Tsunami inundation modelling for Tauranga and Mount Maunganui

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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 Mt. Maunganui and Tauranga areas. Inundation is modelled from the sources based on the results of the Review of Tsunamigenic sources for 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 consist of very large earthquakes (Mw 9.0 and above) in the Kermadec Trench and in some cases the ruptures also include the northern part of the Hikurangi Margin. The scenarios were developed following the segmentation of the subduction interface along the Kermadec Trench in Power et al. (2011), with additional variation of the slip amount on each segment based on studies of the recent 11 March 2011 Mw9.0 Tohoku earthquake in Japan.

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

   - A Whole Kermadec Scenario in Power et al. (2011) with a magnitude of Mw9.4: leading to a significant inundation within the study areas.

   - Variations of the Southern, Central and Northern Kermadec scenarios in Power et al. (2011) by applying an e slip of 30m, such as occurred in the recent 11 March 2011 Mw9.0 Tohoku earthquake in Japan:

     - Variation of the Southern Kermadec Scenario (slip = 30m, Mw = 9.0): causing extensive inundation in the study areas and their surrounding regions;
     - Variation of the Central Kermadec Scenario (slip = 30m, Mw = 9.2): leading to significant 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 scenario (slip = 30m, Mw = 9.0).

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

   - A Kermadec-Hikurangi scenario involving the fault rupture extending from the Kermadec Trench into the northern portion of the Hikurangi Margin, leading to a similar impact to the whole Kermadec scenario (Mw9.4) and those involving the rupture of the southern Kermadec with a slip of 30 m, such as the variation of the southern Kermadec scenario (Mw9.0) and the variation of the Whole Kermadec Scenario (Mw9.45).

Some general results:

- The first arrival of tsunamis in the studied areas ranges from 50 to 70 minutes for all simulated scenario events, with initial negative leading waves (sea level drop). The maximum tsunami elevation along the coastline generally ranges from 6.0 m to 10.0 m above the ambient water level (i.e., MHWS in the modelled scenarios).

- For all the simulated scenarios, the low-lying area between the Mount and Mt. Drury Reserve are exposed to severe tsunami impacts and tsunamis penetrate inland from both sides, from the ocean side with large flow depth and high speed, and from the harbour side with relatively smaller flow depth and lower speed. In these scenarios, inundation also occurs in the areas along Marine Parade and Omanu beach, the low-lying areas of Sulphur Point (opposite of the Marina) and Otumoetai.

- The areas of Mt. Drury Reserve and the Airport do not suffer from tsunami inundation in all the scenario events simulated.

- The model results show that 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 is recommended to recondition the sand dune systems back to their original state, thereby restoring their natural protective function (Prasetya, 2007).

- Strategic mitigation of the tsunami risk is needed within this region, especially in the low-lying areas between the Mount and Mt. Drury Reserve, the areas along Marine Parade and Omanu beach, and the low-lying areas of Sulphur Point (opposite of the Marina) and Otumoetai. Mitigation activities may involve a combination of structural (seawall, existing building for shelter/vertical evacuations) and non-structural methods (sand dunes, trees or green belt) for already developed areas such as the low-lying areas between the Mount and Mt. Drury Reserves. For future development 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 inundation modelling for sources that could cause a land threat to Mount Maunganui and Tauranga based on the results of the Review of Tsunamigenic sources for the Bay of Plenty Region (Prasetya and Wang (2011)).

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 in 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 magnitude and effect on the shoreline are determined by several factors: the amplitude of the wave at the source, which is primarily controlled by the magnitude 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, (such as inundation zones) the modelling of tsunami behaviour is essentially required.

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 as following the Indian Ocean Tsunami in 2004. The *run up 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 the water surface elevation - if already referenced to Mean Sea Level (MSL) or other specified datum - is termed '*tsunami elevation'*. At the inland limit of the flow, the height above MSL (or other specified datum such as the ambient sea level) is termed the run up height, and the horizontal distance from the shoreline is the inundation distance. The run up 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 tsunamis for a long time. However, their effects are 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 different mechanisms. Some sources can be categorised into *far-field* tsunamis 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* tsunamis generated close to New Zealand's coastline and propagated through relatively shallow water.

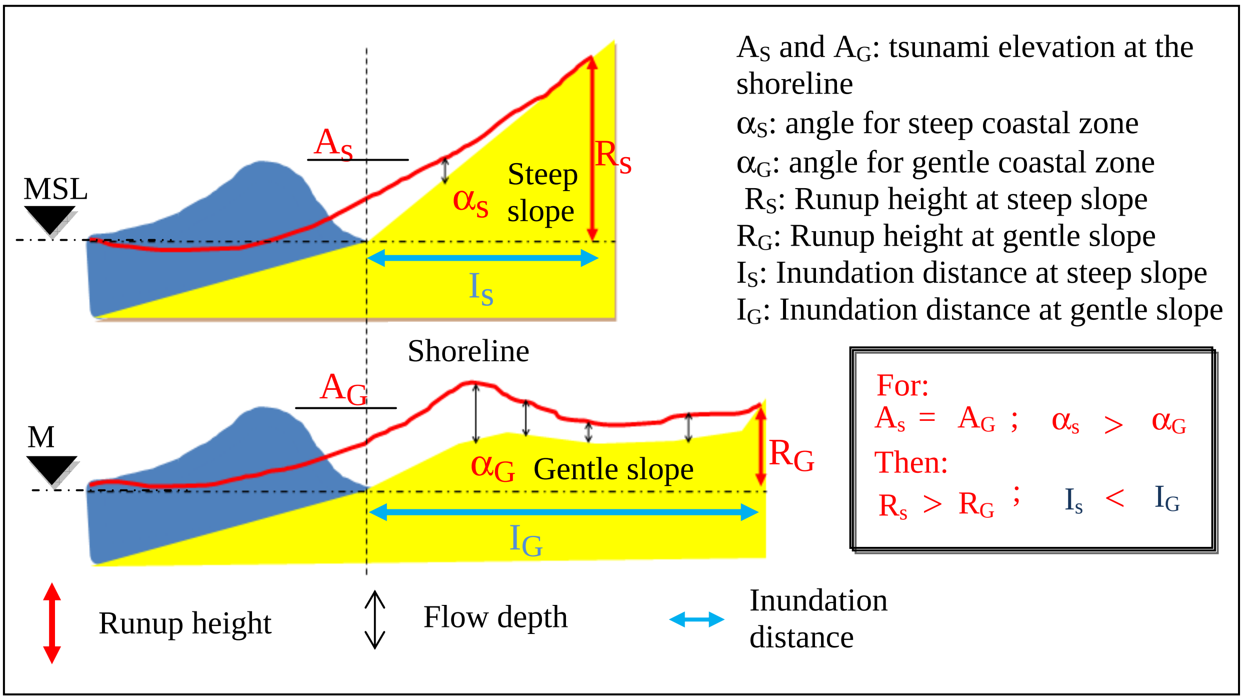

Figure 2.0-1 Schematic diagram for runup height and inundation for different beach slopes (simplified from Prasetya et al. 2011). For the same incoming tsunami height at the coast, those areas with a gentle slope inland will experience lower runup heights but longer inundation distances compared to the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

Note: The numerical simulations carried out for this report were made using Mean High Water Spring (MHWS) as the reference water level, which assumes that tsunamis evolve on this ambient water level for all the scenarios. All the inundation modelling results plotted in subsequent figures use the following convention: from offshore to the coastline we plotted the tsunami elevations relative to the ambient water level (i.e., MHWS) and from coastline to further inland we used flow depth above the ground.

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 a consistent result that the tsunamigenic sources from Kermadec Trench are significant for the Bay of Plenty Region. The previous studies summarized in Prasetya and Wang (2011) show that tsunami elevations greater than 5.0m could potentially occur along the coast of Bay of Plenty, as the result of an earthquake greater than Mw 8.5 along the southern and central Kermadec Trench (though the Bay of Plenty is more sensitive to earthquakes on the southern Kermadec than the central part). For this study, we examine scenarios that suggest a high possibility of inundation (or land threat) to the Tauranga and Mt. Maunganui areas. These scenarios are (Figure 3.0-1):

- 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) (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, and slip = 22.0m on Segment C, Mw9.45)
- Kermadec-Hikurangi scenario (involving the rupture extending from the southern Kermadec, including part of segments A and B in Power et al. (2011), into the northern part of the Hikurangi margin (briefly called Segment H), Mw 9.1)

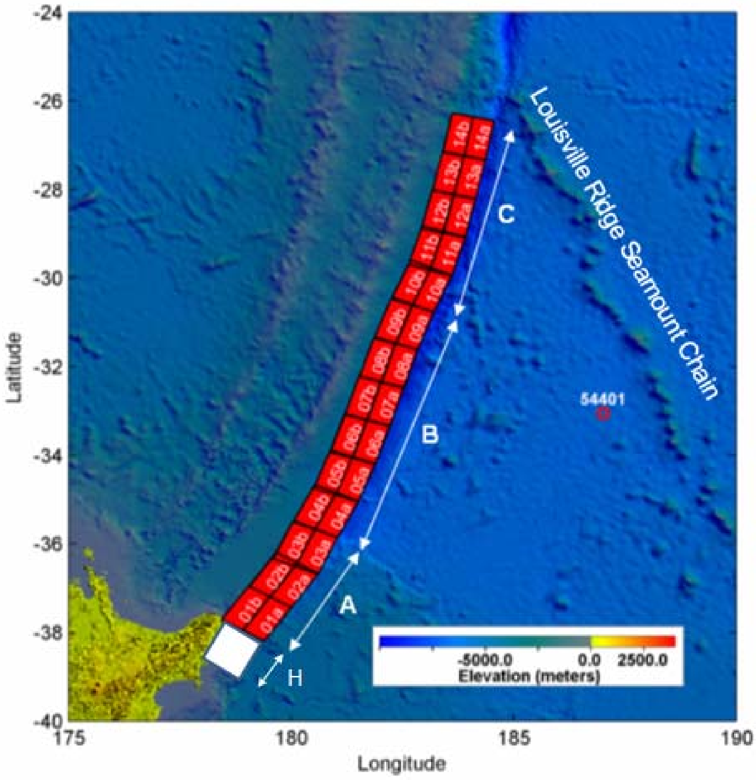

Figure 3.0-1 The segmentation of the Kermadec Trench (Segment A, B, and C) to the south of the Louisville Ridge Seamount Chain (LRSC), with unit sources dimensions of 100 km x 50 km, and the northern part of Hikurangi margin (segment H). The location of the DART 54401 is shown with red circles. (Base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

4.0 MODELLING TSUNAMI INUNDATION

A numerical modelling assessment is 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 0.007 arc minutes (~10.5 m)

All modelling is undertaken assuming Mean High Water Spring (MHWS) conditions.

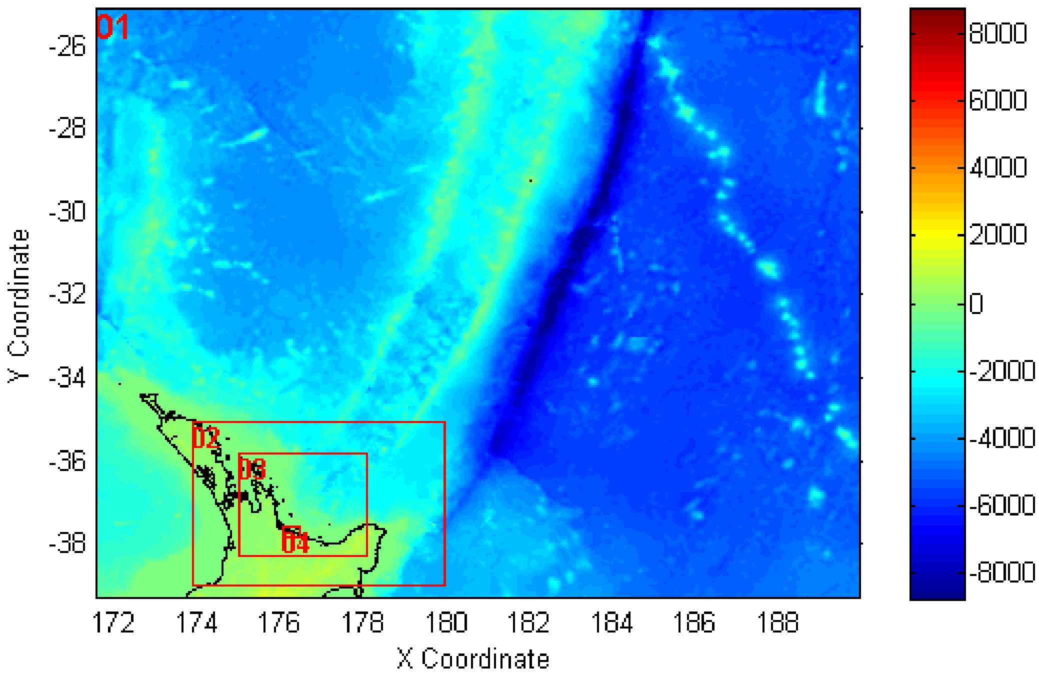

Figure 4.0-1 The nested grid arrangement for numerical modelling assessments (data source: Gebco08 3 arc second, and SRTM 30 arc second resolution). Scale bar unit is metres.

