Tsunami inundation modelling for Whakatane, Ohope and Opotiki

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GNS Science Consultancy Report 2011/194
Revised Version December 2011

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BIBLIOGRAPHIC REFERENCE

Prasetya, G. and Wang X. 2011. Tsunami inundation modelling for Whakatane, Ohope and Opotiki, *GNS Science Consultancy Report* 2011/194. 38 p.

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EXECUTIVE SUMMARY

1. Bay of Plenty Regional Council (BOPRC) provided research funding for GNS Science to undertake tsunami inundation modelling for the Whakatane and Opotiki areas based on the results of the Review of Tsunamigenic Sources of the Bay of Plenty Region (Prasetya and Wang, 2011) that identified tsunami sources which present a land threat to the study areas. The sources modelled here only consider very large earthquakes (Mw 9.0 and above) located along the Kermadec Trench, and in some cases the ruptures also include the northern part of the Hikurangi Margin. The rupture scenarios along the Kermadec Trench were developed based on the segmentation in Power et al. (2011), with additional variation of the slip amount based on studies of the recent 11 March 2011 Tohoku Mw 9.0 earthquake in Japan.

2. The modelled scenarios and inundation modelling results are as follows:

   - A Whole Kermadec scenario in Power et al. (2011) (slip = 22.0m, Mw9.4) leading to significant inundation within the study areas.

   - Three variations of the Kermadec scenarios in Power et al. (2011) were also modelled by applying a slip of 30.0m that occurred in the 11 March 2011 Tohoku earthquake (Mw9.0) in Japan:

     - Variation of the Southern Kermadec scenario (slip = 30.0m on Segment A, Mw = 9.0): leading to extensive inundation in the study areas;
     - Variation of the Central Kermadec scenario (slip = 30.0m on Segment B, Mw = 9.2): leading to localised inundation in the study areas;
     - Variation of the Whole Kermadec scenario (slip = 30.0m on Segments A and B, slip = 22.0m on Segment C, Mw9.45),: leading to extensive inundation in the study areas, similar to the variation of the southern Kermadec (slip = 30.0m, Mw = 9.0).

   Other scenarios involving southern Kermadec with large slips are also likely to provide tsunami threats. For example:

   - A Kermadec-Hikurangi scenario, involving a fault rupture extending from the Kermadec Trench to the south into the northern portion of the Hikurangi Margin (slip= 20 m, Mw9.1): causing a similar impact to the scenarios where the slip on the southern Kermadec is increased to 30 m such as the variation of the Whole Kermadec scenario and the variation of the Southern Kermadec scenario.

Some general results:

- For all the scenario events simulated, the offshore islands (White and Motuhora Islands), submarine ridges and the nearshore bathymetry are observed to play an important role in amplifying or reducing the tsunami impacts. Tsunami energy is steered mainly towards Thornton – Matata – and Pikowai areas, and to some extent towards Opotiki, which resulted in significant inundation of these regions. The tsunami also inundates low-lying areas in Whakatane, however, the impacts are less severe towards Whakatane than its neighbouring areas because the incoming tsunami waves are lower, and the narrow river entrance and the elevated coastal front north to Whakatane River help shield Whakatane from direct impact of tsunami.

- The first arrival of a tsunami in the studied area ranges from 40 to 70 minutes for all scenario events simulated, with an initial negative leading wave (sea level drop). And considering all the scenario modelled in this study, the maximum tsunami elevation along the coastline generally ranges from 3.0 m to 13.0 m above the ambient wave level.

- The model results show that the sand dunes provide an effective and important barrier to a tsunami. The preservation or conservation of these sand dunes along the beach front is critical, and any activities that deteriorate the dune systems should be avoided. If the dune systems are degraded due to storm waves or other extreme events, actions need to be carried out to re-establish the sand dune systems back to their original state to provide a natural protective function (Prasetya, 2007).

- Strategic mitigation of the tsunami risk is needed within this region, especially in coastal areas from Matata to Thornton and from Ohope to Opotiki as well as in low-lying areas of Whakatane. Mitigation activities may involve a combination of structural (seawall, existing building for shelter/vertical evacuations) and non-structural (sand dunes, trees or green belt) methods for already developed areas such as the low-lying areas in Matata, Whakatane and from Ohope to Opotiki. For future development planning within the high risk zone; promotion of retreat from the tsunami hazard by means of land-use planning and building code policy, rules and guidelines as well as financial instruments are the recommended options.

1.0 INTRODUCTION

Bay of Plenty Regional Council (BOPRC) provided research funding for GNS Science to undertake tsunami inundation modelling for Whakatane and Opotiki areas based on the results of the Review of Tsunamigenic Sources of the Bay of Plenty Region (Prasetya and Wang, 2011) that identified tsunami sources that present a land threat to the study areas.

This study aims to provide:

- An inundation map based on LIDAR ground striking data
- A description of the modelling results and their applicability for being used for evacuation planning

2.0 BACKGROUND

A tsunami is a progressive wave with a long wavelength and period, generated by a disturbance of the seafloor associated with various geologic processes such as submarine fault movements accompanying earthquakes; submarine volcanism; landslides; or a combination of these sources. The tsunami's size and effect on the shoreline are determined by several factors: the amplitude of the wave at the source, which is primarily controlled by the size and geometry of the source; the response of the coastal features, such as bays and harbours (which are capable of resonance, thereby amplifying selected wave frequencies); and the nonlinear hydrodynamics of the breaking wave as it rolls onshore. In order to predict detailed and quantitative information, the modelling of tsunami behaviour is an essential requirement.

Scientific terms such as *'runup height'*, '*tsunami wave height'* and '*inundation'* often confuse the general public and can result in misleading information about what happened during tsunami events. This confusion had an impact on public understanding of the tsunami's impacts, and the subsequent rehabilitation, reconstruction and mitigation efforts following the Indian Ocean Tsunami in 2004. The *runup height* depends upon the slope of the ground inland, and the ability of the topography to concentrate wave energy or reflect it. For the same incoming tsunami waves, those areas with a gentle slope inland will experience lower runup heights but longer *inundation distances* compared to the areas that have steeper slopes (Figure 2.0.1). Therefore, in reporting the properties of tsunamis, the location of measurements should be mentioned, as is standard practice in tsunami surveys (Synolakis and Okal, 2005). The *flow depth* is the depth of water under the tsunami wave as it flows inland, and if already referenced to Mean Sea Level (MSL), it is termed '*tsunami elevation'*. At the inland limit of the flow, the height above MSL is termed the runup height, and the horizontal distance from the shoreline is the inundation distance. The runup height was frequently confused with the tsunami wave height in media coverage of the Indian Ocean tsunami of 2004 (Prasetya et al., 2008).

Coastal areas in the Indian and Pacific Oceans have suffered damage from tsunami for a long time. However, tsunami hazard is often underestimated in comparison with earthquake hazard, possibly because of their infrequent occurrence. Based on historical data of tsunami events in the Pacific Ocean, tsunamis affecting the New Zealand coast have been generated by a variety of mechanisms. Some sources can be categorised into *far-field* tsunami which are generated at some distance from New Zealand and propagate through the deep water of the Pacific Ocean before reaching the coast, while some are *near-field* tsunami generated close to New Zealand's coastline and propagated through relatively shallow water.

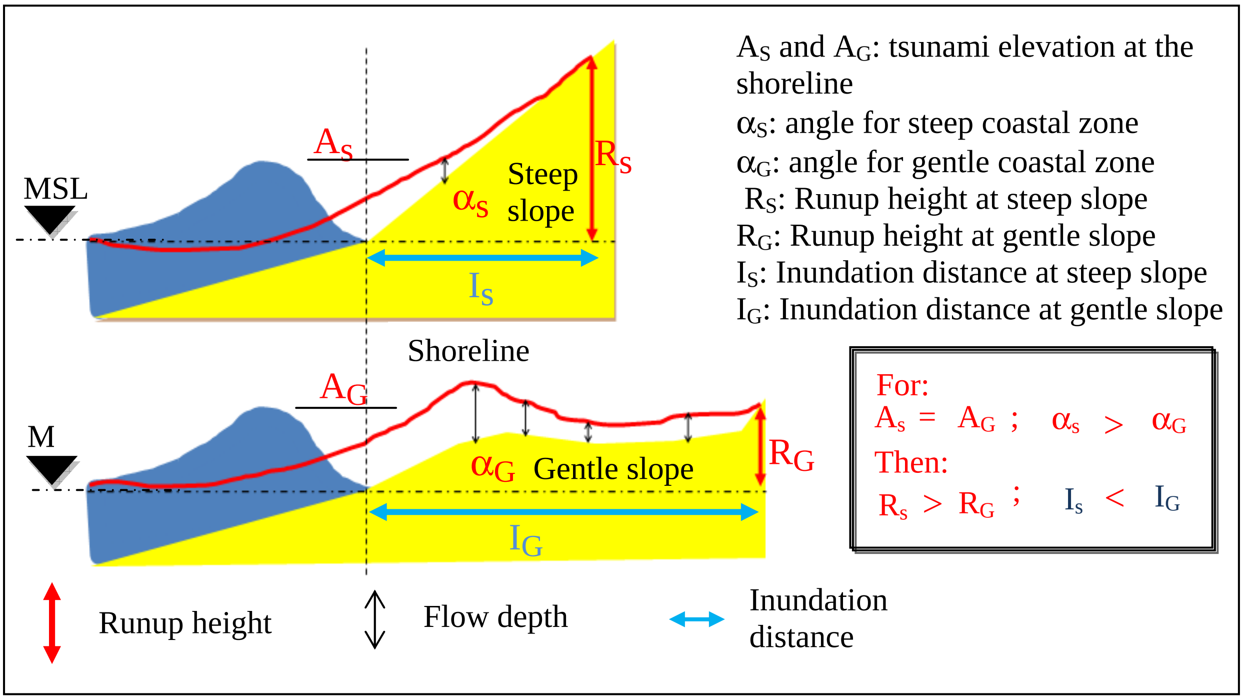

Figure 2.0-1 Schematic diagram for runup height and inundation for different beach slopes (simplified from Prasetya et al. 2011). For the same incoming tsunami height at the coast, those areas with a gentle slope inland will experience lower runup heights but longer inundation distances compared to the areas that have steeper slopes.

Note: Numerical simulations were carried out in this report using Mean High Water Spring (MHWS) as an ambient water level. All the inundation modelling results plotted in subsequent Figures follow the following convention: From offshore to the coastline we plotted the tsunami elevations relative to the ambient water level (i.e., MHWS in this study) and from coastline further inland we used flow depth which is inundation height above the ground. The zero contours in all the figures presented in this report are based on the available DEM data against MHWS.

3.0 POTENTIAL SOURCES

Numerical modelling assessments were carried out by Prasetya and Wang (2011) using a COMCOT tsunami model (Wang and Power, 2011) for all sources based on previous work. The study shows consistent results that the tsunamigenic sources from the Kermadec Trench significantly affect the Bay of Plenty Region. The previous studies summarized in Prasetya and Wang (2011) show that tsunami elevations greater than 5.0 m could potentially occur along the coast of the Bay of Plenty as the result of an earthquake greater than Mw 8.5 along the southern and central Kermadec Trench. For this study we examine scenarios that suggest a high possibility of inundation (or land threat) along the Bay of Plenty coastal region to the Whakatane and Opotiki areas. These scenarios are:

- Whole Kermadec Scenario in Power et al. (2011) (i.e., the combined rupture of Segments A, B and C, slip = 22.0m, Mw9.4)
- Variation of the Southern Kermadec scenario in Power et al. (2011) (slip = 30.0m, Mw 9.0)
- Variation of the Central Kermadec scenario in Power et al. (2011) (i.e., slip = 30.0m, Mw 9.2)
- Variation of the Whole Kermadec scenario in Power et al. (2011) (slip = 30.0m on Segments A and B, slip = 22.0m on Segment C, Mw9.45)
- Kermadec-Hikurangi Scenario (slip = 20.0m, Mw 9.1)

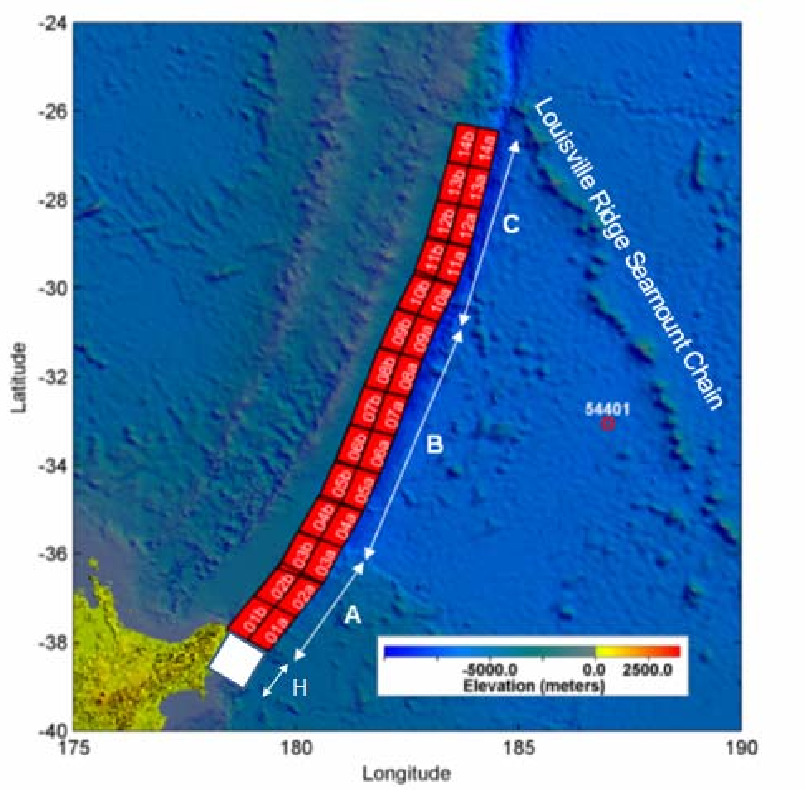

Figure 3.0-1 The segmentation of the Kermadec Trench (Segment A, B, and C) to the south of the Louisville Ridge Seamount Chain (LRSC), with unit sources dimensions of 100 km x 50 km, and the northern part segment of Hikurangi margin (segment H). The location of the DART 54401 is shown with red circles. (Base map Source: Power et al. 2011).

4.0 MODELLING TSUNAMI INUNDATION

A numerical modelling assessment has been carried out using a COMCOT tsunami model (Wang and Power, 2011). The grid resolution for this numerical modelling assessment is based on GEBCO 08 3 arc second and SRTM 30 arc second. LIDAR data was used to setup the topography model grid of the study area. The nested modelling grid setup is as follows (Figure 4.0 -1):

- Level 1: Grid resolution of 1 arc minutes (~ 1.5 km)
- Level 2: Grid resolution of 0.2 arc minutes (~290 m)
- Level 3: Grid resolution of 0.05 arc minutes (~74 m)
- Level 4: Grid resolution of 0.0125 arc minutes (~18 m)

All modelling was undertaken using Mean High Water Spring (MHWS) conditions.

