

HIKURANGI RESPONSE PLAN

LIFE AT THE BOUNDARY



EAST COAST LAB

Please Note: The following scenario has been developed with the purpose of specifically informing the Hikurangi Response Plan. **It represents one of many different scenarios.**

While scientists cannot predict how the Hikurangi subduction zone might behave, they have chosen a magnitude 8.9 scenario as being a serious and credible basis for the response plan.

Scenarios are used by emergency planners to help them determine likely impacts, response priorities and resource requirements during an event, such as an earthquake and tsunami.

Scenarios are useful tools, but they do not represent or predict what will happen in the future. There is no way to predict what the next Hikurangi subduction zone earthquake and tsunami will look like.

Experts have also developed an 'exercise scenario' for the Hikurangi Response Plan. This describes possible impacts and locations that are affected by the earthquake and tsunami- this information has been developed for testing the response plan and is not a prediction of future impacts and locations affected. **Any locations used are arbitrary.**

**Hikurangi Response Plan – Developing a scenario
for an Mw 8.9 Hikurangi earthquake, including
tsunami modelling and a preliminary description of
impacts**

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EXECUTIVE SUMMARY

Hawkes Bay Civil Defence and Emergency Management (CDEM) Group are developing a response plan for a major Hikurangi earthquake and tsunami as part of a CDEM Resilience Fund project entitled “Hikurangi Response Plan – developing a coordinated response to a subduction rupture to assist and enhance community resilience across the North Island East Coast”.

At the ‘Hikurangi Response Plan Hazard Scenario Workshop’ workshop held in June 2018 the decision was made to base the response plan on a realistic scenario of an Mw 8.9 earthquake on the southern portion of the Hikurangi subduction zone. The selected scenario was chosen from a group of Mw 8.9 earthquake scenarios with different distributions of non-uniform slip on the plate boundary, and the choice was made to pick a scenario that showed a strong concentration of slip in the southern Wairarapa area since this region has been found to feature strong coupling on the plate interface according to geodetic studies.

Modelling of the base scenario (presented in Section 2) demonstrates tsunami flow-depths and inundation extents that are likely to cause widespread damage to buildings and infrastructure, and cause significant casualties among those not able to evacuate in Wellington, Napier and Gisborne. In the base scenario the tsunami in Tauranga is much smaller and likely to have a very limited impact.

The location and slip distribution of future Hikurangi earthquakes cannot be predicted ahead of time. Hence the chosen scenario represents just one possibility for what might happen in a future large earthquake of this type. In order to communicate the range of possible impacts, a set of variations on the base scenario are also presented.

One of the variant scenarios demonstrates that should an equivalent earthquake to the base scenario occur on the northern part of the Hikurangi subduction zone, the impact on Tauranga is likely to be very much greater, while the impact on Wellington is likely to be very much less.

Other variants highlight the effects of non-uniform slip: earthquakes of the same magnitude and overall location can vary greatly in their tsunami impact simply according to where the slip is concentrated (and hence where the movement of the seabed is greatest).

In section 3 of this report results are presented showing estimates of earthquake shaking intensity and duration based on seismic wavefield modelling of the base scenario. These show intense shaking MMI 8.0–10.0, and long shaking duration (several 10s of seconds), along the eastern side of the North Island between East Cape and Wellington and also extending into the northeast corner of the South Island. For the base scenario the rupture is assumed to be bilateral (spreading in both directions from a starting point in the middle of the rupture). Also presented are equivalent results based on the assumption of unilateral rupture starting at either the north or south end of the rupture and propagating to the other end. Significant differences are found, illustrating that, like with the tsunami effects, the consequences of any particular earthquake are dependent on unpredictable features specific to the actual event.

In section 4 of this report we describe the results of a preliminary impact assessment for the base scenario. This is presented in the form of a qualitative narrative developed through a series of ‘expert panel’ meetings, focussing on each of the four locations: Wellington, Napier, Gisborne and Tauranga. No quantitative loss modelling was used to prepare this scenario. However, for the purpose of developing a realistic scenario for exercise planning, specific but arbitrary choices (of locations and levels of impact) were made regarding impacts within the

range considered plausible by the panel members. Caution must be taken not to over-interpret the results of this process, as it can give a false impression of precision.

The preliminary impact assessment by the panel members presents a very challenging scenario to deal with, as three major cities are severely impacted by both earthquake and tsunami, leading to widespread loss of essential utilities and heavy casualties (approximately one thousand fatalities and ten times as many injuries).

1.0 INTRODUCTION

This proposal is submitted by the Institute of Geological and Nuclear Sciences Limited (GNS Science) following a request by Lisa Pearce, Team Leader Hazard Reduction in the Hawke's Bay Regional Council Civil Defence and Emergency Management Group.

Hawkes Bay Civil Defence and Emergency Management (CDEM) Group are developing a response plan for a major Hikurangi earthquake and tsunami as part of a CDEM Resilience Fund project entitled "Hikurangi Response Plan – developing a coordinated response to a subduction rupture to assist and enhance community resilience across the North Island East Coast". As part of the process of developing the plan a workshop was held in June to discuss possible options for a scenario for the response plan. The scenario needed to be credible, and as a result not all of the participating CDEM regions would be impacted strongly by it. At the workshop the participants decided to base the scenario around an M8.9 earthquake on the subduction zone.

For this project, Hawkes Bay Civil Defence and Emergency Management Group have requested tsunami models (including both offshore propagation and inundation of Wellington, Napier, Gisborne and Tauranga) to be completed for several (5–8) variations of an M8.9 earthquake on the Hikurangi subduction zone (e.g. different slip distributions, a scenario centred further to the north), and including the base scenario selected at the June workshop. They have requested summary figures and animations to be prepared from the model data and also figures illustrating the ground shaking in the base scenario. The figures showing the results from these models need to be suitable for both subsequent planning and community education.

In addition, Hawkes Bay CDEM group requested that the report include a preliminary assessment of the social and physical impacts, in line with the Hikurangi Response Plan Workshop discussions, to be achieved by putting together an expert panel to provide a qualitative 'scenario' assessment of the potential impact of the base scenario at each the four locations.

2.0 TSUNAMI SCENARIOS

2.1 Scenario A: Mw 8.9 Southern Hikurangi Earthquake

The scenario chosen for this study was of an Mw 8.9 earthquake on the southern portion of the Hikurangi subduction zone. The choice of magnitude was made to represent a realistic large earthquake covering the majority of the Hikurangi subduction zone and that is slightly below the maximum plausible magnitude, which is currently thought to be approximately Mw 9.0 (Power, 2013).

In real earthquakes the distribution of slip on a fault is highly variable, i.e. there will be some portions of the fault plane on which the amount of movement is much greater than others. The particular distribution of slip cannot currently be predicted in advance of an earthquake. For the purpose of this study, a particular earthquake slip-distribution was chosen from a set of randomly-generated slip-distributions that was previously developed for a study by the Earthquake Commission (Horspool et al, 2016).

The particular slip-distribution chosen was one in which there was a strong concentration of earthquake slip at the southern end of the Hikurangi margin in the Wairarapa/Cook Strait area (Figure 2.1). The reasoning for this being that geodetic studies have indicated strong-coupling between the two sides of the plate boundary in this area, which indicates the potential for a large-slip deficit to be released in this region during a future earthquake. We refer to this as Scenario A or the base scenario in the rest of this report.

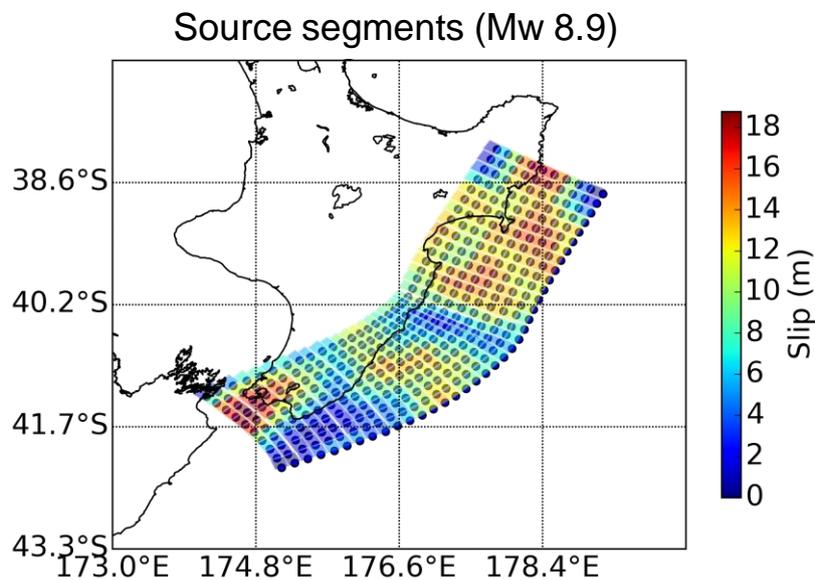


Figure 2.1 Slip distribution on the plate interface for the Mw 8.9 Hikurangi plate-interface earthquake in scenario A.

The peak slip is just over 18 meters, and the average is about 9–10 meters. This corresponds to Mw 8.9 if a rigidity of 35 GPa is assumed. The vertical displacement caused by this earthquake movement is shown in Figure 2.2.

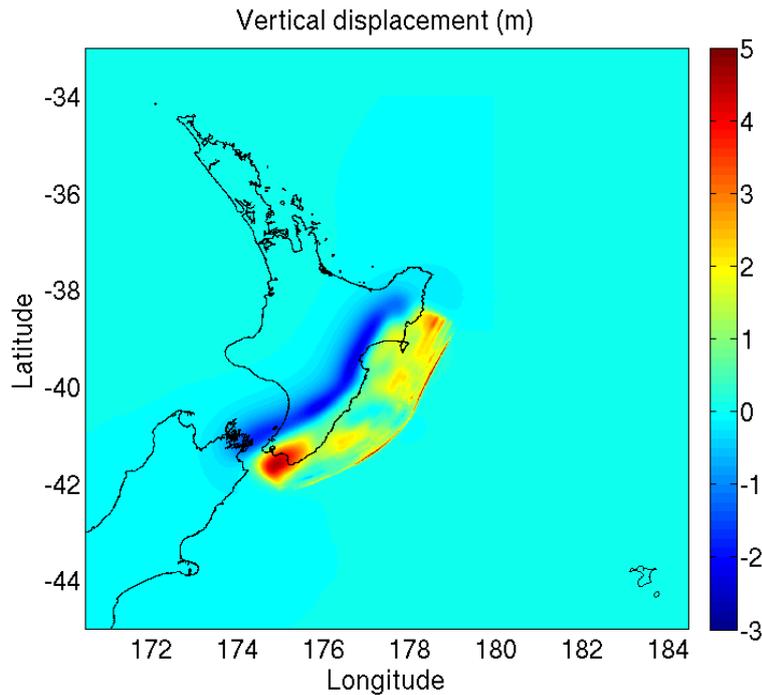


Figure 2.2 Vertical co-seismic displacement for the Mw 8.9 Hikurangi plate-interface earthquake in scenario A.

