figure A45 shows a time series of the modelled Puysegur Trench tsunami. Water would begin to retreat from the beach 1½ hours after the earthquake, with the first wave arriving about 1 hour later. Another large wave would arrive at the river mouth about 5½ hours after the earthquake, and large waves and strong currents would continue to affect the area for another hour and a half. The sea level may fluctuate very quickly, and by up to 4.5m, during the tsunami, as the water retreats and then rushes back in.

Probability of inundation

The probability of maximum water levels of 1.5, 2.0 and 2.5m above MSL occurring as a result of any of the tsunami or elevated sea level scenarios modelled by NIWA is shown in Table 23. The table also provides a generalised explanation of the likely extent of inundation if a tsunami or elevated sea level event that reached 1.5, 2.0 or 2.5m were to occur.[48]

[48]The extent of inundation has been estimated through a simple assessment of coastal topography and elevation. Note that other factors associated with tsunami and elevated sea level events, such as wave velocity and duration of inundation, would also have an impact on particular communities.

Table 23. Likelihood and possible consequences of peak water level due to the modelled storm surge and tsunami scenarios at Taieri Mouth (with current sea level)

Maximum water level (m above MSL)	Probability of occurrence during any 100-year period (%)	Likely extent of inundation
1.5	>99	Inundation limited to areas immediately next to the Taieri River Mouth and low-lying areas near the mouth of Sawmill Creek. Potential inundation of properties alongside Riverside Road.
2.0	85-95	Inundation of low-lying areas alongside the Taieri River, including properties above and below the Taieri Mouth bridge on the south bank.
2.5	25-35	More extensive inundation of properties on the south bank of the river. Potential for ponding to occur in low-lying parts of the main township, including in and around Livingstonia Park.

The probability of maximum water levels reaching any of these heights will increase if the sea level rises in the future. Table 24 shows the probability of maximum water level reaching 1.5, 2.0 or 2.5m above MSL as a result of tsunami or elevated sea level scenarios if 0.5m of sea level rise were to occur.

Table 24. Likelihood of peak water level due to the modelled storm surge and tsunami scenarios at Taieri Mouth (if average sea level were 0.5m higher than at present)

Maximum water level (m above MSL)	Probability of occurrence during any 100-year period (%)
1.5	>99
2.0	>99
2.5	85-95

Cross section profile

Figures A47 and A48 show a cross section profile, which extends across the Taieri River mouth and the Taieri Mouth settlement. The cross section shows the elevation of the land relative to maximum water levels associated with the tsunami and elevated sea level scenarios. Sawmill Creek, in the centre of the cross section, is a low point through which water may flow and inundate the low-lying area behind (as shown in Figures A40 to A42). The cross section shows that low-lying areas of the Taieri Mouth settlement are vulnerable to inundation during the modelled scenarios. This includes parts of the residential area on the south side of the river.

11.3 Community vulnerability

Much of the Taieri Mouth settlement, including the local primary school, is outside the area shown to be inundated under the modelled elevated sea level and tsunami scenarios. However, a number of houses, buildings and infrastructure alongside the lower reaches of the river, and on either side of Sawmill Creek to the south, would probably be affected during these types of event (Figures A40-A44). Figures A43 and A44 show that land beside the river, as far upstream as Henley, may be affected.

As well as the scenarios shown in Figures A40 to A44, properties in these areas may also be vulnerable to lower magnitude events that occur more frequently. Properties along Riverside Road upstream of the bridge are particularly low lying, and priority may need to be placed on evacuating residents from this area during elevated sea level and tsunami events. Any boats in the water in the Taieri Mouth area would also be vulnerable to these events.

Tsunami and elevated sea level events may affect road access within Taieri Mouth and between other settlements to the north. The bridges across the Taieri River and Kaikorai Stream are potentially vulnerable, as maximum water speeds of up to 5m per second could occur around these structures as a result of the Puysegur Trench tsunami.[49] Finlayson Road, which links Taieri Mouth with Waihola, is unlikely to be affected however. The electricity distribution network (power poles and lines), along with other infrastructure, including telephone, water and sewage lines may also be damaged or require inspection.

The greatest risk to the Taieri Mouth community would come from a near-field Puysegur tsunami, because of the time (2½ hours) between an earthquake and tsunami arrival, and the greater levels of inundation and water velocity caused by this event. People within the township and close to the shoreline[50] would need prompt warning of an approaching tsunami if that warning were to be effective. The best warning of an approaching Puysegur Trench tsunami may be the ground shaking associated with the tsunami or a retreat in sea level as the tsunami wave approaches. This shaking may not be felt by everyone, however, and those who do feel it may not immediately associate it with the potential occurrence of a large tsunami.

11.4 Summary

- People in close proximity to the coast at Taieri Mouth are vulnerable to elevated sea level and tsunami events, including lower magnitude events that occur more frequently.
- Residential properties and roads alongside the Taieri River (as far upstream as Henley), and from Taieri Mouth down to Livingstonia Park, may be inundated by waves up to 2m deep, and travelling at up to 4m per second during a near-field Puysegur Trench tsunami.
- Areas used regularly for recreation, such as the beach and river mouth, may experience higher levels of inundation (and maximum water speed during tsunami events). Therefore, people in these areas would be particularly vulnerable, especially at low tide when these areas become more accessible.
- Road access to Taieri Mouth from the north may be restricted or cut.
- Changes in sea level of several metres may occur very quickly along this stretch of coast during tsunami events.
- Any warning before the arrival of a Puysegur Trench tsunami is likely to be minimal at best. Therefore, people would need to be aware of the quickest and safest way to evacuate to an identified safe area.

[49] Maximum water speed associated with a Puysegur Trench tsunami at the mouth of the Kaikorai Stream is shown in Figure A49.
[50] Including estuarine areas in and around Taieri Mouth and along the beach

12. Brighton

12.1 Community description

Brighton is situated near the mouth of Otokia Creek, which drains the hills to the west (Figure A50).[51] About 1,360 people were living along the 3.7km stretch of coastline in the Brighton area in 2006 (from census data). Brighton beach is popular for recreation, so the number of people in the area may be higher at times. The town has a number of external road links, including Brighton-Scroggs Hill Road to the north, and Brighton and Taieri Mouth roads, which extend along the coast to the north-east and south-west, respectively. On the south side of the river, the town has a local primary school and fire station.

There is some capacity for infill (or subdivision) development to occur within the boundaries of Brighton township. The settlement is zoned ‘Residential 1’, with a minimum lot size of $500m^2$, and there is capacity for an additional 293 sections within the town itself (DCC, 2009). Most of this capacity is situated on elevated land at the northern and southern ends of the town, although there is also some ability for infill development on the low-lying land alongside Otokia Creek (Figure 23). There is also some capacity for subdivision on the land zoned ‘Rural Residential’, along Taieri Mouth Road, to the south of Brighton. This zone has a minimum lot size of two hectares, and provides for small-scale farming and residential activities close to existing urban areas.

Figure 23. The mouth of Otokia Creek at Brighton, with low-lying residential land at centre-right (August 2011)

12.2 Effect of elevated sea level and tsunami events

Elevated sea level

NIWA’s (2008) modelling showed that a 1:500-year event would result in an elevated sea level of 2.2m above MSL, and 1.25m above MHWS at Brighton (Table 25). Figure A50 shows that that this event would cause low-lying areas beside Otokia Creek to be inundated up to a depth of 1m. This may affect a number of existing buildings on the north side of the creek upstream of the bridge, as well as the northern approach to the

[51] Refer to the map book (ORC, 2012) for all Figures beginning with ‘A’.

bridge itself (Figure 23). More frequently occurring elevated sea level events would result in inundation of a similar area, as the difference in maximum water level between a 1:20-year and 1:500-year event is just 0.2m (Table 25).

Table 25. The level of the sea (relative to MSL) at MHWS and for a range of modelled elevated sea level events at Brighton. The percentage chance of a particular event occurring in any given 100-year period is shown in brackets

Return period in years (chance of occurring in any 100-year period)	MHWS	20 (99%)	50 (87%)	100 (63%)	500 (18%)
Water level (m above MSL)	0.95	2.0	2.05	2.10	2.20
Existing houses affected?	No	Possible	Yes	Yes	Yes

Far-field tsunami

Figure A53 shows that the modelled 1:500-year South American tsunami would reach Brighton about 15½ hours after the earthquake. The first wave would peak half an hour later. The largest modelled wave would strike the shore about 19 hours 40 minutes after the earthquake. Many smaller waves would continue for another 10 hours. The maximum run-up observed at Brighton from this scenario would be at least 2.5m above MSL. Inundation would largely be confined to the beach, with the exception of the area immediately north of Otokia Creek, where several buildings/houses may be inundated by up to 0.5m.

Maximum wave run-up and inundation associated with a more frequent (1:100-year) South American tsunami is likely to be restricted to the estuary, near-shore dunes and the beach. [52]

Near-field tsunami

Inundation and wave run-up associated with the 1:600-year Puysegur Trench tsunami is likely to be slightly greater than the 1:500-year South American tsunami. Table 26 shows that a Puysegur Trench tsunami may result in maximum wave run-up of 3m above MSL. This type of event could produce water velocities of between 1 and 3 metres per second through the Otokia Estuary, with the greatest velocities experienced near the bridge. Figure A51 shows the extent and depth of inundation around Brighton due to the modelled 1:600-year Puysegur Trench tsunami.

Figure A52 shows a time series of water levels associated with the modelled 1:600-year Puysegur Trench tsunami. Water would retreat from the beach just 1 hour 45 minutes after the earthquake. The first wave would arrive approximately 45 minutes later. Another large wave would strike Brighton 5 hours 45 minutes after the earthquake. Large waves and strong currents would continue to affect the area for another hour and a half. Water level varies by up to 4m in a short space of time during the tsunami as the water retreats and then rushes back in.

[52] Note that inundation extents associated with far-field tsunamis are not shown in the map book (ORC, 2012) for Brighton as they are less extensive than those associated with a Puysegur Trench tsunami.

Table 26. Characteristics of tsunami events at Brighton (as modelled by NIWA 2007)

Characteristic	Puysegur Trench tsunami	1:500-year South American tsunami
Tsunami arrival time (after fault rupture)	1 hour 45 min	15 hours 30 min
Maximum wave amplitude above the undisturbed level of the sea	2m	1.5m
Predominant period of wave arrivals	35 min	80 min
Maximum wave run-up above MSL	3m	>2.5m

Probability of inundation

The probability of maximum water levels of 1.5, 2.0 and 2.5m above MSL occurring as a result of any of the tsunami or elevated sea level scenarios modelled by NIWA is shown in Table 27. The table also provides a generalised explanation of the likely extent of inundation if a tsunami or elevated sea level event that reached 1.5, 2.0 or 2.5m were to occur.[53]

Table 27. Likelihood and possible consequences of peak water level due to the modelled storm surge and tsunami scenarios at Brighton (with current sea level)

Maximum water level (m above MSL)	Probability of occurrence during any 100-year period (%)	Likely extent of inundation
1.5	>99	Wave run-up may elevate water levels around the mouth of the Otokia Creek, largely within the river banks. Inundation of low-lying flats behind Brighton Township is possible.
2.0	>95	Further inundation around the banks of the Otokia River and mouth. Potential overtopping of northern bank near the campground.
2.5	70-80	Extensive inundation within river banks and along beaches. Inundation of low-lying properties in the vicinity of the Brighton Road bridge is likely.

The probability of maximum water levels reaching any of these three heights will increase if sea level rises in the future. Table 28 shows the probability of maximum water level reaching 1.5, 2.0 or 2.5m above MSL as a result of tsunami or elevated sea level scenarios if 0.5m of sea level rise were to occur.

Table 28. Likelihood of peak water level due to the modelled storm surge and tsunami scenarios at Brighton (if average sea level were 0.5m higher than at present)

Maximum water level (m above m.s.l.)	Probability of occurrence during any 100-year period (%)
1.5	>99
2.0	>99
2.5	>99

[53]The extent of inundation has been estimated through a simple assessment of coastal topography and elevation. Note that other factors associated with tsunami and elevated sea level events, such as wave velocity and duration of inundation, would also have an impact on particular communities.