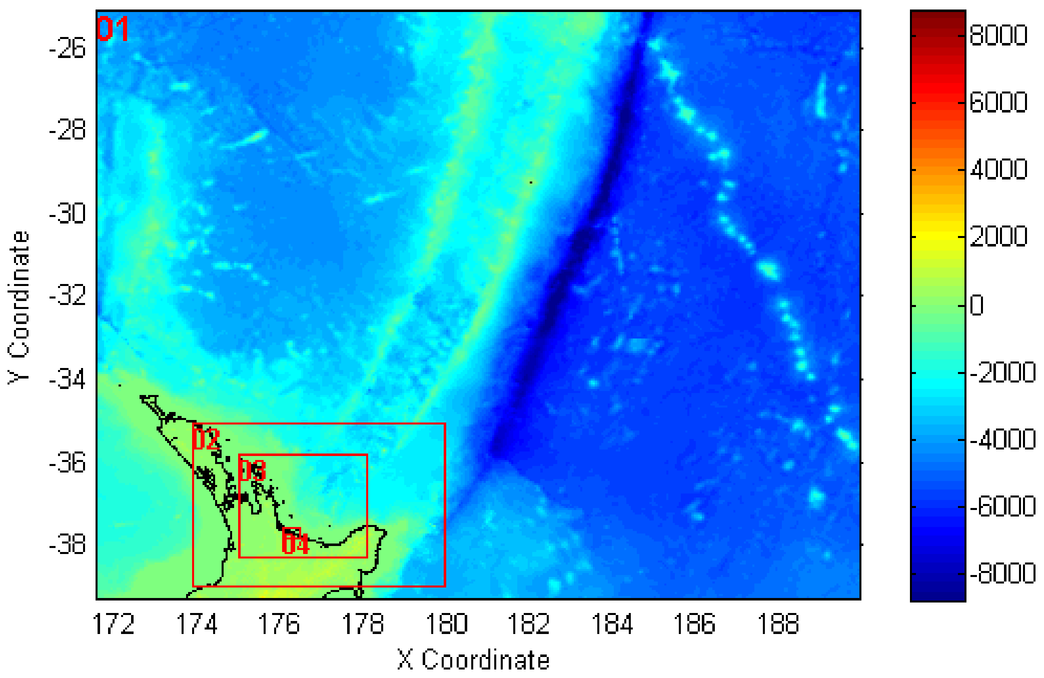

Figure 4.0-1 The nested grid arrangement for numerical modelling assessments (data source for level 1 grids: Gebco08 3 arc second, and SRTM 30 arc second resolution).

4.1 Numerical Modelling of the Whole Kermadec Scenario in Power et al (2011)

Power et al (2011) studied an earthquake scenario with a magnitude of 9.4 involving the rupture of the whole Kermadec Trench, including Segments A, B and C as illustrated in Figure 3.0-1. The general fault parameters for this event are identified in Table 4.1-1.

The modelling for this scenario involved the source area being divided into 28 unit sources (100 km x 50 km). These source units had dip angles that varied from 4° to 17°, strike angles that ranged between 190° to 205°, and depths of between 4.0 km to 20.0 km. The slip angle was uniform at 90° and a uniform slip of 22.0 m was used.

The regional maximum tsunami elevations based on these parameters are shown in Figure 4.1-1. This figure shows a tsunami would affect most of the east coast of the North Island from the East Cape towards the northern end of North Island as a consequence of rupture along the southern and central Kermadec (e.g., Segments A and B), while the tsunami generated from the northern Kermadec (e.g., segment C) propagates further north in a Northwest-Southeast direction. The sub-regional model for the Bay of Plenty Region shows that the maximum tsunami elevation along the east coast varies from 3.0 m to 11.0 above MHWS (Figure 4.1-2). While along the Whakatane and Opotiki coastal zones, the tsunami elevation at the coastline varies from 3.5 m to 8.0 m and up to 11.0 m above MHWS towards Matata. The role of offshore islands, submarine ridges and nearshore bathymetry in refracting and diffracting tsunami can be clearly observed. The offshore Islands, such as White Island, together with submarine ridges and local bathymetry steer most of tsunami energy toward the coastline of Thornton – Matata – Pikowai areas and Opotiki (Figure 4.1-3). In contrast, Whakatane and Ohope are located in a relatively sheltered zone, and the impact of a tsunami at Whakatane is far less severe than in the coastal stretch from Thornton to Matata and in Opotiki. The narrow entrance to Whakatane River and elevated coastal front north to the estuary also help shielding Whakatane from direct attack in this scenario event. While towards Thornton and Matata, significant inundation occurs with tsunami elevation along the coastline ranging from 5.0 to 11.0 m (Figure 4.1-4). The flow depth reaches up to 6.5 m near to the coast and gradually decreases further inland. Towards Ohope and Opotiki significant inundation occurs with tsunami elevation along the coastline varying from 4.0 to 7.0 m for Ohope and up to 8.0 m for Opotiki (Figure 4.1-5).

Table 4.1-1 General fault parameters for the rupture of the Whole Kermadec Scenario

Segment	Length	Width	Slip	Magnitude
A+B+C	1400 km	100 km	22.0 m	Mw 9.4

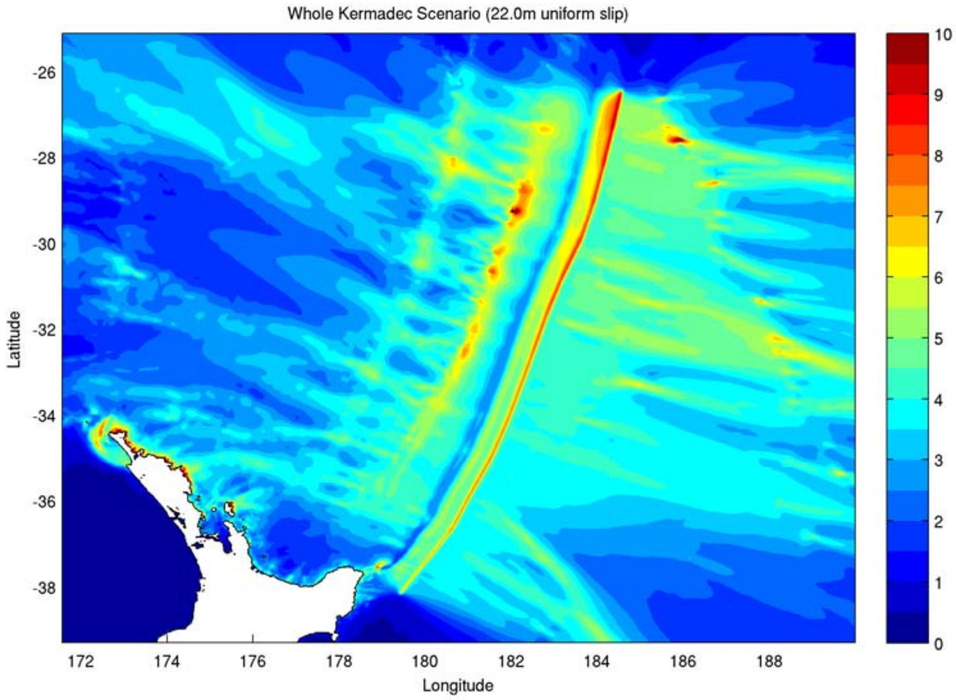

Figure 4.1-1 The maximum tsunami elevation above MHWS resulting from the Whole Kermadec scenario (Mw9.4). This modelling shows that the main source of the tsunami that impacts the east coast of New Zealand is from the rupture of the southern and central Kermadec (e.g., Segments A and B). Scale bar unit is in metres.

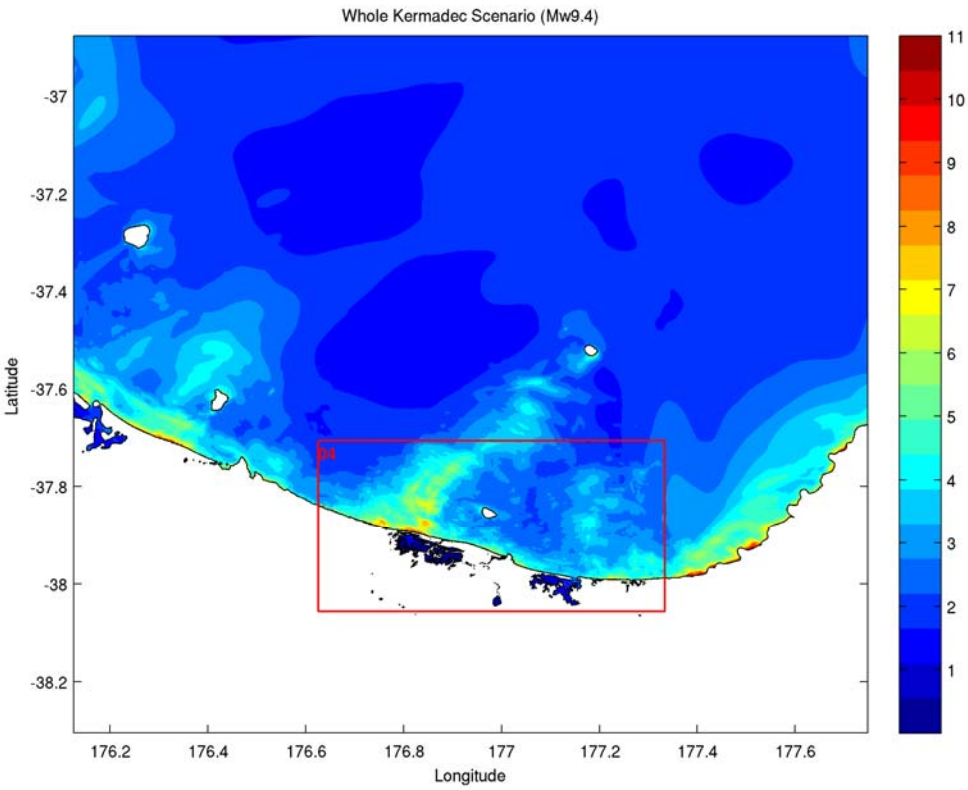

Figure 4.1-2 The maximum tsunami elevation for the Bay of Plenty varies between 3.0 m to 11.0 m above MHWS. Whakatane and Opotiki (inside the red box) are located in a relatively sheltered region. The tsunami waves are focusing towards Thornton and Matata by the offshore White island. The tsunami elevation along the coast of Whakatane and Opotiki varies between 3.5 m to 8.0 m and up to 11.0 m towards Thornton and Matata. Scale bar unit is in metres.

The tsunami inundates Ohope Beach to some distance inland as illustrated in Figure 4.1-6. The flow depth along the Western End areas varies between 6.0 m near to the coast to 0.5 m further inland. Inside the estuary, the water levels are raised to 1.0~3.0m in most areas and the tsunami is not able to overtop most part of the dunes but mainly through the entrance into the estuary. On the east side of the estuary entrance, the tsunami overtops the sand dunes. In contrast, on the west side of the estuary entrance, only the east end of Ohope Beach Golf Course is overtopped. The maximum tsunami elevation inside the estuary coastline varies from 0.5 m to 3.5 m with maximum flow speed of 2.5 m/s.

Significant inundation occurs towards the Opotiki area (Figure 4.1-7). The tsunami inundates the low-lying areas towards the Opotiki township through the river. The relatively low sand dunes on both sides of the river mouth are overtopped by the tsunami, and flooding occurs in most of the low-lying areas towards the town with flow depth varying between 0.5 m to 2.0 m inland. Near to the coast, the flow depth reaches up to 5.0 to 6.0 m while the tsunami elevation along the coastline varies between 5.0 to 8.0 m. Some parts of the town near to the rivers, such as the areas around the Wharf Street, are inundated with flow depths between 0.5 m to 1.5 m.

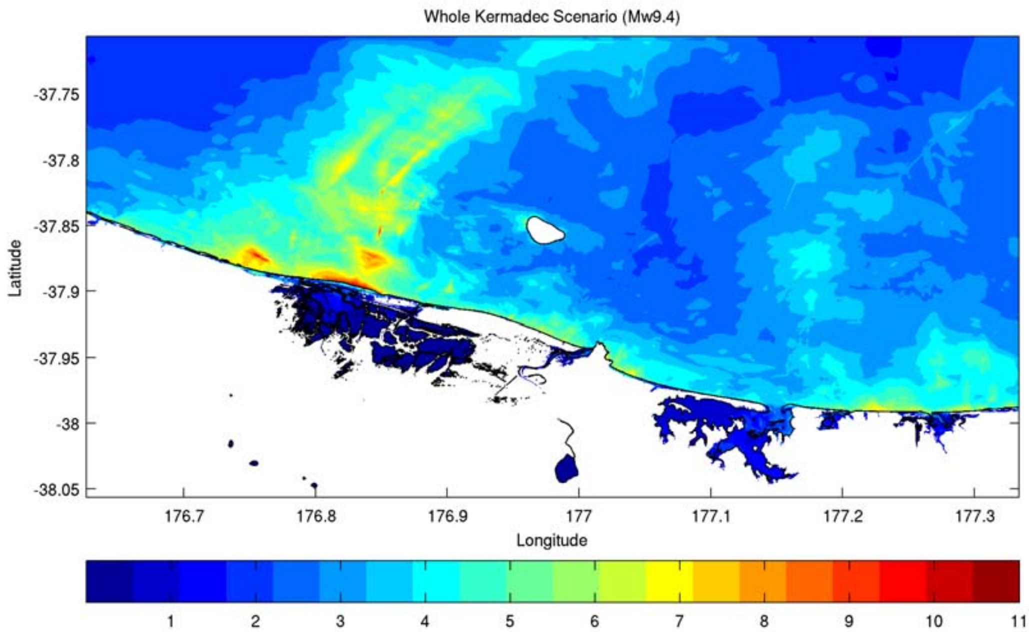

Figure 4.1-3 The maximum tsunami elevation above MHWS along the Matata-Whakatane and Opotiki coastlines shows wave focusing towards the Matata area. Only minor inundation occurs around Whakatane as most of tsunami energy is being directed toward the coastal areas of Matata and Thornton and the relatively narrow entrance to Whakatane River and elevated costal front north to the estuary shield Whakatane from direct attack by the tsunami. The shaded colour presents the computed maximum water surface elevation above ambient water level offshore and flow depth on land. Scale bar unit is in metres.

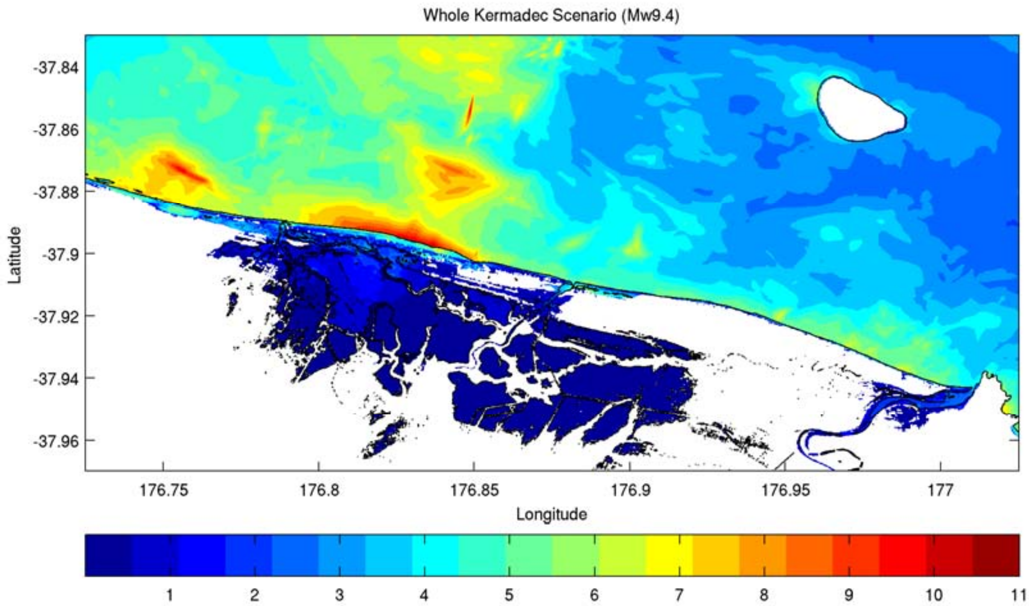

Figure 4.1-4 Detailed inundation pattern for Whakatane – Matata regions. Flow depth ranges from 0.5 m inland to 6.5 m near to the coast. The Matata area experiences extensive inundation but the impact at Whakatane is less severe than in Matata and Opotiki. The shaded colour presents the computed maximum water surface elevation above ambient water level offshore and flow depth on land. Scale bar unit is in metres.

