Hydrodynamic Inundation Modelling and Delineation of Tsunami Evacuation Zones for Wellington Harbour

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EXECUTIVE SUMMARY

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

Tsunami evacuation zones for Wellington Harbour 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.

The COMCOT tsunami model (Wang & Power, 2011) is the core simulation engine of our assessment. The modelling area includes all suburbs of Wellington and Lower Hutt that lie within Wellington Harbour. In addition, the modelling encompasses Island Bay, Lyall Bay, and the southern part of the Miramar Peninsula. The modelling for this area encompasses Owhiro Bay and extends continuously to Point Dorset.

In keeping with national conventions the new zones consist of:

- A Yellow Zone for self-evacuation 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 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.

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 zones. One important anticipated outcome of the study was a reduction in extent of the suggested Yellow and Orange Zones within the CBD, and potentially the Orange Zone in Petone. When compared with the existing tsunami evacuation zones (not shown) we find that the extent of the new suggested areas for Orange and Yellow zones is indeed smaller in almost all areas under consideration including the CBD and Petone.

The current draft of 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 (MHWS) level. However this results in on overly large Red Zone, sometimes extending beyond the orange, in particular in Petone. Hydrodynamic modelling of distant source scenarios which reach the 1m threat level offshore within the Wellington coastal region show inundation extents much more in line with the existing delineation of the Red Zone.

1.0 INTRODUCTION

This report is submitted by the Institute of Geological and Nuclear Sciences Limited (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 Wellington Harbour for the purpose of updating the tsunami evacuation zones in this area. These zones are intended to be marked around Wellington Harbour as part of WREMO and Wellington City Council's Blue Line Project; a public education campaign that shows the anticipated land coverage of the largest credible tsunami events.

The Blue Line Project was initiated in Island Bay in 2010 in order 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.

Tsunami evacuation zones for Wellington Harbour 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, particularly in the densely occupied Wellington Central Business District (CBD), or in flat, low-lying areas such as Petone.

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 the Wellington CBD 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 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. The modelling area includes all suburbs of Wellington and Lower Hutt that lie within Wellington Harbour. In addition the modelling encompasses Island Bay, Lyall Bay, and the southern part of the Miramar Peninsula. The modelling for this area also encompasses Owhiro Bay and extends continuously to Point Dorset.

In keeping with national conventions, as described in MCDEM (2008, 2015), and the existing zones, the new zones consist of:

- A Yellow Zone for self-evacuation 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 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.

The evacuation zones derived from this work will be a more precise representation of the areas of potential inundation in real events than that currently modelled, and it is expected that the extent of the Yellow and Orange Zones within the CBD, and potentially the Orange Zone in Petone, will decrease significantly. 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 greatly 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:

- Digital elevation data (DEM) for both bare earth and canopy height, derived from LiDAR data acquired in 2013/2014 for the Wellington Region and made available by Landcare Research.
- Wellington Harbour Bathymetry data (1m digital grid), provided by the National Institute of Water and Atmospheric Research (NIWA) (Pallentin et al., 2009).

Several different criteria will be considered when determining the Yellow and Orange Zones.

In general terms, the Yellow Zone has been delineated by running a comprehensive set of tsunami simulations that have the Hikurangi subduction interface as a source. An earthquake on the Hikurangi interface with a magnitude of ~9 is considered to be the credible worst case tsunami source affecting central New Zealand. We conclude this for the following reasons:

In the ‘Its Our Fault’ project (Mueller et al., 2014) it was demonstrated that tsunamis caused by earthquakes on the Wairarapa Fault, even allowing for variations in slip, caused consistently less inundation in Wellington than a ~M 9.0 Hikurangi earthquake. Therefore a tsunami on this fault is not expected to be capable of exceeding the Yellow Zone as derived in this report. The same conclusion may be drawn from modeling of the BooBoo Fault (Cousins et al., 2007), and this is believed to hold true for other upper plate faults in the region. The methods used for modeling of the tsunami caused by upper plate faults in the above mentioned reports is more accurate than that used in Power (2013). The assumption that tsunamis from distant sources will not plausibly exceed the Yellow Zone derived here can be justified by consideration of the modeling used to derive the 5m Orange Zone in Sections 4.2 and 5.2. The area derived for the 5m Orange Zone is substantially less than the area of the 50th percentile inundation for the Yellow Zone (see Section 5.1). Yet the scenarios used are very much at (or in some cases exceeding) the maximum plausible slips and magnitudes for these sources. For instance the scenario with the lowest slip was the Peru Central scenario with an **average** slip of 49.4 meters, and a magnitude (after rescaling) of Mw 9.7.

Realistic but randomised distributions of fault movement (slip) across the interface were generated for each of 50 scenarios. A crustal rigidity of 50 GPa was assumed. Each of these simulations was run through to inundation. Maps that document the number of scenarios in which each grid cell of our digital elevation model is flooded were generated and used to identify the evacuation zone.

In order to determine the location of the orange evacuation zone, tsunami simulation scenarios were identified that create a given threat level (based on tsunami wave height at the shore: 3m and 5m considered) from a previously performed threat level and forecasting study for all of New Zealand. Scenarios that generate waves at the upper limit of a threat level were developed for full inundation simulation. An allowance (factor-of-safety) was made to accommodate the situation where only a finite set of scenarios could be modelled that in practise need to cover all of the variations in location and slip that would generate tsunamis of the same shoreline height.

The Red Zone is intended to encompass all tsunamis that generate a ‘marine and beach’ threat level (amplitudes between 0.2 and 1m at the shore).

The final criteria for the development of Yellow and Orange Zones were determined through discussions between GNS Science and WREMO. A meeting between GNS Science Staff and WREMO at GNS’ Avalon office was held to discuss these criteria and the project progress.

Orange and Yellow Zones were modelled using the LiDAR-derived DEM data for the study area.

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 its 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 larger 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., 1994b, 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., 1994a), 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 this tsunami simulation package, 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 3.1). 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 3.2). 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 4.2 arc-seconds (~95m in Wellington Region, Figure 3.3).

The fourth level grids, grid layer 04, cover the Wellington Harbour and its surrounding suburbs at a spatial resolution of about 20 meters (Figure 3.4). This high resolution DEM data was derived from a combination of LiDAR (Light Detection and Ranging) topographic data provided by Wellington Regional Council and multi-beam bathymetric survey data from NIWA (Pallentin et al., 2009) covering the interior of the harbour. Outside of the harbour the bathymetric data is derived from LINZ nautical chart data (see Figure 3.5, for data sources). The purpose of this grid is for high-resolution inundation modelling. Note that while a small area of Makara Beach is included in this grid, the choice of scenarios was not developed with this location in mind, and the modelling results for that area should be disregarded.

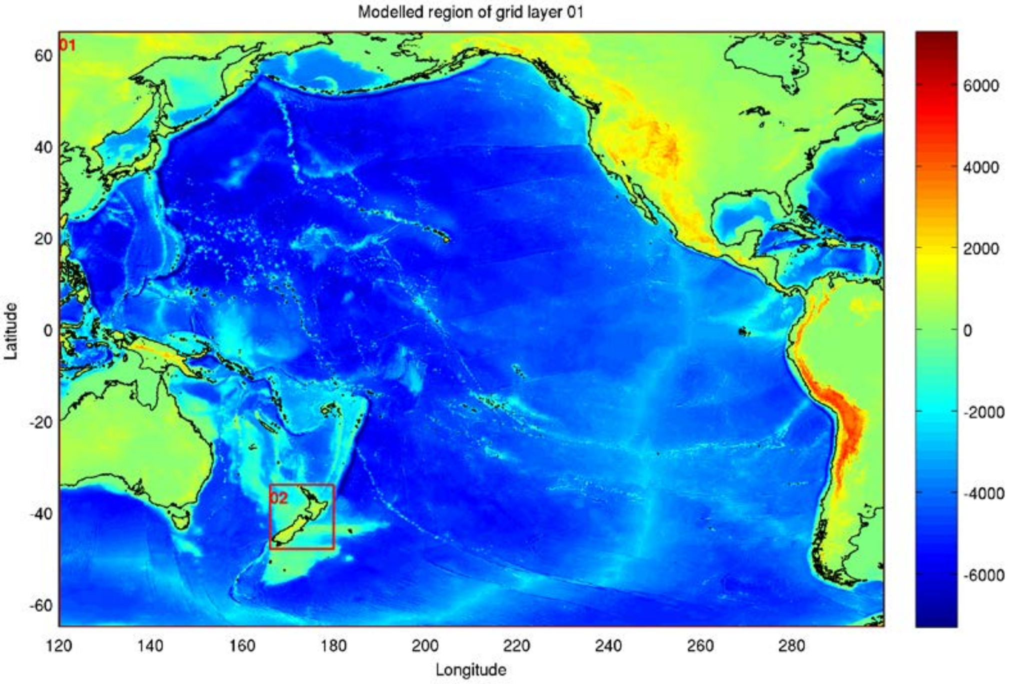

Figure 3.1 Nested grid setup for tsunami generation and propagation modelling. The outer grid layer 01 spans the whole Pacific for tsunamis from distant sources. See Figures 3.2, 3.3 and 3.4 for closer detail of grid layers 02, 03, 04. Elevation above sea level is color-coded in meters.