Cross section profile

Figures A54 and A55 show a cross section profile extending from Brighton Beach inland across Otokia Creek and the adjacent residential area. The profile shows that the land where the school and fire station[54] are located is somewhat elevated, although a number of properties along this stretch of Brighton Road are located within 50m of the shoreline. The profile also shows that the land on the north side of Otokia Creek is low lying and susceptible to inundation, particularly during the modelled 1:600-year Puysegur Trench tsunami.

12.3 Community vulnerability

Most of the Brighton Township would not be affected by the elevated sea level and tsunami scenarios modelled for this report. However, there are a number of buildings, including houses, a campground and shops on the margins of Otokia Creek, which are susceptible to inundation. Some of these properties are situated on land that is just 1.5m above MSL.

The modelled 1:600-year Puysegur Trench tsunami would inundate land on the margins of Otokia Creek to a depth of up to 1.5m, and about a dozen buildings and houses in this area may be inundated to a depth of 0.5m. Other popular recreation areas, including the beach, foreshore and reserves, would also be affected. People in these areas would be particularly vulnerable, due to the short length of time between the earthquake occurring and the arrival of the tsunami. Parts of Brighton Road may also be damaged by inundation or erosion.

Infrastructure and assets that may be affected include low-lying parts of Brighton Road, and the electricity and phone lines that run alongside them. Also at risk would be a number of wastewater manholes located alongside Otokia Creek, upstream of the bridge. Inundation of these could cause wastewater flooding and overflow into the creek. There is also a wastewater pump station about 100m upstream of the bridge. Furthermore, the discharge of stormwater to the creek during heavy rainfall events could be slowed by elevated water levels, causing flooding further up the stormwater network.

12.4 Summary

- People in close proximity to the coast at Brighton are vulnerable to elevated sea level and tsunami events, including lower magnitude events that occur more frequently. Areas where people are particularly vulnerable include:
  - the lower margins of Otokia Creek, including the reserve at the mouth of the creek
  - the stretch of Brighton Road between McIntosh Road and the Otokia Bridge
  - Brighton Beach, and the beaches and rocky outcrops to the north and south.
- Areas used regularly for recreation, such as the beach and river mouth, would experience higher levels of inundation (and maximum water speed during tsunami events). Therefore, people in these areas would be particularly vulnerable, especially at low tide when these areas become more accessible.

[54] A swimming pool, bowling club and several houses are also located on this elevated terrace.

- Residential and commercial properties situated along Brighton Road between McIntosh Road and Otokia Creek would be vulnerable to inundation and damage during elevated sea level and tsunami events.
- Road access to Brighton from the north and south may be restricted or cut. (See also Section 11.3.)
- Changes in sea level of several metres may occur very quickly along this stretch of coast during tsunami events.
- Any warning before the arrival of a Puysegur Trench tsunami would be minimal at best. People would therefore need to be aware of the quickest and safest way to evacuate to an identified safe area.

13. St Kilda/St Clair

13.1 Community description

This low-lying area is bounded by St Clair and St Kilda beaches to the south, Otago Harbour to the north, and hills to the east and west (Figure A56).[55] It includes several residential suburbs, as well as the nearby commercial district between Andersons Bay Road and King Edward Street (Figure A63). Much of the residential land was reclaimed in the late 19th century from marshy swampland, which included the former St Kilda lagoon (Aitken, 1975). Large quantities of sand were mined from the St Clair/St Kilda beach dune system in the mid- to late 1800s for harbour reclamation (DTEC, 2002). This may have contributed to breaches through the dunes in the late 19th and early 20th centuries. Historic records tell of water flooding streets and entering houses on a number of occasions during this period (Newton, 2003).

There is an element of risk associated with elevated sea level and tsunami events in this low-lying area because of the intensity of development that has occurred over the last 150 years. The wider South Dunedin area, extending from Caversham to St Kilda and into Musselburgh, is zoned ‘Residential 2’ in the Dunedin City District Plan and is characterised by small sites, and smaller and older dwellings. The area is popular with older people due to its flatter terrain. Nearly 37% of the properties in this area are flats and units (DCC, 2009). The minimum lot size is 300m^2, and there is limited capacity for infill development.[56] There is only a slender barrier of sand or sea wall between the ocean and the urban area, particularly at the south-west end of the beach (Figure A56), and the beach and dune system is exposed to the ocean from the south.

The most significant tsunami events to affect South Dunedin are likely to be generated by earthquakes on near-field fault zones. NIWA (2007) identified a number of sources to the south of Otago Peninsula that could affect South Dunedin, due to the orientation of these faults and the South Dunedin shoreline. They include the Puysegur Trench subduction zone, the Akatore Fault, the Takapu Fault zone and the Castle Hill Fault zone (Figure 6). Glassey *et al*. (2003) found that near-field tsunami could be generated by local offshore faults that show seafloor expression immediately to the south-east of Dunedin between the Kaikorai Estuary and the mouth of the Taieri River.

The modelled results for a near-field tsunami presented in this report are based on a large subduction zone earthquake (around M8.5) on the Puysegur Fault (see Section 5.3). NIWA (2007) considered such an event to be the most likely near-field tsunami source, and to represent the most probable maximum frequency earthquake for this region. There may be a level of risk associated with other low-likelihood, high-magnitude local earthquake events, although the impact of such events on the South Dunedin area have not been modelled as part of this report. This report therefore presents a lower bound of the true risk.

[55] Refer to the map book (ORC, 2012) for all Figures beginning with ‘A’.

[56] DCC (2009) estimated that 94 new dwelling units could be created in eastern St Kilda. This is the area bordered by Bay View Road to the north-west, Prince Albert Road to the south-west, Musselburgh to the north-east and the coast to the south. The DCC report found that there was minimal capacity for new dwellings elsewhere in South Dunedin.

13.2 Effect of elevated sea level and tsunami events

Elevated sea level

Maximum sea level during the modelled 1:500-year event at St Kilda/St Clair is 2.15m above MSL, and 1.2m above MHWS (Table 29). LiDAR information (collected in 2004) shows that this level is lower than the crest of the sand dunes and the St Clair sea wall. There is no inundation of the South Dunedin urban area as a result of this event (Figure A57). It is noted, however, that these results assume that the dune system remains static. A prolonged event may cause erosion of sand dunes or damage to the sea wall, as has been observed during previous elevated sea level events (Figure 24). This may increase the chance of waves breaching or overtopping the dunes. The likelihood of this occurring is examined in greater detail below.

Furthermore, events that occur more frequently than the modelled 1:500-year scenario may also have a considerable effect on the shoreline, as they still result in sea levels that are elevated well above the normal tidal range. For example, Table 29 shows that the difference in water level between a modelled 1:20-year and 1:500-year event is just 0.2m.

Table 29. The level of the sea (relative to MSL) at MHWS and for a range of modelled elevated sea level events at South Dunedin. The percentage chance of a particular event occurring in any given 100-year period is shown in brackets

Return period in years (chance of occurring in any 100-year period)	MHWS	20 (99%)	50 (87%)	100 (63%)	500 (18%)
Water level (m above MSL)	0.95	1.95	2.0	2.05	2.15
Existing buildings affected?	No	No[57]	No	No	No

Figure 24. St Kilda Beach, showing signs of recent erosion (July 2007)

[57] The St Clair Hot Salt Water Pool is the only development shown to be affected by elevated sea levels, with a return period of 20 years or more.

Far-field tsunami

The modelling undertaken for the 1:500-year South American tsunami (Figure A60) shows that the first wave would peak at the coast almost 16 hours after the earthquake. The largest modelled wave would strike the coast 19 hours and 40 minutes after the earthquake. Many smaller waves would continue for another 8 hours. The maximum run-up observed on the St Kilda/St Clair beaches from this scenario is 2.3m above MSL. This would cause inundation to the upper limit of the beaches and the mouth of Tomahawk Lagoon.

Near-field tsunami

Table 30 shows that the modelled 1:600-year Puysegur Trench tsunami may result in maximum wave run-up on land of up to 3m above MSL. The extent of inundation from the Puysegur Trench tsunami is shown in Figure A58. Figure A59 shows a time series of the water level associated with the modelled Puysegur Trench tsunami. Water would retreat from the beach 1 hour 45 minutes after the earthquake. The first wave would arrive at the shoreline about 45 minutes later, followed by another large wave 20 minutes after that. Large waves would continue to affect the area for 6 hours after the earthquake.

Although the map in Figure A58 does not show inundation of the South Dunedin urban area, it is important to note that the results are based on the dune system remaining static during the tsunami event. In reality, a tsunami event would produce a succession of large waves over an extended period, with a frequency of about one every 30 minutes. This would likely result in erosion of material from the dune system, which may increase the chance of subsequent waves breaching or overtopping the dunes. The section entitled ‘Cross section profiles’ (below) examines the likelihood of this occurring in more detail.

Figure A58 does show that a major tsunami event would inundate the salt water pool at St Clair. The outlet from the Tomahawk Lagoon is also a low point in the dune system, and a tsunami or storm surge event may push water up into the lower reaches of the lagoon.

Table 30. Characteristics of tsunami events at St Kilda/St Clair (as modelled by NIWA, 2007)

Characteristic	Puysegur Trench tsunami	1:500-year South American tsunami
Tsunami arrival time (after fault rupture)	1 hour 45 min	15 hours 30 min
Maximum wave amplitude above the undisturbed level of the sea	1.75m	1.3m
Predominant period of wave arrivals	30 min	80 min
Maximum wave run-up above MSL	3m	2.3m

Probability of inundation

The probability of maximum water levels of 1.5, 2.0 and 2.5m above MSL occurring as a result of any of the tsunami or elevated sea level scenarios modelled by NIWA is shown in Table 31. The table also provides a generalised explanation of the likely extent of inundation if a tsunami or elevated sea level event that reached 1.5, 2.0 or 2.5m were to occur.[58] As noted above, the modelling did not take into consideration the effect of erosion on the dune system at South Dunedin; therefore, the results of Table 31 assume that the dune system would not be breached.

Table 31. Likelihood and possible consequences of peak water level due to the modelled storm surge and tsunami scenarios at St Kilda/St Clair (with current sea level)

Maximum water level (m above MSL)	Probability of occurrence during any 100-year period (%)	Likely extent of inundation
1.5	>99	0.55m above current MHWS. Wave run-up affecting entire beach.
2.0	>95	1.05m above current MHWS. Wave run-up affecting entire beach. Potential for erosion of the dune system. Inundation of the outlet and low-lying margins of Tomahawk Lagoon.
2.5	10-20	1.55m above current MHWS. Wave run-up affecting entire beach. Increased potential for erosion of the dune system. More extensive inundation of Tomahawk Lagoon margins possible.

The probability of maximum water levels reaching any of these three heights will increase if sea level rises in the future. Table 32 shows the probability of maximum water level reaching 1.5, 2.0 or 2.5m above MSL as a result of tsunami or elevated sea level scenarios if 0.5m of sea level rise were to occur.

Table 32. Likelihood of peak water level due to the modelled storm surge and tsunami scenarios at St Kilda/St Clair (if average sea level were 0.5m higher than at present)

Maximum water level (m above MSL)	Probability of occurrence during any 100-year period (%)
1.5	>99
2.0	>99
2.5	>95

Cross section profiles

Figures A61 and A62 show a cross section (or elevation profile) through South Dunedin from St Kilda Beach to Kensington. Maximum run-up levels associated with the modelled 1:600-year Puysegur tsunami, 1:500-year South American tsunami and 1:500-year extreme sea level event are also shown. Figure A56 shows that much of the wider South Dunedin area is less than 1m above MSL. Tsunami or elevated sea level events could extend for a considerable distance inland if they were to breach the coastal dune system. As a result, large areas would potentially be inundated.[59]

Figures A64 to A69 show five short cross sections that extend from the beach, across the St Clair sea wall (cross section 1) or coastal dunes (cross sections 2-5) to the low-lying areas beyond. The cross sections have been plotted using LiDAR data and show the height of the dune crest or sea wall at different locations along the beach. The

[58]The extent of inundation has been estimated through a simple assessment of coastal topography and elevation. Note that other factors associated with tsunami and elevated sea level events, such as wave velocity and duration of inundation, would also have an impact on particular communities.

[59] Box 2 in section 5.2 demonstrates how topography can influence the inundation distance and run-up of tsunami events.

modelled maximum run-up level of a 1:600-year Puysegur Trench tsunami has been overlaid onto the cross sections. This level is 2m lower than the crest of the sea wall at St Clair (cross section 1), and between 8 and 20m below the crest of the sand dunes at cross sections 2 to 5.

