Greater Wellington
Te Pane Matua Taiao

8 July 2024

File Ref: 2024-149

[redacted]
By email: [redacted]
Copy to: informationrequest@kapiticoast.govt.nz

Tēnā koe [redacted]

Request for information 2024-149

I refer to your request for information, partially transferred from Kāpiti Coast District Council on 3 July 2024 to Greater Wellington Regional Council (Greater Wellington) which was received on 3 July 2024. You have requested the following:

> *"By a simple twist of fate, I received the latest version of KCDC's publication "ARE YOU PREPARED FOR A TSUNAAMI". The Tsunami risk is stated as 200-300 meters further inland from the beach. Like you, I am not a climate change expert but having a "long deep fast travelling ocean wave caused by earthquakes ,landslides, or volcanic eruptions beneath or near the ocean" (page 2) coming towards you before you get 300 metres to safety seems a bit scary. Contrasted with the possibility of a couple of millimetres, over a long period of time I do grant you (but still a possibility) , with a 2 kms zone. Proportionate response? Really?*
>
> *Could you advise me which experts did you use for the Tsunami calculation?"*

Greater Wellington's response follows:

The tsunami evacuation mapping is based on work undertaken by GNS Science in 2017 and contained in the report (attachment 1):

> *Mueller C, Power WL, Wang X, Lukovic, B. 2017. Hydrodynamic inundation modelling and delineation of tsunami evacuation zones for Porirua and Kapiti Coast. Lower Hutt (NZ): GNS Science. 37 p. (GNS Science consultancy report; 2017/200).*

Details of the numerical modelling, the digital elevation grid, fault sources, and fault rupture scenarios that were used to produce the tsunami inundation runup overlays that underpin the evacuation maps can all be found in this report.

Follow up work was also undertaken by GNS Science to estimate tsunami arrival and evacuation times to assist Kāpiti emergency management understand the risks and to use as base material for public education and community outreach. This work is contained in the following three reports that can be accessed and download free of charge directly from GNS Science.

1. *Heron DW. Lukovic B, Wang X, Power WL. 2019. Evacuation time estimates for local source tsunami for Porirua and Kapiti suburbs. Lower Hutt (NZ) GNS Science. 192 p. (GNS Science report; 2019/79). doi: 10.21420/YH6M-D367.*

   Online Link: https://shop.gns.cri.nz/sr_2019-79-pdf/

2. *Wang X, Lukovic B, Mueller C, Heron DW, Power WL. 2021. Tsunami travel time estimates for local sources for Porirua and Kāpiti Coast suburbs. Lower Hutt (NZ): GNS Science. 39 p. (GNS Science report: 2020/06). doi: 10.21420/RAVV-9Q93.*

   Online link: https://shop.gns.cri.nz/sr_2020-06-pdf/

3. *Power WL, Henderson A, Lukovic B, Heron DW, Wang X. 2023. Agent-based tsunami evacuation modelling of the Kāpiti coast. Lower Hutt (NZ): GNS Science. 29 p. (GNS Science report; 2023/34) doi: 10.21420/229J-3K15*

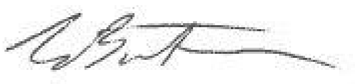
   Online link: https://shop.gns.cri.nz/sr-2023-34-pdf/

Further information about tsunami and emergency preparedness can be found at the Get Ready website: https://getready.govt.nz/emergency/tsunami

If you have any concerns with the decision(s) referred to in this letter, you have the right to request an investigation and review by the Ombudsman under section 27(3) of the Local Government Official Information and Meetings Act 1987.

Please note that it is our policy to proactively release our responses to official information requests where possible. Our response to your request will be published shortly on Greater Wellington's website with your personal information removed.

Nāku iti noa, nā



Lian Butcher
Kaiwhakahaere Matua Rōpū Taiao| Group Manager Environment Group

Hydrodynamic Inundation Modelling and Delineation of Tsunami Evacuation Zones for Porirua and Kapiti Coast

C. Mueller
X. Wang
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B. Lukovic

GNS Science Consultancy Report 2017/200
August 2017

GNS SCIENCE
TE PŪ AO

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Use of Data:

Date that GNS Science can use associated data: October 2017

BIBLIOGRAPHIC REFERENCE

Mueller C, Power WL, Wang X, Lukovic, B. 2017. Hydrodynamic inundation modelling and delineation of tsunami evacuation zones for Porirua and Kapiti Coast. Lower Hutt (NZ): GNS Science. 37 p. (GNS Science consultancy report; 2017/200).

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EXECUTIVE SUMMARY

We performed hydrodynamic inundation modelling of Porirua and Kapiti Coast for the purpose of informing updates to the tsunami evacuation zones in this area. These zones are intended to be marked around Porirua and Kapiti Coast as part of WREMO and Wellington City Council's Blue Line Project.

Tsunami evacuation zones for Porirua and Kapiti Coast are currently based on an empirical 'rule-based' tsunami height attenuation modelling technique. The large coverage generated by the conservative nature of this approach may in some situations lead to evacuation of a larger area than is necessary in the event of a large earthquake or tsunami warning.

In areas where high-resolution topographic and bathymetric data is available, it is possible to conduct more detailed, numerical computational modelling of water movements to calculate the inundation flow depth and velocities if required. With such data the delineation of more accurate evacuation zones becomes possible.

This work provides the underlying modelled data from which GWRC can develop improved tsunami evacuation zones. The COMCOT (Cornell Multi-grid Coupled Tsunami model) tsunami model (Wang & Power 2011) is the core simulation engine of our assessment. The modelling area includes all suburbs of Wellington Region that lie in Porirua and Kapiti Coast Territorial Land Authority areas.

In keeping with national conventions, modelling has been done to support the development of new zones consisting of:

- A Yellow Zone for self-evacuation (along with the orange and red zones) in the event of a strongly-felt or long-duration earthquake, or when a forecast of a regional or distant-source tsunami of above a specific threat level is issued,
- An Orange Zone to be used (along with the red zone) when a forecast tsunami from a regional or distant source is expected to cause some inundation, but not large enough to require evacuating the Yellow Zone, and
- A Red Shore-Exclusion Zone to be used when a tsunami forecast suggests a threat only to beaches and shoreline facilities.

The results that shall serve as a base for the definition of these three zones is presented in Chapter 4 of this report: Yellow Zone - Figure 4.4; Orange Zone (3m and 5m alternatives) - Figure 4.5 and Figure 4.6, respectively; Red Zone - Figure 4.7. It will be used by the council to define the zones at their discretion.

We consider the evacuation zones derived from the results of this study to be a more precise representation of the areas of potential inundation in real events than the previously defined zones of Leonard et al. (2008).

The 'Directors Guidelines for Tsunami Evacuation' (MCDEM 2008, 2016) call for the Red Zone to be defined – in areas of high quality topographic data – by the area less than 2m above the high tide level, i.e. Mean High Water Spring (MHWS). However, this results in an overly large Red Zone in some areas, notably within harbours and estuaries (e.g. the Pauatahanui Park). Hydrodynamic modelling of distant source scenarios which reach the 1m threat level (as per MCDEM, 2017; for which the Red Zone is designed to be evacuated) is provided in this report to help the councils delineate a Red Zone for this threat level more accurately in these areas.

1.0 INTRODUCTION

This report is submitted by the GNS Science to the Wellington Region Emergency Management Office (WREMO) and Iain Dawe of Greater Wellington Regional Council (GWRC) to document hydrodynamic inundation modelling of Porirua and Kapiti Coast for the purpose of updating the tsunami evacuation zones in this area. These zones are intended to be marked around Porirua and Kapiti Coast as part of WREMO and Wellington City Council's Blue Lines Project; a public education campaign that shows the anticipated land coverage of evacuation zones for the largest credible tsunami events.

The Blue Line Project was initiated in Island Bay in 2010 to raise public awareness about tsunami hazard and clearly show locations where it would be safe to evacuate to in the event of a long or strong earthquake that may result in the generation of a large tsunami. The tsunami inundation modelling was conducted by GNS Science and Greater Wellington Regional Council (Mueller et al., 2015).

Tsunami evacuation zones for Porirua and Kapiti Coast are currently based on an empirical 'rule-based' tsunami height attenuation modelling technique, which is conservatively designed to ensure that everyone who needs to evacuate is covered by the modelled zones. The large coverage generated by the conservative nature of this approach, however, results in the delineation of extensive evacuation zones, potentially leading to over-evacuation in the event of a large earthquake or tsunami warning. Over-evacuation causes practical challenges for emergency managers and has the potential for accidental harm or hardship.

In areas where high-resolution topographic and bathymetric data is available, it is possible to conduct more detailed, numerical computational modelling of water movements to calculate inundation flow depth and velocities if required. The good quality data available for Porirua and Kapiti Coast enables this level of hydrodynamic inundation modelling. With such data the delineation of more accurate evacuation zones becomes possible. More accurately delineated evacuation zones may help reduce the challenges faced by the public and WREMO during potential tsunami-generating events.

This project leverages work that has previously been done as part of the "It's Our Fault" programme, led by GNS Science. The programme is the most comprehensive study to date of Wellington's earthquake risk, and one component of the study assesses tsunami related hazards and impacts. Within the scope of this component, GNS Science has developed and is continuing to research new methods that enable us to consider the effects of non-uniform distribution of slip on the earthquake fault interface. In naturally occurring earthquakes the slip is not uniformly distributed and it is not currently possible to predict how this distribution will occur in future earthquakes. Therefore, a representative set of tsunami simulations generated with different possible examples of slip distributions has to be investigated to assess the potential impact of this uncertainty in the earthquake process. GNS Science has, and currently is, investigating the effects of this complexity with regards to tsunami arrival times, inundation extent and evacuation procedures.

The COMCOT tsunami model (Wang & Power 2011) is the core simulation engine of our assessment. It is routinely used and constantly improved for tsunami research at GNS Science. It has been used previously for tsunami inundation modelling for several New Zealand cities exposed to tsunami hazard, including Wellington.

In keeping with national conventions, as described in MCDEM (2008, 2016), this study produces data for the delineation of new zones consisting of:

- A Yellow Zone for self-evacuation (along with the orange and red zones) in the event of a strongly-felt or long-duration earthquake, or when a forecast of a regional or distant-source tsunami of above a specific threat level is issued,
- An Orange Zone to be used (along with the red zone) when a forecast tsunami from a regional or distant source is expected to cause some inundation, but not large enough to require evacuating the Yellow Zone, and
- A Red Shore-Exclusion Zone to be used when a tsunami forecast suggests a threat only to beaches and shoreline facilities.

The evacuation zones derived from this work will be a more precise and accurate representation of the areas of potential inundation in real events than those currently modelled, and it is expected that the extent of the Yellow and Orange Zones will decrease in some areas. The threshold for requiring the Yellow Zone to be evacuated in the event of a very large distant-source tsunami will be set high enough that this will be a very rare situation (i.e., typically occurring only once every several hundred years or more). These projected outcomes will assist emergency managers in preparing for and executing evacuations by reducing the number of people needing to be relocated.

1.1 PROJECT DESIGN

This project has been designed to use the following information sources currently available to GWRC and Porirua City Council (PCC):

- The topographic data included LiDAR (Laser light detection and ranging) based Digital Elevation Models (DEM) provided by PCC and GWRC. The LINZ NZ 8m Digital Elevation Model (2012) was used for the land area not covered by the LiDAR data.
- The Porirua Harbour bathymetric data consisted of sounding supplied by PCC and for Approaches to Porirua Harbour was digitised from the LINZ Nautical Chart NZ 4632, and the Coastal Charts.

Several different criteria were considered when determining the Yellow and Orange zones.

The data for defining the Yellow Zone will be generated by running a comprehensive set of tsunami simulations that have the Hikurangi subduction interface as a source, as well as a set of simulations corresponding to tsunamis caused by upper-plate faults offshore of the Kapiti coast.

To provide data for determining the location of the orange evacuation zone, we will identify tsunami simulation scenarios that create a given threat level (offshore tsunami wave height) from a previously performed threat level and forecasting study for all New Zealand. Scenarios that generate a threat level above a given threshold will be selected for a full inundation simulation.

The Red Zone is defined by all scenarios that generate a marine threat level. This is generally assumed to be the area within a specified elevation or distance from the shore line. This will be aligned with the most current MCDEM guidelines. We also provide a set of hydrodynamic scenario modelling results that assume distant source tsunami that reach the marine threat level in order for GWRC to test the extent of the red zone.

2.0 NUMERICAL METHODS

2.1 TSUNAMI SIMULATION SOFTWARE: COMCOT

The tsunami model, COMCOT (Cornell Multi-grid Coupled Tsunami model), was originally developed at Cornell University, USA in the 1990s (Liu et al. 1995) and since 2009 it has been under development at GNS Science, New Zealand (Wang & Power 2011). Using a modified staggered finite difference scheme to solve linear/nonlinear shallow water equations, COMCOT was developed to investigate the evolution of long waves in the ocean, particularly tsunami, including their generation, propagation, run-up and inundation. To account for the shallowness of water depth and ensure enough spatial resolution in near-shore regions, a nested grid configuration is implemented in COMCOT, through which the model can use a relatively large grid resolution to efficiently simulate the propagation of tsunamis in the deep ocean and then switch to apply finer grid resolutions in coastal regions. In this approach, the computational efficiency and the numerical accuracy can be well balanced.

This model has become publicly available and has been widely used by researchers to study different aspects of tsunami impacts. It has been systematically validated against analytical solutions (Cho 1995), experimental studies (Liu et al. 1994a; Liu et al. 1995; Cho 1995) and benchmark problems (Wang et al. 2008) and has consistently shown its satisfactory accuracy and efficiency. Some of its applications include the study of the 1960 Chilean Tsunami (Liu et al. 1994b), the 1986 Taiwan Hualien Tsunami (Liu et al. 1998), the 2003 Algerian Tsunami (Wang & Liu 2005), the 2004 Indian Ocean Tsunami (Wang & Liu 2006, 2007), and the 2009 Samoa tsunami (Beaven et al. 2010). It has also been applied to evaluate the flooding and tsunami forces on structures in the coastal areas of Galle, Matara and Hambantota in Sri Lanka during the 2004 Indian Ocean (Wijetunge et al. 2008).