The effect of this displacement (which in the tsunami modelling presented here is assumed to be instantaneous) is to initiate a tsunami, which in deep water leads to the maximum water levels shown in Figure 2.3.

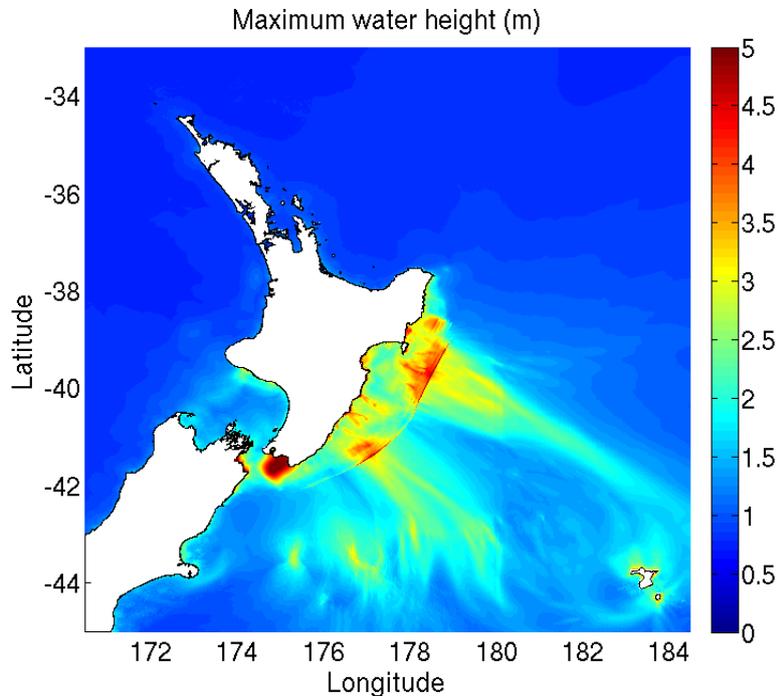


Figure 2.3 Maximum water surface elevation for the Mw 8.9 Hikurangi plate-interface earthquake in scenario A. The colour scale is limited so that water heights above 5m appear as 5m¹.

¹ We limit the colour scale in this figure, and other similar figures, to better highlight the large-scale distribution of tsunami energy. Maximum tsunami heights well in excess of 5m are not uncommon where the waves shoal close to the coast, but are very difficult to resolve on a figure at this scale. Subsequent Figures 2.4-2.7 provide a better feeling for typical near-shore tsunami heights.

This tsunami causes extensive inundation in Wellington, Napier and Gisborne, but has relatively little impact on Tauranga (Figure 2.4–Figure 2.7). The inundation modelling assumes the tsunami occurs close to high tide (a background water level of 0.69 m above MSL was assumed). This scenario is used for the preliminary impacts scenario in Section 3.

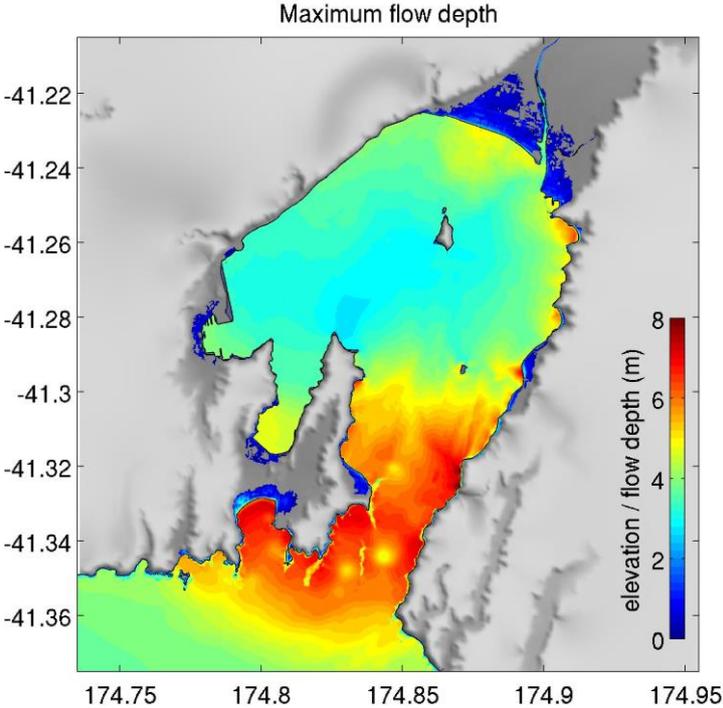


Figure 2.4 Maximum flow depth (height of water above ground level) in Wellington for the Mw 8.9 Hikurangi plate-interface earthquake in scenario A. Offshore the maximum water elevation is shown.

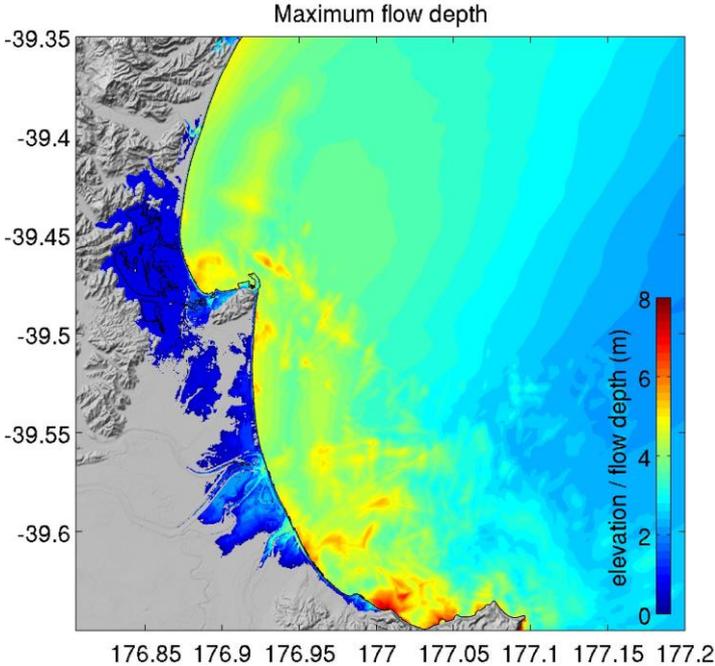


Figure 2.5 Maximum flow depth (height of water above ground level) in Napier for the Mw 8.9 Hikurangi plate-interface earthquake in scenario A. Offshore the maximum water elevation is shown.

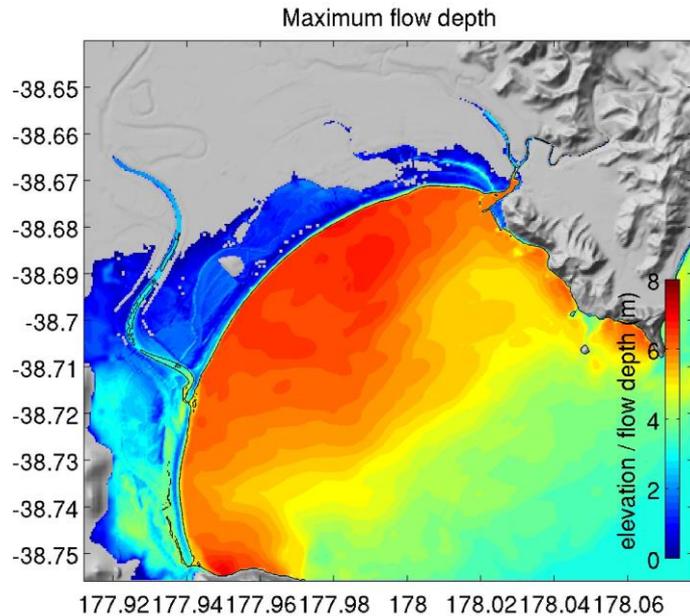


Figure 2.6 Maximum flow depth (height of water above ground level) in Gisborne for the Mw 8.9 Hikurangi plate-interface earthquake in scenario A. Offshore the maximum water elevation is shown.

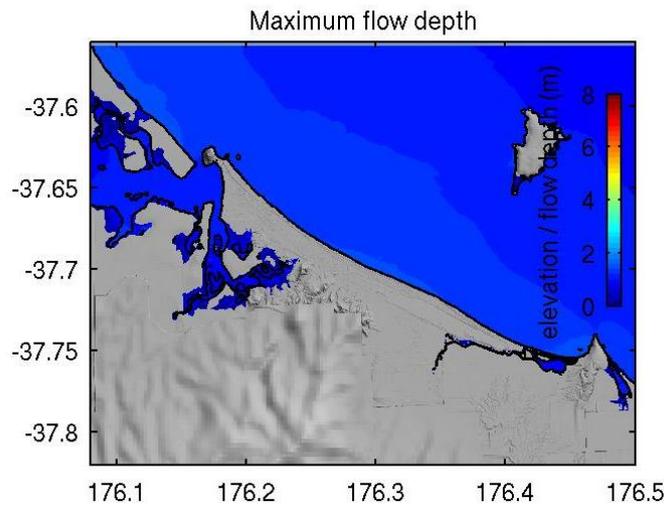


Figure 2.7 Maximum flow depth (height of water above ground level) in Tauranga for the Mw 8.9 Hikurangi plate-interface earthquake in scenario A. Offshore the maximum water elevation is shown.

2.2 Alternative Scenarios

The scenario chosen as the focus for this study is just one example of an Mw 8.9 Hikurangi earthquake. Alternative scenarios differ in both the overall location of the earthquake and the particular slip-distribution (these are the primary factors affecting the tsunami, the earthquake shaking is sensitive to additional parameters besides these, see Section 3.0). In the following subsections we present tsunami modelling results for a selection of alternative scenarios (Table 2.1).