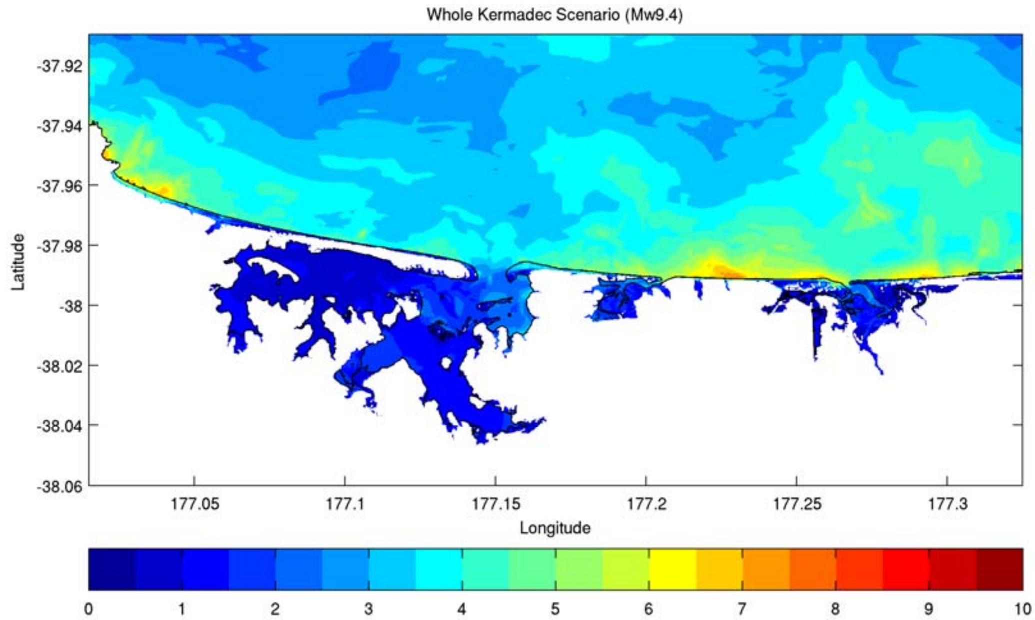

Figure 4.1-5 Detailed inundation pattern for Ohope to Opotiki shows some significant inundation occurs along the coast with flow depth between 0.5 m to 6.0 m. The shaded colour presents the computed maximum water surface elevation above MHWS offshore and flow depth on land. Scale bar unit is in metres.

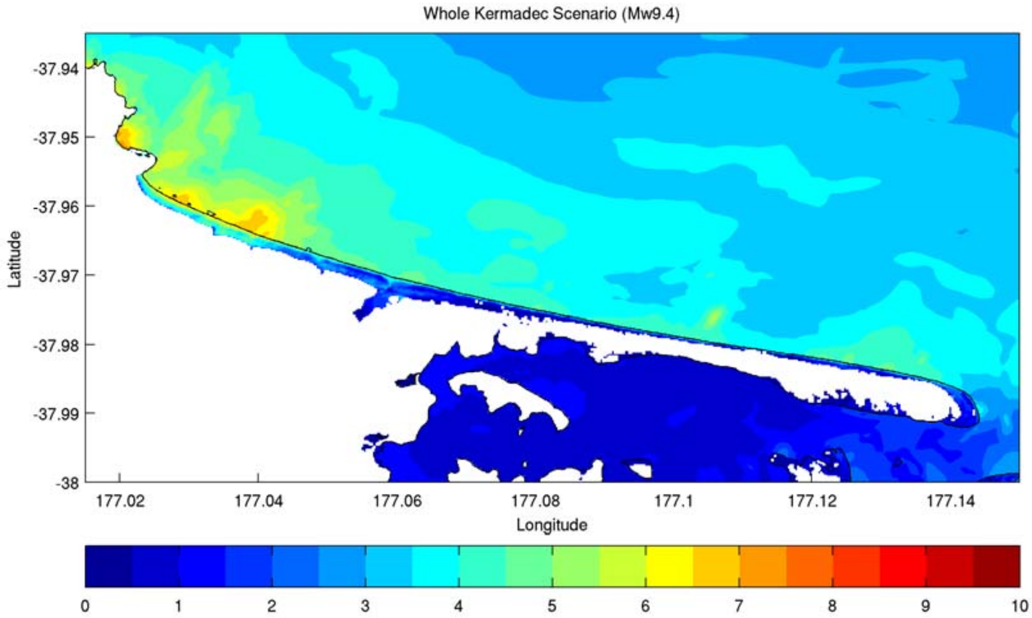

Figure 4.1-6 Inundation pattern along the Ohope coast where the tsunami has more impact towards the west end of Ohope (West End Road). The shaded colour presents the computed maximum water surface elevation above MHWS offshore and flow depth on land. Scale bar unit is in metres.

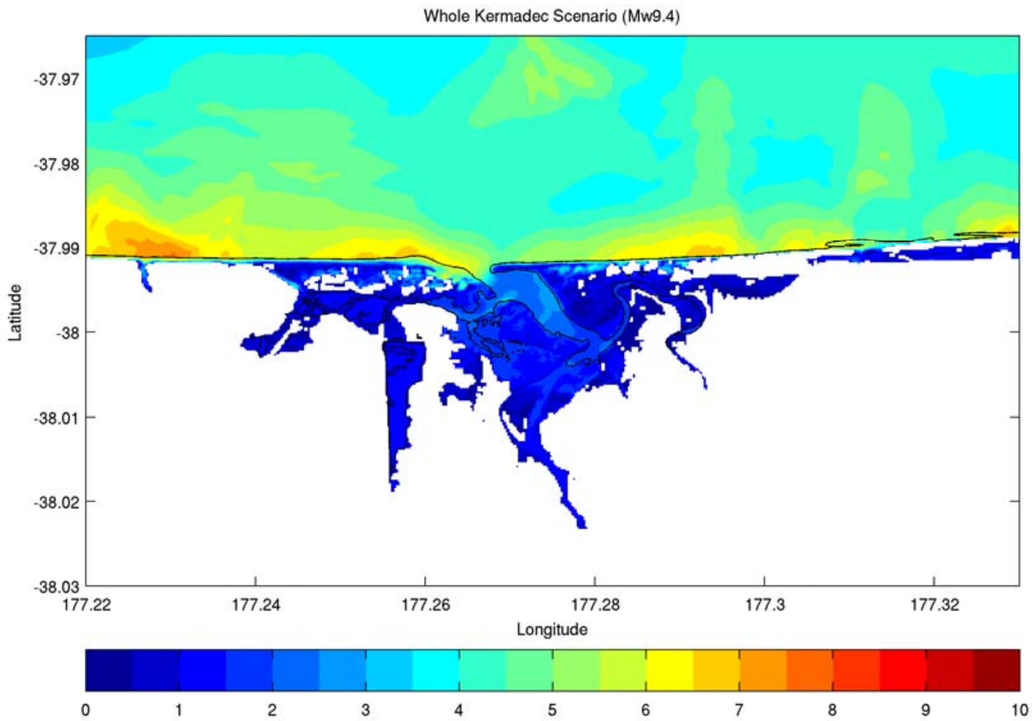

Figure 4.1-7 The inundation pattern in the Opotiki region shows extensive inundation occurs towards the township from tsunami that follow the rivers. The shaded colour presents the computed maximum water surface elevation above MHWS offshore and flow depth on land. Scale bar unit is in metres.

4.2 Inundation modelling for the Kermadec-Hikurangi Scenario

This Kermadec-Hikurangi scenario assumes that a fault rupture extends from the Kermadec to the south into the northern part of the Hikurangi Margin which is briefly called Segment H as identified by Wallace et al. (2009). This fault rupture scenario includes part of the source area of the southern and central Kermadec scenarios (segment A and B) in Power et al (2011) and an extension into the Hikurangi margin, as illustrated in Figure 5.0-2a of Prasetya and Wang (2011). The general fault parameters for this event scenario are listed in Table 4.2-1.

This source model uses a uniform dip angle of 16^o, a strike angle of 210^o, and a uniform depth of 5km. The slip angle is uniform at 90^o and a slip of 20m is used.

The regional maximum tsunami elevation distribution based on these parameters is shown in Figure 4.2-1. This Figure shows the distribution of the tsunami elevation along the east coast of the North Island of New Zealand. The sub-regional model result shows that the maximum tsunami elevation varies between 5.0 m to 11.0 m above MHWS along the coast of the studied areas. The role of offshore islands and nearshore bathymetry in refracting and diffracting tsunami is observed (Figure 4.2-2). White Island, together with submarine ridges, directs most of tsunami energy toward coastal areas along Thornton – Matata – Pikowai. Towards Opotiki and Whakatane, the high accumulations of tsunami energy are mostly due to the nearshore bathymetry configuration. The tsunami waves that propagate along the coast as a trapped wave or as Kelvin waves contribute to the localised high tsunami elevation ranging from 5.0 to 9.0 m above MHWS along the Whakatane and Ohope coast. This may create significant inundations in low-lying areas to some distance inland such as what occurs at the Western End of Ohope and Whakatane (Figure 4.2-3).In the Whakatane area, although the maximum tsunami elevation along the coast is relatively lower near the entrance of the Whakatane River than in Coastlands and Otarawairere Bay and the narrow entrance helps to shield Whakatane from direct impacts, the tsunami is still able to overtop the sand dune west of the entrance and inundate the low-lying business and residential areas up to Landing/Domain Road with a flow depth up to 4.0 meters near the river entrance.

The tsunami propagation patterns are similar to the previous whole Kermadec scenario (Mw 9.4), however, with a more severe impact.

Table 4.2-1 General fault parameters for the Kermadec-Hikurangi scenario

Segment	Length	Width	Slip	Magnitude
A, B and H	537 km	97 km	20.0 m	Mw 9.1

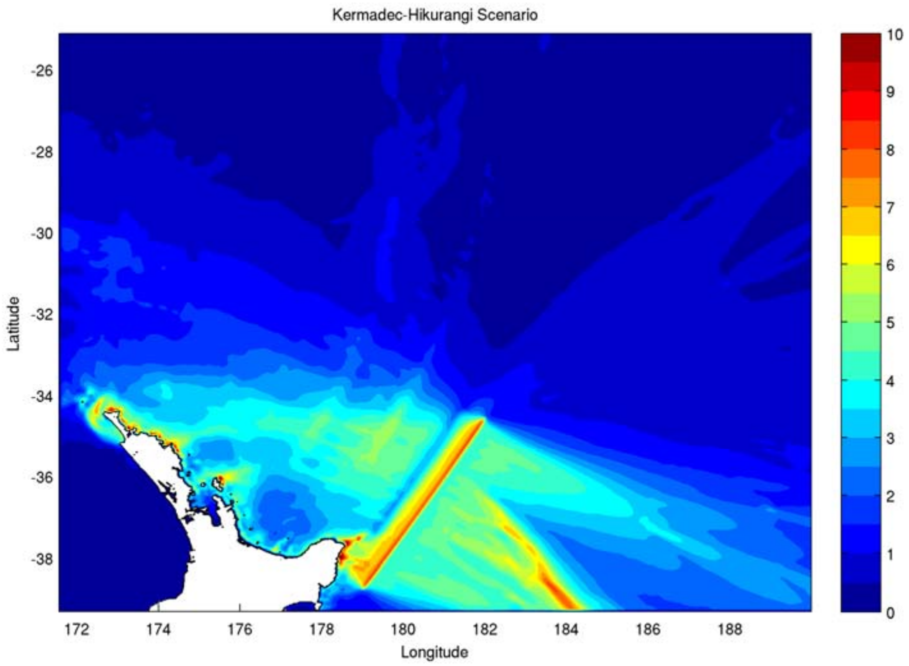

Figure 4.2-1 The maximum tsunami elevation distributions above MHWS show the concentration of tsunami energy along the coast of New Zealand. This scenario shows most of the tsunami impact to the east coast of New Zealand originates from the southern and central Kermadec (e.g., Segments A and B). East Cape is however significantly impacted as a result of the tsunami generated from the rupture of the northern portion of the Hikurangi Margin. Scale bar unit is in metres.

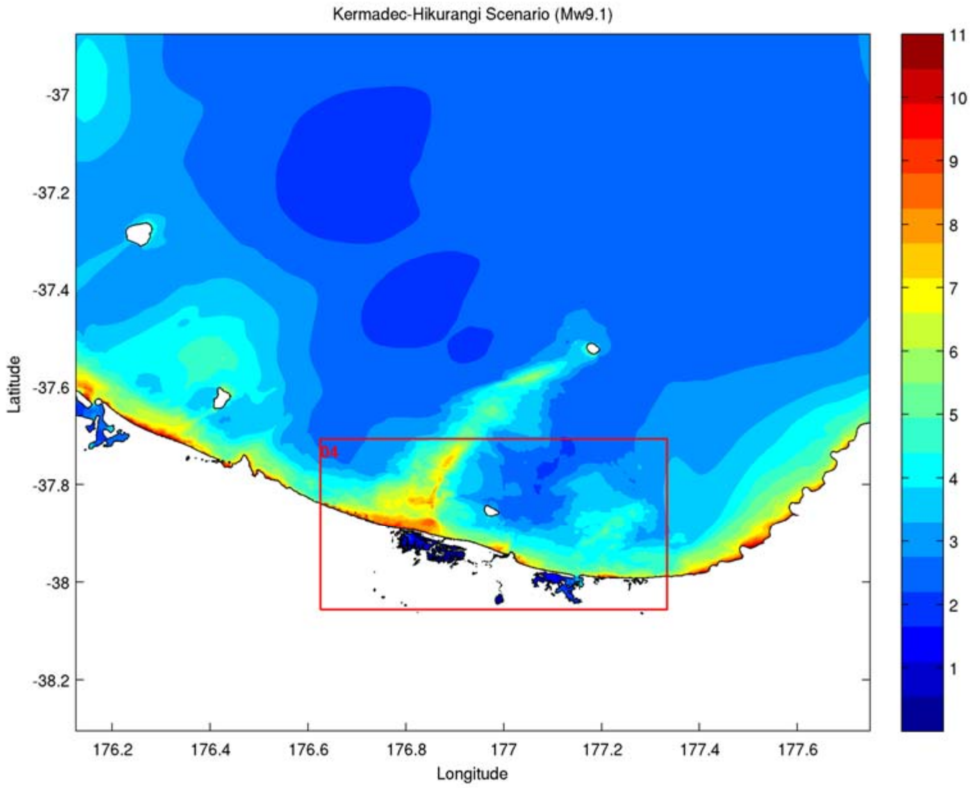

Figure 4.2-2 The maximum tsunami elevation above MHWS varies between 5.0 m 11.0 m with some exception along the areas where the offshore islands and nearshore bathymetry plays a major role in directing the energy of the tsunami. Whakatane and Opotiki (inside the red box) are located in a region where the refraction, diffraction and focusing effects play a major role on the inundation patterns. The tsunami waves are focused towards Thornton and Matata by White island. The tsunami elevation along the coast of Whakatane and Ohope varies between 5.0 m to 9.0 m and up to 11.0 m towards Matata and Opotiki. Scale bar unit is in metres

Significant inundation occurs in the Matata area along the Thornton Road to Arawa Strait. The tsunami flow depth near to the coast at Matata ranges from 3.0 m to 9.0 m, down to 0.5 to 1.0 m further inland. The inundation goes further inland through the Tarawera and Rangitaiki Rivers (Figure 4.2-4).

