Tsunami Evacuation Zones for West Coast Regional Council

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EXECUTIVE SUMMARY

We have performed hydrodynamic inundation modelling of Hokitika, Greymouth and Westport for the purpose of informing updates to the tsunami evacuation zones in this area. A large set of local, regional and distant potential tsunami sources was investigated. A total of 330 individual scenarios were run using the COMCOT (Cornell Multi-Grid Coupled Tsunami model) tsunami model (Wang and Power 2011) as the core simulation engine of our assessment. We investigated 50 potential 'Worst-case' scenarios, including local, regional and distant sources, to develop the Yellow Zone in each location. We define the 'worst-case' scenario as the largest credible earthquake from a given source region. These are then used to propose the Yellow Evacuation Zone boundaries. We also investigated a set of 60 sources from different regions around the Pacific that reached 3 m or 5 m off the coast of tsunami Forecast Zone 39 (Hokitika and Greymouth) and another set of 60 sources for tsunami Forecast Zone 40 (Westport) for assessing the Orange Evacuation Zone boundaries.

We find that the Cape Foulwind Fault local crustal earthquake source does not significantly contribute to the set of potential 'Worst-case' scenarios for the Yellow Zone in any of the areas investigated. The main tsunami sources contributing to the Yellow Zone are the Kermadec, Puysegur, Solomon Islands and New Hebrides Subduction Zones for all three areas.

For each of the three areas, we provide recommended extents for the Yellow, Orange and Red Tsunami Evacuation Zones based on this modelling.

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 Zone to be used when a tsunami forecast suggests a threat only to beaches and shoreline facilities.

The current draft of the 'Director's Guidelines for Tsunami Evacuation' calls for the Red Zone to be defined – in areas of high-quality topographic data – by the area less than 2 m above the high tide (MHWS) level. We developed an algorithm to define the area that is lower than 2 m, and also connected to the sea, to prevent including spurious low-lying areas further inland. The defined area sometimes extends beyond the area inundated by tsunami at the 3 m threshold. In those cases, we removed the area beyond the 3-m-inundation line.

For the Orange Zone, we find modelled scenarios at both 3 m and 5 m target wave heights in Hokitika, Greymouth and Westport. Our recommendation is to adopt an Orange Zone based on the 5 m target height for consistency with how the Orange Zone has been defined elsewhere along the West Coast (Leonard et al. 2015).

For the Yellow Zone, we base the proposed extent on the worst-case scenarios from all sources included in the study, except for scenarios on the New Hebrides subduction zone, for which we include the median inundation extent from the set of modelled scenarios rather than the maximum in the calculation of the proposed Yellow Zone boundary. We conclude that this is comfortably adequate for covering the extent of the 1-in-2500-year tsunami (84% confidence) as required by the Director's Guidelines. Using the maximum of all New Hebrides scenarios instead of the median is more likely to lead to over-evacuation for tsunami at this probability level.

1.0 INTRODUCTION

1.1 Project Background

This report is submitted by the Institute of Geological & Nuclear Sciences Limited (GNS Science) in response to a request from Jo Paterson, Natural Hazards Analyst and Utilities Coordinator of West Coast Regional Council (WCRC), for hydrodynamic tsunami inundation modelling (Level 3/4) to define evacuation zones that meet national civil defence standards for Hokitika, Greymouth and Westport.

The aim of this project is to provide WCRC with recommendations for three levels of evacuation zones for each of the three areas, based on hydrodynamic tsunami inundation modelling. The three tsunami evacuation zones, i.e. Yellow Zone, Orange Zone and Red Zone, were required to be developed so that they meet Tsunami Evacuation Zones Director’s Guideline [DGL 08/16] (MCDEM 2016). Hydrodynamic modelling will be done to determine the location and extent of the three evacuation zones suggested in the DGL 08/16. All modelling will be done with GNS Science’s hydrodynamic code, COMCOT (Wang and Power 2011).

To do this, we have closely followed our approach to Level 3/4 inundation zoning that has been previously applied in other coastal areas such as Wellington, Porirua, Kāpiti, Selwyn and Christchurch. Following the same path for this project a) provides consistency with existing studies of this kind and b) consistency with the ‘Director’s Guidelines’ (MCDEM 2016). This approach was also taken for an earlier study that investigated inundation scenarios for Christchurch, which was commissioned by Environment Canterbury (ECan) in 2018/2019 (Mueller et al. 2019). We will be referring to this earlier study throughout the text as a reference for further details on methodology.

In areas where high-resolution topographic and bathymetric data is available, it is possible to conduct detailed numerical computational modelling of water movements to calculate inundation flow depth and velocities, if required. The good-quality data available for Hokitika, Greymouth and Westport enable this level of hydrodynamic inundation modelling. With such data, delineation of more accurate evacuation zones becomes possible.

This project also builds on previous work carried out for ECan (Mueller et al. 2016). 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 must be investigated to assess the potential impact of this uncertainty in the earthquake process. GNS Science has investigated and is currently investigating the effects of this complexity with regard to tsunami arrival times, inundation extent and evacuation procedures.

The COMCOT tsunami model (Wang and Power 2011) is the core simulation engine of our assessment. It is routinely used and constantly being improved for tsunami research at GNS Science. It has been used previously for tsunami inundation modelling for several New Zealand cities, including Wellington, Napier, Gisborne, Christchurch and Tauranga, to name a few.

1.2 Project Overview

The development of tsunami evacuation zones in Hokitika, Greymouth and Westport were done in three stages.

1.2.1 Stage 1: Yellow Zone

DGL 08/16 requires that this zone is defined in such a way that it encompasses the area expected to be inundated by the 2500-year tsunami at the 84% confidence level (Power 2013; 2014). We selected a range of local and regional tsunami sources (e.g. Puysegur Trench, Kermadec Trench, Solomon Island and crustal faults local to the New Zealand West Coast) at realistic maximum magnitudes and model these to inundation to assess the sources that need to be considered to define the Yellow Zone. It has been demonstrated in recent years that the non-uniform distribution of slip on local crustal- and subduction-zone earthquake faults is the biggest uncertainty in estimating the extent of tsunami inundation for local events (Mueller et al. 2015a). Therefore, the dominating scenarios out of the set described above were also modelled using a comprehensive number of realisations of non-uniform distribution of slip on the fault. We generated maps that document the number of scenarios in which each grid cell of our digital elevation model is flooded and use these to identify the evacuation zone according to the proportion of scenarios that reach the zone boundary.

1.2.2 Stage 2: Orange Zone

To determine 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 recently updated threat level and forecasting study undertaken for all of New Zealand. Scenarios that generate a threat level above a given threshold were considered for a full inundation simulation as described above. The effects of source complexity are believed to be less acute for tsunami originating far from New Zealand. An allowance (factor-of-safety) was made to accommodate the situation where the effects of source complexity are not fully accounted for when a tsunami-threat-level forecast is issued. Since Westport falls into a different tsunami Forecast Zone (defined in NEMA 2020) than Greymouth and Hokitika, we selected and modelled a different set of sources for Westport.

1.2.3 Stage 3: Red Zone

The Red Zone was defined by all scenarios that generate a marine threat level. This is generally assumed to be the area within 2 m elevation above high tide. The tsunami evacuation Director’s guidelines note that drawing the Red Zone using only the 2-m-above-high-tide elevation contour can be problematic within harbours and estuaries. We made comparisons with the modelling results used for the Orange Zone to facilitate cautious reductions in the extent of the Red Zone in these areas.

Deliverables:

1. A consultancy report outlining the methods used to create the models, the limitations of these methods and a discussion of the results (this document).
2. Spatial datasets (compatible with ArcGIS) for layers indicating the extents of Yellow Zones, Orange Zones and Red Zones.
3. The set of source scenarios used to define the three evacuation zones.

2.0 NUMERICAL METHODS

2.1 Simulation Software: COMCOT

The numerical simulation model COMCOT (Cornell Multi-Grid Coupled Tsunami model) was originally developed at Cornell University, USA, in the 1990s (Liu et al. 1998; Wang 2008), and, since 2009, has been under development at GNS Science, New Zealand (Wang and Power 2011). Multiple source mechanisms have been integrated in this simulation tool, such as subaerial/submarine landslides, earthquakes with transient rupture and/or variable slip distributions.

This model has been widely used by researchers worldwide to study various aspects of tsunami, including tsunami generation mechanism, transoceanic propagation, run-up and coastal inundation. In recent years, it has also been increasingly used to investigate storm surges, wave-structure interactions, effects of rivers / tides / sea-level rise on tsunami hazards, and effects of landslides in reservoirs/lakes and to downstream flooding (Wang and Liu 2006; Wijetunge et al. 2008; Beavan et al. 2010; Mueller et al. 2015b; Mountjoy et al. 2019; Liu et al. 2018).

COMCOT uses a modified staggered finite difference scheme to solve Shallow Water Equations, typically governing tsunami, floods and river flows, with a shock-capturing upwind scheme together with breaking algorithm for hydraulic jumps, e.g. in rivers and tsunami bores during inundation. It uses Manning’s formula for the bed friction. To account for the shallowness of water depth and ensure enough spatial resolution in near-shore regions, a nested grid configuration is implemented. It uses a relatively large grid spacing to efficiently simulate the propagation of tsunami in the deep ocean and uses gradually refined grid spacings in coastal regions where high spatial resolutions are needed. This approach balances computational efficiency and numerical accuracy (Wang 2008; Wang and Power 2011).

2.2 Digital Elevation Model Data

Six sets of Digital Elevation Model (DEM, a combination of topography and bathymetry) grids have been used to meet the different levels of spatial accuracy and coverage required for the simulation of tsunami originating from their sources, travelling through open sea and interacting with the coasts of Greymouth, Hokitika, Westport and their surrounding areas. These DEM datasets are

- Hokitika DEM
- Greymouth DEM
- Westport DEM
- New Zealand DEM
- Southwest Pacific DEM, and
- Global DEM.

GNS Science has created three new high-resolution DEM datasets to model the tsunami inundation at and around Hokitika, Greymouth and Westport.

2.2.1 Hokitika DEM

The Hokitika DEM dataset combines:

- bare earth topography, derived from the LiDAR (Light Detecting And Ranging) data provided by WCRC and used where it was available (data was acquired on 16 April 2019);
- DEM derived from LINZ Topo50 elevation contours and spot heights and improved with the data from 2014 GPS survey carried out by GNS Science in the low-lying coastal areas during the development of the Level 2 tsunami evacuation zones – used in low-lying areas where LiDAR was not present;
- Land Information New Zealand's (LINZ) 8 m DEM, used in areas not covered by LiDAR or the previous dataset; and
- bathymetry from nautical charts downloaded in digital form from the LINZ Data Service (soundings and contours), used in areas below sea level.

In some areas, such as lagoons, inland lakes and rivers / water channels, the elevation data was also manually revised according to local knowledge and satellite images. The combined datasets were interpolated to create a DEM with a grid spacing of about 10 m. Heights are all relative to local Mean Sea Level (MSL).

2.2.2 Greymouth DEM

The Greymouth DEM dataset combines:

- bare earth topography, derived from the LiDAR data provided by WCRC and used where it was available (data was acquired on 16 June 2015);
- LINZ Topo50 elevation data (contours and spot heights), modified at the boundaries to fit the LiDAR DEM;
- data from the 2014 GPS survey carried out by GNS Science, used to improve the elevation model in low-lying coastal areas during development of the Level 2 tsunami evacuation zones; and
- bathymetry from nautical charts. Digital data was downloaded from the LINZ Data Service (soundings and contours), and the Grey River mouth bathymetry was digitised from the detailed nautical chart, as it is not available in digital form.

In some areas, such as lagoons, inland lakes and rivers / water channels, the elevation data was also manually revised according to local knowledge and satellite images. The combined datasets were interpolated to create a DEM with a grid spacing of about 10 m. Heights are all relative to local MSL.

2.2.3 Westport DEM

The Westport DEM dataset combines:

- bare earth topography, derived from the LiDAR data (acquired on 18 June 2008) provided by WCRC (Figure 2.1);
- LINZ 8 m DEM;
- data from the 2014 GPS survey; and
- bathymetry from available nautical charts (contours and soundings). Digital data was downloaded from the LINZ Data Service (soundings and contours).

In some areas, such as lagoons, inland lakes and rivers / water channels, the elevation data was also manually revised according to local knowledge and satellite images.

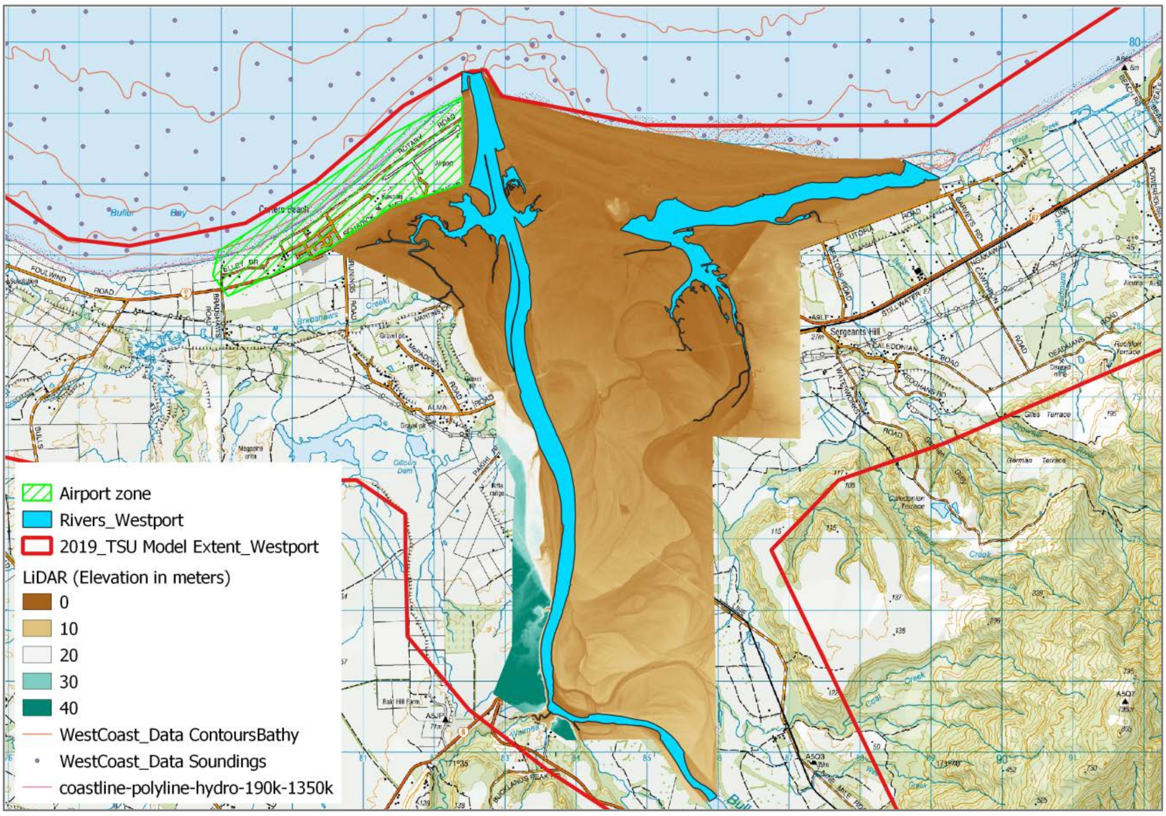

Figure 2.1 LiDAR data coverage for the Westport area. The green hashed area locates the airport zone and Carters Beach village, not covered by LiDAR. The thick red line symbolises the extent of the tsunami modelling zone requested by WCRC. Available bathymetric data contours and soundings, as well as river contours, have been added as additional information.

The bathymetric data used to produce the offshore part of the Westport DEM comes from digitised nautical charts. As the available charts do not cover the whole area needed for the project, especially along the coast to the east of the Buller River mouth, manual interpretation of maps and aerial images has been performed to improve the coverage as shown on Figure 2.1 and thus prevent final interpolation artifacts. In addition, the geometry of the shore close to the Buller River mouth is constantly changing; thus, it has been decided to use only bathymetric data corresponding to the March 2005 nautical charts release and not aerial orthophotos of 2016 that do not provide any altitude information. For the river, nautical charts have been used and enhanced with riverbanks contours coming from the LiDAR dataset.

Westport Airport is located close to the shore on the west of the Buller River mouth. Unfortunately, the LiDAR coverage does not include the airport or Carters Beach village, although they must be included in the tsunami hazard zoning. In order to model this area correctly, GPS survey points obtained for 2014 Level 2 tsunami modeling have been used, as well as new contours of the airport runway digitised from 1:25,000 scale orthophotos (LINZ 2000–2001). The altitude of these runway contours has been determined to be at 3.3 m, in agreement with the neighboring GPS data and the mean altitude value of the easternmost part of the runway provided by LiDAR data. Heights are all relative to local MSL.

2.2.1 New Zealand DEM

This set of DEM grids was derived from NIWA’s 250 m New Zealand bathymetry (Mitchell et al. 2012) and GEBCO 08 (General Bathymetric Chart of the Oceans, version 20120927) datasets[1], as well as LINZ’s 8 m DEM, interpolated to be at a spatial resolution of 10 arc-seconds.

2.2.2 Southwest Pacific DEM

This set of DEM grids was derived from a collection of LINZ Charts, LINZ’s 8 m DEM, the Seabed Mapping CMAP and GEBCO 08 datasets[1]. This DEM dataset covers the main islands of New Zealand and their offshore regions at 30 arc-seconds (~640–740 m in New Zealand).

2.2.3 Global DEM

A set of global DEM grids was developed at a spatial resolution of 2 arc-minutes using ETOPO2v2 as a base model (National Geophysical Data Center 2006). ETOPO2v2 is a 2 arc-minute global relief model of Earth’s surface that integrates land topography and ocean bathymetry, available from the National Centre for Environmental Information of National Oceanic and Atmospheric Administration (NOAA). In our global DEM data, the New Zealand DEM data is used to update the New Zealand region for improved data accuracy.

2.3 Numerical Grid Setup

The COMCOT tsunami modelling software (Wang and Power 2011) uses a series of nested ‘grids’ constructed from bathymetric and topographic data, i.e. DEMs, to account for spatial resolution requirements by a tsunami travelling in different regions. In this study, seven layers of numerical modelling grids at five levels of cascading spatial resolutions were used to simulate tsunami generation, propagation and coastal flooding. Land elevation and water depth information at the numerical grids were interpolated from the six sets of DEMs we have developed.

The first-level grid, layer 01, covers the whole Pacific to simulate tsunami generation and propagation from a variety of tsunami sources at a spatial resolution of 2 arc-minutes (~1.8 km on the Equator; Figure 2.2). The elevation data of the layer 01 grids was extracted from the global DEM data, as described in Section 2.2.6. The second-level grid, layer 02, covers the New Zealand mainland at a spatial resolution of 30 arc-seconds (~640–740 m in New Zealand; Figures 2.2 and 2.3). The elevation data of the layer 02 grids was interpolated from the Southwest Pacific DEM data, as described in Section 2.2.5.

The third-level grid, layer 03, covers the northern South Island and its offshore at a spatial resolution of 6.0 arc-seconds (~120 m; Figure 2.3). The elevation data of the layer 03 grids was interpolated from the 10 arc-second New Zealand DEM data described in Section 2.2.4.

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[1] https://www.gebco.net/: “GEBCO’s gridded bathymetric data sets are global terrain models for ocean and land and includes the GEBCO 2014 Grid, a global 30 arc-second interval grid.” CMAP: digitisation of marine charts created by Seabed Mapping International Ltd, Port Nelson, New Zealand.

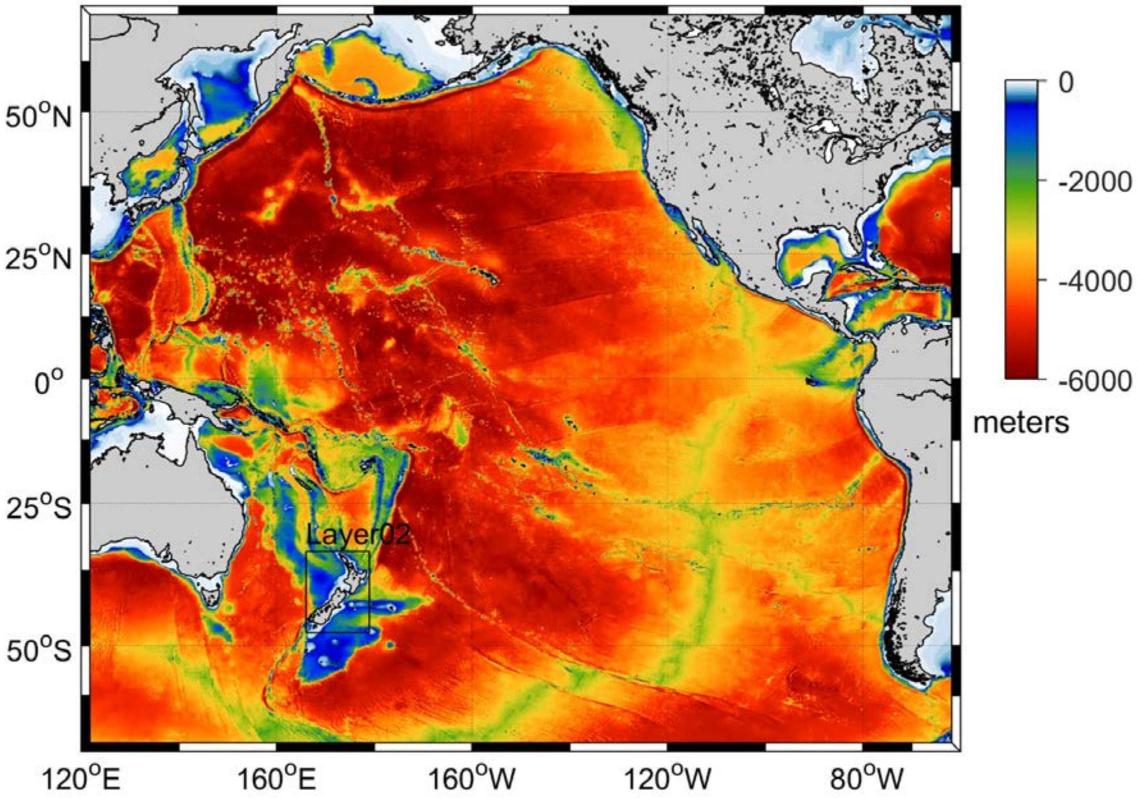

Figure 2.2 Nested grid set-up for tsunami generation and propagation modelling. The outer grid layer 01 spans the whole Pacific for tsunami from distant sources. See Figures 2.3 and 2.4 for more detail of grid layers 02, 03 and 04. Elevation above sea level is colour-coded in metres.

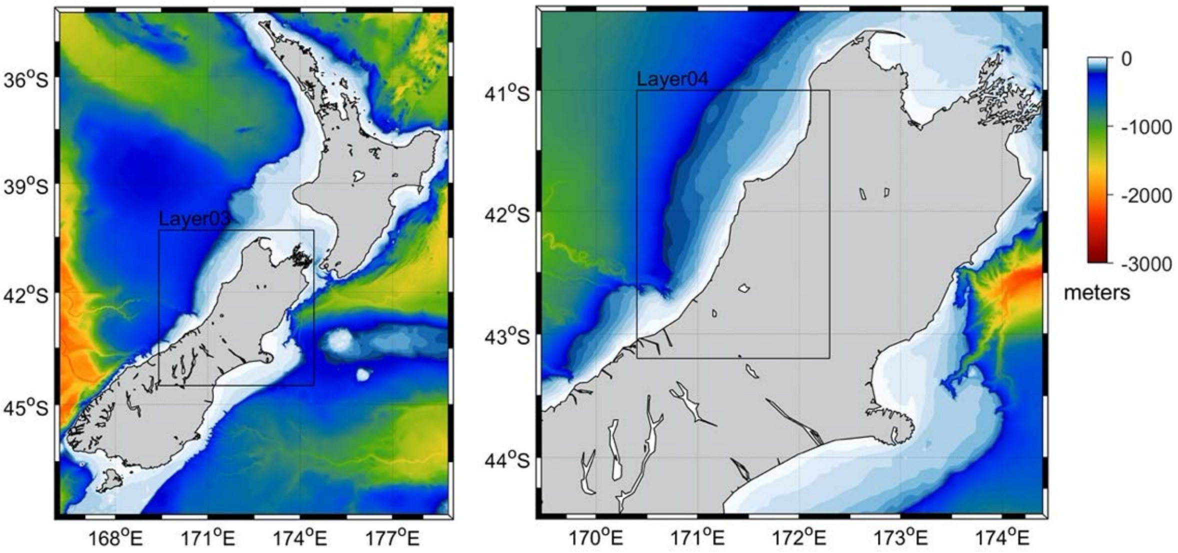

Figure 2.3 The coverage of nested grid layers 02, 03 and 04 for the numerical simulation of tsunami.

The fourth-level grid, layer 04, covers the coastal stretch from Hokitika, Greymouth and Westport at a spatial resolution of 1.50 arc-seconds (~ 30 m, Figures 2.3 and 2.4). The elevation data at layer 04 grid was interpolated from the same source of the third-level grids, i.e. the 10 arc-second New Zealand DEM data.

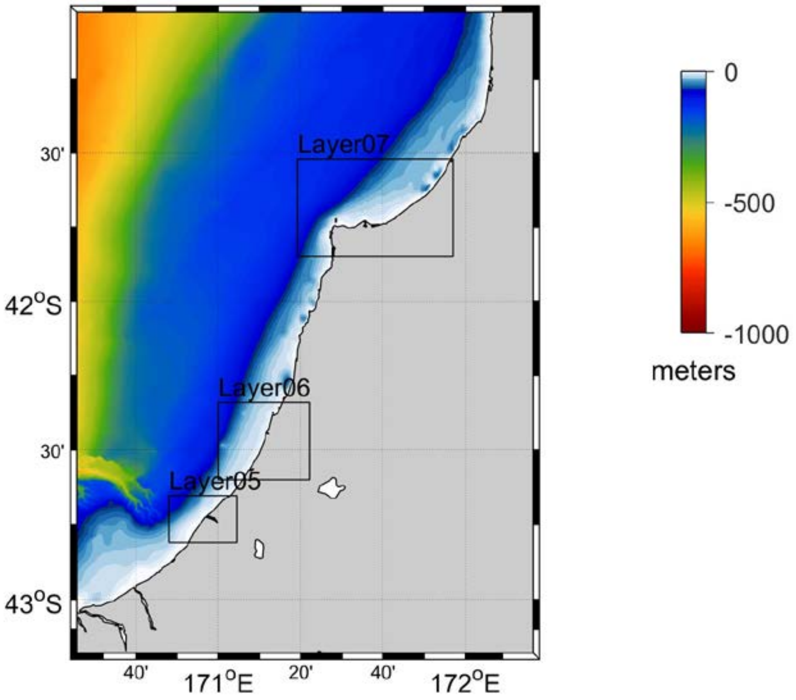

Figure 2.4 The nested grid setting and coverage of grid layers 04, 05, 06 and 07 for the numerical simulations of tsunami propagation.

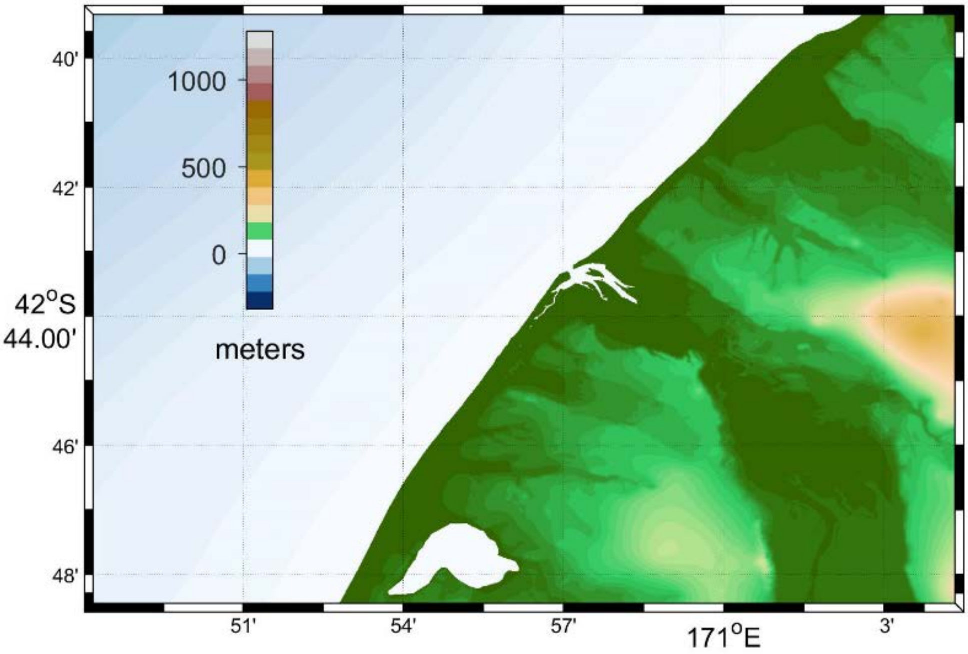

Figure 2.5 The topography and bathymetry of grid layer 05 in the tsunami inundation modelling domain for Hokitika.

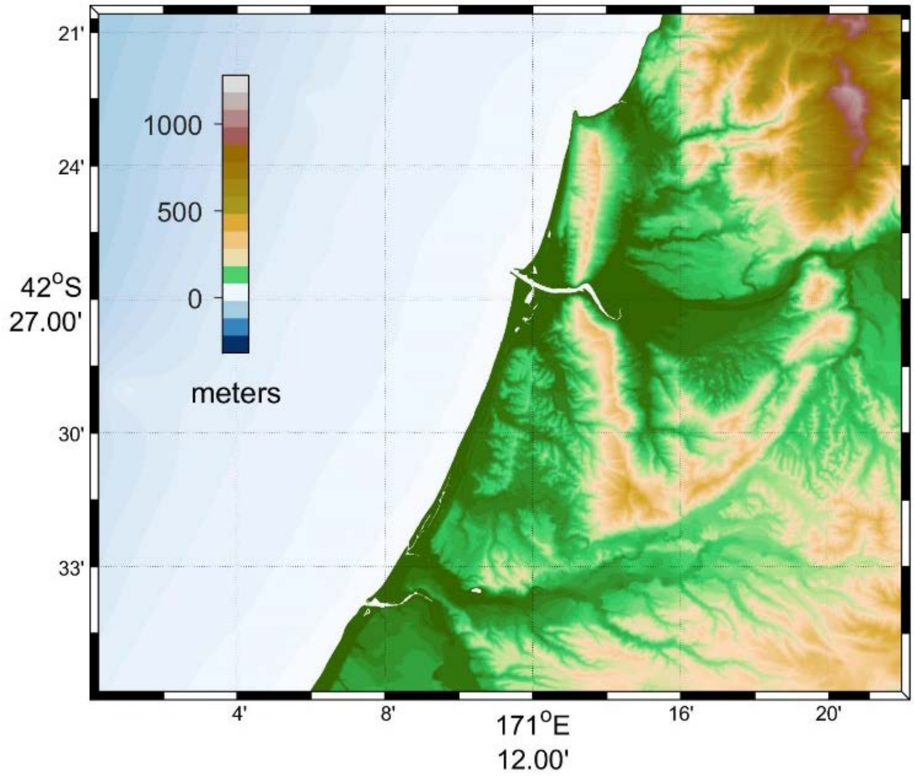

Figure 2.6 The topography and bathymetry of grid layer 06 in the tsunami inundation modelling domain for Greymouth.