These five cross sections show that a 1:600-year Puysegur Trench tsunami would be unlikely to overtop the dunes, playing fields or sea walls separating the suburbs of St Kilda and St Clair from the sea. However, a succession of large waves associated with such an event may cause erosion of the dunes or damage to the sea wall at St Clair, which may increase the risk of these defences being breached. The narrowest section of elevated land[60] that could be identified using the LiDAR data is located near cross section 2 (Figure A66). At this point, there is about 80m of elevated land between the beach and the low-lying urban area. This distance is an estimate based on LiDAR information collected in 2004. Changes to the beach and dune system may have occurred since this time.

13.3 Community vulnerability

The wider South Dunedin area is low lying (Figure 56) and, due to its proximity to the coast, may be exposed to some level of risk during elevated sea levels or tsunami events. Figure A63 demonstrates that South Dunedin contains a range of land uses, with high density residential being the most predominant. The vulnerability of South Dunedin varies depending on the primary land use, topography and distance from the shoreline. A summary is provided below, based on these aspects.

Dunes, parks and fields

The area of land closest to the sea is mainly used for recreational purposes (Figure A63). It includes the dune system and the parks and fields immediately behind the dunes. This area is popular with Dunedin residents and visitors to the city as it provides easy access to the surrounding beaches, sports fields and playgrounds.

Much of this area sits at a higher elevation than the greater South Dunedin urban area, and the topography is dominated by low hummocks and ridges associated with the coastal dune system. The Tahuna Wastewater Treatment Plant is also located at the eastern end of this area.

Residents or visitors to this area would be the first to be affected by a storm surge or tsunami event. People on the beach or fore-dunes would be at greater risk than those on the higher dunes and playing fields. The warning times associated with a far-field tsunami or storm surge would probably be sufficient for appropriate action to be taken to ensure public safety. Warning times associated with a near-field tsunami may be considerably less, and, in the case of local events, there may effectively be no warning other than the earthquake itself (Glassey *et al*., 2003).

Forbury Park, St Kilda, Tainui and Musselburgh

A large area of residential land (including the suburbs of Forbury Park, St Kilda, Tainui and Musselburgh) is located behind the dune system and recreational area. This area has a high population density of over 3,300 people per km^2 and is generally low lying, particularly around Tainui and parts of Musselburgh (Figure A56). Figure A63 shows

[60] 'Elevated land', in this instance, is defined as 'elevated above the modelled maximum run-up level from a 1:600-year Puysegur tsunami'.

that Musselburgh and Tahuna schools, along with several pre-schools, are located within the area, which is within half a kilometre of the shoreline. A small retirement village and residential enclave are also nestled between the dune system and Victoria Road. Other community features located within this area include Forbury racecourse, other sporting clubs and several rest homes.

There may be an expectation amongst this community that the dune system will be able to withstand the erosive effects of a tsunami or storm surge event. (See ‘Cross section profiles’ above.) If a significant amount of water were to breach the dune or sea-wall defences, the results could be devastating for this densely populated and low-lying area. Any water that did flow into this area would eventually pool in the low-lying areas, including eastern St Kilda and Tainui.

Property and infrastructure within South Dunedin are also vulnerable to high groundwater levels.[61] Under present conditions, the water table lies at a very shallow depth across much of this area and has a good connectivity to the open sea[62] (ORC, 2011). Prolonged periods of elevated sea level could result in higher groundwater levels, which may be exacerbated if a high magnitude elevated sea level event is accompanied by heavy rainfall. This may result in localised flooding, particularly in low-lying areas.

Forbury Corner, South Dunedin

Beyond the main area of residential land use is an area of mixed use, including residential, industrial and commercial. Within this area are the South Dunedin and Andersons Bay Road shopping centres. A large number of pre-schools, schools and health facilities are also found here, and the Otaki Street electricity substation is located to the north-east. Its topography rises gradually towards the north-west[63], and it is further back from the Pacific Ocean.[64] The area is, therefore, less likely to be directly affected by elevated sea level or tsunami events, although surface ponding may occur in some places if an event coincided with heavy rainfall. In this case, stormwater may be unable to drain away due to a higher than normal water table. If a tsunami wave were to breach the coastal dune system, it would need to maintain considerable velocity and water depth to reach this area and cause significant inundation.

St Clair

To the south-west of South Dunedin is the reasonably elevated St Clair residential area, which lies very close to the ocean. The land rises gradually towards the western hills (Figure A64). The area includes the busy St Clair Esplanade and has a high population density. Figures A63 and A65 show that there is urban development right up to the edge of the St Clair sea wall. People in this near-shore area may be affected by wave splash or overtopping jets of water during a large storm surge or tsunami event.

[61] This is particularly true in for these suburbs that have the lowest-lying topography (Figures A56 and A63).
[62] That is, there is a tidal influence on groundwater levels up to 1km from the beach.
[63] There is approximately a 0.5m rise in land surface between Bay View and Hillside roads.
[64] Parts of this area also lie within 500m of the Otago Harbour. The adjacent commercial zone to the north-east provides some protection from high water levels in the harbour, however, as it is generally of a higher elevation than much of South Dunedin itself. (See also Section 14.)

13.4 Summary

- Inundation associated with modelled extreme sea level and tsunami events would be restricted to the coastal dunes and beaches, and the entrance to the Tomahawk Lagoon. People in this area would be particularly exposed to tsunami events.
- Tsunami or extreme sea level events could inundate parts of South Dunedin if they were to breach the dunes that separate the beach from the urban area. People and property in South Dunedin therefore remain vulnerable, due to the low-lying nature of this area and its proximity to the coast.
- Lower magnitude events that occur more frequently may also cause coastal erosion.
- The sea wall at St Clair would need to be able to withstand extended periods of elevated sea levels and wave action to avoid being damaged during these events.
- The lowest-lying suburbs in South Dunedin are Tainui and eastern St Kilda.
- Any warning before the arrival of a near-field tsunami may be minimal at best. People would, therefore, need to be aware of the quickest and safest way to evacuate to an identified safe area. They would also require clear instructions on when and how to use these evacuation routes.
- Changes in sea level of several metres may occur very quickly along this stretch of coast during tsunami events.

14. Upper Otago Harbour

14.1 Community description

For the purposes of this study, the upper Otago Harbour extends from Ravensbourne, around the harbour, to the Cove on Portobello Road (Figure A70).[65] Land use in this area is mainly commercial and industrial, with some important infrastructure (including the Otaki Street electricity substation) and transport links also situated near the harbour. Much of the shoreline area is used regularly for recreation, including the playing fields alongside the Andersons Bay Inlet, cycle ways and boating clubs. About 120 people live permanently in the low-lying areas that fringe the upper harbour.[66] Most of these live close to the Andersons Bay Inlet on Somerville and Marne streets, and DCC (2009) identified that there may be some capacity for infill development in this area.

The Otago Harbour is sheltered from the open sea, and so the effects of a tsunami would be minor. However, its narrow, confined nature (Figure 1) means that extensive inundation may occur during elevated sea level events, as a result of persistent strong winds from the north-east.

Figure 25. Andersons Bay Inlet, at the head of the Otago Harbour. The inlet is bordered by playing fields to the south and Marne Street, which runs alongside the northern side. In the centre distance are low-lying residential properties and a rest home, near the intersection of Marne and Somerville streets (August 2007)

14.2 Effect of elevated sea level and tsunami events

Elevated sea level

NIWA's (2008) modelling showed that a 1:500-year event would result in an elevated sea level of about 1m above MHWS in the Otago Harbour (Table 33). This would cause low-lying sections of Portsmouth Drive, Midland and Teviot streets to be inundated to a depth of 0.5-1.0m (Figure A70). Such an event would also inundate roads and properties to a similar depth in the vicinity of Somerville and Marne streets in Andersons Bay. Wave run-up may temporarily extend the area of inundation on flat land at the head of the harbour. The maximum extent of wave run-up may include Orari Street through to

[65] Refer to the map book (ORC, 2012) for all Figures beginning with 'A'.
[66] According to the 2006 Census.

SH1 at the Queens Gardens, the northern end of Fryatt Street, either side of the mouth of the Water of Leith and reclaimed land at Ravensbourne.[67]

The upper Otago Harbour is also susceptible to inundation during lower magnitude events that occur more frequently. Figure A71 shows the extent and depth of inundation for a modelled 1:20-year extreme sea level event, while Table 33 shows that the water level associated with such an event is just 0.25m lower than a 1:500-year event.

Table 33. The level of the sea (relative to MSL) at MHWS and for a range of modelled elevated sea level events in Otago Harbour. The percentage chance of a particular event occurring in any given 100-year period is shown in brackets

Return period in years (chance of occurring in any 100-year period)	MHWS	20 (99%)	50 (87%)	100 (63%)	500 (18%)
Water level (m above MSL)	1.0	1.75	1.85	1.90	2.0
Existing buildings affected?	No	Yes	Yes	Yes	Yes

Far-field tsunami

The modelled effects of a 1:500-year South American tsunami include waves in the upper harbour, with a maximum amplitude of 0.5m above the undisturbed level of the sea (Table 34). The extent of inundation associated with such an event is shown in Figure A72. Inundation would generally be restricted to the intertidal zone, although minimal inundation may occur near the harbour cycleway between the boat harbour and Ravensbourne. The effects of a far-field tsunami would be felt over a period of 12 hours, with the initial effects felt for 16 hours after the earthquake (Figure A74).

Near-field tsunami

The effects of the modelled 1:600-year Puysegur Trench tsunami are expected to be minimal, with a maximum wave amplitude of only 0.15m above the undisturbed level of the sea (Table 34). Any effects would be felt over a period of less than 2 hours, with the initial effects being felt 4 hours after the earthquake (Figure A73).

The modelling for both tsunami scenarios indicated that there would not be any run-up or inundation beyond that which occurs regularly as a consequence of normal tidal variations and atmospheric forcing. Velocities associated with either tsunami scenario would be less than 1m per second. Coastal erosion would therefore be minimal.

Table 34. Characteristics of tsunami events in the upper Otago Harbour (as modelled by NIWA 2007)

Characteristic	**Puysegur Trench tsunami**	**1:500-year South American tsunami**
Tsunami arrival time (after fault rupture)	4 hours	15 hours 30 min
Maximum wave amplitude above the undisturbed level of the sea	0.15m	0.5m
Predominant period of wave arrivals	1 hour 30 min	105 min
Maximum wave run-up above MSL	NA	NA

[67] The amount of wave run-up is not shown on Figure A70, as it is dependent on local topography in the urban area, which includes buildings, roads and stormwater infrastructure, such as gutters and silt traps. Many of these features are likely to have changed since the LiDAR information was collected in 2004 and will continue to change in the future.

Probability of inundation

The probability of maximum water levels of 1.5, 2.0 and 2.5m above MSL occurring as a result of the tsunami or elevated sea level scenarios modelled by NIWA is shown in Table 35. The table also provides a generalised explanation of the likely extent of inundation if a tsunami or elevated sea level event that reached 1.5, 2.0 or 2.5m were to occur.[68]

Table 35. Likelihood and possible consequences of peak water level due to the modelled storm surge and tsunami scenarios at the upper Otago Harbour (with current sea level)

Maximum water level (m above MSL)	Probability of occurrence during any 100-year period (%)	Likely extent of inundation
1.5	>99	Wave run-up may overtop lower lying areas around the edge of the harbour.
2.0	15-25	Inundation of property and roads adjoining Portsmouth Drive, and around Marne and Somerville streets.
2.5	0 [69]	More extensive inundation of roads and the commercial area adjoining Portsmouth Drive, and around Andersons Bay Inlet.

The probability of maximum water levels reaching any of these three heights will increase if the sea level rises in the future. Table 36 shows the probability of maximum water level reaching 1.5, 2.0 or 2.5m above MSL as a result of tsunami or elevated sea level scenarios if 0.5m of sea level rise were to occur.

Table 36. Likelihood of peak water level due to the modelled storm surge and tsunami scenarios at the upper Otago Harbour (if average sea level were 0.5m higher than at present)

Maximum water level (m above MSL)	Probability of occurrence during any 100-year period (%)
1.5	>99
2.0	>99
2.5	15-25

Cross section profile

Figures A75 and A76 show a cross section profile around the head of the harbour. This profile shows that there are three low-lying areas, including parts of Kitchener, Midland and Teviot streets, which would be subject to inundation during a high magnitude storm surge event. Parts of Portsmouth Drive, Midland and Teviot streets are currently affected during normal spring-tide conditions.