Along the Ohope to Opotiki areas, significant inundation occurs at several places (Figure 4.2-5). At the Ohope beach Golf Course (near to the estuary entrance) and also towards the Western End (Figure 4.2-6), tsunami flow depth near to the coast varies from 5.0 m near to the estuary entrance to ~9.0 m at the Western End. The tsunami flow penetrates further inland through the creek and inundates the area between Maraetotara and Bluett Roads with flow depth ranging from 1.0 m to 5.0 m near the coast.

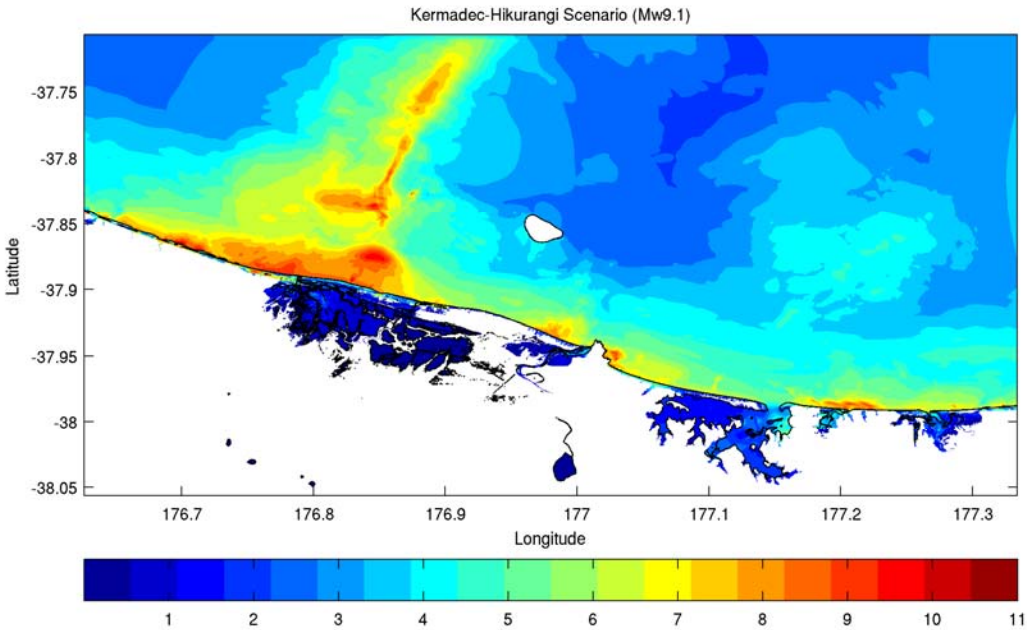

Figure 4.2-3 The maximum tsunami elevation above MHWS along the Matata-Whakatane and Opotiki coastlines shows the wave focusing towards Matata. No inundation occurs along Whakatane as the major portion of the tsunami energy is directed west to the estuary, and the narrow entrance of Whakatane River and elevated coastal barrier west to the entrance also help shield Whakatane from direct impact of the tsunami. The shaded colour presents the computed maximum water surface elevation above MHWS offshore and flow depth on land. Scale bar unit is in metres.

Significant inundation occurs towards the Opotiki area (Figure 4.2-7). The tsunami inundates the low-lying areas towards Opotiki township through the river. The relatively shallow sand dunes on both sides of the river mouth are overtopped by the tsunami, and most of the low-lying areas towards the town are flooded with flow depths mostly varying between 0.5 m to 2 m inland. Near to the coast the flow depth reaches 5.0 to 6.0 m while the tsunami elevation along the coastline varies between 6.0 to 8.0 m. Some parts of the town near to the rivers, such as the areas around Wharf Street are inundated with flow depths between 0.5 m and 2.0 m. The tsunami inundates the low-lying areas further inland as gravitational flows. In the areas north and west to John Burdett Park, the flow depth may reach up to 3.0 to 4.0 meters. Both Otara and Waioeka rivers contribute to the extent of inundation further inland. However, Opotiki Airport is safe from any inundation.

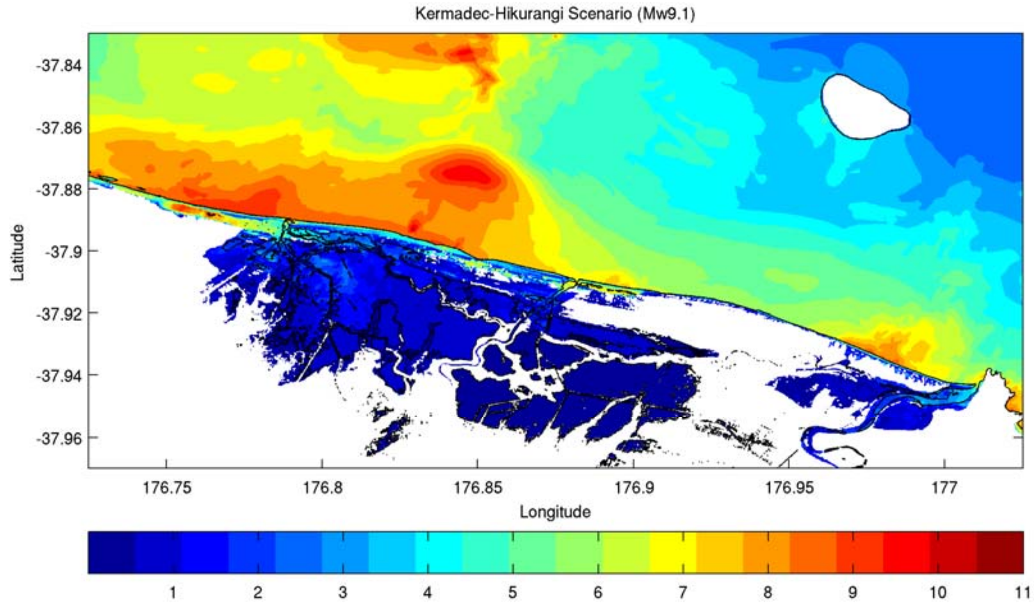

Figure 4.2-4 Detailed inundation pattern for Whakatane – Matata areas. Flow depth ranges from 0.5 m inland to 9.0 m near to the coast. The tsunami inundates the Matata area but the impact at Whakatane is more modest. The shaded colour presents the computed maximum water surface elevation above MHWS offshore and flow depth on land. Scale bar unit is in metres.

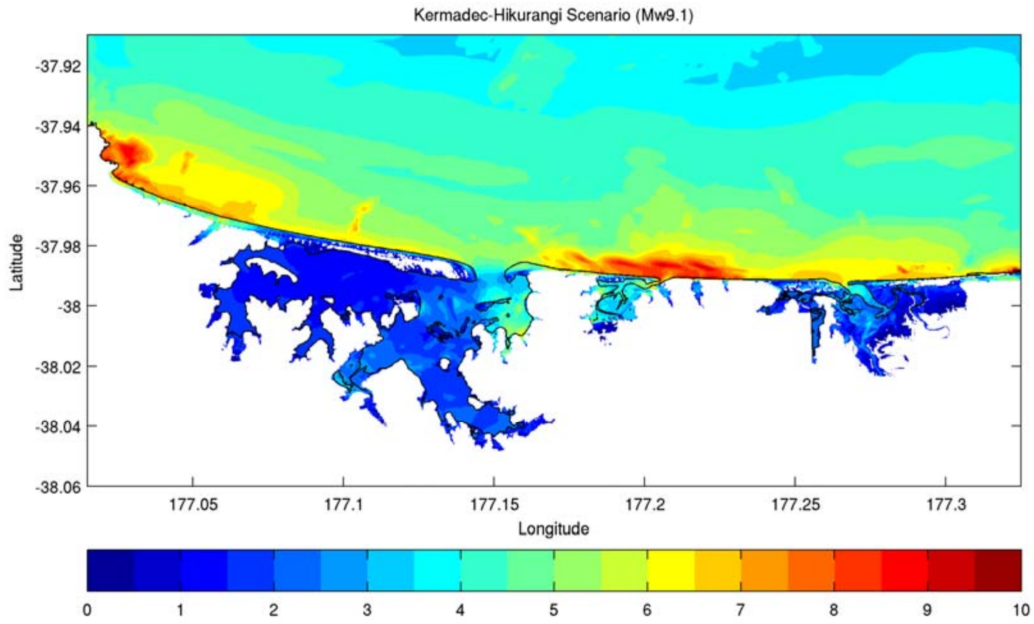

Figure 4.2-5 Detailed inundation pattern for Ohope to Opotiki shows significant inundation occurs along the coast. The shaded colour presents the computed maximum water surface elevation above MHWS offshore and flow depth on land. Scale bar unit is in metres.

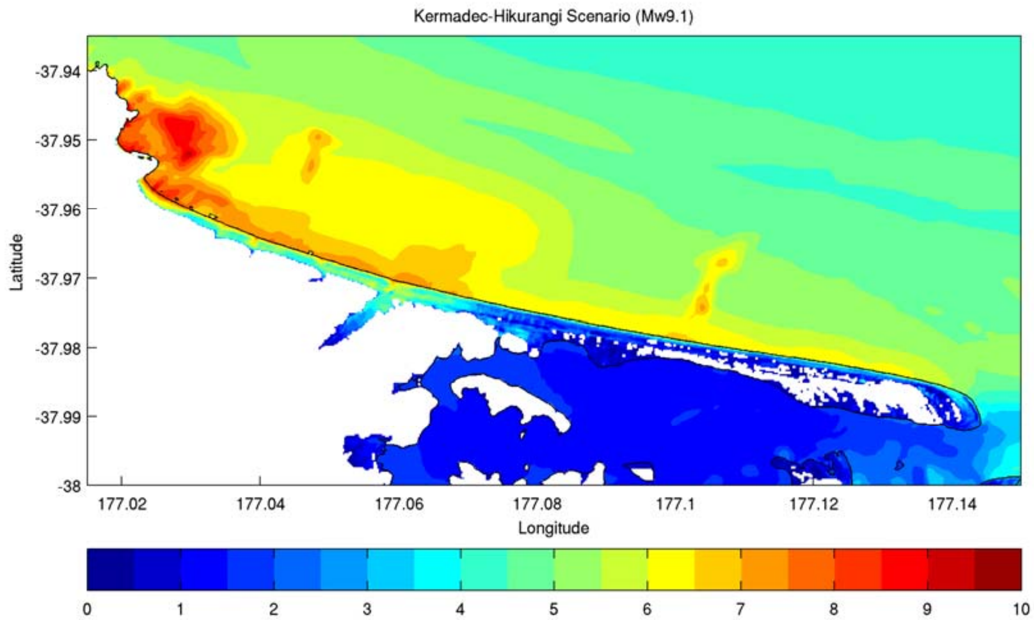

Figure 4.2-6 Inundation pattern along the Ohope coast where the tsunami causes more impact towards the west end of Ohope (West End Road). The shaded colour presents the computed maximum water surface elevation above MHWS offshore and flow depth on land. Scale bar unit is in metres

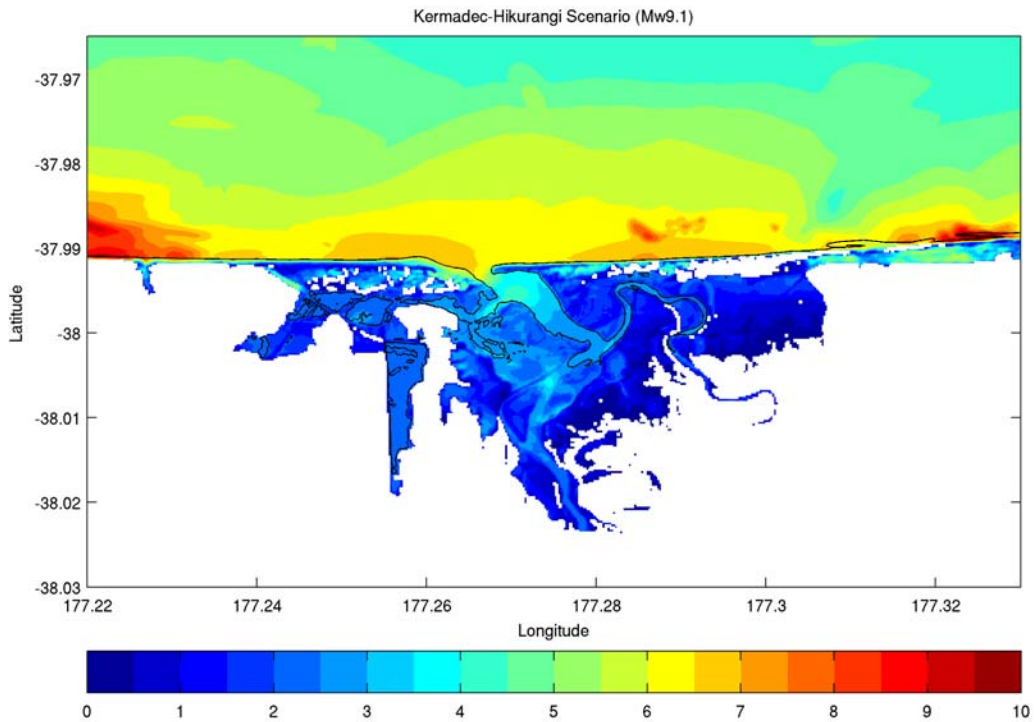

Figure 4.2-7 Inundation pattern in the Opotiki area shows extensive inundation occurs towards the township due to tsunami overtopping over the sand dunes and intrusion from the rivers. The shaded colour presents the computed maximum water surface elevation above MHWS offshore and flow depth on land. Scale bar unit is in metres.

4.3 Inundation Modelling of Variations of Scenarios in Power et al (2011)

The amount of co-seismic slip associated with the Indian Ocean 2004 Boxing Day earthquake, and with the recent 11 March 2011 Tohoku Mw9.0 earthquake in Japan was greater than originally thought likely to occur on these subduction zones (Ozawa et al. 2011). The recent Tohoku earthquake demonstrates that the largest earthquakes may recur over very long time intervals and the size of maximum earthquakes may be much bigger than previously expected. As such, additional modelling has been undertaken to investigate the resulting tsunami if a slip of 30.0m were applied to the Kermadec scenarios in Power et al. (2011). These variations of the Kermadec scenarios include a variation of the Southern Kermadec scenario (slip = 30.0m, Mw9.0), a variation of the Central Kermadec scenario (slip = 30.0m, Mw9.2) and a variation of the Whole Kermadec Scenario (slip = 30.0m on segment A and B, and slip = 22.0m on Segment C).

4.3.1 Variation of Southern Kermadec Scenario

A variation of the Southern Kermadec Scenario in Power et al. (2011) has been modelled to take into account the parameters observed in the recent 11 March 2011 Tohoku earthquake in Japan (Mw = 9.0 with maximum slip of > 30 m). The fault rupture in this scenario is increased to 30 m along Segment A while the other fault parameters are kept the same as the original setup.

These parameters result in an earthquake with a magnitude of Mw = 9.0. The resulting modelling identified that a tsunami generated from the southern Kermadec affects most of the coastal areas along the east coast of the North Island. The sub-regional modelling results show the tsunami elevation along the coastline of Bay of Plenty is greater than that of the whole Kermadec Mw 9.4 scenario and the Kermadec-Hikurangi (Mw 9.1) scenario that were previously modelled (section 4.1 and 4.2). However, the wave patterns are similar to the previous source scenario event. Whakatane and Ohope are located in a relatively sheltered zone, where White Island and associated submarine ridges as well as local bathymetry steer tsunami energy toward the coasts along Thornton – Matata – Pikowai areas and towards Opotiki. The maximum tsunami elevation ranges from 5.0 m to 13.0 m above MHWS along the coastline of the studied areas (Figures 4.3.1-1 and -2). The flow depth at Whakatane is relatively small compared to other regions in the study area. Thornton, Matata, Ohope and Opotiki experience significant inundation (Figures 4.1-3 and 7).