Table 2.1 Tabulated summary of the main differences between the scenarios presented in Section 2.

Scenario Name	Commentary
Scenario A	The base scenario, a Mw 8.9 southern Hikurangi earthquake, modelled with non-uniform slip. This scenario has a patch of large slip under southern Wairarapa.
Scenario B	A scenario with a rupture ~300 km further to the north than the base scenario, but based on the same slip-distribution.
Scenario C	A scenario with the same overall rupture extent as the base scenario, but with a different non-uniform distribution of slip.
Scenario D	A scenario with the same overall rupture extent as the base scenario, but with a uniform distribution of slip.
Scenario E	A scenario in which a weighting function has been applied to the base scenario to concentrate slip around the region of strong coupling at the southern end of the Hikurangi Margin.

A systematic study of the effects of non-uniform slip on the large-scale patterns of tsunami energy can be found in Appendix 1.

2.2.1 Scenario B: A Rupture Further to the North

In this scenario the only change has been to relocate the earthquake rupture approximately 300 km further to the north (Figure 2.8–Figure 2.9).

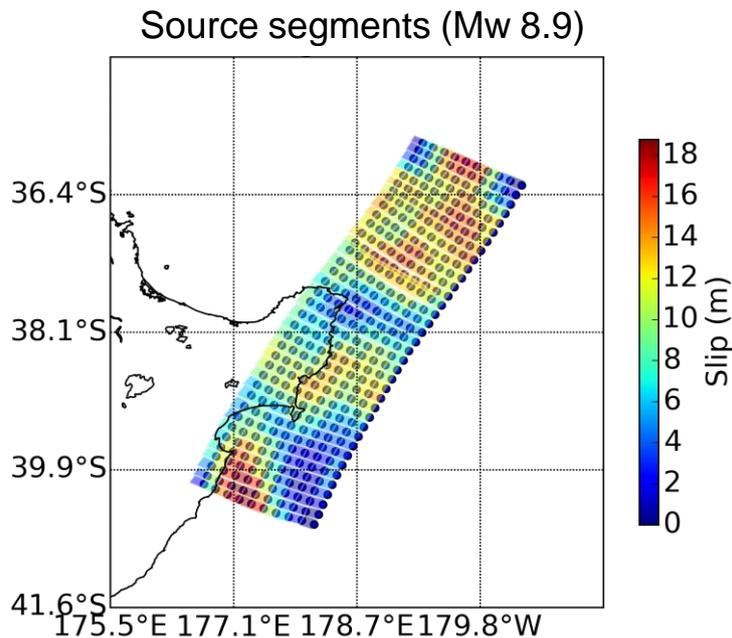


Figure 2.8 Slip distribution on the plate interface for the Mw 8.9 Hikurangi plate-interface earthquake in scenario B.

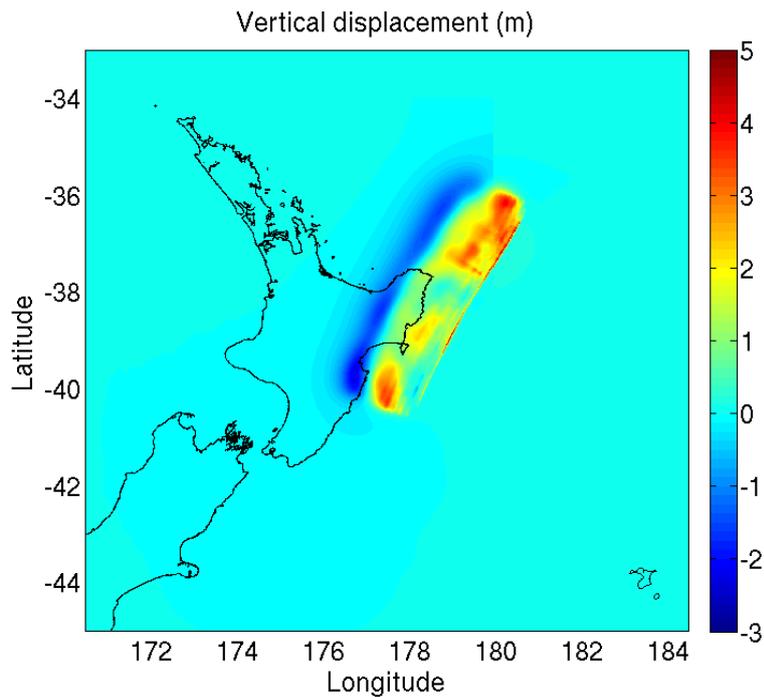


Figure 2.9 Vertical co-seismic displacement for the Mw 8.9 Hikurangi plate-interface earthquake in scenario B.

This has the effect of dramatically increasing the tsunami impact on Tauranga and other areas of northern New Zealand, while also greatly reducing the impact on Wellington. The differences in Napier and Gisborne are less dramatic, with Napier experiencing greater inundation and Gisborne less (Figure 2.10–Figure 2.14).

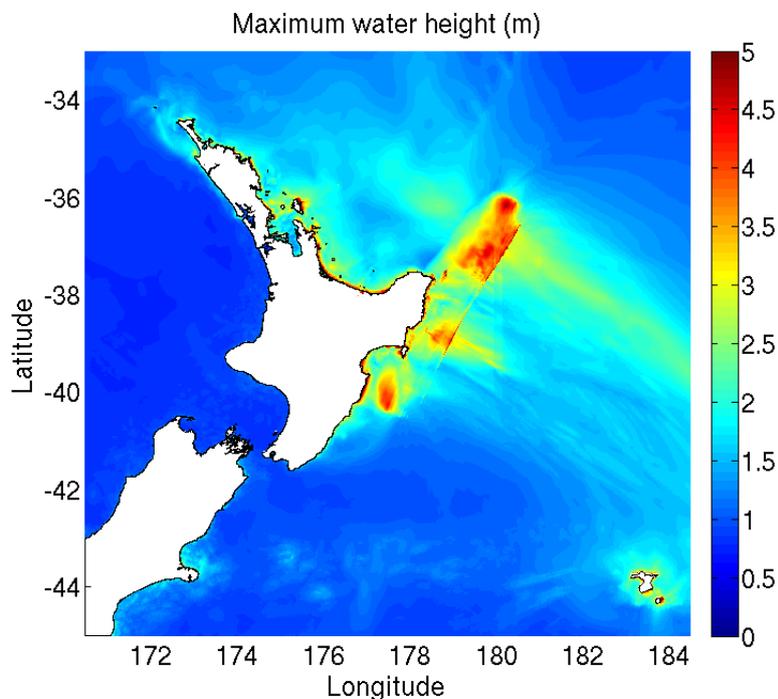


Figure 2.10 Maximum water surface elevation for the Mw 8.9 Hikurangi plate-interface earthquake in scenario B. The colour scale is limited so that water heights above 5m appear as 5m.

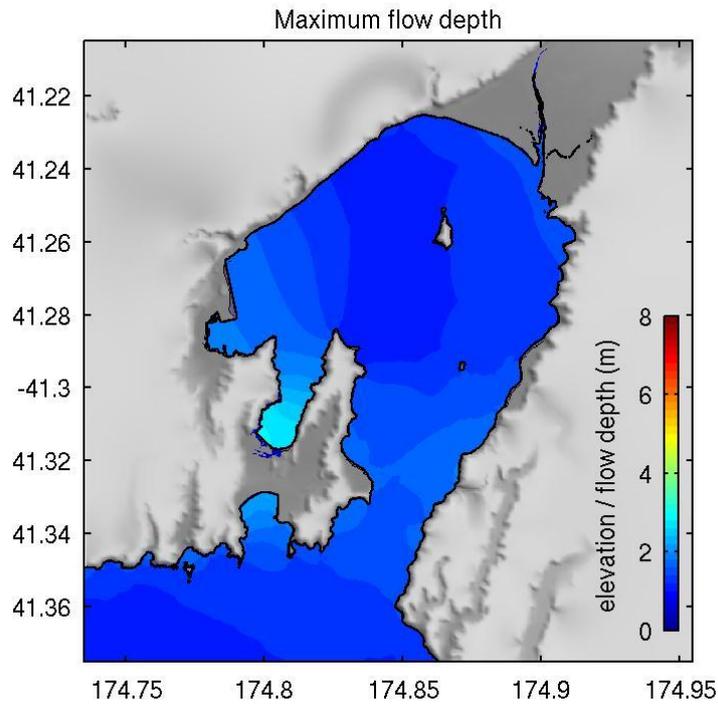


Figure 2.11 Maximum flow depth (height of water above ground level) in Wellington for the Mw 8.9 Hikurangi plate-interface earthquake in scenario B. Offshore the maximum water elevation is shown.

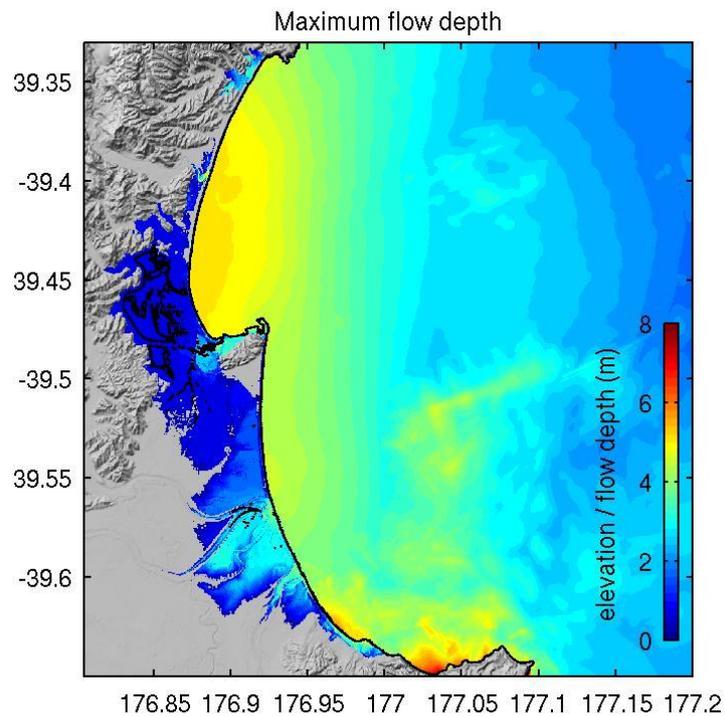


Figure 2.12 Maximum flow depth (height of water above ground level) in Napier for the Mw 8.9 Hikurangi plate-interface earthquake in scenario B. Offshore the maximum water elevation is shown.