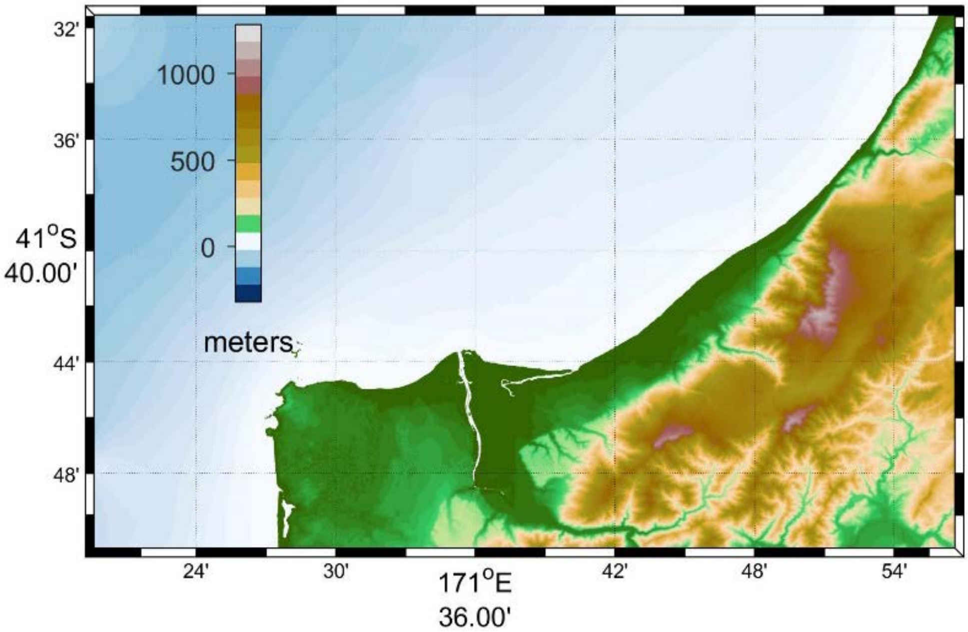

Figure 2.7 The topography and bathymetry of grid layer 07 in the tsunami inundation modelling domain for Westport.

The fifth-level grids include three grid layers, layer 05, 06 and 07, all at a spatial resolution of 0.75 arc-seconds (~15 m; Figures 2.4–2.7) for high-resolution numerical simulations of tsunami coastal interaction, run-up and inundation. The elevation data of the layer 05, 06 and 07 grids were interpolated from the Hokitika, Greymouth and Westport DEMs, respectively. Layer 05 covers Hokitika town and the surrounding coastal area. Layer 06 covers the coastal area from the Taramakau River, Greymouth and the coastal community of Rapahoe. Layer 07 covers the coastal area around Cape Foulwind and Westport.

A summary of nested grid set-up and modelling settings is given in Table 2.1.

Table 2.1 Parameters for tsunami propagation and inundation simulations. Note that COMCOT uses staggered grid stencils for water surface elevation and velocity components, leading to an internal grid spacing half of the input grid size between its water surface elevation and velocity calculations.

Layer	Δx (arc-min)	Δy (arc-min)	Δt (sec)	Roughness	Wet/Dry Threshold
01	2.0	0.845–2.000	3.218	Disabled	Vertical wall at coast
02	0.5	0.333–0.416	1.609	Disabled	Vertical wall at coast
03	0.1	0.0713–0.0763	0.536	Disabled	Vertical wall at coast
04	0.025	0.01822–0.01887	0.2682	Disabled	Vertical wall at coast
05	0.0125	0.00917–0.00919	0.134	n = 0.025 (land), 0.011 (water)	10^{-5} m for calculation; 10^{-4} m for output
06	0.0125	0.00920–0.00924	0.134	n = 0.025 (land), 0.011 (water)	10^{-5} m for calculation; 10^{-4} m for output
07	0.0125	0.00931–0.00936	0.134	n = 0.025 (land), 0.011 (water)	10^{-5} m for calculation; 10^{-4} m for output

2.4 Effects of Earth Curvature, Rotation and High Latitude

This study adopts tsunami governing equations in a Spherical Coordinate System (SCS) to simulate tsunami from selected sources to the modelled inundation areas of interest. This is necessary for tsunami simulations over a large area due to the curvature of the Earth's surface. The effect of Earth's rotation was also evaluated through the inclusion of Coriolis force in both linear and non-linear tsunami models (Wang and Power 2011).

In high-latitude regions, the common approach of using 'square' grids in spherical coordinates, i.e. equal cell edges in arc-degrees, leads to grid cells that are highly elongated when measured in metres. In COMCOT, the size of a numerical grid cell varies along its meridian (i.e. lines of longitude) and is self-adjusted according to its latitude so that its size along the parallel (i.e. circles of latitude) and its size along the meridian are equal in metres to ensure that 'square' grids (in metre terms) are created for numerical calculations. This is why grid size along the meridian (Δy in arc-minutes) in Table 2.1 is presented as a range rather than a constant value for each grid layer.

This adaptive grid approach not only improves the stability of tsunami simulations but also maintains a consistent accuracy of modelled tsunami in all directions, in contrast to some other models that do not adjust grid spacing adaptively along the meridian.

2.5 Virtual Tsunami Sensors

To be able to calculate and record the time series of modelled water surface fluctuations relative to MSL resulting from the modelled tsunami, a set of three virtual tsunami sensors (gauges) were deployed at following locations:

- Offshore Hokitika River mouth (at 170.958465° E and 42.713088° S).
- Offshore Grey River / Māwheranui mouth (at 171.185331° E and 42.436545° S).
- Offshore Buller River (at 171.587279° E and 41.723595° S).

In numerical simulations, values at a virtual sensor location were interpolated from its neighbouring grid cells within the model.

2.6 Ambient Sea Level and Lake Level

The tsunami inundation modelling was carried out assuming that each tsunami occurs at high tide, specifically, at Mean High Water Springs (MHWS). MHWS was modelled as a static level above local MSL, not as changing over time. The tide levels that represent the MHWS used for tsunami numerical simulations in Hokitika, Greymouth and Westport are 1.1, 1.4 and 1.45 m above MSL, respectively. Table 2.2 shows the chosen tide level for the simulation based on MSL and MHWS.

Table 2.2 Tide levels for tsunami numerical simulation, given in metres above lowest astronomical tide (chart datum).

Location	MHWS (m)	MSL (m)
Hokitika	2.3	1.2
Greymouth	3.3	1.9
Westport	3.2	1.75

2.7 Other Simulation Settings

In the tsunami simulations, the co-seismic ground surface and seafloor displacement in an earthquake event is calculated using the elastic finite fault theory documented in Okada (1985) and is then used as the initial condition of tsunami generation.

In a local earthquake event, the co-seismic uplift or subsidence may potentially change the ground and seafloor elevation as defined in the input DEM (i.e. current-day DEM or pre-event DEM). The COMCOT model calculates the co-seismic displacements, adjusts the input DEM with the computed co-seismic uplift/subsidence and simulates the subsequent tsunami with the co-seismic displacement adjusted DEM (i.e. post-event DEM) to calculate tsunami hazard parameters, e.g. tsunami elevation, flow depth and inundation range.

In the numerical simulations, distant and regional source tsunami were simulated for 30 hours from generation at their source to ensure that the maximum tsunami hazard parameters were obtained in the modelled areas. The tsunami from local crustal fault (Cape Foulwind Fault) were simulated for three hours. Manning’s formula was used to model frictional effects of seafloor and ground surface features on tsunami on the highest grid level, i.e. grid layers 05, 06 and 07, as shown in Figures 2.5, 2.6 and 2.7, with roughness value n = 0.025 for land area and n = 0.011 for water area. These values are slightly toward the low end to be conservative for the purposes of evacuation zone modelling.

When modelling an earthquake-triggered tsunami, COMCOT requires an earthquake magnitude and hypocentre, a rupture plane and an estimate of the rigidity of the ruptured slab. In this project, the magnitudes provided are calculated using a rigidity of 40 GPa.

3.0 SOURCE SIMULATION AND SELECTION METHODOLOGY

In the following section, we will discuss our approach to selecting and modelling tsunami sources relevant to the tasks requested for this study. We present simulation results from ensembles of scenarios in order to keep the length of the report reasonable. An 'ensemble' is defined as a set of tsunami simulations that belong to a given category such as 'all source scenarios from all source areas' or 'all scenarios from the same source area, but with different distributions of slip across the fault surface'.

3.1 Existing Tsunami Scenario Database and Local Crustal Fault

3.1.1 Existing Tsunami Scenario Database

GNS Science has previously developed a tsunami scenario database with threat level maps for New Zealand that can be used for tsunami early warning purposes (Gusman et al. 2019). The threat-level maps are based on local, regional and distant earthquake scenarios in subduction zones around the Pacific Ocean. The earthquake magnitudes for the distant, regional and local sources are ranged from 8.7 to 9.3, 8.1 to 9.3 and 6.9 to 9.3, respectively, with a magnitude interval of 0.2. The spatial distance between reference points for the earthquake sources for distant and regional sources is 300 km, while for local sources this is 150 or 100 km, depending on the magnitude. Each group of scenarios has their own set of reference points and earthquake magnitude range. The total number of reference points is 135. The tsunami heights of all scenarios are calculated for all New Zealand Tsunami Forecast Zones and Hazard Modelling Zones.

3.1.2 Local Crustal Fault: Cape Foulwind Fault

The North Westland deformation front runs offshore for 320 km between Cape Farewell and Hokitika at a distance of 3–30 km from the coast. Marine seismic reflection profiles, integrated with published sediment core and coastal uplift data, were used to infer late Quaternary activity on six major reverse faults (Barnes and Ghisetti 2016). The principal structures are the Cape Foulwind, Kahurangi and Kongahu faults and Farewell, Elizabeth and Razorback faults. Nine potential earthquake sources are identified, including four segments of the Cape Foulwind Fault. They vary in length from 20–120 km, are potentially capable of producing moderate- to large-magnitude earthquakes of Mw 6.7–7.8 and represent a seismic risk to coastal communities. Best estimates of recurrence intervals for individual fault sources range from about 7600 years to 30,400 years, with large uncertainties in slip rates of up to -0.4, +1.0 mm/yr, reflected by the wide range of recurrence intervals (Barnes and Ghisetti 2016).

The Cape Foulwind Fault is a segmented reverse structure extending along the inner shelf for 240 km between Hokitika and Kahurangi Point (Figure 3.1). The fault has a complex trace, an average strike of 030°, dips 50–60°E and has a blind upper tip, typically lying within the Miocene–Pliocene sequence 300–700 m beneath the seafloor. The Miocene–late Quaternary units are folded above the buried fault tip, suggesting up-dip propagation of shortening during a prolonged period of fault displacement at depth (Ghisetti et al. 2014).

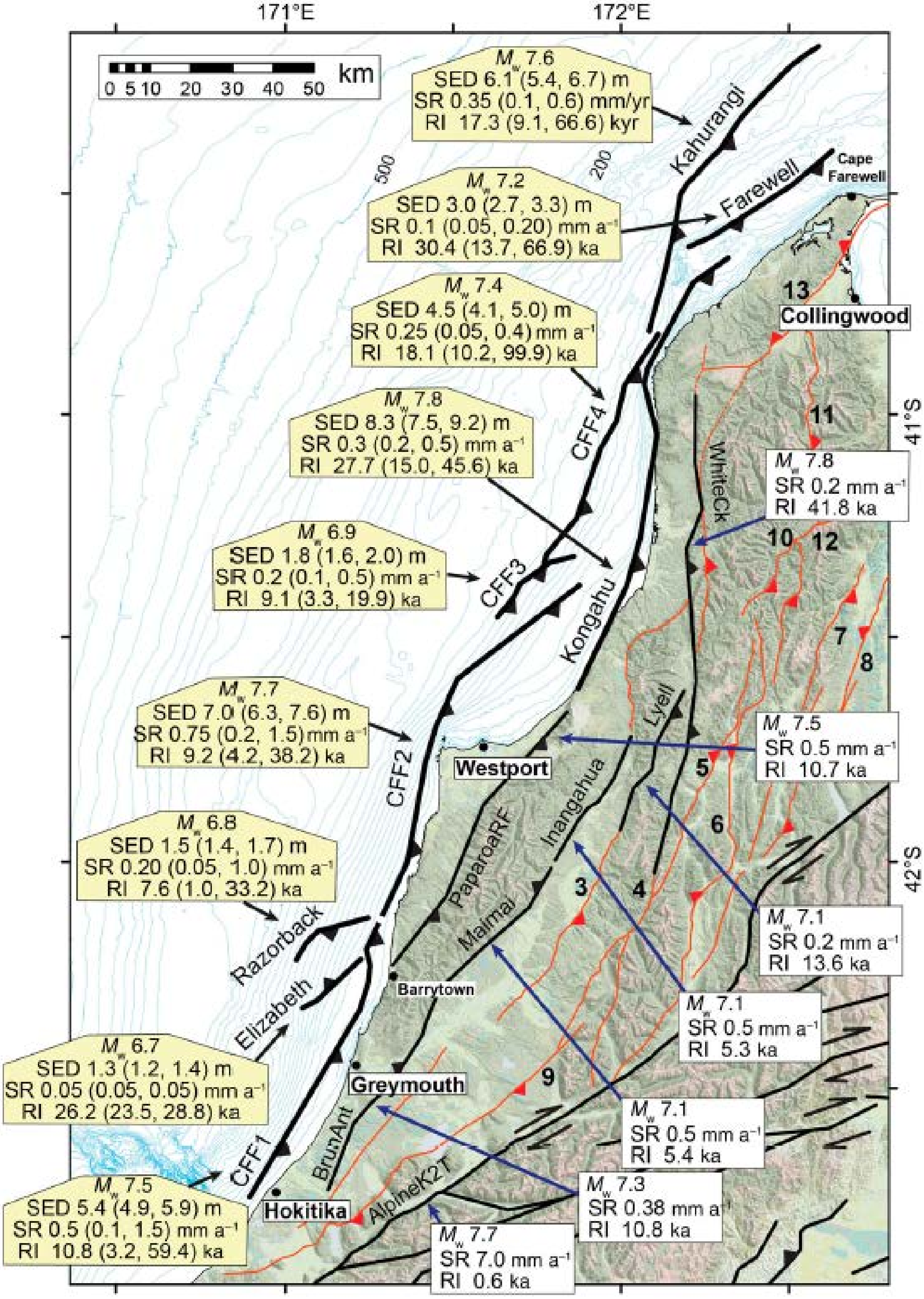

Figure 3.1 Local Interpretation of earthquake fault sources along the North Westland deformation front (Barnes and Ghisetti 2016). Bold black lines are individual earthquake fault sources. Mw = moment magnitude; RI = recurrence interval; SED = coseismic single-event displacement; SR = slip rate.

The southern section of the fault (between Hokitika and Cape Foulwind) lies close to the coast about 3–6 km from shore, in 20–40 m water depth. Off Barrytown, there is a change in strike, where the fault bends across an inferred basement step-over about 5 km in width. Between Barrytown and Cape Foulwind, where Late Cretaceous–Paleogene units are exposed in the coastal hanging wall, the total vertical displacement on the fault exceeds 3 km. There, the fault strongly controls the strike of the coastline (Nathan et al. 2002). Immediately north of Cape Foulwind, the fault swings to a north-easterly orientation (052°) and terminates at a major 10-km-wide, left step-over located 20 km off Kongahu Point. Across the step-over, the faults overlap by 20 km of strike length, with all fault surfaces dipping to the southeast. Within the step-over region, there is a broad anticlinal fold and at least two discrete fault traces. At its northern end, the fault strikes 025°, lies in about 110 m water depth and extends for 70 km from the step-over off Kongahu Point to Kahurangi Point. Off Kahurangi Point, the fault converges with the northern end of the Kongahu Fault and the southern end of the Kahurangi Fault. Structural interconnection between these faults cannot be ruled out.

3.2 Coastal Zones

The tsunami scenario database includes tsunami amplitude (height above the MSL) along the coast of New Zealand. The coast of New Zealand is divided into 43 forecast zones (hereafter, Forecast Zone), and the 99th percentile of the simulated tsunami heights for each zone from the earthquake source scenarios are stored in the database. The forecast zones in the study area are shown in Figure 3.2. The 99th percentile of the simulated tsunami heights are also calculated for the 268 coastal zones (hereafter, Hazard Zone) used to calculate the probabilistic tsunami hazard for New Zealand. Each of these Hazard Zones is approximately 20 km long as measured along the open coast. The Hazard Zones for the three study areas are shown in Figures 3.3, 3.4 and 3.5.

To select the source regions for the worst-case scenarios, the simulated tsunami heights in the 268 Hazard Zones were extracted. For the selection of earthquake source scenarios for the Orange Zone, the simulated tsunami heights in the 43 forecast zones were extracted. The total number of pre-computed scenarios in the database is currently 998.

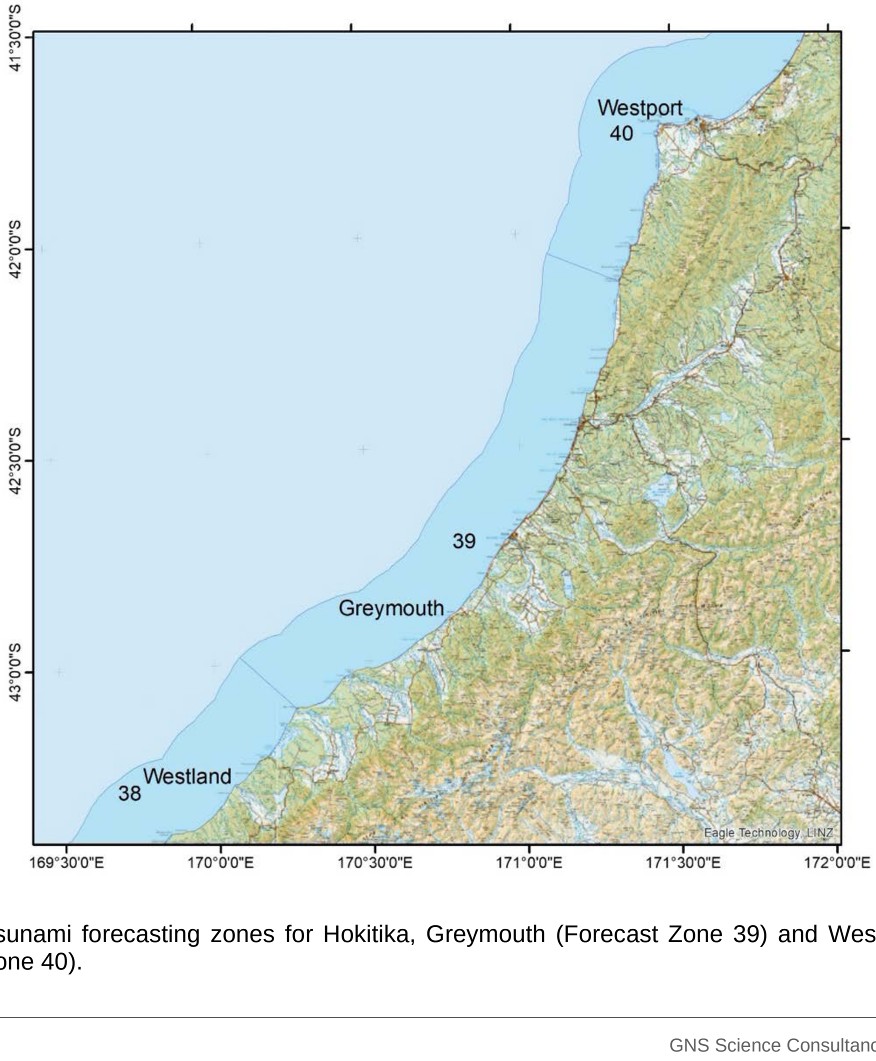

Figure 3.2 Tsunami forecasting zones for Hokitika, Greymouth (Forecast Zone 39) and Westport (Forecast Zone 40).

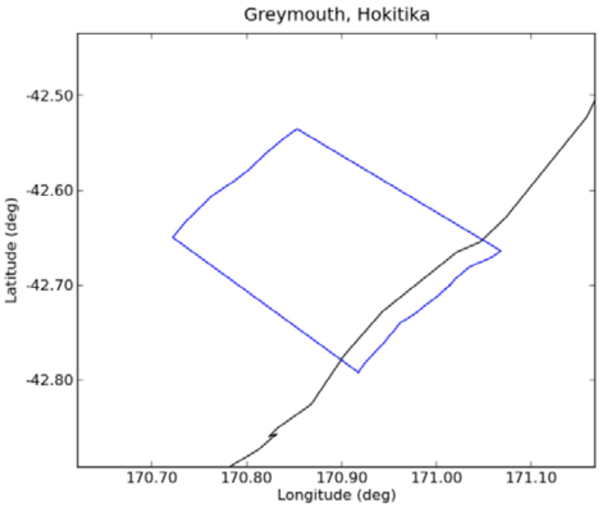

Figure 3.3 Tsunami Hazard Zone 226 for Hokitika.

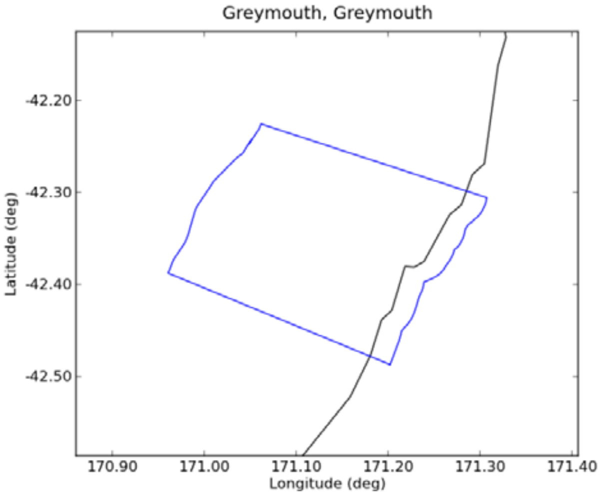

Figure 3.4 Tsunami Hazard Zone 228 for Greymouth.

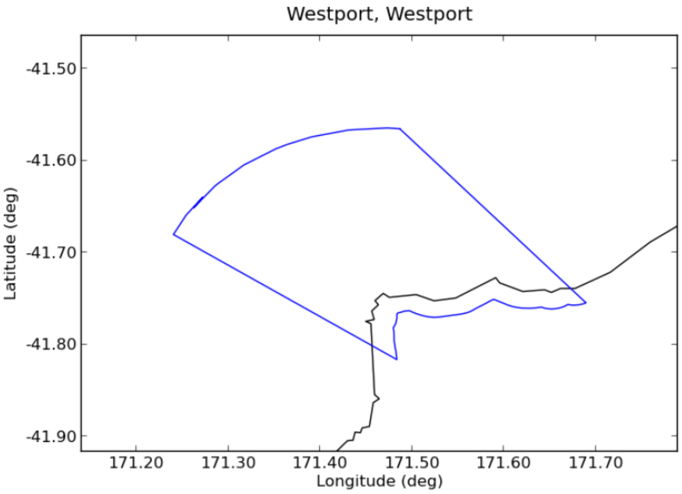

Figure 3.5 Tsunami Hazard Zone 232 for Westport.

3.3 ‘Worst-Case’ Scenarios

3.3.1 Distant, Regional and Local ‘Worst-Case’ Sources

From the New Zealand Tsunami Threat Level database, we identified the source regions around the Pacific that produced the largest offshore wave heights in the 20-km-long Hazard Zones where the study sites are located. Hokitika is in Hazard Zone 226, Greymouth is in Hazard Zone 228 and Westport is in Hazard Zone 232.

The threat level database includes scenarios up to Mw 9.3 (assuming 40 GPa rigidity) and was searched to find which of these produced the largest coastal tsunami heights for each Hazard Zone (Figures 3.3, 3.4 and 3.5). Coloured circles in Figures 3.6, 3.7 and 3.8 show the tsunami height from all source locations at Hokitika, Greymouth and Westport, respectively. The source areas for the largest tsunami at Hokitika, Greymouth and Westport are the same, namely the Puysegur, Kermadec, New Hebrides and Solomon Islands subduction zones. The magnitude for the worst-case scenarios for each subduction zone (Table 3.1) is based on the ‘Maximum of Maximum Magnitudes’ in the Global Earthquake Model (GEM; Berryman et al. 2015).

Initially, we used the ‘Preferred Maximum Magnitudes’ in the GEM for the Solomon Islands, New Hebrides, Kermadec and Puysegur subduction zones, which are 8.7, 8.83, 8.76 and 8.43, respectively (Note: we assume that the Solomon Islands and New Hebrides subduction zones are capable of ‘whole margin’ earthquakes but that the Kermadec Trench is an independent segment of the Hikurangi-Kermadec-Tonga subduction zone). However, these magnitudes give tsunami amplitudes along the coast of Greymouth that are too small for making a Yellow Zone. For example, scenarios from the Solomon Islands subduction zone with magnitudes of 8.7 have tsunami amplitudes of only around 2 m at the coast of Greymouth, much smaller than the 1-in-2500-year tsunami return period at 84% confidence level, which is approximately 7 m (Power 2013). Therefore, for this study, we use the ‘Maximum of Maximum Magnitudes’ in Berryman et al. (2015) for the Solomon Islands, New Hebrides, Kermadec and Puysegur subduction zones for the Yellow Zones. These are Mw9.3, 9.37, 9.42 and 9.07, respectively (Table 3.1).

For the Cape Foulwind Fault worst-case scenarios, we combined two of the fault segments, CFF1 and CFF2, shown in Figure 3.1. The maximum magnitudes of CFF1 is Mw 7.5, while that of CFF2 is Mw 7.7. The combined magnitude of these faults is Mw 7.8, which is used for the Cape Foulwind worst-case scenarios.

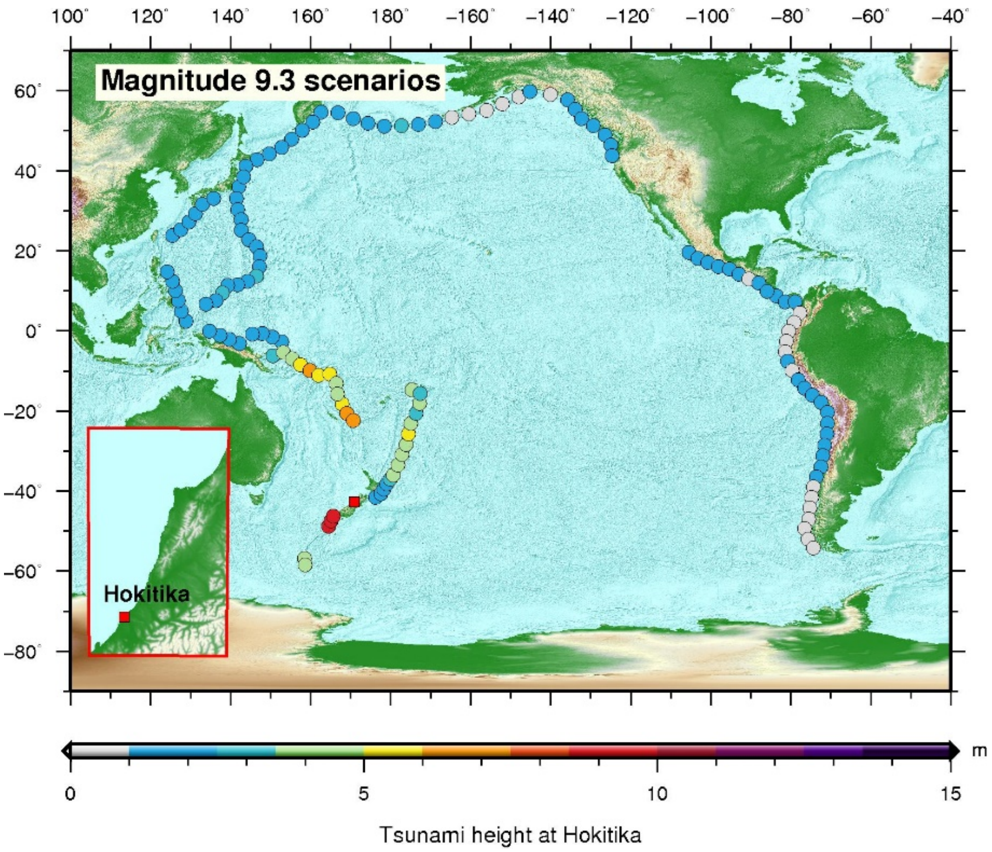

Figure 3.6 Tsunami heights at Hokitika from the source scenarios with magnitude of Mw 9.3 in the tsunami threat level database.

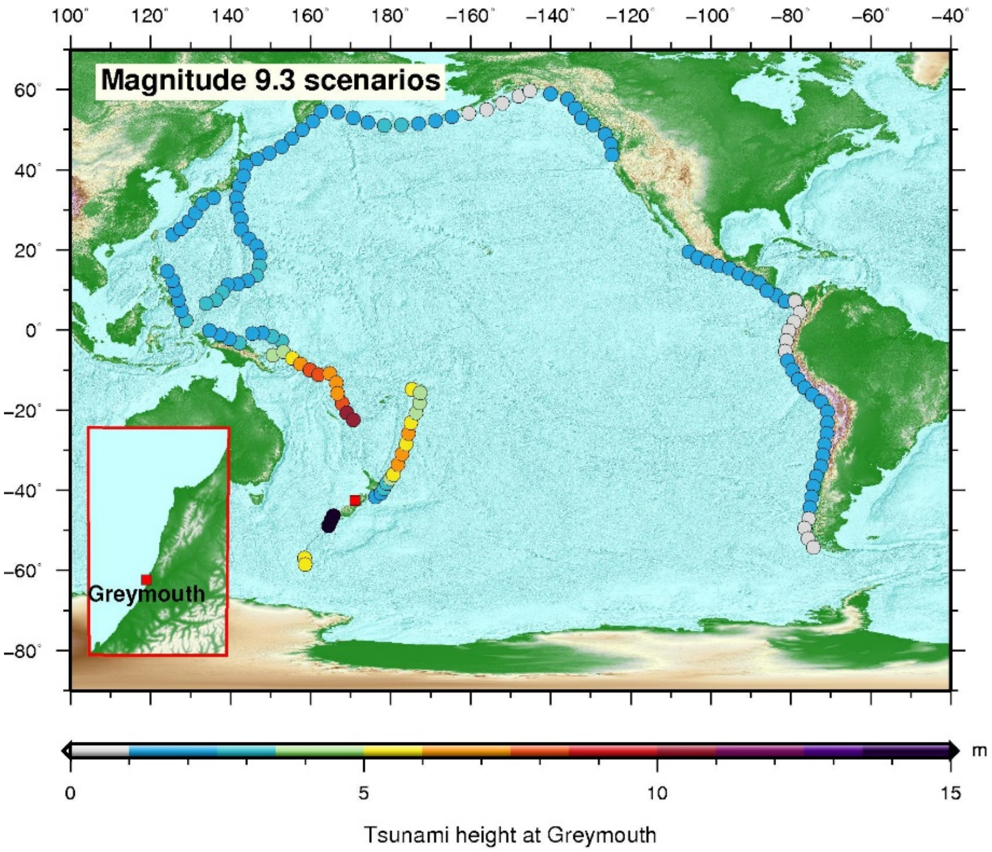

Figure 3.7 Tsunami heights at Greymouth from the source scenarios with magnitude of Mw 9.3 in the tsunami threat level database.