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 whole Kermadec 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 at depths between 4 km to 20 km. The slip angle was uniform at 90° and a uniform slip of 22m was used.

The distribution of regional maximum tsunami elevations based on these parameters is shown in Figure 4.1-1. This figure shows that a tsunami would affect most of the east coast of the North Island from the East Cape towards the Cape Reinga as a consequence of rupture along the southern and central Kermadec (i.e., Segments A and B). The energy from the northern Kermadec (i.e., Segment C) is directed in a NW-SE direction (not directly to New Zealand).

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

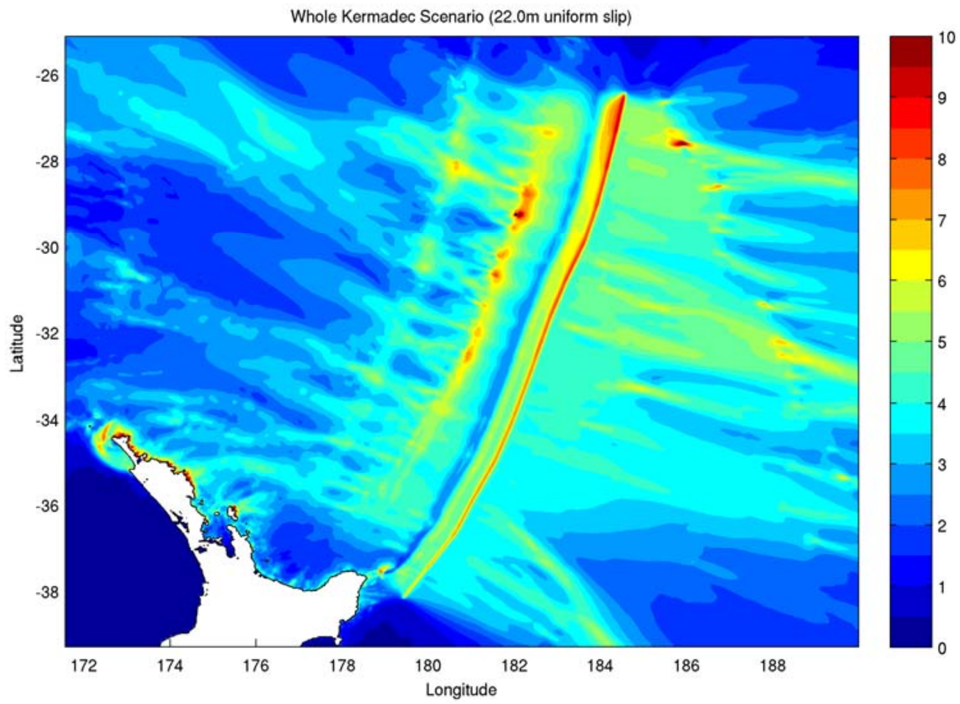

Figure 4.1-1 The distribution of maximum tsunami elevation in metres above MHWS resulting from the whole Kermadec Scenario shows that the main source of the tsunami to impact the east coast of New Zealand is from the rupture of the southern and central Kermadec (e.g., Segments A and B). Scale bar unit is in metres.

The sub-regional model for Bay of Plenty Region shows that the maximum tsunami elevation varies from 5.0 m to 10.0 m above MHWS along the east coast (Figure 4.1-2) and the first waves arrive 50.0 minutes after fault rupture. Significant inundation due to tsunami energy concentration occurs to the areas along Papamoa up to the border of Omanu Beach (Figure 4.1-3). Tsunami elevation at the coastline reaches up to 10 m above MHWS and gradually decreases towards Mt. Maunganui. Relatively less inundation occurred along Omanu Beach where the tsunami elevation reduced from 7.5 to 5.5 m, and the sand dunes are relatively high compared to the incoming tsunami. Approximately one (1) km toward Moturiki Island, the inundation level slightly increased as the sand dunes along this point are relatively low compared to the incoming tsunami elevations. Total inundations occur at the low-lying areas between Moturiki Island and The Mount. The overland flow depth towards Tauranga Harbour varies from 8.0 m near the open coast to 2.0 m on the coast within the Harbour. Inundations were extended along The Mall areas. The overland flow speed ranges from 1.0 to 5.0 m/s m for most of the inundation areas with the exception of higher overland flow speeds over 10.0 m/s which occur in the low-lying areas between the Mount and Mt Drury Reserve (Figure 4.13). Some areas in the middle of Mt. Maunganui were not inundated by a tsunami from this model scenario. The current speed inside the Harbour reaches up to 9.0 m/s through the entrance and inside the harbour varies between 1.0 to 4.0 m/s (Figures 4.1-3 to 5).

A localised inundation with flow depth varies from 0.5 to 1.0 m occurs inside the Harbour, along the coast at Waipu Bay near Tauranga Airport, Rangatau and Welcome Bays, and Waimapu and Waikareao Estuaries. The low-lying areas at the tip of Otumoetai are also inundated by a tsunami.

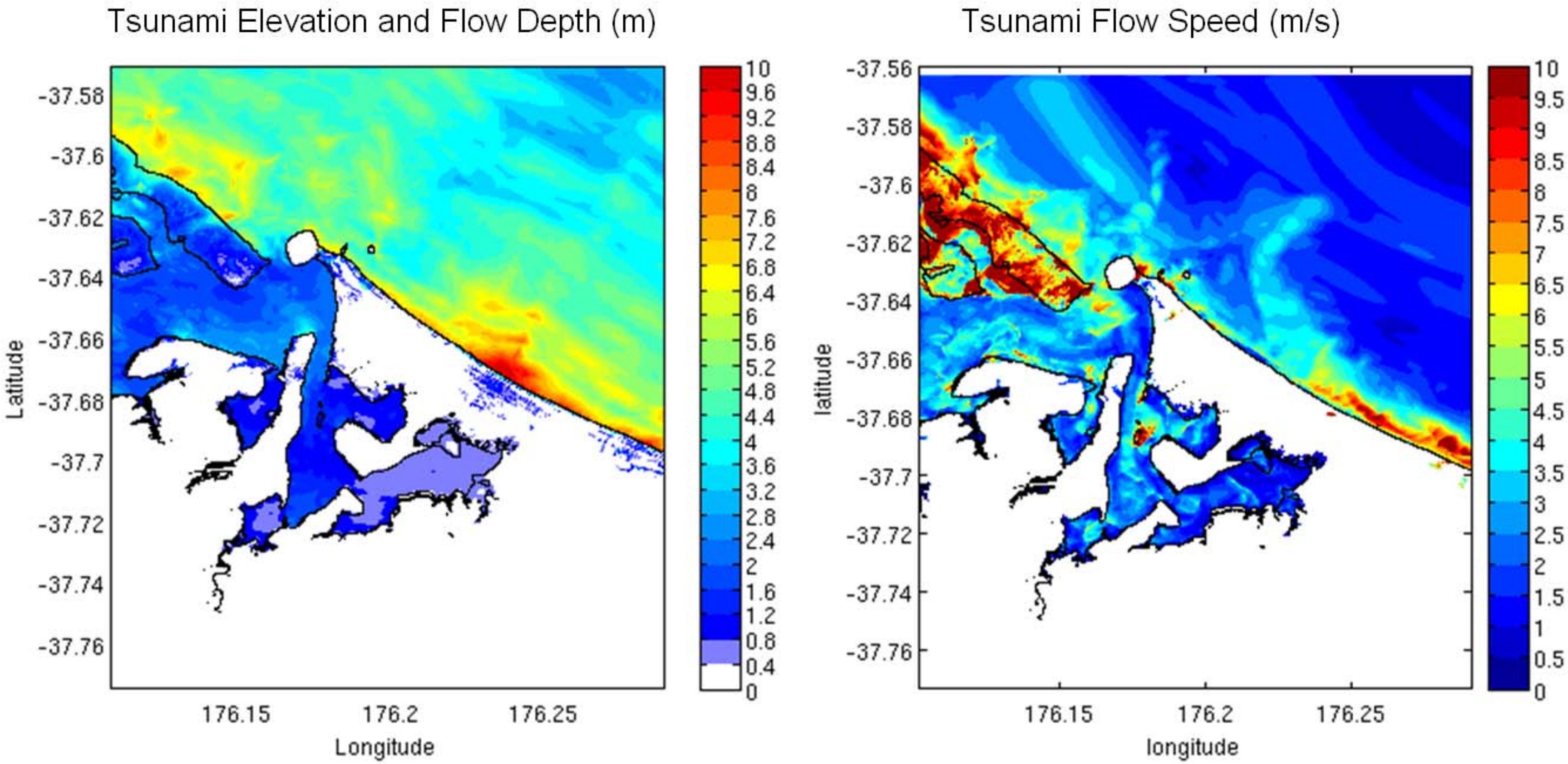

Figure 4.1-2 The numerical modelling results from this scenario show the extent of maximum tsunami elevation and flow depth (figure left) and flow speed (figure right) around the Mt. Maunganui and Tauranga areas. Maximum tsunami elevation varies from 5 m to 11 m above MHWS for the Bay of Plenty from Papamoa to Matakana Island. Inundation occurs at some places along the coastline such as Papamoa, Mt Maunganui and Matakana Island with high tsunami flow speed near to the coast. In the left figure panel, the shaded colour represents the maximum tsunami elevation above MHWS offshore, or the flow depth if on land. The colour scale is in meters.

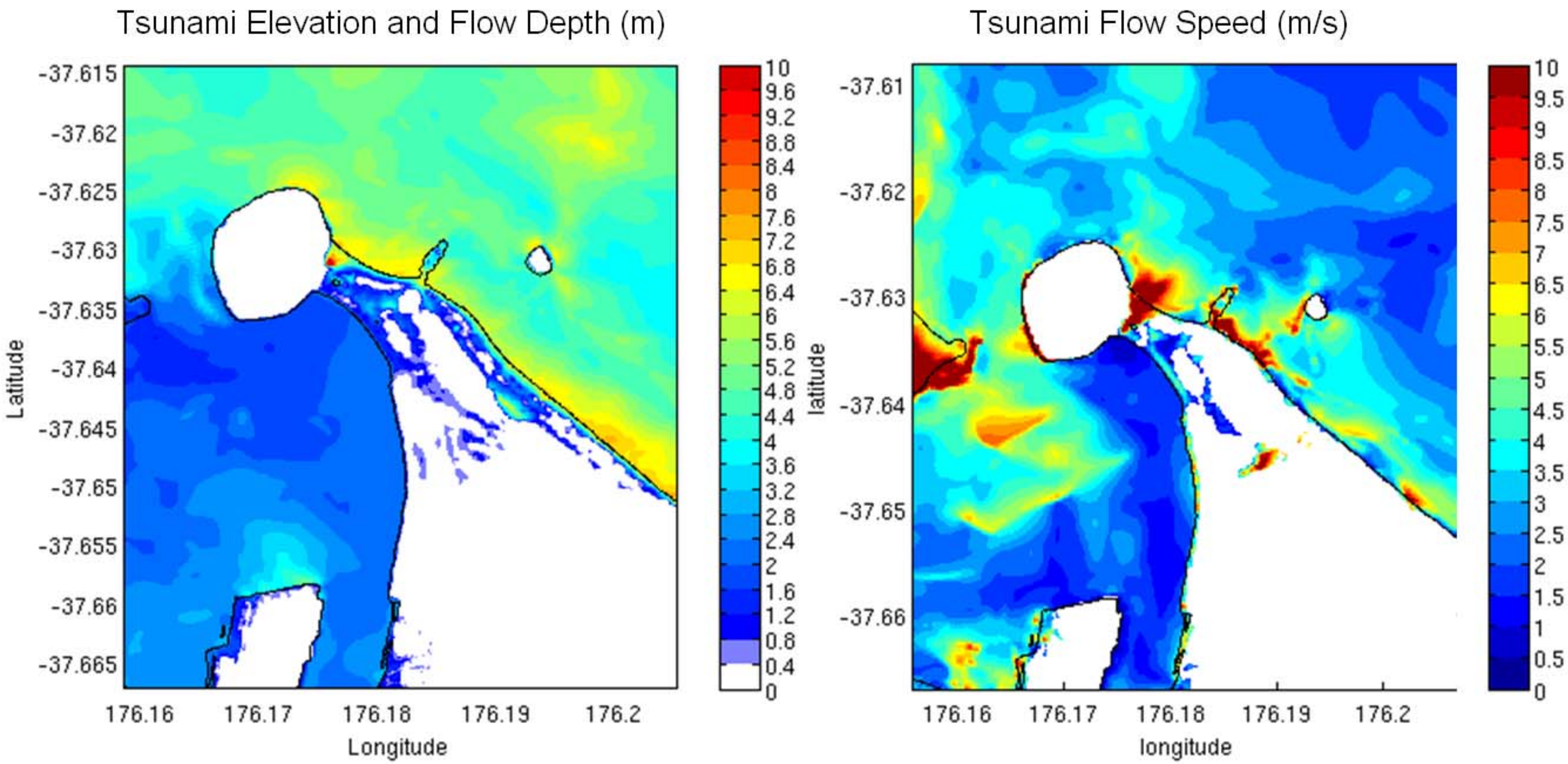

Figure 4.1-3 The maximum tsunami elevation at the coast and inundation depth (flow depth) on land at Mt. Maunganui – Tauranga show the highest flow depth ~ 8.0 m at the camping ground of the Mount with high flow speed over ~ 10 m/s. The flow speeds inside the harbour at the Port locations are relatively low and vary between 1.0 to 4.0 m/s, while at the entrance flow speed varies between 5.0 to 7.5 m/s. In the left figure panel, the shaded colour represents the flow depth where the tsunami is over land, and the maximum tsunami elevation above MHWS where it is offshore. The colour scale is in meters.