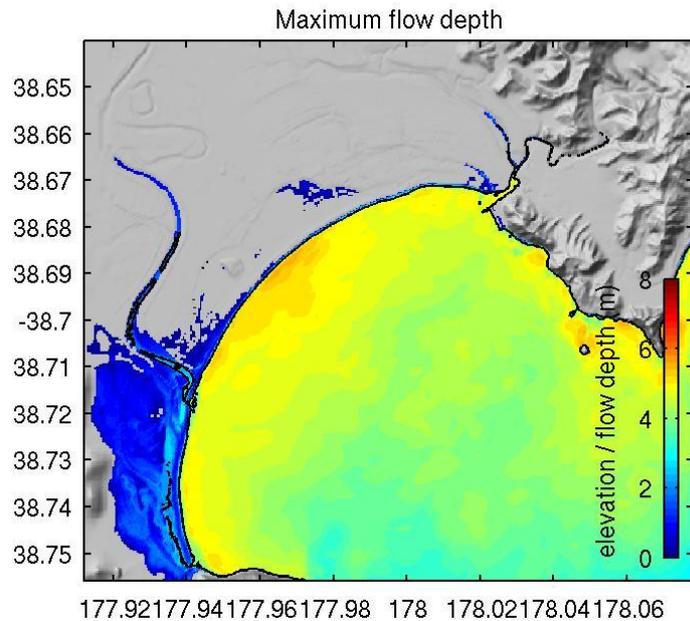


Figure 2.13 Maximum flow depth (height of water above ground level) in Gisborne for the Mw 8.9 Hikurangi plate-interface earthquake in scenario B. Offshore the maximum water elevation is shown.

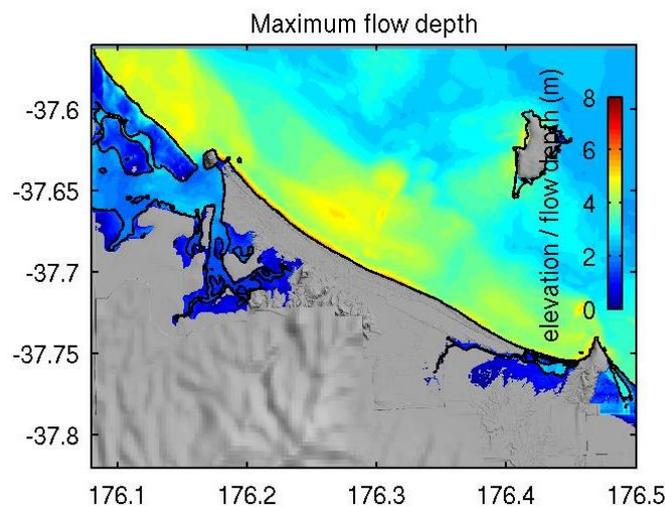


Figure 2.14 Maximum flow depth (height of water above ground level) in Tauranga for the Mw 8.9 Hikurangi plate-interface earthquake in scenario B. Offshore the maximum water elevation is shown.

2.2.2 Scenario C: A Different Distribution of Slip

In this scenario we return to the southern Hikurangi location of the main scenario (scenario A), but randomly² select a different slip distribution (Figure 2.15).

² Although slip distributions are generated 'randomly' this is done in such a way that the slip distributions have statistical properties consistent with real events, see Mueller et al (2014) for further details.

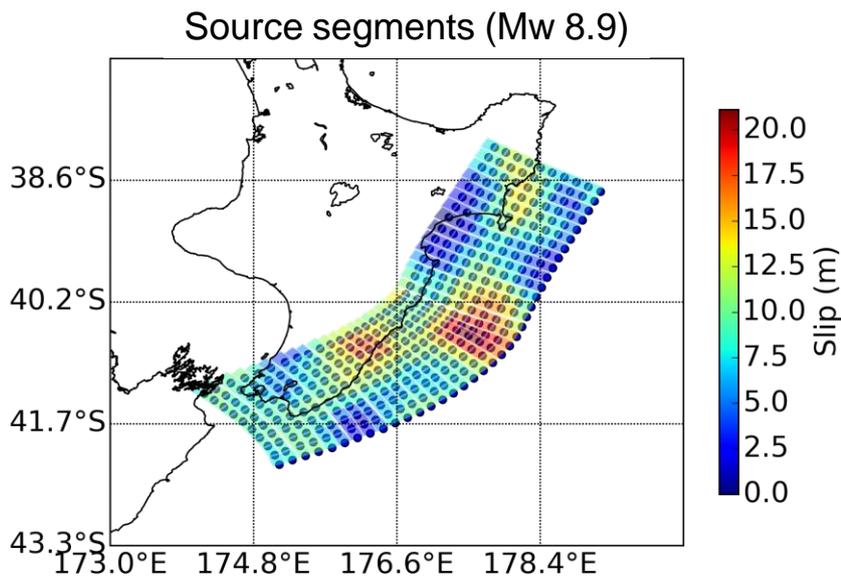


Figure 2.15 Slip distribution on the plate interface for the Mw 8.9 Hikurangi plate-interface earthquake in scenario C.

In this case we have two large patches of 15–20 m slip, one on the shallow part of the subduction interface offshore the north Wairarapa coast, and the other under the central Wairarapa coast. A third lesser patch of high (12–15 m) slip occurs offshore of Poverty Bay.

The distribution of vertical deformation approximately follows the distribution of slip (Figure 2.16).

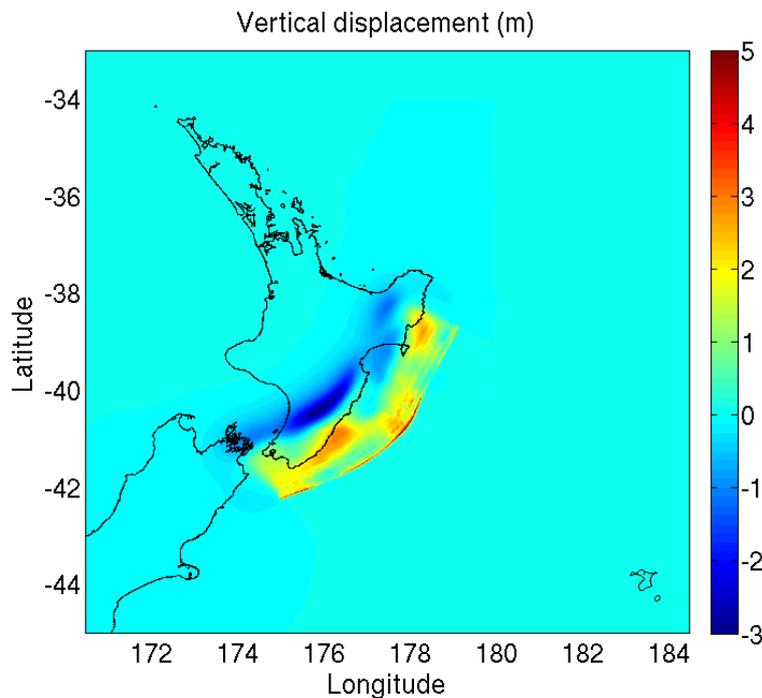


Figure 2.16 Vertical co-seismic displacement for the Mw 8.9 Hikurangi plate-interface earthquake in scenario C.

The resulting tsunami is particularly large along the central and northern Wairarapa Coast (Figure 2.17).

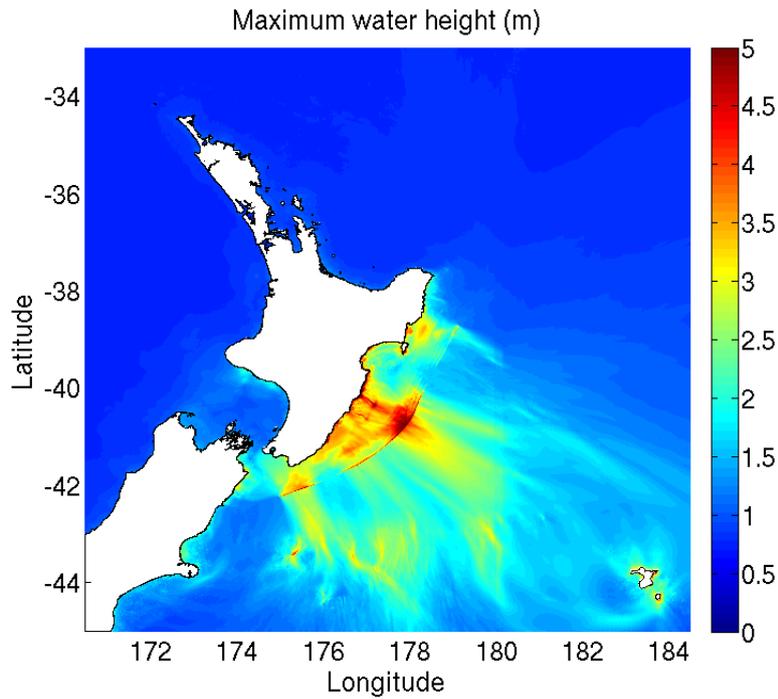


Figure 2.17 Maximum water surface elevation for the Mw 8.9 Hikurangi plate-interface earthquake in scenario C. The colour scale is limited so that water heights above 5m appear as 5m.

There is significantly less inundation than the baseline Scenario A in Wellington, slightly less inundation in Napier, while the impacts on Gisborne and Tauranga are similar (Figure 2.18–Figure 2.21).