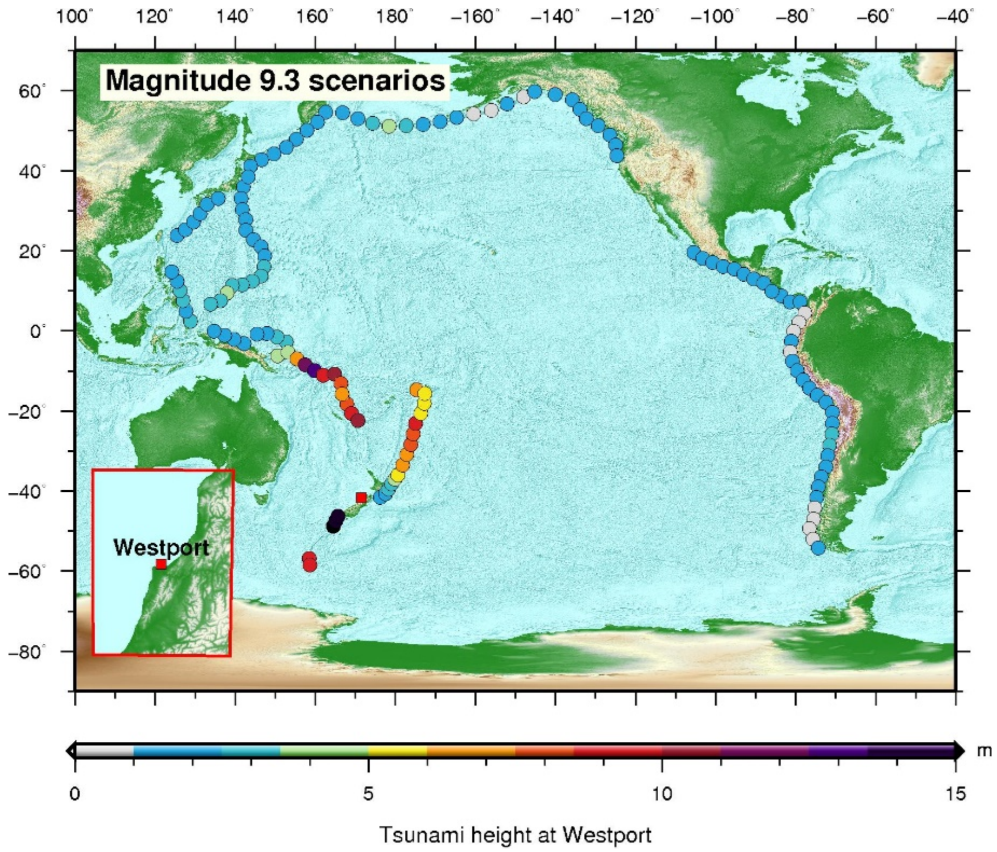

Figure 3.8 Tsunami heights at Westport from the source scenarios with magnitude of Mw 9.3 in the tsunami threat level database.

Table 3.1 Parameters for distant, regional and local worst-case scenario candidates.

ID_Code	Source Area	M_W	Number of Realisations
NBSV_Pt5	Solomon Islands	9.30	10
NBSV_Pt12	New Hebrides	9.37	10
KT_Pt5	Kermadec	9.42	10
PT_Pt3	Puysegur	9.07	10
CFF	Cape Foulwind	7.80	10

We have selected and designed tsunami sources for this category following the process described above. To consider the potential effects of slip occurring in a non-uniform fashion we modelled 10 different realisations of non-uniform slip. Technically, these are created by combining a set of NOAA[2] unit sources with appropriate slip (non-uniformly distributed), scaled to result in a required moment magnitude.

3.3.2 Fault Patches

The majority of the tsunami threats to New Zealand come from earthquakes in the subduction zones surrounding the Pacific Ocean. The Center for Tsunami Research at NOAA has developed fault patches in subduction zones around the Pacific Ocean for tsunami simulation

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[2] National Oceanic and Atmospheric Administration: American scientific agency within the United States Department of Commerce that focuses on the conditions of the oceans, major waterways and the atmosphere (Wikipedia contributors 2020).

purposes. Each fault patch has a fault length of 100 km and width of 50 km, equivalent to an earthquake of M_W7.7; the rake angle is assumed to be 90°, while the strike and dip angles are based on the geometry of the plate interface. The number of rows of theses patches can be two or more. These fault patches will be selected and used to generate non-uniform slip distribution for the worst-case scenarios.

The fault parameters for Cape Foulwind Fault that we use in this project are shown in Table 3.2. The fault segments shown in Table 3.2 were developed to describe the CFF1 and CFF2 faults shown in Figure 3.1. These fault parameters were used to generate non-uniform slip distribution for the worst-case scenarios for this local crustal fault.

Table 3.2 Fault parameters for Cape Foulwind Fault.

Segment	Longitude (°)	Latitude (°)	Length (m)	Width (m)	Depth (°)	Strike (°)	Dip (°)	Rake (°)
CFF_01	171.063752	-42.528298	53410	17701	500	30.11	55	115
CFF_02	171.237378	-42.250041	15681.74	17701	500	6.37	55	115
CFF_03	171.315057	- 42.074567	25898.27	17701	500	25.36	55	115
CFF_04	171.403910	- 41.862472	23994.88	17701	500	8.64	55	115
CFF_05	171.473416	- 41.666384	21380.28	17701	500	21.81	55	115
CFF_06	171.702989	- 41.474536	37886.84	17701	500	53.16	55	115

3.3.3 Non-Uniform Slip Model Creation

The methodology that 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 an earthquake magnitude, a rigidity of 40 GPa has been assumed, consistent with Gusman et al. (2019). Rigidity is an uncertain parameter, and typical estimates used for tsunami modelling range from 30–50 GPa.

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.

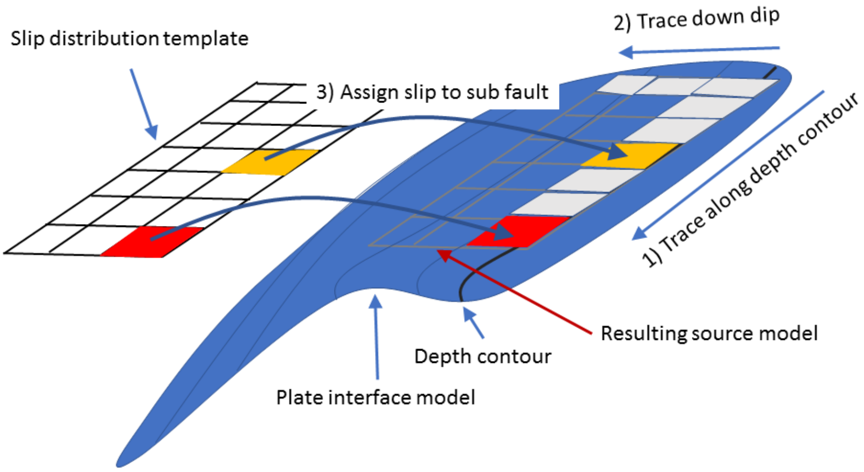


Figure 3.9 The sub-fault tracing method to create a non-uniform slip subduction interface source model.

First, a non-uniform slip distribution is created on a regular grid with dimensions (length [x-direction] and width [y-direction]) controlled by a scaling relationship suggested by Abe (1979) (slip distribution template; Figure 3.9). This grid is interpreted as a collection of sub-faults with cell dimensions dx and dy (dx = dy). As an example, we describe the process of creating a non-uniform slip model for the Hikurangi subduction zone that has a highly detailed interface model (Williams et al. 2013). Distant, regional subduction sources and local crustal fault sources are treated accordingly, with the difference that the projection is performed onto rectangular sections of the faults as provided by NOAA or the New Zealand seismic hazard model (Stirling et al. 2010). The cell dimensions are set to be the shallowest depth of the resulting source. The sub-faults are projected onto the subduction zone interface as follows: We chose a position on the interface, given by the earthquake epicentre, and mapped the first row from our grid (x-direction) onto the corresponding depth contour (up and down the strike direction of the interface from the hypocentre). From each sub-fault on the depth contour, the sub-faults in y-direction are traced down-dip and, consequently, all sub-faults are mapped onto the interface model. To obtain a fully connected set of sub-faults, the cell dimension in y-direction is adjusted. Figure 3.9 shows an example of source model generated with this process. This approach has the advantage of resulting in a final source with sub-faults of almost equal size, independent of depth.

Altogether, we have considered a total of 50 source models to assess ‘worst-case’ scenarios from one local crustal fault (Cape Foulwind) and four subduction interfaces (Puysegur, Kermadec, New Hebrides and Solomon Islands). The non-uniform slip sources were created following the approach described above (‘sub-fault tracing’).

Figure 3.10 gives an example of the generated non-uniform slip source model and initial sea surface displacement in New Hebrides subduction zone. All source models for each of the subduction zones are scaled to the conservative magnitude (Table 3.1) by assuming 40 GPa interface rigidity.

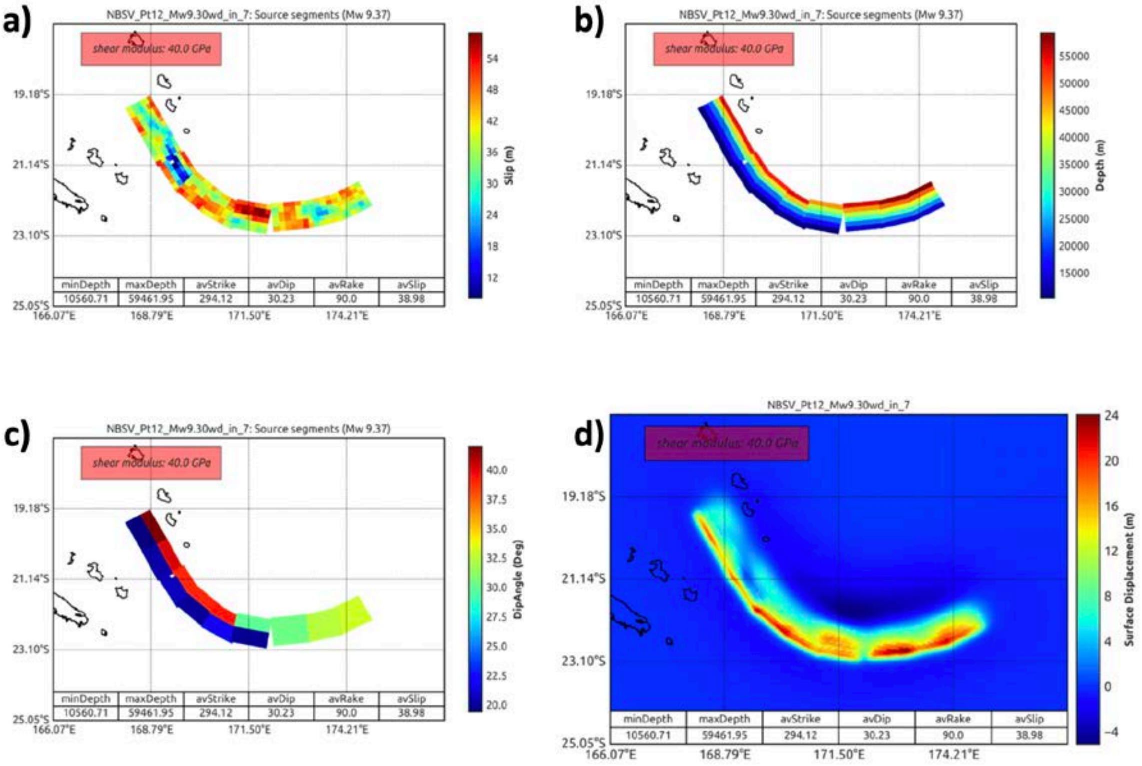


Figure 3.10 A generated source scenario in the New Hebrides subduction zone. a) Non-uniform fault slip example, b) depth attached to each sub-fault, c) dip angle attached to each sub-fault and d) seafloor displacement from the non-uniform fault slip shown in (a).

3.4 3 m and 5 m Scenario Source Identification and Scaling Methodology

The approach taken in this study to determine scenarios that generate 3 m and 5 m tsunami wave heights at coast is in line with the methodology to develop the Orange Evacuation Zones in the 'Director's Guidelines' (MCDEM 2016).

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 (1–3 m or 3–5 m) 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 5 m threat level) is shown in Figure 3.11, and individual steps are explained in greater detail below.

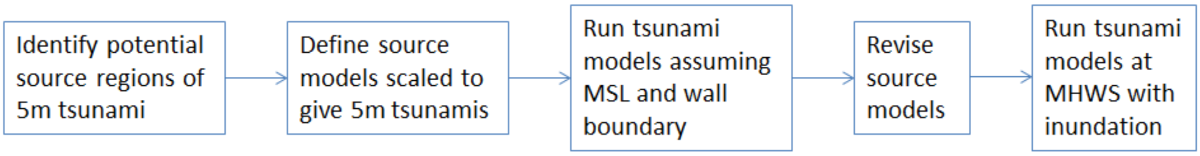


Figure 3.11 Outline of scheme for Orange Zone calculation. The scheme shown here is for developing a zone capable of encompassing a 5 m tsunami.

3.4.1 '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 a 5 m (or 3 m) tsunami in the forecast zone were identified and estimates of the magnitudes required to do this were tabulated (Section 3.2.5). Hokitika and Greymouth are both located in Forecast Zone 39, while Westport is in Forecast Zone 40.

The threat level database for distant tsunami sources includes scenario earthquakes of Mw 8.7, 8.9, 9.1 and 9.3 and, for regional sources, earthquakes of Mw 7.3, 7.5, 7.7, 7.9, 8.1, 8.3, 8.5, 8.7, 8.9, 9.1 and 9.3 (Gusman et al. 2019). Interpolation and extrapolation, based on Abe (1979), was used to identify earthquake magnitudes that would produce tsunami of the required height (3 m or 5 m) at the coast. Some scenarios exceeded the maximum plausible magnitude in Berryman et al. (2015) for the source location but were used anyway to provide a broad coverage of tsunami sources that approach the study area from different directions. We note that the threat level database does not include local crustal faults to New Zealand.

3.4.2 'Run Tsunami Models at MSL and Wall Boundary'

Initially, scenario sources based on the sources in Tables 3.3–3.6 were modelled as if they occurred at a tidal level of MSL, 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.

3.4.3 'Revise Source Models'

Analysis of the results from the previous step identified that, in several cases, the modelled tsunami heights in the study area differed significantly from the intended height of 5 m (or 3 m). Here, the 99th percentile maxima within the forecast zone were used to assess the intended height. The primary reason for this is thought to be that the Abe (1979) scaling rule may cease to hold well for very large earthquakes. Also, the grid set-up for the current study differs from the grid set-up used to create the threat level database. It should also be noted that these values occur at different locations in the forecast zone. The approach here is in line with the MCDEM guidelines and is designed to apply when the respective threat level (3 m or 5 m) is being forecast in a response situation.

To correct for this issue, the source models were revised according to the scheme shown in Figure 3.12. The first step here is to estimate the maximum tsunami height in the models developed in the previous step. 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 5 m (or 3 m) tsunami. Examination of modelling results suggests that 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 3.12). In practice this means that, in order to develop an evacuation zone for 5 m tsunami, we use a set of scenario models that aim to produce 5 x 1.2 = 6 m tsunami.

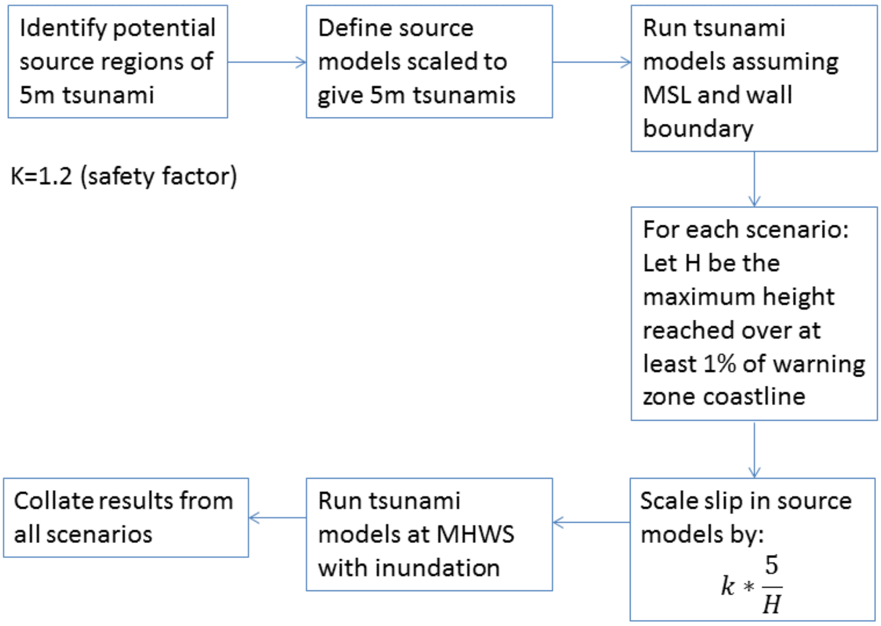


Figure 3.12 Expanded schematic, illustrating the process indicated by ‘Revise source models’.

3.4.4 ‘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. 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 should be used as the maximum extent of the boundary of the Orange Zone.

3.4.5 Scenarios with 3 m Target Wave Height

Please refer to Table 3.3 for the list of sources and parameters that cause a coastal wave height of ~3 m in Forecast Zone 39 for Hokitika and Greymouth; the sources and parameters that cause a coastal wave height of ~3 m in Forecast Zone 40 for Westport are listed in Table 3.4. We initially selected sources to cause a ‘maximum’ wave height (here, the 99th percentile of all wave heights in the zone) ranging between 2.7 and 3.5 m. This initial information was taken from the current threat level database. Before inundation simulation, an initial scaling was applied to achieve a 1.2*3 m = 3.6 m wave height locally, as described above (at MSL).

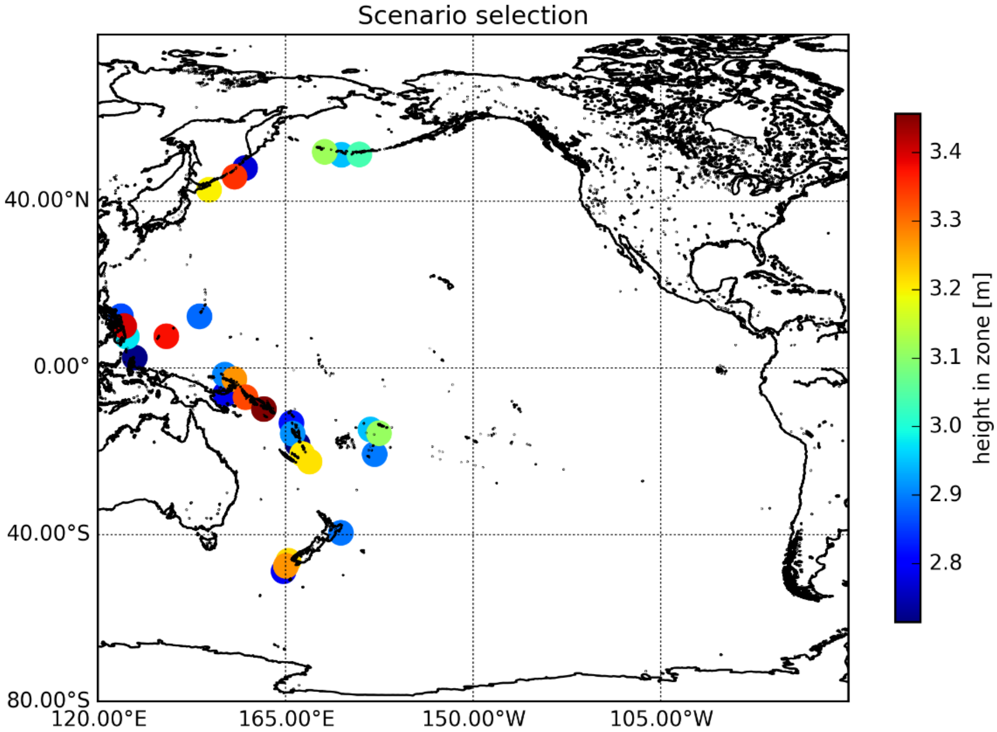


Figure 3.13 Source scenarios selected with 3 m target wave height. Indicative locations for the sources listed in Table 3.3. Colour indicates the tsunami height at Forecast Zone 39 from the source model. The source ID labels are shown for each source scenario.

Table 3.3 Parameters for scenarios with 3 m target wave heights in the Hokitika and Greymouth forecasting zone (Zone 39 in the New Zealand Tsunami Threat Level database).

No.	Source_ID	Original M_W	Original Slip	Scale Factor (First Iteration)	Scaled Slip (First Iteration)	Scale Factor (Second Iteration)	Scaled Slip (Second Iteration)
1	Alaska_Pt3_Mw9.30	9.3	30.49	0.96	29.35	1.42	41.75
2	Alaska_Pt4_Mw9.30	9.3	30.47	1.02	31.02	1.22	37.69
3	Alaska_Pt5_Mw9.30	9.3	30.48	0.99	30.09	1.29	38.83
4	EPhil_Pt1_Mw9.30	9.3	45.74	1.10	50.45	1.12	56.36
5	EPhil_Pt3_Mw9.30	9.3	30.49	1.01	30.72	1.04	32.06
6	EPhil_Pt4_Mw9.30	9.3	30.48	0.88	26.89	1.15	30.82
7	EPhil_Pt5_Mw9.30	9.3	30.49	1.05	31.97	1.20	38.43
8	Hiku-Ker_Pt3_Mw9.30	9.3	32.28	1.04	33.47	1.00	33.31
9	Ker-Tonga_Pt10_Mw8.90	8.9	19.79	1.02	20.14	1.01	20.27
10	Ker-Tonga_Pt7_Mw9.10	9.1	21.51	1.04	22.28	0.96	21.28
11	Ker-Tonga_Pt9_Mw9.10	9.1	21.50	0.96	20.73	1.10	22.87
12	KJIMY_Pt20_Mw9.30	9.3	30.47	1.04	31.70	0.93	29.36
13	KJIMY_Pt24_Mw9.30	9.3	30.48	0.89	27.09	1.19	32.23
14	KJIMY_Pt4_Mw9.30	9.3	15.24	1.08	16.51	1.49	24.62
15	KJIMY_Pt5_Mw9.30	9.3	15.24	0.90	13.64	1.51	20.54
16	KJIMY_Pt7_Mw9.30	9.3	15.24	0.94	14.29	1.28	18.28
17	Manus_Pt1_Mw9.30	9.3	34.29	0.92	31.44	1.34	42.21
18	Manus_Pt2_Mw9.30	9.3	30.47	1.03	31.46	1.42	44.66
19	NBSV_Pt1_Mw9.10	9.1	23.29	1.08	25.09	1.11	27.84
20	NBSV_Pt10_Mw8.90	8.9	13.86	1.11	15.32	1.19	18.16
21	NBSV_Pt11_Mw8.90	8.9	13.86	0.94	12.97	1.17	15.22
22	NBSV_Pt12_Mw8.70	8.7	8.82	0.93	8.23	0.90	7.42
23	NBSV_Pt3_Mw9.10	9.1	19.96	0.90	17.96	1.17	21.05
24	NBSV_Pt5_Mw8.90	8.9	13.86	0.87	12.03	1.17	14.05
25	NBSV_Pt8_Mw8.90	8.9	13.87	1.06	14.75	1.25	18.51
26	NBSV_Pt9_Mw8.90	8.9	13.86	1.03	14.28	1.13	16.21
27	Puysegur_Pt1_Mw8.70	8.7	11.76	1.07	12.63	1.00	12.64
28	Puysegur_Pt2_Mw8.70	8.7	8.82	0.92	8.08	0.92	7.40
29	Puysegur_Pt3_Mw8.50	8.5	5.83	0.93	5.43	0.97	5.27

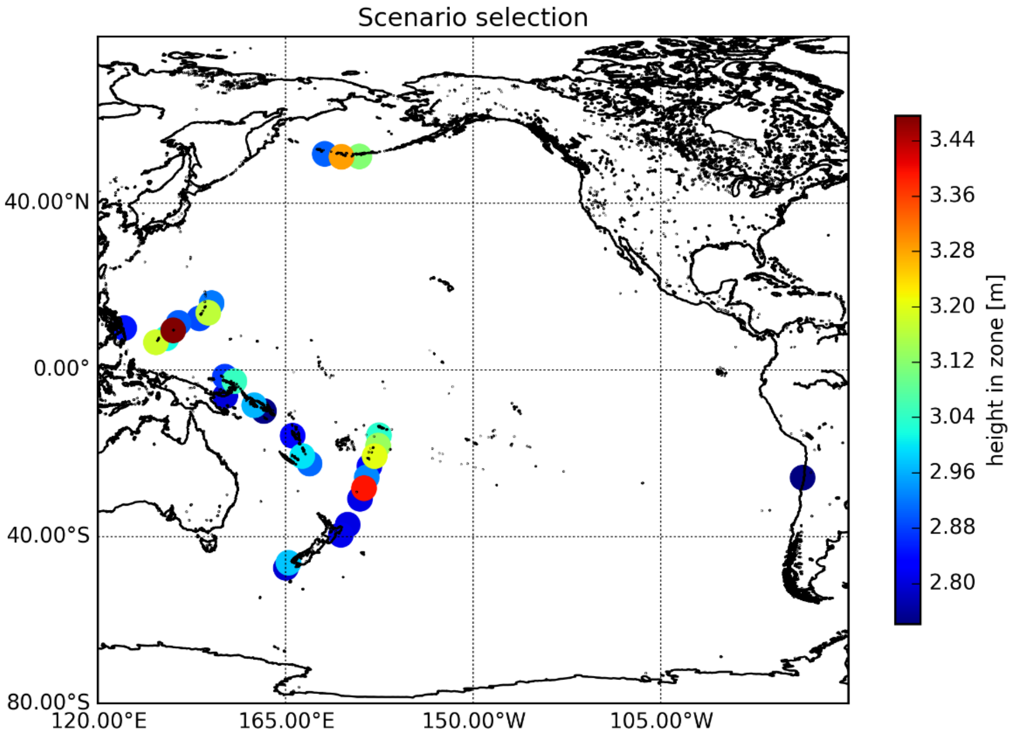


Figure 3.14 Source scenarios selected with 3 m target wave height threshold. Indicative locations for the sources listed in Table 3.4. Colour indicates the tsunami height at Forecast Zone 40 from the source model. The source ID labels are shown for each source scenario.

Table 3.4 Parameters for scenarios with 3 m target wave heights in the Westport forecasting zone (Zone 40 in the New Zealand Tsunami Threat Level database).

No.	Source_ID	Original M_W	Original Slip	Scale Factor (First Iteration)	Scaled Slip (First Iteration)	Scale Factor (Second Iteration)	Scaled Slip (Second Iteration)
1	Alaska_Pt3_Mw9.30	9.3	30.47	1.03	31.49	1.56	48.99
2	Alaska_Pt4_Mw9.30	9.3	30.48	0.91	27.83	1.59	44.24
3	Alaska_Pt5_Mw9.30	9.3	30.47	0.96	29.35	1.51	44.17
4	CSAmerica_Pt26_Mw9.30	9.3	30.49	1.09	33.37	1.48	49.25
5	EPhil_Pt4_Mw9.30	9.3	30.47	1.05	32.09	1.49	47.71
6	Hiku-Ker_Pt3_Mw9.30	9.3	32.28	1.07	34.44	0.98	33.67
7	Hiku-Ker_Pt5_Mw9.10	9.1	21.50	1.07	22.99	0.93	21.28
8	Ker-Tonga_Pt3_Mw8.90	8.9	13.86	1.07	14.79	1.22	18.06
9	Ker-Tonga_Pt4_Mw8.90	8.9	13.86	0.88	12.25	1.35	16.54
10	Ker-Tonga_Pt5_Mw8.90	8.9	13.87	1.02	14.18	1.18	16.67
11	Ker-Tonga_Pt6_Mw8.90	8.9	13.85	1.06	14.74	1.27	18.70
12	Ker-Tonga_Pt7_Mw9.10	9.1	21.51	0.94	20.16	1.08	21.87
13	Ker-Tonga_Pt8_Mw9.10	9.1	21.50	0.96	20.58	1.32	27.22
14	Ker-Tonga_Pt9_Mw9.10	9.1	21.50	0.99	21.26	1.07	22.74
15	KJIMY_Pt18_Mw9.30	9.3	30.47	1.03	31.28	1.47	45.90
16	KJIMY_Pt19_Mw9.30	9.3	30.48	0.95	28.87	1.54	44.54
17	KJIMY_Pt20_Mw9.30	9.3	30.48	1.04	31.67	1.42	45.02
18	KJIMY_Pt22_Mw9.30	9.3	30.48	1.03	31.52	1.48	46.56
19	KJIMY_Pt23_Mw9.30	9.3	39.18	0.86	33.81	1.46	49.46
20	KJIMY_Pt24_Mw9.30	9.3	30.48	1.00	30.33	1.38	41.71
21	KJIMY_Pt25_Mw9.30	9.3	45.71	0.94	43.09	1.19	51.25
22	Manus_Pt1_Mw9.30	9.3	34.29	0.98	33.75	1.33	44.99
23	Manus_Pt2_Mw9.30	9.3	30.48	1.04	31.82	1.45	46.23
24	NBSV_Pt1_Mw9.10	9.1	23.30	1.07	24.95	1.06	26.38
25	NBSV_Pt11_Mw8.90	8.9	13.86	1.00	13.86	1.13	15.62
26	NBSV_Pt12_Mw8.70	8.7	8.82	1.03	9.10	1.22	11.12
27	NBSV_Pt4_Mw8.70	8.7	8.82	1.01	8.92	1.48	13.24
28	NBSV_Pt5_Mw8.70	8.7	8.82	1.09	9.64	1.51	14.55
29	NBSV_Pt9_Mw8.90	8.9	13.86	1.06	14.71	1.36	19.95
30	Puysegur_Pt2_Mw8.70	8.7	8.82	1.07	9.47	1.24	11.77
31	Puysegur_Pt3_Mw8.70	8.7	8.82	1.01	8.90	0.68	6.05

3.4.6 Scenarios with 5 m Target Wave Height

Please refer to Table 3.5 for the list of sources and parameters that cause a coastal wave height of ~5 m in the forecast zone for Hokitika and Greymouth (Zone 39 in the New Zealand Tsunami Threat Level database). The sources and parameters that cause a coastal wave height of ~5 m in Forecast Zone 40 for Westport are listed in Table 3.6. We initially selected sources to cause a 'maximum' wave height (here, the 99th percentile of all wave heights in the zone) ranging between 4 and 6 m. Again, this initial information was taken from the current threat level database. Before modelling inundation simulation, an initial scaling was applied to achieve a 1.2*5 m = 6 m wave height locally, as described above (at MSL).