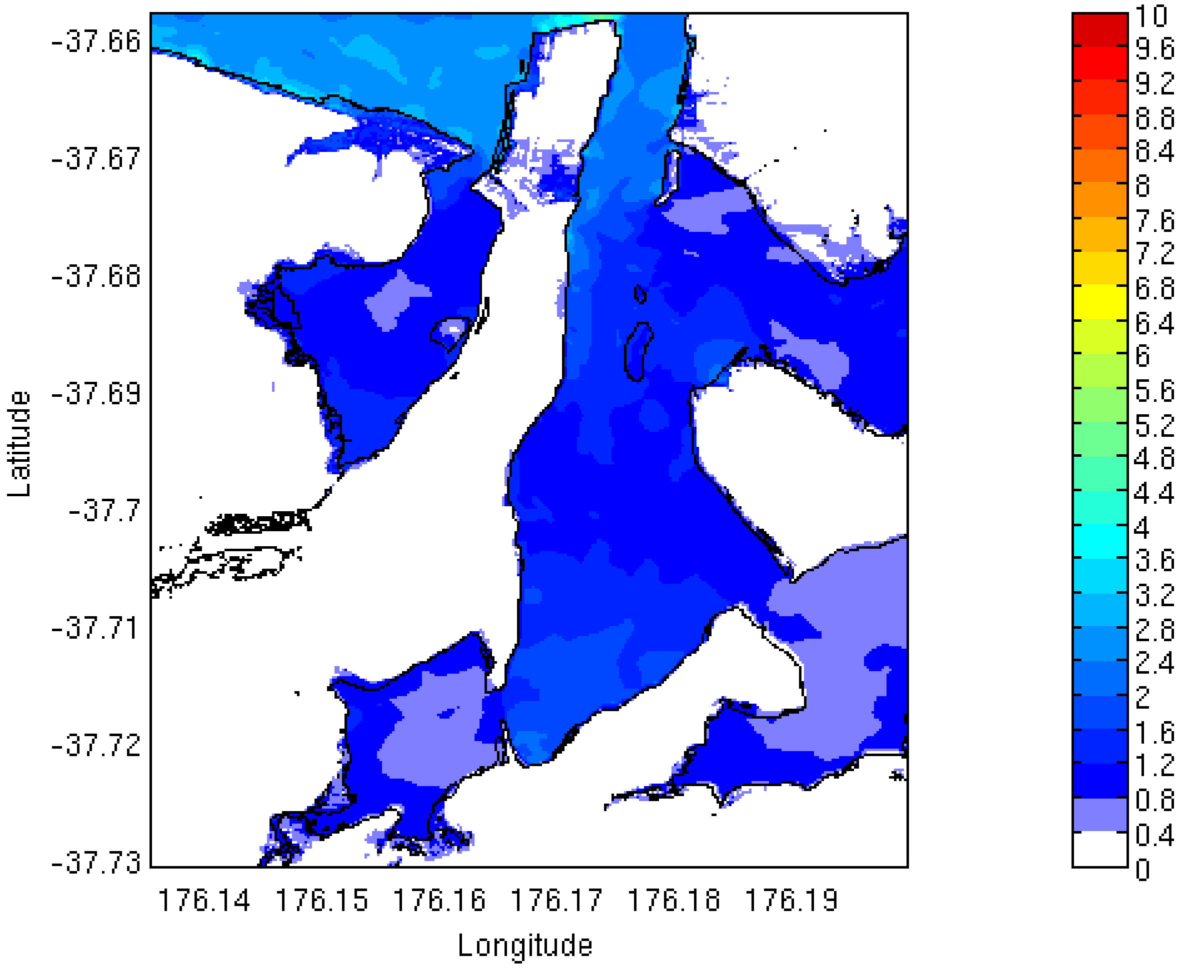

Figure 4.1-4 Inundation pattern inside the harbour show most of the low-lying areas inside the harbour are inundated by tsunamis with flow depth ranges from 0.5 to 1.0 m. The shaded colour represents the maximum tsunami elevation above MHWS offshore, or the flow depth if on land. The colour scale is in meters.

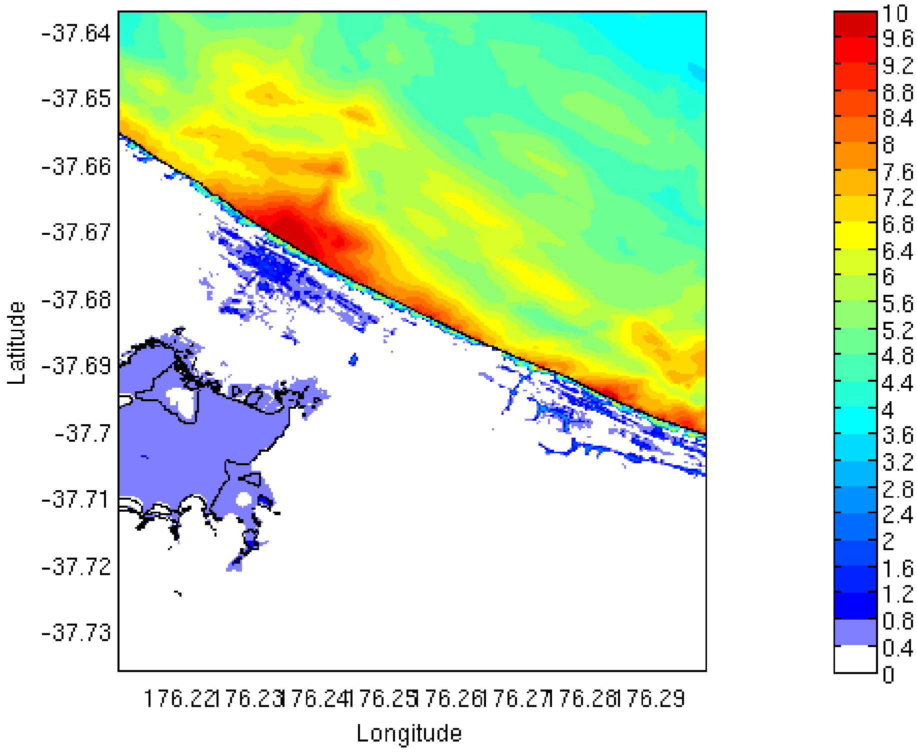

Figure 4.1-5 Detailed inundation pattern along the Papamoa coastline towards Omanu Beach areas as well as inside Rangataua Bay show the flow depth ranges from 0.5 to 1.0 m. Near to the open coast, the flow depth varies from 4.0 to 6.0 m. The tsunami overtops the sand dunes and inundates further inland through gravitational flows. The inundation follows the local terrain conditions such as the low-lying areas between the sand ridges. The shaded colour represents the maximum tsunami elevation above MHWS offshore, or the flow depth if on land. Scale bar unit is in metres.

4.2 Inundation modelling of the Kermadec-Hikurangi Scenario

This Kermadec-Hikurangi scenario assumes that a fault rupture extends from the Kermadec to the south into 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 (Segments 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 are listed in Table 4.2-1.

This source scenario used a uniform dip angle of 16^{o}, a strike angle 210^{o}, and at a uniform depth of 5 km. The slip angle was uniform at 90^{o} and a slip of 20m was used.

The regional maximum tsunami elevations based on these parameters are 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 (nested grid) result shows the maximum tsunami elevation for Bay of Plenty between Papamoa and Matakana Island varies from 6.0 m to 11 m above MHWS.

Table 4.2-1 General fault parameters for the Kermadec–Hikurangi Scenario (Segment H and part of Segments A and B)

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

The first wave arrives at the coast of studied areas about 50 minutes after fault rupture with a leading depression of water level. Extensive inundation ~ 1.5 km from the coastline to State Highway 2 occurs along the Papamoa coastline as the tsunami overtops the sand dunes up to the coastal areas along Omanu Beach. The inundation distance decreases towards Moturiki Island, as the tsunami elevation along the coast also decreases. However, between The Mount and Moturiki Island – Mt. Drury Reserves, the inundation distance increases as low-lying areas between these two places are completely inundated by tsunami waves (or overland flow). The flow depth near to the coast reaches up to 6.0 m, and down to 0.5 m towards the Tauranga Harbour. Extensive inundation also occurs along the beach inside the Tauranga Harbour along Sulphur Point, the port facilities, and around the Airport and Rangataua Bay as illustrated in Figure 4.2-2 to -5. The airport runway and other facilities are not affected by tsunami inundation. High speed overland flow occurs in most of the inundation areas, and reaches over 10 m/s. At the Harbour entrance, the flow speed varies from 6.0 to 9.0 m/s. While at the port facilities, the flow speed varies between 3.0 to 6.0 m/s.

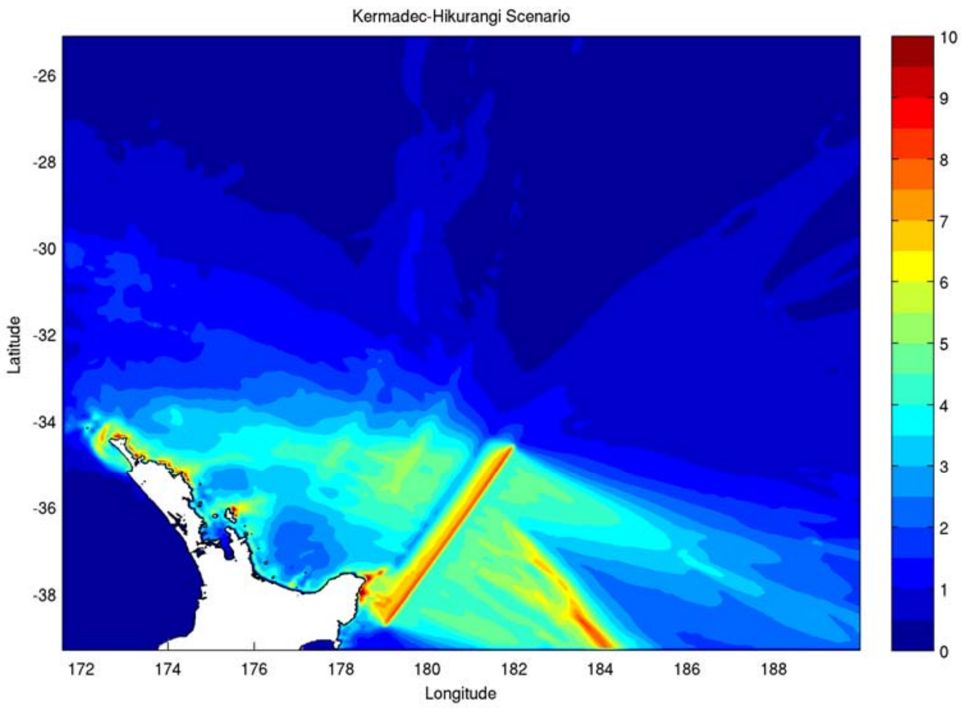

Figure 4.2-1 The distribution of maximum tsunami elevation above MHWS for the Kermadec-Hikurangi scenario that shows most of the tsunami impact to the east coast of New Zealand originates from the southern and central Kermadec (e.g., Segments A and B). East Cape is however significantly impacted as a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