Multiple source mechanisms have been integrated in the tsunami simulation package for this project, including subaerial/submarine landslides and earthquakes with transient rupture and/or variable slip distributions. The actual surface displacement is calculated using the displacement theory documented in Okada (1985).

2.2 DEM DEVELOPMENT AND MODEL SETUP

The COMCOT tsunami modelling software (Wang & Power, 2011) uses a series of nested ‘grids’ constructed from bathymetric and topographic data to account for spatial resolution requirements by a tsunami travelling in different regions. In this study, four levels of Digital Elevation Model (DEM, a combination of topography and bathymetry) grids at different spatial resolutions were used to simulate tsunami generation, propagation and coastal flooding.

The data for the first level grids, grid layer 01, came from the NGDC ETOPO topographic and bathymetric database which covers the whole Pacific to simulate tsunami generations and propagations from distant sources at a spatial resolution of 2 arc-minutes (~1.8km on the Equator, Figure 2.1). The data for the second level grids, grid layer 02, was derived from LINZ Charts, the Seabed Mapping CMAP and GEBCO 08 datasets which covers the whole New Zealand and its offshore regions at 30 arc-seconds (~640–740m in New Zealand, Figure 2.2). The third level grids, i.e., grid layer 03, derived from the same sources as the second level grids, covers the southern end of North Island at a spatial resolution of 6.0 arc-seconds (~135m in Wellington Region, Figure 2.3).

The fourth level grid, grid layer 04, covers Porirua Harbour and Kapiti Coast at a spatial resolution of about 25-27 metres (Figure 2.4) and its purpose is for high-resolution inundation modelling. The best available data was used for this high-resolution DEM. The topographic data included LiDAR based (DEM) provided by (PCC) and (GWRC). A 1 m resolution DEM based on the 2015 LiDAR data covering the Porirua City area was supplied by PCC and was considered the most accurate data layer. The remainder of the Wellington Region area was covered by the 1 m resolution GWRC DEM based on the 2013 LiDAR data. This model included buildings in some areas and it was necessary to remove these before the elevation data was used in the final DEM. The LINZ NZ 8m Digital Elevation Model (2012) was used for the remaining land area, not covered by the LiDAR data. This model was originally created by Geographx and was primarily derived from January 2012 LINZ Topo50 data. The Porirua Harbour bathymetric data consisted of sounding data collected during the 2009 hydrographic survey of the Porirua Harbour undertaken by Discovery Marine Ltd. and supplied by PCC. The bathymetric data for Approaches to Porirua Harbour was digitised from the LINZ Nautical Chart NZ 4632, and the Coastal Charts (1:90k – 1:350k) Data, obtained from LINZ in a digital form, was used for the remaining offshore area (see Figure 2.5, for data sources).

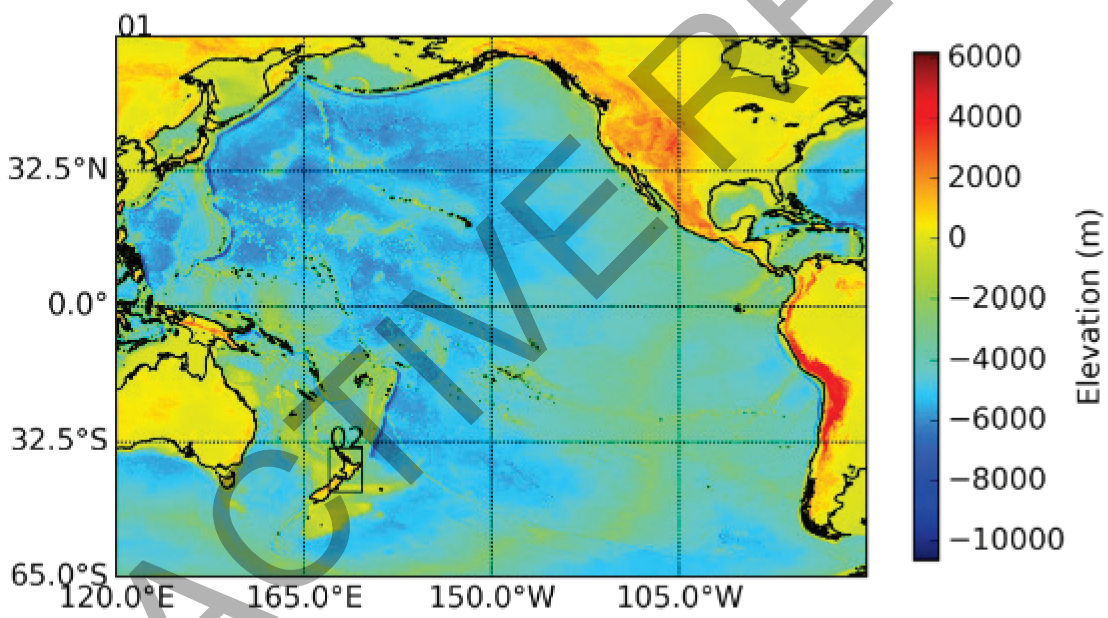


Figure 2.1 Nested grid setup for tsunami generation and propagation modelling. The outer grid layer 01 spans the whole Pacific for tsunamis from distant sources. See Figure 2.2, 2.2 and 2.4 for closer detail of grid layers 02, 03, 04. Elevation above sea level is colour-coded in metres.

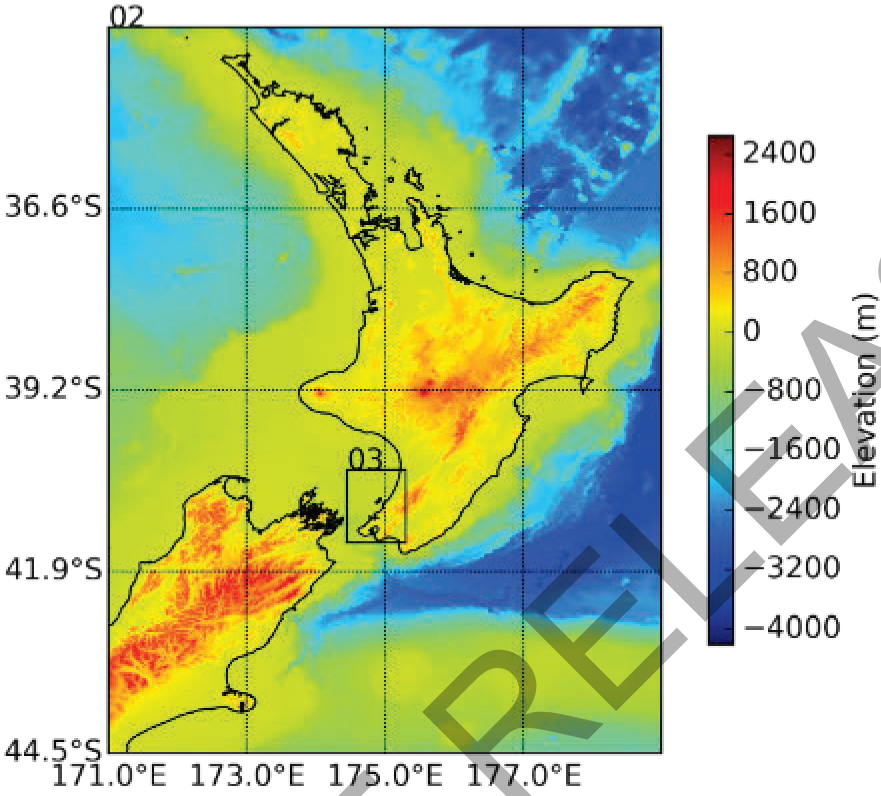


Figure 2.2 Nested grid setup for tsunami generation and propagation modelling. This figure shows the nested grid layers 02 (full extent of the map) and 03 which both focus on New Zealand and offshore regions at increasing levels of detail. Elevation above sea level is colour-coded in metres.

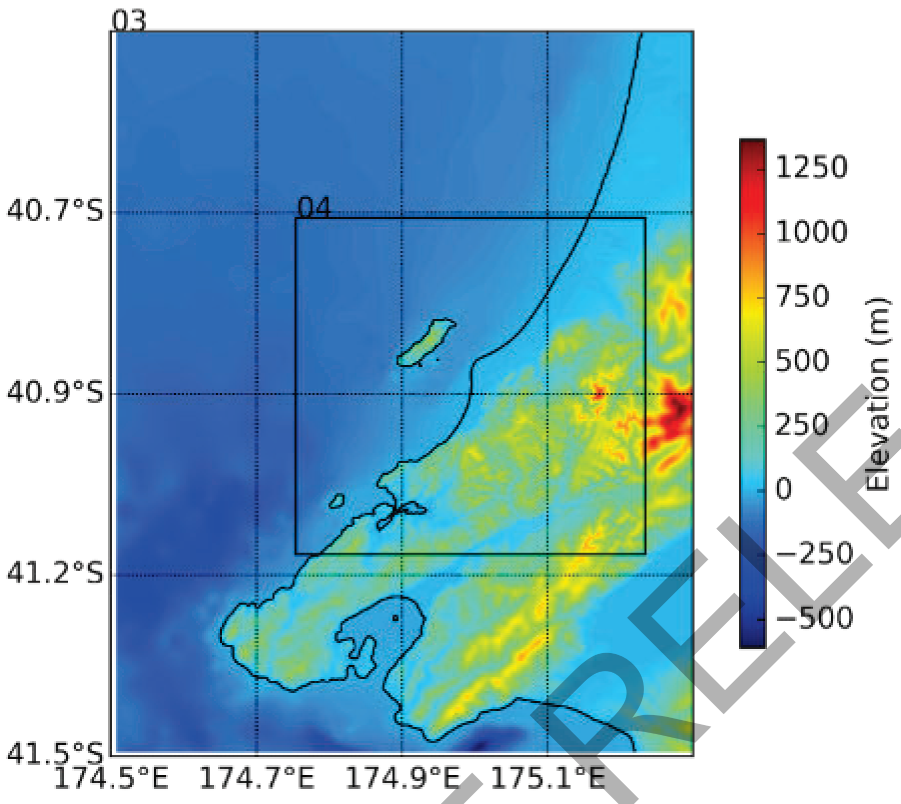


Figure 2.3 Nested grid setup for tsunami propagation modelling. This figure shows nested grid layers 03 (full extent of the map) and 04 which focus on the Kapiti coast and Porirua region at increasing levels of detail. Elevation above sea level is colour-coded in metres.

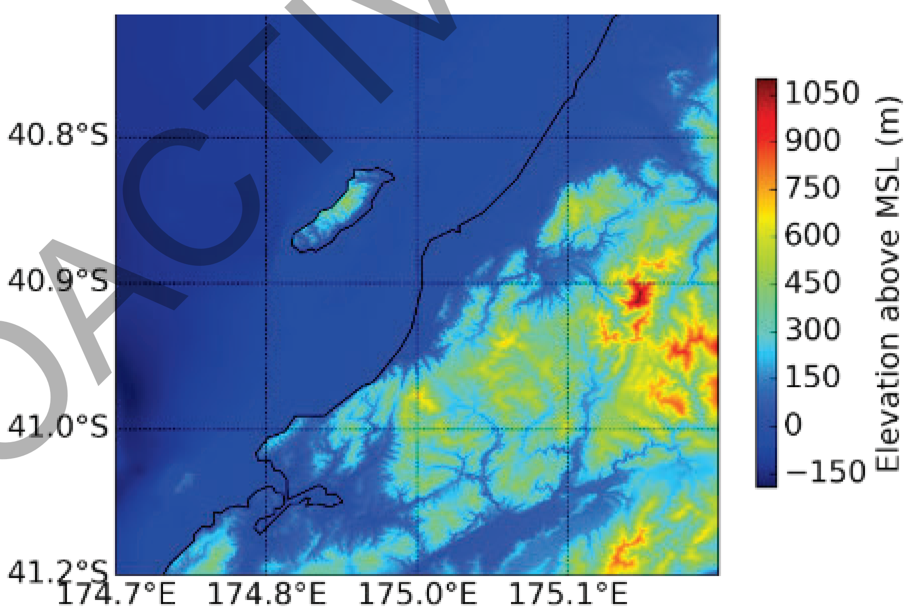


Figure 2.4 Digital elevation model used for tsunami propagation and inundation modelling in at Kapiti coast and Porirua. This figure shows nested grid layer 04 which has the highest level of detail. Elevation above sea level is colour-coded in metres.