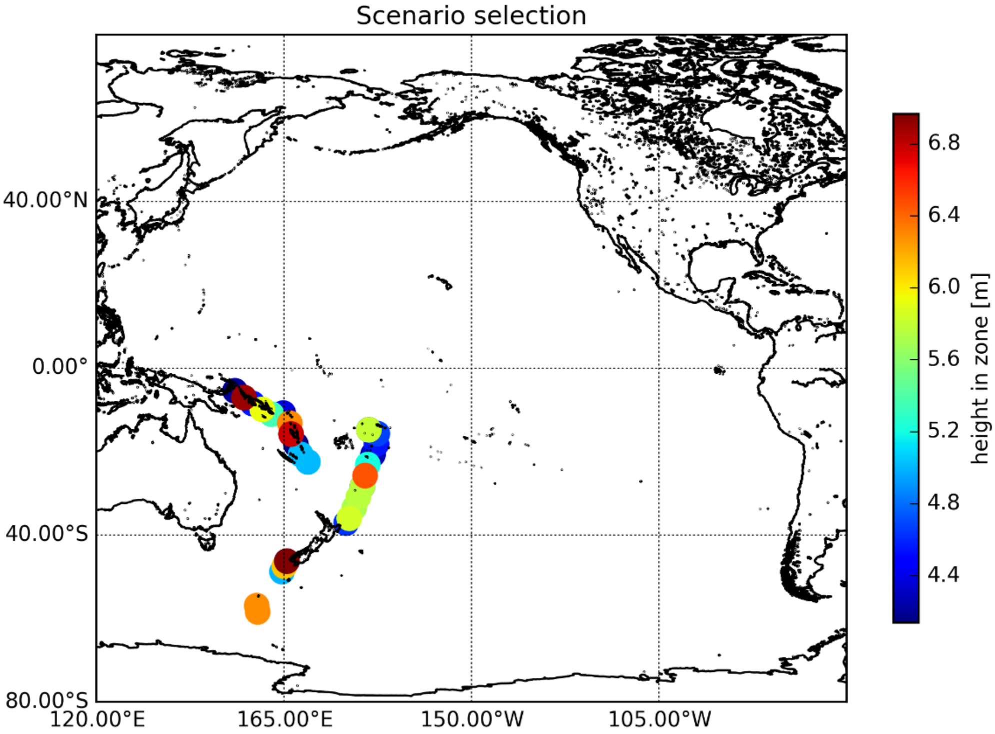


Figure 3.15 Source scenarios selected with 5 m target wave height threshold. Indicative locations for the sources listed in Table 3.5. Colour indicates the tsunami height at Forecast Zone 39 from the source model. The source ID labels are shown for each source scenario.

Table 3.5 Parameters for scenarios with 5 m target wave heights in the Hokitika and Greymouth forecasting zone (Zone 39 in the New Zealand Tsunami Threat Level database).

No.	Source_ID	Original M_W	Original Slip	Scale Factor (First Iteration)	Scaled Slip (First Iteration)	Scale Factor (Second Iteration)	Scaled Slip (Second Iteration)
1	Hiku-Ker_Pt5_Mw9.30	9.3	32.28	1.08	34.85	0.93	32.33
2	Hjort_Pt1_Mw9.30	9.3	54.85	0.80	43.61	0.80	35.08
3	Hjort_Pt2_Mw9.30	9.3	54.85	0.80	43.61	0.80	35.08
4	Ker-Tonga_Pt1_Mw9.30	9.3	32.28	0.86	27.61	0.71	19.66
5	Ker-Tonga_Pt10_Mw9.10	9.1	31.04	1.17	36.36	1.04	37.93
6	Ker-Tonga_Pt10_Mw9.30	9.3	49.89	0.86	43.04	0.96	41.43
7	Ker-Tonga_Pt2_Mw9.30	9.3	32.27	0.88	28.25	0.91	25.62
8	Ker-Tonga_Pt3_Mw9.30	9.3	32.27	0.87	27.95	0.90	25.11
9	Ker-Tonga_Pt4_Mw9.10	9.1	21.50	1.19	25.66	1.82	46.72
10	Ker-Tonga_Pt4_Mw9.30	9.3	32.27	0.87	27.98	0.96	26.83
11	Ker-Tonga_Pt5_Mw9.30	9.3	32.26	0.77	24.94	0.90	22.45
12	Ker-Tonga_Pt6_Mw9.30	9.3	32.27	0.96	30.98	0.82	25.47
13	Ker-Tonga_Pt7_Mw9.30	9.3	32.26	1.17	37.78	0.98	36.93
14	Ker-Tonga_Pt8_Mw9.30	9.3	32.26	1.10	35.39	1.02	36.02
15	Ker-Tonga_Pt9_Mw9.30	9.3	32.26	1.07	34.51	1.03	35.52
16	NBSV_Pt10_Mw9.10	9.1	19.96	1.21	24.11	1.09	26.20
17	NBSV_Pt11_Mw9.10	9.1	19.96	1.00	19.87	1.05	20.90
18	NBSV_Pt12_Mw8.90	8.9	13.86	1.00	13.85	0.98	13.55
19	NBSV_Pt2_Mw9.30	9.3	30.49	1.19	36.28	1.13	40.94
20	NBSV_Pt3_Mw9.30	9.3	30.48	0.73	22.12	1.45	32.17
21	NBSV_Pt4_Mw9.10	9.1	19.95	1.10	21.95	1.14	24.98
22	NBSV_Pt5_Mw9.10	9.1	19.96	0.84	16.81	1.34	22.53
23	NBSV_Pt6_Mw9.10	9.1	19.96	0.93	18.63	1.33	24.82
24	NBSV_Pt7_Mw9.10	9.1	19.96	1.14	22.81	1.14	25.95
25	NBSV_Pt8_Mw9.30	9.3	30.49	0.79	24.21	1.26	30.54
26	NBSV_Pt9_Mw9.10	9.1	19.96	1.16	23.22	2.26	52.38
27	NBSV_Pt9_Mw9.30	9.3	30.48	0.74	22.50	1.15	25.92
28	Puysegur_Pt1_Mw8.90	8.9	19.78	1.00	19.81	0.93	18.47
29	Puysegur_Pt2_Mw8.90	8.9	13.86	0.82	11.33	0.85	9.59
30	Puysegur_Pt3_Mw8.70	8.7	8.82	1.16	10.24	0.81	8.31
31	Puysegur_Pt3_Mw8.90	8.9	15.40	0.72	11.05	0.75	8.26

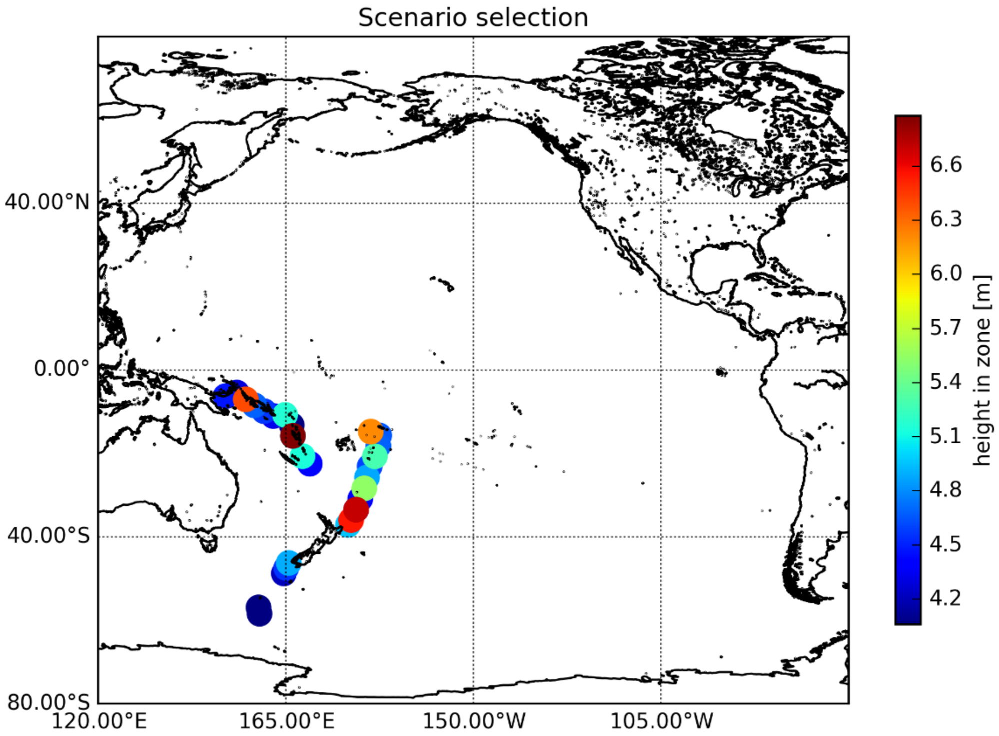


Figure 3.16 Source scenarios selected with 5 m target wave height threshold. Indicative locations for the sources listed in Table 3.6. Colour indicates the tsunami height at Forecast Zone 40 from the source model. The source ID labels are shown for each source scenario.

Table 3.6 Parameters for scenarios with 5 m target wave heights in the Westport forecasting zone (Zone 40 in the New Zealand Tsunami Threat Level database).

No.	Source_ID	Original M_W	Original Slip	Scale Factor (First Iteration)	Scaled Slip (First Iteration)	Scale Factor (Second Iteration)	Scaled Slip (Second Iteration)
1	Hiku-Ker_Pt5_Mw9.30	9.3	32.27	1.01	32.59	0.87	28.20
2	Hjort_Pt1_Mw9.10	9.1	27.96	1.23	34.39	1.61	55.49
3	Hjort_Pt2_Mw9.10	9.1	27.96	1.23	34.39	1.61	55.49
4	Ker-Tonga_Pt1_Mw9.30	9.3	32.28	0.76	24.61	0.98	24.07
5	Ker-Tonga_Pt10_Mw9.30	9.3	49.87	0.80	40.11	1.10	43.93
6	Ker-Tonga_Pt2_Mw9.10	9.1	21.50	1.17	25.26	0.94	23.76
7	Ker-Tonga_Pt2_Mw9.30	9.3	32.26	0.75	24.06	0.95	22.79
8	Ker-Tonga_Pt3_Mw9.10	9.1	21.50	1.15	24.63	1.09	26.72
9	Ker-Tonga_Pt4_Mw9.10	9.1	21.50	0.90	19.42	1.37	26.60
10	Ker-Tonga_Pt5_Mw9.10	9.1	21.50	1.02	22.00	1.34	29.50
11	Ker-Tonga_Pt6_Mw9.10	9.1	21.50	1.09	23.37	1.36	31.80
12	Ker-Tonga_Pt7_Mw9.30	9.3	32.27	0.95	30.52	1.28	38.96
13	Ker-Tonga_Pt8_Mw9.30	9.3	32.28	1.07	34.48	1.24	42.62
14	Ker-Tonga_Pt9_Mw9.30	9.3	32.28	1.07	34.63	1.10	38.02
15	NBSV_Pt1_Mw9.30	9.3	39.20	1.12	43.82	1.06	46.34
16	NBSV_Pt11_Mw9.10	9.1	19.96	0.97	19.39	1.18	22.84
17	NBSV_Pt12_Mw8.90	8.9	13.86	1.13	15.67	1.22	19.17
18	NBSV_Pt2_Mw9.30	9.3	30.49	1.17	35.57	1.06	37.59
19	NBSV_Pt3_Mw9.30	9.3	30.48	0.78	23.81	1.37	32.61
20	NBSV_Pt4_Mw8.90	8.9	13.86	1.07	14.81	1.70	25.15
21	NBSV_Pt5_Mw8.90	8.9	13.87	1.10	15.20	1.43	21.68
22	NBSV_Pt6_Mw8.90	8.9	13.86	1.16	16.01	1.60	25.59
23	NBSV_Pt7_Mw9.10	9.1	19.96	0.97	19.32	1.46	28.27
24	NBSV_Pt8_Mw9.10	9.1	19.96	1.23	24.58	1.34	32.97
25	NBSV_Pt9_Mw9.10	9.1	19.97	1.06	21.23	1.53	32.39
26	NBSV_Pt9_Mw9.30	9.3	30.47	0.73	22.15	1.20	26.65
27	Puysegur_Pt1_Mw8.90	8.9	19.79	1.19	23.50	1.22	28.58
28	Puysegur_Pt2_Mw8.90	8.9	13.87	1.10	15.23	0.68	10.38
29	Puysegur_Pt3_Mw8.90	8.9	15.41	1.02	15.76	0.54	8.49

4.0 SIMULATION RESULTS

In this section, we summarise the main findings from this study. We present simulation results from source ensembles to keep the length of the report reasonable. We define ‘ensemble’ as a set of tsunami simulations that belong to a given category such as ‘all local crustal source scenarios’ or ‘all scenarios from the same source region’ but with different distributions of slip across the fault or plate interface. We refer to the variable parameters of such a set of sources as ‘ensemble parameters’. As an example, we could be discussing the ensemble maximum of the maximum wave height for a set of scenarios or the ensemble inundation extent, which is the union of all inundation distributions for a set of scenarios.

The ‘worst-case’ source regions for Hokitika, Greymouth and Westport turn out to be the same. We have categorised the ‘worst-case’ scenario ensembles into five source regions (Cape Foulwind Fault and Kermadec, Puysegur, New Hebrides and Solomon Islands subduction zones) for an initial discussion and later combine ensemble results to describe the full potential impact of these sources. Following this, we discuss results from the 3 m and 5 m inundation scenarios. Please note that the local crustal Cape Foulwind Fault source scenarios were used in tsunami inundation simulations in the ‘worst-case’ scenario category.

4.1 Worst-Case Scenarios

Here, we present the inundation results and wave time series at points of interest in Hokitika, Greymouth and Westport. For each location, we present the ensemble map for each source region. The relatively large number of scenarios are best presented by looking at ensemble diagrams, which summarise the impact of certain scenario sets.

4.1.1 Comparison of Worst-Case Candidates in Hokitika

In the following, we present results from the set of scenarios considered possible worst-case candidates for Hokitika. The source areas include the Puysegur, Kermadec, Solomon Islands and New Hebrides subduction zones and Cape Foulwind Fault. Please refer to Section 3.3 for detail on how these sources were derived. For each subduction zone, 10 non-uniform slip scenarios were generated. The maximum ensemble inundation flow depth in Hokitika for the combination of all 10 non-uniform slip scenarios from Puysegur at magnitude M_W 9.07 (40 GPa) is shown in Figure 4.1. The ensemble inundation flow depth from all Kermadec scenarios at magnitude Mw 9.42 is shown Figure 4.2. The ensemble inundation flow depth from all New Hebrides scenarios at magnitude Mw 9.37 is shown in Figure 4.3. The ensemble inundation flow depth from all Solomon Islands scenarios at magnitude Mw 9.3 is shown in Figure 4.4. The ensemble inundation flow depth from all Cape Foulwind Fault scenarios at magnitude Mw 7.8 is shown in Figure 4.5. It should be noted that each of these figures shows ensemble maximum water level above MSL in the offshore. On land, the figures show ensemble maximum flow depth. Individual scenario results (inundation flow depth, inundation extent and time series at points of interest) are provided in the electronic supplement to this report. Please see Section 8 for details.

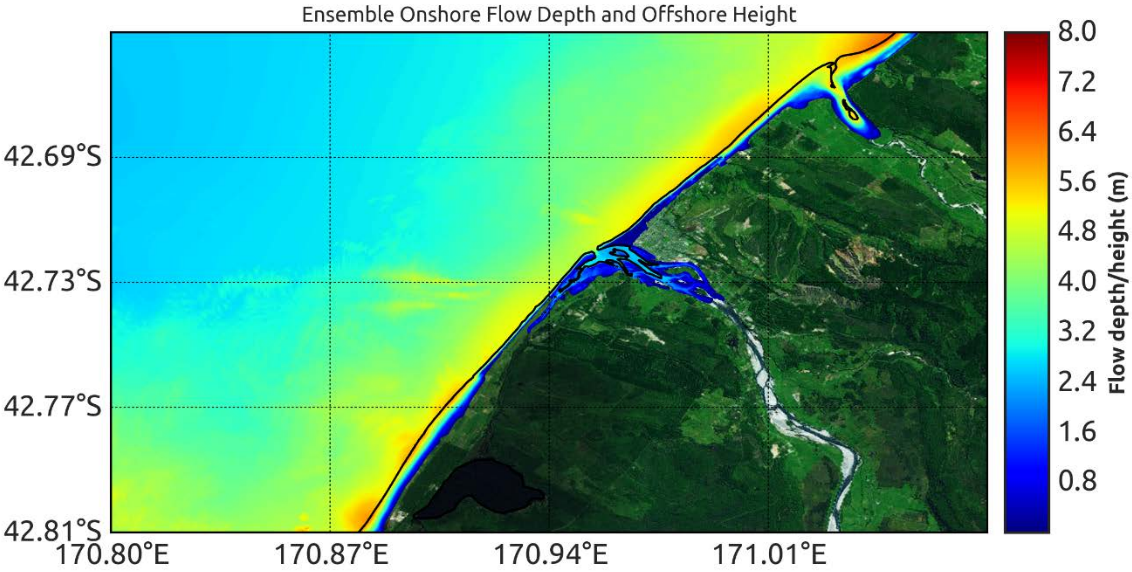


Figure 4.1 Ensemble inundation extent and ensemble maximum flow depth in Hokitika for **all 10 non-uniform slip scenarios with Mw 9.07 from Puysegur (PT_Pt3)** (onshore: flow depth; offshore values refer to maximum wave amplitudes). Simulations assume that the largest waves arrive at MHWS (1.1 m above MSL).

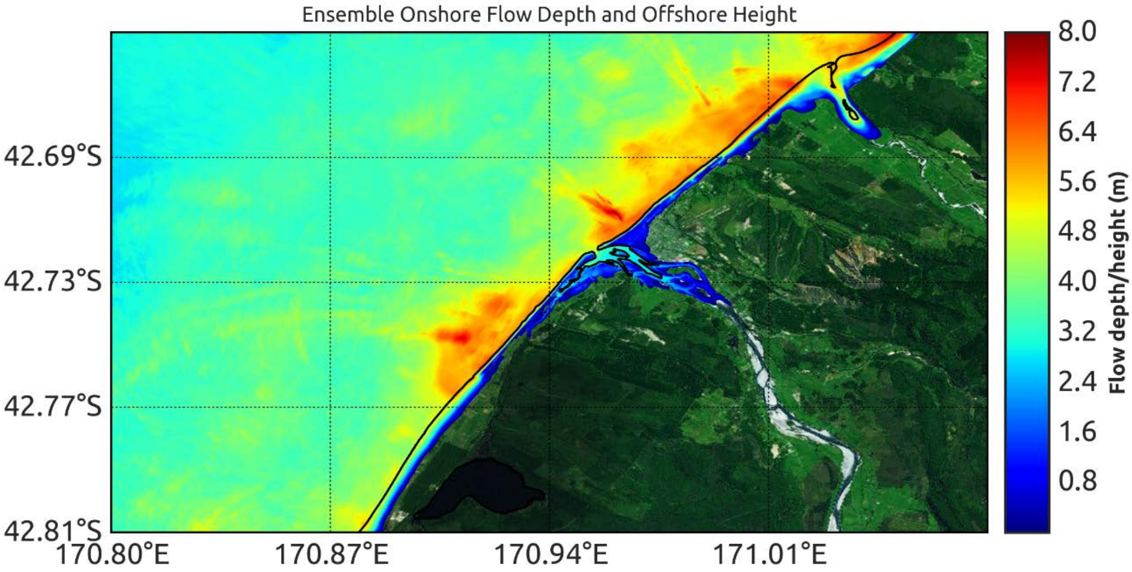


Figure 4.2 Ensemble inundation extent and ensemble maximum flow depth in Hokitika for **all 10 non-uniform slip scenarios with Mw 9.42 from Kermadec (KT_Pt5)** (onshore: flow depth; offshore values refer to maximum wave amplitudes). Simulations assume that the largest waves arrive at MHWS (1.1 m above MSL).

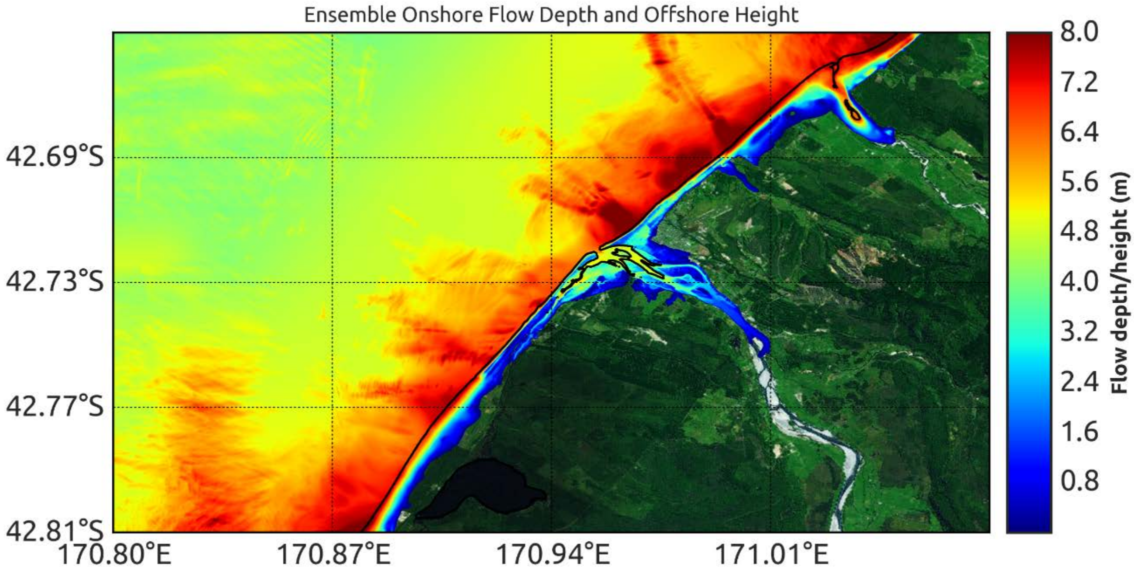


Figure 4.3 Ensemble inundation extent and ensemble maximum flow depth in Hokitika for **all 10 non-uniform slip scenarios with Mw 9.37 from New Hebrides (NBSV_Pt12)** (onshore: flow depth; offshore values refer to maximum wave amplitudes). Simulations assume that the largest waves arrive at MHWS (1.1 m above MSL).

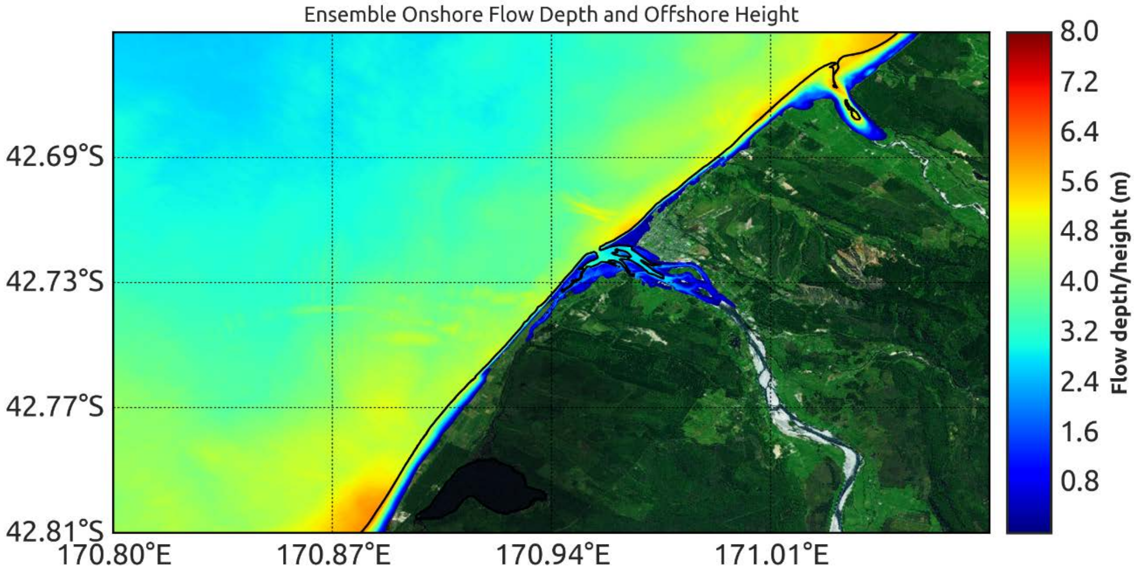


Figure 4.4 Ensemble inundation extent and ensemble maximum flow depth in Hokitika for **all 10 non-uniform slip scenarios with Mw 9.3 from Solomon Islands (NBSV_pt5)** (onshore: flow depth; offshore values refer to maximum wave amplitudes). Simulations assume that the largest waves arrive at MHWS (1.1 m above MSL).

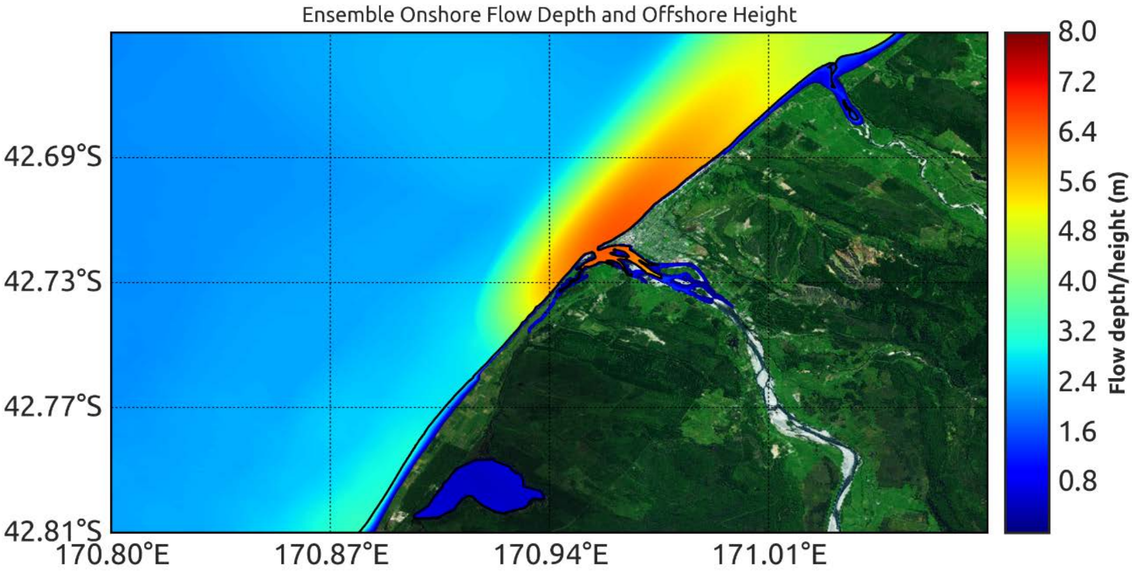


Figure 4.5 Ensemble inundation extent and ensemble maximum flow depth in Hokitika for **all 10 non-uniform slip scenarios with Mw 7.8 from Cape Foulwind Fault (CFF)** (onshore: flow depth; offshore values refer to maximum wave amplitudes). Simulations assume that the largest waves arrive at MHWS (1.1 m above MSL).

Comparing the results, we observe that the largest impact in terms of inundation extent and maximum wave heights offshore at the Hokitika coast is found from the New Hebrides scenario ensemble.

Tsunami heights along the coast from the scenarios in the Puysegur and Solomon Islands subduction zones (4.8–6.3 m) are smaller than 7 m from the 2500-year tsunami return period at 84% confidence level (Power 2014). The tsunami heights from the scenarios in the Kermadec subduction zone are close (5.7–7.1 m) to the value for the return period, whereas most of the tsunami heights from the New Hebrides scenarios are slightly larger (7.2–10.0 m) than the value for the return period. The maximum tsunami height around Hokitika from the Cape Foulwind scenarios is up to 8 m above MSL. However, the tsunami causes little inundation of the land (Figure 4.5) because the fault movement uplifts the town; the uplift is almost the same as the maximum tsunami height. The tsunami from the Cape Foulwind Fault scenarios give little tsunami inundation, although an earthquake from the fault will be strongly felt in Hokitika. The Puysegur subduction zone remains the source of the largest tsunami that are expected to be accompanied by strongly felt earthquake shaking.

The maximum tsunami inundation from all considered scenarios is shown in Figure 4.8. Almost all coastal land within 300–500 m of the shoreline, and many areas adjacent to the Hokitika River mouth, are inundated (in at least some of the scenarios). Figure 4.7 shows the frequency of each modelling cell being inundated from the set of scenarios. In previous evacuation zone studies that GNS Science has done, the council involved has used an envelope that covers a proportion (e.g. 75%) of the scenarios for the evacuation zone in order to exclude those areas that are very rarely inundated (Note: this needs to be done in such a way that the 2500-year 84% minimum requirement is still met – see Section 5 for explanation of how this was applied in this study).

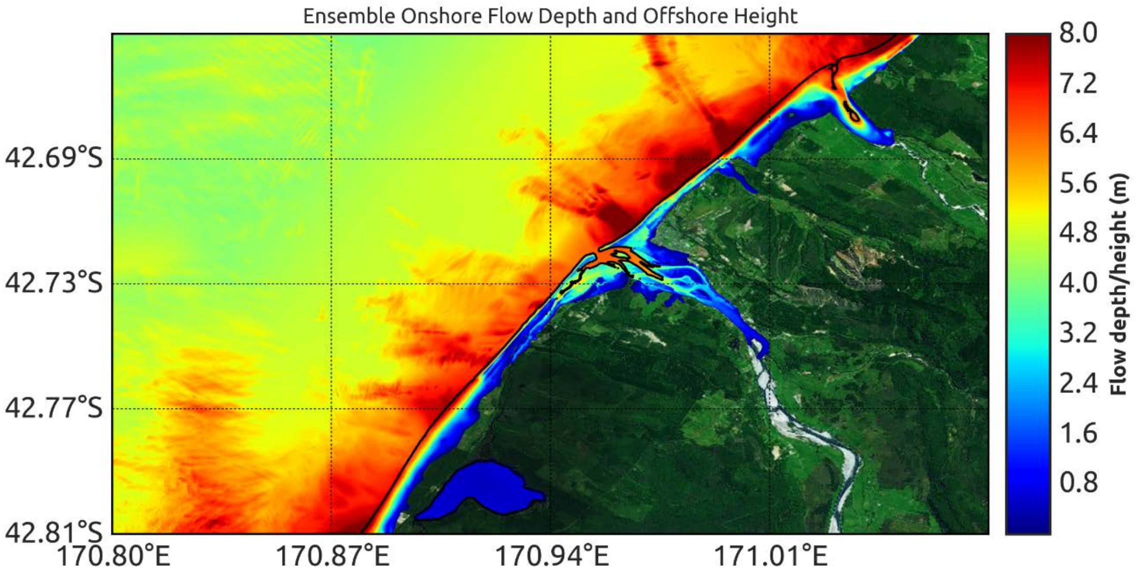


Figure 4.6 Ensemble inundation extent and ensemble maximum flow depth in Hokitika for **all 50 non-uniform slip scenarios** from Cape Foulwind Fault and Puysegur, Kermadec, New Hebrides and Solomon Islands subduction zones (onshore: flow depth; offshore values refer to maximum wave amplitudes). Simulations assume that the largest waves arrive at MHWS (1.1 m above MSL).