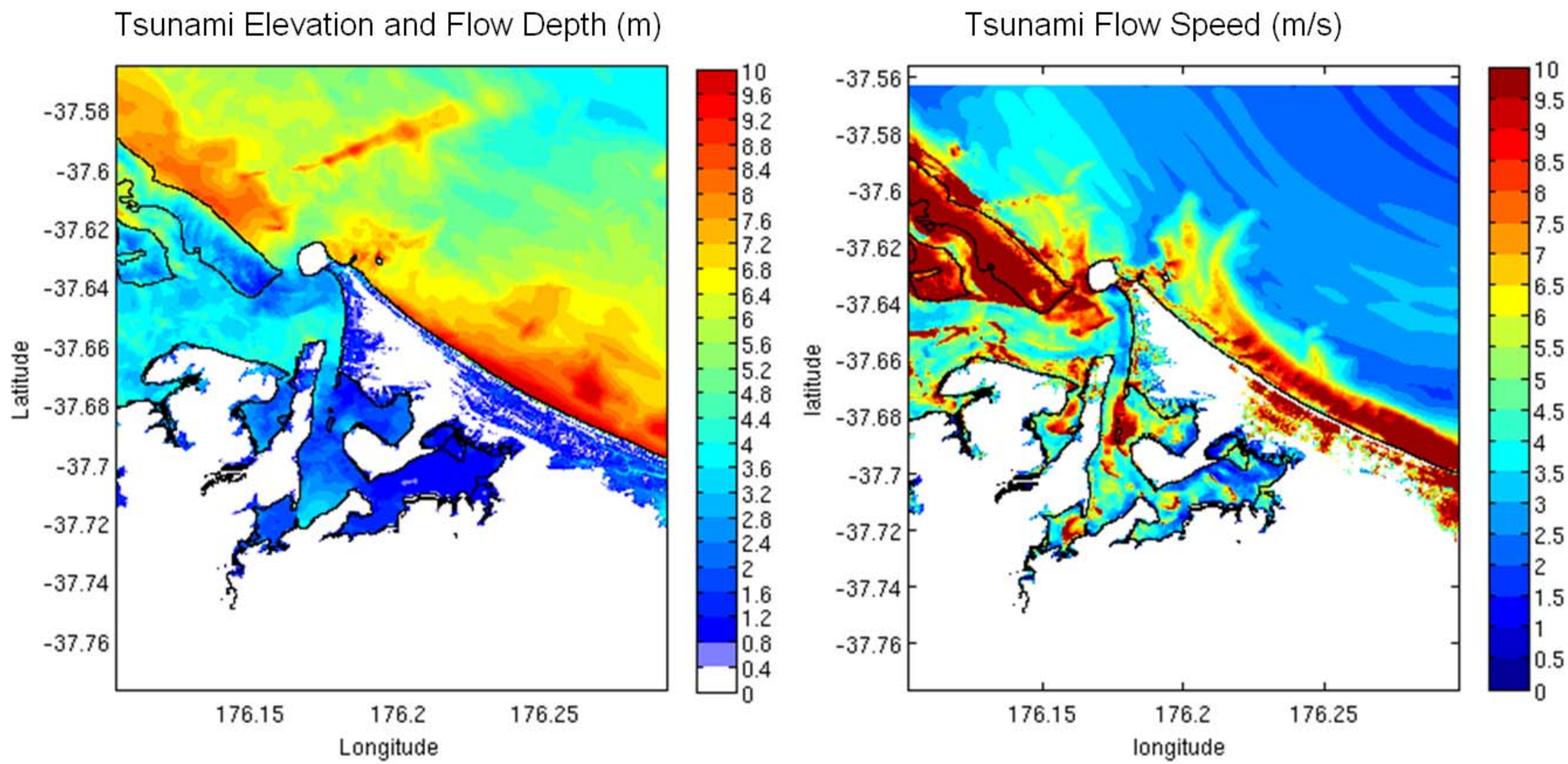

Figure 4.2.-2 The numerical modelling results from this event scenarios show the extent of maximum tsunami elevation and flow depth (left panel) and flow speed (right panel) around the Mt. Maunganui and Tauranga areas. Maximum tsunami elevation varies from 6.0 m to over 11.0 m above MHWS for the Bay of Plenty from the Papamoa to Matakana Island. Inundation occurs at some places along the coast such as at Papamoa, Mt Maunganui and Matakana Island with high tsunami flow speed near to the coast. In the left figure panel, the shaded colour represents the maximum tsunami elevation above MHWS offshore, or the flow depth if on land. The colour scale is in meters.

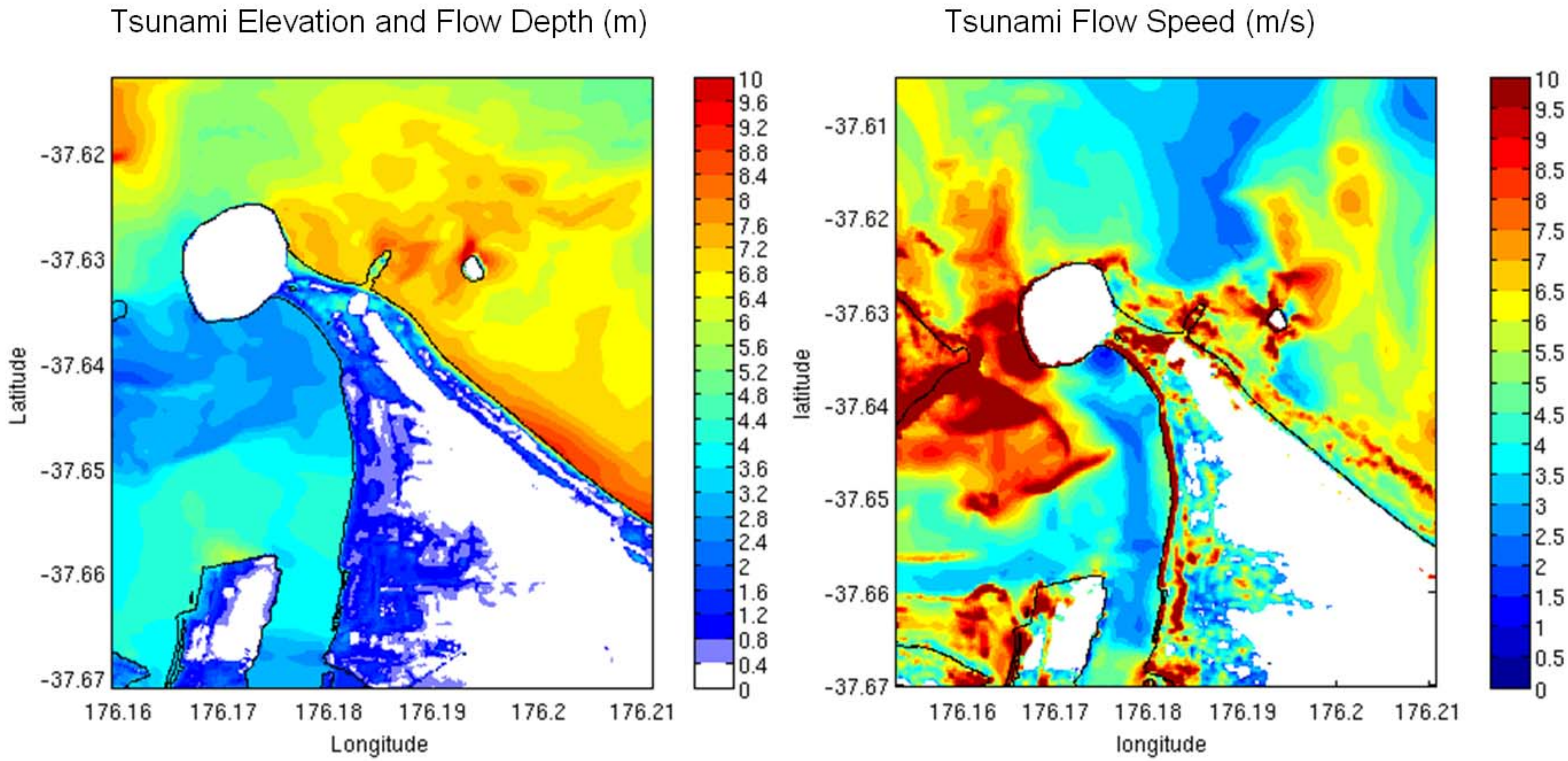

Figure 4.2-3 Detailed inundation patterns along the Omana Beach to Mt Maunganui and inside the harbour (Port facilities) show an extensive inundation with maximum flow depth of 6.0 m near to the coast at the Open Ocean and 4.0 to 2.0 m overland flow depth inland around 1.0 to 0.5 m inside the harbour. The tsunami elevation inside the harbour is less than 4.0 m above MHWS, however, strong currents of over 10 m/s occurs at the harbour entrance. In the left figure panel, the shaded colour represents the maximum tsunami elevation above MHWS offshore or flow depth if on land. The colour scale is in meters.

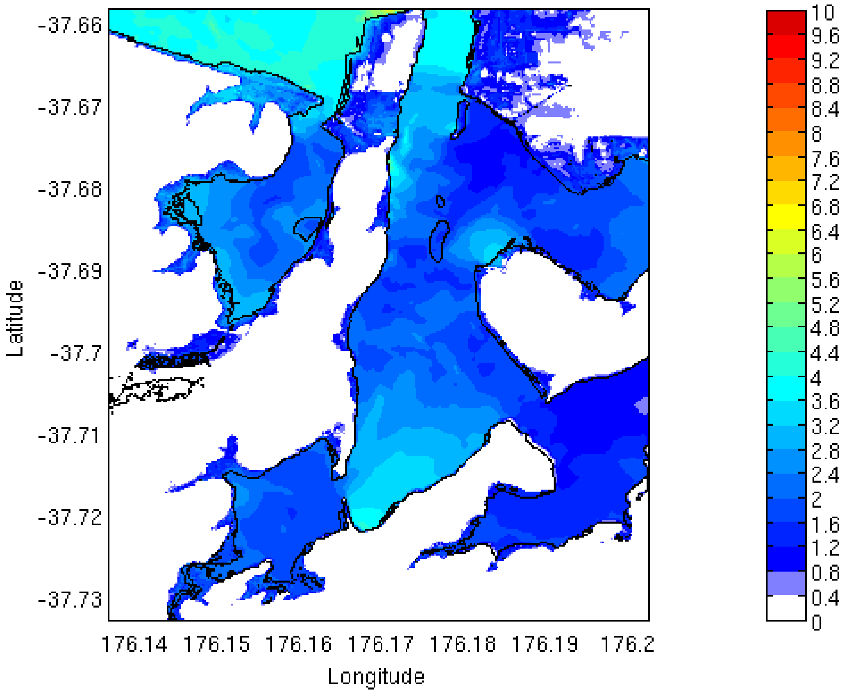

Figure 4.2-4 The inundation pattern and distribution inside the harbour show the maximum flow depth (~ 4.0 m) occurs in the low-lying areas at Otumoetai and elsewhere inside the harbour. The typical flow depth varies from 0.5 to 2.0 m. Tsunami elevations inside the harbour are less than 4.0 m. The shaded colour represents the maximum tsunami elevation above MHWS offshore or flow depth if on land. The scale bar unit is metres.

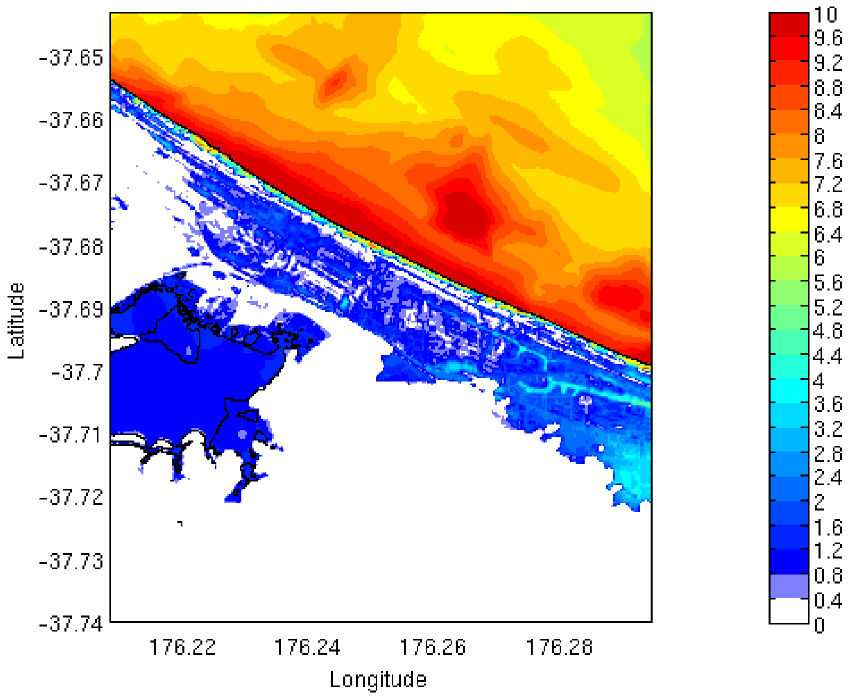

Figure 4.2-5 Extensive inundation with flow depth ranges from 0.4 m to 2.0 m further inland and up to 6.0 m near to the coast occurs along Papamoa towards Omanu Beach. The shaded colour represents the maximum tsunami elevation above MHWS offshore or the flow depth if on land. Scale bar unit is in metres.