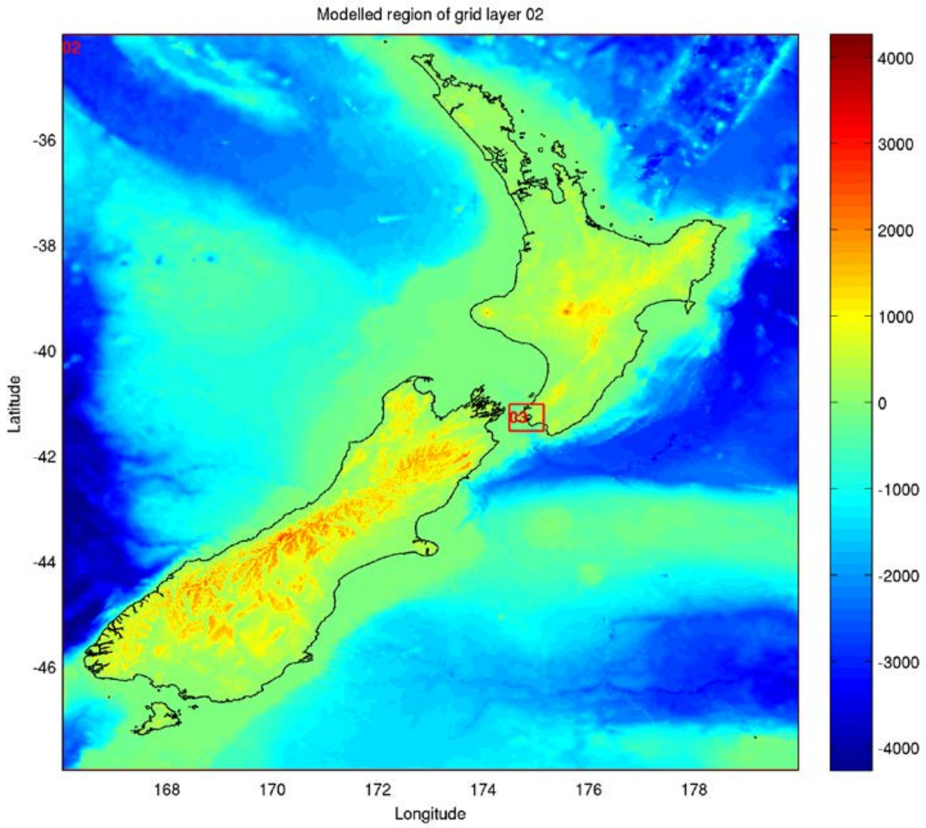

Figure 3.2 Nested grid setup for tsunami generation and propagation modelling. This figure shows the nested grid layers 02 (full extent of the map) and 03 which focus on New Zealand and offshore region at increasing levels of detail. Elevation above sea level is color-coded in meters.

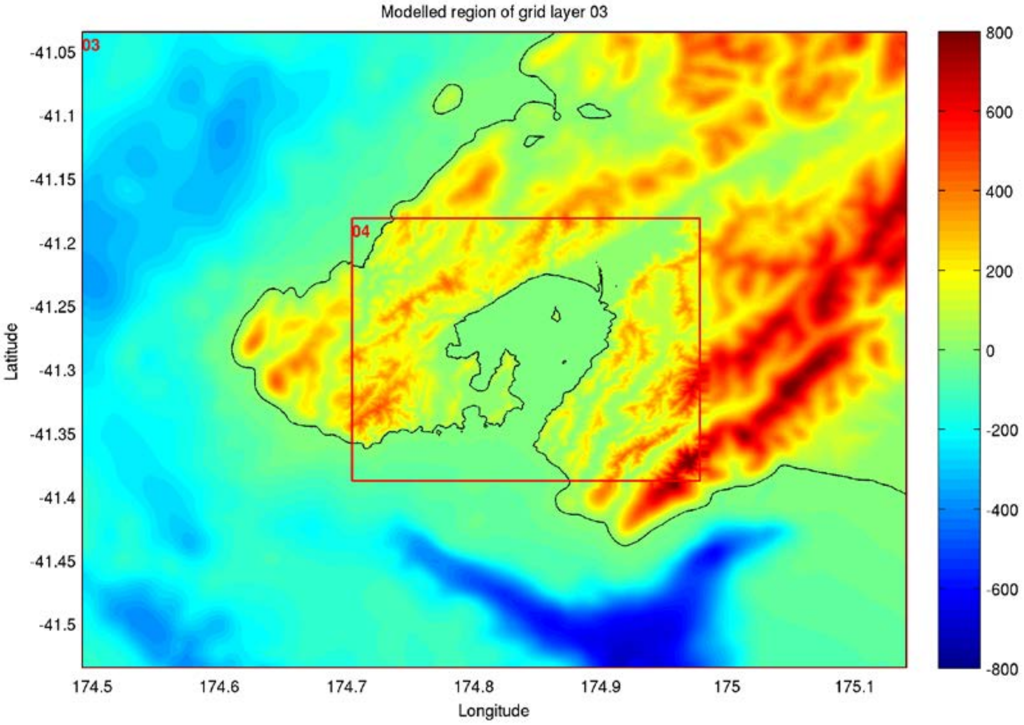

Figure 3.3 Nested grid setup for tsunami propagation modelling. This figure shows nested grid layers 03 (full extent of the map) and 04 which focus on the Wellington region at increasing levels of detail. Elevation above sea level is color-coded in meters. Wellington Harbour Bathymetry (1m digital grid) provided by NIWA (Pallentin et al., 2009)