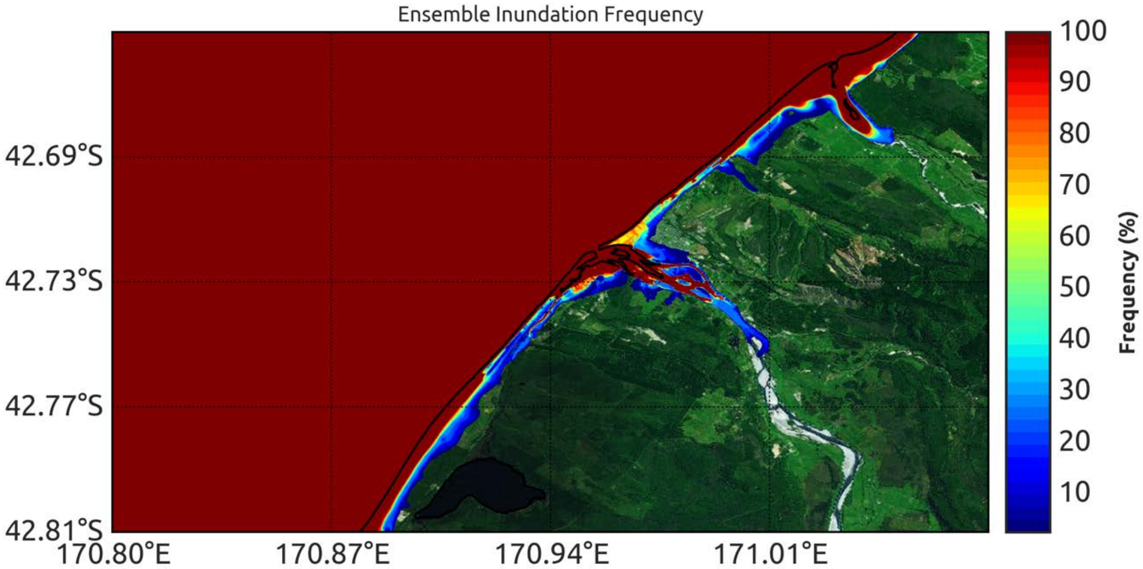


Figure 4.7 Frequency of inundation map showing how often each modelling cell is inundated by all considered earthquake scenarios in Hokitika.

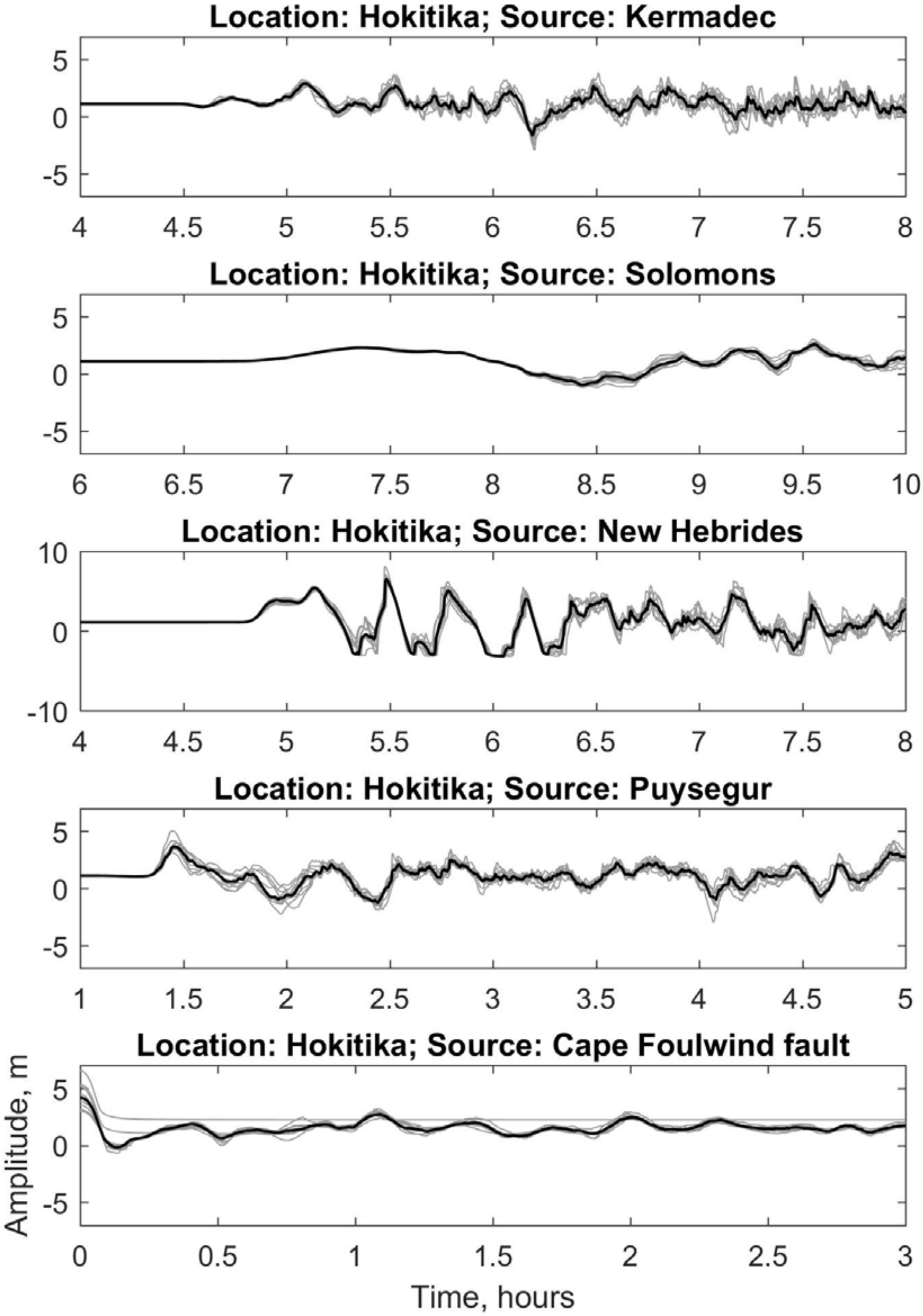


Figure 4.8 Ensemble time series at points of interest at Hokitika River mouth for **all modelled Kermadec, Solomon Islands, New Hebrides, Puysegur and Cape Foulwind scenarios**. In grey are all time series and, in black, the average time series out of all scenarios. Ambient water level is assumed to be at MHWS (1.1 m above MSL).

4.1.2 Comparison of Worst-Case Candidates in Greymouth

In the following, we present results from the set of scenarios considered possible worst-case candidates for Greymouth. The source areas include the Puysegur, Kermadec, Solomon Islands and New Hebrides subduction zones. Please refer to Section 3.3 for detail on how these sources were derived. For each subduction zone, 10 non-uniform slip scenarios were generated. The ensemble inundation flow depth in Greymouth for the combination of all 10 non-uniform slip scenarios from Puysegur at magnitude Mw 9.07 (40 GPa) is shown in Figure 4.9. The ensemble inundation flow depth from all Kermadec scenarios at magnitude Mw 9.42 is shown in Figure 4.10. The ensemble inundation flow depth from all New Hebrides scenarios at magnitude Mw 9.37 is shown in Figure 4.11. The ensemble inundation flow depth from all Solomon Islands scenarios at magnitude Mw 9.3 is shown in Figure 4.12. Lastly, the ensemble inundation flow depth from all Cape Foulwind Fault scenarios at magnitude Mw 7.8 is shown in Figure 4.13. Individual scenario results (inundation flow depth, inundation extent and time series at points of interest) are provided in the electronic supplement to this report. Please see Section 8 for details.

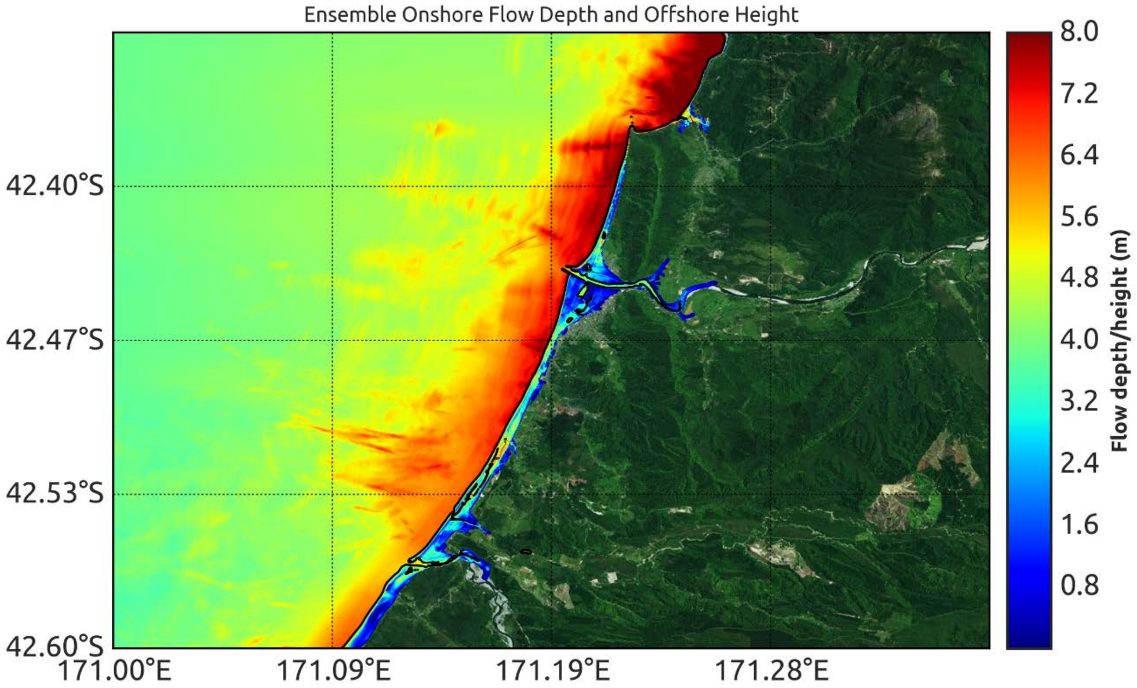


Figure 4.9 Ensemble inundation extent and ensemble maximum flow depth in Greymouth for **all 10 non-uniform slip scenarios with Mw 9.07 from Puysegur (PT_Pt3)** (onshore: flow depth; offshore values refer to maximum wave amplitudes). Simulations assume that the largest waves arrive at MHWS (1.4 m above MSL).

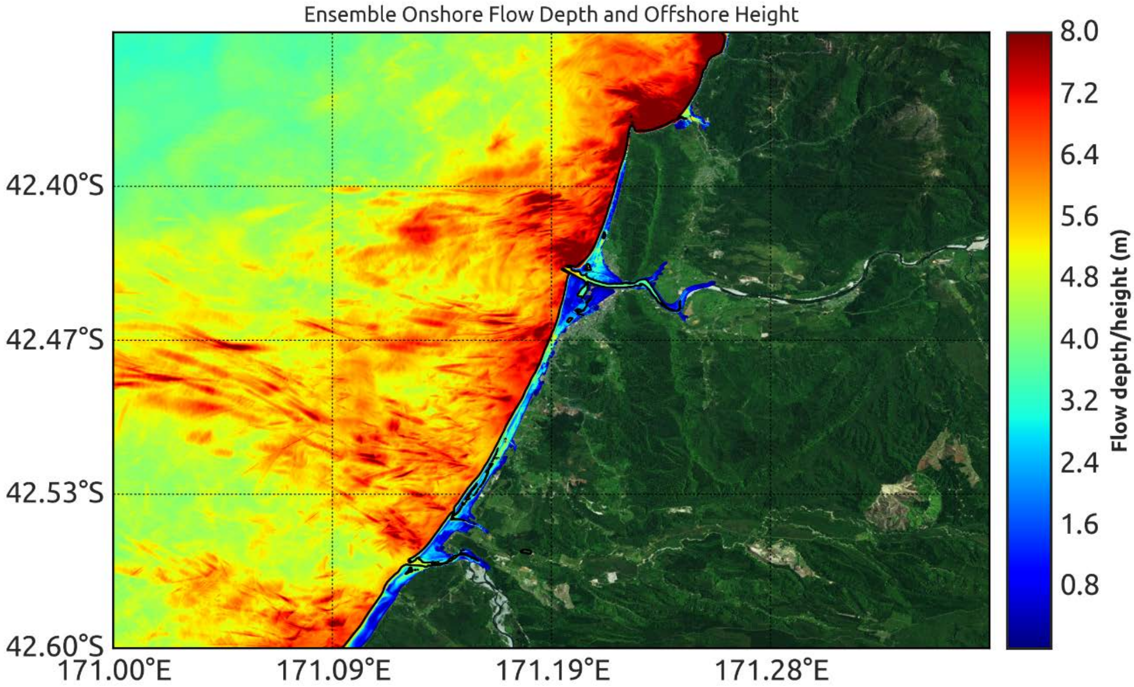


Figure 4.10 Ensemble inundation extent and ensemble maximum flow depth in Greymouth for **all 10 non-uniform slip scenarios with Mw 9.42 from Kermadec (KT_Pt5)** (onshore: flow depth; offshore values refer to maximum wave amplitudes). Simulations assume that the largest waves arrive at MHWS (1.4 m above MSL).

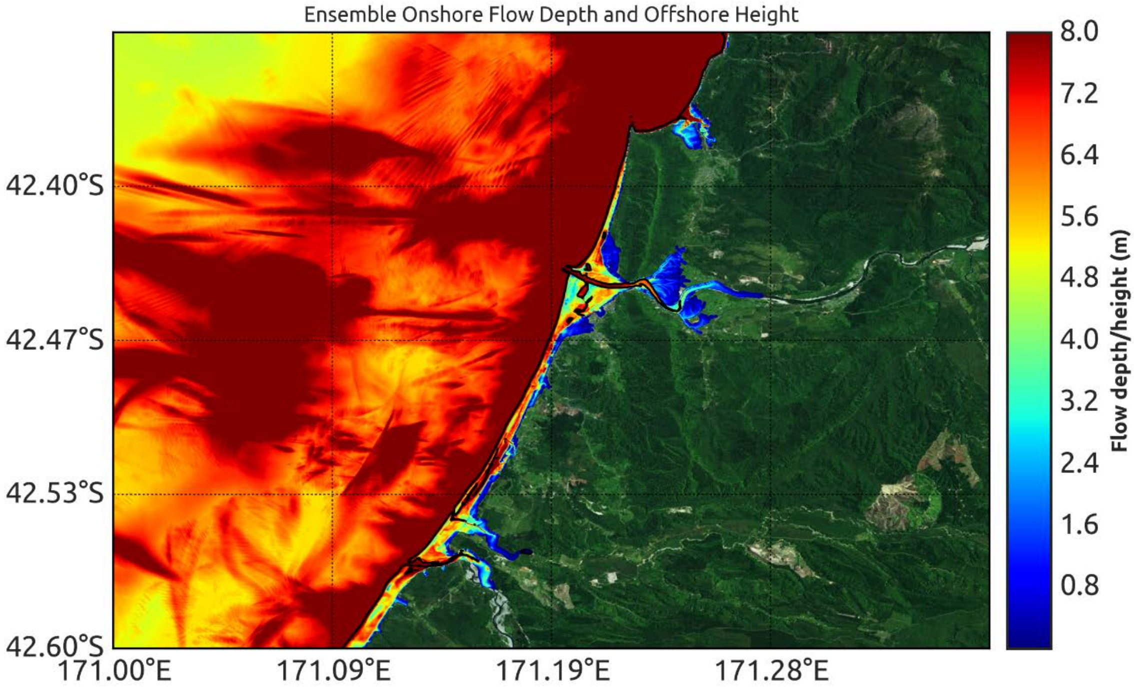


Figure 4.11 Ensemble inundation extent represented as ensemble maximum flow depth in Greymouth **for all 10 non-uniform slip scenarios with Mw 9.37 form New Hebrides (NBSV_Pt12)** (onshore; offshore values refer to maximum wave amplitudes). Simulations assume that the largest waves arrive at MHWS (1.4 m above MSL).

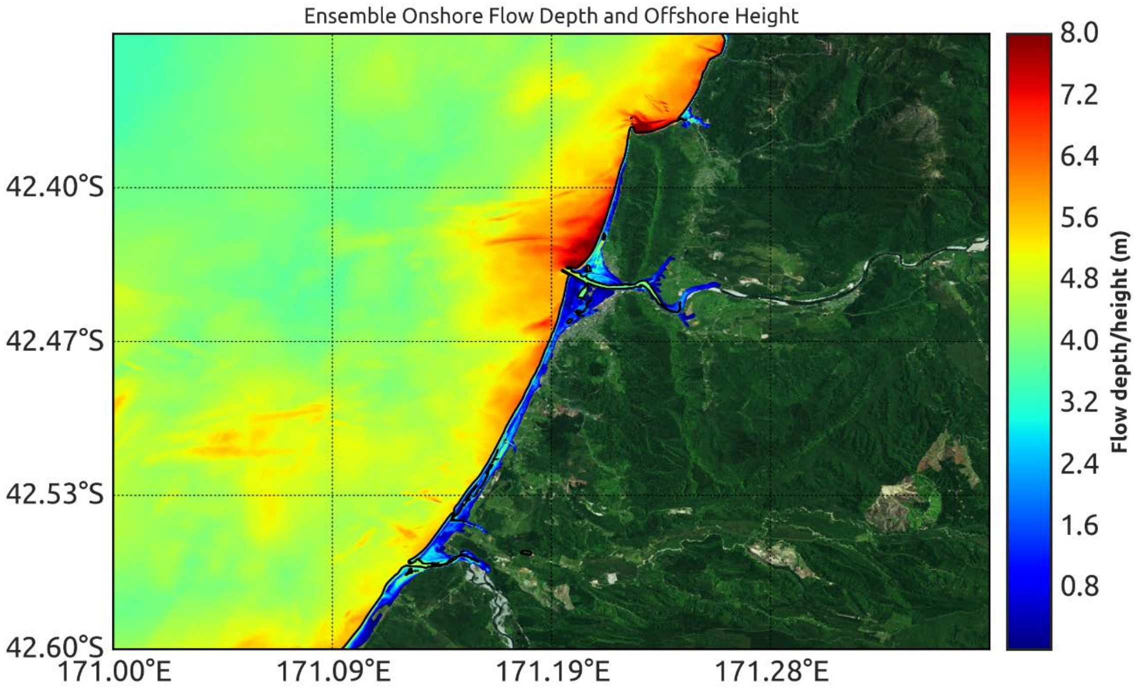


Figure 4.12 Ensemble inundation extent and ensemble maximum flow depth in Greymouth for **all 10 non-uniform slip scenarios with Mw 9.3 from Solomon Islands (NBSV_pt5)** (onshore: flow depth; offshore values refer to maximum wave amplitudes). Simulations assume that the largest waves arrive at MHWS (1.4 m above MSL).

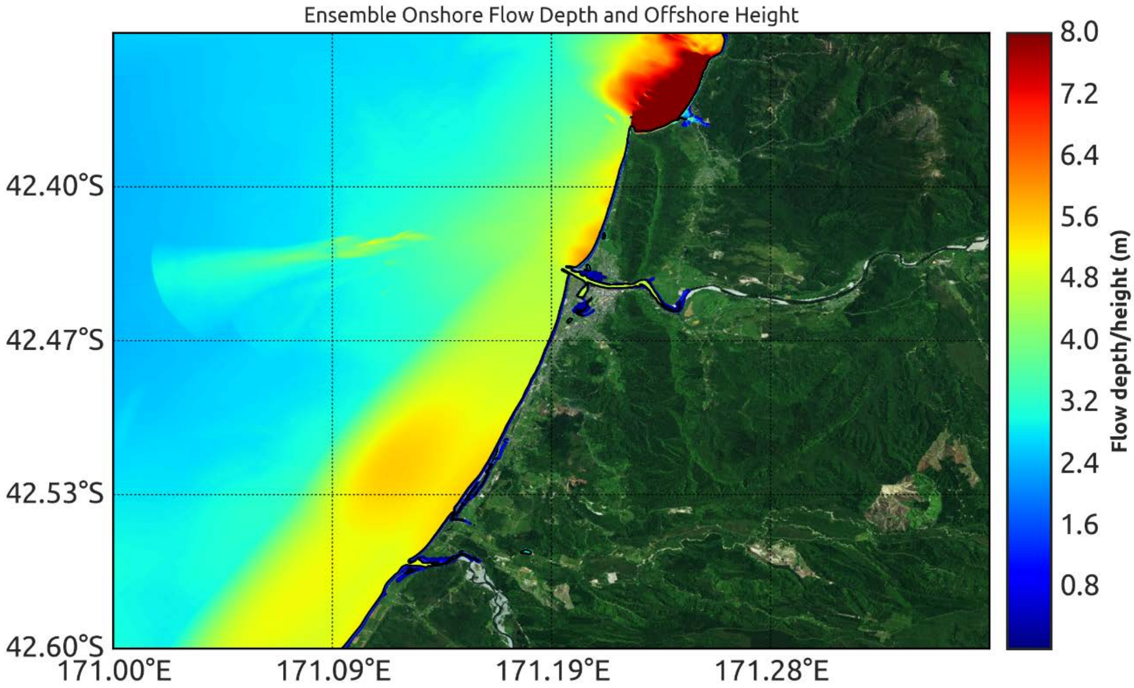


Figure 4.13 Ensemble inundation extent and ensemble maximum flow depth in Greymouth for **all 10 non-uniform slip scenarios with Mw 7.8 from Cape Foulwind Fault (CFF)** (onshore: flow depth; offshore values refer to maximum wave amplitudes). Simulations assume that the largest waves arrive at MHWS (1.4 m above MSL).

By comparing the results, we observe that the main impact in terms of inundation extent and maximum wave heights offshore at the Greymouth coast is again found from the New Hebrides scenario ensemble. Tsunami heights along the coast from the Solomon Islands, Kermadec and Puysegur scenarios are between 6.9 m and 11.6 m, which are still close to the 7 m tsunami height for the 2500-year return period. Whereas, the tsunami heights along the coast from the New Hebrides scenarios are between 12.8 and 15.9 m, about twice as large as the value for the return period. The Cape Foulwind Fault scenarios give little inundation, as the uplift is almost the same as the maximum tsunami height. The maximum tsunami height around Greymouth (Grey River) is up to 5 m above MSL. However, the tsunami causes little land inundation (Figure 4.13) because the fault movement uplifts the town; the uplift is almost the same as the maximum tsunami height, just like the case for Hokitika. The Puysegur subduction zone remains as the source of the largest tsunami that are expected to be accompanied by strongly felt earthquake shaking.

The maximum tsunami inundation from all considered scenarios is shown in Figure 4.16. Almost all coastal land within 1 km of the shoreline, and many areas adjacent to riverbanks, are inundated (in at least one of the New Hebrides scenarios). Areas of low topography farmland next to the Grey River are inundated (in at least some scenarios) up to about 3.5 km from the shoreline. Figure 4.15 shows the frequency of each modelling cell being inundated from the set of scenarios.

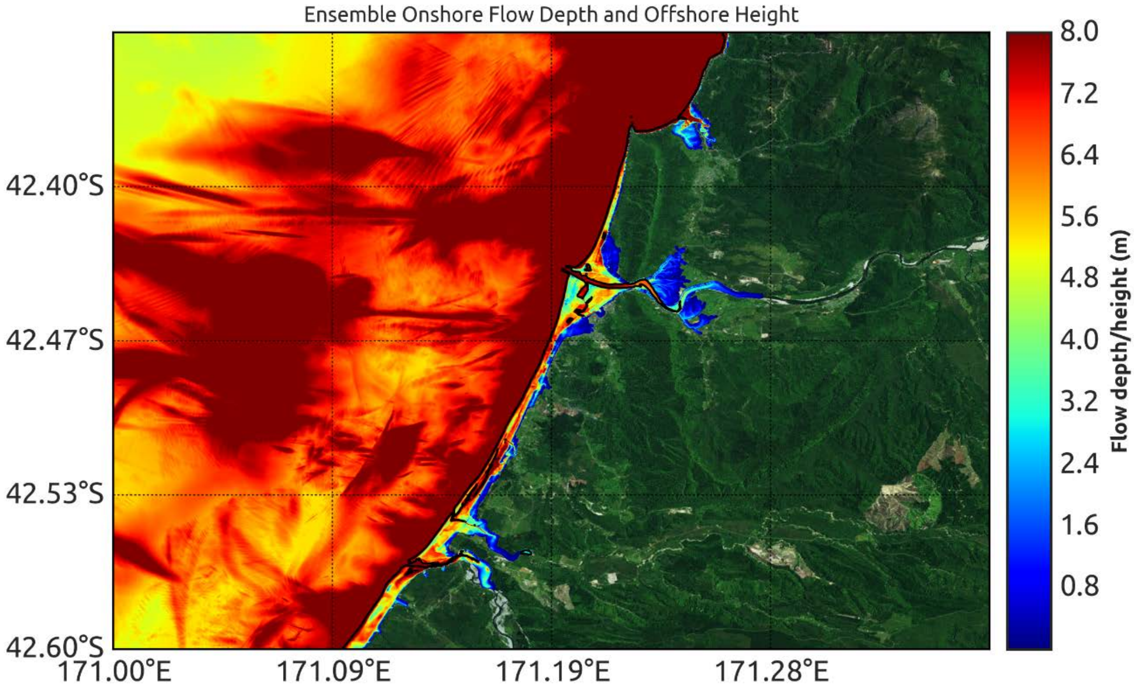


Figure 4.14 Ensemble inundation extent and ensemble maximum flow depth in Greymouth for **all 50 non-uniform slip scenarios** from Cape Foulwind Fault and the Puysegur, Kermadec, New Hebrides and Solomon Islands subduction zones (onshore: flow depth; offshore values refer to maximum wave amplitudes). Simulations assume that the largest waves arrive at MHWS (1.4 m above MSL).

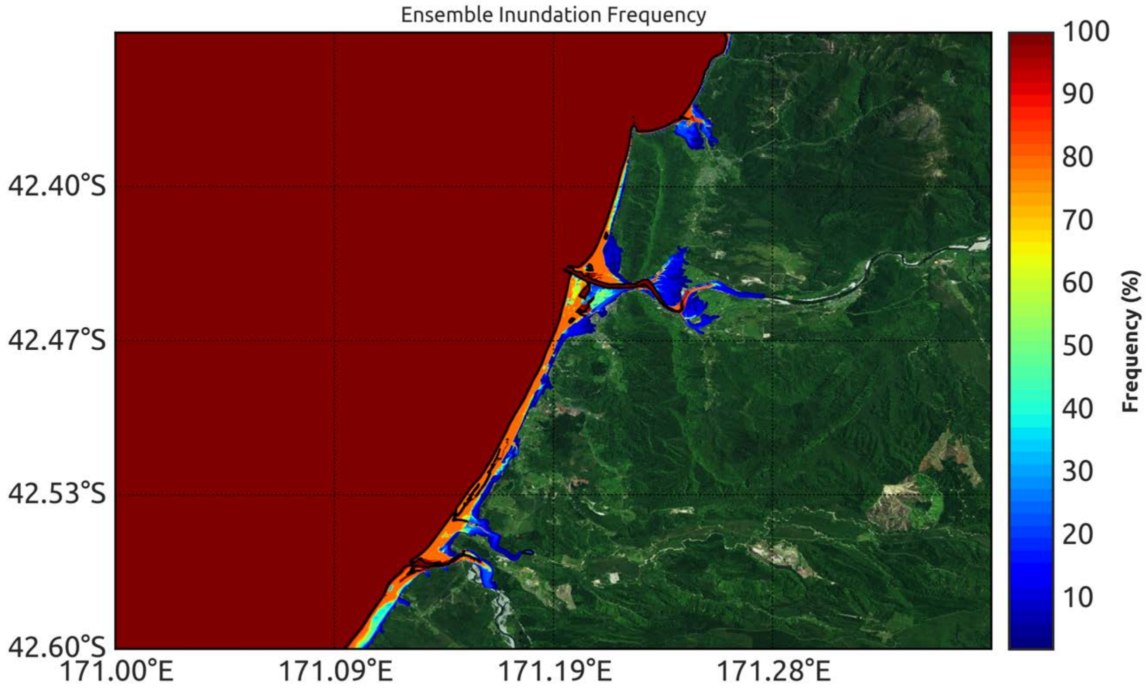


Figure 4.15 Frequency of inundation map showing how often each modelling cell is inundated by all considered earthquake scenarios in Greymouth.

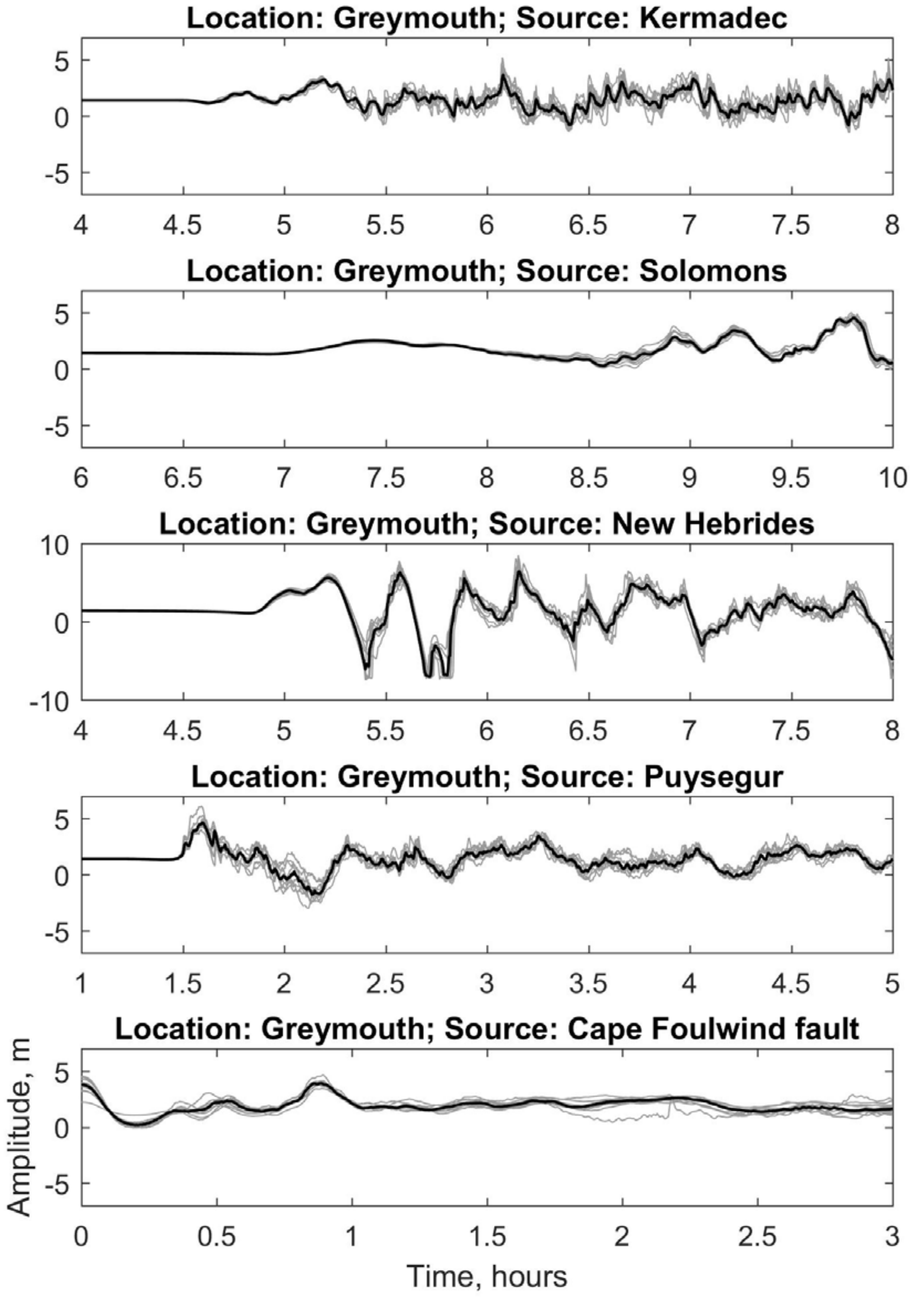


Figure 4.16 Ensemble time series at points of interest at Grey River mouth for **all** modelled **Kermadec, Solomon Islands, New Hebrides, Puysegur and Cape Foulwind scenarios**. In grey are all time series and, in black, the average time series out of all scenarios. Ambient water level is assumed to be at MHWS (1.4 m above MSL).