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

The amount of co-seismic slip associated with the 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 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 30m were applied to the Kermadec scenarios in Power et al. (2011). These variations of the scenarios in Power et al. (2011) 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 segments 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). In this scenario, the slip on Segment A was increased to 30m while the other fault parameters were kept the same as the original setup.

These parameters resulted 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 inundation within the Bay of Plenty coastline between Papamoa and Matakana Island is greater than that of the Whole Kermadec Mw 9.4 scenario involving the combined rupture of Segments A, B and C previously modelled. The first wave arrives 50.0 minutes after the fault ruptures. The maximum tsunami elevation along the coastline ranges from 8.0m to 13.0m about MHWS (Figures 4.3.1-1 and -2). Significant inundation occurs at the coast along Papamoa to Mt. Maunganui. The extent of inundation from this event scenario is similar to the event scenario from Kermadec-Hikurangi (section 3.2). However, the flow depth and tsunami elevation are slightly higher along the coast, and lower inside the harbour. Extensive inundation up to 1.5 km inland occurs along Papamoa up to Omanu with flow depth up to 7.0 m near the coast. These flow depths gradually abate to 0.5 m further inland.

The low-lying areas between The Mount and Moturiki Island – Mt. Drury Reserves are completely inundated. The flow depth varies from 6.0 m at the beach down to 1.5 m at the coast inside the Tauranga Harbour. Extensive inundation also occurs along the beach inside the Tauranga Harbour along Sulphur Point, the port facilities, around the Airport and Rangataua Bay as illustrated in Figure 4.3.1-3 to -5. The runway and other airport facilities are safe from inundation in this scenario event. The flow speed varies from 7.5 to over 10.0 m/s across the harbour entrance, and at the intertidal flat areas. The overland flow speed varies from 9.0 m/s at the camping ground near to the coast of The Mount to 0. 5 m/s further inland.

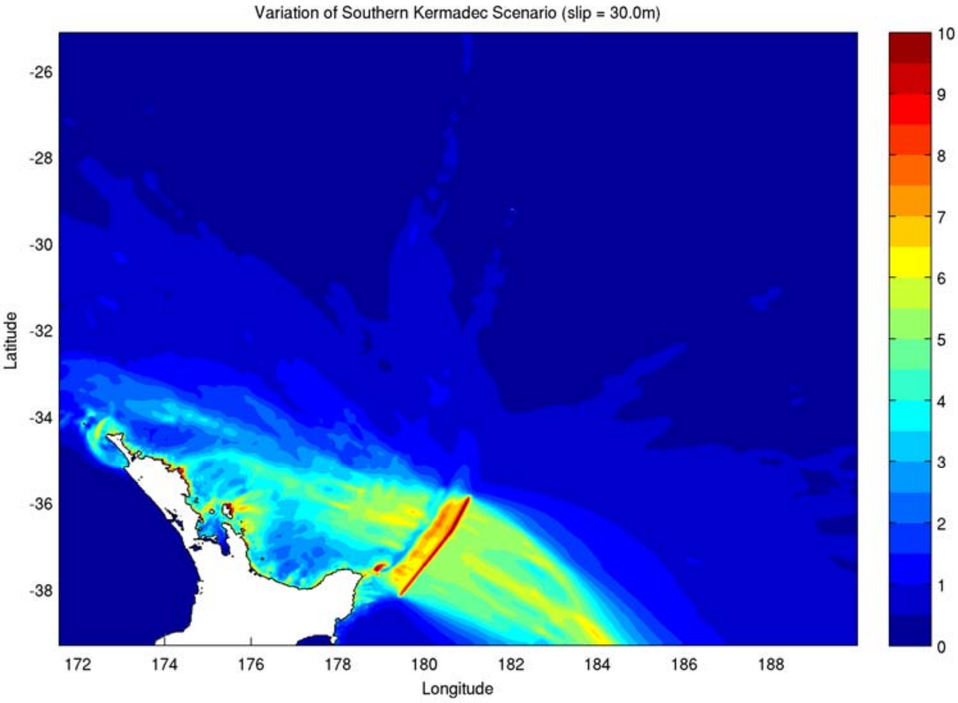

Figure 4.3.1-1 The distribution of maximum tsunami elevation above MHWS for the rupture of southern Kermadec with a slip of 30.0m, taking into account the Japan Earthquake shows a tsunami generated from the rupture of the southern Kermadec mostly affects the east coast of the North Island, New Zealand. Scale bar unit is in meters.

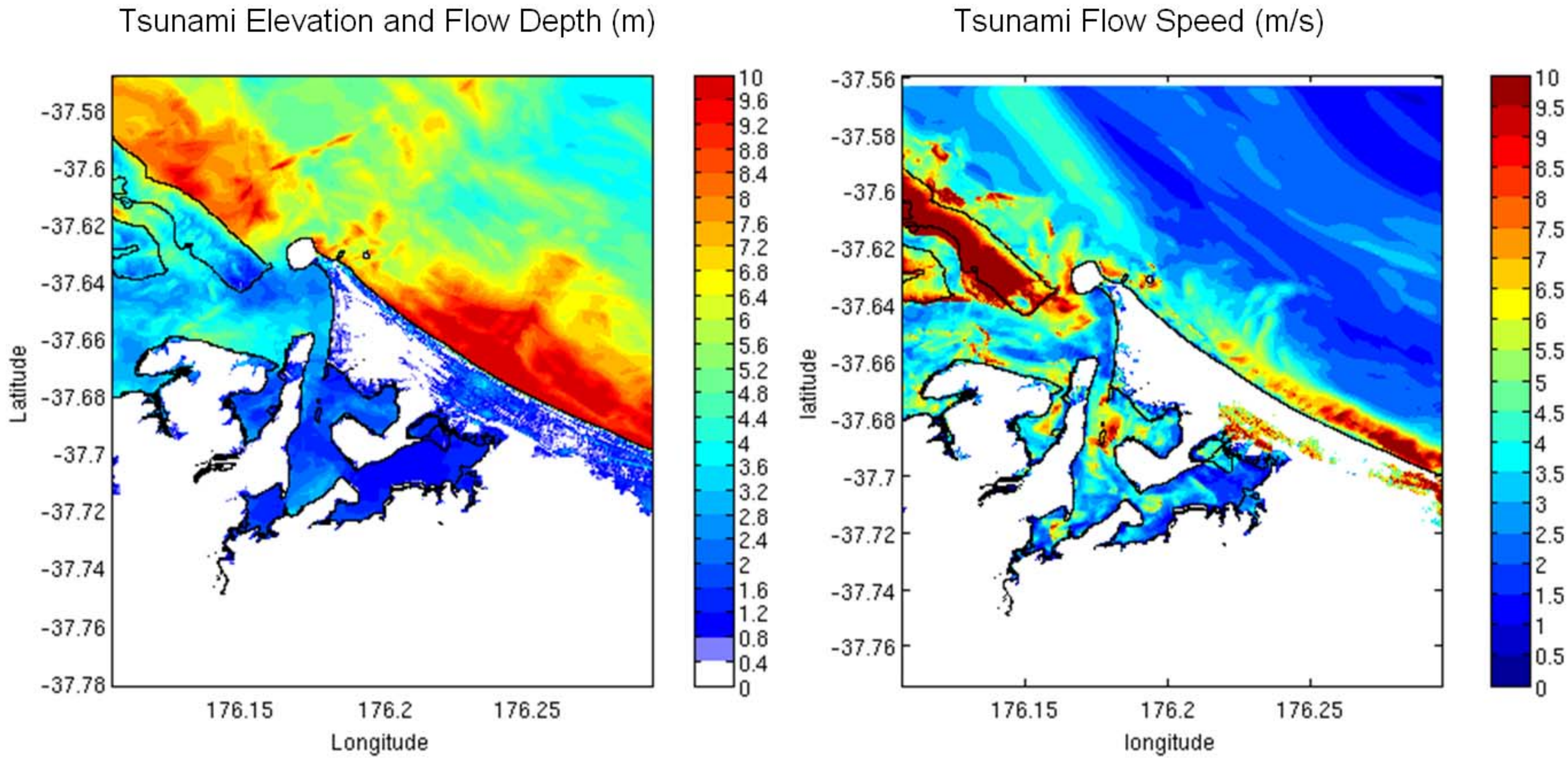

Figure 4.3.1-2 The sub-regional model shows the maximum tsunami elevation ranges from 8.0 m to 13.0 m above MHWS between Papamoa and Matakana Island (left panel). Extensive inundation occurs with flow depth varying from 6.0 m near to the coast to 0.5 m further inland. The flow speed distribution (figure right) also show a high flow speed distribution across the inundation area (right panel). In the left figure panel, the shaded colour represents the maximum tsunami elevation above MHWS offshore or flow depth if on land. The colour scale is in meters.

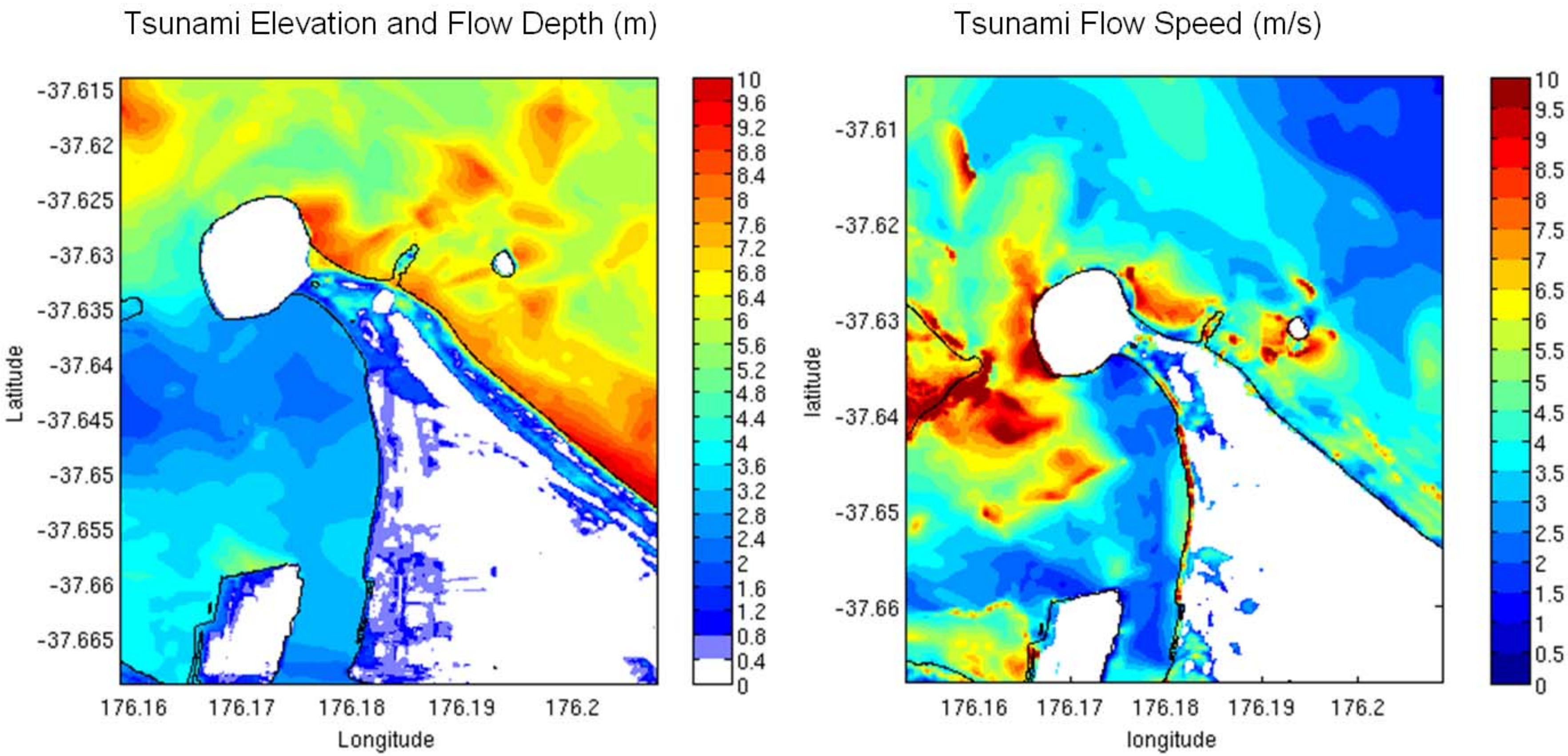

Figure 4.3.1-3 Detailed inundation modelling shows the extent of inundation for Mt. Maunganui and Tauranga Harbour areas. Most of low-lying areas between Moturiki Island and The Mount are completely inundated with flow depth ranges from 1.5 m to 6.0 mat the camping ground of The Mount with the flow speed of 3.0 to 7.0 m/s. The flow depth along the low-lying areas inside the harbour varies from 1.0 m to 0.4 m. In the left figure panel, the shaded colour represents the maximum tsunami elevation above MHWS offshore, or the flow depth if on land. The colour scale is in meters.