The tsunami inundates Ohope to some distance inland as illustrated in Figure 4.1-6 with a significant inundation occurring towards the Western End. The flow depth along the West End area varies between 6.0 m near to the coast to 3.0 m further inland. Inside the estuary the maximum tsunami elevation varies from 1.0 m to 3.0 m above MHWS in most of places with exceptions near the entrance where the tsunami elevation may reach up to 4.0-5.0 meters.

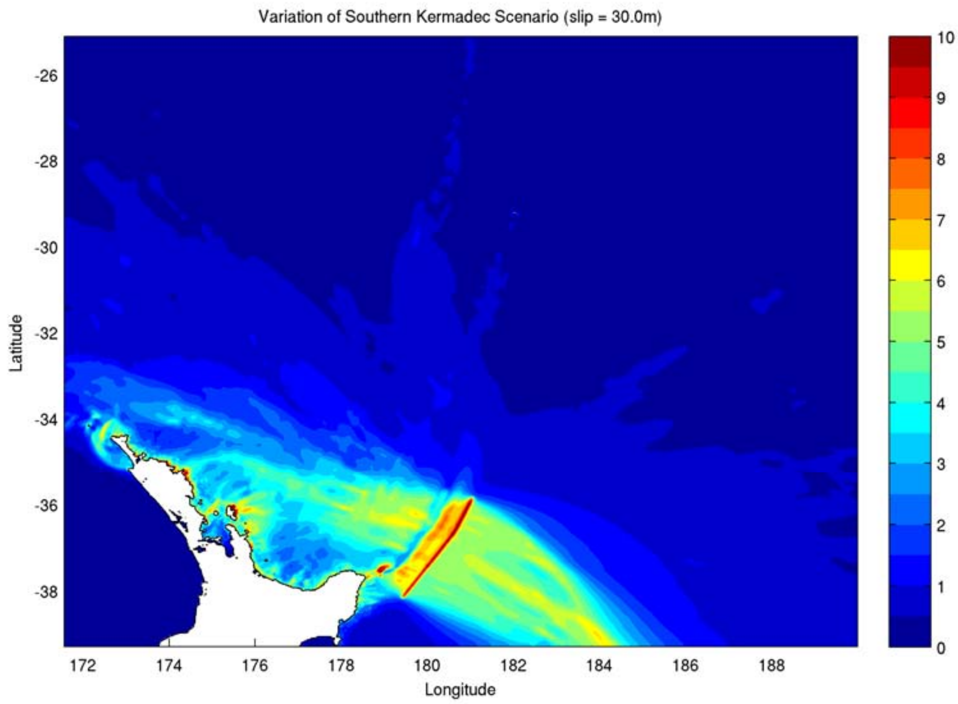

Figure 4.3.1-1 The maximum tsunami elevation above MHWS along the New Zealand coast for the rupture of the southern Kermadec with a slip of 30 m. This modelling shows that a tsunami generated from the southern Kermadec mostly affects the east coast of the North Island, New Zealand. Scale bar unit is in metres.

Significant inundation occurs towards the Opotiki area (Figure 4.1-7). The tsunami inundates the low-lying areas towards the Opotiki township through the river. The sand dunes on both sides of the river mouth are overtopped by the tsunami, and most of the low-lying areas towards the town are flooded with a flow depth varying between 0.5 m to 2.0 m. The flow depth may reach up to 3.0 meters north and west to John Burdett Part. Near to the coast the flow depth reaches 5.0 to 8.0 m, while the tsunami elevation along the coastline varies between 6.0 to 10.0 m.

The tsunami extensively inundates the low-lying areas further inland as gravitational flows. Even though most of the area between the two rives is completely inundated, the Opotiki Airport area remains safe.

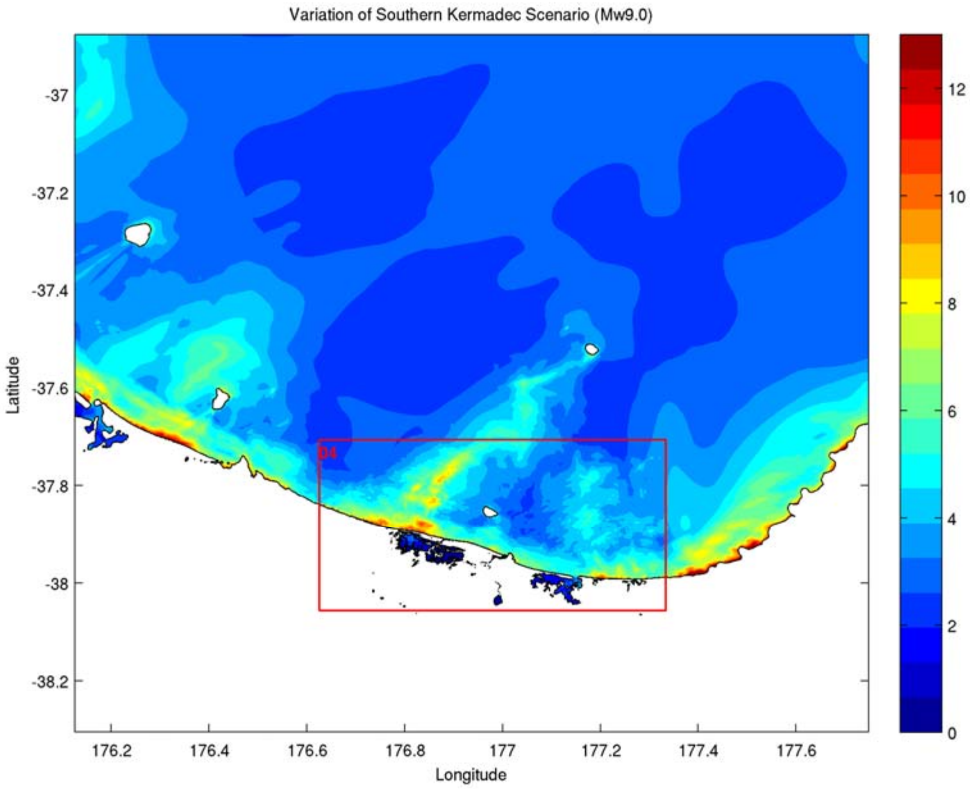

Figure 4.3.1-2 The maximum tsunami elevation above MHWS varies between 5.0 m to 13.0 m and the offshore islands and nearshore bathymetry plays a major role in focussing the tsunami. The tsunami waves are focused towards Thornton and Matata by the offshore island White island. The tsunami elevation along the coast of Whakatane and Ohope varies between 5.0 m to 10.0 m and up to 13.0 m towards Matata and Opotiki. The shaded colour presents the computed maximum water surface elevation above mHWS offshore and flow depth on land. Scale bar unit is in metres.

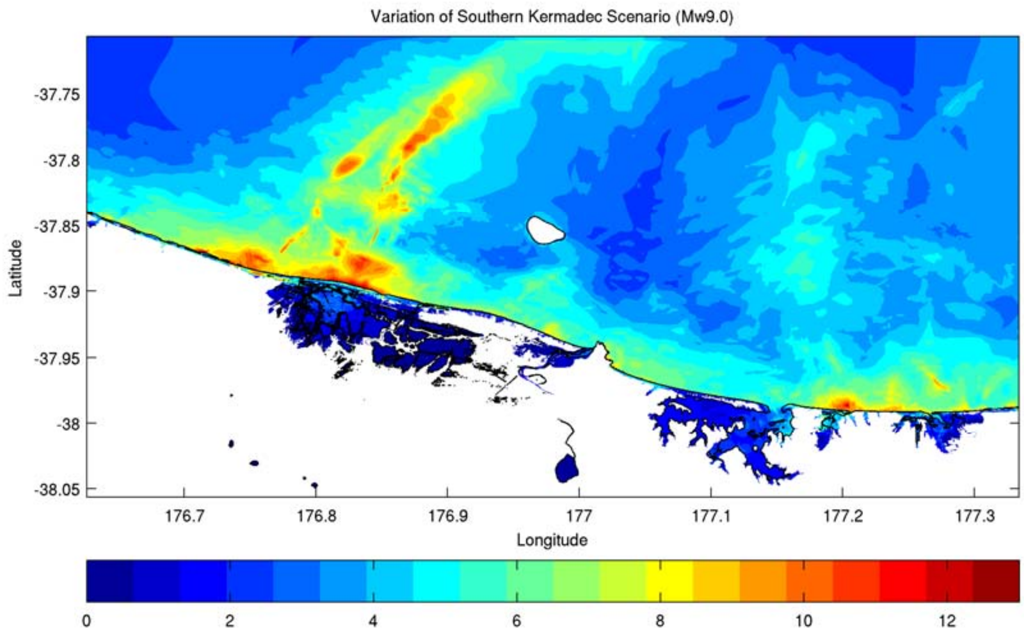

Figure 4.3.1-3 The maximum tsunami elevation above MHWS along the Matata-Whakatane and Ohope - Opotiki coastlines shows the wave focusing towards Thornton - Matata areas and Opotiki. In Whakatane area, the tsunami may inundate up to Landing/Domain Road, the tsunami impact is less severe than in other areas. . The shaded colour presents the computed maximum water surface elevation above MHWS offshore and flow depth on land. Scale bar unit is in metres.

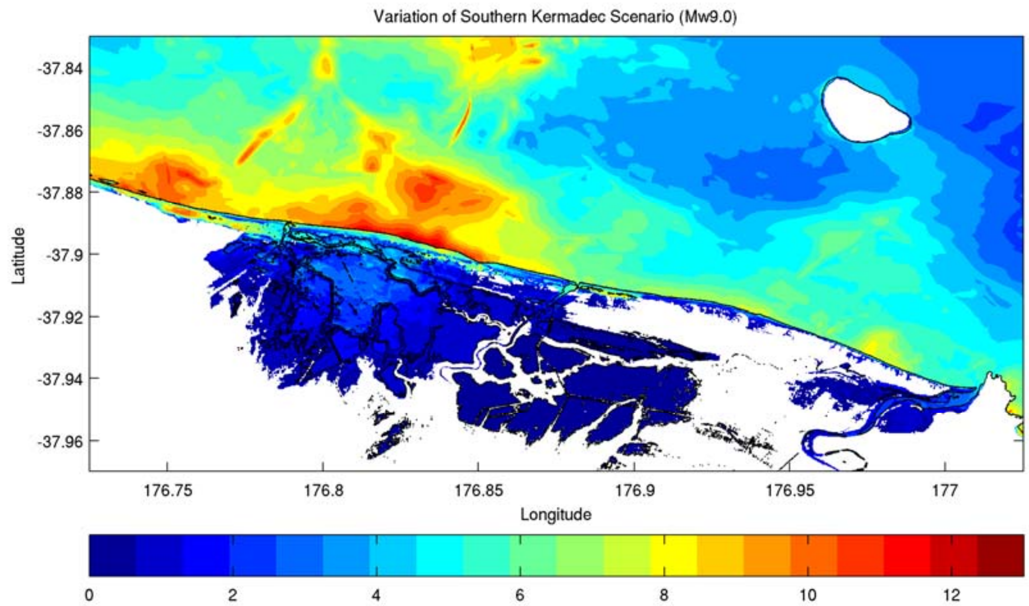

Figure 4.3.1-4 Detailed inundation pattern for Whakatane – Matata areas with flow depth ranges from 0.5 m inland to 10.0 m near to the coast. The tsunami inundates Matata areas but the impact at Whakatane is less severe. The shaded colour presents the computed maximum water surface elevation above MHWS offshore and flow depth on land. Scale bar unit is in metres.

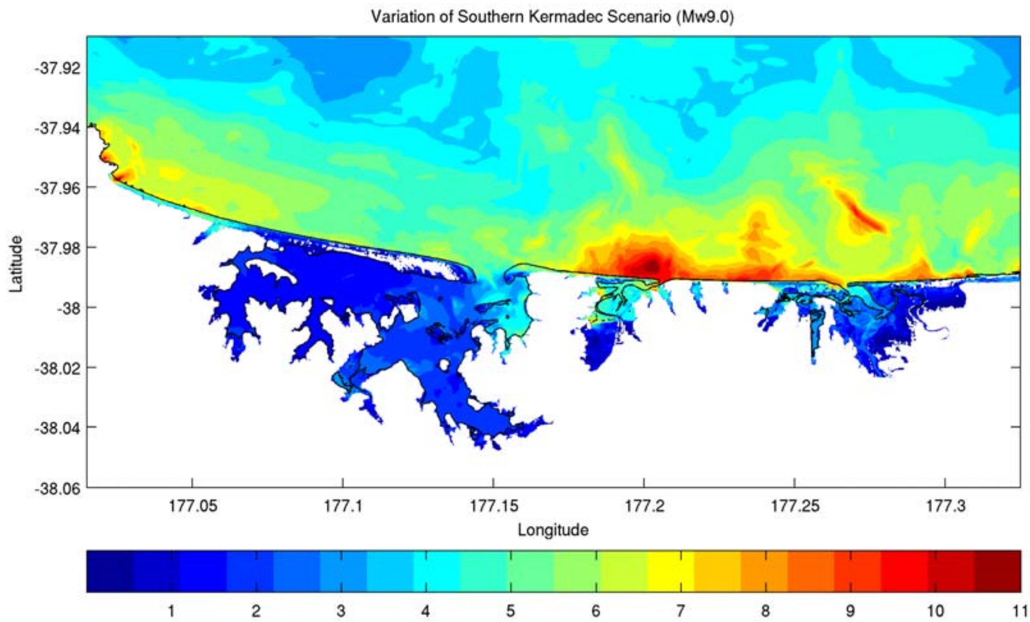

Figure 4.3.1-5 Detailed inundation pattern from Ohope to Opotiki shows significant inundation occurs along the coast. The shaded colour presents the computed maximum water surface elevation above MHWS offshore and flow depth on land. Scale bar unit is in metres.

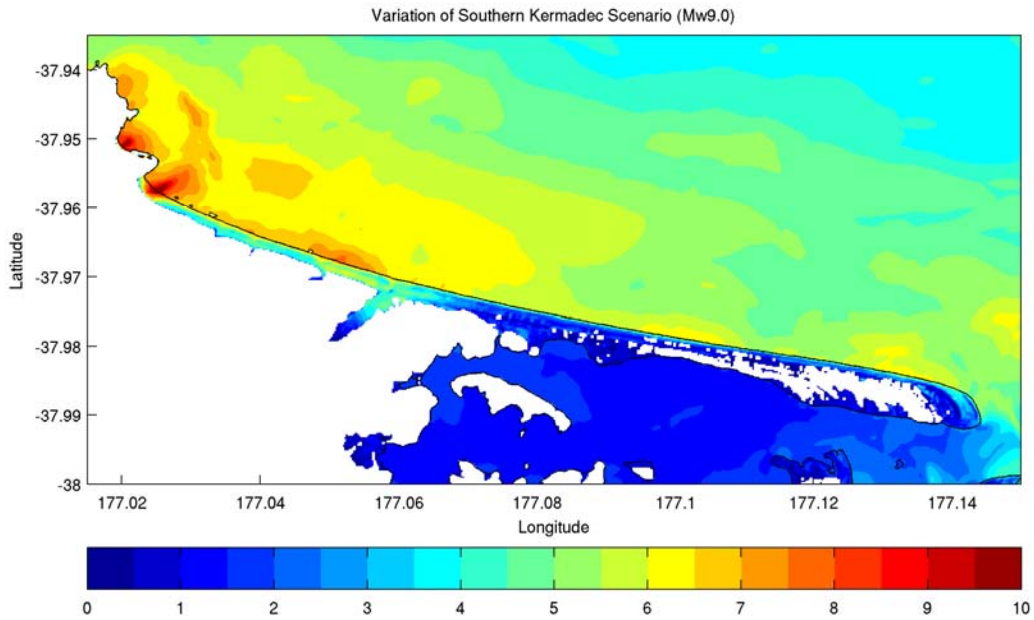

Figure 4.3.1-6 Inundation pattern along the Ohope coast shows more impact towards the centre and tip of West End (West End Road). The shaded colour presents the computed maximum water surface elevation above MHWS offshore and flow depth on land. Scale bar unit is in metres.