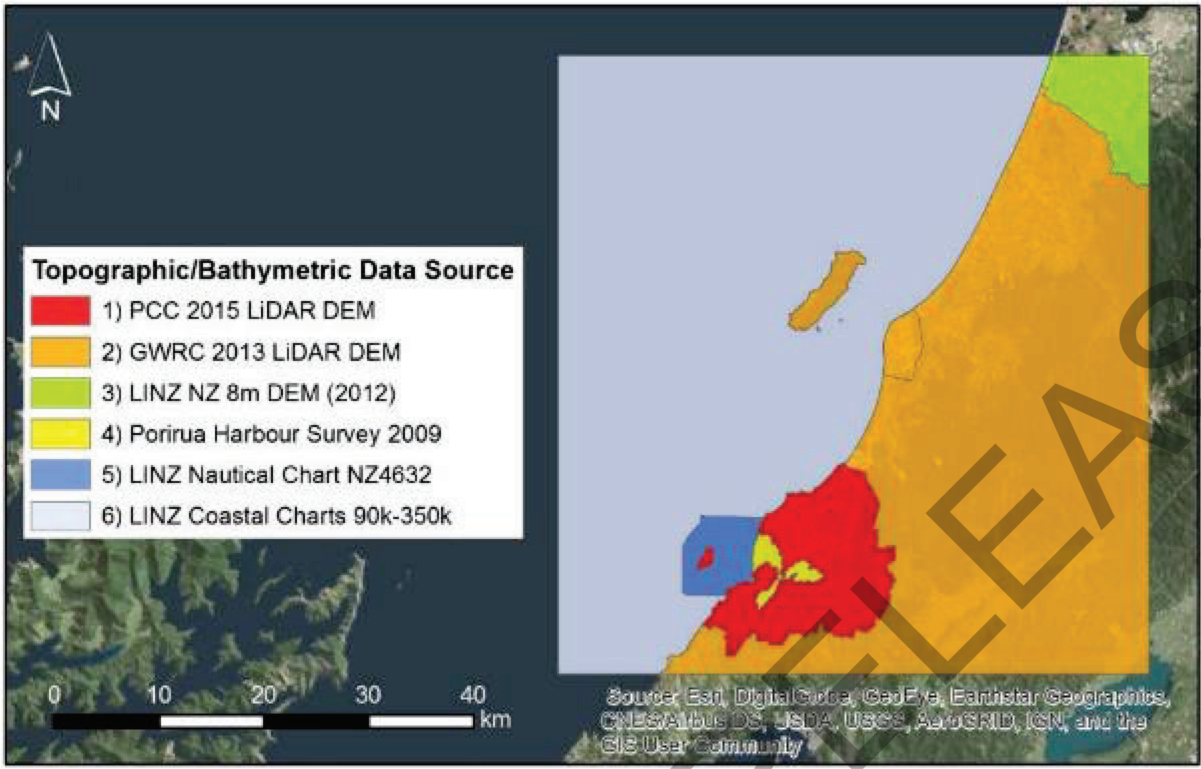


Figure 2.5 Data sources for the grid layer 04 DEM: Polygons outline the areas for different data sources that were used to construct the DEM (see legend).Sources 1, 2, and 3 refer to the topographic (land elevation) data and sources 4, 5, and 6 to the bathymetric data.

3.0 EVACUATION ZONE SIMULATIONS: METHODOLOGY

In the following section, we will discuss our approach to modelling scenarios relevant to defining the individual evacuation zones. This methodology follows the evacuation zone definitions/recommendations as described in MCDEM (2008, 2016).

3.1 YELLOW ZONE DEFINITION AND SOURCES

It has recently been recognised by the international tsunami science community and through research at GNS Science that the extents of tsunami inundation are highly sensitive to the specific distribution of establishing slip on the earthquake fault, which is particularly relevant when the faults are nearby (Mueller et al. 2015). The distribution of slip across an earthquake source (fault) can currently not be predicted and it is therefore necessary to consider the many possible ruptures that can occur on a particular fault (ensemble simulations). Ensemble simulations with non-uniform slip also make the assessment more conservative. Over the last few years, GNS Science has developed a framework for simulating tsunami inundation extent and distribution that involves modelling a broad spectrum of possible tsunami-generating events, representing the set of possible earthquakes. For this study a set of source scenarios was made representing 50 different potential non-uniform slip distributions on the subduction interface, and 8 different slip distributions on the Fisherman Fault.

Under the current guidelines for evacuation zoning the Yellow Zone is expected to at least cover the 2500 year inundation extent at the 84% confidence level. The zone can be further extended to cover areas with a longer return period, but this should take into account the practical implications of the evacuation process.

To identify the source or sources that could potentially contribute to the yellow zone we simulated a set of uniform slip scenarios for known offshore crustal faults (3.1.1) and different subduction zone scenarios (3.1.2). The set of sources we investigated were identified in a meeting that was held as part of the current It's Our Fault project tsunami arrival time investigation for Kapiti coast on Friday, June 02 at GNS Science. The meeting was attended by seismologists, geologists, tsunami scientists and GIS specialists from GNS Science and NIWA.

After careful consideration and analysis of this initial set of simulations we identified the main sources of tsunami hazard at long return periods (> 3,000 year) and high confidence levels (e.g., 84%) to stem from earthquakes of ~Mw 9.0 on the Hikurangi subduction interface, and from earthquakes on the Fisherman Fault and the Manaota Fault.

Please refer to Appendix 1 for a discussion on how to relate the set of inundation scenarios to the inundation return period and confidence level.

3.1.1 Local crustal fault sources for Porirua and Kapiti cost region

Porirua and Kapiti Coast sit above the northwest portion of southern Hikurangi Subduction Interface, and are also cut by a number of active crustal faults (Nodder et al. 2007; Stirling et al. 2012; Litchfield et al. 2014; Langridge et al. 2016), as shown in Figure 3.1. Among them, the Hikurangi Subduction Interface is the major tectonic feature and has the potential to generate biggest tsunami in this region (Mueller et al. 2014). The local active crustal faults are of three types of faulting: reverse faulting, normal faulting and strike-slip (Stirling et al. 2012). This study only considers those crustal faults that can generate tsunamis within one hour travel time and with potential of posing a land threat to Porirua and Kapiti Coast.

Most of strike-slip faults are not investigated due to their inefficiency of tsunami generation, except for Wairau Fault and Ohariu Fault (Figure 3.1). Both extend to seafloor and show evidence of co-seismic vertical displacements. For Wairau Fault, a rake angle of 28 degrees is used to calculate ground and seafloor displacement with Okada's method (Okada 1985) and match recommended ~5m subsidence-to-uplift displacement (Barnes, per comm. 2017; Grapes and Wellman 1986); for Ohariu Fault (OhariuS, OhariuC) a rake angle of -7 degrees is used to match the recommended ~1m subsidence-to-uplift displacement (van Dissen, per. comm. 2017). The crustal faults investigated in this study are summarized in Table 3.1, with fault names, fault types, magnitudes and other fault parameters extracted from National Seismic Hazard Model (NSHM) (Stirling et al. 2012).

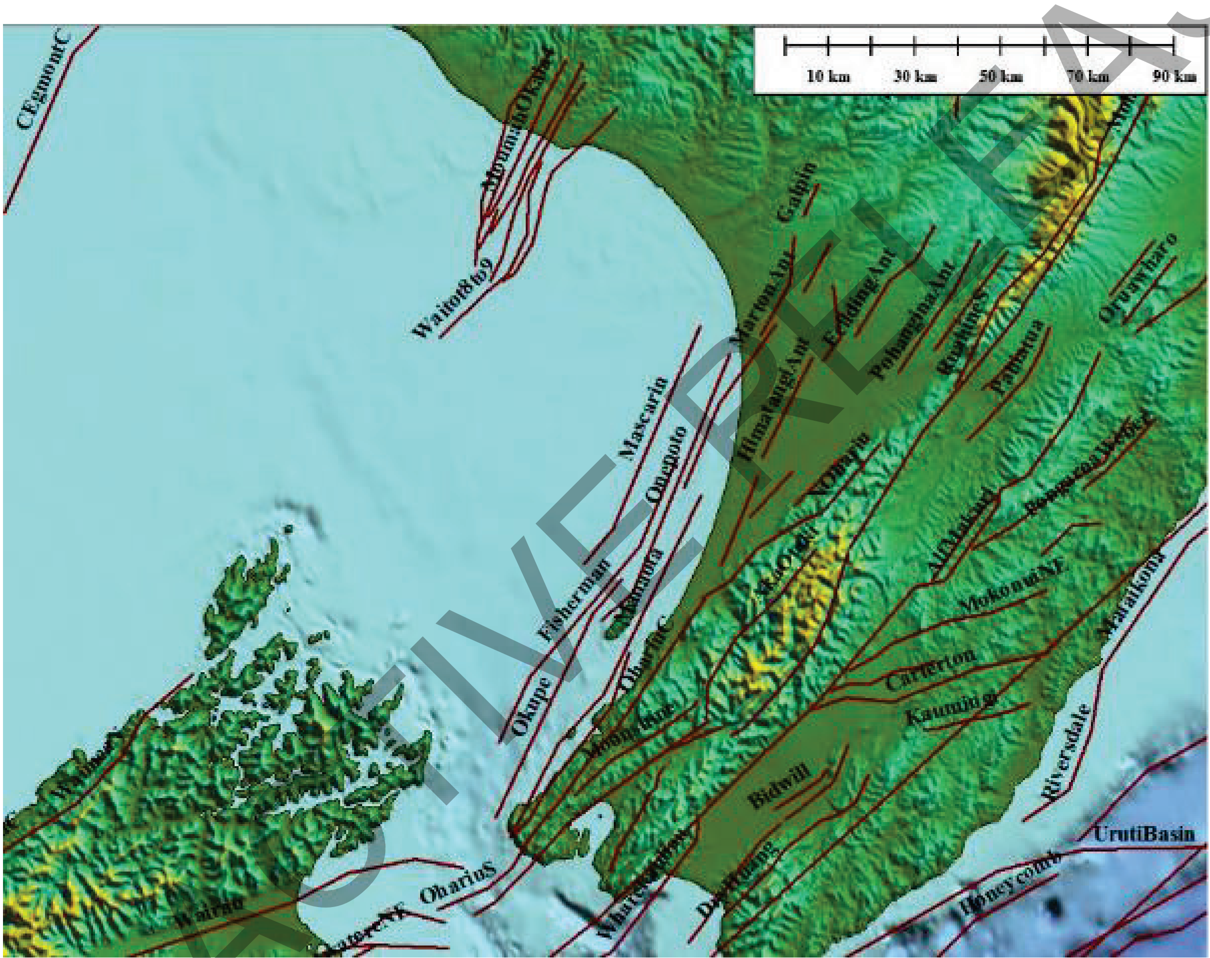


Figure 3.1 Active crustal faults in Porirua and Kapiti Coast region, reproduced from National Seismic Hazard Model (Stirling et al. 2012).

Table 3.1 Local active crustal fault sources for evacuation zone modelling in Porirua and Kapiti Coast. The fault names, types and parameters are extracted from NSHM (Stirling et al. 2012).

Label No.	Fault Name	Type	Mw	Slip (m)	R.I. (years)[1]
1	Fisherman	rv	7.5	5.5	5,500
2	OhariuC	ss	7.2	3.1	2,000
3	OhariuS	ss	7.4	3.7	2,500
4	Okupe	rv	7.4	4.3	5,400
5	Onepoto	rv	7.4	4.8	4,800
6	Manaota	rv	7.6	6.3	21,000
7	Mascarin	rv	7.4	4.3	1,400
8	Rangioffsh	rv	7.2	3.1	3,800
9	Wairau	ss	7.8	10.0	2,500

Note: Abbreviations for fault type: ss – strike slip; rv-reverse fault.

3.1.2 Subduction zone interface source

Geometry

Williams et al. (2013), present a description of the Hikurangi subduction interface geometry, making use of datasets that have become available since the original AB1996 model was developed (Ansell and Bannister 1996). They provide a parametric surface representation, so that the depth and the surface normal at any selected point to the interface can be determined. The data that were interpreted and then used to define the interface geometry include: earthquake hypocenter locations and tomographic inversion results; active-source seismic-reflection and refraction results; and the bathymetric expression of the trench. The geometry of the interface is shown in Figure 3.2 expressed as a set of depth contours.

We have used this surface geometry to define the source representing the Mw 9.0 event modelled in this study to define the extent of the yellow evacuation zone.

[1] R.I. – Return Interval

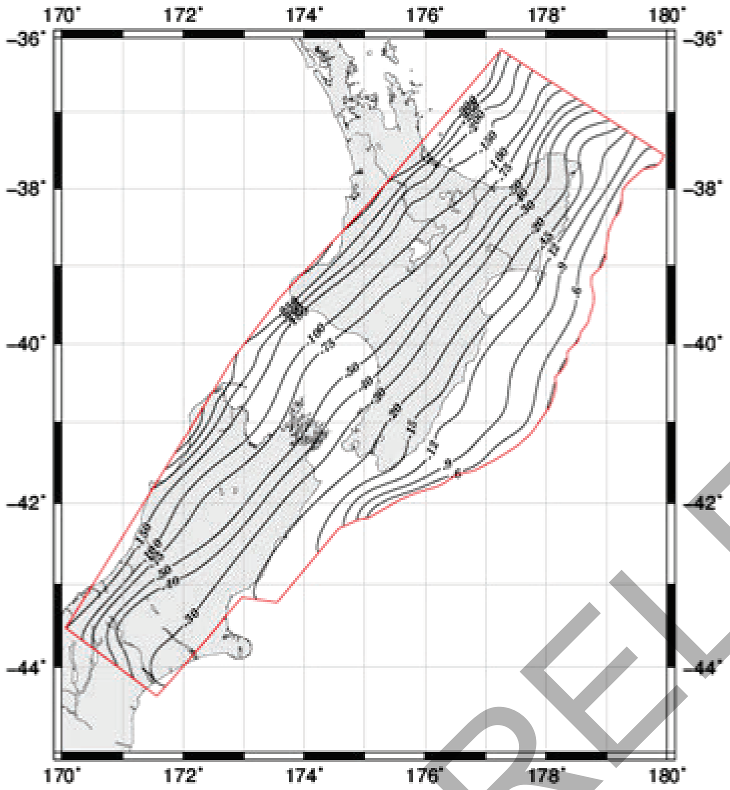


Figure 3.2 Revised Hikurangi subduction zone interface model after Williams et al. (2013). The model is represented as a depth contour plot in this figure. Each contour is labelled with its depth value (km). The red outline describes the validity region of the model. The model was used to generate subduction zone sources for this study.

Non-uniform slip calculations

The methodology we used to simulate slip distribution on the rupture interface follows that described by Geist (2002), which in turn is based on the method suggested by Herrero and Bernard (1994). In scaling the slip to a magnitude of Mw 9.0 a rigidity of 50 GPa has been assumed, consistent with Power (2013) and Mueller et al., (2014). Rigidity is an uncertain parameter and typical estimates used for tsunami modelling range from 35–50 GPa: if instead a rigidity of 35 GPa were to be assumed the magnitude of the earthquake would be Mw 8.9.