4.1.3 Comparison of Worst-Case Candidates in Westport

In the following, we present results from the set of scenarios considered possible worst-case candidates for Westport. The source areas include the Puysegur, Kermadec, Solomon Islands and New Hebrides subduction zones and crustal fault Cape Foulwind Fault. Please refer to Section 3.3 for detail on how these sources were derived. For each subduction zone, 10 non-uniform slip scenarios were generated. The ensemble inundation flow depth in Westport for the combination of all Puysegur scenarios at magnitude Mw 9.07 (40 GPa) is shown in Figure 4.17. The ensemble inundation flow depth for the combination of all Kermadec scenarios at magnitude Mw 9.42 is shown in Figure 4.18. The ensemble inundation flow depth for the combination of all New Hebrides scenarios at magnitude Mw 9.37 is shown in Figure 4.19. The ensemble inundation flow depth for the combination of all Solomon Islands scenarios at magnitude Mw 9.3 is shown in Figure 4.20. The ensemble inundation flow depth for the combination of all Cape Foulwind Fault scenarios at magnitude Mw 9.3 is shown in Figure 4.21. Individual scenario results (inundation flow depth, inundation extent and time series at points of interest) are provided in the electronic supplement to this report. Please see Section 8 for details.

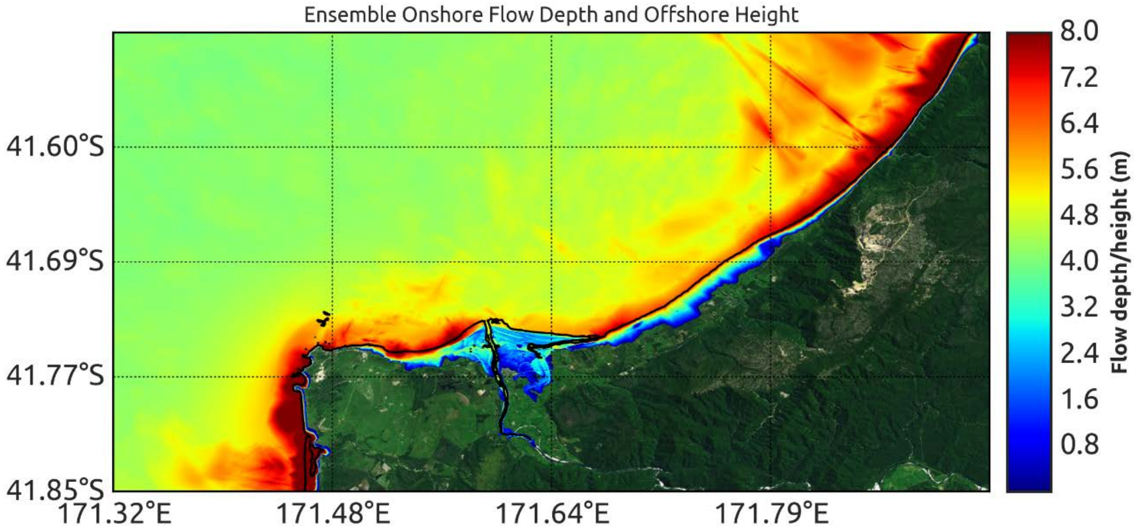


Figure 4.17 Ensemble inundation extent and ensemble maximum flow depth for **all 10 non-uniform slip scenarios with Mw 9.07 from Puysegur (PT_Pt3)** (onshore: flow depth; offshore values refer to maximum wave amplitudes). Simulations assume that the largest waves arrive at MHWS (1.45 m above MSL).

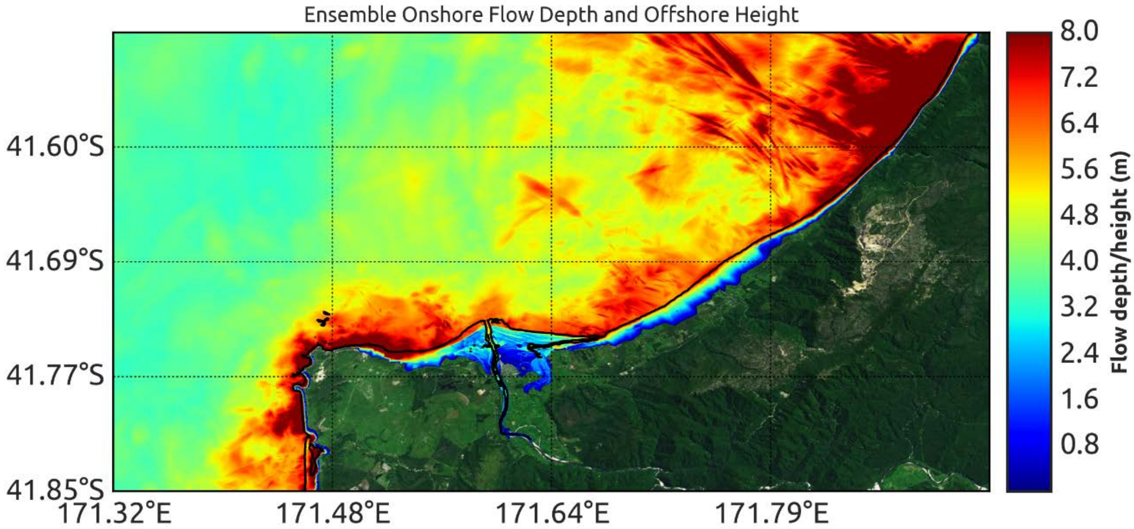


Figure 4.18 Ensemble inundation extent and ensemble maximum flow depth in Westport for **all 10 non-uniform slip scenarios with Mw 9.42 from Kermadec (KT_Pt5)** (onshore: flow depth; offshore values refer to maximum wave amplitudes). Simulations assume that the largest waves arrive at MHWS (1.45 m above MSL).

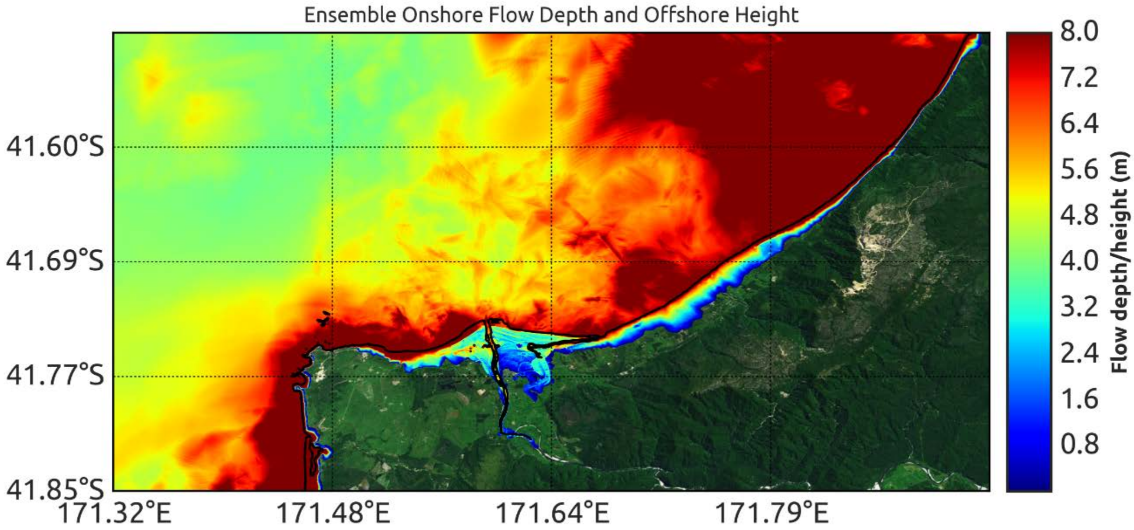


Figure 4.19 Ensemble inundation extent and ensemble maximum flow depth in Westport for **all 10 non-uniform slip scenarios with Mw 9.37 from New Hebrides (NBSV_Pt12)** (onshore; offshore values refer to maximum wave amplitudes). Simulations assume that the largest waves arrive at MHWS (1.4 m above MSL).

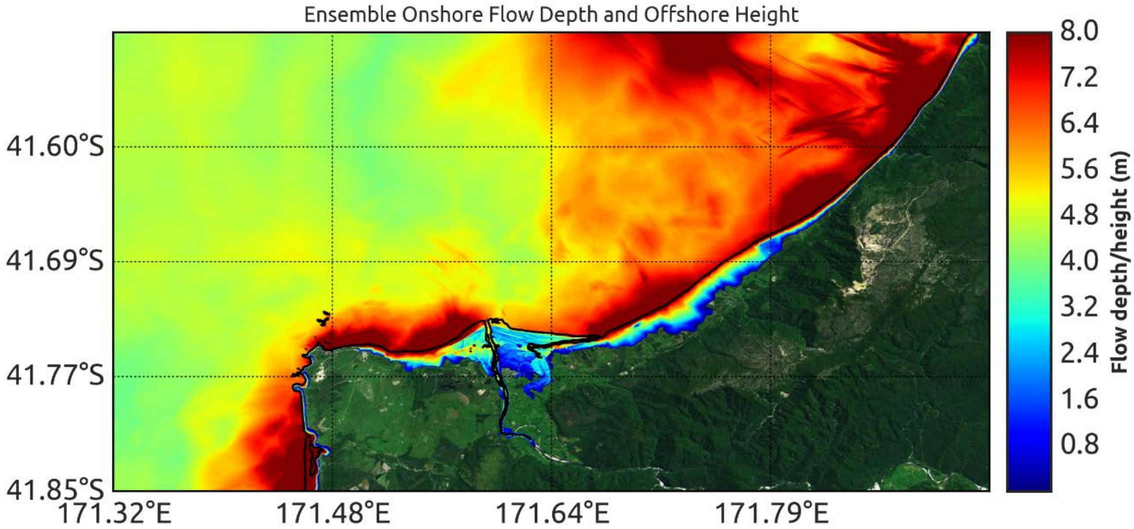


Figure 4.20 Ensemble inundation extent and ensemble maximum flow depth in Westport for all **10 non-uniform slip scenarios with Mw 9.3 from Solomon Islands (NBSV_pt5)** (onshore: flow depth; offshore values refer to maximum wave amplitudes). Simulations assume that the largest waves arrive at MHWS (1.45 m above MSL).

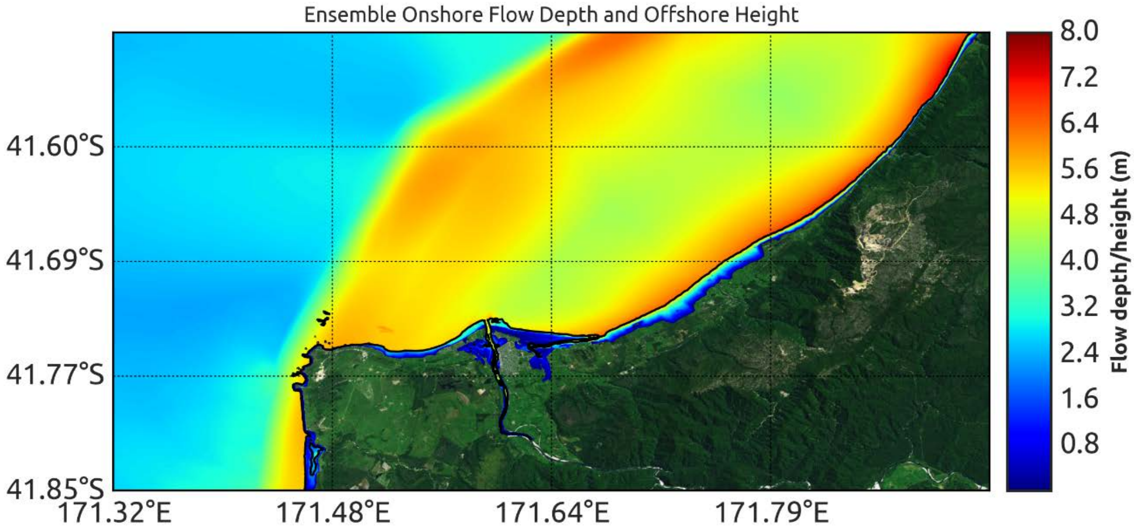


Figure 4.21 Ensemble inundation extent and ensemble maximum flow depth in Westport for **all 10 non-uniform slip scenarios with Mw 7.8 from Cape Foulwind Fault (CFF)** (onshore: flow depth; offshore values refer to maximum wave amplitudes). Simulations assume that the largest waves arrive at MHWS (1.45 m above MSL).

By comparing the results, we observe that the tsunami inundation extent in Westport from the Puysegur, Kermadec, New Hebrides and Solomon Islands ensemble scenarios are almost the same. The maximum tsunami height at the coast of Westport from the ensemble scenarios for every source region is about 8 m. This height is close to the 7 m tsunami height for the 2500-year return period for Westport.

The uplift in Westport from the Cape Foulwind scenarios are 3–5 m, depending on the scenario. Unlike Hokitika and Greymouth, the fault line near Westport is farther offshore. For some of the Cape Foulwind scenarios, the tsunami height at the Westport coast is higher than the uplift, thus the beaches and lowlands around Buller River and Orowaiti Lagoon are inundated. However, the inundated area is still much smaller those from any of the distant and regional subduction zone worst-case scenarios. The Puysegur subduction zone (which is on the border between being a local and regional source) remains as the source of the largest tsunami that are expected to be accompanied by strongly felt earthquake shaking.

The maximum tsunami inundation from all considered scenarios is shown in Figure 4.22. More than half of the town of Westport is inundated in the ensemble inundation map. Only the southern part of the town is not inundated. Figure 4.23 shows the frequency of each modelling cell being inundated from the set of scenarios.

In this case, there is little difference in the maximum inundation extent from any of the scenarios. The area inundated seems to be mainly controlled by topography.

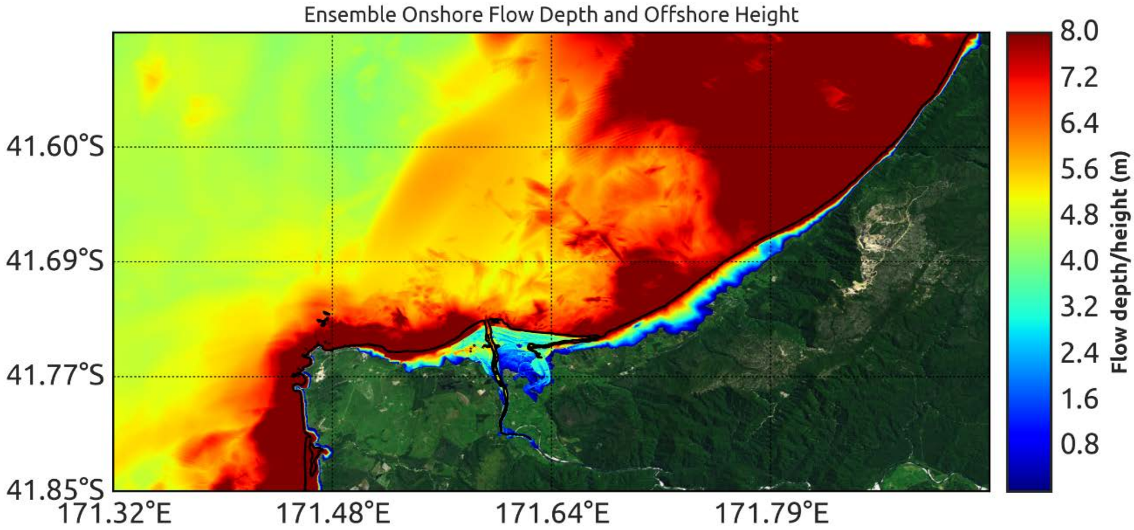


Figure 4.22 Ensemble inundation extent and ensemble maximum flow depth in Westport for **all 50 non-uniform slip scenarios** from Cape Foulwind Fault and Puysegur, Kermadec, New Hebrides and Solomon Islands subduction zones (onshore: flow depth; offshore values refer to maximum wave amplitudes). Simulations assume that the largest waves arrive at MHWS (1.45 m above MSL).

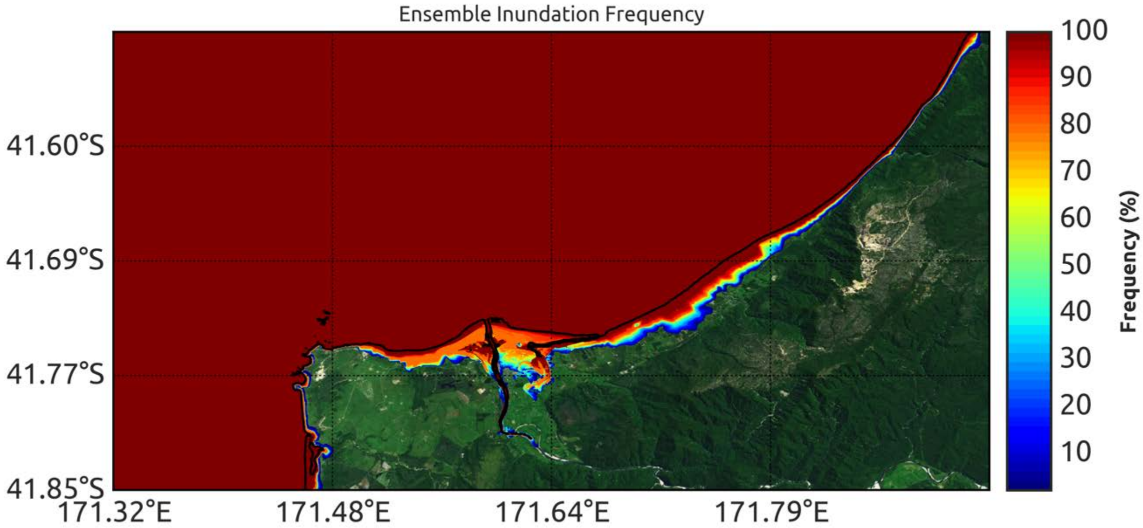
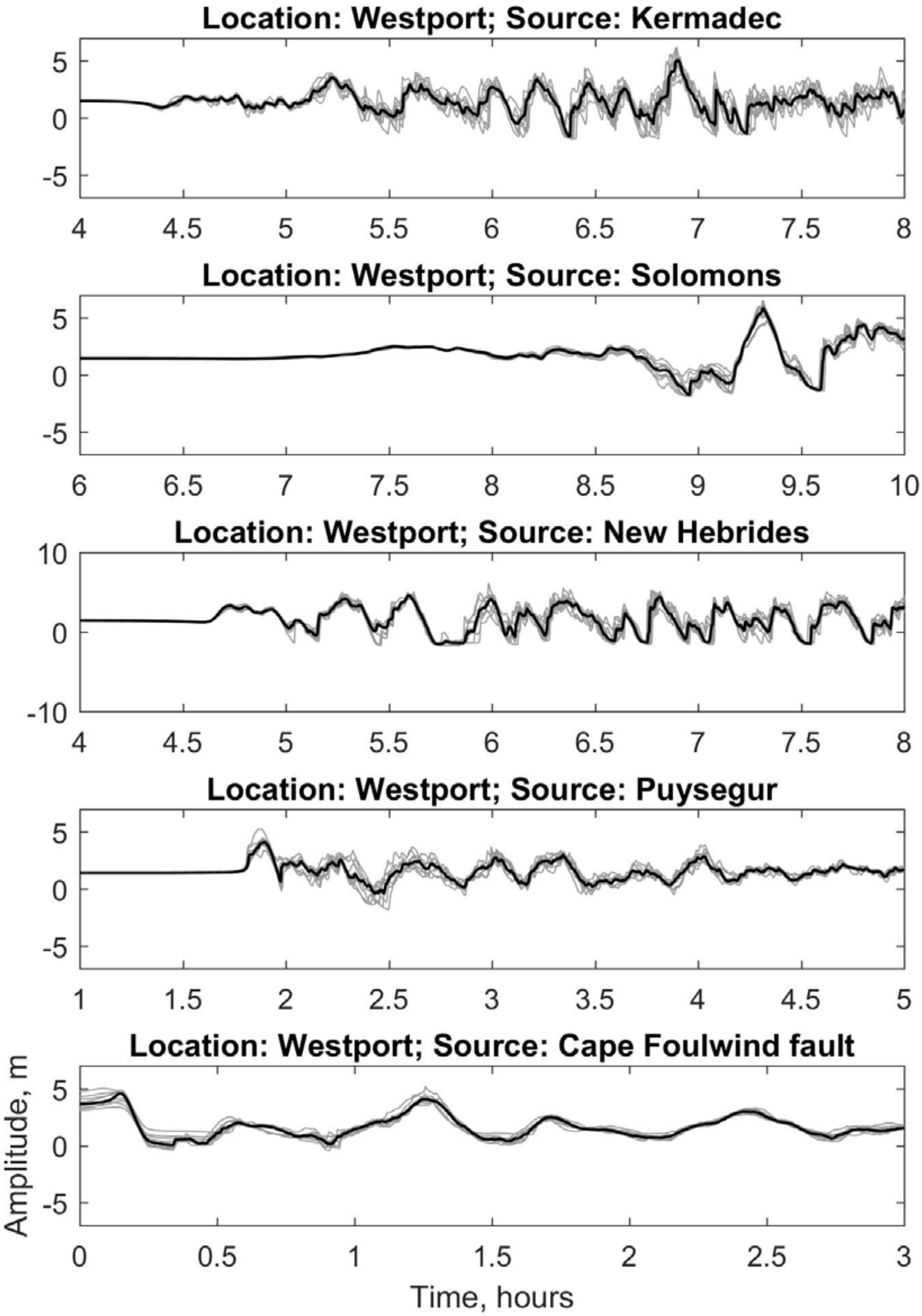


Figure 4.23 Frequency of inundation map showing how often each modelling cell is inundated by all considered earthquake scenarios for the Yellow Zone in Westport.


Location: Westport; Source: Kermadec

Location: Westport; Source: Solomons

Location: Westport; Source: New Hebrides

Location: Westport; Source: Puysegur

Location: Westport; Source: Cape Foulwind fault

Figure 4.24 Ensemble time series at points of interest at Buller River mouth for **all modelled Kermadec, Solomon Islands, New Hebrides, Puysegur and Cape Foulwind scenarios**. In grey are all time series and, in black, the average time series out of all scenarios. Ambient water level is assumed to be at MHWS (1.45 m above MSL).

4.2 Scenarios With 3 m and 5 m Target Wave Heights

In this section, we present the inundation simulation results and simulated waves at given points of interest for the scenarios that reach 3 m and 5 m in the tsunami Forecast Zones 39 (for Hokitika and Greymouth) and 40 (for Westport), as described in Section 3.4. Again, the relatively large number of scenarios are best presented by looking at ensemble diagrams. We considered 29 scenarios for the 3 m case and 31 for the 5 m case. All scenarios assumed uniform slip. Ensembles represent sets that have the same target wave height in the forecast zone.

4.2.1 Scenarios with 3 m Target Wave Heights

The first step to find the Orange Zone is to identify the subduction zones in the Pacific that could generate 3 m or 5 m tsunami offshore of Hokitika, Greymouth and Westport. Because Hokitika and Greymouth are located in the same Forecast Zone 39, the selected scenarios for both locations are the same (Tables 3.3 and 3.4). There are other sets of scenarios (Tables 3.5 and 3.6) for Westport, which is within Forecast Zone 40.

In the 3 m case for Hokitika and Greymouth, the Alaska, Kuril, East Philippines, Manus, New Britain, Solomon Islands, New Hebrides, Tonga, Hikurangi and Puysegur subduction zones were selected. For each subduction zone, we modelled between 1–4 scenarios each. Details of the scenarios can be seen in Section 3.4.5. The ensemble tsunami inundation in Hokitika from all considered scenarios for a 3 m threat level is shown in Figure 4.25. The inundated area for the 3 m threshold is very limited to the beach and marshland around Hokitika River, and the built-up area in the town of Hokitika is not inundated. The ensemble tsunami inundation in Greymouth from all considered scenarios for a 3 m threat level is shown in Figure 4.27. The inundated area in Greymouth for the 3 m threshold is very limited to the beach and marshland, and the built-up area in the town is not inundated. The tsunami time series from all scenarios at the Hokitika River mouth and Grey River mouth are shown in Figures 4.26 and 4.28, respectively.

For Westport (Forecast Zone 40), the South America, Alaska, East Philippines, Manus, Solomon Islands, New Hebrides, Tonga, Kermadec, Hikurangi and Puysegur subduction zones are selected. For each subduction zone, we modelled between 1–4 scenarios each. Details of the scenarios can be seen in Section 3.4.5. The ensemble tsunami inundation in Westport from all considered scenarios for a 3 m threat level is shown in Figure 4.29. A large area around the mouth of Buller River and Orowaiti Lagoon is inundated from the scenarios. This area includes the beach, Westport Airport and some built-up area in the northern part of the town. The tsunami time series from all scenarios at Buller River mouth is shown in Figure 4.30.

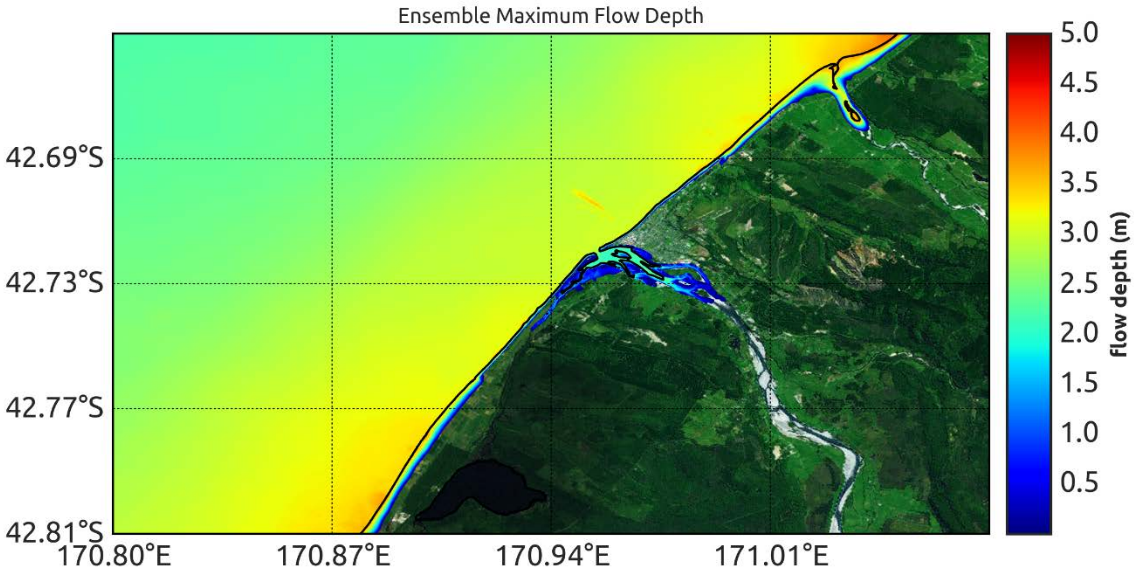


Figure 4.25 Ensemble inundation extent in Hokitika, represented as ensemble maximum flow depth for all **3 m scenarios for Forecast Zone 39** (29 uniform slip scenarios). Simulations assume that the largest waves arrive at MHWS (1.1 m above MSL). It should be noted that the figure shows ensemble maximum water level above MSL in the offshore. On land, the figures shows ensemble maximum flow depth.

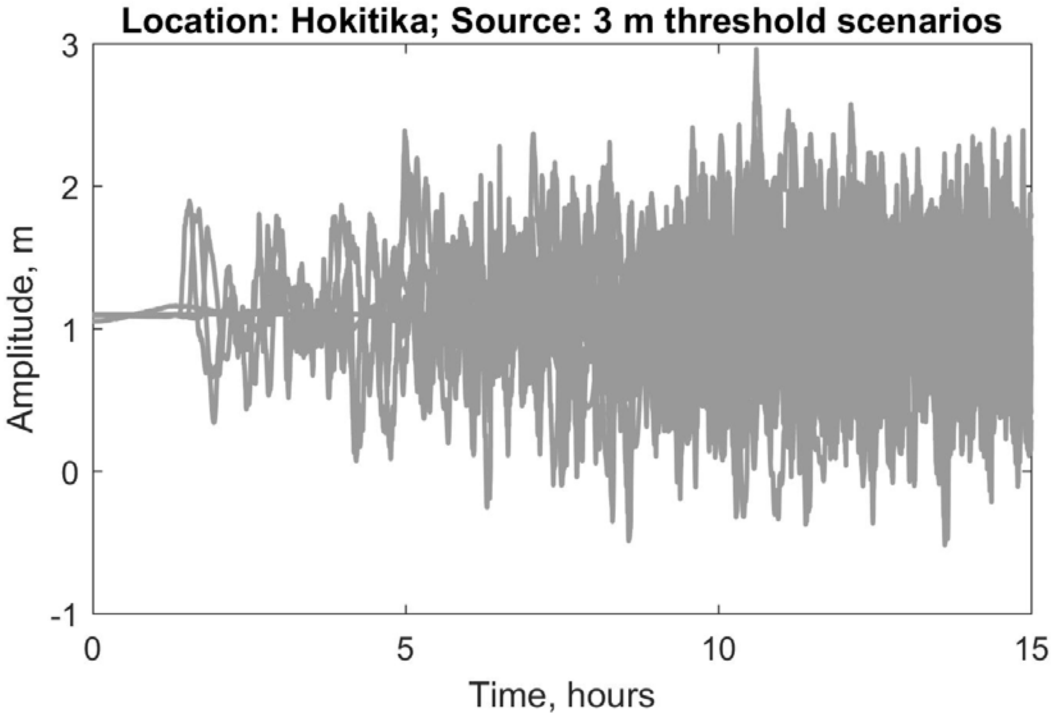


Figure 4.26 Ensemble time series at points of interest at Hokitika River mouth in Hokitika for all sets of the **3 m scenarios for Forecast Zone 39**. Ambient water level at each location is assumed to be at MHWS, which is 1.1 m above MSL in Hokitika.