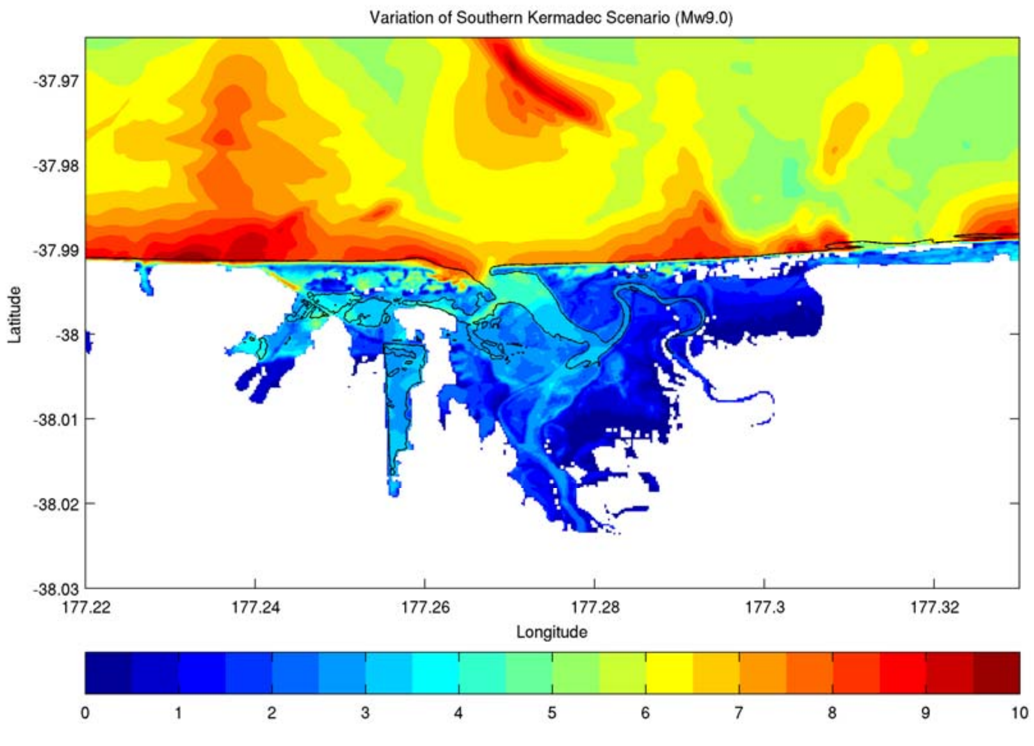

Figure 4.3.1-7 Inundation pattern in the Opotiki area shows extensive inundation occurs towards the township from a tsunami that overtops the sand dunes and comes from the rivers. The shaded colour presents the computed maximum water surface elevation above MHWS offshore and flow depth on land. Scale bar unit is in metres.

4.3.2 Variation of Central Kermadec Scenario

A variation of the Central Kermadec Scenario along Segment B in Power et al. (2011) was also modelled by taking into account the findings in the 11 March 2011 Tohoku Mw9.0 earthquake in Japan. In this scenario, the slip along the southern Kermadec trench (i.e., Segment B) was increased to 30.0 m while the other fault parameters were kept the same as the original setup.

These parameters result in an earthquake with a magnitude of Mw = 9.2. The modelling identifies that a tsunami generated from this event mostly affects the northern part of the coastal areas along the east coast of the North Island (Figure 4.3.2-1). This is due to the directivity of the tsunami energy that is mainly perpendicular to the strike of the fault, causing the tsunami to affect the northern region of the North Island. The sub-regional modelling results identify that the maximum tsunami elevation within the study areas ranges from 3.0 m to 7.0 m above MHWS (Figure 4.3.2-2). The impacts of a tsunami from this source scenario in the study area is minimal compared to the source scenarios with a rupture further into the south along the Kermadec Trench in this study, where the tsunami elevation reaches up to 11.0~13.0 m above MHWS. In this scenario, the highest tsunami elevation within the study area occurs in the Matata-Thornton area, causing a localised inundation with flow depth up to 5.0 m. No significant inundation occurs along Whakatane and Opotiki coastal areas. However, at the West End of Ohope and along the coastal front, the flow depth may reach up to 4.0 m. The sand dunes along the coast are high enough not to be overtopped by tsunami (Figures 4.3.2-3 and 5).

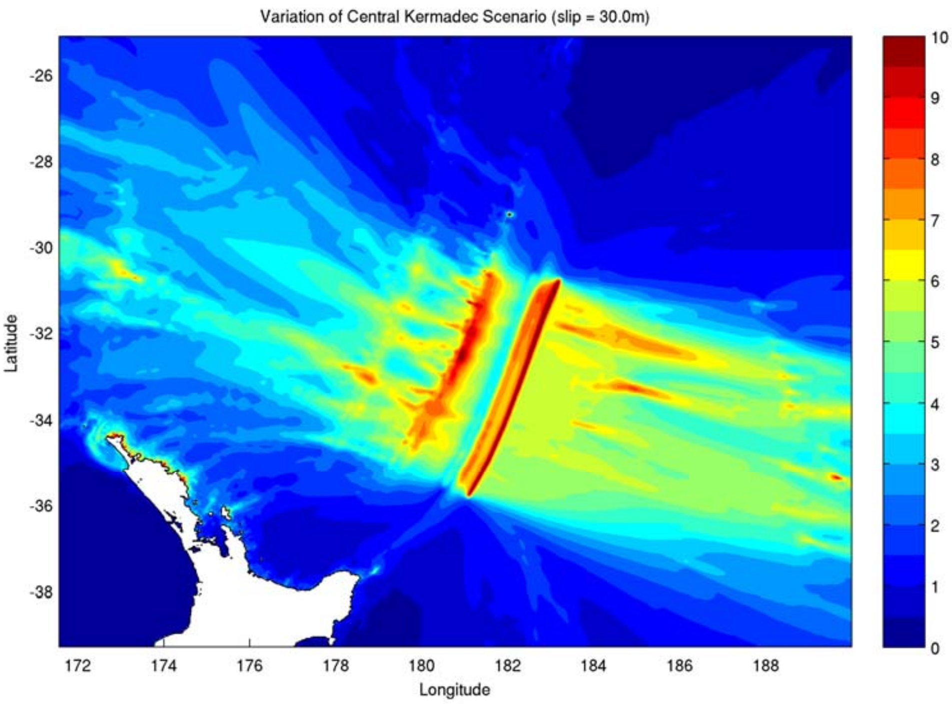

Figure 4.3.2-1 The maximum tsunami elevation distribution above MHWS for the rupture of the central Kermadec with a slip of 30.0m. This modelling identifies that a tsunami generated from a rupture of this segment mostly affects the northern part of the East Coast of the North Island New Zealand and is not directed towards to the Bay of Plenty region. Scale bar unit is in metres.

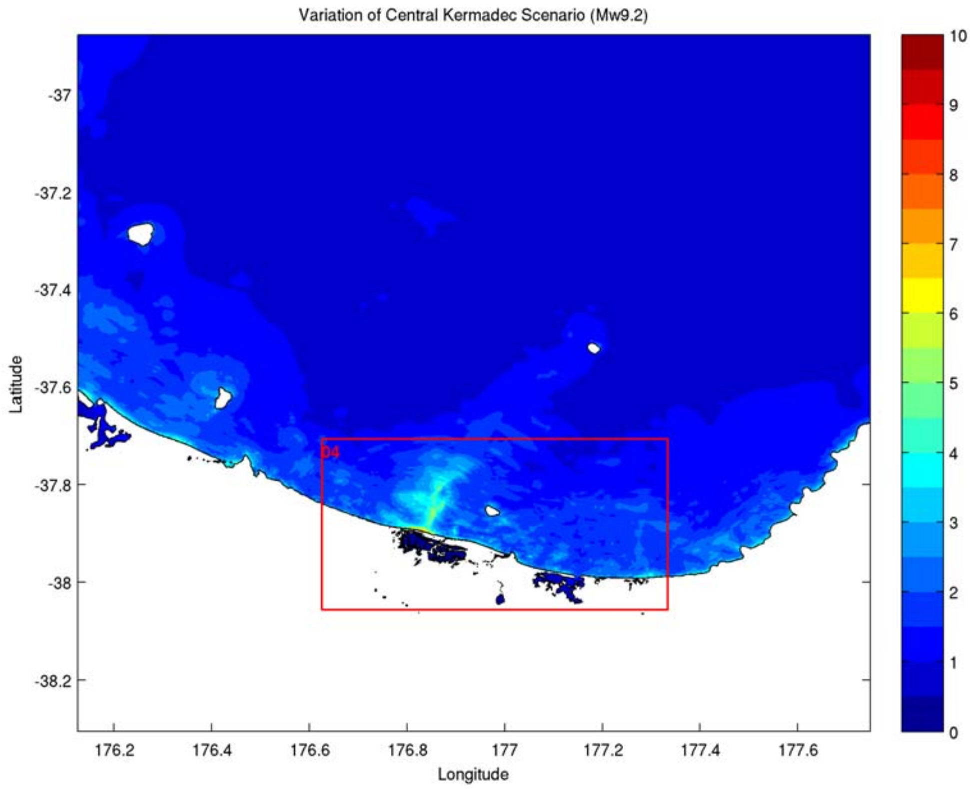

Figure 4.3.2-2 The maximum tsunami elevation for the study areas varies between 3.0 to 7.0 m above MHWS. Whakatane and Opotiki are located inside the red box in the region where refraction, diffraction and focusing effects play a major role in the inundation patterns. The tsunami waves are focused towards Thornton and Matata by the offshore island White Island. The tsunami elevation along the coast of Whakatane and Ohope varies between 3.0 m to 4.5 m and up to 7.0 m towards Matata and 5.5 m at Opotiki. Scale bar unit is in metres.

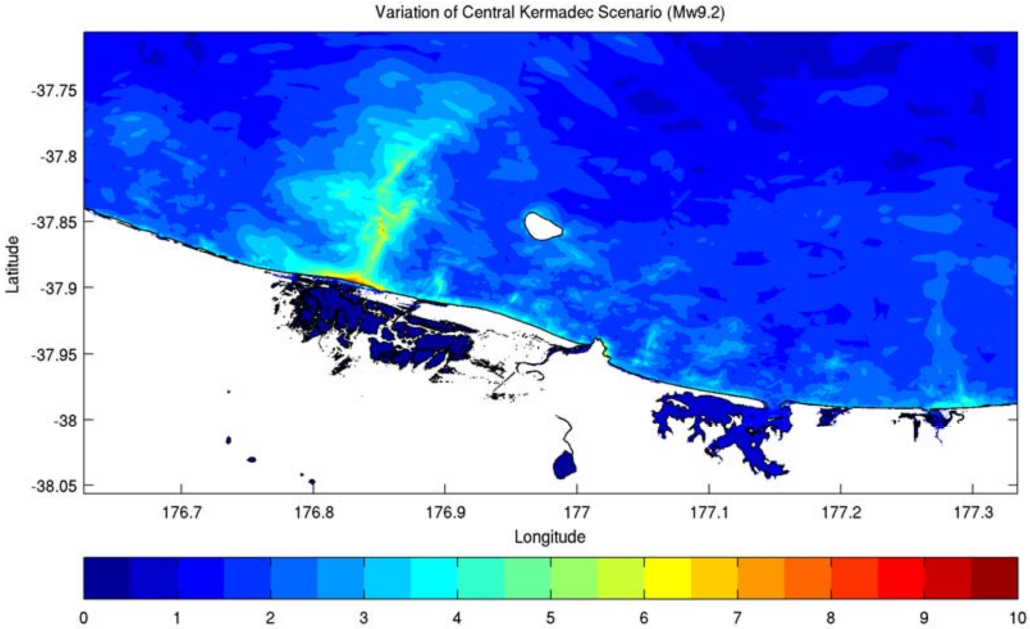

Figure 4.3.2-3 The maximum tsunami elevation above MHWS along the Matata-Whakatane and Ohope - Opotiki coastlines shows the wave focusing towards Thornton - Matata areas and Opotiki. However, no significant inundation occurs along the coast. The shaded colour presents the computed maximum water surface elevation above MHWS offshore and flow depth on land. Scale bar unit is in metres.

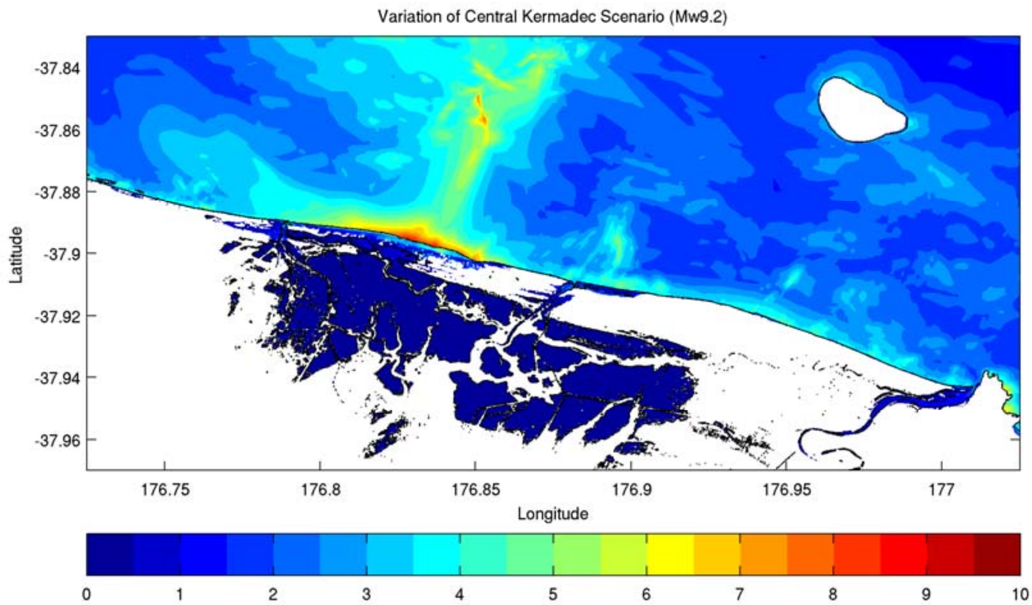

Figure 4.3.2-4 The maximum tsunami elevation above MHWS along the Matata-Whakatane coastal area showing the wave focusing towards Thornton - Matata areas and producing a significant height and a localised inundation with flow depth up to 5.0 m. No significant inundation occurs along the Whakatane coast. The shaded colour presents the computed maximum water surface elevation above MHWS offshore and flow depth on land. Scale bar unit is in metres.