Slip distributions are first calculated on a rectangular grid, and then this grid is projected onto the fault surface. We are restricted to using rectangular patches in our projection onto the subduction surface due to current limitations in the algorithm that calculates the surface deformation resulting from this slip distribution.

Expert weighting scheme

Wallace et al. (2012) report a strong potential for the southern part of the Hikurangi subduction interface to be locked (see Figure 3.3). This suggests that there is an increased chance for slip to establish predominantly in areas where the slip-rate deficit is at a maximum (red areas of Figure 3.3).

We have incorporated this effect of predominant accumulation of slip into our source setup by applying a weighting function along the extent of the Hikurangi interface from north to south.

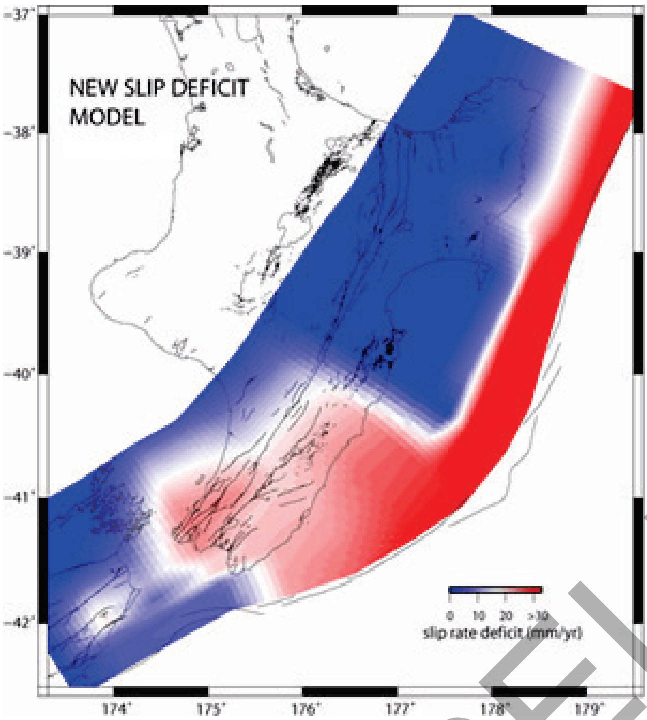


Figure 3.3 Subduction interface slip rate deficit for the Hikurangi subduction interface (from Wallace et al. (2012)).

We have calculated scenarios of stochastic non-uniform slip with this weighting scheme

It was shown in a previous study that the extent of inundation in Wellington coastal areas is larger for scenarios that take this weighting into account. In the current study we have chosen the set of scenarios with expert weighting applied as the basis for our zoning recommendations to take the most conservative approach.

- **Down dip tapers:** In an expert panel workshop it was decided to cut off generation of slip in down dip direction starting from two different depths, i.e. 60,000 m and 120,000m respectively. We created a taper function that starts to supress slip for depths greater than these values. The taper shape is a Hanning window which was arbitrarily chosen.
- **Epicentre locations:** We chose two different locations for the epicentre of our base scenarios, i.e. (177.34, -40.78) and (176.50, -40.29). The first is close to the subduction trench and would represent a scenario similar to those chosen for the Wellington harbour blue lines project. The second is generating slip further down dip assuming that this might have an influence on the tsunami generation potential of the Hikurangi Interface for Kapiti coast and Porirua.

Figure 3.4 shows the source models for these 4 base scenarios:

- Hikurangi_south_0: Epicentre at (177.34, -40.78), down dip taper with 60,000 m taper start depth.
- Hikurangi_south_1: Epicentre at (177.34, -40.78), down dip taper with 120,000 m taper start depth.
- Hikurangi_south_2: Epicentre at (176.50, -40.29), down dip taper with 60,000 m taper start depth.
- Hikurangi_south_3: Epicentre at (176.50, -40.29), down dip taper with 120,000 m taper start depth.

Generating the most significant cases from Hikurangi

Scenario selection for evacuation zoning is a life safety consideration and therefore conservative scenarios must be identified. We approached this problem by creating 4 base scenarios with uniform slip that already have a strong focus of slip being generated in the southern part of the Hikurangi subduction interface. The four base scenarios are a combination of two types of down dip tapers and two epicentre locations (Figure 3.4).

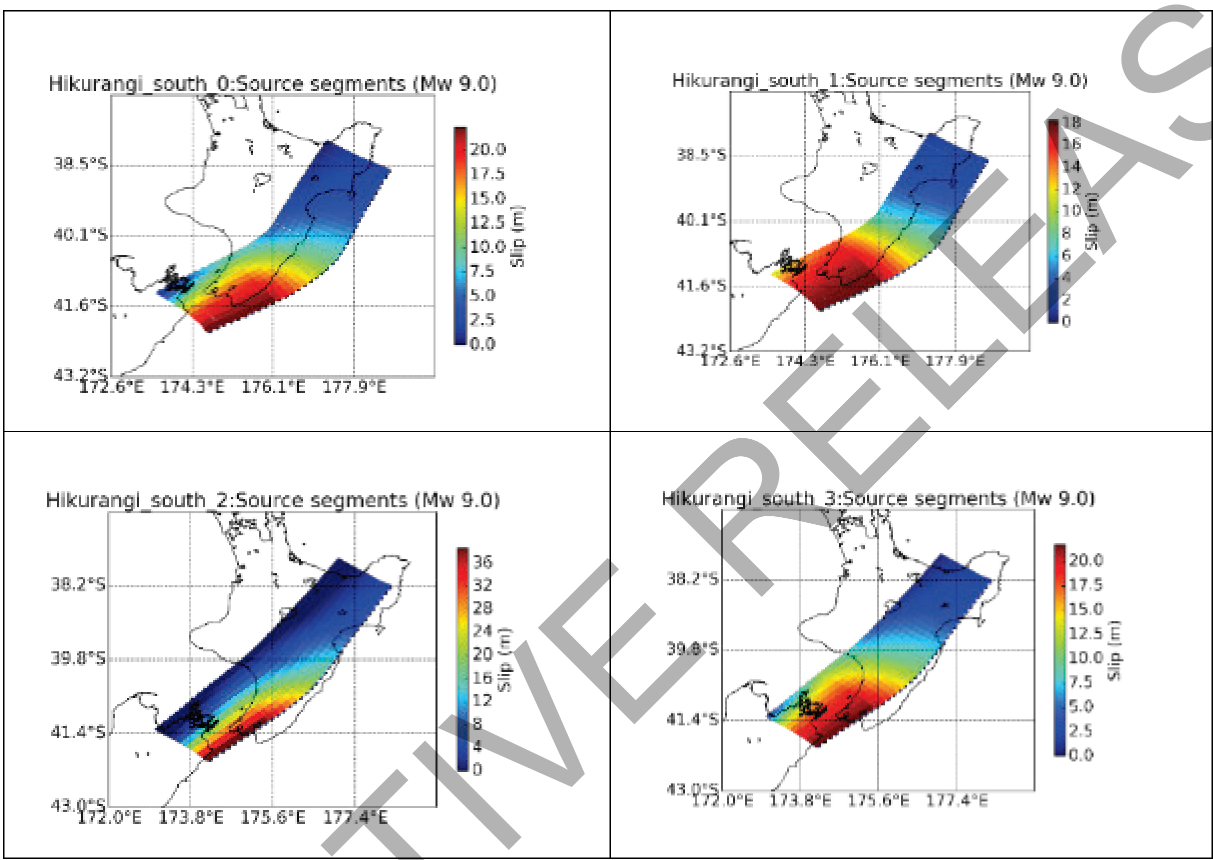


Figure 3.4 Base scenario set with uniform slip and tapers applied. The distribution of slip amplitudes here is generated by the expert weighting scheme (rupture focussing in the south of the interface), two different tapers applied and two different epicentres assumed. Hikurangi_south_0: Epicentre at (177.34, -40.78), down dip taper with 60,000 m taper start depth. Hikurangi_south_1: Epicentre at (177.34, -40.78), down dip taper with 120,000 m taper start depth. Hikurangi_south_2: Epicentre at (176.50, -40.29), down dip taper with 60,000 m taper start depth. Hikurangi_south_3: Epicentre at (176.50, -40.29), down dip taper with 120,000 m taper start depth.

In a subsequent selection process, the scenario named Hikurangi_south_2 was ruled out because the very concentrated area of maximum slip becomes unrealistic once non-uniform slip is introduced. This base scenario did create significant inundation, but we still removed it from the final set because it would not make sense scientifically. Inundation simulations of the remaining set suggest that non-uniform slip scenarios based on scenarios Hikurangi_south_0 and Hikurangi_south_3 should produce the most conservative but credible cases. We subsequently set up 10 simulations each for these two base scenarios and ran these with non-uniform slip to further discriminate which base scenarios to include in the final set of 50 simulations for the yellow zone. We find that base scenario Hikurangi_south_0 creates to largest extending inundation scenarios and it was used in the final simulation run to contribute to the final Yellow zone extent. Figure 3.5 shows 4 examples from this final set.

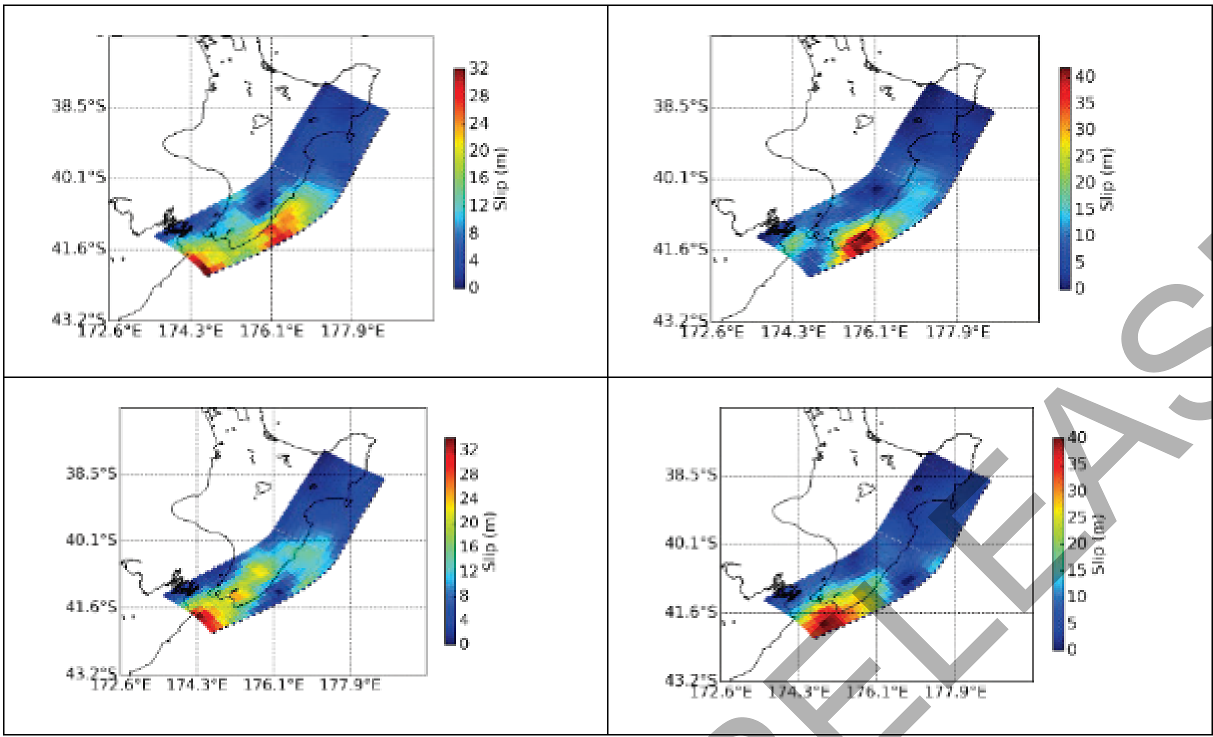


Figure 3.5 Example source scenarios with non-uniform slip on the Hikurangi subduction interface. These are a subset from 50 scenarios used to delineate the yellow zone for this project.

3.2 ORANGE ZONE: DEFINITIONS AND CALCULATION METHODOLOGY

The overall methodology for developing the Orange Zone is to model a range of scenarios that meet, or slightly exceed, the maximum criteria for the corresponding threat-level (1–3m or 3–5m), and then to outline the area that is inundated in one or more of these scenarios. The set of scenarios should be as broad as practicable, and an allowance is made for the fact that all possible scenarios cannot be modelled. An outline of the scheme used (as an example for the 5m threat level) is shown in Figure 3.6, and individual steps are explained in greater detail below.

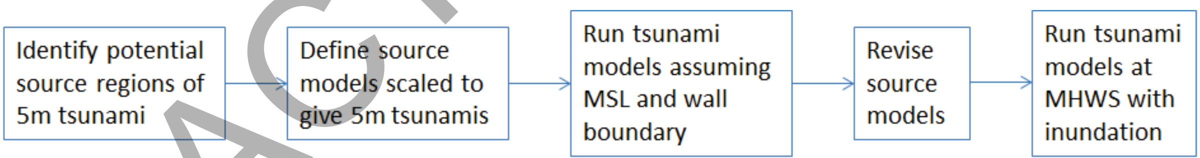


Figure 3.6 Outline of scheme for Orange Zone calculation. The scheme shown here is for developing a zone capable of encompassing a 5m tsunami. MSL = Mean Sea Level, MHWS = Mean High Water Springs ('high tide').

'Identify potential source regions' and 'Define source models'

These steps were performed using data that has been collected for preparing tsunami threat-level forecasts. Regions of the Pacific where earthquakes of plausible magnitudes result in 5m (or 3m) tsunami were identified, and estimates of the magnitudes required to do this were tabulated.