[68] The extent of inundation has been estimated through a simple assessment of coastal topography and elevation. Note that other factors associated with tsunami and elevated sea level events, such as wave velocity and duration of inundation, would also have an impact on particular communities.

[69] None of the modelled current sea level scenarios used to generate this probability distribution returned a maximum water level exceeding 2.5m in the upper Otago Harbour. The maximum predicted sea level height used to calculate these probabilities was 2.02m above m.s.l, resulting from a 1:500-year elevated sea level scenario.

14.3 Community vulnerability

Modelling undertaken by NIWA (2008) shows that a 1:500-year elevated sea level event would inundate parts of Portsmouth Drive, Teviot and Midland streets and low-lying parts of Andersons Bay by up to 1m, with waves overtopping the harbour walls. Residential and commercial property in these areas may also be inundated. These same areas would also experience inundation during more frequent lower magnitude extreme sea level events. Elevated sea level events would also affect access on roads next to the harbour. The lowest-lying areas are only 1m above MSL.

Inundation caused by either of the modelled tsunamis is expected to be minor. Low-lying parts of the shoreline in Andersons Bay and the area between the mouth of the Leith and Ravensbourne may be affected. Boat sheds along the margin of the harbour would also be vulnerable to inundation.

Wastewater and stormwater networks along this stretch of coast have a level of vulnerability to elevated sea level or tsunami events. Overtopping of sea water into the wastewater network (via manholes and cracks in pipes) during storm events can cause minor operational issues at the Tahuna Wastewater Treatment Plant. Manholes, sewer lines and pump stations would need to be able to withstand extended periods of inundation for the system to remain operative, and to avoid damage occurring.

14.4 Summary

- People close to the shoreline around the upper Otago Harbour would have limited vulnerability to elevated sea level and tsunami events because:
    - sea level fluctuations during tsunami events are likely to be less than ± 0.25m
    - elevated sea level events would inundate a reasonably wide area, although this would develop over an extended period of time. Drivers, cyclists and pedestrians would need to remain alert, however, to avoid areas of deeper water.
- Residential and commercial properties, roads and other infrastructure near the harbour would be affected by inundation and wave action during elevated sea level events, including lower magnitude events that occur more frequently. A 1:500-year elevated sea level event may result in wave run-up that extends some distance inland.
- Localities likely to be worst affected by inundation during elevated sea level events include parts of Portsmouth Drive, Teviot and Midland streets and low-lying parts of Andersons Bay, due to their physical setting and proximity to the coast.
- Wave run-up may also affect the area between Orari Street and SH1 at Queens Gardens.

15. Long Beach, Purakanui, Aramoana and Harwood

15.1 Community descriptions

These four settlements are located on the north-eastern tip of the Otago Peninsula, close to the Pacific Ocean and/or the Otago Harbour. They consist of low-density residential development, with larger sections (minimum lot size is 1000 m^2), and they do not have reticulated water or sewerage services.[70]

The NIWA studies did not model the effects of elevated sea level and tsunami events at Aramoana or Harwood. However, the orientation of the shoreline and the closeness of these settlements mean that they would probably experience similar effects as Long Beach and Purakanui, particularly for elevated sea level and far-field tsunami events.

Long Beach and Purakanui

Long Beach and Purakanui are situated between the mouth of Otago Harbour and Waitati (Figure A77). About 260 people lived in the Long Beach and Purakanui areas in 2006 (from census data).[71] There are several weekend and holiday homes in Long Beach and Purakanui, so the population may at times be higher. Development can occur as of right on empty sections within both settlements, and DCC (2009) identified a number of vacant lots at the south-eastern end of Long Beach.

The Long Beach settlement is relatively low lying, and situated on loose, well-sorted sand deposits 200-300m back from the beach (Figure 26). Most of the residential sections at Purakanui are located on more elevated hill slopes, although some development does exist close to the margins of Purakanui Inlet.

Figure 26. Looking northeast towards Long Beach from Mihiwaka Road (August 2007)

Aramoana

Aramoana is located at the entrance to the Otago Harbour (Figure A79). The township had 140 permanent residents in 2006 and is a popular holiday/weekend destination. The DCC (2009) identified 26 vacant residential sections as available for development at Aramoana. These empty sections are spread evenly across the settlement.

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[70] All four settlements are zoned ‘Residential 5’ under the Dunedin City District Plan.
[71] This includes the hill country to the south of these two townships.

In this study, an elevation map of Aramoana (using LiDAR data) has been combined with modelled Long Beach/Purakanui water levels from the NIWA studies to give an indication of community vulnerability.

Harwood

The settlement of Harwood is located inside the Otago Harbour entrance. This area had about 250 permanent residents in 2006, with the majority living close to the shoreline on the low-lying land between Otakou and lower Portobello. There is significant potential for development along this stretch of coastline, both from infill (subdivision) of larger properties and on existing empty sections. DCC (2009) identified 497 possible section sites on land between Harrington Point and Harwood that is less than 5m above MSL. Figure A80 shows an elevation map of Harwood, created from LiDAR data.

15.2 Effect of elevated sea level and tsunami events

Elevated sea level

Maximum sea level during the modelled 1:500-year event is 1.9m above MSL, and 1m above MHWS at Long Beach (Table 37). Much of the Long Beach settlement would be inundated by up to 0.5m during such an event, particularly those houses close to the beach and the outlet of Drivers Creek (Figure A77). Table 37 shows that the difference in water level between modelled 1:20-year and 1:500-year elevated sea level events would be just 0.2m. Consequently, low-lying areas at Long Beach are also susceptible to inundation during more frequent lower magnitude storm surge events.

Table 37. The level of the sea (relative to MSL) at MHWS and for a range of modelled elevated sea level events at Long Beach. The percentage chance of a particular event occurring in any given 100-year period is shown in brackets

Return period in years (chance of occurring in any 100 year period)	MHWS	20 (99%)	50 (87%)	100 (63%)	500 (18%)
Water level (m above MSL)	0.9	1.7	1.75	1.8	1.9
Existing buildings affected?	No	Yes	Yes	Yes	Yes

Modelled inundation extents are not available for Aramoana and Harwood. However, Harwood’s low elevation and proximity to the harbour mean that much of the settlement is prone to elevated sea level as a result of strong winds and storm surge. Figure 27 shows inundation along Tidewater Drive in Harwood due to strong south-westerly winds and high perigean spring or ‘king’ tides in July 2011.

The Aramoana settlement is slightly more elevated than Harwood (Figures A79 and A80). Furthermore, the dunes to the north and wetland to the south of Aramoana provide a level of protection against elevated sea level events.

Figure 27. A car is driven along Tidewater Drive in Harwood, 12 July 2011. Photo credit: Heidi Robertson; supplied by the Otago Daily Times

Far-field tsunami

Figure A78 shows the extent and depth of inundation caused by the modelled 1:500-year South American tsunami. At Long Beach, the area around Drivers Creek behind the dunes would be inundated up to a depth of 0.5m. Figure A78 shows inundation of up to 1.5m around the margins of Purakanui Inlet, although this is generally restricted to the intertidal zone and the reserves and roads beside the shoreline. Inundation extents and maximum water speed associated with tsunami events have not been modelled for Aramoana and Harwood.

Table 38 shows that the maximum wave run-up and wave amplitude associated with both the Puysegur Trench and South American tsunamis are very similar. However, the modelling shows that a 1:500-year South American tsunami would cause considerably more inundation at Long Beach and Purakanui than would the Puysegur tsunami. This is because the orientation of these settlements is towards the north-east; a tsunami generated in South America, therefore, would be less impeded as it approached this stretch of coastline. The speed and wave amplitude of a tsunami approaching from the south (e.g. a Puysegur Trench tsunami) would be moderated by the Otago Peninsula as it swung round towards Blueskin Bay.

Figure A82 shows that the 1:500-year South American tsunami would reach Long Beach and Purakanui approximately 15½ hours after an earthquake. The third wave would be the biggest, arriving almost 4½ hours later, with smaller waves occurring for at least another 8 hours after this.

Near-field tsunami

Table 38 shows that a Puysegur Trench tsunami may produce waves of up to 1.3m amplitude, with a maximum run-up on land of 2m above MSL. Figure A81 shows a time series of water levels associated with the modelled 1:600-year Puysegur Trench tsunami. Water would retreat from the beach approximately 2 hours 10 minutes after the earthquake. The first wave would arrive approximately half an hour later. The next wave would arrive approximately 3 hours 50 min after the earthquake. The effect of the tsunami would continue to affect water level and currents in the area for a further 3 hours.

Table 38. Characteristics of tsunami events at Long Beach and Purakanui (as modelled by NIWA 2007)

Characteristic	Puysegur Trench tsunami	1:500-year South American tsunami
Tsunami arrival time (after fault rupture)	2 hours 10 min	15 hours 30 min
Maximum wave amplitude above the undisturbed level of the sea	1.3m	1.3m
Predominant period of wave arrivals	Long Beach 20-80 min Purakanui 30-40min.	80-105 min
Maximum wave run-up above MSL	2m	2.2m

Probability of inundation

The probability of maximum water levels of 1.5, 2.0 and 2.5m above MSL occurring as a result of any of the modelled tsunami or elevated sea level scenarios modelled by NIWA is shown in Table 39. The table also provides a generalised explanation of the likely extent of inundation if a tsunami or elevated sea level event that reached 1.5, 2.0 or 2.5m were to occur.[72]

Table 39. Likelihood and possible consequences of peak water level due to the modelled storm surge and tsunami scenarios at Long Beach, Purakanui, Aramoana and Harwood (with current sea level)

Maximum water level (m above MSL)	Probability of occurrence during any 100-year period (%)	Likely extent of inundation
1.5	>99	Inundation generally restricted to coastal margins up to the dunes and within Purakanui Inlet. Some inundation of the lowest-lying properties on Tidewater Drive in Harwood.
2.0	25-35	Inundation of low-lying properties along Tidewater Drive and coastal margins in Harwood. Access to Aramoana restricted due to inundation of Aramoana Road. Potential for surface water ponding in low-lying parts of Aramoana and Long Beach due to reduced drainage capacity. Low-lying areas behind the Long Beach dune system may also be inundated by wave run-up pushing inland from the mouth of Drivers Creek.
2.5	0 [73]	Similar to the above description, but with more extensive inundation, due to surface water ponding and wave run-up.

The probability of maximum water levels reaching any of these three heights will increase if the sea level rises in the future. Table 40 shows the probability of maximum water level reaching 1.5, 2.0 or 2.5m above MSL as a result of tsunami or elevated sea level scenarios if 0.5m of sea level rise were to occur.

[72] The extent of inundation has been estimated through a simple assessment of coastal topography and elevation. Note that other factors associated with tsunami and elevated sea level events, such as wave velocity and duration of inundation, would also have an impact on particular communities.

[73] None of the modelled current sea level scenarios used to generate this probability distribution returned a maximum water level exceeding 2.5m at these communities. The maximum predicted sea level height used to calculate these probabilities was 2.2m above m.s.l, resulting from the 1:500-far-field tsunami scenario. It is possible that a water level of 2.5m or greater could be generated by an event that was not modelled as part of this report.

Table 40. Likelihood of peak water level due to the modelled storm surge and tsunami scenarios at the Long Beach, Purakanui, Aramoana and Harwood (if average sea level were 0.5m higher than at present)

Maximum water level (m above MSL)	Probability of occurrence during any 100-year period (%)
1.5	>99
2.0	>99
2.5	25-35

Cross section profiles

Figures A83 and A84 show a cross section (or elevation) profile extending from the main beach and inland across the township of Aramoana. The cross section shows that the residential area of Aramoana is generally slightly lower than the maximum modelled level of the elevated sea level and tsunami scenarios, and therefore may be at risk of inundation during these types of event. Aramoana is afforded some protection from the 300m strip of coastal dunes between the beach and the residential area.

Figures A85 and A86 show a similar cross section profile through Long Beach. The maximum modelled height for elevated sea level and near and far-field tsunami scenarios are shown relative to the land along this section. Parts of the residential area are lower than the modelled water levels and are therefore potentially vulnerable to inundation.