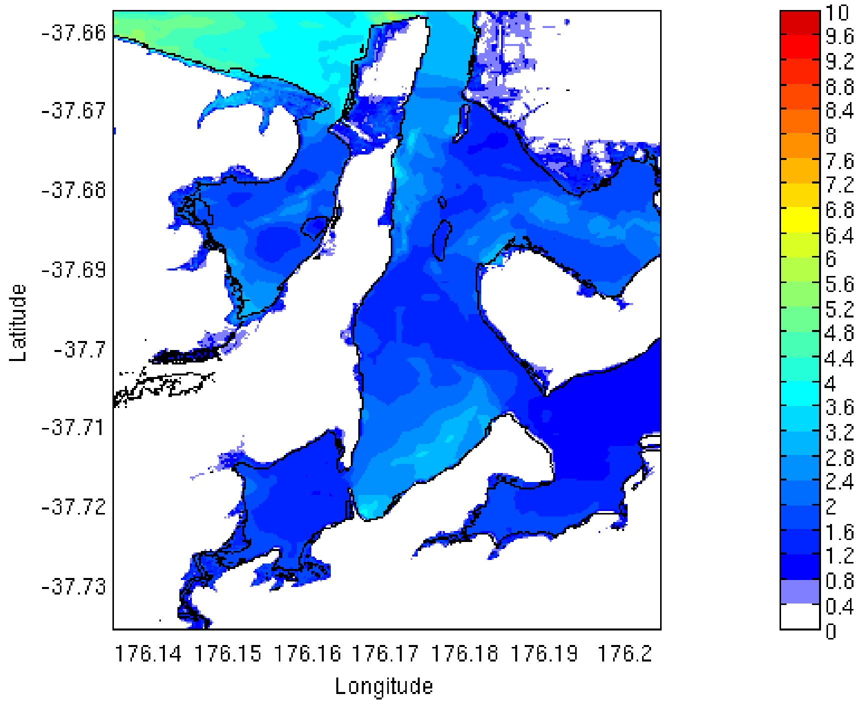

Figure 4.3.1-4 The inundation pattern and distribution inside the Harbour show the maximum flow depth ~ 4.0 m occurs in the low-lying areas at Otumoetai. While elsewhere along the coast inside the Harbour, the typical flow depth varies between 0.5 to 2.0 m. Tsunami elevations inside the harbour are less than 4.0 m. The shaded colour represents the maximum tsunami elevation above MHWS offshore or the flow depth if on land. Scale bar unit is in metres.

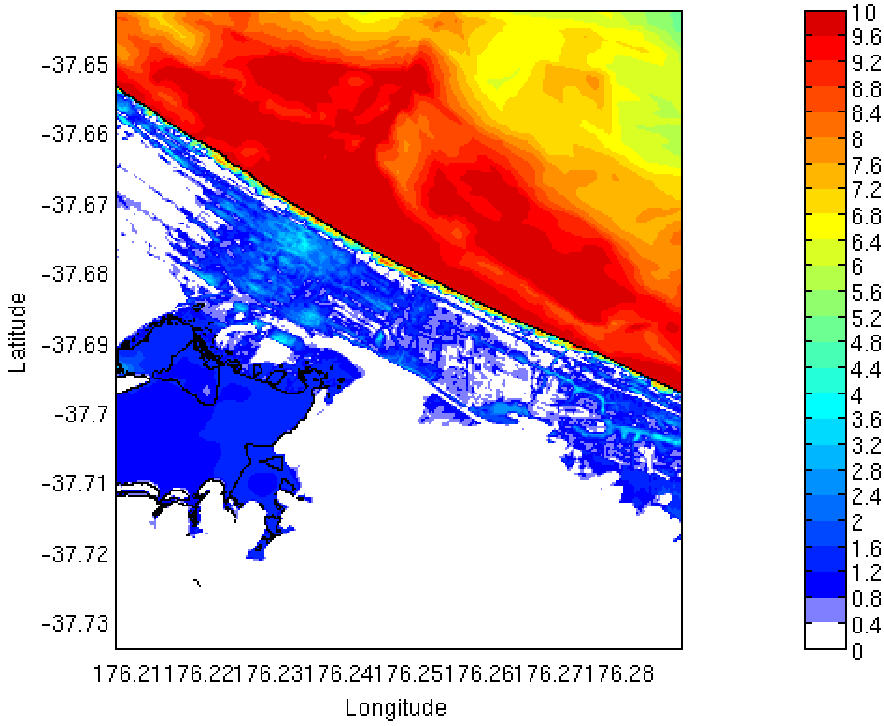

Figure 4.3.1-5 Extensive inundation with flow depth ranges from 0.4 m to 2.0 m inland and up to 7.0 m near to the coast occur along Papamoa to Omanu Beach. The shaded colour represents the maximum tsunami elevation above MHWS offshore or the flow depth if on land. Scale bar unit is in metres.

4.3.2 Variation of Central Kermadec Scenario

A variation of the Central Kermadec Scenario along Segment B in Power et al. (2011) is modelled to take into account the parameters observed in the recent 11 March 2011 Tohoku 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 resulted 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). The sub-regional modelling results identify that the maximum tsunami elevation within Mt. Maunganui and Tauranga range from 3.5 m to 8.0 m above MHWS (Figure 4.3.2-2). No significant inundation occurs between Papamoa and Omanu Beach. However, a significant inundation occurs along the Marine Parade towards The Mount. The low-lying areas between The Mount and Mt. Drury Reserve are inundated with flow depth ranges from 0.5 to 6.0 m. High overland flow speed occurs with a maximum speed of 9.0 m/s (Figure 4.3.2-3). A localised inundation occurs inside the Harbour at low-lying areas of Sulphur Point and Otumoetai areas. No inundation occurs at the port facilities. A localised inundation occurs further inside the estuary along Waimapu estuary, Welcome and Rangataua Bays. The flow speeds inside the harbour are relatively low and vary from 0.5 to 3.5 m/s along the port facilities to a maximum of 6.0 m/s at the Harbour entrance.

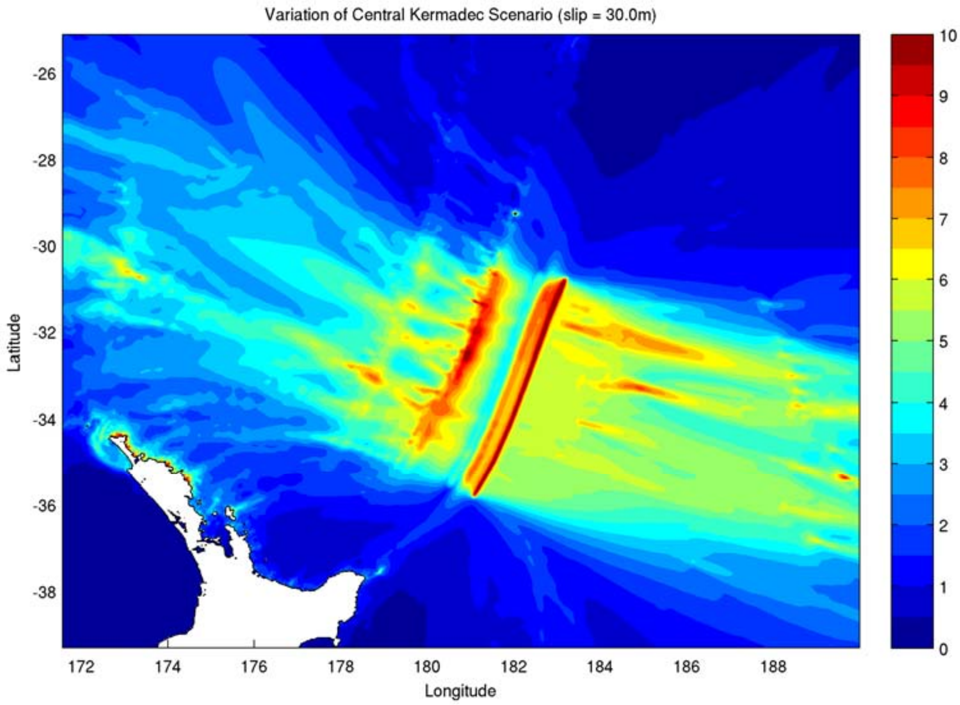

Figure 4.3.2-1 The maximum tsunami elevation above MHWS for the rupture of the central Kermadec with a slip of 30.0m. This modelling identifies that a tsunami generated from a rupture of this segment mostly affects the northern part of the East Coast of the North Island, New Zealand. Scale bar unit is in metres.

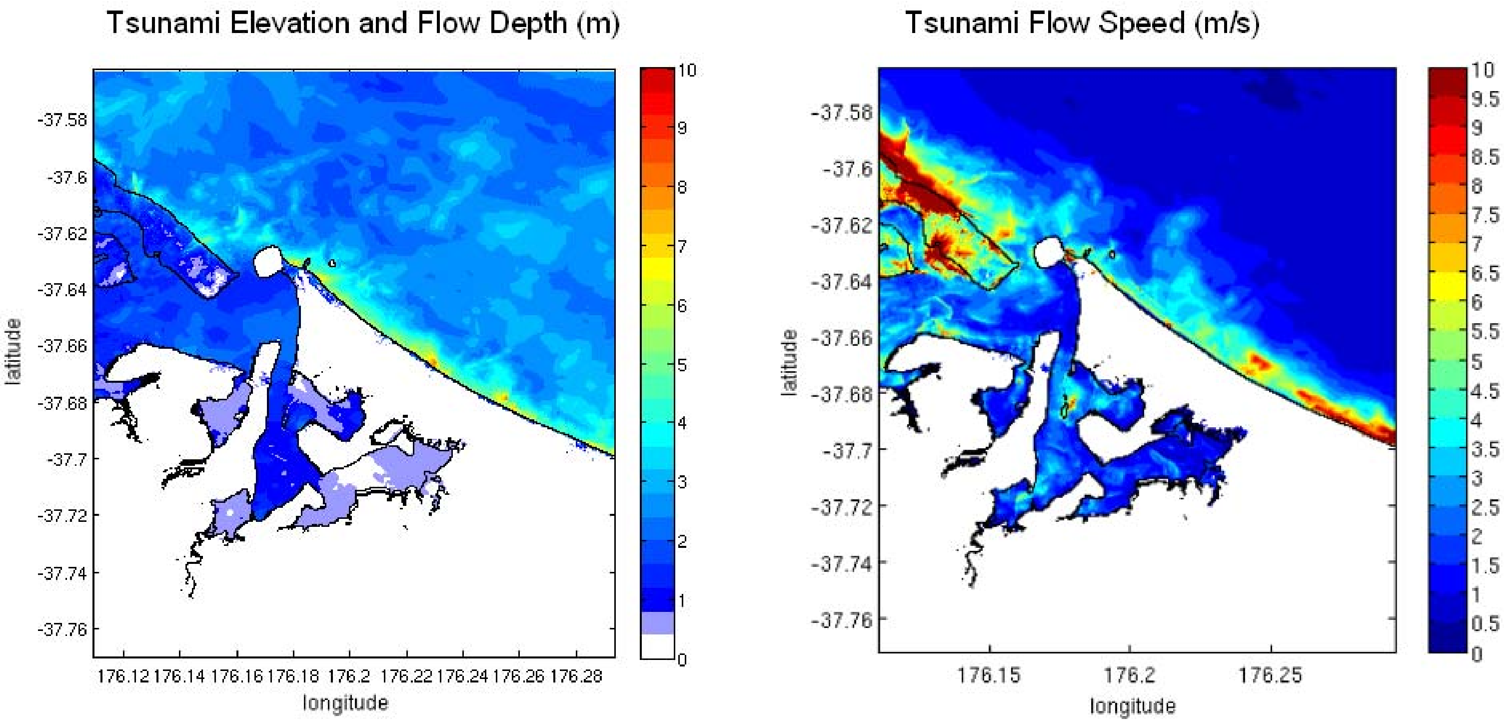

Figure 4.3.2-2 The sub-regional model shows the maximum tsunami elevation ranges from 3.5 m to 8.0 m above MHWS between Papamoa and Matakana Island (left panel). Extensive inundation occurs with flow depth varying from 6.0 m near to the coast to 0.5 m further inland. The flow speed distribution (figure right) show the flow speed distribution along the Mt. Maunganui and Tauranga area varies 3.0 to 6.0 m/s with exceptions in the areas between The Mount and Mt. Drury Reserve that reach up to 9.0 m/s. In the left figure panel, the shaded colour represents the maximum tsunami elevation above MHWS offshore, or the flow depth if on land. The colour scale is in meters.