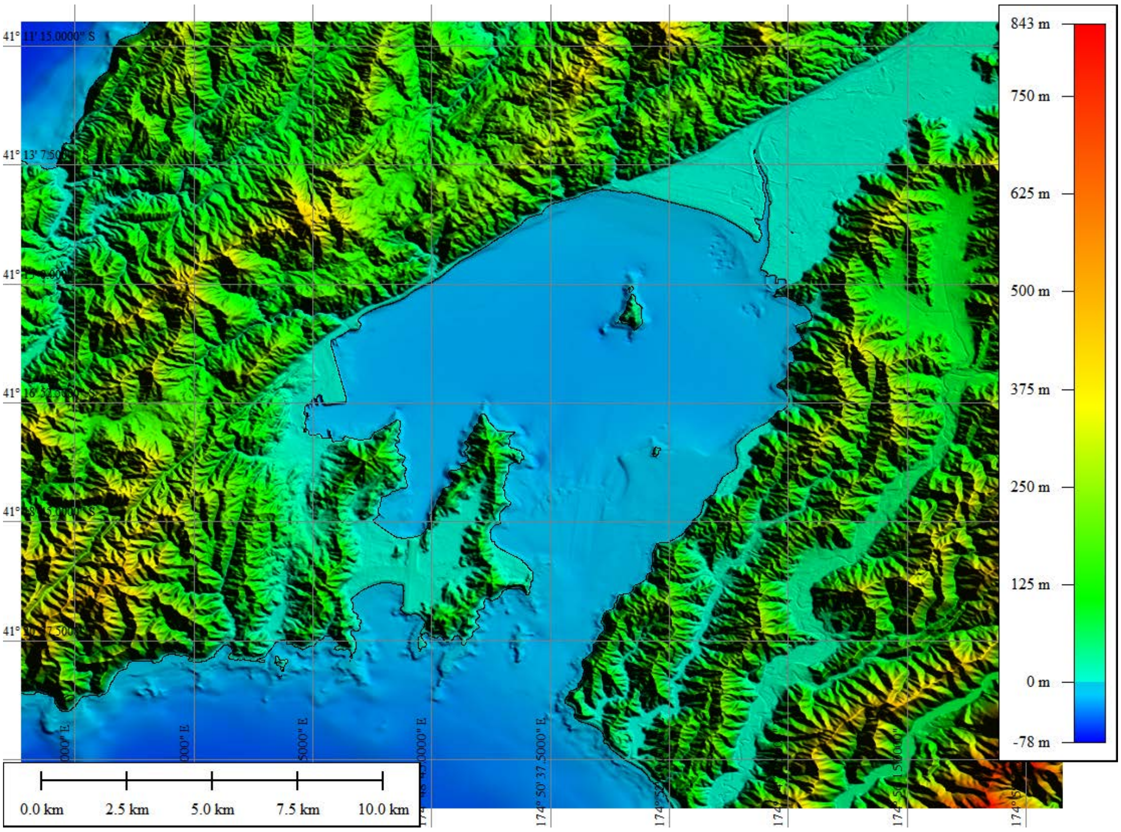

Figure 3.4 Digital elevation model used for tsunami propagation and inundation modelling in Wellington Harbour. This figure shows nested grid layer 04 which has the highest level of detail. Elevation above sea level is color-coded in meters. Wellington Harbour Bathymetry (1m digital grid) provided by NIWA (Pallentin et al., 2009)

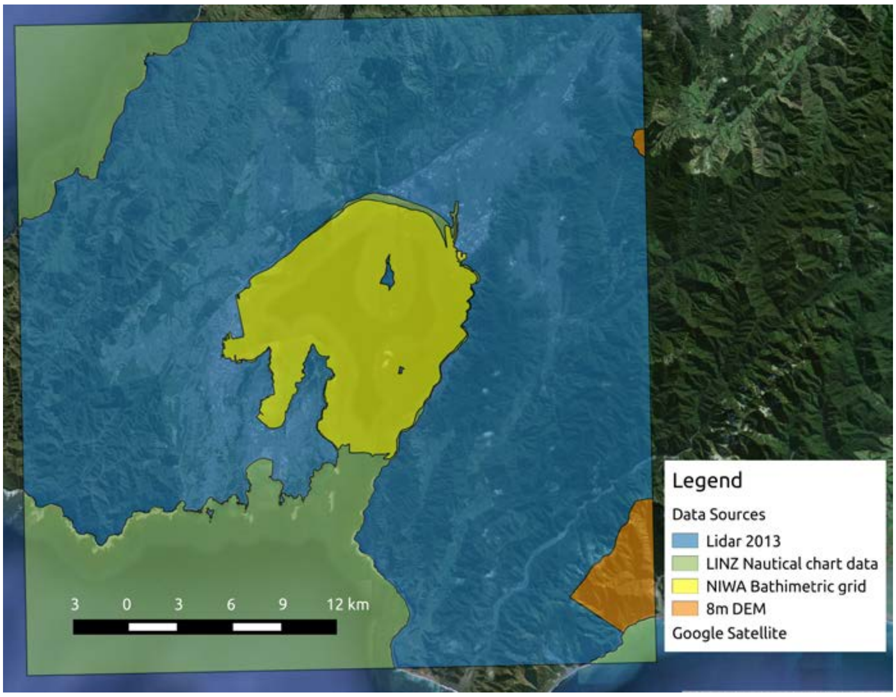

Figure 3.5 Data sources for the DEM: Polygons outline the areas for different data sources that were used to construct the DEM (see legend). The DEM was slightly edited to make offshore values negative and onshore values positive in areas where there were contradictions with respect to the 50K LINZ coastline. Background image: Google Earth, TerraMetrics, 2015.

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. We then briefly summarize the evacuation zone definitions/recommendations as described in MCDEM (2008, 2015).

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. 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 with generated a set of source scenarios that represent 50 different potential non-uniform slip distributions on the subduction interface.

Under the current draft guidelines 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.

The main source of tsunami hazard at long return periods (> 3000 year) and high confidence levels (e.g., 84%) is assumed to stem from earthquakes of ~Mw 9.0 on the Hikurangi subduction interface based on comparison with inundation models for other sources (see further explanation in Section 2.1; and note the acknowledged limitations of the modelling of upper plate faults in Power 2013).

Please refer to Appendix 1 for a discussion on how to relate the set of inundation scenarios considering the effects of non-uniform slip to the return period at 84% confidence level. It is concluded there that the 50th percentile of inundation extent can be assumed to be covering the area of the 3000 year inundation event with 84% confidence and the 75th percentile to be covering the area of the 6000 year inundation event.

3.1.1 Subduction zone interface 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 4.1 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.

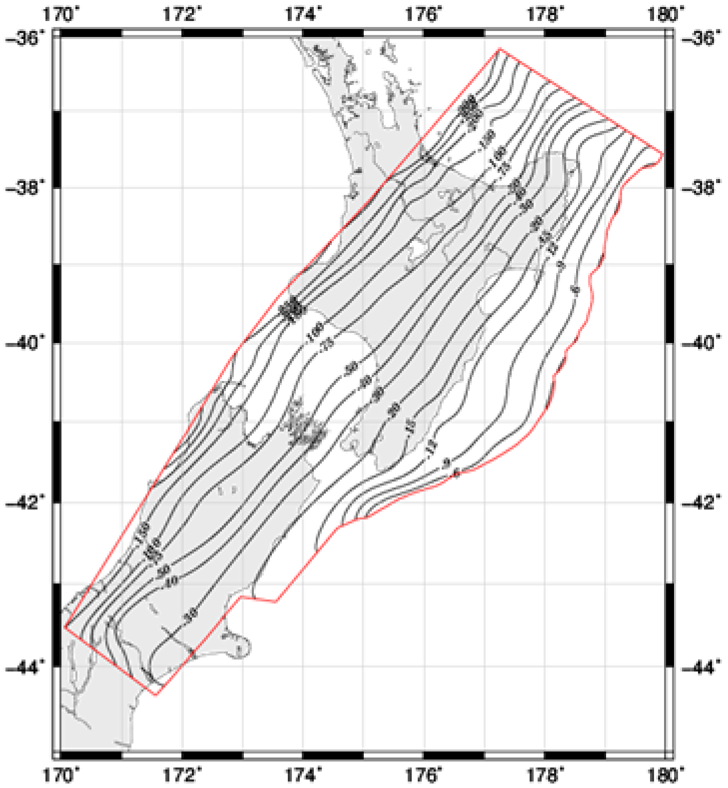

Figure 4.1 Revised Hikurangi subduction zone interface model after Williams et al., 2013. The model is represented as a depth contour plot in this figure. Each contour is labelled with its depth value (km). The red outline describes the validity region of the model. The model was used to generate subduction zone sources for this study.

3.1.2 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 (see Figure 4.2 for an example). 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. The undulating nature of the interface model requires us adapt the size of the source patches to follow the surface shape. This causes the visual appearance of the non-uniform slip model to appear more warped than then the interface model. This is however only an optical illusion.