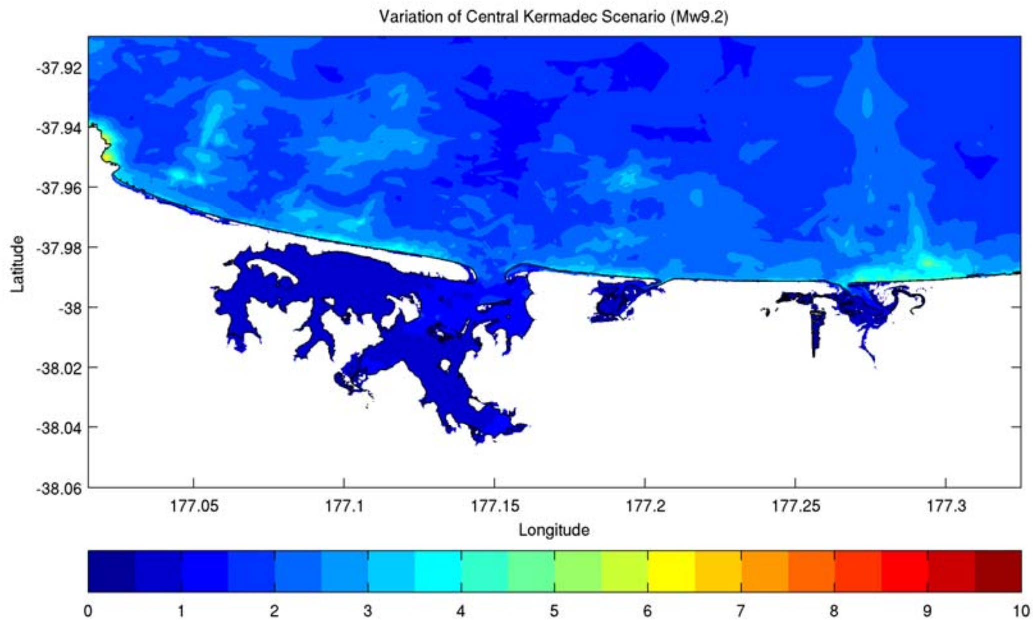

Figure 4.3.2-5 The maximum tsunami elevation above MHWS along the Ohope - Opotiki coastline shows the tsunami are relatively small (3.0 to 5.5 m) compared to the height of the sand dunes. The tsunami causes an inundation up to the highest water mark along the beach front and inside the estuary. No notable inundation occurs at Opotiki. The shaded colour presents the computed maximum water surface elevation above MHWS offshore and flow depth on land. Scale bar unit is in metres.

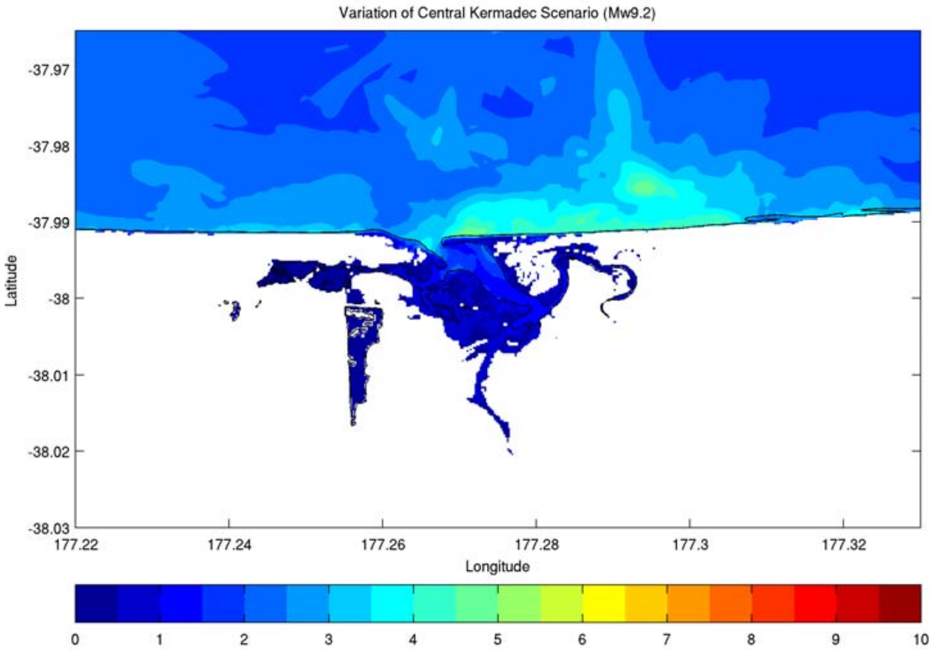

Figure 4.3.2-6 The inundation pattern in the Opotiki region shows no notable inundation occurs towards the township, but the low-lying areas near next to Rivers are inundated. The shaded colour presents the computed maximum water surface elevation above MHWS offshore and flow depth on land. Scale bar unit is in metres.

4.3.3 Variation of Whole Kermadec Scenario

A variation of the Whole Kermadec scenario in Power et al. (2011) has been modelled by taking into account observations of the 11 March 2011 Tohoku Mw9.0 earthquake in Japan. The variation to the fault rupture along Segments A, B and C in Power et al. (2011) was carried out by increasing the slip for Segments A and B to 30m and retained a slip of 22m for Segment C.

These parameters resulted in an earthquake with a magnitude of Mw = 9.45. The modelling identifies that a tsunami generated from this event affects most of the east coast of the North Island. The sub-regional modelling results show the tsunami elevations along the coastline of the Bay of Plenty are greater than the whole Kermadec Scenario (Mw 9.4) and the Kermadec-Hikurangi scenario (Mw 9.1), but similar to the scenario rupturing the southern Kermadec (i.e., segment A) with slip 30 m (Mw 9.0). This clearly shows that the Bay of Plenty regions would get a significant impact from the tsunami generated from the southern segment of the Kermadec Trench. The maximum tsunami elevation along the coastline ranges from 5.0m to 13.0m along the coasts of the studied areas (Figures 4.3.3-1 and -2). The overall tsunami propagation patterns are similar to the Whole Kermadec scenario (Mw9.4) in Power et al. (2011) and the variation of the Southern Kermadec Scenario (Mw9.0) previously modelled. Whakatane and Opotiki are also located in a relatively sheltered zone as the major portion of tsunami energy was directed by White Island and associated submarine ridges towards Thornton – Matata – Pikowai coastal areas. Significant inundation occurs in these areas. In comparison with the original whole Kermadec scenario (Mw9.4) in Power et al (2011), the impact of tsunami along the Ohope-Opotiki coasts is increased as illustrated in Figure 4.3.3-3. Tsunami climbs up to the sand dunes areas, but does not cause any further inundation inland.

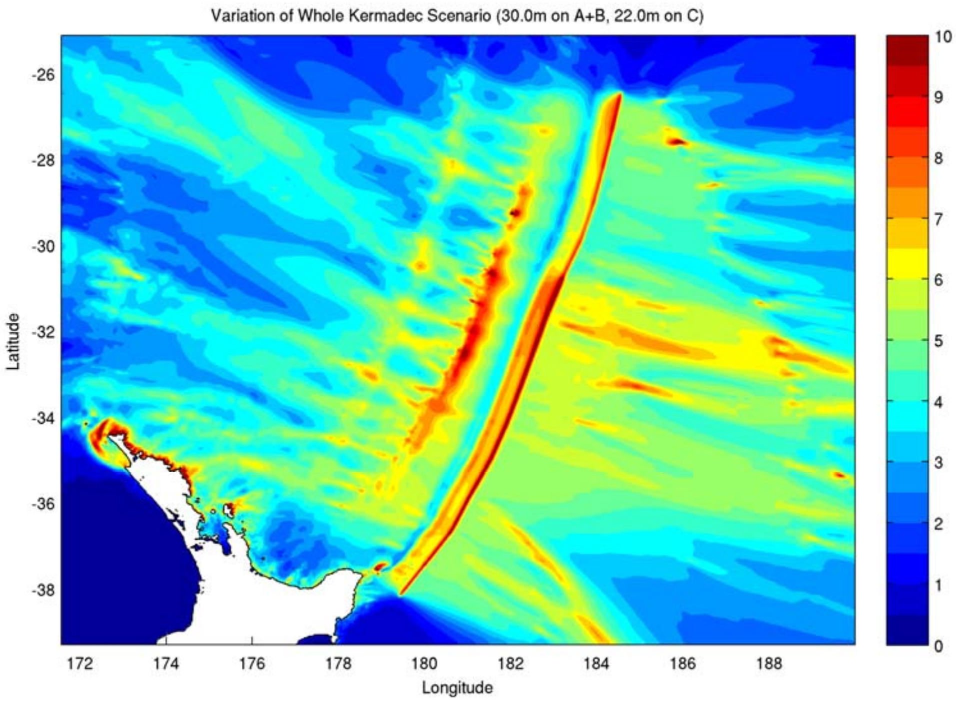

Figure 4.3.3-1 The maximum tsunami elevation above MHWS for the variation of the whole Kermadec scenario in Power et al. (2011) with a slip of 30.0m on Segment A and B and 22.0m on Segment C. The modelling identifies that a tsunami generated from this event affects most of the east coast of the North Island, New Zealand. Scale bar unit is in metres.

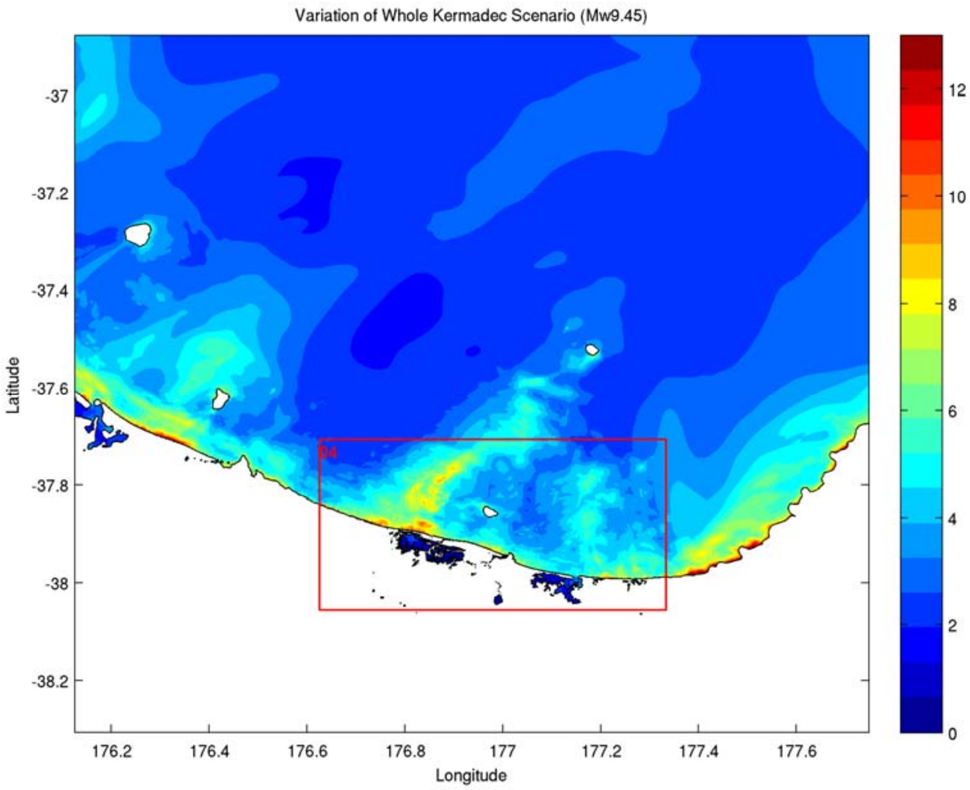

Figure 4.3.3-2 The sub-regional model shows the maximum tsunami elevation above MHWS varies between 5.0 m 13.0 m along the coasts of the studied areas. Whakatane and Opotiki (inside red box) are located on the relatively sheltered zone where the tsunami waves are steered by the offshore White island towards Thornton and Matata. The shaded colour presents the computed maximum water surface elevation above MHWS offshore and flow depth on land. Scale bar unit is in metres

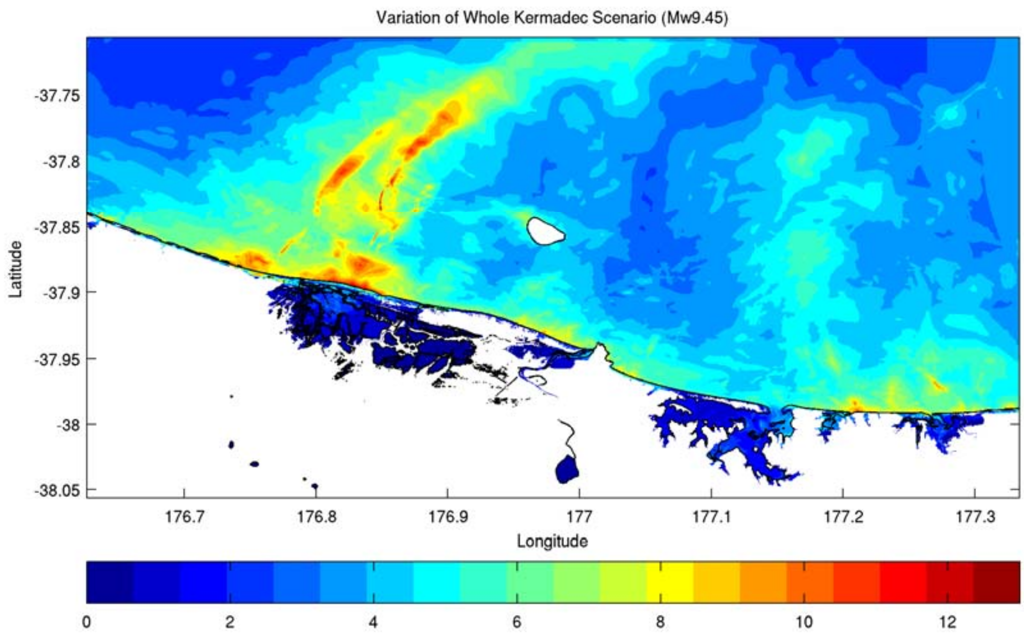

Figure 4.3.3-3 Detail inundation modelling identifying the extent of inundation inland along the Matata to Opotiki coastline. Most of the low-lying areas along Thornton- Matata, Ohope estuary and Opotiki are inundated by the tsunami. Low-lying areas in Whakatane are also inundated up to Landing/Domain Road however the impact is less severe than in Matata and Opotiki. The shaded colour presents the computed maximum water surface elevation above MHWS offshore and flow depth on land. Scale bar unit is in metres.

The tsunami elevation along the Thornton – Matata coastline varies from 8.0 to 13.0 m (Figure 4.3.3-4) with flow depth ranges up to 9.0 m near to the coast. Significant inundation occurs in this region where the tsunami penetrates further inland towards the low-lying areas.

The tsunami elevation reaches up to 6.0~7.0 m along the Whakatane coastline, notable inundation occurs up to Landing/Main Road in the area of Whakatane with a maximum flow depth around 1.0 m in most places. However, in the business area near the river entrance, the maximum flow depth may reach up to 2.0~4.0 m.

The maximum tsunami elevation along the Ohope and Opotiki coastline ranges from 5.0 to 10 m above MHWS. In Ohope area, the tsunami elevation towards West End Road varies from 7.0 to 9.5 m above MHWS. The tsunami penetrates further inland through the river between Maraetotara Road and Bluett Road. The tsunami is also able to overtop the coastal stretch of Ohope from Domain to Tauwhare Pa Scenic Park into the estuaries with a flow depth between 0.5 to 1.0 m.