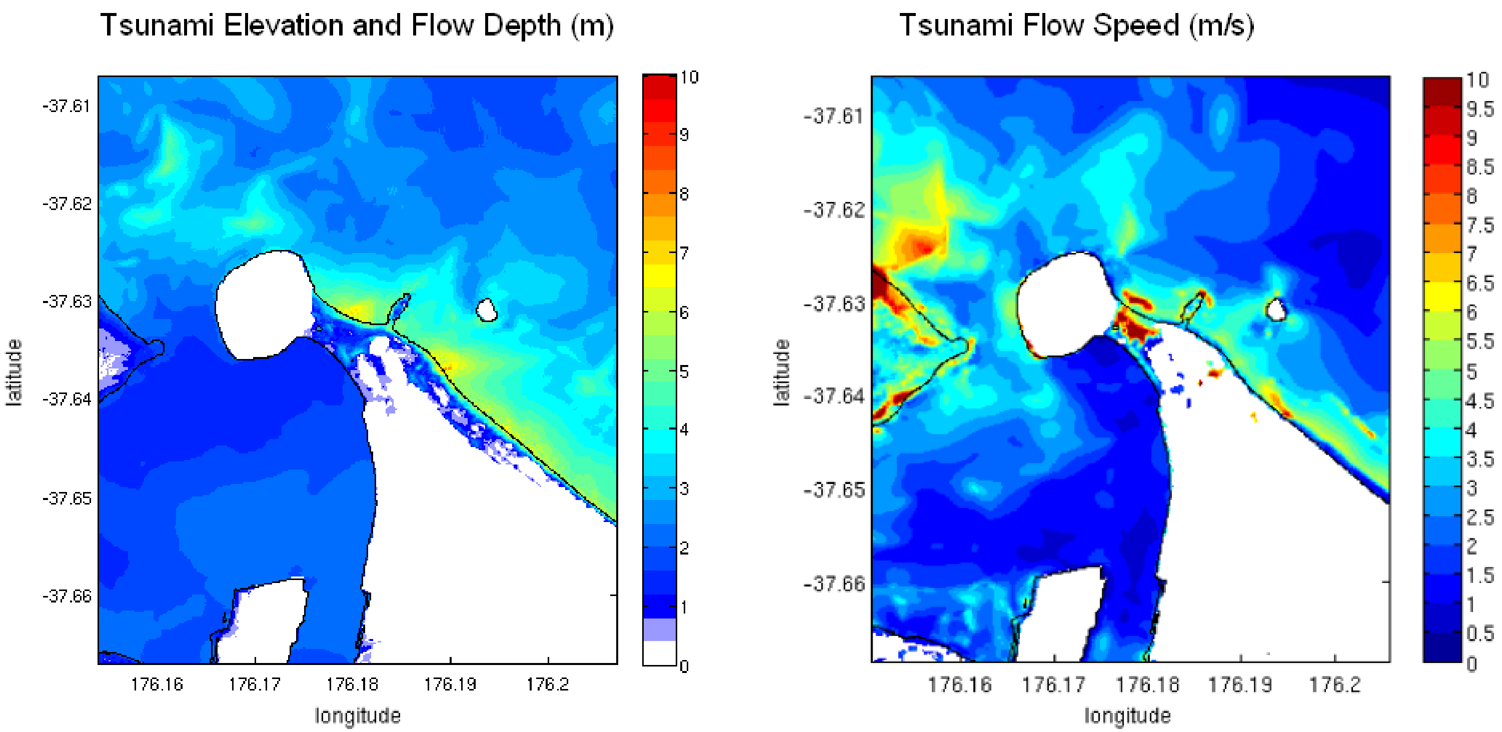

Figure 4.3.2-3 The maximum tsunami elevation at the coast and inundation depth (flow depth) on land at Mt. Maunganui - Tauranga show the highest flow depth (~ 6.0 m above MSL) occurs at the camping ground of The Mount with a high flow speed of ~ 9.0 m/s. The flow speed inside the Harbour at the Port locations is relatively low and varies between 0.0 to 2.0 m/s. The current speed at the entrance ranges between 5.0 to 6.0 m/s. In the left figure panel, the shaded colour represents the maximum tsunami elevation above MHWS offshore, or the flow depth if on land. The colour scale is in meters.

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 the observation in the recent 11 March 2011 Tohoku 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 retaining a slip of 22m for Segment C. These parameters resulted in an earthquake with a magnitude of Mw = 9.45.

The modelling results identify that a tsunami generated from this event affects most of the east coast of the North Island. The sub-regional modelling results show a significant inundation occurs within Bay of Plenty between Papamoa and Matakana Island, similar to the previous scenarios such as the Kermadec–Hikurangi scenario (Mw 9.1) and the variation of the Southern Kermadec scenario (Mw 9.0). The first wave arrives about 50.0 minutes after the fault rupture. The maximum tsunami elevation along the coastline ranges from 8.0 m to 14 m above MHWS. The flow depth ranges from 1.0 to 4.0 m with exceptions in some areas that reach up to 9.0 m. The level of inundation caused by this tsunami is similar to the variation of the Southern Kermadec scenario (Mw 9.0) as illustrated in Figures 4.3.3.-1 to 5, but greater than the Whole Kermadec scenario (Mw 9.4) with the combined rupture of segment A, B, C in Power et al. (2010). This is as expected, because the magnitude and slip amount involved in this scenario are higher.

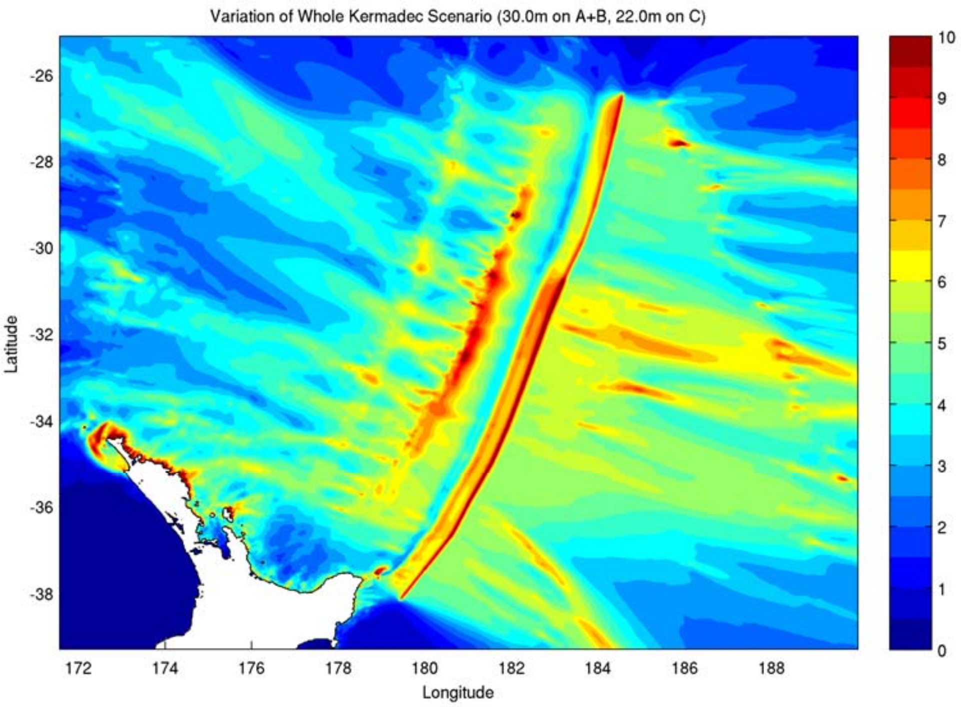

Figure 4.3.3-1 The distribution of maximum tsunami elevation above MHWS for the variation of the Whole Kermadec scenario in Power et al. (2011) with different slip values (A = 30.0m, B = 30.0m, C = 22.0m) show the affected areas along the North Island, New Zealand. Scale bar unit is in metres.

The inundation height or flow depth and inundation extent at Mt. Maunganui and Tauranga Harbour are increased considerably from previous scenarios, with flow depth at The Mount camping ground reaching 9.0 m (Figure 3.3.3-3), and a flow speed of greater than 10.0 m/s. However, the Mt. Drury Reserve area was not inundated in this scenario. The surrounding areas experienced flow depths between 1.6 to 4.0 m. The flow depth at the port facilities near Totara Streets varies from 0.4 - 0.8 m, while the flow depth at the inundation areas across Sulphur Point ranges from 1.0 to 2.0 m (Figure 3.3.3-4), and up to 4.0 m in low-lying areas of Otumoetai.

Inundation with flow depth ranging from 0.5 to 1.0 m mostly occurs inside the Harbour along the coast of Waipu Bay near to the Tauranga Airport, Rangataua and Welcome Bays, and Waimapu and Waikareao Estuaries. The Tauranga Airport facilities and the runway are not inundated in this scenario. The flow speed distribution inside the harbour and across the entrance varies from 5.0 to 9.0 m/s. While at the intertidal areas, the flow speed is greater than 10.0 m/s. At the port locations, the flow speed varies from 1.0 to 4.0 m/s.

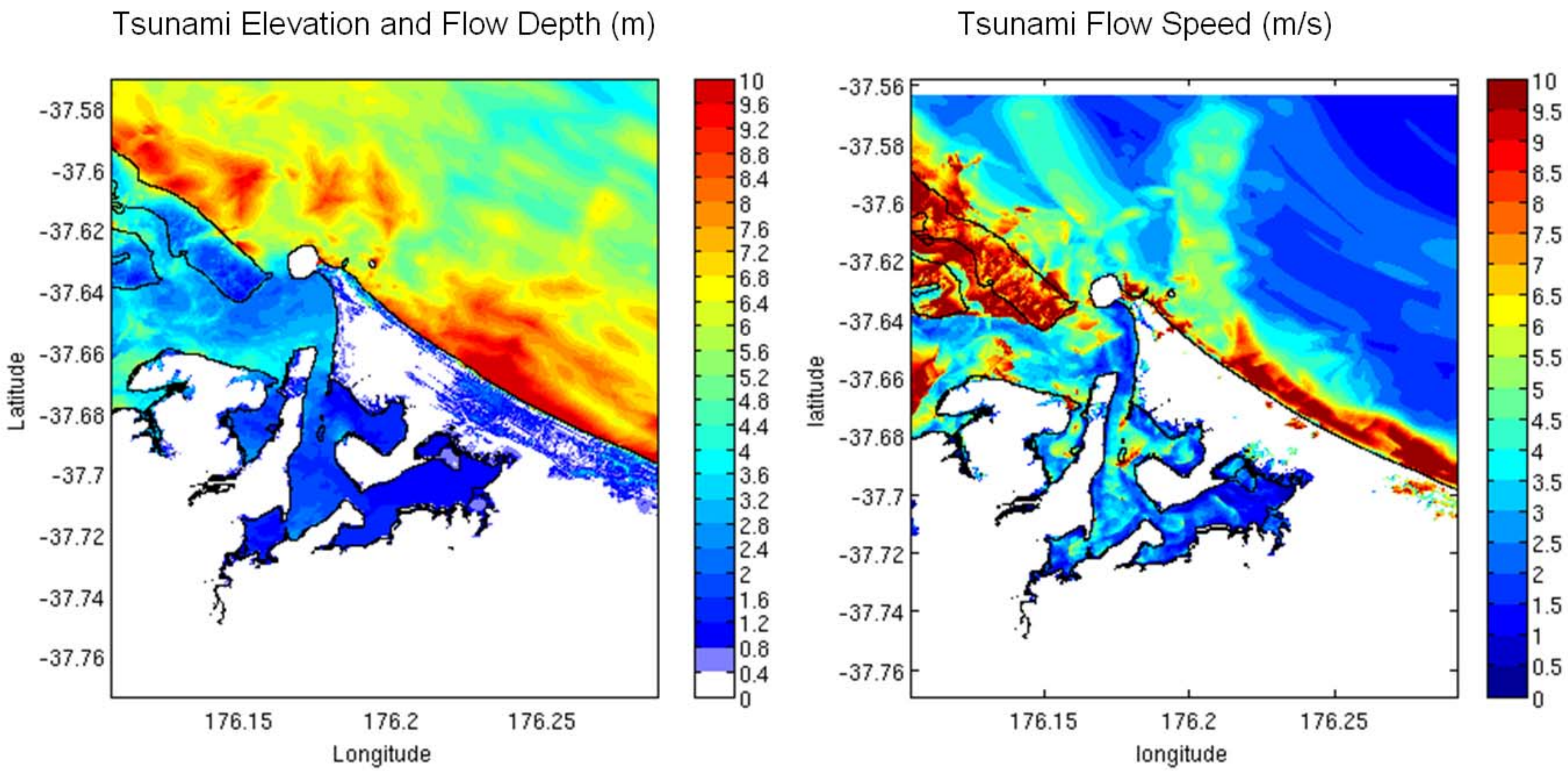

Figure 4.3.3-2 The sub-regional model shows the maximum tsunami elevation above MHWS between Papamoa and Matakana Island ranges from 8.0m to 14m (left panel). Large scale inundation occurs along Papamoa towards Omanu – Te Maunga areas, and around Mt. Maunganui. High speed flow occurs along the nearshore zone and over Matakana Island (right panel). In the left figure panel, the shaded colour represents the maximum tsunami elevation above MHWS offshore, or the flow depth if on land. The colour scale is in meters.