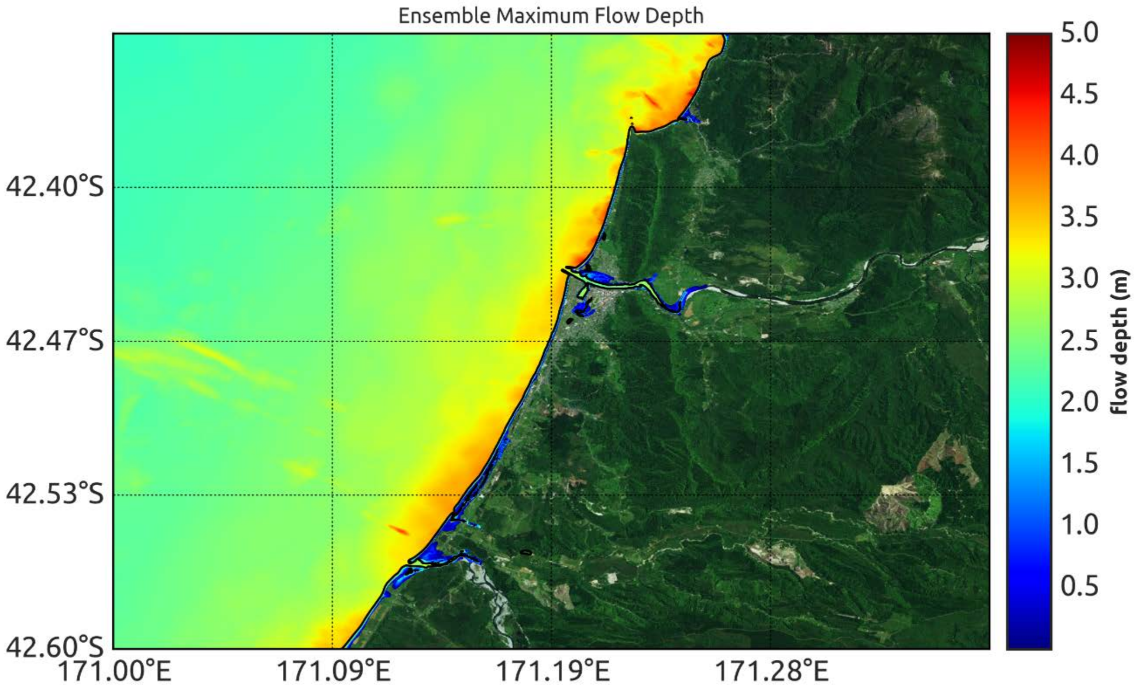


Figure 4.27 Ensemble inundation extent in Greymouth, represented as ensemble maximum flow depth for all **3 m scenarios for Forecast Zone 39** (29 uniform slip scenarios). Simulations assume that the largest waves arrive at MHWS (1.4 m above MSL). It should be noted that the figure shows ensemble maximum water level above MSL in the offshore. On land, the figures shows ensemble maximum flow depth.

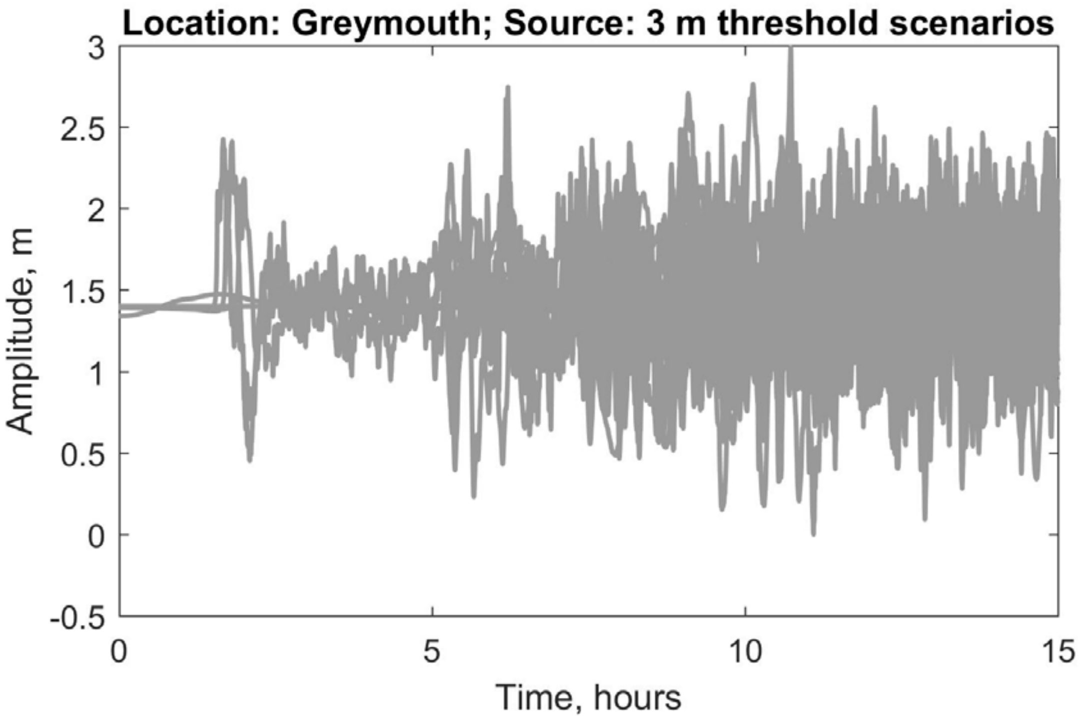


Figure 4.28 Ensemble time series at points of interest at Grey River mouth in Greymouth for all sets of the **3 m scenarios for Forecast Zone 39**. Ambient water level at each location is assumed to be at MHWS, which is 1.4 m above MSL in Greymouth.

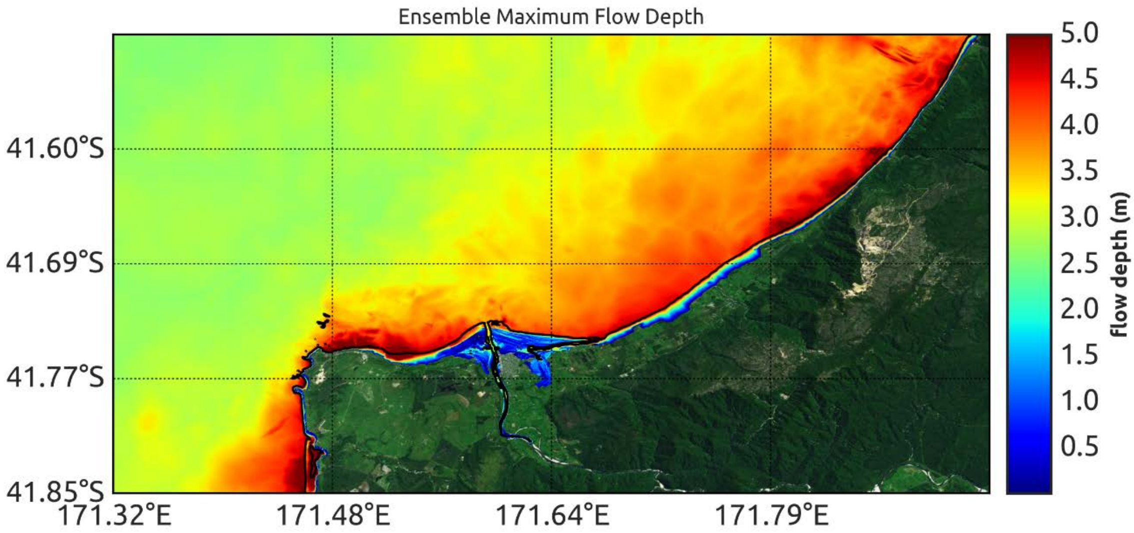


Figure 4.29 Ensemble inundation extent in Westport, represented as ensemble maximum flow depth for all **3 m scenarios for Forecast Zone 40** (31 uniform slip scenarios). Simulations assume that the largest waves arrive at MHWS (1.45 m above MSL). It should be noted that the figure shows ensemble maximum water level above MSL in the offshore. On land, the figures shows ensemble maximum flow depth.

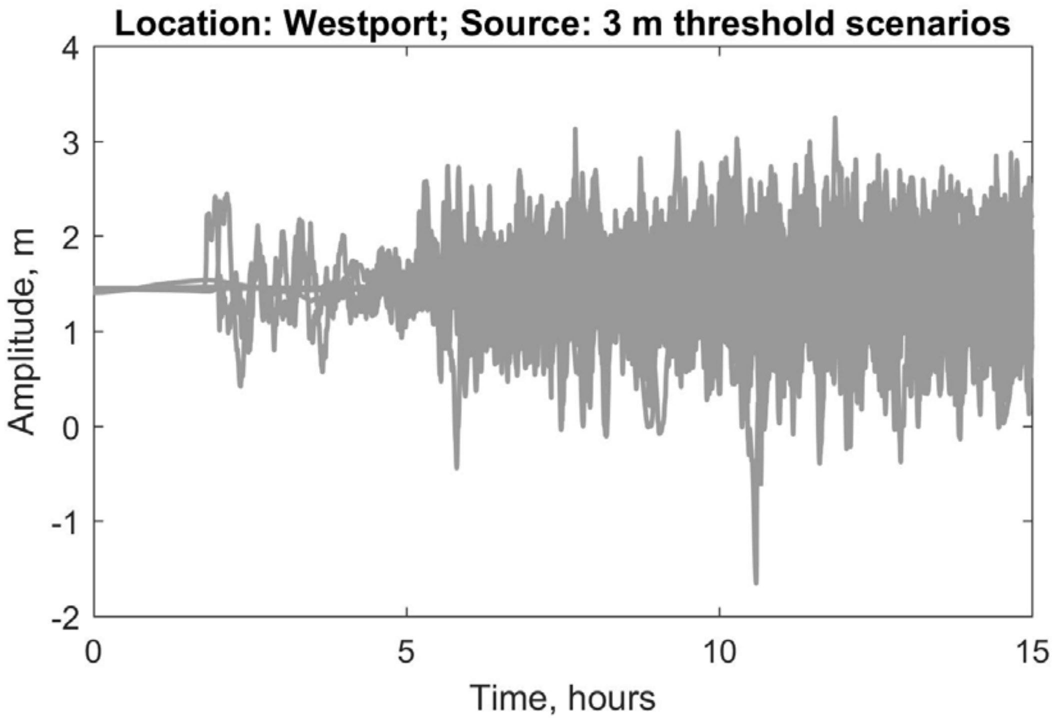


Figure 4.30 Ensemble time series at points of interest at Buller River mouth in Westport for all sets of the **3 m scenarios for Forecast Zone 40**. Ambient water level at each location is assumed to be at MHWS, which is 1.45 m above MSL in Westport.

4.2.2 Scenarios with 5 m Target Wave Heights

For the 5 m scenarios, the source regions were New Britain, Solomon Islands, New Hebrides, Tonga, Kermadec, Hikurangi, Puysegur and Hjort. Just like the case for the 3 m threshold, because the Forecast Zone 39 for Hokitika and Greymouth is the same, the selected scenarios for both study areas are the same. For each zone, we modelled 3–5 scenarios. The maximum tsunami inundation from all considered scenarios for a 5 m threat level in Hokitika and Greymouth are shown in Figures 4.31 and 4.33, respectively. For the 5 m threshold in the town of Hokitika, some parts of the town located on the seaward side of Fitzherbert St are inundated with flow depths of less than 1 m. Most of the inundated area south of Hokitika River and the seaward side of Ruatapu Rd is either beach or marshland. In Greymouth, the inundated area for the 5 m threshold south of the Grey River is largely located on the seaward side of the rail line and mostly has around 1 m of flow depth, while the built area in Cobden suburb, north of the Grey River, is mostly inundated with ensemble flow depths of 2–3 m. The tsunami time series from all scenarios at the Hokitika River mouth and Grey River mouth are shown in Figures 4.32 and 4.34, respectively.

The source regions of the scenarios that reach 5 m in Forecast Zone 40 (Westport) include New Britain, Solomon Islands, New Hebrides, Tonga, Kermadec, Hikurangi, Puysegur and Hjort subduction zones. For each zone, we modelled 1–5 scenarios. The maximum tsunami inundation from all considered scenarios for a 5 m threat level in Westport is shown in Figure 4.35. The topography around the mouth of Buller river and Orowaiti Lagoon is quite low, and large areas in these places are inundated by the scenarios. This area includes the beach, Westport Airport and some built-up area in the northern part of the town. The tsunami time series from all scenarios at Buller River mouth is shown in Figure 4.36.

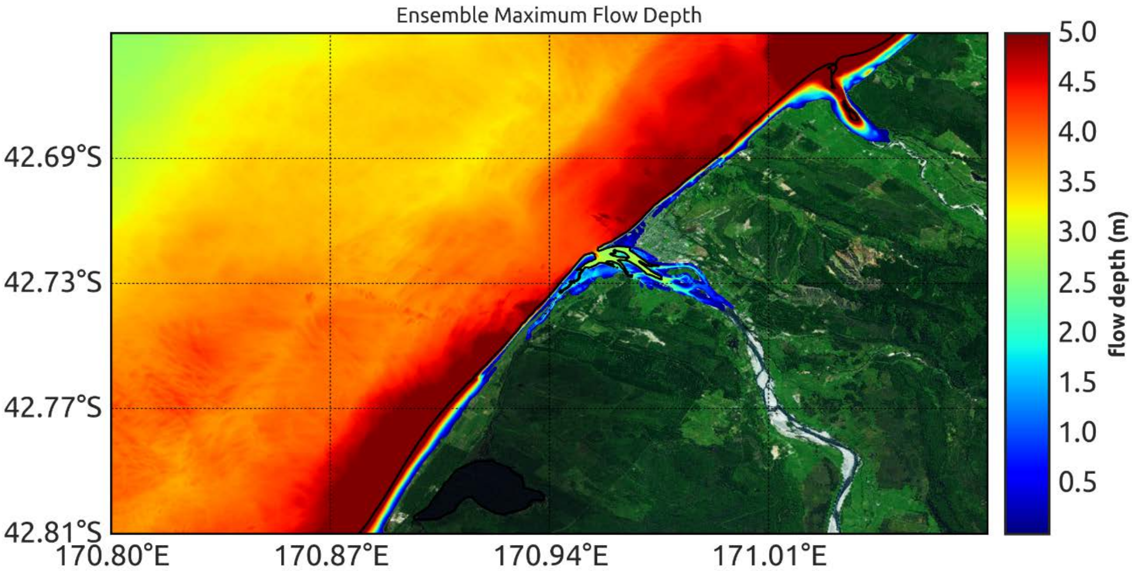


Figure 4.31 Ensemble inundation extent in Hokitika, represented as ensemble maximum flow depth for all **5 m scenarios for Forecast Zone 39** (31 uniform slip scenarios). Simulations assume that the largest waves arrive at MHWS (1.1 m above MSL). It should be noted that the figure shows ensemble maximum water level above MSL in the offshore. On land, the figures shows ensemble maximum flow depth.

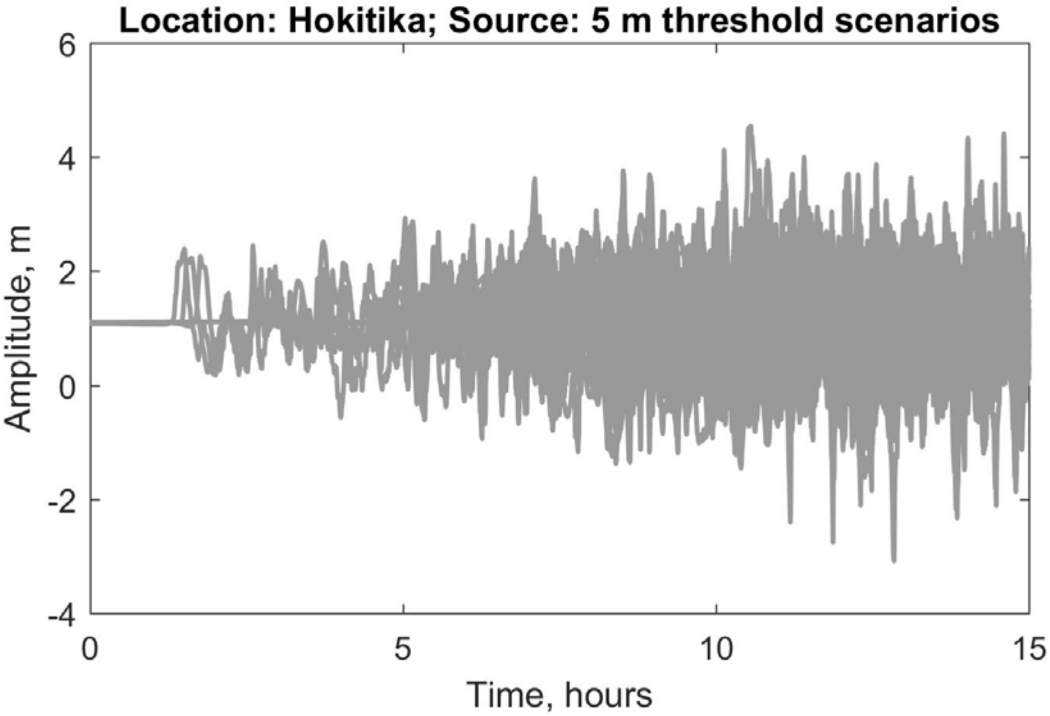


Figure 4.32 Ensemble time series at points of interest at Hokitika River mouth in Hokitika for all sets of the **5 m scenarios for Forecast Zone 39**. Ambient water level at each location is assumed to be at MHWS, which is 1.1 m above MSL in Hokitika.

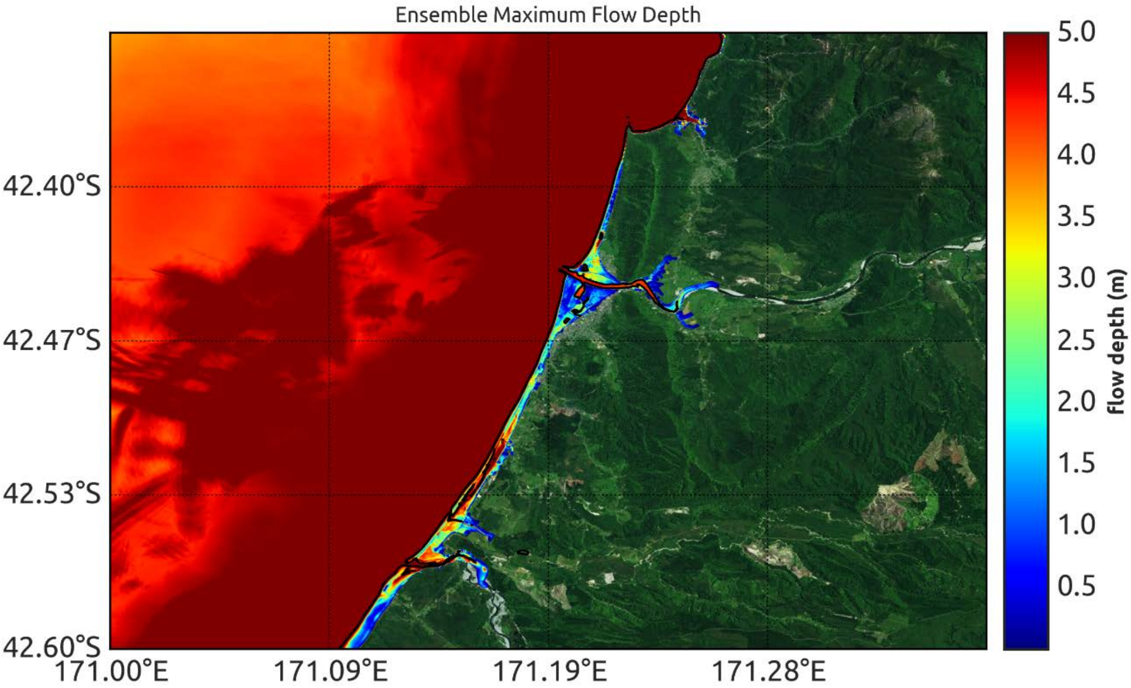


Figure 4.33 Ensemble inundation extent in Greymouth, represented as ensemble maximum flow depth for all **5 m scenarios for Forecast Zone 39** (31 uniform slip scenarios). Simulations assume that the largest waves arrive at MHWS (1.4 m above MSL). It should be noted that the figure shows ensemble maximum water level above MSL in the offshore. On land, the figures shows ensemble maximum flow depth.

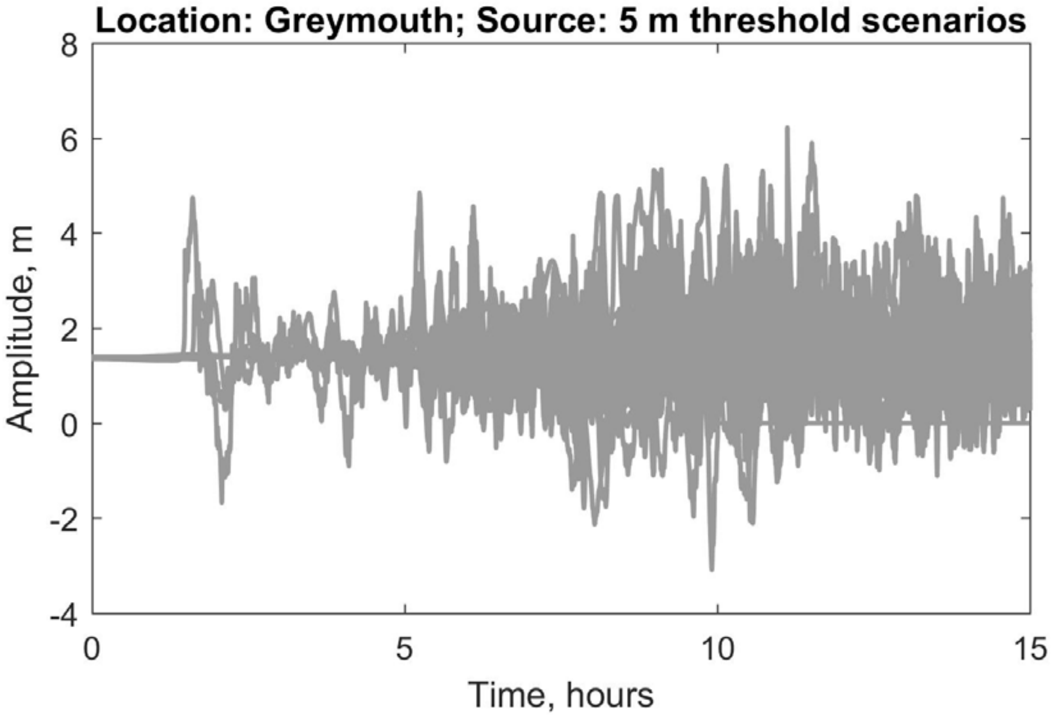


Figure 4.34 Ensemble time series at points of interest at Grey River mouth in Greymouth for all sets of the **5 m scenarios for Forecast Zone 39**. Ambient water level at each location is assumed to be at MHWS, which is 1.4 m above MSL in Greymouth.

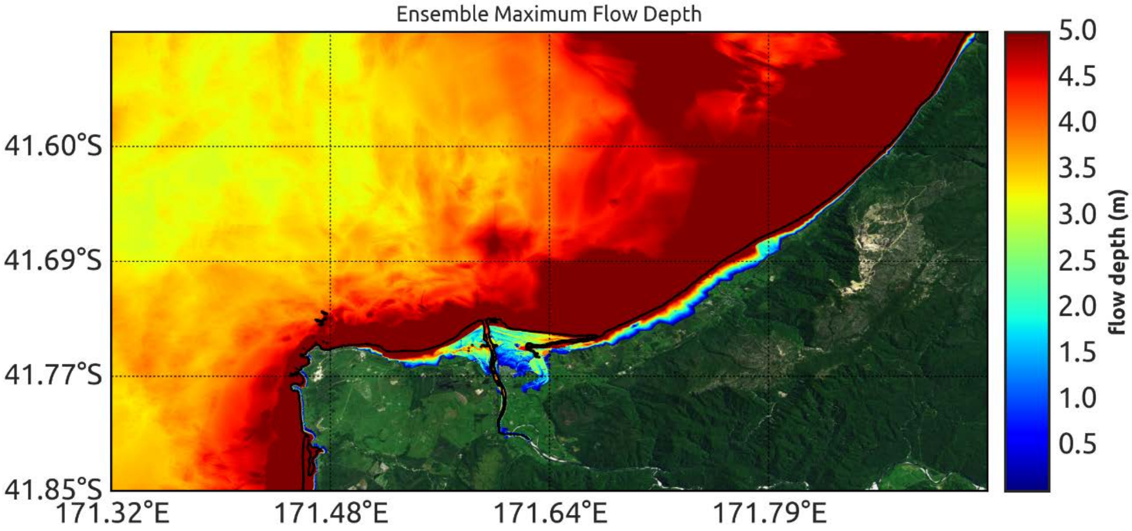


Figure 4.35 Ensemble inundation extent in Westport, represented as ensemble maximum flow depth for all **5 m scenarios for Forecast Zone 40** (29 uniform slip scenarios). Simulations assume that the largest waves arrive at MHWS (1.45 m above MSL). It should be noted that the figure shows ensemble maximum water level above MSL in the offshore. On land, the figures shows ensemble maximum flow depth.

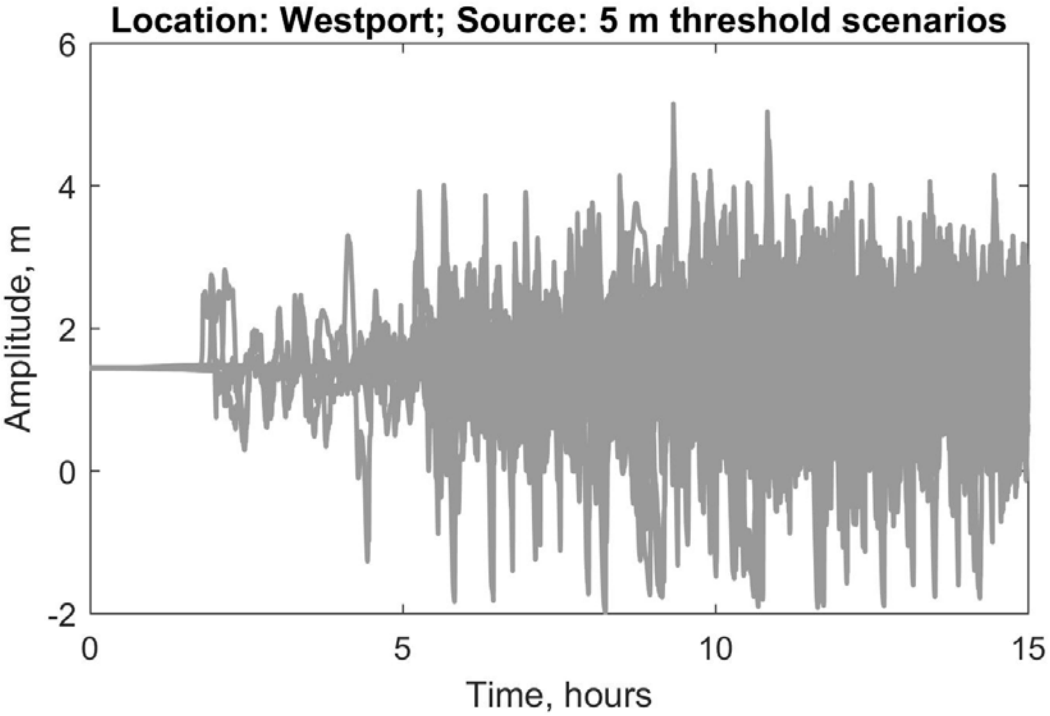


Figure 4.36 Ensemble time series at points of interest at Buller River mouth in Westport for all sets of the **5 m scenarios for Forecast Zone 40**. Ambient water level at each location is assumed to be at MHWS, which is 1.45 m above MSL in Westport.

4.3 Coastal Area below 2 m

Here, we present results that can be used to determine the Red Zone for Hokitika, Greymouth and Westport. The Red Zone is intended to be a ‘Marine and Beach’ evacuation zone that is tied to the 0.2–1.0 m ‘Marine and Beach Threat’ threat level in National Emergency Management Agency (NEMA) tsunami forecasts.

The current draft of the ‘Director’s Guidelines for Tsunami Evacuation’ (MCDEM 2016) call for the Red Zone to be defined (where high-quality topographic data is available) by the area less than 2 m above the high-tide (MHWS) level. This approach is known as the bathtub method. However, this is acknowledged to be problematic inside harbours and estuaries where some parts of them may not be possible to be inundated by a tsunami. The areas in all three locations that lie less than 2 m above high tide were found to clearly illustrate these problems, as the area substantially exceeds the potentially inundated area for the scenarios presenting a 3 m threat level for each town (Section 4.2.1). Therefore, we remove areas further inland beyond the simulated inundation extent from the 3 m threshold even when they were below 2 m elevation.

The result that can be used to determine the Red Zone for Hokitika is shown in Figure 4.37; for Greymouth, is shown in Figure 4.38; and, for Westport, is shown in Figure 4.39. Most of the built-up area in Hokitika is not within the proposed Red Zone. The inundated area includes beaches and lowlands, and most of these inundated lowlands are south of the Hokitika river. The inundated area in Greymouth includes beaches, waterways and undeveloped lowlands. The topography in Westport around the mouth of Buller river and Orowaiti Lagoon is quite low; this area should be included in the Red Zone.

Figure 4.37 The inundation area produced by tracing the grids that are connected to the sea and lower than 2 m above the MHWS level of 1.1 m for Hokitika.

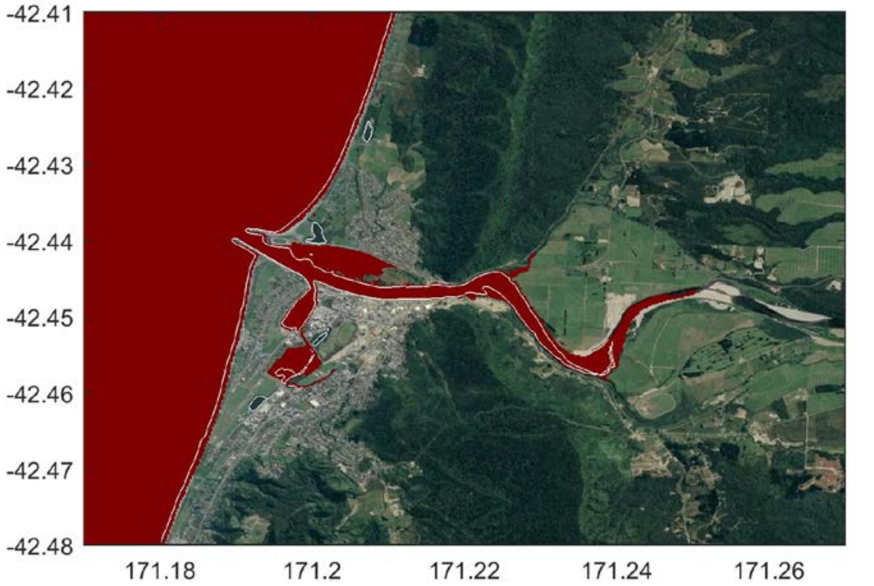


Figure 4.38 The inundation area produced by tracing the grids that are connected to the sea and lower than 2 m above the MHWS level of 1.4 m for Greymouth.