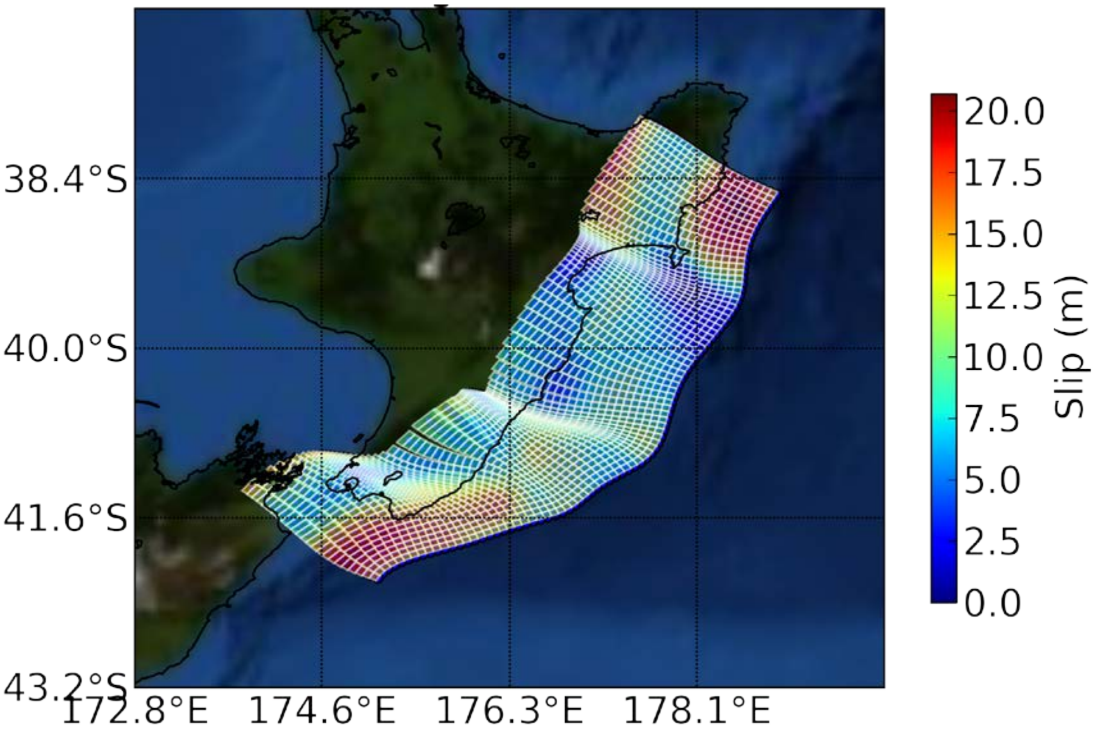

Figure 4.2 Example of a subduction zone source model with a non-uniform distribution. The undulating nature of the interface model requires us adapt the size of the source patches to follow the surface shape. This causes the visual appearance of the non-uniform slip model to appear more warped than then the interface model. This is however only an optical illusion.

3.1.3 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 4.3). 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 4.3).

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.

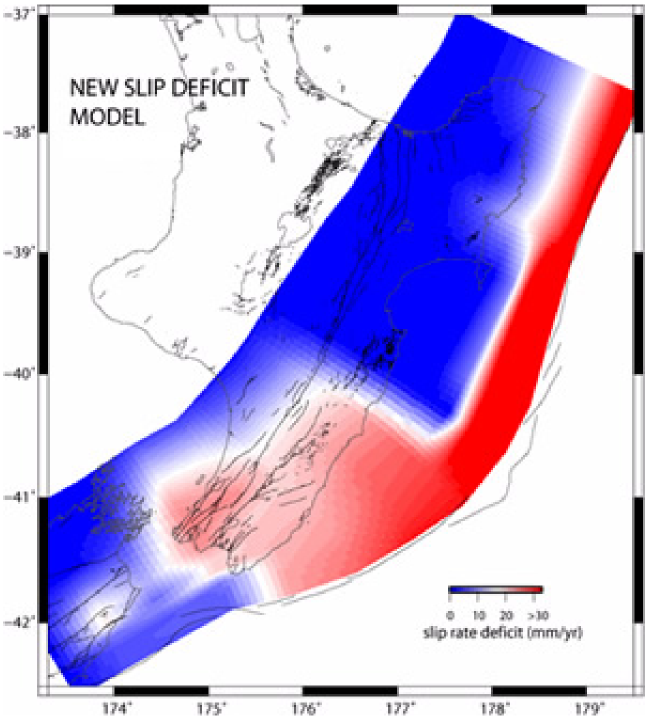

Figure 4.3 Subduction interface slip rate deficit for the Hikurangi subduction interface (from Wallace et al., 2012)

We have calculated scenarios of stochastic non-uniform slip with and without this weighting scheme in order to study the impact of this expert weighting on inundation extent and inundation likeliness. Figure 4.4 shows the same distribution of slip as shown in Figure 4.2 but with an emphasis towards the south of the interface by multiplying the slip distribution with the weighting function.

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.

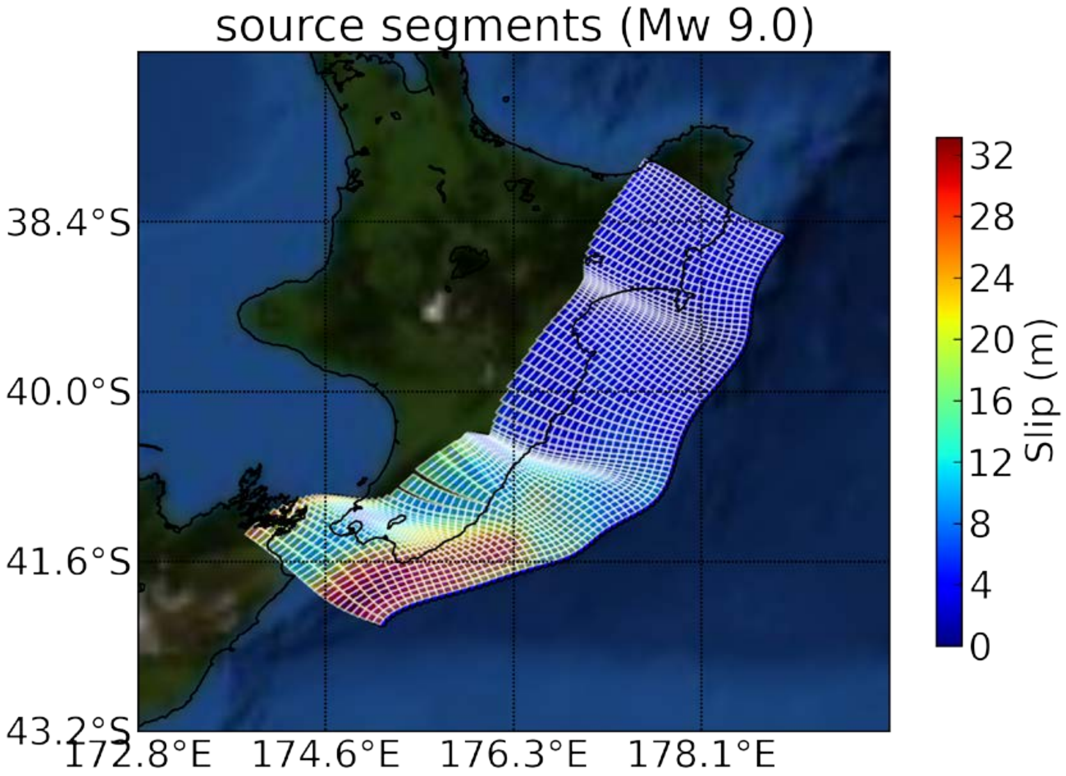

Figure 4.4 Example of a subduction zone source model with a non-uniform distribution with expert weighting scheme applied. Slip is focused mainly in the south of the interface. The undulating nature of the interface model requires us adapt the size of the source patches to follow the surface shape. This causes the visual appearance of the non-uniform slip model to appear more warped than then the interface model. This is however only an optical illusion.

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 4.5, and individual steps are explained in greater detail below.

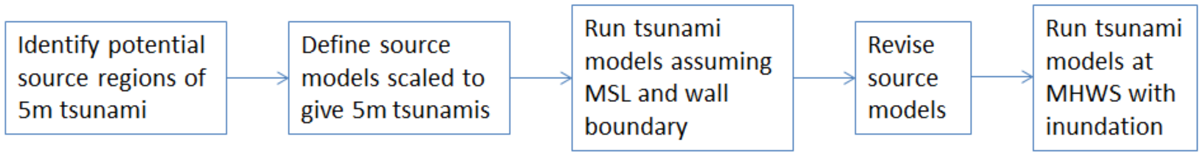

Figure 4.5 Outline of scheme for Orange Zone calculation. The scheme shown here is for developing a zone capable of encompassing a 5m tsunami. MSL = Mean Sea Level, MHWS = Mean High Water Springs (‘high tide’).

‘Identify potential source regions’ and ‘Define source models’

These steps were performed using data that has been collected for the purpose of 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. Exponential interpolation was used to estimate maximum tsunami heights within the Wellington forecast zone where the hypothetical earthquake the magnitudes fell between those of the events in the threat-level database; and extrapolation, based on Abe (1979) was used to estimate maximum tsunami heights at larger magnitudes than Mw 9.3.

Maximum plausible magnitudes were based on Table A3.1 in Power (2013). For Regional sources some scenarios exceeded the maximum plausible magnitude, but were used anyway to provide a broad coverage of tsunami sources that approach Wellington from different directions.