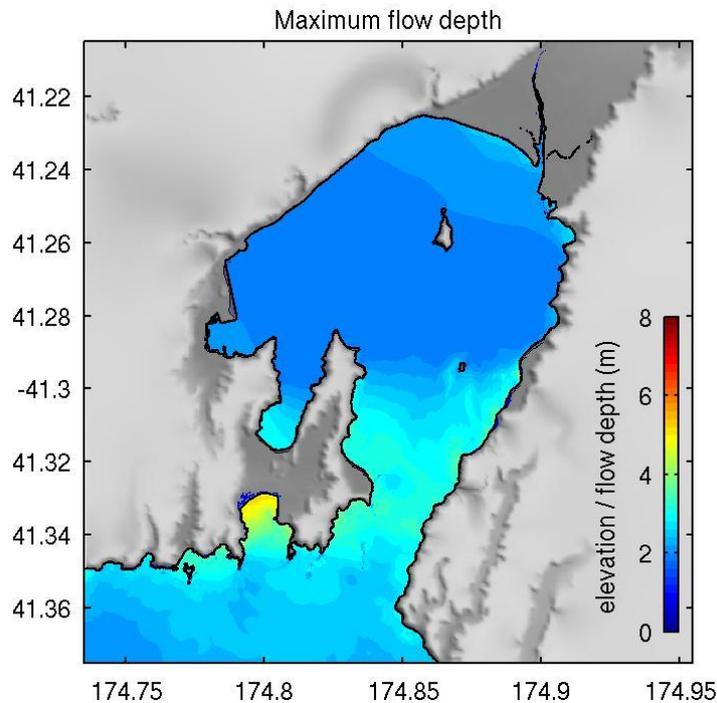


Figure 2.18 Maximum flow depth (height of water above ground level) in Wellington for the Mw 8.9 Hikurangi plate-interface earthquake in scenario C. Offshore the maximum water elevation is shown.

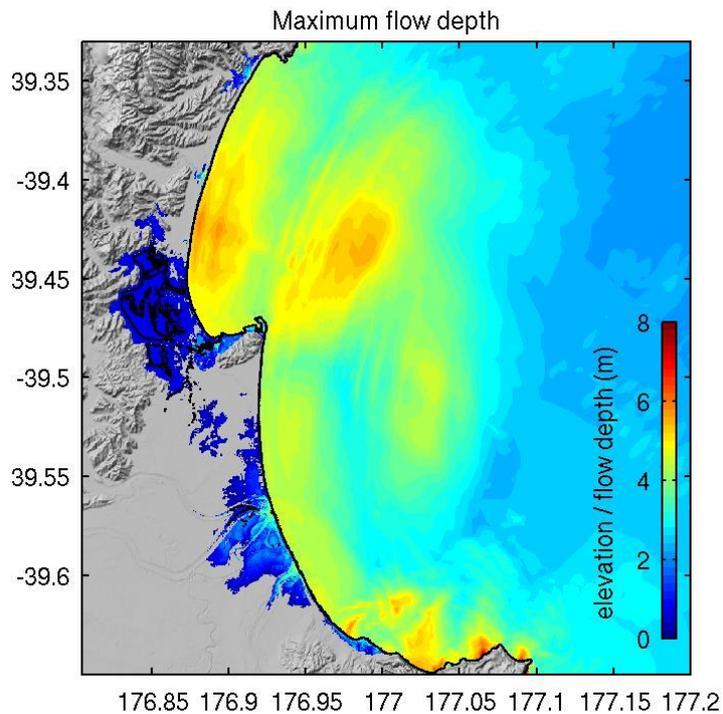


Figure 2.19 Maximum flow depth (height of water above ground level) in Napier for the Mw 8.9 Hikurangi plate-interface earthquake in scenario C. Offshore the maximum water elevation is shown

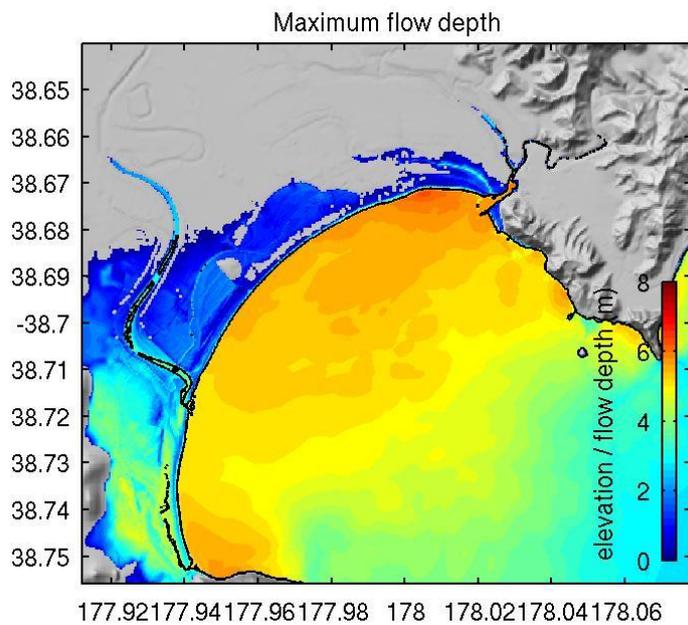


Figure 2.20 Maximum flow depth (height of water above ground level) in Gisborne for the Mw 8.9 Hikurangi plate-interface earthquake in scenario C. Offshore the maximum water elevation is shown.

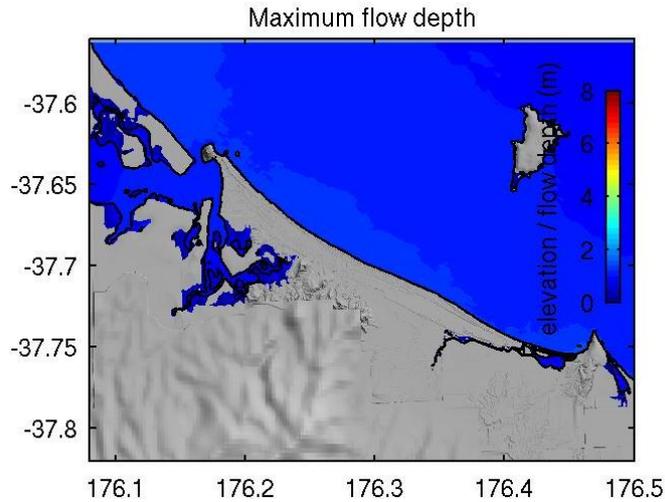


Figure 2.21 Maximum flow depth (height of water above ground level) in Tauranga for the Mw 8.9 Hikurangi plate-interface earthquake in scenario C. Offshore the maximum water elevation is shown.

For further information on the possible range of different non-uniform slip scenarios, please see Appendix 1.

2.2.3 Scenario D: A Uniform Distribution of Slip

It is generally quite common for tsunami modelling to be performed assuming a uniform-distribution of slip on a fault plane, although in reality this situation never exactly occurs (some ruptures may be closer to uniform than others). In this scenario we present the results of an Mw 8.9 earthquake, the same as used in the other scenarios, and occupying the same southern Hikurangi region as our reference scenario A, but this time with the slip uniformly distributed (Figure 2.22).

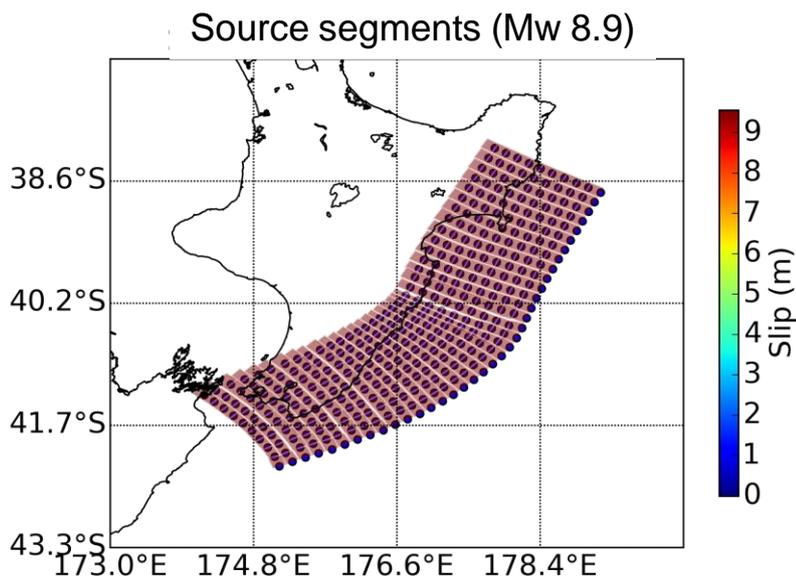


Figure 2.22 Slip distribution on the plate interface for the Mw 8.9 Hikurangi plate-interface earthquake in scenario D.

The result of this is a fairly uniform distribution of uplift of around 1–2m offshore, with a thin strip of greater uplift (3–4m) near the trench, and subsidence of up to 1.5m mostly onshore but also affecting the Kapiti coast and Marlborough Sounds (Figure 2.23).

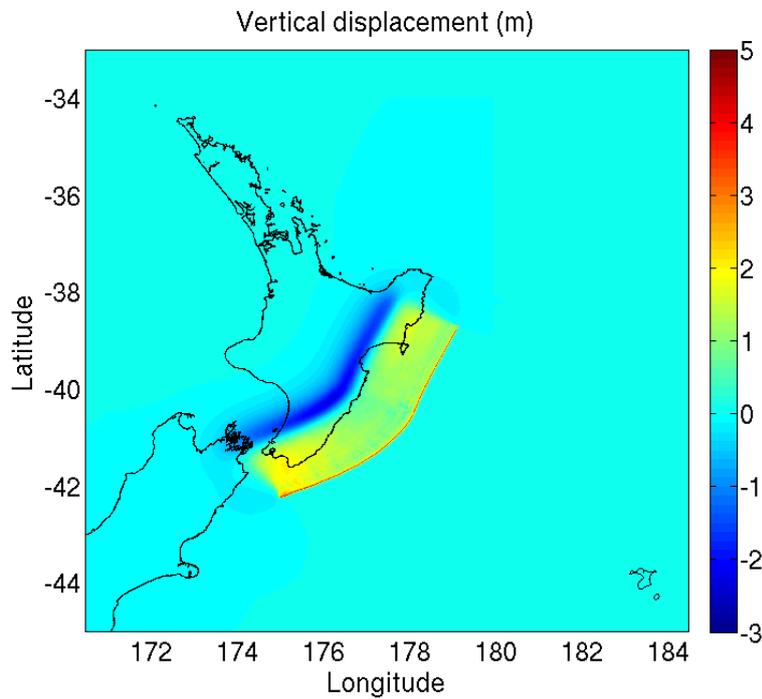


Figure 2.23 Vertical co-seismic displacement for the Mw 8.9 Hikurangi plate-interface earthquake in scenario D.

The consequences of this scenario are a tsunami that is relatively uniform in height along the coasts above the rupture (but still far from constant due to the effects of bathymetric variations, the shape of the coast and the shape of the interface).