The threat-level database for distant tsunami sources includes scenario earthquakes of Mw 8.7, 9.0, 9.3; and for regional sources earthquakes of Mw 8.1, 8.4, 8.7, 9.0, 9.3. Interpolation and extrapolation, based on Abe (1979), was used to identify earthquake magnitudes that would produce tsunamis of the required (3m or 5m) height at the coast. Some scenarios exceeded the maximum plausible magnitude for the source location, but were used anyway to provide a broad coverage of tsunami sources that approach Porirua and the Kapiti coast from different directions.

'Run tsunami models at MSL and wall boundary'

Initially scenario models based on the sources in Table 3.2 were modelled as if they occurred at a tidal level of Mean Sea Level, and assuming a solid-wall boundary at the coastline. The reason for this is to reproduce the approximations under which tsunami-threat level forecasts are typically made.

'Revise source models'

Analysis of the results from the previous step identified that in several cases the modelled tsunami heights at the Wellington coast differed significantly from the intended height of 5m (or 3m). The primary reason for this is thought to be that the Abe (1979) scaling rule may cease to hold well for very large earthquakes.

To correct for this issue the source models were revised according to the scheme shown in Figure 3.7. The first step here is to estimate the maximum tsunami height in the models developed in the previous step. This was assessed by analysis of maximum tsunami-height data; the maximum height was taken to be that exceeded over at least ~1% of the Kapiti and Porirua coastline.

Subsequently a re-scaling of the seismic slip in the earthquake source model was made, with the intention of achieving a better agreement with the targeted tsunami height.

In our analysis, it is only possible to develop a finite set of scenarios, but in reality there are many variations on the possible set of earthquakes that could cause a 5m (or 3m) tsunami. Examination of modelling results suggests there are many similarities in the patterns of tsunami heights that are consistent between different scenarios, but there are also differences in detail. To make allowance for the variations in scenarios beyond those included in this study, we included an extra 20% 'safety factor' (k=1.2 in Figure 3.7). In practice this means that in order to develop an evacuation zone for 5m tsunamis we use a set of scenario models that aim to produce 5 x 1.2 = 6m tsunamis.

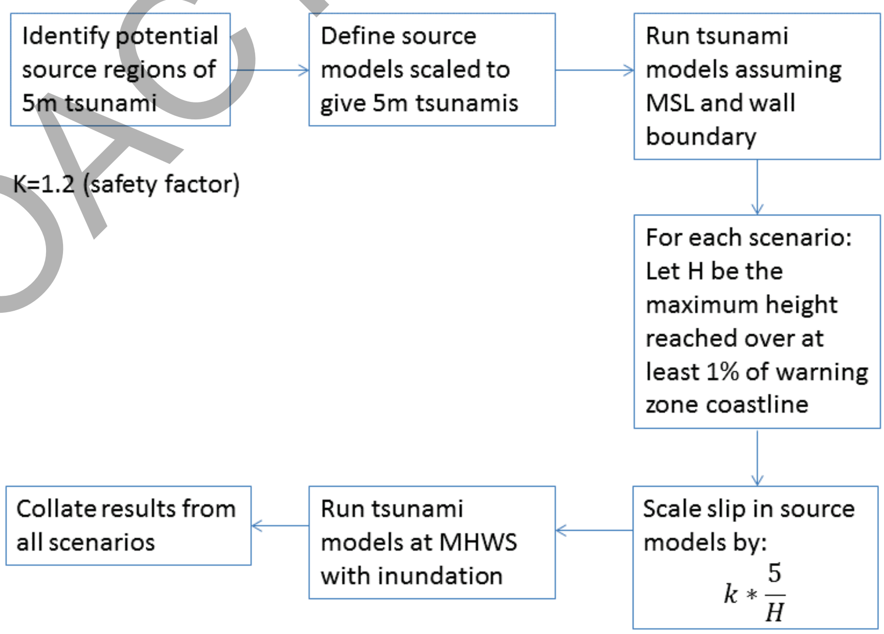


Figure 3.7 Expanded schematic, illustrating the process indicated by 'Revise source models'.

'Run tsunami models at MHWS with inundation'

After revising the source models according to the previous step, the new tsunami source models were used as inputs to tsunami inundation models of Porirua and Kapiti Coast. These models were run assuming a high tide at MHWS.

The results of these model runs were then collated and processed. The outline of the areas inundated in at least one of the scenarios is taken to be the minimum boundary of the Orange Zone.

Table of scenarios

The scenarios used for this study are tabulated in Table 3.2.

Table 3.2 Source Regions and scenarios, including revised slip estimates used for inundation modelling for the Orange Zone.

			Modelled with wall boundary and at MSL			Modelled with Inundation at MHWS	
ID_code	**Location Description**	**Intended height (m)**	**Slip (m)**	**Magnitude2**	**Max height (m)**	**Scaling factor**	**Modified slip (m)**
K3_NH_mw93_1	Solomons	3	61.12	9.3	3.0	1.22	74.6
K3_MO_mw93_1	Manus	3	55.33	9.5	2.1	1.73	95.7
KW_PE_mw93_1	Puysegur	3	91.53	9.6	2.9	1.23	112.5
K3_KT_mw93_6	Tonga	3	33.79	9.4	3.0	1.21	40.9
K3_PW_mw93_20	Aleutians	3	49.31	9.5	2.4	1.48	73.1
K3_HT_mw93_1	Hjort T.	3	37.33	9.3	3.0	1.19	44.3
K3_KT_mw93_1	Kermadec	3	57.86	9.4	3.3	1.10	63.5
K3_KT_mw93_2	Kermadec	3	23.8	9.3	3.3	1.09	25.9
K3_KT_mw93_3	Kermadec	3	20.24	9.3	3.1	1.17	23.7
K3_KT_mw93_4	Kermadec	3	23.16	9.3	3.0	1.20	27.7
K3_KT_mw93_5	Tonga	3	27.23	9.4	2.9	1.23	33.5
K3_KT_mw93_7	Tonga	3	37.65	9.5	2.9	1.22	46.1
K3_KT_mw93_8	Tonga	3	37.33	9.3	2.7	1.31	49.0
K3_NH_mw90_10	N. Hebrides	3	17.19	9.0	2.7	1.35	23.2
K3_NH_mw90_3	Solomons	3	20.75	9.1	2.6	1.39	28.8
K3_NH_mw90_4	Solomons	3	18.63	9.1	3.8	0.95	17.7
K3_NH_mw90_5	Solomons	3	17.18	9.1	2.7	1.35	23.2
K3_NH_mw90_9	N. Hebrides	3	16.28	9.1	3.4	1.06	17.3
K3_NH_mw93_10	N. Hebrides	3	19.15	9.0	2.9	1.22	23.4
K3_NH_mw93_2	Solomons	3	21.95	9.3	2.9	1.26	27.7
K3_NH_mw93_3	Solomons	3	14.64	9.2	2.4	1.50	22.0
K3_NH_mw93_4	Solomons	3	14.64	9.2	3.3	1.08	15.8
K3_NH_mw93_5	Solomons	3	15.04	9.2	3.9	0.93	14.0
K3_NH_mw93_6	Vanuatu	3	18.17	9.2	2.7	1.34	24.4
K3_NH_mw93_7	Vanuatu	3	14.64	9.2	2.4	1.53	22.3
K3_NH_mw93_8	Vanuatu	3	16.76	9.2	2.9	1.25	20.9
K3_NH_mw93_9	N. Hebrides	3	13.14	9.1	3.3	1.10	14.4
K3_PT_mw90_1	Puysegur	3	13.12	9.0	3.0	1.19	15.6
K3_PT_mw93_1	Puysegur	3	12.1	9.0	2.8	1.31	15.8

2 Magnitudes have been estimated assuming a crustal rigidity of 50 GPa. This was done for consistency with existing tsunami modelling work done by GNS Science. If instead a rigidity of 35 GPa was assumed, the magnitudes would be approximately 0.1 less.

ID_code	Location Description	Intended height (m)	Modelled with wall boundary and at MSL			Modelled with Inundation at MHWS	
			Slip (m)	Magnitude2	Max height (m)	Scaling factor	Modified slip (m)
K5_NH_mw93_1	Solomon I.	5	130.1	9.5	6.8	0.88	76.3
K5_NH_mw93_2	Solomon I.	5	47.99	9.5	5.1	1.18	56.7
K5_HT_mw93_1	Hjort T.	5	79.47	9.5	5.6	1.07	85.2
K5_KT_mw93_2	Kermadec	5	50.66	9.5	5.7	1.05	53.3
K5_KT_mw93_3	Kermadec	5	43.08	9.5	5.0	1.20	51.6
K5_KT_mw93_4	Kermadec	5	49.31	9.5	5.7	1.05	52.0
K5_KT_mw93_5	Kermadec	5	61.19	9.6	5.7	1.05	64.1
K5_KT_mw93_8	Tonga	5	81.64	9.5	4.4	1.36	110.8
K5_NH_mw90_10	N. Hebrides	5	36.6	9.2	5.1	1.17	43.0
K5_NH_mw90_9	N. Hebrides	5	34.65	9.3	6.2	0.97	33.8
K5_NH_mw93_10	N. Hebrides	5	40.77	9.2	5.4	1.11	45.2
K5_NH_mw93_3	Solomon I.	5	31.17	9.4	4.5	1.32	41.2
K5_NH_mw93_4	Solomon I.	5	31.17	9.4	5.8	1.04	32.3
K5_NH_mw93_5	Solomon I.	5	32.02	9.4	8.8	0.68	21.8
K5_NH_mw93_6	Vanuatu	5	38.68	9.5	5.6	1.06	41.1
K5_NH_mw93_7	Vanuatu	5	31.17	9.4	5.0	1.19	37.2
K5_NH_mw93_8	Vanuatu	5	35.67	9.4	6.0	1.00	35.7
K5_NH_mw93_9	N. Hebrides	5	29.53	9.4	5.9	1.01	29.9
K5_PT_mw90_1	Puysegur	5	27.93	9.2	6.7	0.89	25.0
K5_PT_mw93_1	Puysegur	5	26.46	9.2	5.4	1.10	29.2

3.3 RED ZONE

The Red Zone is intended to be a 'Marine and Beach' evacuation zone that is tied to the 0.2m–1.0m 'Marine and Beach Threat' threat-level in MCDEM tsunami forecasts.

The 'Directors Guidelines for Tsunami Evacuation' (MCDEM 2008, 2016) call for the Red Zone to be defined – in areas of high quality topographic data – by the area less than 2m above MHWS. However, this is acknowledged to be problematic inside harbours and estuaries, in which areas exceptions are permissible. An estimation of the areas within Porirua harbour that lie less than 2m above high tide clearly illustrate these problems, because they sometimes cover almost the full extent of the proposed orange and yellow zones (e.g. in the Pauatahanui Park and similar areas of the Porirua Harbour, please see Section 4.2). It is worth noting that the orange and the yellow zone also fall very close together in these areas.

It was proposed to provide data for testing or modifying the Red Zone in these locations with a set of scenario models of 1 x 1.2 = 1.2m amplitude tsunami. These scenarios were developed using the same methodology as the Orange Zone. These scenarios are intended to test the validity of the zone, rather than to define the Red Zone; this is because the range of possible source regions for 1m tsunamis is very great and only a small sample of these can be modelled.

The set of scenario models is shown in Table 3.3.

Table 3.3 Source Regions and scenarios, including revised slip estimates used for inundation modelling for the Red Zone.

			Modelled with wall boundary and at MSL			Modelled with Inundation at MHWS	
ID_code	**Location Description**	**Intended height (m)**	**Slip (m)**	**Magnitude**	**Actual max height (m)**	**Scaling factor**	**Modified slip**
MO_mw90_2	Manus	1	16.28	9.1	0.70	1.70	27.74
NG_mw93_1	N. N. Guinea	1	33.13	9.4	0.98	1.22	40.53
PE_mw90_5	Puysegur	1	17.18	9.1	1.19	1.01	17.27
PE_mw93_12	Puysegur	1	27.98	9.4	1.02	1.17	32.83
PE_mw93_20	Puysegur	1	18.17	9.2	1.08	1.11	20.24
PE_mw93_28	Puysegur	1	21.36	9.3	0.89	1.35	28.86
PW_mw90_1	Guam	1	16.28	9.1	0.94	1.27	20.72
PW_mw90_12	Japan	1	16.28	9.1	0.75	1.60	26.00
PW_mw90_17	Kuril I.	1	18.13	9.1	0.82	1.46	26.39
PW_mw90_21	Aleutian I.	1	11.46	9.0	0.72	1.66	18.97
PW_mw93_31	Cascadia	1	21.95	9.3	0.82	1.46	32.10
PW_mw93_5	Mariana I.	1	18.67	9.3	1.04	1.16	21.65
PW_mw93_9	Japan	1	20.24	9.3	0.88	1.36	27.52
RN_mw93_3	Japan	1	27.23	9.4	1.10	1.09	29.76
HT_mw87_1	Hjort T.	1	7.25	8.7	0.86	1.39	10.06
KT_mw87_3	Kermadec	1	6.51	8.7	0.88	1.37	8.93
KT_mw87_5	Kermadec	1	7.45	8.7	0.97	1.24	9.21
KT_mw90_1	Kermadec	1	10.57	8.9	1.04	1.15	12.14
NH_mw84_3	Solomon I.	1	6.12	8.5	0.92	1.30	7.98
NH_mw84_9	N. Hebrides	1	5.64	8.4	0.94	1.28	7.22
NH_mw87_6	Tonga	1	6.69	8.7	0.85	1.41	9.45
PT_mw84_2	Puysegur	1	5.06	8.4	0.89	1.35	6.85

4.0 SIMULATION RESULTS

In this section, we summarize the main findings from this study. We present simulation results from individual scenarios and ensembles. As an 'ensemble' we define a set of tsunami simulations which all have the same parameters characterising the source, but with one parameter, i.e., the distribution of slip across the rupture interface randomly varied from scenario to scenario. We refer to this variable parameter as the 'ensemble parameter'. By running a few of these scenarios, we can study the effect of uncertainty of the distribution of slip. In our simulation studies, for each individual scenario, we record the maximum flow depth registered in each grid cell. As flow depth, we define the separation between the surface of the digital elevation model and the water surface. Flow velocities have not been recorded.