15.3 Community vulnerability

The vulnerability of each of the Long Beach, Purakanui, Aramoana and Harwood communities is described below. Vulnerable infrastructure within these four settlements (or which links them to the wider area) is generally limited to the electricity distribution network (power lines and poles), roads and telecommunication landlines. Residents rely on tank-water supply and septic tanks, and these facilities may also be affected by extended periods of inundation or high water speeds.

Long Beach

Long Beach Township is generally low lying, with a number of houses situated just 1-2m above MSL. Properties in Long Beach are already prone to inundation during high perigean spring or ‘king’ tides, with a number having occurred in recent years (DCC, 2010). A higher magnitude extreme sea level event, such as the modelled 1:500-year scenario shown in Figure A77, would result in more extensive inundation, to a depth of up to 0.5m.

A 1:500-year South American tsunami would cause inundation of up to 0.5m, particularly on the mid-section of Beach Road, between Driver Street and Mihiwaka Road. Water speed of up to 1m per second could occur in this area, which would be fast enough to move vehicles and sweep people off their feet.

The modelled Puysegur Trench tsunami is unlikely to cause significant inundation in the Long Beach settlement. However, people in low-lying areas close to the shoreline may be affected by large waves. The time (about 2 hours) between earthquake and tsunami arrival means that people in these areas would require prompt warning in order to move to safe ground quickly.

Purakanui

Most residential properties in Purakanui are elevated and outside the area inundated under the modelled scenarios. As at Long Beach, however, people close to the shoreline and on the estuary itself may be caught unprepared by a tsunami, particularly those generated by near-field sources. The time between an earthquake and the arrival of a tsunami means that people in these areas would require prompt warning in order to move to safe ground quickly.

Roads around the margins of the Purakanui Inlet are also likely to be inundated during extreme sea level and tsunami events and may experience damage as a result.

Aramoana

The physical characteristics of the Aramoana settlement, including the orientation of its shoreline, are similar to those of Long Beach (Goldsmith, 1995). The dune system that separates each settlement from the ocean is of a similar extent, although at Long Beach, the dunes are incised by the Drivers Creek outlet. Therefore it seems likely that Aramoana would have a similar level of vulnerability as Long Beach, particularly in the case of elevated sea level events and far-field tsunami events that approach from the north-east. However, modelled inundation extents and wave velocities at Aramoana are not available to confirm this similarity.

Harwood

Modelled inundation extents and wave velocities for extreme sea level and tsunami events are not available for Harwood. As the settlement is located within the Otago Harbour, it has a different level of exposure to events that may affect nearby towns which are more exposed to the open ocean (such as Aramoana and Long Beach). Much of the residential development at Harwood is located next to the harbour, with little or no protection from sand dunes. As the area is also very low lying (Figure A80), large waves or elevated sea level events may affect much of the township.

15.4 Summary

- People close to the shoreline at Long Beach, Purakanui and Aramoana and Harwood are vulnerable to elevated sea level and tsunami events.
- Changes in sea level of at least 2.5m would occur very quickly along the open coast during a far-field South American tsunami. People on the beach or estuary may be particularly vulnerable, especially at low tide, when these areas are more accessible.
- Residential properties at Long Beach on Beach Road may be inundated by up to 0.5m during either a 1:500-year elevated sea level event or a 1:500-year South American tsunami.
- Inundation of residential property is also likely at Harwood. However, the depth and extent of inundation associated with specific events has not been modelled for this settlement.
- Lower magnitude elevated sea level events that occur more frequently would also cause inundation in this area.

16. Warrington and Blueskin Bay

16.1 Community description

Warrington and Blueskin Bay are located to the north of the Otago Peninsula, 15-20 minutes' drive north of Dunedin (Figure A87). About 320 people lived in the Warrington area at the time of the last census (2006). The sand spit at Warrington separates the ocean bay from the shallow Blueskin Bay Estuary (Figure 28), and DTEC (2002) noted that there had been erosion on the seaward and estuary sides of the dune islands at the end of the spit. The Waitati River and several small streams drain into the estuary.

The settlements of Evansdale, Waitati and Doctors Point are located on the margins of Blueskin Bay. In 2006, about 45 people lived in Evansdale and about 390 lived in the area fringing Blueskin Bay from Waitati to Doctors Point. There is a school and a Playcentre in Warrington and a school, Playcentre and fire station in Waitati.

Figure 28. Looking north towards Warrington and Blueskin Bay (August 2007)

There is capacity for considerable development along this stretch of coastline, both from infill (subdivision) of larger properties and on existing empty sections. The DCC (2009) identified 346 section sites in Warrington, another 206 sites between Waitati and Doctors Point and several sites in Evansdale. Most of these potential building sites are located on relatively high ground, 5m or more above MSL. However, a number were identified on residential zoned land[74] in Evansdale (at the southern end of King Street) and Waitati (to the east of Foyle Street), which is less than 2m above MSL. These areas are shown in Figure 29 and Figure 30, respectively.

[74] 'Residential 5' zoning, which has a minimum lot size of 1000m^2

Figure 29. Residential development at Evansdale, next to Blueskin Bay (August 2008)

Figure 30. Intertidal area and adjacent houses near the mouth of the Waitati River. Much of the flat land in the middle distance is zoned 'Residential' in the Dunedin City District Plan (August 2007)

16.2 Effect of elevated sea level and tsunami events

Elevated sea level

NIWA's (2008) modelling showed that a 1:500-year event would result in an elevated sea level of about 1.9m above MSL, and 1m above MHWS in Blueskin Bay (Table 41). This would cause inundation of low-lying land (including the intertidal margins of the estuary) at Evansdale and Waitati to a depth of up to 1m (Figure A87).[75] Water would also overtop the southern end of the sand spit at Warrington to a depth of up to 1.5m, with wave run-up extending up to 150m into the dunes at the northern end. Low-lying areas in Blueskin Bay are also susceptible to inundation during more frequent events, and Table 41 shows that the difference in water level between a 1:20-year storm surge and a 1:500-year storm surge is just 0.25m.

Table 41. The level of the sea (relative to MSL) at MHWS and for a range of modelled elevated sea level events in Warrington and Blueskin Bay. The percentage chance of a particular event occurring in any given 100-year period is shown in brackets

Return period in years (chance of occurring in any 100-year period)	MHWS	20 (99%)	50 (87%)	100 (63%)	500 (18%)
Water level (m above MSL)	0.9	1.65	1.7	1.75	1.9
Existing buildings affected?	No	Likely	Yes	Yes	Yes

Far-field tsunami

Figure A91 shows that the modelled 1:500-year South American tsunami would reach Warrington and Blueskin Bay about 15½ hours after the earthquake. The first wave would peak at the coast half an hour later. The largest modelled wave would impact the coast about 4 hours later. Smaller waves and strong currents would continue for at least another 8 hours. Table 42 shows that the maximum run-up observed at Blueskin Bay and Warrington from this scenario would be 2.3m above MSL. Figure A88 shows up to 0.5m of inundation on the margins of Blueskin Bay at Evansdale and Waitati. The tsunami is likely to overtop the southern end of the sand spit at Warrington.

Table 42 shows that maximum wave run-up and wave amplitude associated with the Puysegur Trench tsunami would be greater than those generated by a South American tsunami. However, the modelled inundation maps show that a 1:500-year South American tsunami would result in a greater extent and depth of inundation than the 1:600-year Puysegur tsunami at both Waitati and Evansdale. This is because the orientation of these settlements is towards the east. Therefore, a tsunami generated in South America would be less impeded as it approached this stretch of coastline. The speed of a tsunami approaching from the south (e.g. a Puysegur Trench tsunami) would be moderated by the Otago Peninsula as it swung round towards Blueskin Bay.

Near-field tsunami

The modelled Puysegur Trench tsunami is likely to overtop the southern end of the sand spit at Warrington, with inundation up to a depth of 2.5m on the 'scoured' areas[76] between the remnant dune features (Figure A89). Some inundation would also occur around the margins of Blueskin Bay, near Evansdale and Waitati, although this is not as extensive as for a far-field South American tsunami. Figure A90 depicts a time series of

[75] Refer to the map book (ORC, 2012) for all Figures beginning with 'A'.
[76] These scoured areas are maintained by tidal flows at or near high tide (NIWA 2007b).

water levels associated with the modelled Puysegur Trench tsunami. Water would retreat from the beach about 2 hours 10 minutes after the earthquake. The first wave would arrive about 35 minutes later. Another wave would impact about 4 hours after the earthquake. Large waves would continue to affect the area for another 7 hours.

Table 42. Characteristics of tsunami events at Warrington and Blueskin Bay (as modelled by NIWA, 2007)

Characteristic	Puysegur Trench tsunami	1:500-year South American tsunami
Tsunami arrival time (after fault rupture)	2 hours 10 min	15 hours 30 min
Maximum wave amplitude	1.7m	1.3m
Predominant period of wave arrivals	30 min	80 min and 105 min
Maximum wave run-up	2.8m	2.3m

Probability of inundation

The probability of maximum water levels of 1.5, 2.0 and 2.5m above MSL occurring as a result of any of the tsunami or elevated sea level scenarios modelled by NIWA is shown in Table 43. The table also provides a generalised explanation of the likely extent of inundation if a tsunami or elevated sea level event that reached 1.5, 2.0 or 2.5m were to occur.[77]

Table 43. Likelihood and possible consequences of peak water level due to the modelled storm surge and tsunami scenarios at Warrington and Blueskin Bay (with current sea level)

Maximum water level (m above MSL)	Probability of occurrence during any 100-year period (%)	Likely extent of inundation
1.5	>99	Inundation along the coastal margin, up to the dunes and within the Blueskin Bay Estuary. Some inundation of land and Doctors Point road near mouth of the Waitati River (as shown in Figure 30). Overtopping would occur along the southern tip of Warrington Beach.
2.0	25-35	Potential inundation around residential properties near the mouth of the Waitati River (Figure 30) and in Evansdale (Figure 29). Inundation also extends further into the margins of the coastal dunes and the estuary.
2.5	10-25	Similar to the above description, but with more extensive inundation due to surface water ponding and wave run-up, particularly in low-lying areas of Waitati.

The probability of maximum water levels reaching any of these three heights will increase if sea level rises in the future. Table 44 shows the probability of maximum water level reaching 1.5, 2.0 or 2.5m above MSL as a result of tsunami or elevated sea level scenarios if 0.5m of sea level rise were to occur.

[77] The extent of inundation has been estimated through a simple assessment of coastal topography and elevation. Note that other factors associated with tsunami and elevated sea level events, such as wave velocity and duration of inundation, would also have an impact on particular communities.

Table 44. Likelihood of peak water level due to the modelled storm surge and tsunami scenarios at Warrington and Blueskin Bay (if average sea level were 0.5m higher than at present)

Maximum water level (m above MSL)	Probability of occurrence during any 100-year period (%)
1.5	>99
2.0	>99
2.5	25-35

16.3 Community vulnerability

Most properties within Warrington and the settlements surrounding Blueskin Bay are elevated and therefore beyond the area inundated in the modelled scenarios. However, a number of residential properties and empty sections near the mouth of the Waitati River (Figure 30) and close to the shoreline at Evansdale (Figure 29) are less than 2m above MHWS. These properties are prone to inundation during elevated sea level events and may also be affected by high magnitude tsunami events. The Waitati Playcentre is located next to the upper limit of the modelled inundation from a 1:500-year extreme sea level event.

A 1:500-year extreme sea level event may also inundate low-lying sections of SH1, between Waitati and Evansdale, and parts of Coast Road, between Evansdale and Warrington. These sections of road may be temporarily impassable. It is unlikely that any houses or buildings would be inundated in Warrington. The school and Playcentre are elevated and set well back from the coast.

Aside from the road network, potentially vulnerable infrastructure in Blueskin Bay includes:

- the electricity distribution network (power poles, lines and power transformers)
- telecommunication networks
- sewage settling ponds, pumping stations and land used for effluent disposal
- the wastewater and stormwater pipe network, including manholes.

These assets would need to withstand extended periods of inundation and high water velocities to avoid failure or damage occurring.

People close to the shoreline and on the Blueskin Bay Estuary itself may be caught unprepared by tsunami events, particularly those generated by near-field sources. The estuary is a popular recreational area, especially at low tide when the extensive areas of mudflats can be accessed. The time between a near-field earthquake occurring and the arrival of any tsunami means that people in these areas would require prompt warning in order to move to safe ground quickly.