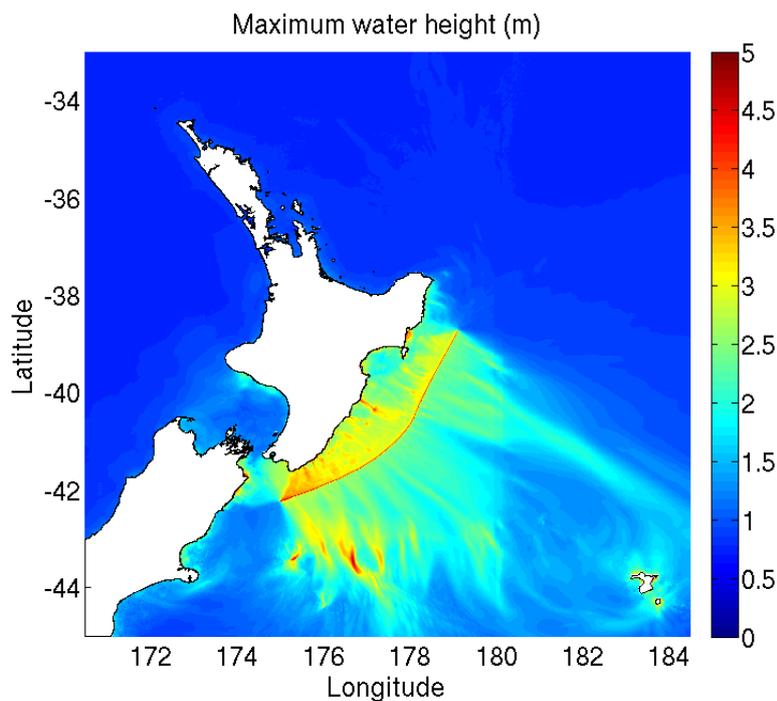


Figure 2.24 Maximum water surface elevation for the Mw 8.9 Hikurangi plate-interface earthquake in scenario D. The colour scale is limited so that water heights above 5m appear as 5m.

The effects of inundation on Wellington are significantly less than in our base scenario A, the impacts on Napier and Tauranga are quite similar to those in scenario A, and the impact on Gisborne is moderately less (Figure 2.25–Figure 2.28).

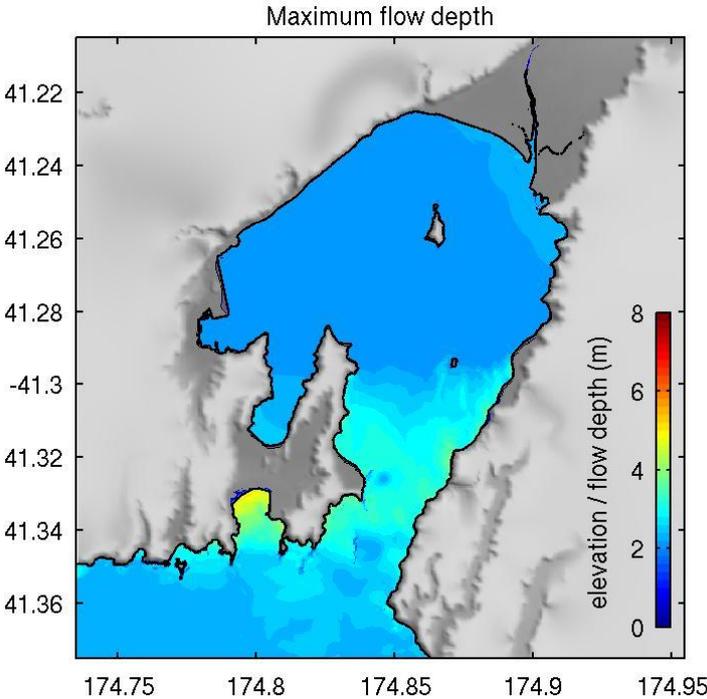


Figure 2.25 Maximum flow depth (height of water above ground level) in Wellington for the Mw 8.9 Hikurangi plate-interface earthquake in scenario D. Offshore the maximum water elevation is shown.

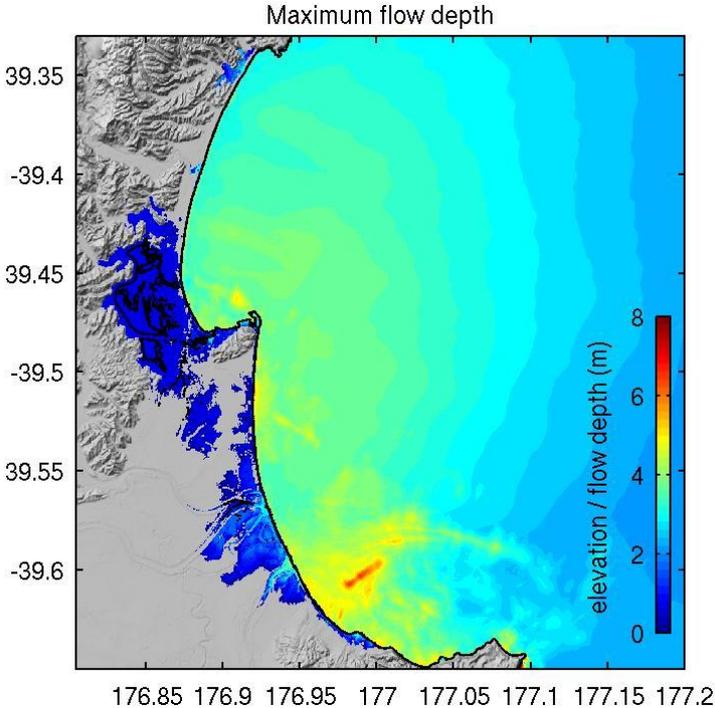


Figure 2.26 Maximum flow depth (height of water above ground level) in Napier for the Mw 8.9 Hikurangi plate-interface earthquake in scenario D. Offshore the maximum water elevation is shown.

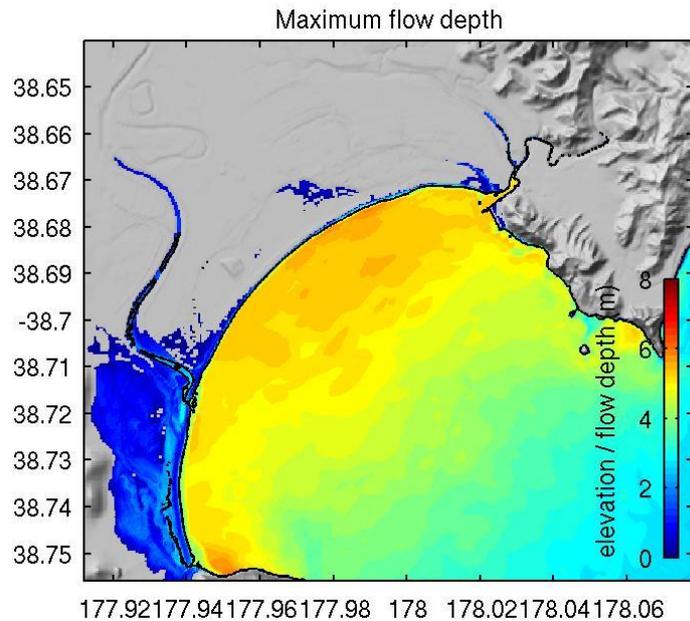


Figure 2.27 Maximum flow depth (height of water above ground level) in Gisborne for the Mw 8.9 Hikurangi plate-interface earthquake in scenario D. Offshore the maximum water elevation is shown.

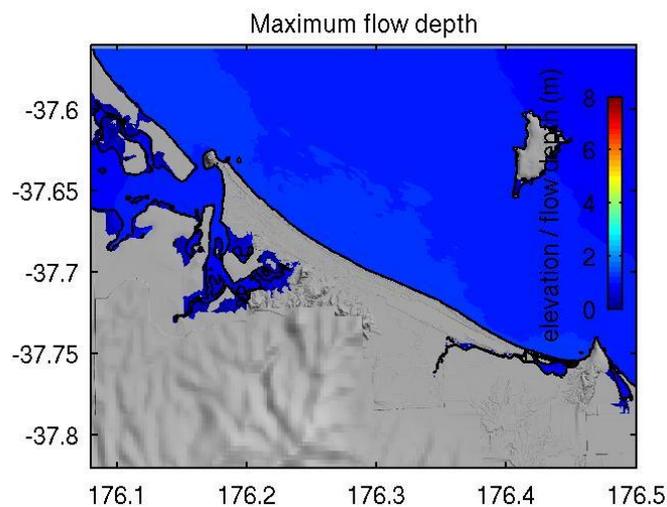


Figure 2.28 Maximum flow depth (height of water above ground level) in Tauranga for the Mw 8.9 Hikurangi plate-interface earthquake in scenario D. Offshore the maximum water elevation is shown.

2.2.4 Scenario E: A Scenario Weighted Towards Southern Hikurangi

Studies of GPS movement have implied that the subduction interface is currently locked (fully coupled) under the southern North Island, and less strongly coupled elsewhere (Figure 2.29). A plausible assumption is that the areas of strong present-day coupling a more likely to experience large movement in a future plate boundary earthquake.

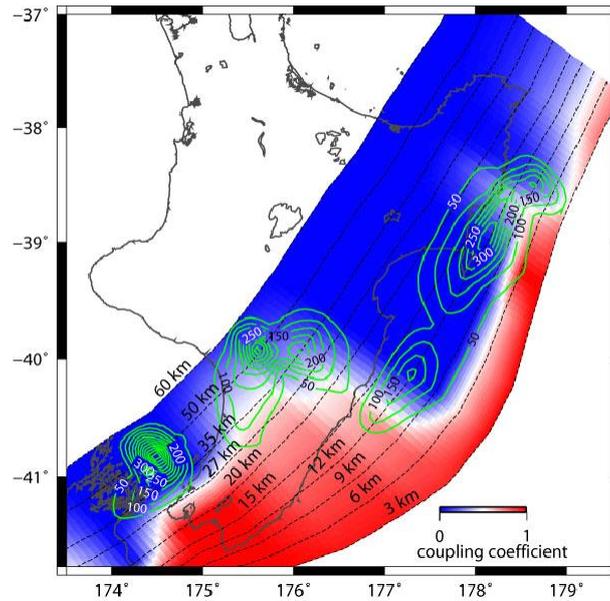


Figure 2.29 Distribution of interseismic coupling on the subduction interface (red is 100% coupling, blue is aseismic creep), and cumulative slip in slow slip events at the Hikurangi margin since 2002 (contours in mm) (Wallace and Beavan, 2010).