4.1 YELLOW ZONE SCENARIOS

4.1.1 Local crustal fault sources

Uniform slip simulations for the set of crustal sources considered here show that only the Fisherman fault and the Manaota fault generate inundation significant enough to be considered for yellow zone delineation. However, since the Manaota fault has a comparably large return period of 21,000 years, including it into the set of possible sources is seen as appropriately conservative, without considering non-uniform slip. We therefore only ran a scenario with uniform slip on the fault. Figure 4.1 shows the areas inundated by this scenario (indicated in red) assuming 35 GPa for the rigidity since this is more typical for crustal faults. Reducing the shear modulus (or rigidity) of a fault will generate more slip for any fixed magnitude and therefore increase tsunami wave heights generated by the fault.

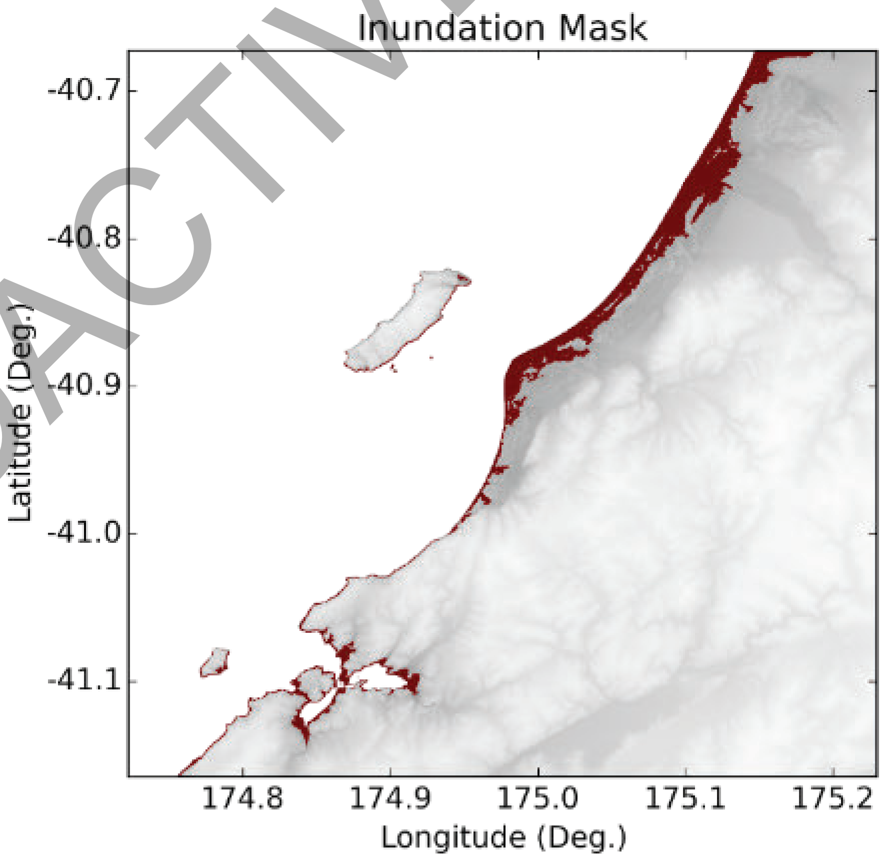


Figure 4.1 Manaota fault scenario inundation extent (35 GPa assumed for rigidity).

We selected the Fisherman fault for non-uniform slip simulations to compare it against non-uniform slip inundation experiments from the subduction zone scenarios. We also reduced the shear modulus for this fault from 50 GPa as used for the subduction zone to 35 GPa.. The Fisherman fault can create considerable inundation along the Kapiti coast and in Porirua. However even with such conservative assumptions, i.e. non-uniform slip and reduced shear modulus we find that scenarios that stem from the subduction zone still create larger inundations extents in most areas. Figure 4.2 shows the union inundation extent from a set of 8 non-uniform slip scenarios for the Fisherman fault assuming 35 GPa rigidity for the fault mechanism (indicated in red).

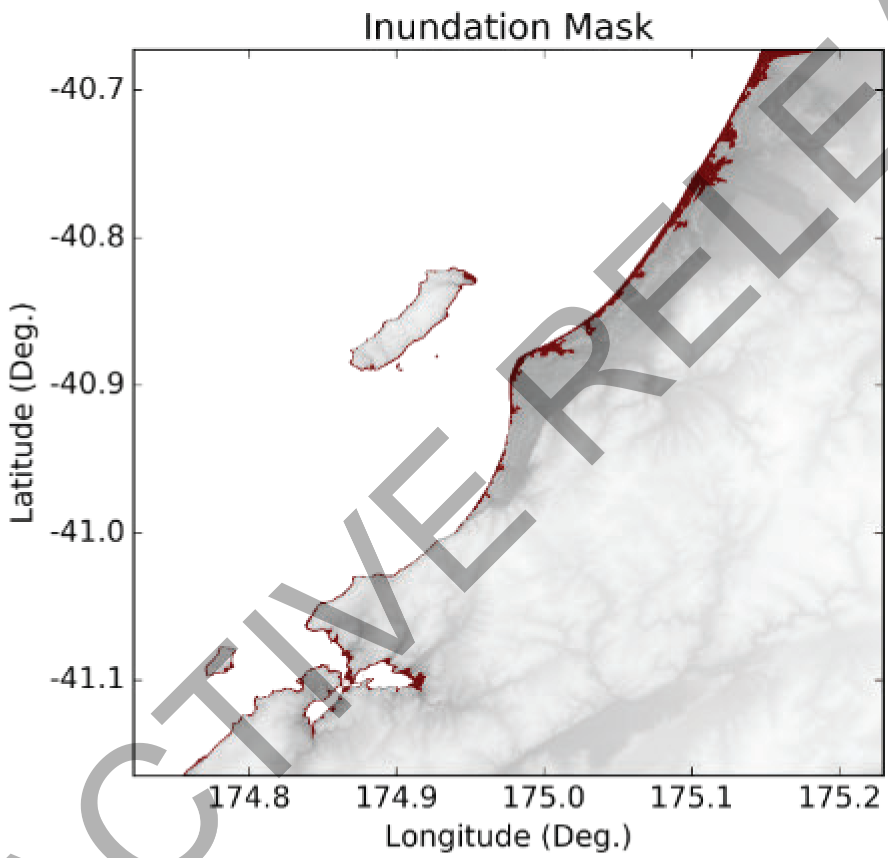


Figure 4.2 Union of all non-uniform slip scenarios for Fisherman with 35 GPa rigidity assumed.

4.1.2 Hikurangi subduction interface sources

As described in Section 3.1.2 we have simulated 50 potential Hikurangi subduction zone events with an assumed Moment Magnitude of Mw 9.0 and an expert weighting scheme applied as discussed there as well. The ensemble parameter is the distribution of slip establishing for each potential event. We assume that this ensemble of scenarios and its respective inundation distribution is representing the breadth of potential worst case scenarios for Porirua and Kapiti coast.

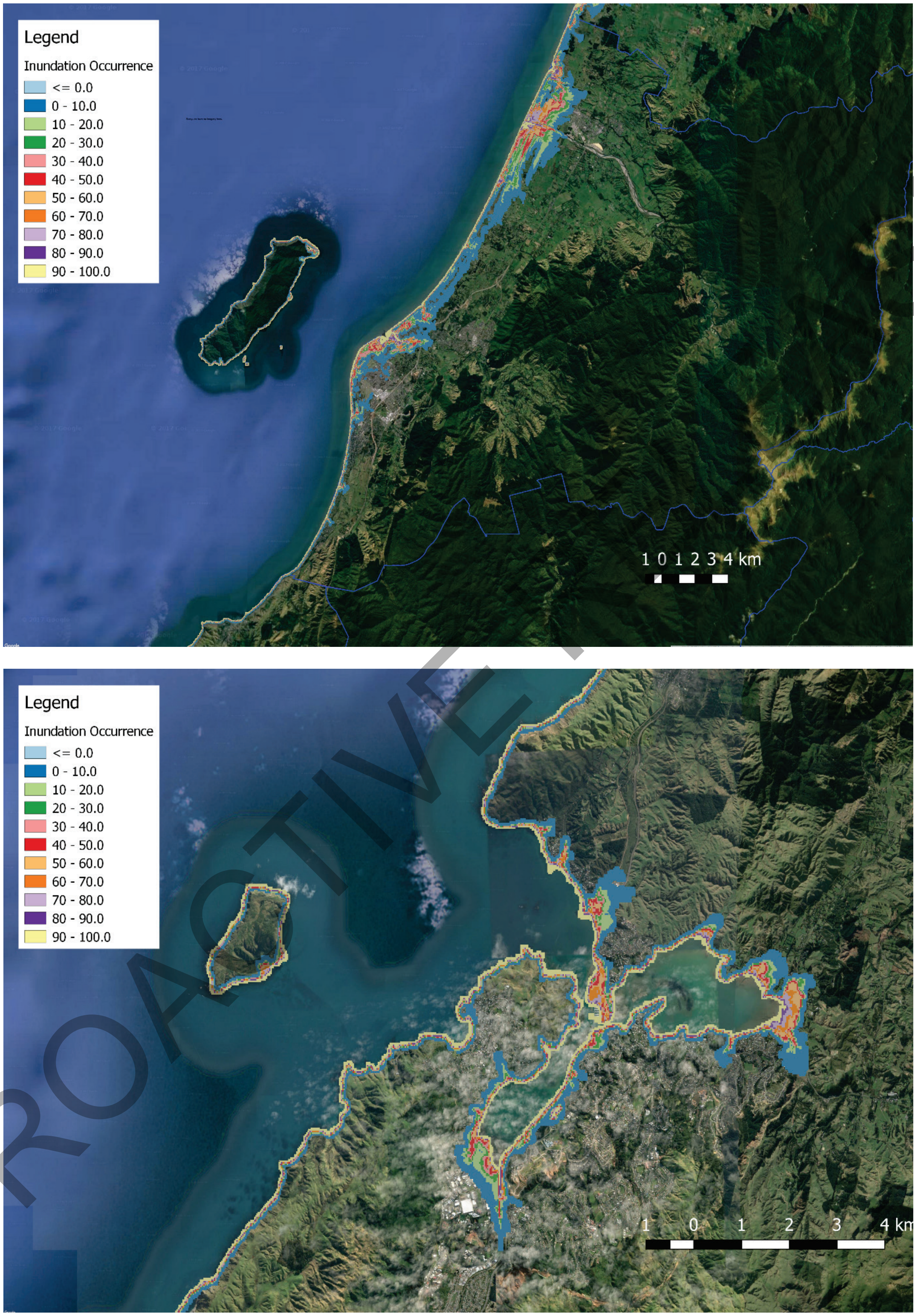
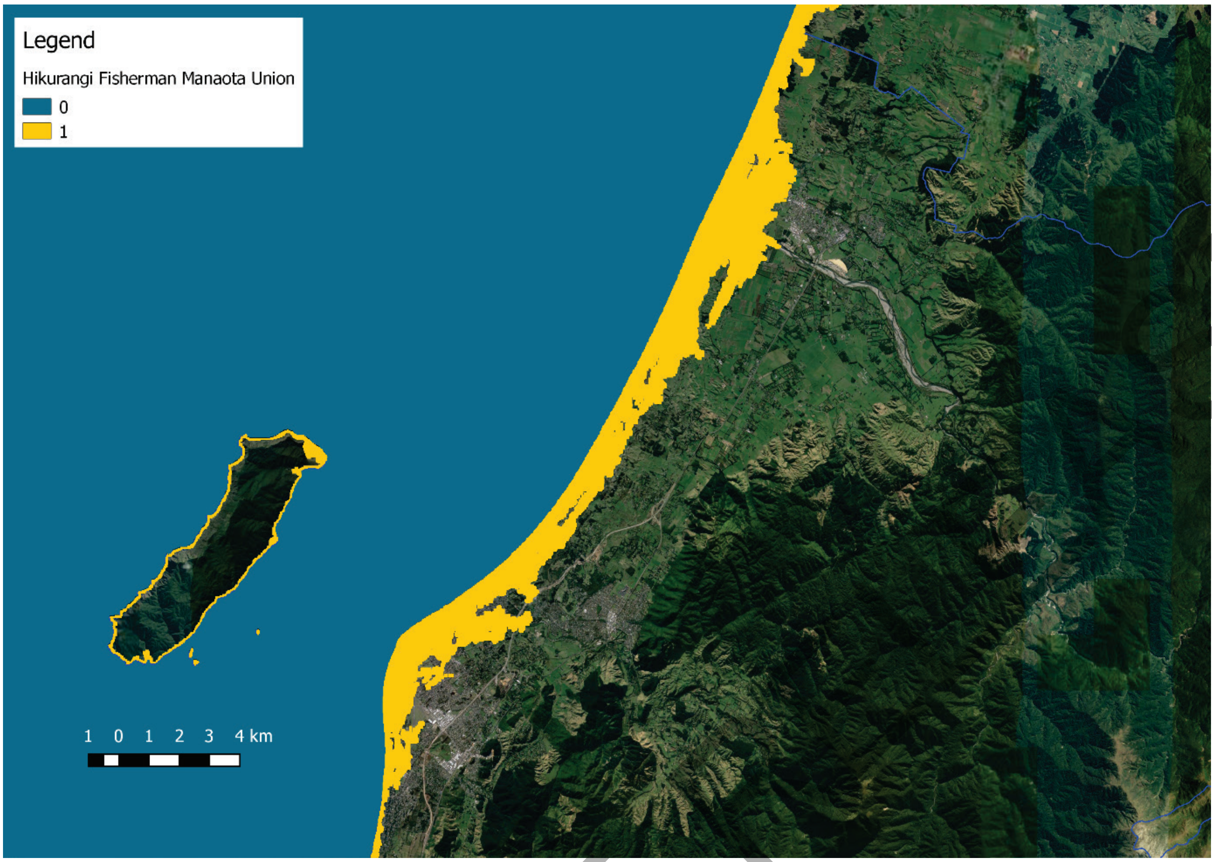


Figure 4.3 Ensemble assessments for the non-uniform slip scenarios (50) showing how often coastal areas are inundated in our study scenarios (inundation occurrence in percent). Moment magnitude assumed to be Mw 9.0, rigidity 50 GPa, expert weighting was applied (see Section 3.1.2 for further details). A Google satellite image (terraMetrics 2017) is used as a back drop for the figure.