16.4 Summary

- People close to the shoreline at Warrington, Doctors Point, Waitati and Evansdale, or on the Blueskin Bay Estuary are vulnerable to elevated sea level and tsunami events.
- Changes in sea level of at least 3m would occur over short periods of time during the modelled tsunami events, particularly to the east of Warrington Beach and at

the mouth of the Blueskin Bay Estuary. People in these areas would be particularly vulnerable, especially at low tide, when beach and estuary areas are more accessible.

- Residential properties near the mouth of the Waitati River, and near the shoreline at Evansdale, may be inundated by up to 0.5m during either a 1:500-year elevated sea level event, or a 1:500-year South American tsunami. Lower magnitude elevated sea level events that occur more frequently would also cause inundation in this area.
- Road access to Doctors Point and from Evansdale to Warrington may be restricted or cut.

17. Karitane and Waikouaiti

17.1 Community description

The towns of Karitane and Waikouaiti are located half an hour's drive north of Dunedin and at opposite ends of Waikouaiti Beach (Figure A92)[78]. Karitane is located at the mouth of the Waikouaiti River (Figure 33), while Waikouaiti is situated 4km to the north near the Hawksbury Lagoon. There are primary schools in both towns and early childcare facilities at Waikouaiti.

Flood events in the Waikouaiti River are usually caused by strong easterly quarter winds that bring moist air in from the Pacific Ocean (ORC, 2008). Large floods are relatively infrequent, although more than one large flood event can occur in one year.[79] A large flood event in June 1980 is known to have affected properties in Karitane (ORC, 2008).

Karitane

About 360 residents were living in Karitane at the time of the last census (2006). The residential areas are generally concentrated on outcrops of higher land next to the Waikouaiti River or the Pacific Ocean. Access to the town is by Coast Road, either along a causeway next to the Waikouaiti River, or along the coast from the south. Several houses and empty sections in Karitane are located close to the estuary and are less than 2m above MSL (Figure 31 and Figure 32).

There is potential for a large amount of development in Karitane, and a DCC report (2009) identified 350 sections that could be developed, either by infill (subdivision) of larger properties or on existing empty sections. Most of these potential building sites are located on relatively high ground, 6m or more above MSL. However, subdivision potential and vacant lots were also identified on residential-zoned land[80], which is less than 2m above sea level at two locations:

- About 4,400m^2 of currently undeveloped land is located in a secondary flood channel of the Waikouaiti River, to the south of Grimness and Kerr streets.
- About 3,200m^2 of land with infill potential is located on the isthmus between Karitane and the headland known as 'Huriawa' (Figure A92). This low-lying block of land is bordered by Rona, Sulisker and Roneval streets.

A recent decision by the Dunedin City Council (DCC), upheld by the Environment Court, resulted in a change in land use from rural to residential in an area subject to coastal storm surge and tsunami.

[78] Refer to the map book (ORC, 2012) for all Figures beginning with 'A'.
[79] For example, of the floods over 50m^3/s on record in the north branch of the Waikouaiti River, three occurred in 1992, but none in 1996, 1998 or 1999. The continuous flow record for the north branch of the Waikouaiti River, at Bucklands, began in January 1991 and finished in August 1999.
[80] The Karitane settlement is zoned 'Residential 1' in the Dunedin City District Plan, with a minimum lot size of 500m^2.

Figure 31. Residential properties in Karitane, bordering the Waikouaiti Estuary (May 2008)

Figure 32. Residential properties and undeveloped land bordering the Waikouaiti Estuary (a) looking east from the end of Grimness Street towards the estuary (b) looking south from the same location towards Halkirk Street. (August 2007)

The spit behind Waikouaiti Beach is well vegetated and has remained reasonably stable over recent decades (DTEC, 2002). However, there has been some erosion of dunes on the southern tip of the spit due to storm events. Consequently, storm waves can cross the tip of the spit more easily and affect the shoreline on the southern margin of the estuary, particularly along Karitane Reserve Road (Figure 33). The DCC has put in place measures to stabilise the southern end of the spit and prevent erosion along Karitane Reserve Road.

Figure 33. Entrance to the Waikouaiti Estuary (August 2007)

Waikouaiti

At the time of the last census in 2006, about 1,000 people lived in Waikouaiti, with 330 of these living within 1.2km of the coast. The dwellings situated closest to the shoreline are located on Stewart Street, some 350m back from the beach (Figure A92). This is also the lowest-lying section of the town, with residential properties situated on land that is less than 2m above MSL. The rest of the town lies further back from the ocean on land that is at least 5m above MSL.

The DCC (2009) identified that there is substantial capacity for infill (subdivision) development in Waikouaiti, with up to 632 potential sections in the wider residential area. Many of these are well back from the coast and reasonably elevated. However, the report does identify two areas that may have some exposure to tsunami and elevated sea level. These are:

- a 7-hectare block of undeveloped land, bordered by the beach, Fell and Beach streets, which is less than 3.5m above MSL
- the north side of Stewart Street (beside the Hawksbury Lagoon), which is situated on land less than 2m above MSL.

17.2 Effect of elevated sea level and tsunami events

Elevated sea level

Maximum sea level during the 1:500-year elevated sea level event at Karitane is 1.97m above MSL and 1.05m above MHWS (Table 45). This event would result in extensive inundation of low-lying land on the north and south banks of the Waikouaiti River (Figure A92). The northern part of Karitane would be completely surrounded by water up to 1.5m deep during such an event. Although somewhat elevated, the sections of

SH1 and Coast Road, next to the Waikouaiti River, may also be inundated, with water up to 1m deep on the surrounding farmland.

Table 45 shows that Karitane is also susceptible to inundation during more frequent low-magnitude storm surge events. The difference in water level between a 1:20-year storm surge and a 1:500-year storm surge is only 0.22m.

Table 45. The level of the sea (relative to MSL) at MHWS and for a range of modelled elevated sea level events at Karitane and Waikouaiti. The percentage chance of a particular event occurring in any given year is shown in brackets

Return period in years (chance of occurring in any year)	MHWS	20 (99%)	50 (87%)	100 (63%)	500 (18%)
Water level (m above MSL)	0.92	1.75	1.82	1.86	1.97
Existing buildings affected?	No	Yes	Yes	Yes	Yes

Tsunami

Figure A96 shows that the modelled 1:500-year South American tsunami would reach Karitane about 15½ hours after the earthquake. The first wave would peak at the coast half an hour later. The largest modelled wave would strike the coast another 4 hours later. Smaller waves and strong currents would continue for at least another 8 hours after this. Table 46 shows that the maximum run-up at Karitane for this scenario would be 2.1m above MSL, which, as Figure A93 shows, would result in inundation up to a depth of 1m of low-lying areas surrounding Karitane.

Table 46 shows that the modelled 1:600-year Puysegur tsunami would result in maximum wave run of 2.7m above MSL. The extent of inundation for the Puysegur tsunami is similar to that caused by the modelled South American tsunami, with inundation of low-lying land alongside the Waikouaiti River and the entrance to the Hawksbury Lagoon up to a depth of 1m (Figure A94). Figure A95 shows a time series of modelled water level associated with the Puysegur Trench tsunami. Water would retreat from the beach about 2 hours 20 minutes after the earthquake. The first wave would arrive 25 minutes later. Large waves would continue to impact the area for nearly 7 hours.

Table 46. Characteristics of tsunami events at Karitane and Waikouaiti (as modelled by NIWA 2007)

Characteristic	**Puysegur Trench tsunami**	**1:500-year South American tsunami**
Tsunami arrival time (after fault rupture)	2 hours 20 min	15 hours 30 min
Maximum wave amplitude	1.55m	1.2m
Predominant period of wave arrivals	25 min	80 and 105 min
Maximum wave run-up	2.7m	2.1m

Tsunami waves may result in water velocities of up to 4m per second at the mouth of the Waikouaiti River, decreasing as they travel towards the upper reaches of the estuary. Shore stabilisation works and the river bank beside Karitane (Figure 31 and Figure 33) would need to withstand the combined effect of this increased velocity and depth over an extended period to avoid being damaged.

Probability of inundation

The probability of maximum water levels of 1.5, 2.0 and 2.5m above MSL occurring as a result of any of the tsunami or elevated sea level scenarios modelled by NIWA is shown in Table 47. The table also provides a generalised explanation of the likely extent of inundation if a tsunami or elevated sea level event that reached 1.5, 2.0 or 2.5m were to occur.[81]

Table 47. Likelihood and possible consequences of peak water level due to the modelled storm surge and tsunami scenarios at Karitane and Waikouaiti (with current sea level)

Maximum water level (m above MSL)	Probability of occurrence during any 100 - year period (%)	Likely extent of inundation
1.5	>99	Inundation of low-lying flats next to the Waikouaiti River. Water may also push up into the Hawksbury Lagoon.
2.0	25-35	Potential for inundation of properties between Stewart Street and the Hawksbury Lagoon, and the nearby playing fields in Waikouaiti. More extensive inundation of the low-lying flats next to the Waikouaiti River. Coast Road, between SH1 and Karitane, and in the vicinity of Stornoway Street, is also likely to be inundated.
2.5	10-20	Extensive flooding of low-lying rural land next to the Waikouaiti River and neighbouring wetlands. Inundation of the narrow strip of land that separates Karitane from the Huriawa headland, as well as other low-lying and riverside residential properties in Karitane.

The probability of maximum water levels reaching any of these heights will increase if sea level rises in the future. Table 48 shows the probability of maximum water level reaching 1.5, 2.0 or 2.5m above MSL as a result of tsunami or elevated sea level scenarios if 0.5m of sea level rise were to occur.

Table 48. Likelihood of peak water level due to the modelled storm surge and tsunami scenarios at Karitane and Waikouaiti (if average sea level were 0.5m higher than at present)

Maximum water level (m above MSL)	Probability of occurrence during any 100-year period (%)
1.5	>99
2.0	>99
2.5	25-35

Karitane cross section profile

The cross section in Figures A97 and A98 shows the elevation of the land between Karitane beach and the main trunk line, and modelled storm surge and tsunami levels at the coast. Development in Karitane tends to occur on areas of higher ground. While developed areas are generally above the modelled storm surge and tsunami levels, they may still be surrounded by water during a storm surge or tsunami event. Lower-lying properties on the verge of these areas of higher ground would be more likely to experience inundation.

[81]The extent of inundation has been estimated through a simple assessment of coastal topography and elevation. Note that other factors associated with tsunami and elevated sea level events, such as wave velocity and duration of inundation, would also have an impact on particular communities.

Waikouaiti cross section profile

Figures A99 and A100 show a cross section profile extending through Waikouaiti, from the beach towards the main trunk railway line. The profile shows that low-lying areas, such as the camp ground, are less than 2.5m above MSL, which is lower than the maximum wave run-up at the coast from the 1:600-year Puysegur tsunami. The substantial dune system would provide some protection from storm surge or tsunami events.

17.3 Community vulnerability

Most existing residential properties within Karitane and Waikouaiti are outside the area shown to be inundated under the modelled elevated sea level and tsunami scenarios. However, a number of houses and undeveloped land are located on low-lying land, either alongside the Waikouaiti River or Hawksbury Lagoon, or near the coast. Properties on Stewart Street (in Waikouaiti) and low-lying parts of Stornoway Street and Coast Road in Karitane are most likely to be affected (Figures A92-A94). As well as the modelled scenarios shown in these Figures, properties in this area are also vulnerable to lower magnitude events that occur more frequently. Parts of Karitane would also be vulnerable to inundation if an elevated sea level event were to coincide with a flood event in the Waikouaiti River.

The Karitane Primary School is about 10m above MSL and is, therefore, unlikely to be inundated. However, the school buildings are situated less than 150m from the beach and the playing fields extend almost to the shoreline.

Tsunami and elevated sea level events may affect road access between Karitane and other nearby settlements, due to inundation and erosion/damage of local roads. Much of Karitane would be totally surrounded by water up to a depth of 1.5m during a 1:500-year elevated sea level event (Figure A92). This would restrict or inhibit access for emergency services and residents trying to evacuate.

Aside from the road network, potentially vulnerable infrastructure includes:

- the electricity distribution network (power poles, lines and power transformers)
- telecommunication networks
- sewage settling ponds, pumping stations and land used for effluent disposal
- the wastewater and stormwater pipe network, including manholes.