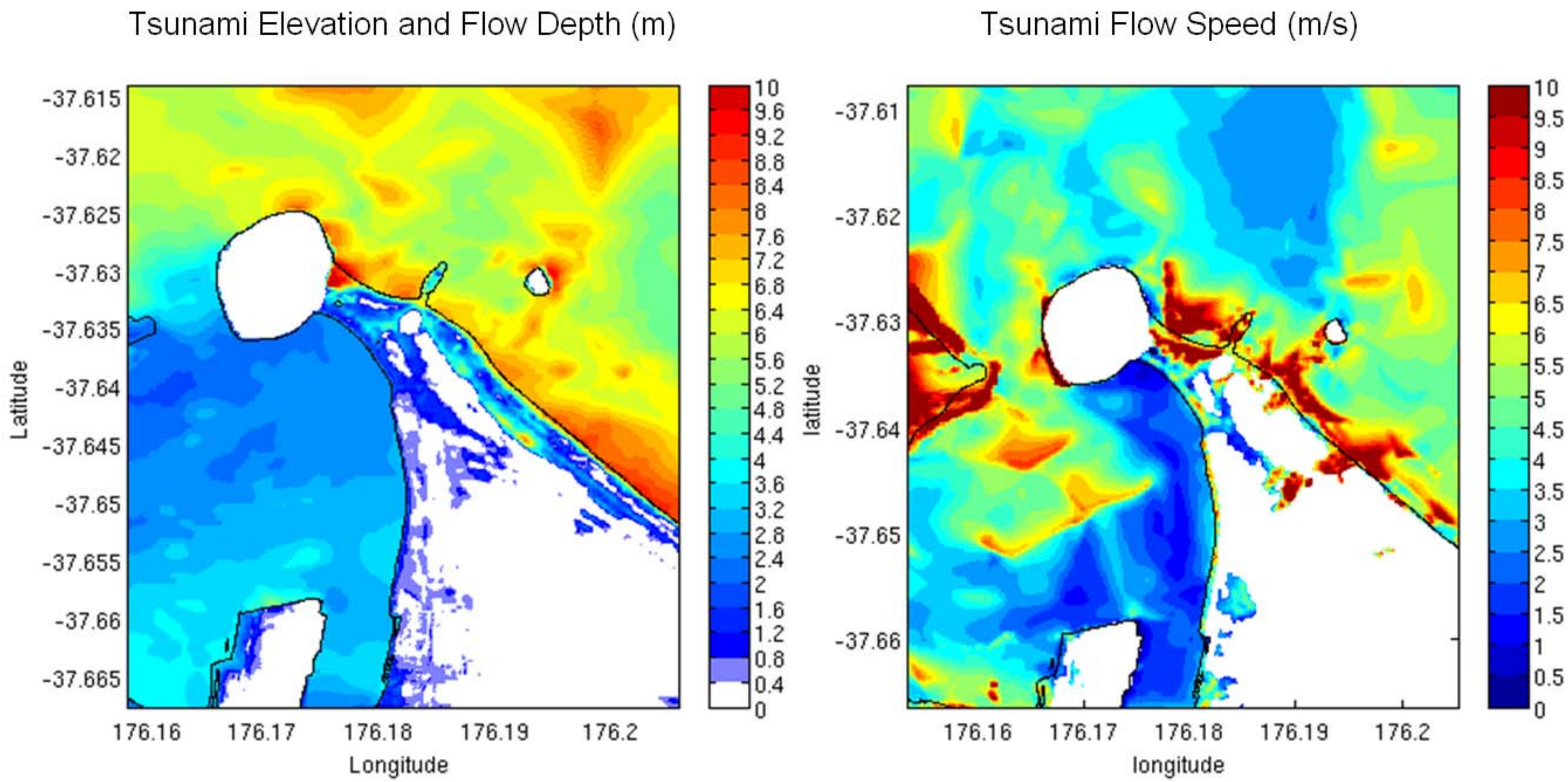

Figure 4.3.3-3 Detailed inundation modelling identifies the extent of inundation inland along Mt. Maunganui and Tauranga Harbour. Most of the sand dunes were overtopped in this scenario event. The flow depth at The Mount camping ground reaches ~ 9.0 m with the overland flow speed greater than 10.0 m/s. The tsunami elevation inside the harbour varies from 2.0 to 4.0 m above MHWS. The flow speed varies from 1.0 to 4.0 m/s at the port location and up to 9.0 m/s at the entrance and greater than 10.0 m/s along the intertidal areas. In the left figure panel, the shaded colour represents the maximum tsunami elevation above MHWS offshore, or the flow depth if on land. The colour scale is in meters.

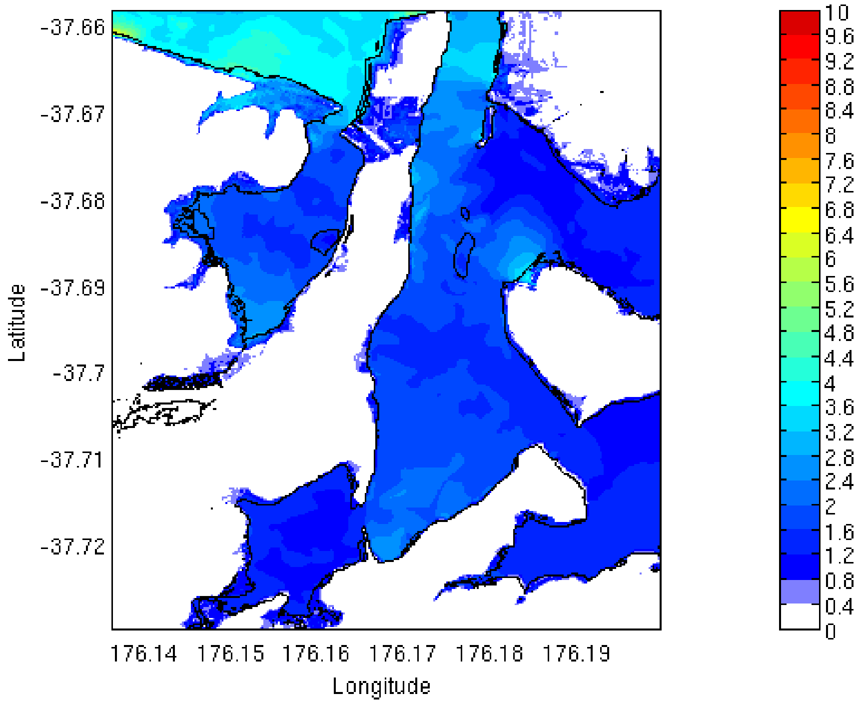

Figure 4.3.3-4 Inside the Harbour, the inundation take place along the low-lying areas with flow depth varying from 0.4 to 4.0 m and with tsunami elevation varying between 1.0 m to 3.0 m above MHWS. The shaded colour represents the maximum tsunami elevation above MHWS offshore, or the flow depth if on land. The colour scale is in meters.

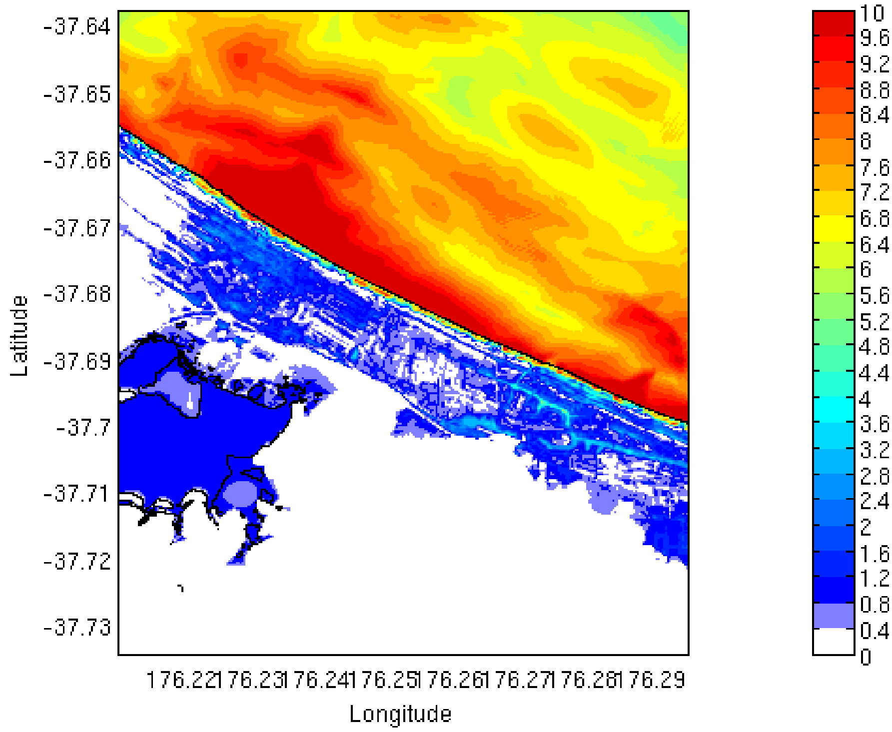

Figure 4.4.3-5 The inundation extent along the Papamoa – Omanu coastline indicates that the tsunami overtopped the sand dunes along the beach in front of Papamoa and overland flows propagate down to the low-lying areas further inland. The low-lying areas inside Rangataua Bay were inundated by tsunami waves that come through the Harbour and estuary with flow depth ranges between 0.4 to 1.0 m. the shaded colour represents the maximum tsunami elevation above MHWS offshore, or the flow depth if on land. The colour scale is in meters.

5.0 CONCLUSIONS

- The inundation modelling results show the study areas are highly affected by a tsunami generated along the Kermadec Trench. The arrival time of the first wave ranges from 50 to 70 minutes and the tsunami maximum elevations at most places along the coasts are greater than 5.0 meters above the ambient water level (i.e. MHWS in all the scenarios).
- A Whole Kermadec Mw 9.4 scenario with a uniform slip of 22.0m and combined rupture of segments A, B and C in Power et al. (2011) shows a significant inundation within the study areas.
- Three variations of the Kermadec scenarios in Power et al. (2011) were developed by applying the slip of 30m that occurred within the recent 11 March 2011 Tohoku Earthquake in Japan :
    - Variation of the Southern Kermadec scenario (slip = 30.0 m along segment A, Mw = 9.0): leading to an extensive inundation in the study areas;
    - Variation of the Central Kermadec scenario (slip = 30,.0 m along segment B, Mw = 9.2): leading to significant inundation in the study areas;
    - Variation of the Whole Kermadec scenario (slip of 30 m on Segments A and B and a slip of 22 m on Segment C (Mw = 9.45): leading to 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 from the Kermadec Trench (part of Segment A and B in Power et al. (2011)) to the south into the northern portion of the Hikurangi Margin (Segment H), with uniform dip = 16^{o} and slip= 20 m, provides a impact on the study areas (Mt. Maunganui and Tauranga) similar to the variation of the Southern Kermadec scenario (slip = 30.0m, Mw9.0) as well as to the Whole Kermadec scenario with 22 m slip in Power et al. (2011) and its variation (slip = 30 m on segments A and B and slip = 22 m on segment C, Mw9.45).
- The model results show that the sand dunes provide an effective and important barrier to tsunami inundation. The preservation or conservation of these sand dunes along the beachfront 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 a natural protective function (Prasetya, 2007).
- Strategic mitigation of the tsunami risk is needed within this region. 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 between The Mount and Mt. Drury Reserves. For future development planning within the high risk zone; promoting a 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 LIMITATION OF THE CURRENT WORK

- No erosion or sedimentation has been considered or taken into account during the modelling processes. Therefore, no morphology changes to beaches and sand dunes which may occur due to strong currents and wave breaking have 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 uniform slip (the exception being the variation of the whole Kermadec scenario which involves a single change in slip along strike). 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 near-field events (close to the source) more than distant events, far from the source (Geist, 1998). The uniform slip distribution used here may represent an approximation of the average event rather than 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

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