This ensemble assessment is summarised using a record of how often each grid cell is flooded for all scenarios in the ensemble. When expressed as a percentage we call this count the ‘inundation occurrence’. Figure 4.3 shows the *inundation occurrence* calculated for the ensemble.

As already mentioned above, most of the crustal sources do not inundate very far compared to the majority of the Hikurangi scenarios, except for the Fisherman and the Manaota fault (Figure 4.1 and Figure 4.2). After consultation with Greater Wellington Regional Council we suggest to construct the yellow zone as the union inundation extents from Hikurangi, Fisherman and Manaota. For Hikurangi we will only consider areas that are inundated in 90% of all tested non-uniform slip scenarios. Figure 4.4 shows this union to illustrate the extent of the proposed yellow zone.



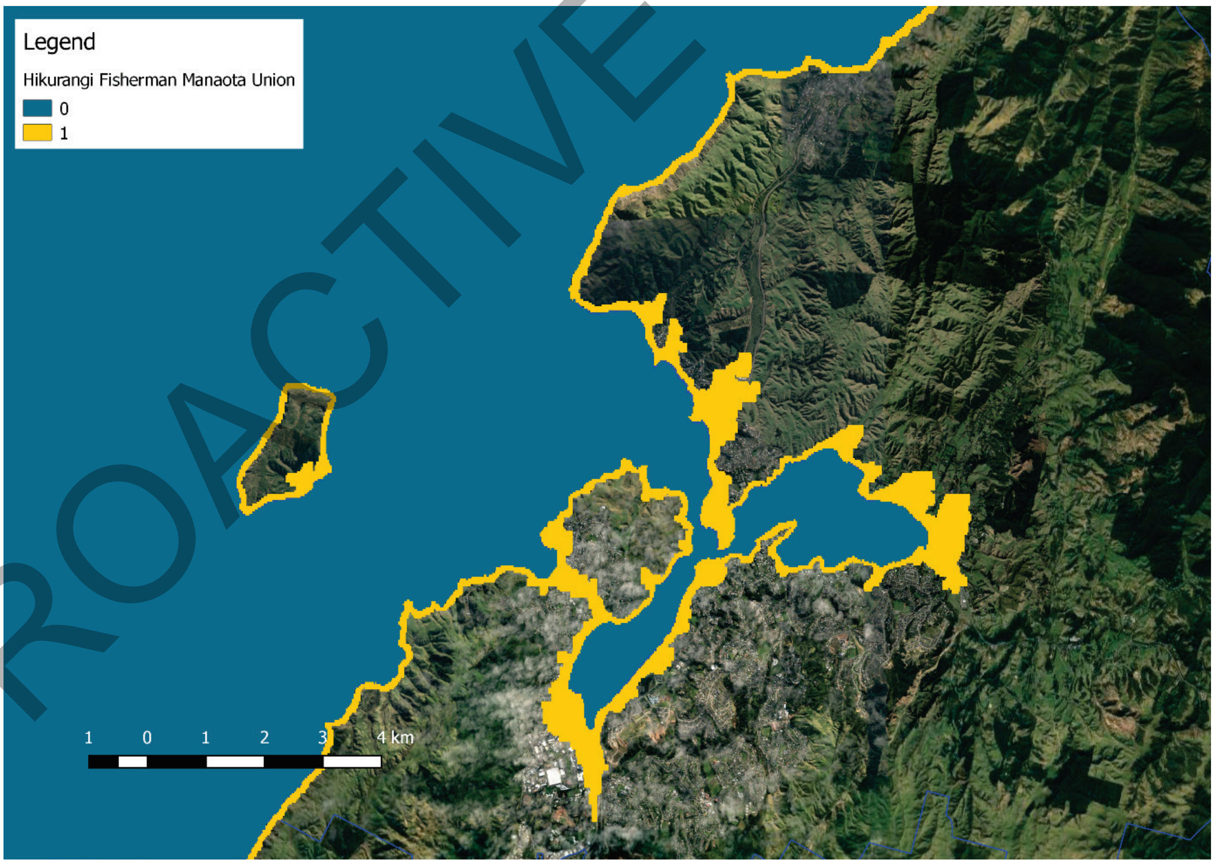


Figure 4.4 Suggested extent of the yellow zone, constructed as the union extent of all non-uniform slip Fisherman scenarios, the Manaota scenario and the area inundated by 90% of the Hikurangi Scenarios.

4.2 ORANGE ZONE SCENARIOS (DISTANT SOURCES, 3M AND 5M THREAT LEVEL)

As discussed in Section 3.2 we assessed the extent of the Orange Zone by simulating a number of scenarios for distant source events assuming to be representative for all potential events of this type. Scenarios were chosen to present either a 3m threat level or a 5m threat level somewhere within the Porirua and Kapiti offshore coastal region.

To summarize the simulations, we present the union of all inundation areas observed in these simulation runs. Figure 4.5 shows the extent of the potentially flooded area for the scenarios presenting a 3m threat level offshore and Figure 4.6 for scenarios presenting a 5m threat level.

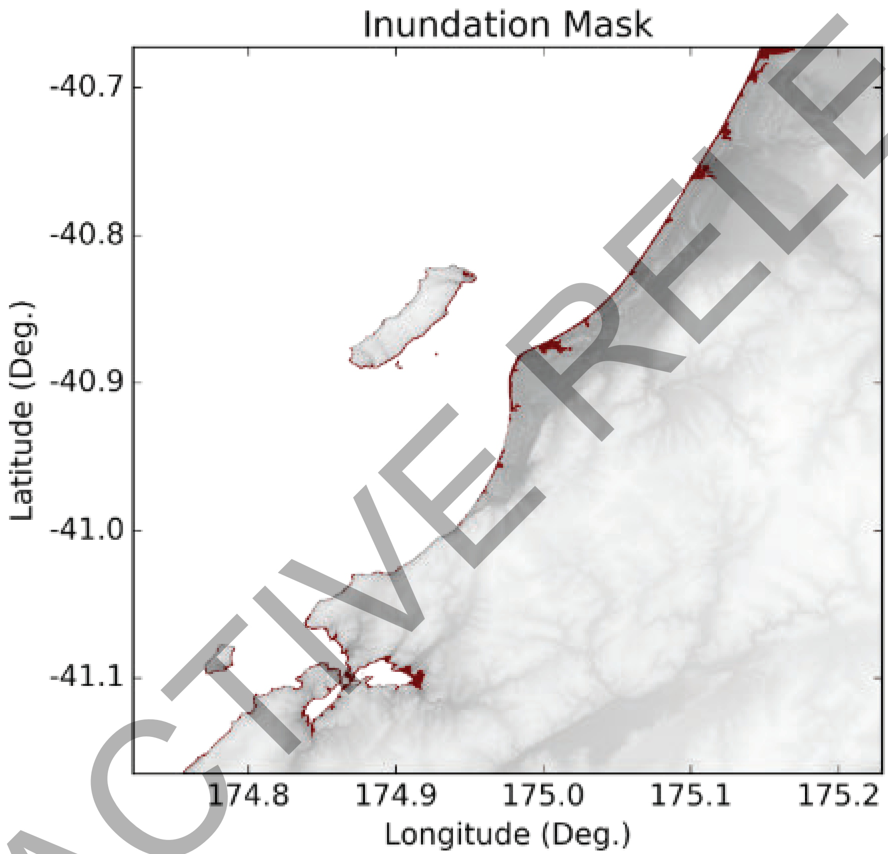


Figure 4.5 Union of all areas inundated by the scenarios assumed to reach the 3m threat level in the Kapiti offshore region (red). The Digital elevation model is used as a back drop for the figure printed in a logarithmic grey scale to emphasis landscape structure on all elevation levels.

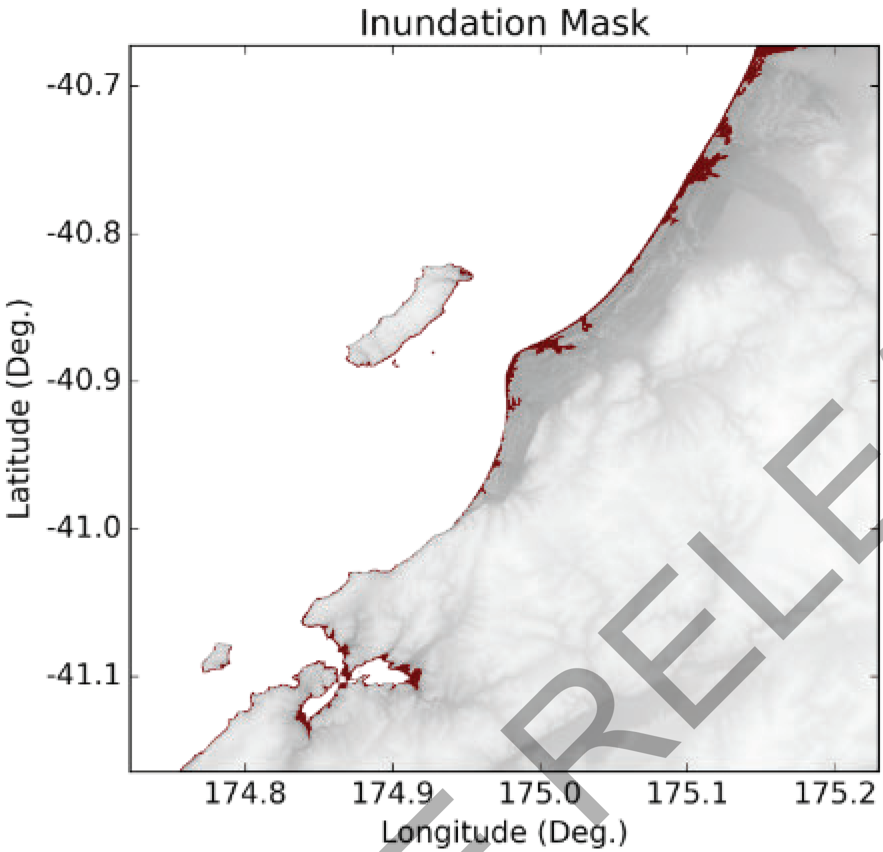


Figure 4.6 Union of all areas inundated by the scenarios assumed to reach the 5m threat level in the Kapiti offshore region (red). The Digital elevation model is used as a back drop for the figure printed in a logarithmic grey scale to emphasis landscape structure on all elevation levels.

4.3 RED ZONE SCENARIOS (DISTANT SOURCES, 1M THREAT LEVEL)

As discussed in Section 3.3 the currently recommended definition for the Red Zone can be impractical to apply in harbours and estuaries with large areas of low lying land. The 2m above high tide elevation contours often extend quite far inland and in some cases cover almost all of the proposed areas for the orange and the yellow zones.

We have run several scenarios that reach the 1m threat level in order to test and refine the areas included in the Red Zone, in particular within harbours and estuaries. Figure 4.7 shows the union of the areas flooded by the scenario tsunamis. It is anticipated that GWRC will compare this data with the existing Red Zone using GIS, and thereby check the validity of the existing zone. Outside of problem areas it is suggested that GWRC maintain compatibility with the national guidance based on at least 2m above high tide (MHWS), but that the information given here may be used to guide and test cautious reduction of the Red zone extent below this criterion inside harbours and estuaries and/or to test the validity of the previously established Red zone boundaries.

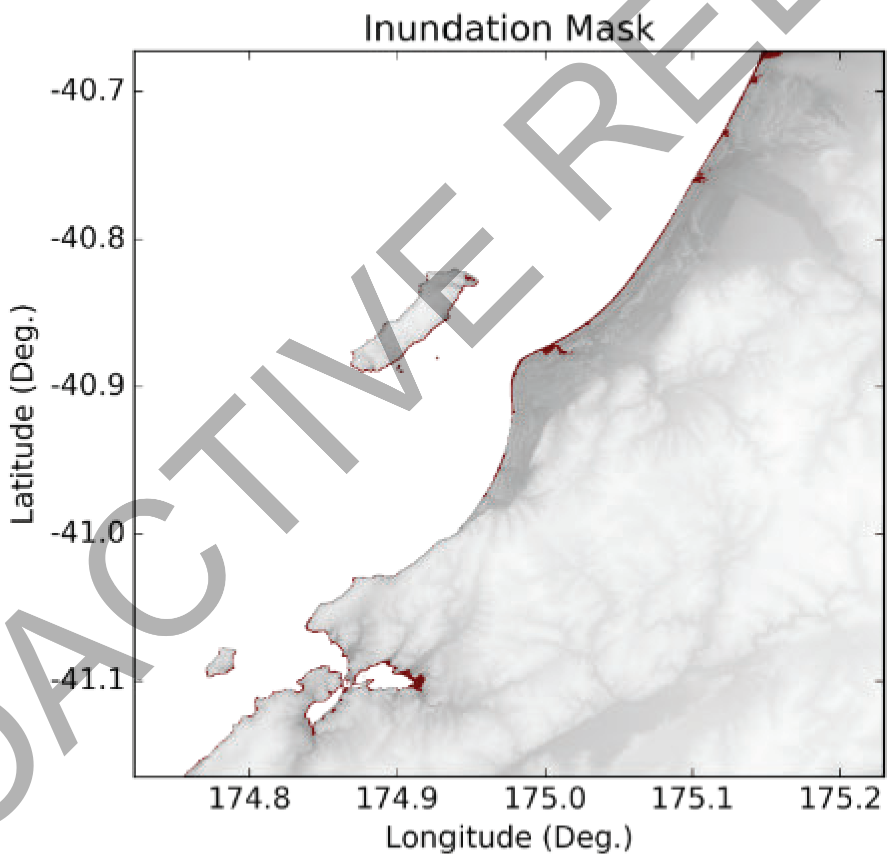


Figure 4.7 Union of all areas inundated by the scenarios assumed to reach the 1m threat level in the Kapiti offshore region (red). The Digital elevation model is used as a back drop for the figure printed in a logarithmic grey scale to emphasis structure on all elevation levels.