‘Run tsunami models at MSL and wall boundary’

Initially scenario models based on the sources in Table 4.1 were modelled as is 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 were below 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 4.6. The first step here is to estimate the maximum tsunami height in the models developed in the previous step. This was assessed by visual examination of maximum tsunami-height plots; the maximum height was taken to be that exceeded over at least ~1% (500m-1km) of the Wellington coastline.

Where the maximum tsunami height was less than the targeted height 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 (e.g., the maximum tsunami heights are frequently to be found in the Lyall Bay and Evans Bay areas), 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 4.6). 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.

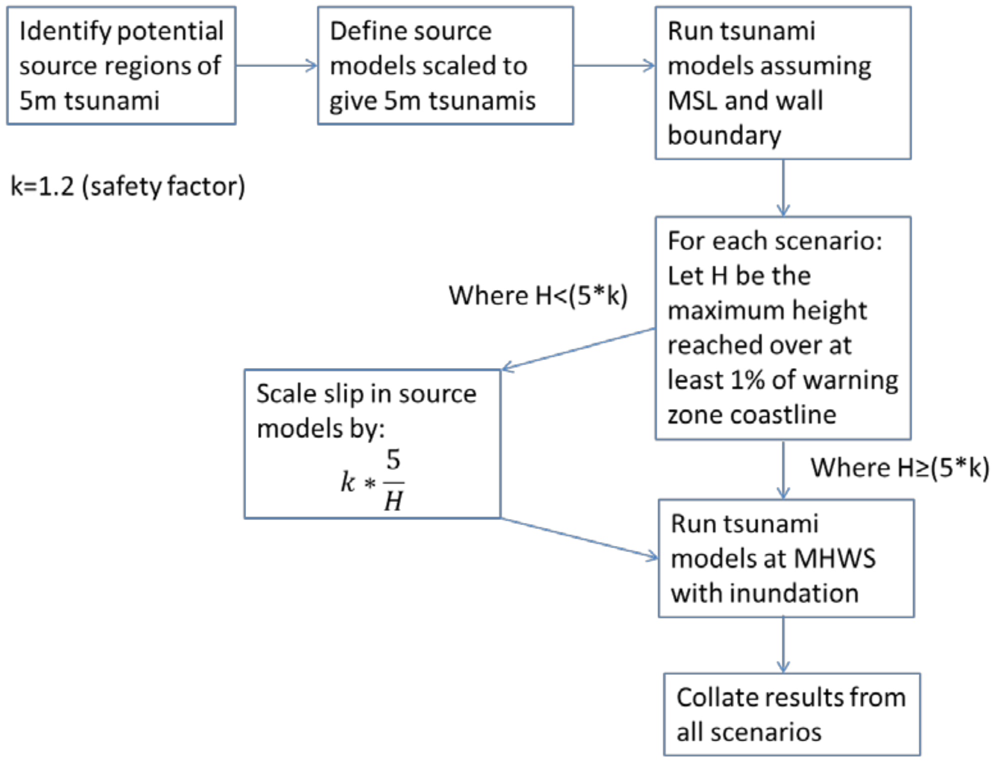

Figure 4.6 Expanded schematic, illustrating the process indicated by 'Revise source models'.

'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 Wellington harbour. These models were run assuming a high tide at Mean High Water Springs (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 4.1.

Table 4.1 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 and high resolution**	
ID_code	**Location Description**	**Intended height (m)**	**Slip (m)**	**Magnitude**[1]	**Max height (m)**	**Scaling factor**	**Modified slip (m)**
PE_14_3m	Peru North	3	23	9.4	1.6	2.25	51.8
PE_16_3m	Peru Central	3	19	9.2	2	1.80	34.2
PE_18_3m	Peru South	3	15	9.2	1.5	2.40	36.0
PW_14_3m	Kurile Islands	3	23	9.4	2.1	1.71	39.4
PW_16_3m	Kamchatka	3	23	9.4	1.8	2.00	46.0
PW_21_3m	Aleutians	3	28	9.5	3	1.20	33.6
NH_04_3m	Solomon Islands	3	23	9.4	1.8	2.00	46.0
NH_07_3m	Vanuatu	3	23	9.4	1.9	1.89	43.6
KT_03_3m	Kermadec Trench	3	23	9.4	2.6	1.38	31.8
PT_02_3m	Puysegur Trench	3	19	9.1	2.4	1.50	28.5
PE_14_5m	Peru North	5	34	9.6	2.8	2.14	72.9
PE_16_5m	Peru Central	5	28	9.5	3.4	1.76	49.4
PE_18_5m	Peru South	5	24	9.4	2.3	2.61	62.6
PW_14_5m	Kurile Islands	5	34	9.6	2.5	2.40	81.6
PW_16_5m	Kamchatka	5	34	9.6	3	2.00	68.0
PW_21_5m	Aleutians	5	39	9.7	3.3	1.82	70.9
NH_04_5m	Solomon Islands	5	33	9.6	2.1	2.86	94.3
NH_07_5m	Vanuatu	5	33	9.6	2.8	2.14	70.7
KT_03_5m	Kermadec Trench	5	33	9.6	4[2]	1.50	49.5

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[1] 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.

[2] For this particular scenario it was observed that significantly greater tsunami heights were occurring outside of Modelling layer 4, yet still within the Wellington tsunami forecast zone. The height estimate of 4m takes this into account.

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 current draft of the ‘Directors Guidelines for Tsunami Evacuation’ (MCDEM 2008, 2015) 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 (MHWS) level. However this is acknowledged to be problematic inside harbours and estuaries, in which areas exceptions are permissible. An estimation of the areas within Wellington harbour that lie less than 2m above high tide was found to clearly illustrate these problems, as this area substantially exceeds the proposed Orange Zone area (Section 4.2).

Instead it was proposed to test the existing Red Zone 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 existing 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 4.2.

Table 4.2 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 and high resolution**	
ID_code	**Location Description**	**Intended height (m)**	**Slip (m)**	**Magnitude**	**Actual max height (m)**	**Scaling factor**	**Modified slip**
PE_16_1m	Peru Central	1	7	8.8	1.15	1.04	7.3
PW_16_1m	Kamchatka	1	11	9	0.95	1.26	13.9
PW_21_1m	Aleutians	1	11	9	0.9	1.33	14.7
NH_04_1m	Solomon Islands	1	10	8.9	0.8	1.50	15.0
PT_02_1m	Puysegur Trench	1	5	8.5	0.85	1.41	7.1
PE_14_1m	Peru North	1	9	8.8	0.8	1.50	13.5
PE_18_1m	Peru South	1	6	8.6	0.75	1.60	9.6
PW_14_1m	Kurile Islands	1	9	8.9	0.65	1.85	16.6
NH_07_1m	Vanuatu	1	7	8.7	0.6	2.00	14.0
KT_03_1m	Kermadec Trench	1	7	8.7	0.85	1.41	9.9

4.0 SIMULATION RESULTS

In the following section we summarize the main findings from this study. We present simulation results from individual scenarios and ensembles. As a scenario we define a specific tsunami simulation with one set of parameters characterising the tsunami source. As 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.

4.1 YELLOW ZONE ENSEMBLES (HIKURANGI SUBDUCTION INTERFACE)

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.

As described in Section 4.1 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 in Section 4.1.3. 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 Wellington.

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 5.1 shows the *inundation occurrence* calculated for the ensemble.