Simulations have been made that use a ‘weighting-factor’ for force the slip distribution to be greater in the region that is strongly coupled under the southern North Island³. The general effect of this weighting factor is to increase the impact of the tsunami on Wellington, and reduce the impacts at the other locations.

For this scenario we apply such a weighting factor to our base scenario A, while retaining the magnitude of Mw 8.9. Since scenario A was chosen because it had, by chance, an asperity (patch of large slip) under the southern Wairarapa, the resulting weighted scenario may be viewed as somewhat unrealistic as it has a patch of ~30m slip under southern Wairarapa.

³ The narrow strip of strong coupling close to the trench north of the Wairarapa coast in Figure 2.29 is not well constrained by geodetic data, and not included in the weighting factor used here.

Source segments (Mw 8.9)

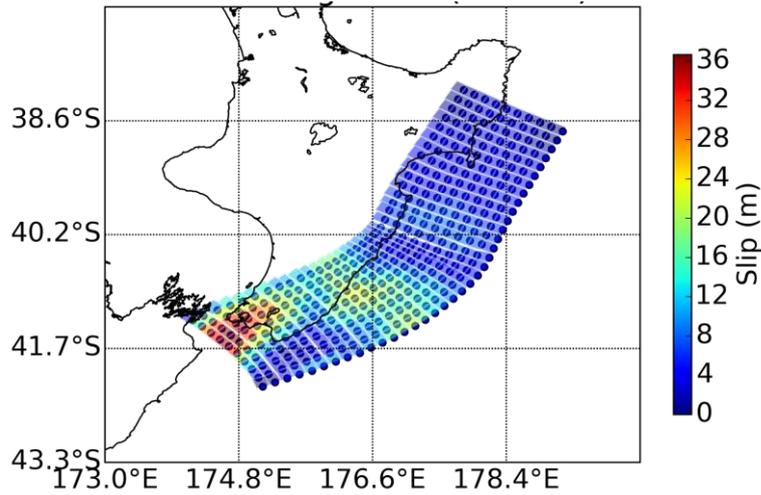


Figure 2.30 Slip distribution on the plate interface for the Mw 8.9 Hikurangi plate-interface earthquake in scenario E.

This results in a large patch of uplift in Cook Strait and southern Wairarapa, and a corresponding strong subsidence in the Marlborough Sounds and on the Kapiti coast.

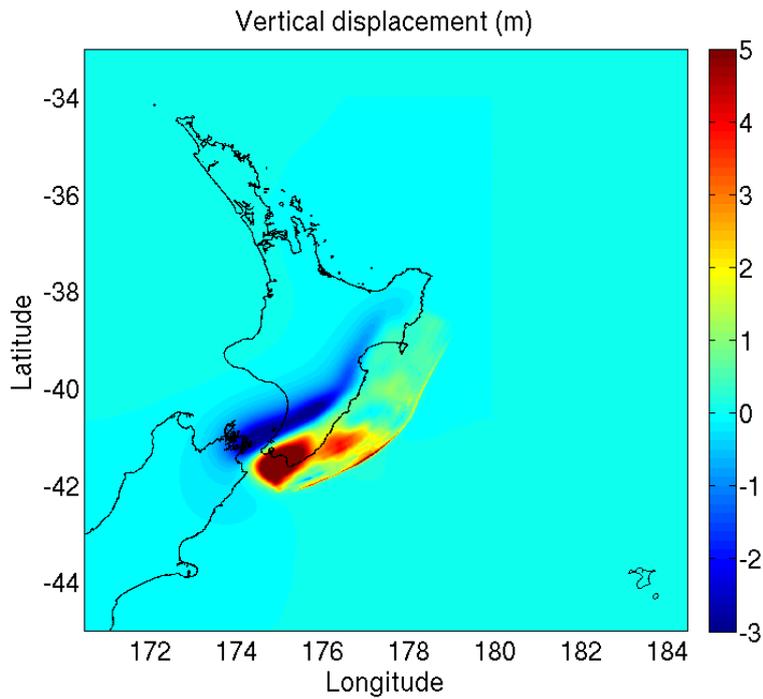


Figure 2.31 Vertical co-seismic displacement for the Mw 8.9 Hikurangi plate-interface earthquake in scenario E.

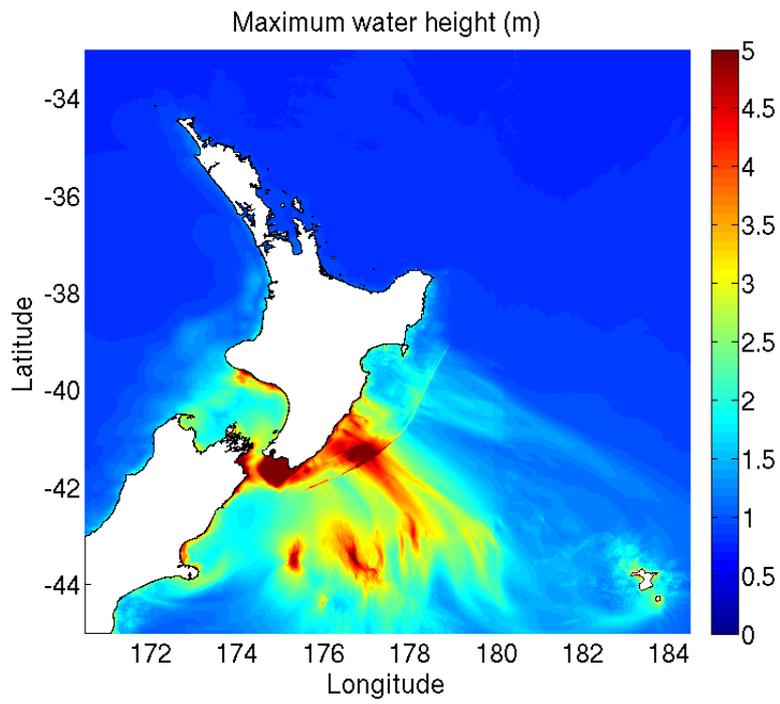


Figure 2.32 Maximum water surface elevation for the Mw 8.9 Hikurangi plate-interface earthquake in scenario E. The colour scale is limited so that water heights above 5m appear as 5m.

The resulting tsunami inundation, in this borderline-unrealistic scenario, is very extensive in Wellington, with the tsunami reaching to the limits of the currently defined tsunami evacuation zone (Figure 2.32).

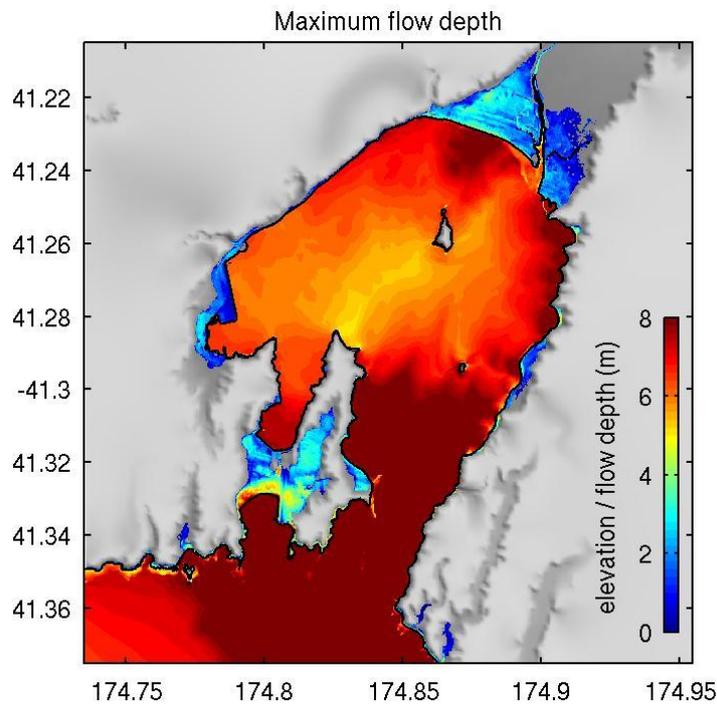


Figure 2.33 Maximum flow depth (height of water above ground level) in Wellington for the Mw 8.9 Hikurangi plate-interface earthquake in scenario A. Offshore the maximum water elevation is shown.

In Napier the tsunami impact is relatively small (Figure 2.34).

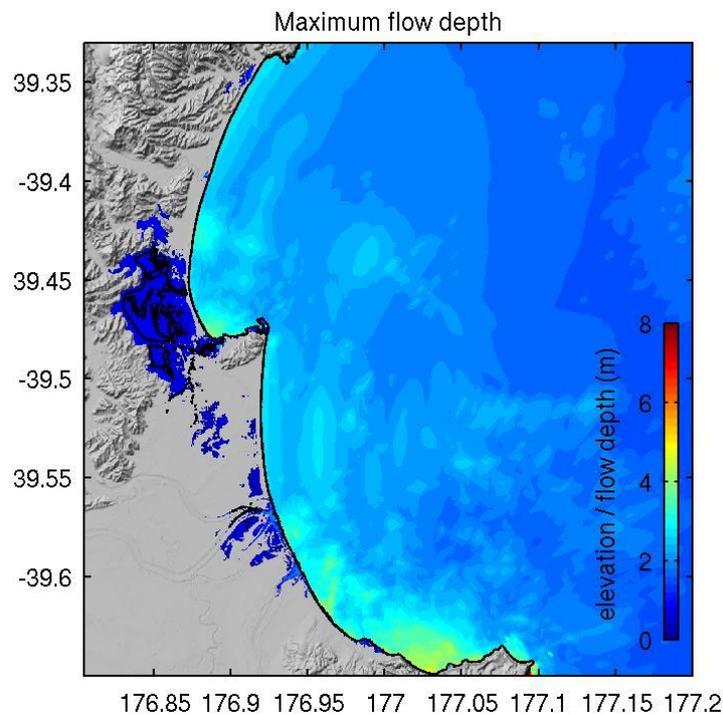


Figure 2.34 Maximum flow depth (height of water above ground level) in Napier for the Mw 8.9 Hikurangi plate-interface earthquake in scenario E. Offshore the maximum water elevation is shown.