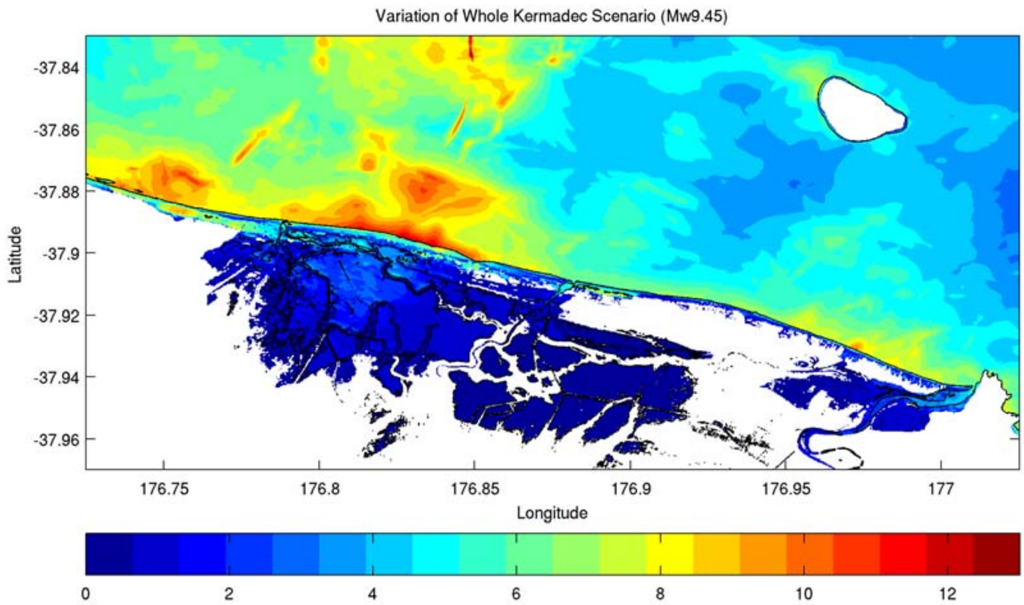

Figure 4.3.3-4 The inundation extends inland at Thornton – Matata indicating that the tsunami has overtopped the sand dunes along the beach. The tsunami overland flows propagate into the low-lying areas with flow depth varying between 5.0 to 9.0 m near to the coast. The shaded colour presents the computed maximum water surface elevation above MHWS offshore and flow depth on land. Scale bar unit is in metres.

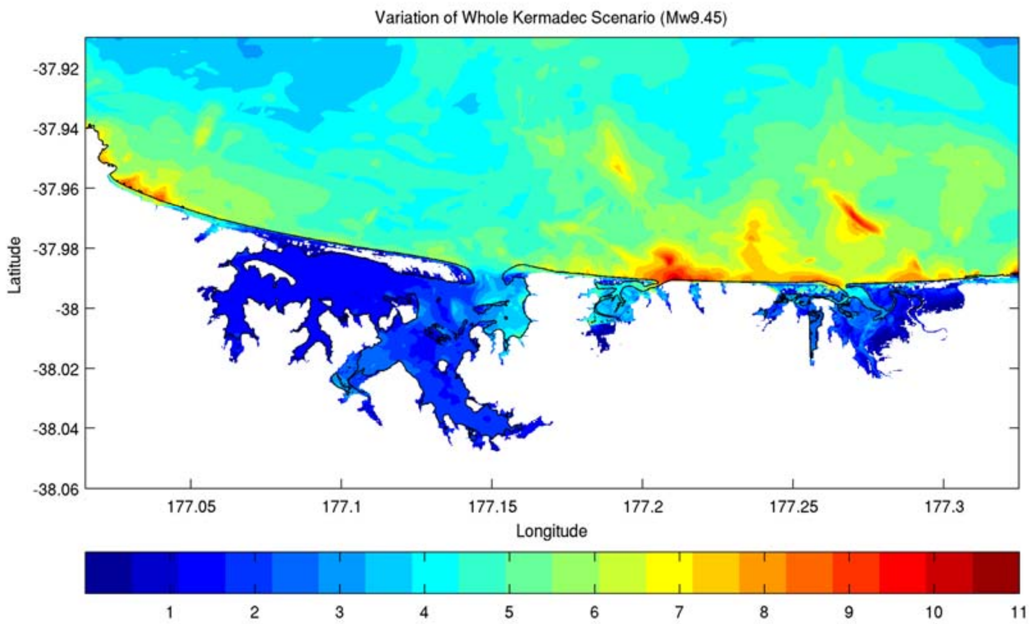

Figure 4.3.3-5 The inundation extent along the Ohope – Opotiki coastline indicates the great variations of tsunami height along the coast as well as the extent of inundation further inland through the river and estuarine system. The shaded colour presents the computed maximum water surface elevation above MHWS offshore and flow depth on land. Scale bar unit is in metres.

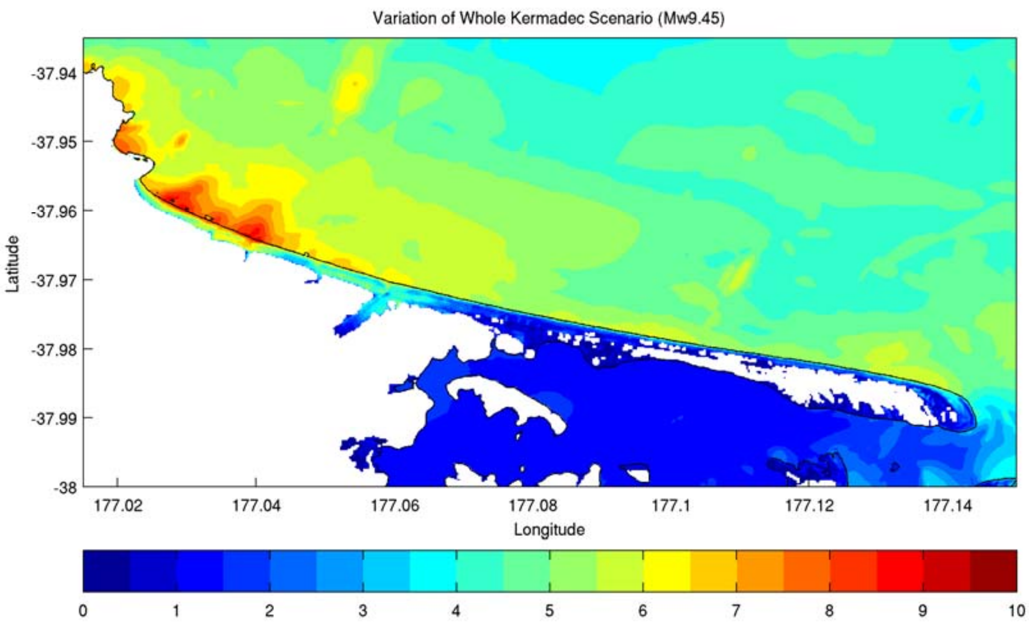

Figure 4.3.3-6 The inundation extent along the Ohope coastline indicates that the tsunami overtopped the sand dunes along the beach and that overland flows propagate down to the low-lying areas towards the estuary for the central region. High flow depth 5.0~ 8.5 m occurs at the Western End region and gradually decreases towards the estuary entrances. The shaded colour presents the computed maximum water surface elevation above MHWS offshore and flow depth on land. Scale bar unit is in metres.

Significant inundation occurs at Opotiki, as the tsunami penetrates further inland up to Bridge Street. The tsunami elevation along the coast varies from 6.0 to 10.0 m and overtops most of the sand dunes on both sides of the river mouth. This contributes towards extensive inundation along the rivers towards the townships. The tsunami inundates most of the townships with a flow depth around 2.0 m and in areas north and west to John Burdett Park the flow depth may reach up to 3.0 meters (Figure 4.4.3-7). Near the coast front, relatively high flow depth occurs on the areas to the left of the River mouth from State Highway 2 towards Waiotahi Beach Road. A localised inundation also occurs through small rivers along Pohutukawa Dr.

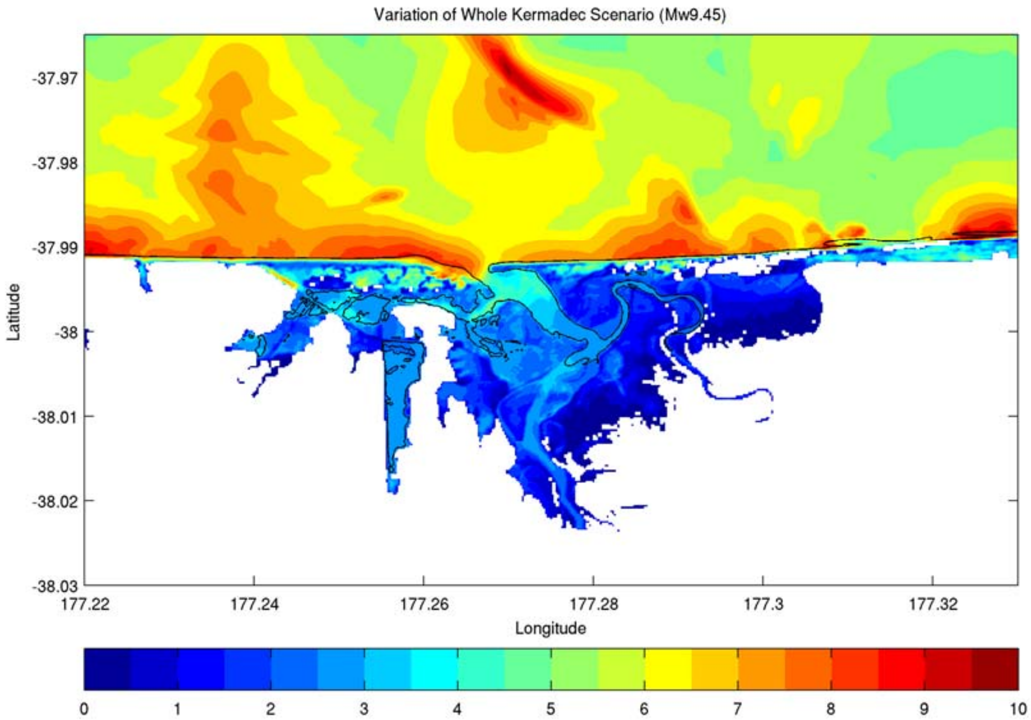

Figure 4.3.3-7 Extensive inundation occurs at Opotiki and surrounding areas. The maximum tsunami elevation along the coast varies from 6.0 m to 10.0 m. The tsunami overtops the sand dunes on both sides of the rivers and causes a major inundation to the township. The shaded colour presents the computed maximum water surface elevation above MHWS offshore and flow depth on land. Scale bar unit is in metres.

5.0 CONCLUSIONS

- The inundation modelling results show the study areas are highly affected by tsunami generated along the Kermadec Trench. The arrival time of the first wave ranges from 40 to 70 minutes in the scenarios, and the maximum tsunami elevations along the coast typically range between 6.0 and 10.0 m above MHWS in the studied scenarios.
- A Whole Kermadec scenario in Power et al. (2011) (slip = 22.0m, Mw9.4) leads to significant inundation within the study areas.
- Variations of the three Kermadec scenarios in Power et al. (2011) were developed by applying the slip of 30.0m that occurred in the 11 March 2011 Tohoku earthquake (Mw9.0) in Japan:

- Variation of the Southern Kermadec scenario in Power et al. (2011) (slip=30m, Mw = 9.0): leading to an extensive inundation in the study areas;
- Variation of the Central Kermadec scenario in Power et al. (2011) (slip=30m, Mw = 9.2): leading to a localised inundation in the study areas;

- Variation of the Whole Kermadec scenario in Power et al. (2011) (slip = 30m on Segment A and B, and slip = 22m on Segment C, Mw9.45): leading to an extensive inundation in the study areas, similar to the variation of the southern Kermadec scenario (slip = 30.0m, Mw = 9.0).

- A Kermadec-Hikurangi Mw9.1 scenario, involving a fault rupture extending from the Kermadec Trench to the south into the northern portion of the Hikurangi Margin, with uniform dip = 16^{o} and slip = 20.0 m, provides an impact similar to the scenarios involving the rupture of the southern Kermadec with a slip of 30.0m, such as the variation of the Southern Kermadec scenario (slip = 30.0m, Mw9.0) and the variation of the whole Kermadec scenario (slip = 30.0m on Segment A and B, slip = 22.0m on Segment C, Mw9.45).

- For all scenario events simulated, the offshore islands (White and Motuhora Island), submarine ridges and nearshore bathymetry play a significant role in amplifying or reducing the tsunami impacts. White Island and associated submarine ridges direct most of tsunami energy towards Thornton – Matata – and Pikowai areas, and to some extent towards Opotiki which results in significant inundation in these regions. The tsunami also inundates Whakatane area, however the flow depths are smaller in the inundated areas of Whakatane than in the other areas because offshore islands and ridges steer most of tsunami energy away from this area and thus it is located in relatively sheltered zone. The narrow entrance to Whakatane River and elevated coastal front north to the River also help shield Whakatane from direct attack by tsunami.

- The model results show that an elevated coastal front such as provided by sand dunes forms an effective and important barrier to tsunami. The preservation or conservation of these sand dunes along the beach front is critical, and any activities that deteriorate the dune systems should be avoided. If the dune systems are degraded due to storm waves or other extreme events, actions need to be carried out to re-condition the sand dune systems back to their original state, to provide their natural protective function (Prasetya, 2007).

- Strategic mitigation of the tsunami risk is needed within this region, especially in coastal areas from Matata to Thornton and from Ohope to Opotiki as well as in Whakatane. Mitigation activities may involve a combination of structural (seawall, existing building for shelter/vertical evacuations) and non-structural (sand dunes, trees or green belt) methods for already developed areas such as the low-lying areas in Matata, Whakatane and from Ohope to Opotiki. For future development planning within the high risk zone; promotion of retreat from the tsunami hazard by means of land-use planning and building code policy, rules and guidelines as well as financial instruments are the recommended options.

6.0 LIMITATIONS OF THE CURRENT WORK

- No erosion or sedimentation has been considered or taken into account during the modelling processes. Therefore, morphology changes to beaches and sand dunes, which may occur due to the strong currents and wave breaking, have not been incorporated into this model.

- The modelling in this report was undertaken on the assumption that tsunami inundation takes place over a smooth (frictionless) landscape. In practise buildings and vegetation will impede the flow of water, limiting its penetration inland but potentially increasing the depth near the coast. As such the results will tend towards overestimating the area of inundation, while near-shore flow-depths may in some cases be underestimated. The flow of water around buildings and trees is very difficult to model on a large scale, and it can produce highly localized effects.

- Most of the scenarios used in this report assume earthquake rupture with limited variable slip. However, in real events, the slip varies on a variety of spatial scales. The pattern of slip distribution may strongly affect the resulting tsunami in the near-field (close to the source) more than at a distance from the source (Geist, 1998). The uniform slip distribution used here represents an approximation of the average event rather than the real earthquakes of the same magnitude which may have larger slip in some areas and lesser slips in others.

- The scenarios used in this work represent a few examples from the wide range of possible events. As such it is appropriate to draw general conclusions based on common features of the inundation in these scenarios, but it should not be anticipated that future tsunamis should correspond directly to any one scenario.

- There is much uncertainty regarding the maximum size of earthquake that the Kermadec Trench could experience. The scenarios presented here represent possibilities that cannot currently be ruled out, but are believed to lie towards the more severe end of the range of possible maximum events.

7.0 ACKNOWLEDGEMENTS

The authors would like to thank Dick Beetham, SR Uma, and Maureen Coomer of GNS Science for reviewing the manuscripts and provided valuable discussions and comments, and Penny Murray for her support and general assistance in producing the report.

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