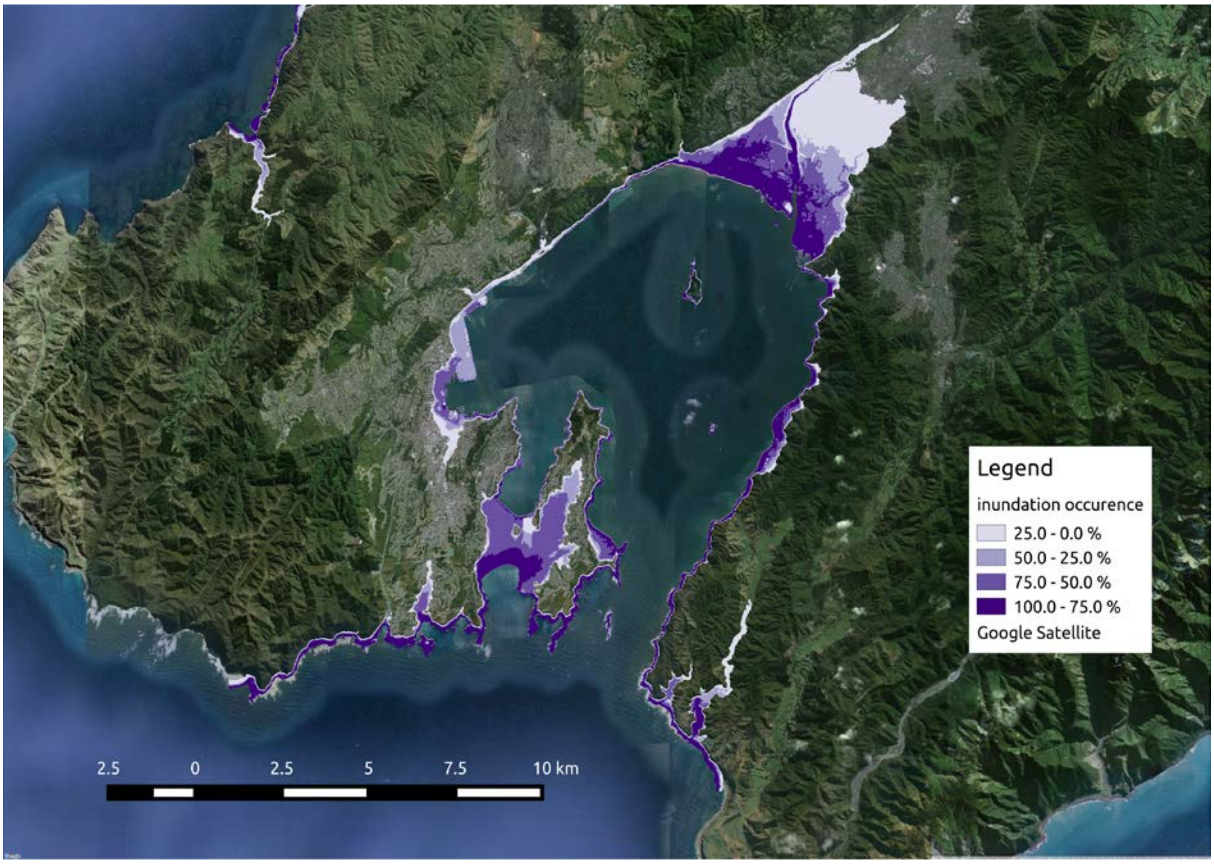

Figure 5.1 Ensemble assessments for the non-uniform slip scenarios showing how often coastal areas will be inundated in our study (inundation occurrence in percent). Moment magnitude assumed to be Mw 9.0, rigidity 50 GPa, expert weighting was applied (see Section 4.1 for further details). A Google satellite image (terraMetrics, 2015) is used as a back drop for the figure. Scenarios that inundate to the 50th percentile are estimated to have a 3000 return period at the 84% confidence level and scenarios that inundate to the 25th percentile are estimated to have a 6000 year return period at the 84% confidence level (see Appendix A for further details).

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

As discussed in Section 4.2.1 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 Wellington offshore coastal region.

To summarize the simulations we present the union of all inundation areas (‘*total inundation extent*’) observed in these simulation runs. Figure 5.2 shows the extent of the potentially flooded area for the scenarios presenting a 3m threat level offshore and Figure 5.3 for scenarios presenting a 5m threat level. At the mid-project workshop an Orange Zone based on the 5m threat level emerged as the preferred choice, however the results from the 3m modelling are also presented here.

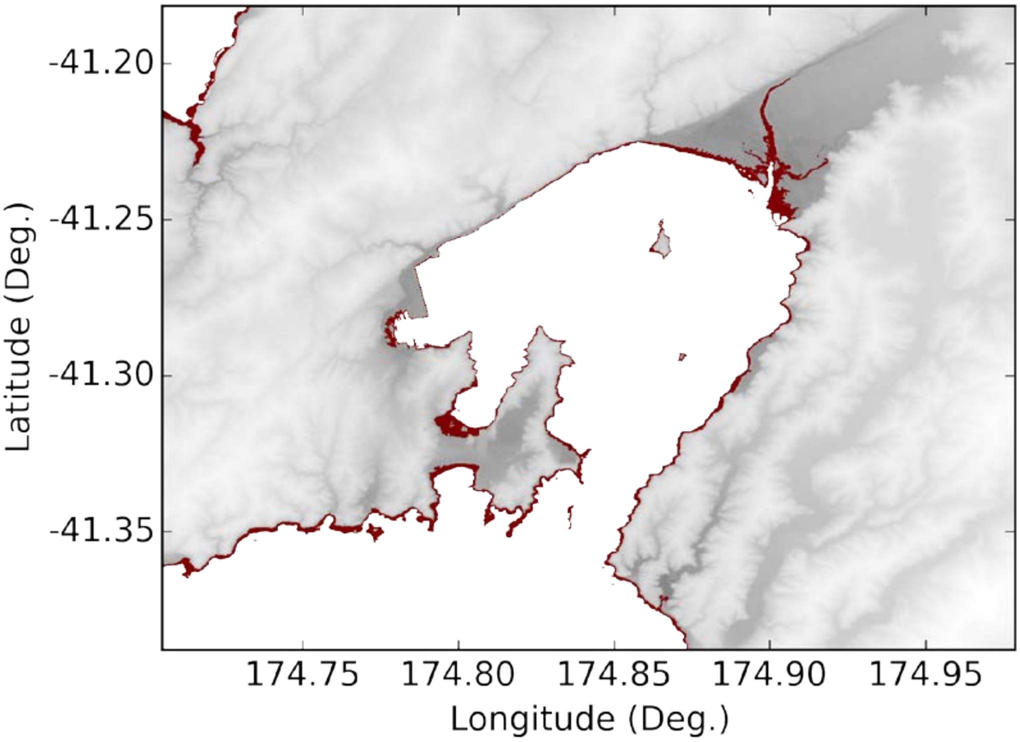

Figure 5.2 Union of all areas inundated by the scenarios assumed to reach the 3m threat level in the Wellington offshore region (red). The Digital elevation model is used as a back drop for the figure printed in a logarithmic grey scale to emphasis structure on all elevation levels.

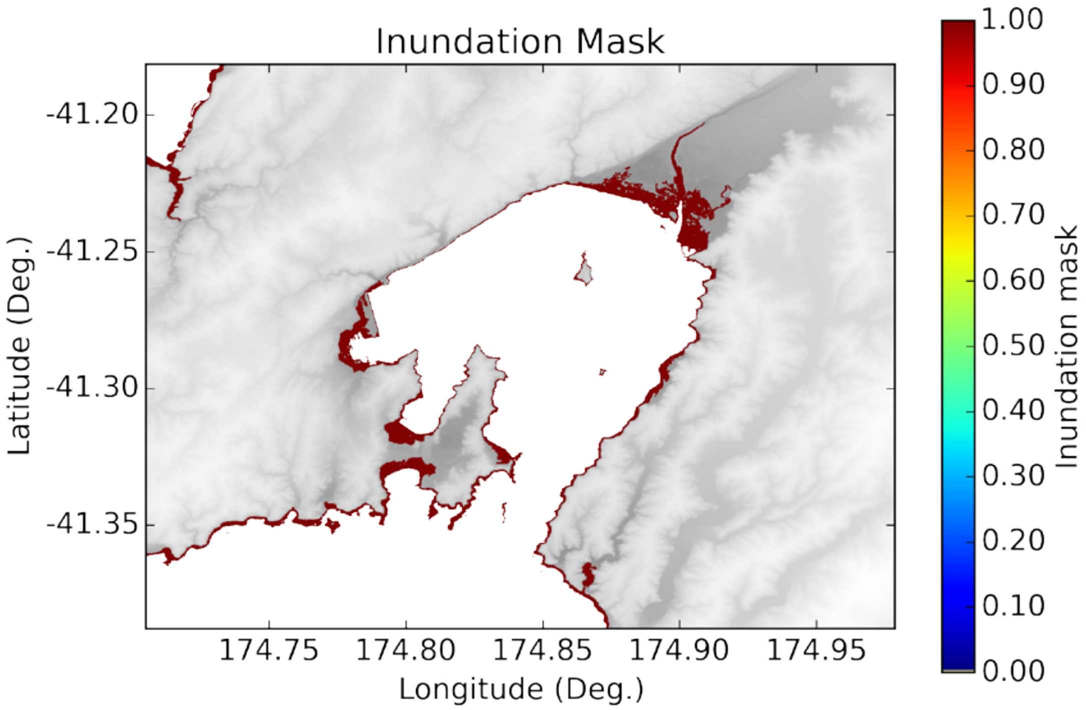

Figure 5.3 Union of all areas inundated by the scenarios assumed to reach the 5m threat level in the Wellington offshore region (red). The Digital elevation model is used as a back drop for the figure printed in a logarithmic grey scale to emphasis structure on all elevation levels.