These assets would need to withstand extended periods of inundation and high water velocities to avoid failure or damage occurring. DCC (2011) provides some additional analysis of vulnerable wastewater assets in Waikouaiti and Karitane.

The greatest risk to these two communities would come from elevated sea levels (or storm surge) because of the extensive inundation likely to result from such an event. A near-field Puysegur tsunami also presents a significant risk, due to the time (less than 2½ hours) between earthquake and tsunami arrival. People in low-lying areas and close to the shoreline would need prompt warning of an approaching tsunami if that warning were to be effective. People in these areas would also need to be aware of the quickest route to a safe area.

17.4 Summary

- People close to the shoreline at Karitane and Waikouaiti, or on the Waikouaiti River Estuary, are vulnerable to elevated sea level and tsunami events.
- Changes in sea level of more than 3m may occur very quickly along this stretch of coast during tsunami events. People near the coast would be particularly vulnerable, especially at low tide, when beach and estuary areas are more accessible.
- Any warning before the arrival of a Puysegur Trench tsunami would probably be minimal. People would need to be aware of the quickest and safest way to evacuate to an identified safe area.
- Residential properties, roads and other infrastructure near the mouth of the Waikouaiti River may be inundated by waves up to 1m deep, and travelling at up to 4m per second during a near-field Puysegur Trench tsunami.
- A number of residential properties near the mouth of the Waikouaiti River and beside the Hawksbury Lagoon may be inundated by up to 1m during a 1:500-year elevated sea level event, with inundation of up to 1.5m on nearby low-lying rural land.
- Road access between Karitane and Waikouaiti may be restricted or cut.

18. Taranui and Kakanui

18.1 Community description

The twin settlements of Taranui and Kakanui are located 15 minutes south of Oamaru at the mouth of the Kakanui River. Kakanui is located on a low river terrace to the north of the river (Figure 34), while Taranui is situated on an elevated headland on the south side of the river (Figure 35). At the time of the 2006 Census, about 270 people lived in Taranui and about 100 were living in Kakanui. The Kakanui Primary School is located on the south bank of the river in Taranui. Road access is via a number of routes: Oamaru to the north, Maheno to the west and Waianakarua to the south. A bridge across the Kakanui River, approximately 1km upstream of the mouth, links the two towns. The Kakanui River can produce significant flood events.[82]

Figure 34. Looking north towards the Kakanui River mouth and Kakanui Township (August 2007)

Figure 35. Looking south towards Taranui from Kakanui Road (August 2007)

[82] The largest flood event at the Kakanui at Mill Dam site (near Maheno) between December 1989 (when records began) and December 2011 occurred in May 2010, and peaked at $557m^3/s$. ORC records indicate that a $490m^3/s$ flood has an approximately 20% chance of occurring in any given year.

18.2 Effect of elevated sea level and tsunami events

Elevated sea level

NIWA's (2008) modelling showed that a 1:500-year event would result in an elevated sea level of about 2.3m above MSL and 1.35m above MHWS at Kakanui (Table 49). The extent and depth of inundation associated with this event is shown in Figure A101.[83] Kakanui Beach, the lower Kakanui River Estuary and the lower sections of river terrace to the south of Kakanui area would be subject to continuous inundation during the peak of such an event. Figure A101 shows that the maximum extent of wave run-up would extend some distance beyond this area of continuous inundation and may affect some properties on the southern boundary of Kakanui.[84]

Kakanui is also susceptible to inundation during more frequent elevated sea level events, and Table 49 shows that the difference in water level between a 1:20-year and a 1:500-year storm surge is just 0.25m.

Table 49. The level of the sea (relative to MSL) at MHWS and for a range of modelled elevated sea level events at Kakanui. The percentage chance of a particular event occurring in any given 100-year period is shown in brackets

Return period in years (chance of occurring in any 100-year period)	MHWS	20 (99%)	50 (87%)	100 (63%)	500 (18%)
Water level (m above MSL)	0.95	2.05	2.15	2.2	2.3
Existing buildings affected?	No	Yes	Yes	Yes	Yes

Far-field tsunami

Figure A105 shows that the modelled 1:500-year South American tsunami reaches Kakanui about 15½ hours after the earthquake. The first wave peaks at the coast 45 minutes later. Large waves strike the coast about 24 hours 40 minutes and again 26 hours 40 minutes after the earthquake.

The maximum wave run-up observed at Kakanui from this scenario is 2.8m above MSL (Table 50). Figure A102 shows that the river terrace on the north bank of the Kakanui River (including parts of Kakanui Township) would be inundated up to a depth of 1m. Properties at the junction of Waianakarua Road and Maheno-Kakanui Road would also be affected, and the western approach to the Kakanui River Bridge may be inundated to a depth of 0.5m. Inundation of up to 2.5 metres would occur along the coast (including beach and wave-cut platform features) between Kakanui and the beach at All Day Bay to the south of Taranui.

The depth and extent of inundation associated with a 1:100-year far-field tsunami would be considerably less than for a 1:500-year event, although some undeveloped land on the river terrace to the south of Kakanui River would be inundated by up to 1m. Inundation of greater than 1m is restricted to the beach and Kakanui River mouth.

[83] Refer to the map book (ORC, 2012) for all Figures beginning with 'A'.
[84] Refer to Section 4 for a description of the various components of elevated sea level, including wave run-up.

Near-field tsunami

Table 50 shows that the modelled 1:600-year Puysegur tsunami may cause waves of up to 2m above MSL. The extent and depth of inundation for a Puysegur tsunami would be substantially less than that caused by either of the modelled South American tsunami events. Kakanui is offered some protection from the headland to the south, which would attenuate a tsunami arriving from this direction.

Figure A103 shows that the north bank of the river may be inundated up to a depth of 0.5m. Figure A104 shows a time series of modelled water levels associated with the modelled Puysegur Trench tsunami. Water would retreat from the beach approximately 2 hours 20 minutes after the earthquake. The first wave peaks 35 minutes later. Waves and strong currents continue to impact the area for nearly 7 hours.

Table 50. Characteristics of tsunami events at Kakanui (as modelled by NIWA, 2007)

Characteristic	Puysegur Trench tsunami	1:500-year South American tsunami
Tsunami arrival time (after fault rupture)	2 hours 20 min	15 hours 30 min
Maximum wave amplitude	0.9m	1.8m
Predominant period of wave arrivals	25 and 100 min	80 and 105 min
Maximum wave run-up	2m	2.8m

Probability of inundation

The probability of maximum water levels of 1.5, 2.0 and 2.5m above MSL occurring as a result of any of the tsunami or elevated sea level scenarios modelled by NIWA is shown in Table 51. The table also provides a generalised explanation of the likely extent of inundation if a tsunami or elevated sea level event that reached 1.5, 2.0 or 2.5m were to occur.[85]

Table 51. Likelihood and possible consequences of peak water level due to the modelled storm surge and tsunami scenarios at Taranui and Kakanui (with current sea level)

Maximum water level (m above MSL)	Probability of occurrence during any 100-year period (%)	Likely extent of inundation
1.5	>99	Inundation is generally restricted to the coastal margin, and within the banks of the Kakanui River. Some ponding may occur on low-lying rural land on the north bank of the river near Kakanui.
2.0	>99	As above, but with additional inundation of low-lying areas directly behind the dune system and beach at Kakanui.
2.5	15-25	Extensive inundation of low-lying land on the north bank of the Kakanui River, including overtopping of spit. Potential flooding of properties on the southern- most margin of Kakanui. The road between Kakanui and Taranui may also be affected.

[85] The extent of inundation has been estimated through a simple assessment of coastal topography and elevation. Note that other factors associated with tsunami and elevated sea level events, such as wave velocity and duration of inundation, would also have an impact on particular communities.

The probability of maximum water levels reaching any of these three heights will increase if sea level rises in the future. Table 52 shows the probability of maximum water level reaching 1.5, 2.0 or 2.5m above MSL as a result of tsunami or elevated sea level scenarios if 0.5m of sea level rise were to occur.

Table 52. Likelihood of peak water level due to the modelled storm surge and tsunami scenarios at Taranui and Kakanui (if average sea level were 0.5m higher than at present)

Maximum water level (m above MSL)	Probability of occurrence during any 100-year period (%)
1.5	>99
2.0	>99
2.5	>99

18.3 Community vulnerability

The Kakanui and Taranui communities are vulnerable to inundation during extreme sea level and tsunami events. The two settlements are near the coast, and the Kakanui River and parts of the Kakanui Township are situated on a low-lying terrace, which is prone to inundation as a result of these hazards. People on the shoreline in this area would also be vulnerable, particularly in regard to tsunami waves, which may arrive unexpectedly.

Figure 36. Boat sheds and residential properties in Taranui at the mouth of the Kakanui River (August 2007)

The modelled effects of the 1:500-year elevated sea level event and the 1:500-year South American tsunami include extensive inundation on the north bank of the Kakanui River (Figures A101 and A102). Several properties at the southern end of Cobblestone and Clayton streets in Kakanui would also be affected. Direct road access between the two towns may be restricted due to inundation or damage to Waianakarua Road.

Maximum water speed during the 1:500-year South American tsunami would be 4m per second at the mouth of the Kakanui River, which would create a hazard for boats or people in the water and may cause erosion of the riverbank. The speed of tsunami waves on the terrace to the north of the river would be considerably lower (1-2m per second), although this would still knock people off their feet or carry away vehicles.

As well as the modelled scenarios shown in the accompanying map book (ORC, 2012), properties in this area are also vulnerable to lower magnitude events that occur more frequently.

The greatest risk to these two communities would come from elevated sea levels (or storm surge) due to inundation caused by wave run-up during such an event. People in low-lying areas and close to the shoreline would need prompt warning of an approaching tsunami if that warning were to be effective. People in these areas would also need to be aware of the quickest route to a safe area.

18.4 Summary

- People close to the shoreline at Kakanui and Taranui, or on the Kakanui River Estuary, are vulnerable to elevated sea level and tsunami events.
- Changes in sea level of more than 2m may occur very quickly along this stretch of coast during tsunami events. People near the coast would be particularly vulnerable, especially at low tide, when the beach and estuary are more accessible.
- Any warning before the arrival of a Puysegur Trench tsunami is likely to be minimal. People would therefore need to be aware of the quickest and safest way to evacuate to an identified safe area.
- Residential properties on the south side of Kakanui may be affected by wave action during a 1:500-year elevated sea level event or a South American 1:500-year tsunami. On the outskirts of this residential area, the latter scenario may produce waves up to 0.5m deep, and travelling at up to 1m per second.
- Road access between Kakanui and Taranui may be restricted or cut.

19. Oamaru

19.1 Community description

Oamaru is located on the east coast of North Otago, on the southern edge of the Waitaki River delta. Much of the town lies on a low coastal terrace, approximately 8-10m above MSL. This terrace is composed of alluvial deposits and capped by up to 5m of loess or wind-blown silt (Forsyth, 2009). The seaward edge of the terrace is an actively eroding sea cliff, which exposes the loess underlying the coastal terrace, but generally not the alluvial deposits beneath. (See Box 3.)

Since it was first settled by Europeans in the 19th century, Oamaru has grown outwards from the harbour area and now covers the coastal terrace for approximately 5km to the north, as well as the surrounding hills to the west and south. The town had a population of 11,500 in 2006 (Forsyth, 2009), which has remained reasonably static over the last decade (Statistics NZ website). The main transport links through the town include SH1 and the Main Trunk railway line (which passes along the coastal side of the township). The main industries in Oamaru are meat and other food processing, support for agriculture and horticulture in the wider district, and education and tourism.

Figure 37. Looking north towards central Oamaru from the Cape Wanbrow lookout (May 2008)

Box 3. Coastal erosion at Oamaru

The coastline at Oamaru is generally in a long-term state of retreat (Gibb, 1978). Rock armouring has been placed for approximately 1.5km along the shoreline where the railway line runs closest to the sea, from just north of the mouth of Oamaru Creek to about Orwell Street. The photo below shows rock protection in the vicinity of Orwell Street (looking south) in May 2008. The rock armouring has helped to stabilise this stretch of shoreline, although ongoing maintenance has been required.