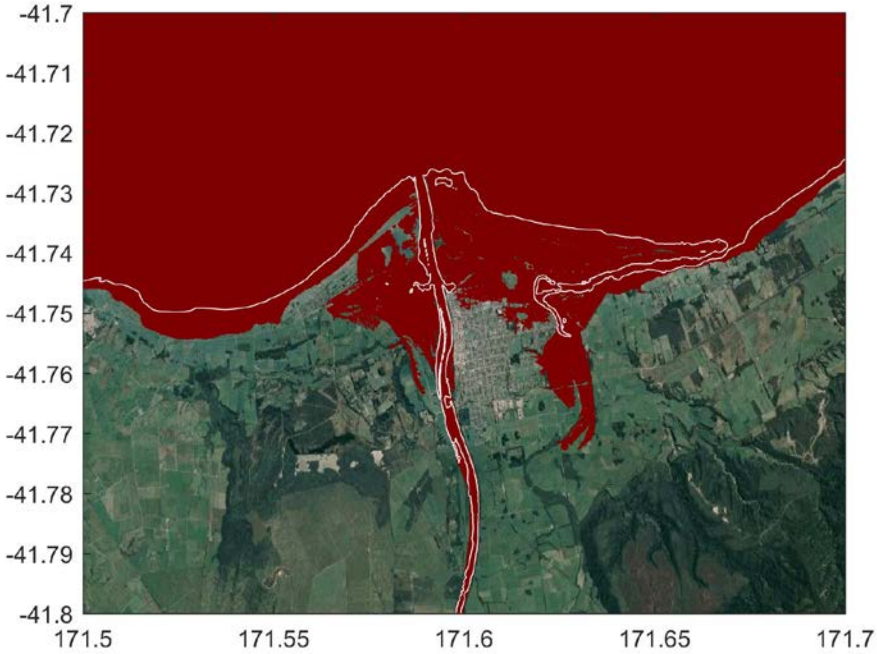


Figure 4.39 The inundation area produced by tracing the grids that are connected to the sea and lower than 2 m above the MHWS level of 1.45 m for Westport.

5.0 RECOMMENDATION FOR THE EVACUATION ZONES

For this region, we recommend that the Yellow Zone is large enough to cover the union of the maximum extent of the Solomon Islands, Kermadec and Puysegur events with the 50th percentile of the New Hebrides scenarios. The recurrence interval (at 84% confidence) of a typical earthquake of this magnitude from the New Hebrides zone is estimated to be of the order of 10,000+ years, so taking the median event of this size in the union with the others seems reasonable (see Appendix 1). The probability of an event that inundates further than this would be lower than the required threshold (the Yellow Zone must encompass the 2500-year event at 84% confidence) and so may be overly conservative. As stated in the evacuation zoning guidelines, a balance has to be made between making the evacuation zone too large and over-evacuating and making it too small and potentially under-evacuating. In our opinion, we think this union is a reasonable balance point. Therefore, we recommend that the WCRC uses the provided boundary as the initial zone extent and then moves the exact boundary further from the coast if that would help with the evacuation design and communication (e.g. to make the Yellow Zone boundary align with a road or other geographic feature).

The Orange Zone exists to enable a smaller evacuation to be called (compared to evacuating the whole Yellow Zone) in the event of a tsunami forecast that is expected to cause land inundation within a specified threat level. Tsunami forecasts issued by NEMA specify a threat level for each section of coast: the threat levels are 0.3–1 m, 1–3 m, 3–5 m, 5–8 m and 8 m+.

The existing Orange Zones for the whole West Coast (Leonard et al. 2015) are based on the 5 m threshold (such that only the Red and Orange Zones need to be evacuated in the event of a 1–3 m or 3–5 m threat level). We strongly recommend consistency in the choice of threat level used for the Orange Zone across the whole WCRC coastline, as variations in how the Orange Zone is defined increase the risk of mistakes in choosing the right zones to evacuate during an event. We therefore recommend that the 5 m threshold is used to provide consistency with the existing evacuation zone mapping for the rest of the West Coast, and results in the following sections are based on this choice.

We have also calculated what the evacuation zones would look like if the Orange Zone was based on the 3 m threshold; these may be seen in Appendix 2. Our main reason for not recommending this threshold is because of inconsistency with the evacuation mapping for other regions for the West Coast, although we also note that the 5 m threshold provides more leeway in the event that a distant-source tsunami were to coincide with strong river flows following heavy rain and that the Orange Zone based on the 3 m threshold is often hard to visually distinguish from the Red Zone.

5.1 Hokitika

Figure 5.1 shows the recommended Yellow, Orange and Red Zones for Hokitika, assuming that the Orange Zone is based on the 5 m threshold. The zones are shown prior to any adjustments to the boundaries that WCRC may choose to make, e.g. to align with roads.

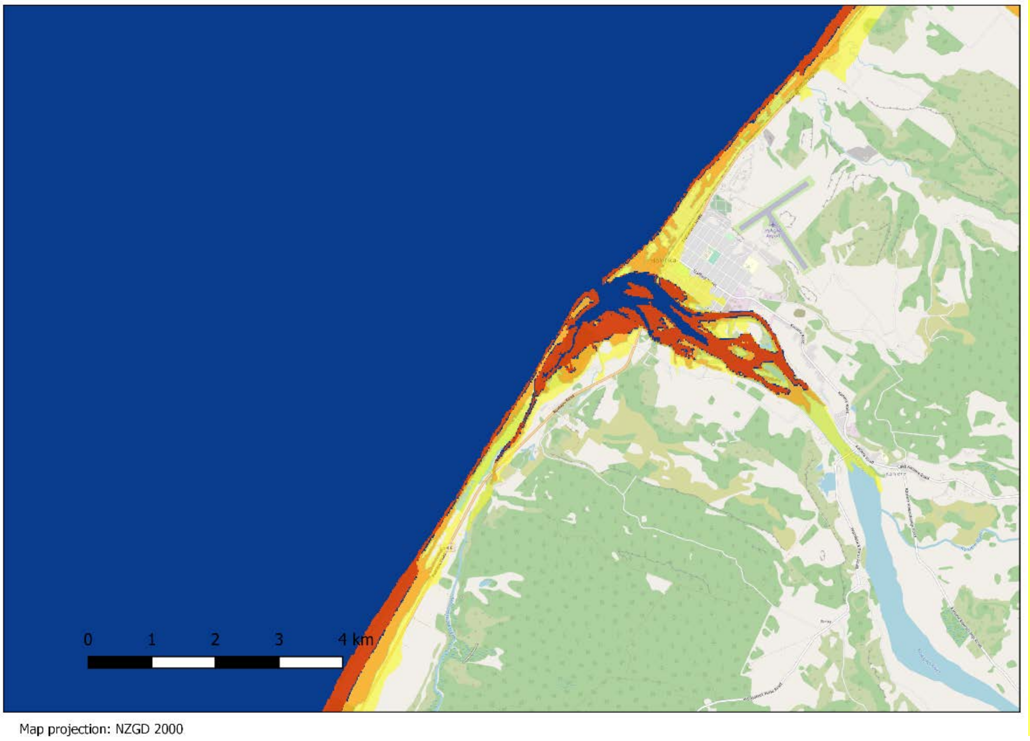


Figure 5.1 Recommended Yellow, Orange (5 m threshold) and Red Zones for Hokitika.

5.2 Greymouth

Figure 5.2 shows the recommended Yellow, Orange and Red Zones for Greymouth, assuming that the Orange Zone is based on the 5 m threshold. The zones are shown prior to any adjustments to the boundaries that WCRC may choose to make. e.g. to align with roads.

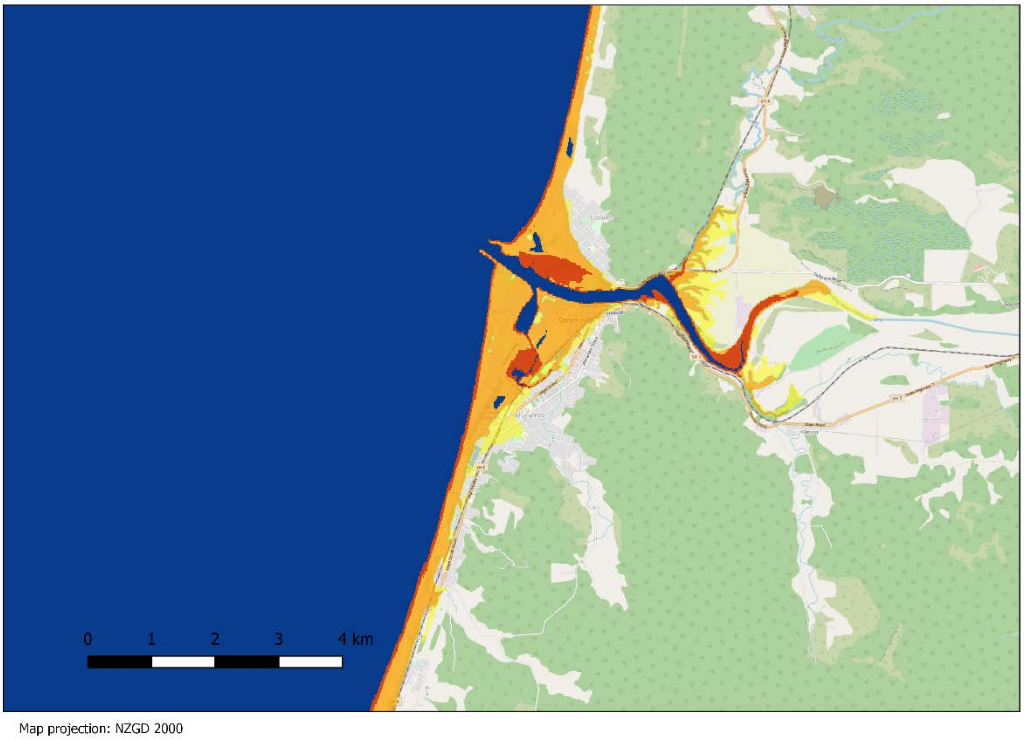
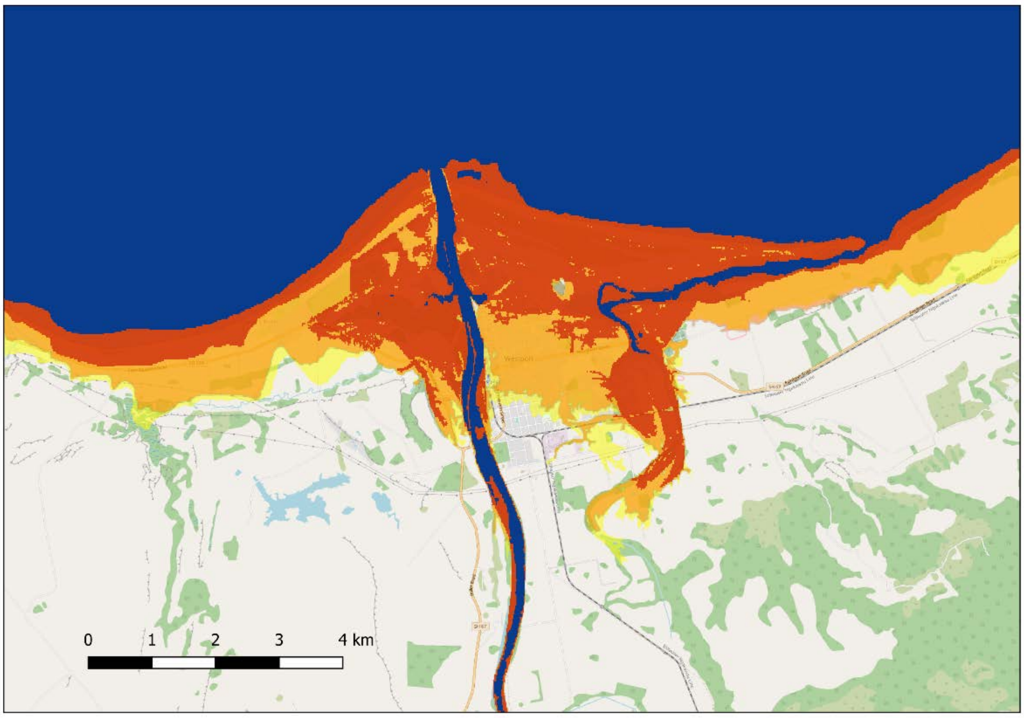


Figure 5.2 Recommended Yellow, Orange (5 m threshold) and Red Zones for Greymouth.

5.3 Westport

Figure 5.3 shows the recommended Yellow, Orange and Red Zones for Hokitika, assuming that the Orange Zone is based on the 5 m threshold. The zones are shown prior to any adjustments to the boundaries that WCRC may choose to make, e.g. to align with roads.



Map projection: NZGD 2000

Figure 5.3 Recommended Yellow, Orange (5 m threshold) and Red zones for Westport.

6.0 LIMITATIONS OF THIS STUDY

The simulations carry several unknowns that 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. There are also limitations with respect to the accuracy of the numerical modelling, as well as the limited number of non-uniform slip scenarios that were used here. 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 for local and regional sources (Geist 2002; Mueller et al. 2015a; Mueller et al. Forthcoming 2020), 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. All simulations of subduction plate interface sources assume a rigidity of $\mu = 40$ GPa for consistency with the new New Zealand threat level database National Tsunami Hazard Model (Gusman et al. 2019).

The data provided in this report is intended to form the basis for the council to develop their evacuation zones if they wish to do so in the future: 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 study only considers tsunami created by fault movement; it does not consider tsunami created by non-seismic processes such as landslides. The modelling also treats rivers as static bodies of water.

7.0 CONCLUSION

A large set of local, regional and distant potential tsunami sources was investigated. A total of 330 tsunami inundation simulations were undertaken for Hokitika, Greymouth and Westport in order to develop the tsunami evacuation zones. The highest quality topographic and bathymetric data that are publicly available were used to build the DEM for the simulation. All simulations were run using a high-tide level of Mean High-Water Springs.

We investigated a total of 50 potential ‘worst-case’ scenarios, including local, regional and distant sources. The local scenarios are from the local crustal Cape Foulwind Fault, which is located directly beneath the three coastal towns. The regional sources include scenarios on the Puysegur and Kermadec subduction zones, while the distant sources include scenarios on the New Hebrides and Solomon Islands subduction zones. The magnitude for each of the source regions is based on the ‘Maximum of Maximum Magnitudes’ in the Global Earthquake Model (GEM; Berryman et al. 2015). For each source region, 10 non-uniform slip scenarios are generated by assuming a rigidity of 40 GPa and used in the tsunami simulation.

We also investigated a large set of scenarios from different regions around the Pacific that reach 3 m and 5 m target wave heights at coast in the Forecast Zones for Hokitika, Greymouth and Westport. Hokitika and Greymouth are in Forecast Zone 39, while Westport is in Forecast Zone 40. The scenarios for each Forecast Zone and target wave were selected from the Tsunami Threat Level Database. This database was built for tsunami warning purposes in New Zealand.

From the worst-case scenarios to determine the Yellow Zone, we found that scenarios from the New Hebrides subduction zone dominated the ensemble tsunami inundation extent in Hokitika and Greymouth. In Westport, the ensemble tsunami inundation extents from the various subduction zone source scenarios are similar. In every town evaluated here, the ensemble tsunami inundation extent from the local Cape Foulwind Fault scenario is much smaller than those from the subduction zone scenarios (including Puysegur, which, like the Cape Foulwind Fault, is expected to cause strongly felt shaking on the West Coast).

For the Orange Zone, we modelled scenarios at both 3 m and 5 m target wave heights in Hokitika, Greymouth and Westport. Our recommendation is to adopt an Orange Zone based on the 5 m target height for consistency with how the Orange Zone has been defined elsewhere along the West Coast.

To get the inundation extent as the basis to determine the Red Zone, we first traced the area that lies less than 2 m above high tide and is connected to the sea in Hokitika, Greymouth and Westport. Using this approach, the traced area in some places exceeds the area for the 3 m threat level scenarios. Therefore, we remove the area identified with the 2 m criteria where it extends beyond the simulated inundation area found using the 3 m target wave threshold.

As described in the MCDEM guidelines, there needs to be a balance between the risks that come from potentially over-evacuating, by setting the zone limits to encompass very rare events, and under-evacuating. This report provides all simulation results in GIS format to help WCRC make an informed decision on where to draw that line.

8.0 DATA PRODUCTS

This report is accompanied by digital products corresponding to the data presented and discussed in this report.

The digital products are provided as zip files, and the following each contain a set of scenarios:

Zip File Name	Description
ZonesNZTM.gdb.zip	Recommended Yellow, Orange and Red Zones in Hokitika, Greymouth and Westport (NZTM projection)
ZonesWGS84.gdb.zip	Recommended Yellow, Orange and Red Zones in Hokitika, Greymouth and Westport (WGS84 projection)
Ensemble_models.zip	Ensemble models in Hokitika, Greymouth and Westport
Hokitika_worstcase_scenarios.zip	All worst-case scenarios (for Yellow Zone development) in Hokitika
Hokitika_3m_scenarios.zip	All scenarios with 3 m target wave height (for Orange Zone development) in Hokitika
Hokitika_5m_scenarios.zip	All scenarios with 5 m target wave height (for Orange Zone development) in Hokitika
Greymouth_worstcase_scenarios.zip	All worst-case scenarios (for Yellow Zone development) in Greymouth
Greymouth_3m_scenarios.zip	All scenarios with 3 m target wave height (for Orange Zone development) in Greymouth
Greymouth 5m_scenarios.zip	All scenarios with 5 m target wave height (for Orange Zone development) in Greymouth
Westport_worstcase_scenarios.zip	All worst-case scenarios (for Yellow Zone development) in Westport
Westport_3m_scenarios.zip	All scenarios with 3 m target wave height (for Orange Zone development) in Westport
Westport 5m_scenarios.zip	All scenarios with 5 m target wave height (for Orange Zone development) in Westport

9.0 ACKNOWLEDGEMENTS

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APPENDICES

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APPENDIX 1 JUSTIFICATION FOR USING THE MEDIAN NEW HEBRIDES EVENT

The Yellow tsunami evacuation zone is expected to, at minimum, encompass the 2500-year event at the 84% level of confidence. While larger and rarer events may be included in the design, consideration should be given to the possibility of over-evacuation in more frequent smaller events, especially where these are local events with strong earthquake shaking, as over-evacuation causes additional hardship to those dealing with the consequences of the earthquake shaking. Note that, of the strongly felt local sources examined here, the Puysegur Trench scenarios cause the largest inundation.

For both Hokitika and Greymouth, our results show that the New Hebrides scenarios tend to consistently produce the most extensive inundation; although, for Westport, the dominance of the New Hebrides scenarios is not as clear-cut.

We examined the rate of occurrence of earthquakes with effective magnitudes (see Power 2013) larger than 9.27 using a version of the National Tsunami Hazard Model updated with the current Global Earthquake Model source parameters, under the assumption that whole-margin ruptures of the New Hebrides Trench are possible (see Table A1.1).

Table A1.1 Seismic source parameters for the New Hebrides subduction zone, assuming whole margin segmentation from Berryman et al. (2015). See Berryman et al. (2015) for additional geometrical and kinematic parameters for this subduction zone.

Segment	Coupling Coefficient (Min.)	Coupling Coefficient (Max.)	Mmax (Pref.)	Mmax (Min.)	Mmax (Max.)	B-value (Pref.)	B-value (Min.)	B-value (Max.)
Whole Margin	0.27	0.73	8.83	8.30	9.37	0.90	0.60	1.20

At the 84% level of confidence, we find that the return period for these events is in excess of 10,000 years (Figure A1.1) according to this model. The effective magnitude includes an allowance for variabilities such as non-uniform slip and, as such, may be compared to the ‘typical’ or median event of this magnitude (see Appendix 7.3 in Power 2013). We also note that we have made an additional allowance of 0.1 magnitude by using Mw 9.27 rather than Mw 9.37 in this analysis and can therefore confidently claim that the median inundation from a Mw 9.37 earthquake in the New Hebrides is sufficient to comfortably encompass the 2500-year 84% confidence requirement when combined with the union of the other scenarios.

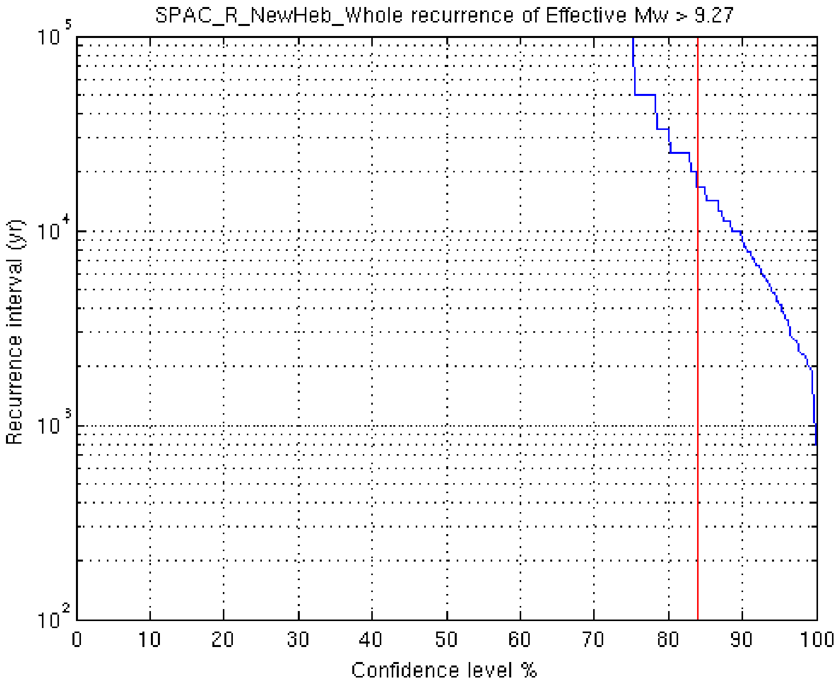


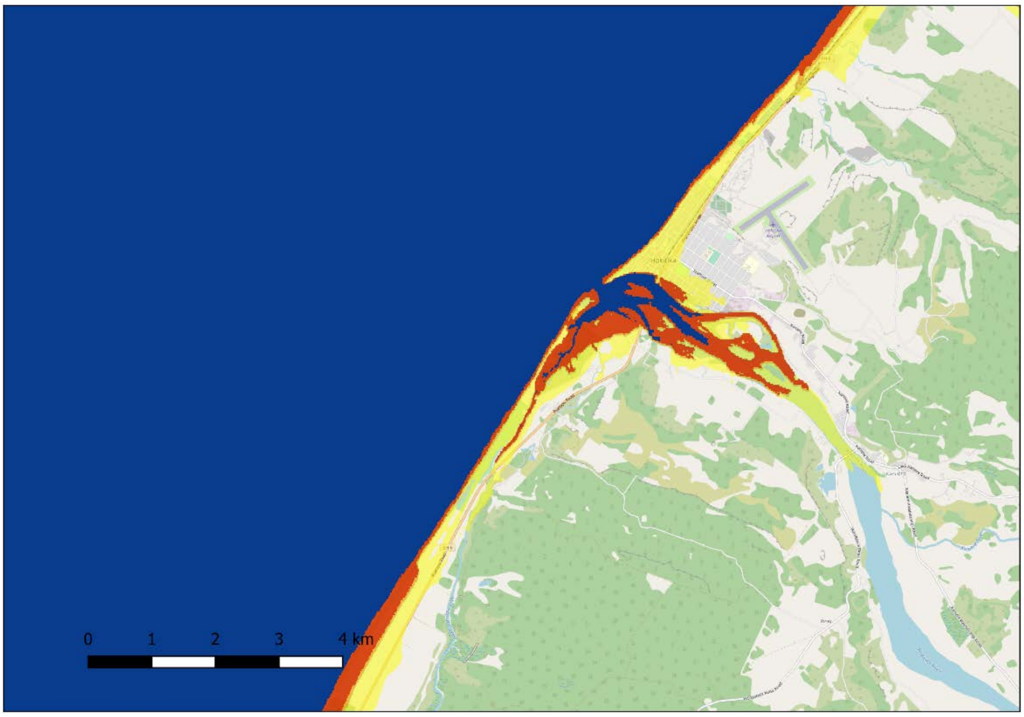
Figure A1.1 Recurrence interval of New Hebrides earthquakes with effective magnitude >9.27, as a function of confidence level (blue line). Red line indicates 84% level of confidence.

APPENDIX 2 EVACUATION ZONE MAPS IF THE 3 M THRESHOLD WERE USED FOR THE ORANGE ZONE

In this section, we present evacuation map results if the 3 m threshold is used for the Orange Zone instead of the 5 m threshold.

A2.1 Hokitika

Figure A2.1 shows the Yellow, Orange and Red Zones for Hokitika when the Orange Zone is defined using the 3 m threshold. In this case, it is hard to distinguish the Orange Zone from the Red Zone, as the boundaries are often very similar. If the 3 m threshold was adopted, some thought may need to be given as to how this is represented to the public (e.g. the Orange Zone boundary may need to be extended slightly from the Red Zone boundary in order to make it visible).

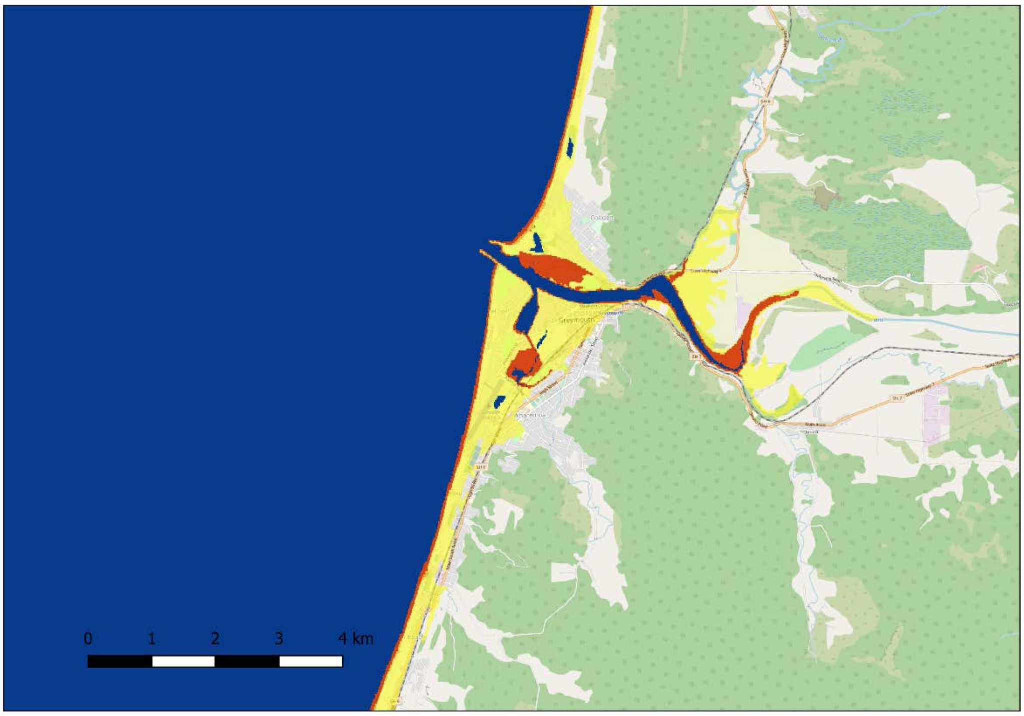


Map projection: NZGD 2000

Figure A2.1 Recommended Yellow and Red Zones, with an alternative Orange Zone based on the 3 m threshold, for Hokitika.

A2.2 Greymouth

Figure A2.2 shows the Yellow, Orange and Red Zones for Greymouth when the Orange Zone is defined using the 3 m threshold. In this case, it is hard to distinguish the Orange Zone from the Red Zone, as the boundaries are often very similar. If the 3 m threshold was adopted, some thought may need to be given as to how this is represented to the public (e.g. the Orange Zone boundary may need to be extended slightly from the Red Zone boundary in order to make it visible).

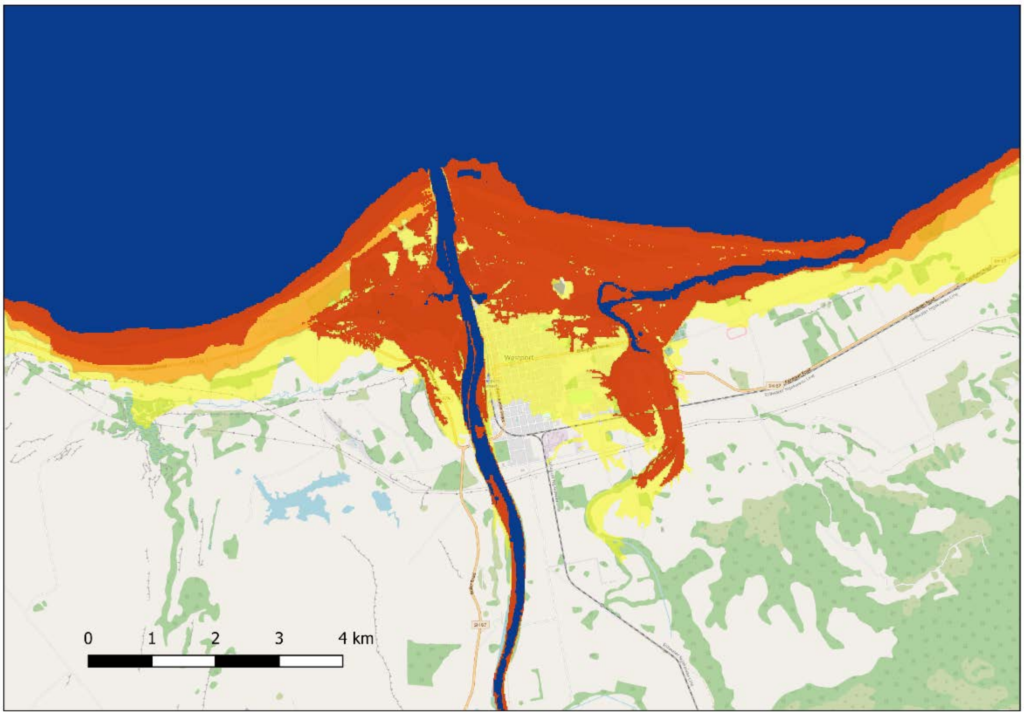


Map projection: NZGD 2000

Figure A2.2 Recommended Yellow and Red Zones, with an alternative Orange Zone based on the 3 m threshold, for Greymouth.

A2.3 Westport

Figure A2.3 shows the Yellow, Orange and Red Zones for Westport when the Orange Zone is defined using the 3 m threshold. In some locations, it is hard to distinguish the Orange Zone from the Red Zone, as the boundaries are often very similar. If the 3 m threshold was adopted, some thought may need to be given as to how this is represented to the public (e.g. the Orange Zone boundary may need to be extended slightly from the Red Zone boundary in order to make it visible).



Map projection: NZGD 2000

Figure A2.3 Recommended Yellow and Red Zones, with an alternative Orange Zone based on the 3 m threshold, for Westport.

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