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

As discussed in Section 4.3 the currently recommended definition for the Red Zone seems to be impractical to apply in harbours and estuaries with large areas of low lying land. The 2m elevation contours often extend quite far inland and in some cases encloses a larger area than the Orange Zone.

We have run several scenarios that reach the 1m threat level in order to test that the areas identified in the pre-existing Wellington Red Zone are sufficient to remain as the red zone. Figure 5.4 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.

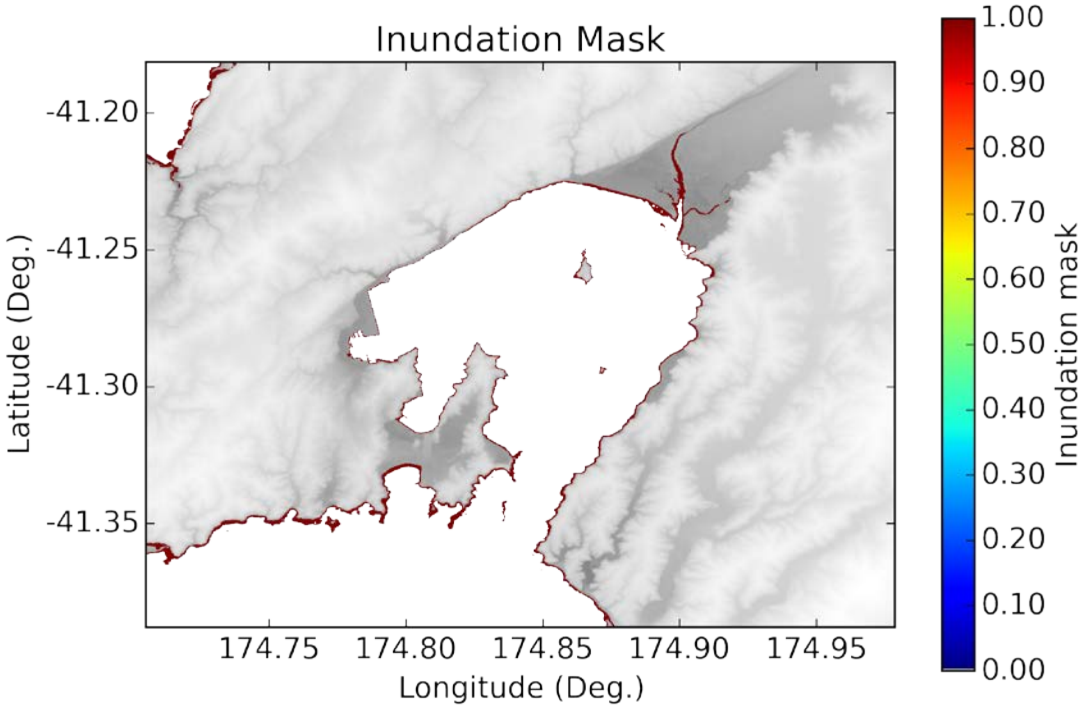

Figure 5.4 Union of all areas inundated by the scenarios assumed to reach the 1m threat level in the Wellington offshore region (red). The Digital elevation model is used as a back drop for the figure printed in a logarithmic grey scale to emphasis structure on all elevation levels.

5.0 DISCUSSION

The simulations carry a number of 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) 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 any investigation the effects of this uncertainty. For all simulations presented in this report we have assumed a rigidity of μ = 50 GPa (Abe, 1975); this choice provides consistency with the earthquake magnitude-frequency model in Power (2013) used to estimate return periods for the Yellow Zone inundations.

The primary focus of this study has been the interior of Wellington harbour. Outside of the harbour the quality of bathymetric data is lower, and here greater conservatism is recommended in developing evacuation zones from the inundation results. Results shown for the coast around Makara Beach should be dis-regarded, as the scenarios used are not appropriate for this site, and the inclusion of this area in the modelling grid is coincidental.

6.0 DATA PRODUCTS

This report is accompanied by digital products corresponding to data presented in Figure 5.1 to Figure 5.4 (see descriptions for the individual data sets in Section 5).

The digital data are in geo referenced raster format (GeoTIFF and ArcASCII). They are presented in a ZIP archive as an electronic supplement to this report:

electronicSupplement_GNS_Science_CR_2015-176.zip

The data sets are named as follows:

Data type (related zone and figure number for reference)	Filename (no extension)
Inundation occurrence (Yellow Zone, Fig. 5.1)	yellow_zone_inocc
Total inundation extent, 3m threat level (Orange Zone, Fig. 5.2)	orange_zone_3m_totinext
Total inundation extent, 5m threat level (Orange Zone, Fig. 5.3)	orange_zone_5m_totinext
Total inundation extent, 1m threat level (Red Zone, Fig. 5.4)	red_zone_1m_totinext

7.0 CONCLUSION

In this study we have used hydrodynamic modelling to delineate the extension of the evacuation zones for all suburbs of Wellington and Lower Hutt that lie within Wellington Harbour. We also included Island Bay, Lyall Bay, and the southern part of the Miramar Peninsula in our assessment. The modelling for this area encompasses Owhiro Bay and extends continuously to Point Dorset.

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

- A Yellow Zone for self-evacuation 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 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 impact of a local subduction zone event, we considered 50 different distributions of non-uniform slip with a focus in the south of the Hikurangi interface (Yellow Zone scenarios). For the Orange Zone we considered 10 scenarios which would reach the 3m threat level and 9 which would reach the 5m threat level in the wellington 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. One important anticipated outcome of the study was the reduction of areal extent of the Yellow and Orange Zones within the CBD, and potentially the Orange Zone in Petone. When compared with the existing tsunami evacuation zones (not shown) we find that the extent of the new suggested areas for Orange and Yellow Zones are smaller in almost all areas under consideration including the CBD and Petone.

The current draft of 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 (MHWS) level. However this results in on overly large extent of a Red Zone sometimes extending beyond the orange, in particular in Petone. Hydrodynamic modelling of distant source scenarios which reach the 1m threat level offshore within the Wellington coastal region show inundation extents very much in line with the existing delineation of the Red Zone (10 scenarios in total considered).

8.0 ACKNOWLEDGEMENTS

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We also thank David Burbidge and Nick Horspool from GNS Science for reviewing this report.

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APPENDICES

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

In this study we have modelled a random sample of possible Mw 9.0 Hikurangi earthquakes, and estimated their inundation extents. In order to use this information to draw evacuation maps it is helpful to make a connection between these scenarios and the return period of inundation.

Under the current draft guidelines 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.

In order to link the scenarios modelled here to the return period of their occurrence, a connection was made to the modelling used for the New Zealand Probabilistic Tsunami Hazard Model (NZPTHM; Power, 2013).

In the NZPTHM geophysical parameters that determine the magnitude-frequency distribution of earthquakes on the Hikurangi interface are randomly sampled using estimates of the uncertainty in those parameters. For each set of samples a synthetic catalogue of earthquake events was generated. The sampling of parameters and creation of the catalogue was repeated 300 times.

Within the NZPTHM the effect of non-uniform slip is approximated by treating the effect of the non-uniformity as if it were locally equivalent to a change in the overall magnitude of the earthquake. Consequently for each earthquake event in the synthetic catalogue an ‘effective magnitude’ was assigned.

For the purposes of the current study the set of synthetic catalogues was examined to identify the frequency with which earthquakes with Meff > 9.0 occurred. This frequency, expressed in terms of return period, varies from catalogue to catalogue. The results of this examination are shown in Figure A1.1.

In Figure A1.1 the confidence level expresses what percentage of the 300 catalogues have a return period that is longer than that shown by the blue line. So for example, half of the catalogues (50%) have a return period for Meff > 9.0 that is greater than 30,000 years.

Based on this analysis we infer that the return period for Meff > 9.0 is at least 3000 years with 84% confidence.