The shoreline to the north of this rock armouring is more vulnerable to episodes of erosion. An example is shown in the photo below, where commercial premises in lower Weaver Street were affected by coastal erosion in June 2007 (photo courtesy of the Otago Daily Times).

19.2 Effect of elevated sea level and tsunami events

Elevated sea level

NIWA's (2008) modelling showed that a 1:500-year event would result in an elevated sea level of about 2.35m above MSL and 1.4m above MHWS at Oamaru (Table 53). Figure A106[86] shows that an event of this magnitude would not inundate residential or commercial property in Oamaru continuously, although it is likely to result in sea spray for some distance inland. (See lower image in Box 3.) Maximum wave run-up[87] would also result in wave crests travelling up to 130m inland on the western and southern margins of the Oamaru boat harbour (Figure A106), inundating a number of commercial properties on Waterfront Road. Wave action during elevated sea level events is also likely to result in increased rates of coastal erosion in some areas.

The harbour area is also susceptible to inundation during more frequent elevated sea level events, and Table 53 shows that the difference in water level between a 1:20-year and a 1:500-year storm surge is just 0.25m.

Table 53. The level of the sea (relative to MSL) at MHWS and for a range of modelled elevated sea level events at Oamaru. The percentage chance of a particular event occurring in any given 100-year period is shown in brackets

Return period in years (chance of occurring in any 100-year period)	MHWS	20 (99%)	50 (87%)	100 (63%)	500 (18%)
Water level (m above MSL)	0.95	2.1	2.2	2.25	2.35
Existing buildings affected?	No	No	No	No	No

Far-field tsunami

Figure A110 shows that the modelled 1:500-year South American tsunami would reach Oamaru approximately 15½ hours after the earthquake. The initial waves would result in only a moderate increase in water level (0.6 to 0.7m above MHWS). The sea would then retreat up to 200-400m, particularly around the harbour area, 1½ hours after the initial effects are felt. The largest wave would strike the coast 26 hours and 40 minutes after the earthquake (Figure A110-image 5).

Table 54 shows that the maximum wave run-up observed at Oamaru from this scenario is 2.6m above MSL. Figure A107 shows that inundation would largely be confined to the beach, with the exception of the harbour breakwaters, which would be inundated by >2.5m. Localised areas along the margins of Oamaru Creek, Waterfront Road and the foreshore area would also be inundated.

Near-field tsunami

Table 54 shows that the modelled 1:600-year Puysegur Trench tsunami may result in wave run-up on land of up to 2.6m above MSL. The extent of inundation associated with the Puysegur Trench tsunami would be similar to that caused by a South American tsunami, despite the influence of Cape Wanbrow, which would partially attenuate waves approaching from the south.

[86] Refer to the map book (ORC, 2012) for all Figures beginning with 'A'.
[87] The temporary increase in water level associated with the highest breaking waves as they run-up onto the shore

Figure A109 shows a time series of water level associated with the modelled Puysegur Trench tsunami. Water would retreat from the beach approximately 2 hour 25 minutes after the earthquake. The first wave would peak 35 minutes later. Large waves and strong currents would continue to affect the area for nearly 7 hours. This could cause significant coastal erosion in the Oamaru area, particularly the northern end of the town, which is more exposed to the open coast and is afforded less protection from Cape Wanbrow, to the south.

Table 54. Characteristics of tsunami events at Oamaru (as modelled by NIWA, 2007)

Characteristic	Puysegur Trench tsunami	1:500-year South American tsunami
Tsunami arrival time (after fault rupture)	2 hours 25 min	15 hours 30 min
Maximum wave amplitude	1.6m	1.6m
Predominant period of wave arrivals	25 and 100 min	80 and 105 min
Maximum wave run-up	2.6m	2.6m

Probability of inundation

The probability of maximum water levels of 1.5, 2.0 and 2.5m above MSL occurring as a result of any of the tsunami or elevated sea level scenarios modelled by NIWA is shown in Table 55. The table also provides a generalised explanation of the likely extent of inundation if a tsunami or elevated sea level event that reached 1.5, 2.0 or 2.5m were to occur.[88]

Table 55. Likelihood and possible consequences of peak water level due to the modelled storm surge and tsunami scenarios at Oamaru (with current sea level)

Maximum water level (m above MSL)	Probability of occurrence during any 100-year period (%)	Likely effect on community
1.5	>99	Wave run-up and inundation extends up into lower reaches of Oamaru Creek.
2.0	>99	As above. Also potential overtopping of Oamaru harbour breakwater.
2.5	25-35	Additional inundation and wave run-up of the lower reaches of Oamaru Creek and over-topping of the breakwater. Inundation of the Oamaru urban area does not occur at this level, although wave run-up may affect properties next to the coast and on Waterfront Road near the boat harbour.

The probability of maximum water levels reaching any of these heights will increase if sea level rises in the future. Table 56 shows the probability of maximum water level reaching 1.5, 2.0 or 2.5m above MSL as a result of tsunami or elevated sea level scenarios if 0.5m of sea level rise were to occur.

[88] The extent of inundation has been estimated through a simple assessment of coastal topography and elevation. Note that other factors associated with tsunami and elevated sea level events, such as wave velocity and duration of inundation, would also have an impact on particular communities.

Table 56. Likelihood of peak water level due to the modelled storm surge and tsunami scenarios at Oamaru (if average sea level were 0.5m higher than at present)

Maximum water level (m above MSL)	Probability of occurrence during any 100-year period (%)
1.5	>99
2.0	>99
2.5	>99

19.3 Community vulnerability

Most of Oamaru is unlikely to be affected by the elevated sea level and tsunami scenarios modelled as part of this study, due to its elevated position of 8m or more above MSL. Inundation would mainly be confined to the beach area, with the exception of the harbour breakwaters, the lower reaches of Oamaru Creek and properties around the margins of the boat harbour. The modelled 1:500-year elevated sea level event is shown to have the greatest effect in these areas, with wave run-up extending up to 130m inland near Waterfront Road. Although NIWA's (2007) modelling shows that tsunami waves would not extend this far inland, they would still have a major impact on the boat harbour area. Waves up to 2.5m high and travelling at 1-2m per second are shown to overtop the harbour breakwaters.

People in or near the boat harbour (including the breakwaters, the foreshore and the penguin colony) would be vulnerable, particularly during a near-field tsunami, as any warning of such an event would be minimal. Buildings and other infrastructure on the breakwaters or within the harbour would need to withstand the water velocities and elevated water levels associated with these events to avoid being damaged. Areas of existing development, north of the boat harbour and near the coast, also have some level of vulnerability, as extended periods of higher than normal water levels and large waves may cause rapid coastal erosion.

As well as the modelled scenarios shown in Figures A107 to A109, people and properties in the harbour area are also vulnerable to lower magnitude events which occur more frequently.

19.4 Summary

- People close to the shoreline at Oamaru are vulnerable to elevated sea level and tsunami events.
- Changes in sea level of up to 3m may occur very quickly along this stretch of coast during tsunami events. People near the coast would be particularly vulnerable, especially at low tide, when the foreshore and harbour are more accessible.
- The ocean may retreat by up to 400m before the arrival of tsunami waves, particularly near the boat harbour.
- Any warning before the arrival of a Puysegur Trench tsunami is likely to be minimal. People would therefore need to be aware of the quickest and safest way to evacuate to an identified safe area.
- Roads and properties near the harbour would be affected by wave action during tsunami and elevated sea level events. A 1:500-year elevated sea level event may result in wave run-up that extends up to 130m inland, while tsunami waves up to

2.5m deep and travelling at 1-2m per second are shown to overtop the harbour breakwaters.

20. Glossary

Alluvial deposits	Sourced from rivers or streams.
Cumec	A measure of flow rate, referring to a cubic metre of water per second.
Hazard	An unavoidable danger or threat to property and human life, resulting from naturally occurring events.
LiDAR	LiDAR (Light Detection and Ranging) is a mass of spot height information captured over a wide area using an aircraft mounted laser. The Otago Regional Council's LiDAR dataset has a vertical accuracy of ± 0.14m, and was collected in 2004.
LIM	A LIM (Land Information Memorandum) is a report that is prepared by a territorial authority in relation to each (if any) special feature or characteristic of the land concerned; which are known to the territorial authority, but which are not apparent from the district plan. The requirements of a LIM are specified in section 44A of the Local Government Official Information and Meetings Act 1987 (LGOIMA).
MHWS	MHWS (Mean High Water Springs) is the highest level to which spring tides reach on average over a period of time. This level is generally close to being the 'high water mark' where debris accumulates on the shore annually.
MSL	MSL (Mean Sea level) is the sum average of the tides (i.e. a middle level between high and low tides). Current MSL is relative to Dunedin Vertical Datum 1958 (DVD-58) + 12cm to account for sea level rise since 1958.
Morphology	The form or structure of the land.
Perigean spring tide	A perigean spring tide occurs when the moon is closest to the Earth during the spring tide.
Refraction	The process by which the direction of a wave is changed when moving into shallow water at an angle to the bathymetric contours. The crest of the wave advancing in shallower water moves more slowly than the crest still advancing in deeper water, causing the wave crest to bend toward alignment with the underwater contours.

Risk[89]

The chance of something happening that will impact on objectives.

Note:
1. Risk is often characterised in terms of an event or circumstance and the consequences that may flow from that event or circumstance.
2. Risk is measured in terms of a combination of consequences of an event and the likelihood of those consequences occurring.

Seiche

A rhythmic oscillation of water in a lake or a partially enclosed coastal inlet, such as a bay, gulf, or harbour.

Tidal bore

A vertical wall of turbulent water and debris water that travels up a river or narrow bay against the direction of the river or bay's current.

Tidal range

The difference in height between consecutive high and low waters. The tidal range varies from a maximum during spring tides to a minimum during neap tides.

True left river bank

The bank that is on the left hand of someone facing downstream.

True right river bank

The bank that is on the right hand of someone facing downstream.

Vulnerability

Liability or exposure to a hazard or disaster.

89 Definition adopted from NZS 9401:2008, *Managing flood risk – A Process Standard*

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Appendix 1. Combined probability calculation

To calculate the combined probability of a specified water level occurring in the next 100 years, the probability of no events occurring from any of the modelled scenarios (P) was calculated using the following binomial equation:

$$P(event\,not\,occuring\,in\,n\,years) = \binom{n}{r} p^r (1-p)^{(n-r)}$$

where p is the probability of an event occurring in any given year (the return period), and

$$\binom{n}{r} = \frac{n!}{r!(n-r)!}$$

where r is the number of successes[90] and n is the number of trials[91].

In summary, the above equations calculate:

$$P(event\,not\,occuring\,in\,n\,years) = (1-p)^n$$

Where the maximum predicted water level for a modelled scenario exceeded the selected water level (1.5m, 2.0m and 2.5m), *P(event not occurring in n years)* for that event was applied in the following equations to establish the probability of an event occurring from any of the modelled sources.

$$P(none\,events\,occuring\,in\,n\,years) = \prod_{event\,type} P(event\,not\,occuring\,in\,n\,years)$$

$$P(event\,occuring) = 1 - P(none\,events\,\,occuring\,in\,n\,years)$$

[90] For the purposes of this calculation, *r=0*, or no events occurring in any given year.
[91] For the purposes of this calculation, *n=100*, or 100 years.

Appendix 2. Aerial photography metadata

The following table shows the flight date and agency responsible for the collection of the aerial photography used in the Figures in the accompanying map book (ORC, 2012).

Area	Flight Date	Agency
Papatowai	26/3/2006	Otago Regional Council
Catlins (wider area)	26/3/2006	Otago Regional Council
Pounawea	23/3/2007	Clutha District Council
New Haven	12/4/2006	Clutha District Council
Lower Clutha	26/3/2006	Otago Regional Council
Toko Mouth	26/3/2006	Otago Regional Council
Taieri Mouth (wider area)	26/3/2006	Otago Regional Council
Taieri Mouth (township)	13/4/2008	Clutha District Council
Brighton	26/3/2006	Otago Regional Council
St Kilda / St Clair	30/3/2006	Otago Regional Council
Otago Harbour	30/3/2006	Otago Regional Council
Long Beach / Purakanui	1/4/2006	Otago Regional Council
Warrington	1/4/2006	Otago Regional Council
Karitane	30/3/2006	Otago Regional Council
Kakanui	31/3/2006	Otago Regional Council
Oamaru	26/2/2006	Otago Regional Council