5.0 DISCUSSION

The simulations carry several unknowns which will lead to over- or under-estimation of the actual amount of inundation observed for each scenario. These include uncertainties in modelled surface roughness, digital elevation and bathymetric models as well as variability of the modelled geometry of the rupture surface, the sequence in which slip is triggered on that surface and the rake angle of individual slip patches. These effects have not been studied for reasons of practicality. We currently assume that the effect of rupture complexity in the form of non-uniform slip is one of the most important ones (Geist 2002, Mueller et al., 2015) which is supported by our results. Another important factor that is carrying a significant amount of uncertainty is the actual rigidity (stiffness) of the subduction interface and the medium surrounding it. Our study also does not include an investigation into the effects of this uncertainty. However, we considered the effect by modifying the rigidity of some crustal sources for yellow zone considerations. For the simulations based on the Hikurangi plate interface we have assumed a rigidity of μ = 50 GPa, and for the final inundation simulations of the Fisherman and Manaota Faults μ = 35 GPa was assumed. The rigidity value for the Hikurangi plate interface has been used for consistency with the National Tsunami Hazard Model (Power, 2013) and has been used by GNS Science for tsunami hazard and evacuation zoning studies in the recent past. Further investigation of the effect of changes to the assumed rigidity (which in reality varies with both depth and distance from the interface) on inundation extents is recommended for future research.

The data provided in this report is intended to form the basis for the council to develop their evacuation zones: encompassing the areas indicated as being subject to inundation, but also using a conservative approach to simplifying the outlines of the zones e.g. in areas where the modelled inundation has an irregular boundary, or to align the evacuation zone boundary with clearly identifiable features such as roads.

The primary focus of this study has been Porirua and Kapiti Coast. Close to the northern boundary of the innermost grid the quality of bathymetric data is lower (see section 2.2 and Figure 2.5), and here greater conservatism is recommended in developing evacuation zones from the inundation results.

6.0 DATA PRODUCTS

This report is accompanied by digital products corresponding to data presented in Figure 4.1 to Figure 4.7 (see descriptions for the individual data sets in Section 4).

The digital data are in georeferenced raster format (ArcASCII). They are included, together with metadata and projection files, in a ZIP archive as an electronic supplement to this report:

electronicSupplement_GNS_Science_CR_2017-43.zip

The data sets are named as follows:

Data type	Filename (no extension)
Manaota inundation extent (single scenario, 35 GPa, Fig. 4.0)	manaota_indxtnt_35GPa
Fisherman inundation extent (8 scenarios, 35 GPa, Fig. 4.1)	fisherman_ indxtnt_35GPa
Hikurangi inundation occurrence (50 scenarios, 50 GPa, Fig. 4.2)	hikurangi_inocc
Hikurangi, Fisherman, Manaota union inundation extent (Fig. 4.3)	yellow_zone_indxtnt
Total inundation extent, 3m threat level (Fig. 4.4)	orange_zone_3m_ indxtnt
Total inundation extent, 5m threat level (Fig. 4.5)	orange_zone_5m_ indxtnt
Total inundation extent, 1m threat level (Fig. 4.6)	red_zone_1m_ indxtnt

7.0 CONCLUSION

In this study, we have used hydrodynamic modelling to provide a basis for the delineation of tsunami evacuation zones for all suburbs of Porirua and Kapiti Coast.

We chose a set of sources for our study that are in accordance with zoning definitions as described in the MCDEM (2008, 2016) guidelines:

- A Yellow Zone for self-evacuation (along with the orange and red zones) in the event of a strongly-felt or long-duration earthquake, or when a forecast of a distant-source tsunami of above a specific threat level is issued,
- An Orange Zone to be used (along with the red zone) when a forecast tsunami from a distant source is expected to cause some inundation, but not large enough to require evacuating the Yellow Zone, and
- A Red Shore-Exclusion Zone to be used when a tsunami forecast suggests a threat only to beaches and shoreline facilities.

Uncertainties in establishing slip play an important role for the actual tsunami impact of a local subduction zone event, and we considered 50 different distributions of non-uniform slip with a focus in the south of the Hikurangi interface. We also modelled 8 different distributions of slip on the Fisherman Fault, and 1 example of a Manaota Fault earthquake (Yellow Zone scenarios). This final set is the result of a careful selection process based on inundation modelling for a much larger set of sources. We consider this subset of sources to cover the wider range of possible tsunamigenic faults in the region. For the Orange Zone we considered 29 scenarios which would reach the 3m threat level and 20 which would reach the 5m threat level in the Porirua/Kapiti coastal area.

We regard the evacuation zones suggested from modelling results in this study as more precise representation of the areas of potential inundation in real events than those previously modelled.

The ‘Directors Guidelines for Tsunami Evacuation’ call for the Red Zone to be defined – in areas of high quality topographic data – by the area less than 2m above the high tide level, i.e. MHWS. However, this results in on overly large extent of a Red Zone sometimes extending beyond the orange, in some harbour and estuary areas. Hydrodynamic modelling of distant source scenarios which reach the 1m threat level offshore within the Porirua/Kapiti coastal region allows for checking and cautious modification of the existing delineation of the Red Zone (22 scenarios in total considered) in these problem areas.

We find that as an example in the Pauatahanui arm of the Porirua Harbour (e.g. in the Pauatahanui Park) the union of all (red zone) inundation scenarios assessed here covers a smaller area than the 2m above high tide elevation contour. This also holds for estuaries further north along the Kapiti Coast. Therefore, the 2m contour approach is more conservative in such cases. However, it seems more consistent to base the zones on multi scenario hydrodynamic modelling as the separation between the areas covered by the different zones defined in this manner is more systematic, i.e. the red zone is smaller than the orange zone and the orange zone is smaller than the red zone.

It is left to the council to exercises their own conservative assessment for outlining the zones based on the data provided with this report.

8.0 ACKNOWLEDGEMENTS

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APPENDICES

A1.0 APPENDIX 1: AVERAGE RETURN PERIOD OF YELLOW ZONE SCENARIOS

Under the current guidelines for evacuation zoning the Yellow Zone is expected to at least cover the 2,500-year inundation extent at the 84% confidence level. The zone can be further extended to cover areas with a longer return period, but this should take into account the practical implications of the evacuation process, for further details please refer to the guidelines (MCDEM, 2016).

The data used for the design of the Yellow zone presented here is based on modelling of tsunamis from three separate sources: The Hikurangi subduction zone, the Fisherman Fault and the Manaota Fault. It is useful to consider the return periods associated with tsunami inundation from these sources both individually and in combination, both to check that the guidelines are being met, and for comparison to the criteria used for the design of the Yellow zone in Wellington Harbour.

A return period for the Mw 9.0 Hikurangi source, and more specifically the 10% inundation occurrence contour used in the construction of the Yellow zone, can be derived using the method presented in Mueller et al. (2015). In that report an approximate analysis was made that assigned a 3000 year return period (at the 84% level of confidence) to the 50% inundation occurrence contour. Tsunamis that reach the 10% inundation occurrence contour would, by that method, occur 5 times less often. Correspondingly we associate a 15,000 year return period (at the 84% level of confidence) to the set of Hikurangi events used here as part of the Yellow line definition.

Characteristic earthquakes on the Fisherman Fault are assigned a 5,500 year recurrence interval in the National Seismic Hazard Model. In the construction of the Yellow zone we use the union of inundation from 8 different randomly generated samples of Fisherman Fault earthquakes, so to this union we approximately associate an 8 x 5,500 = 44,000 year return period. Although a level of confidence has not been systematically assigned, all scenarios were modelled at the maximum magnitude assigned to this fault in the national seismic hazard model, so the analysis is conservative with respect to this key area of uncertainty.

Characteristic earthquakes on the Manaota Fault are assigned a 21,000 year recurrence interval in the National Seismic Hazard Model. Although a level of confidence has not been systematically assigned, the scenarios modelled was at the maximum magnitude assigned to this fault in the national seismic hazard model, so the analysis is conservative with respect to this key area of uncertainty.

The return periods for each of these three components are individually well beyond the 2,500 year guideline. However the extent of inundation from each of these is generally quite similar, so we approximately estimate a collective return period for inundation from the three events combined of:

$$\frac{1}{\left(\frac{1}{15{,}000}+\frac{1}{44{,}000}+\frac{1}{21{,}000}\right)} \approx 7{,}300\ yr$$

We stress the approximate nature of this result, as (a) confidence intervals have not been quantitatively assigned to the Fisherman or Manaota Fault, although the modelling of these is conservative with regard to magnitude, and (b) there are some areas where the inundation extent does vary considerably between the three fault sources and since we have taken the union of the inundations the return period in those areas could be much greater than 7,300 years.

The purpose of this analysis is to confirm that the guidelines for the Yellow zone have been comfortably met, and to demonstrate a degree of consistency with the Wellington Harbour Yellow zone definition which was estimated at a 6,000 year return period (at 84% confidence).

These results should not be used for land-use planning, risk assessment or insurance purposes; for which other more suitable methods of probabilistic assessment are available.

Geological Perspective

Paleoseismic and paleotsunami investigations have recently confirmed the occurrence of Hikurangi subduction interface earthquakes (and associated tsunami) at times earlier than recorded in written history (Clark et al. 2015; Figure A1.1). The geological record remains incomplete and the task of correlating observations at different sites, in order to establish the dimensions of earthquakes, is on-going. At this time the occurrence of large subduction zone earthquakes that extend across the Southern and Central regions of the Hikurangi interface is regarded as increasingly plausible; but it is not currently possible to reconstruct a magnitude-frequency distribution directly from the geological record.

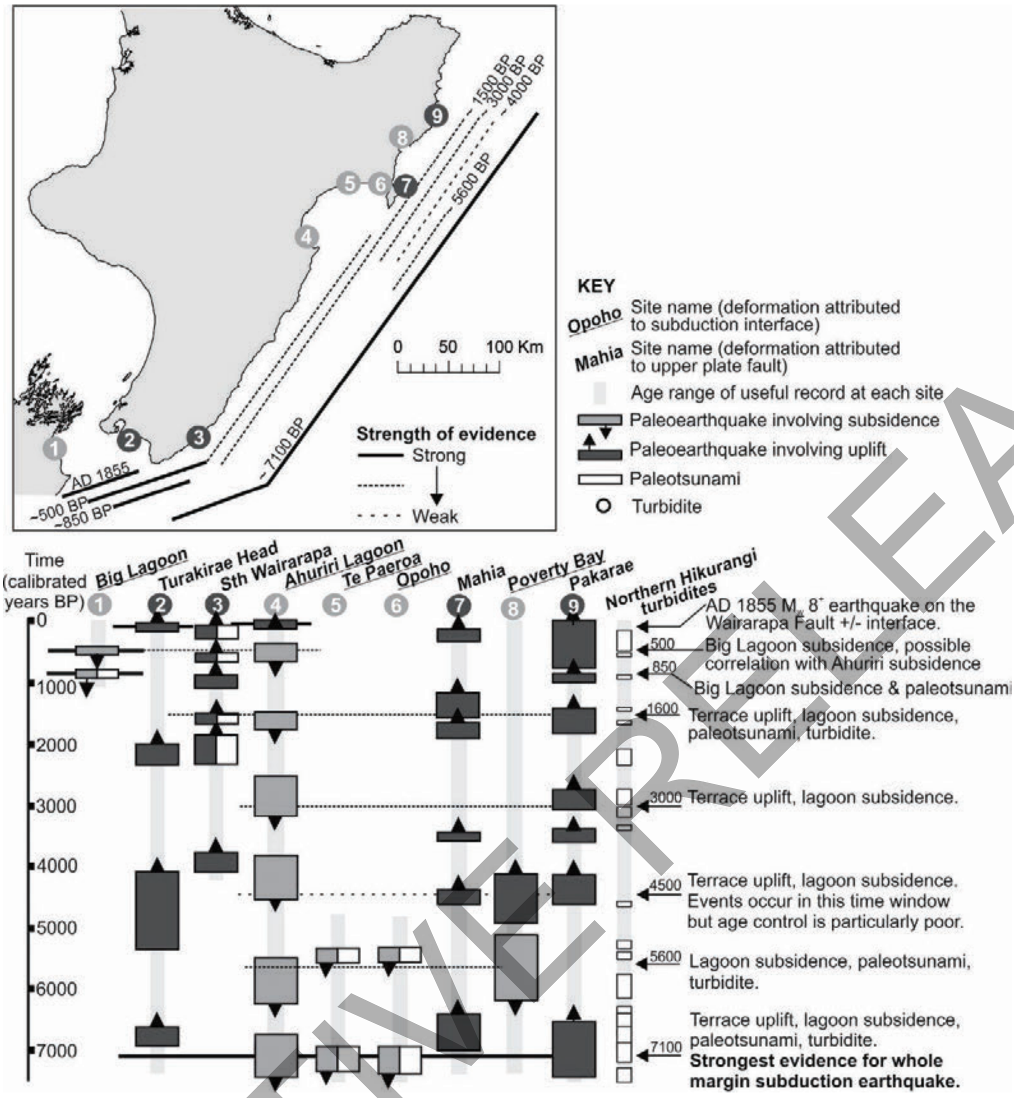

Figure A1.1 Summarised evidence for Paleotsunami and Paleoearthquakes on the Hikurangi margin. From Clark et al. (2015) and references therein.

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