We approximate the 50th inundation percentile in Figure 5.1 (i.e., a ‘typical’ inundation caused by a Mw 9.0 Hikurangi earthquake) with Meff = 9.0, and therefore a return period of 3000 years at 84% confidence. Therefore an evacuation zone based around this percentile in Figure 5.1 meets the requirement to at least cover the area with 2500 year (84% confidence) inundation return period (under the assumption that Hikurangi subduction earthquakes become the dominant component of the tsunami hazard at long return periods, see further explanation in Section 2.1).

Under the draft guidelines it would be appropriate to extend evacuation zones to cover areas of lower probability of inundation (longer return periods) where this can be achieved without adding too much to the problems caused by the evacuation itself.

Within the current study we assume Hikurangi sources with different non-uniform slip to be equally likely. Therefore tsunamis that inundate to the 25th percentile of inundation in Figure 5.1 are half as likely as those that reach to the 50th percentile, so we may assume that these equate to a return period of at least 2 x 3000 = 6000 years at 84% confidence.

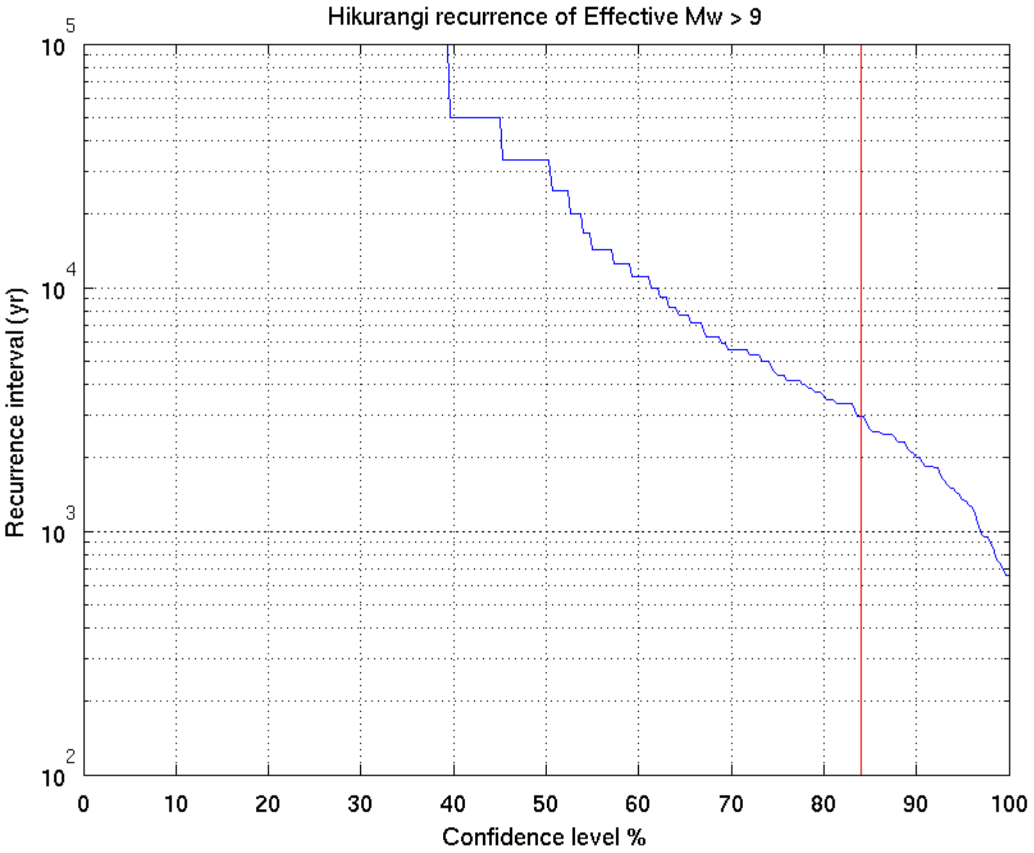

Figure A1.1 Estimate of the minimum Recurrence Interval of Meff>9.0 Hikurangi subduction zone earthquakes at different levels of confidence (see text). The red line indicates the 84% confidence level.

This analysis that equates the results of the current tsunami modelling study to the NZPTHM is only approximate and based on the assumptions explained above. In addition, the results of the NZPTHM are subject to the approximations and limitations described in Power (2013; summarised on p. 169).

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 A1.2). 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.

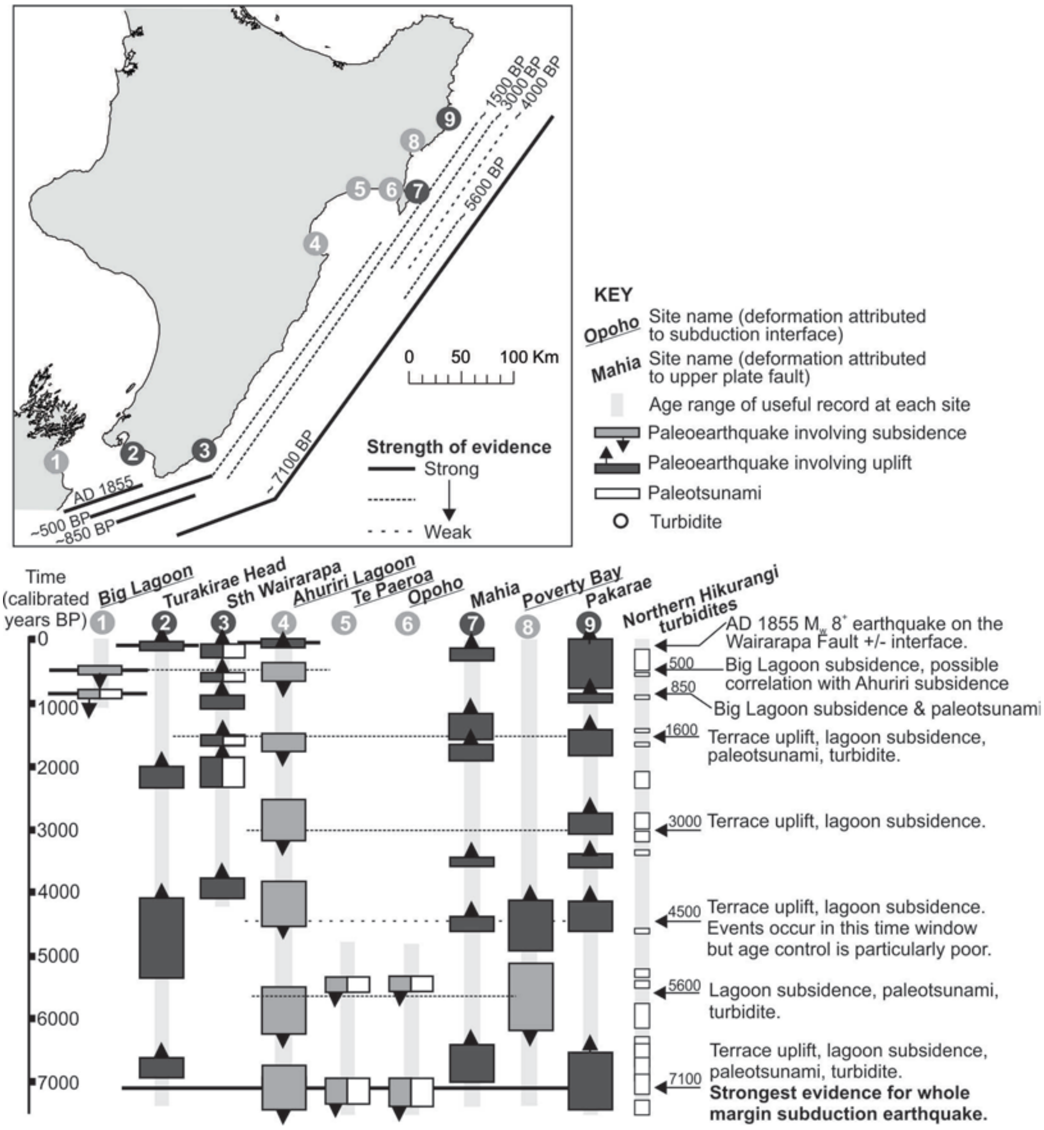

Figure A1.2 Summarised evidence for Paleotsunami and Paleoearthquakes on the Hikurangi margin. From Clark et al. (2015) and references therein.

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