In Gisborne the tsunami is quite mild and only inundates low-lying coastal areas (Figure 2.35).

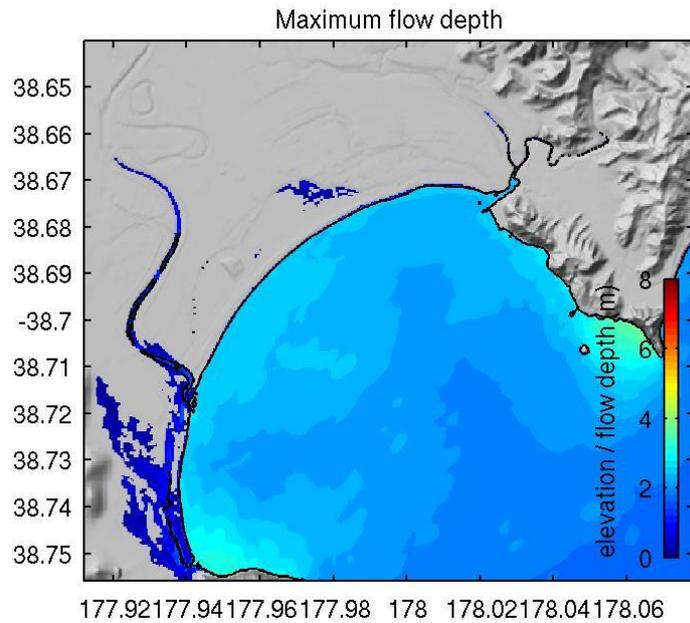


Figure 2.35 Maximum flow depth (height of water above ground level) in Gisborne for the Mw 8.9 Hikurangi plate-interface earthquake in scenario E. Offshore the maximum water elevation is shown.

And in Tauranga the tsunami is very minor (Figure 2.36).

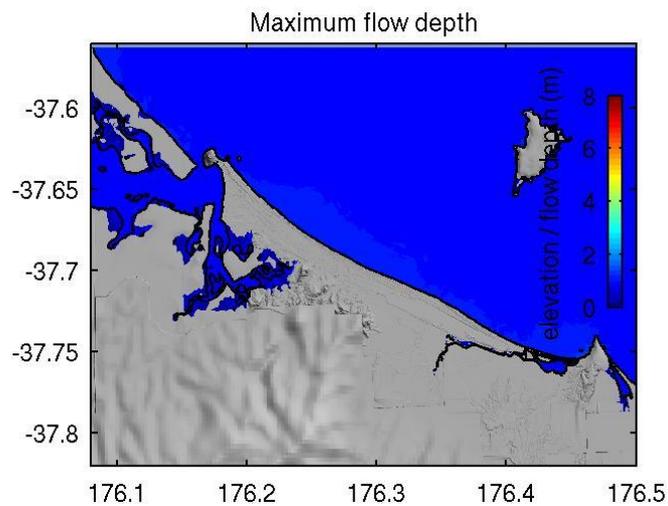


Figure 2.36 Maximum flow depth (height of water above ground level) in Tauranga for the Mw 8.9 Hikurangi plate-interface earthquake in scenario E. Offshore the maximum water elevation is shown.

3.0 GROUND MOTION SIMULATIONS FOR A POTENTIAL M8.9 HIKURANGI EARTHQUAKE

We (Yoshihiro Kaneko and Caroline Holden) compute synthetic ground motions resulting from a potential M8.9 Hikurangi earthquake using open-source seismic wave propagation software SPECFEM3D (Komatitsch and Vilotte, 1998; Komatitsch and Tromp, 1999). Our approach utilises 3D velocity and attenuation models for New Zealand (Eberhart-Phillips et al., 2010; Eberhart-Phillips and Bannister, 2015) and topography and bathymetry of the region. We use a finite fault approach (e.g., Hjörleifsdóttir et al., 2009) where a set of point sources are used to represent the evolution in time and space of slip on the fault ruptured during the Hikurangi earthquake. The same slip distribution as in the base tsunami wave simulation (scenario A) is assumed. The fault surface is 500 km wide by 150 km along dip, ranging roughly from Gisborne to Cook Strait to the south. The assumed rupture velocity is roughly consistent with that of global subduction earthquakes. The same ground-motion simulation approach was previously applied to and validated against the 2016 M7.8 Kaikōura earthquake (Holden et al, 2017). We derive Modified Mercalli Intensity (MMI) values and total shaking duration above MMI of 7 from the ground motion synthetics calculated on a 5km spaced grid.

Figure 3.1 shows simulated long-period (> 2 seconds) ground motions on hard rock for a M8.9 earthquake with the hypocentre located at the centre of the rupture zone, which results in bilateral rupture propagation (referred to as scenario A.1). In scenario A.1, the east coast of the North Island and Wellington would experience intense ground shaking (MMI greater than 8) with the highest shaking of up to MMI of 10. Severe ground shaking (MMI = 7) is expected for the rest of North Island and northern and central South Island. The MMI here is derived empirically from the peak ground velocity at long period (>2 seconds) seismic waves. Closer to the subduction fault, more intense ground motion is expected and further away from the fault, less is expected. The entire east coast of the North Island and Wellington would experience long duration (>30 seconds) of intense ground shaking (Figure 3.1b).

To explore the effect of a hypocentre location (the point where the rupture starts) on resulting ground motions, we consider two additional scenarios (referred to as scenarios A.2 and A.3). In scenario A.2 (Figure 3.2a and Figure 3.2b), the hypocentre is set to be at the northern end of the rupture zone while keeping the other model parameters the same as in scenario A.1. The northern hypocentre leads to unilateral rupture propagation towards the south, causing a strong rupture directivity effect (analogous to the Doppler effect in sound waves). As a result, much of the lower North Island and northern South Island would experience stronger and long-duration shaking than that shown in scenario A.1 (compare Figure 3.1 and Figure 3.2a). Conversely, in scenario A.3 where the rupture is starts at the southern end of the rupture zone near Wellington (Figure 3.2c and Figure 3.2d), the north-eastern North Island including Gisborne would experience stronger and longer-duration shaking than in the other two scenarios. However, the overall ground motions are least severe among the three scenarios because much of the wave energy goes offshore to the northeast.

Overall these scenarios show that there would be intense (MMI greater than 8) ground shaking lasting over tens of seconds across the east coast of the North Island and Wellington. The rest of the North Island and northern South Island would still experience severe ground shaking (MMI greater than 7). Such long-lasting intense ground shaking would be unprecedented in New Zealand, and is a robust common feature among many scenarios. However ground motion intensity at a given location strongly depends on the assumed model parameters, as illustrated in Figure 3.1 and Figure 3.2, and local site effects (influence of local geology on ground shaking amplification) are not accounted for in the present approach.

For the purposes of the impact study used in this report, we have assumed a bilateral rupture (scenario A.1).

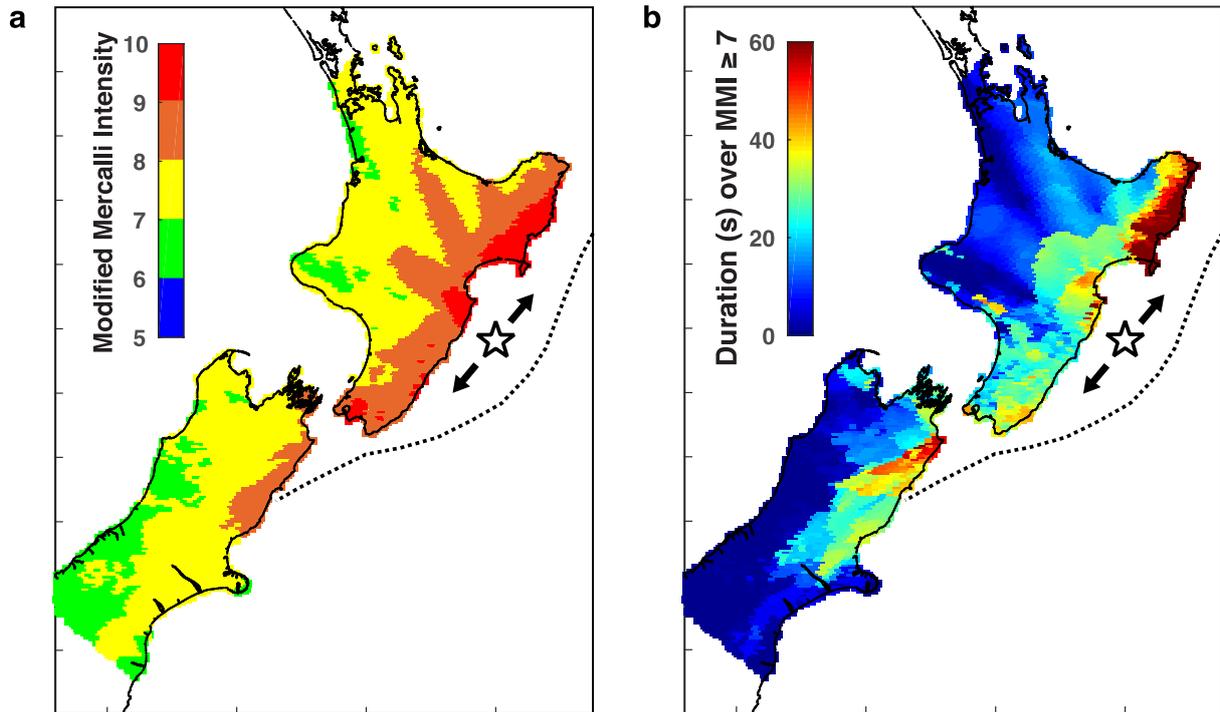


Figure 3.1 Synthetic ground motions from a potential M8.9 Hikurangi subduction earthquake with the hypocentre located at the centre of the rupture zone. (a) A map of Modified Mercalli Intensity (MMI) derived from the magnitude of long-period (>2 seconds) peak ground velocity using empirical scaling relation (Worden et al., 2012). The hypocentre is indicated by a star. Dashed line corresponds to the Hikurangi trench. Arrows show the predominant directions of rupture propagation. (b) Duration of severe ground shaking. Here the duration of ground shaking is defined as the time interval over which intensity exceeds MMI = 7 for the first time until it falls below MMI = 7 for the last time.

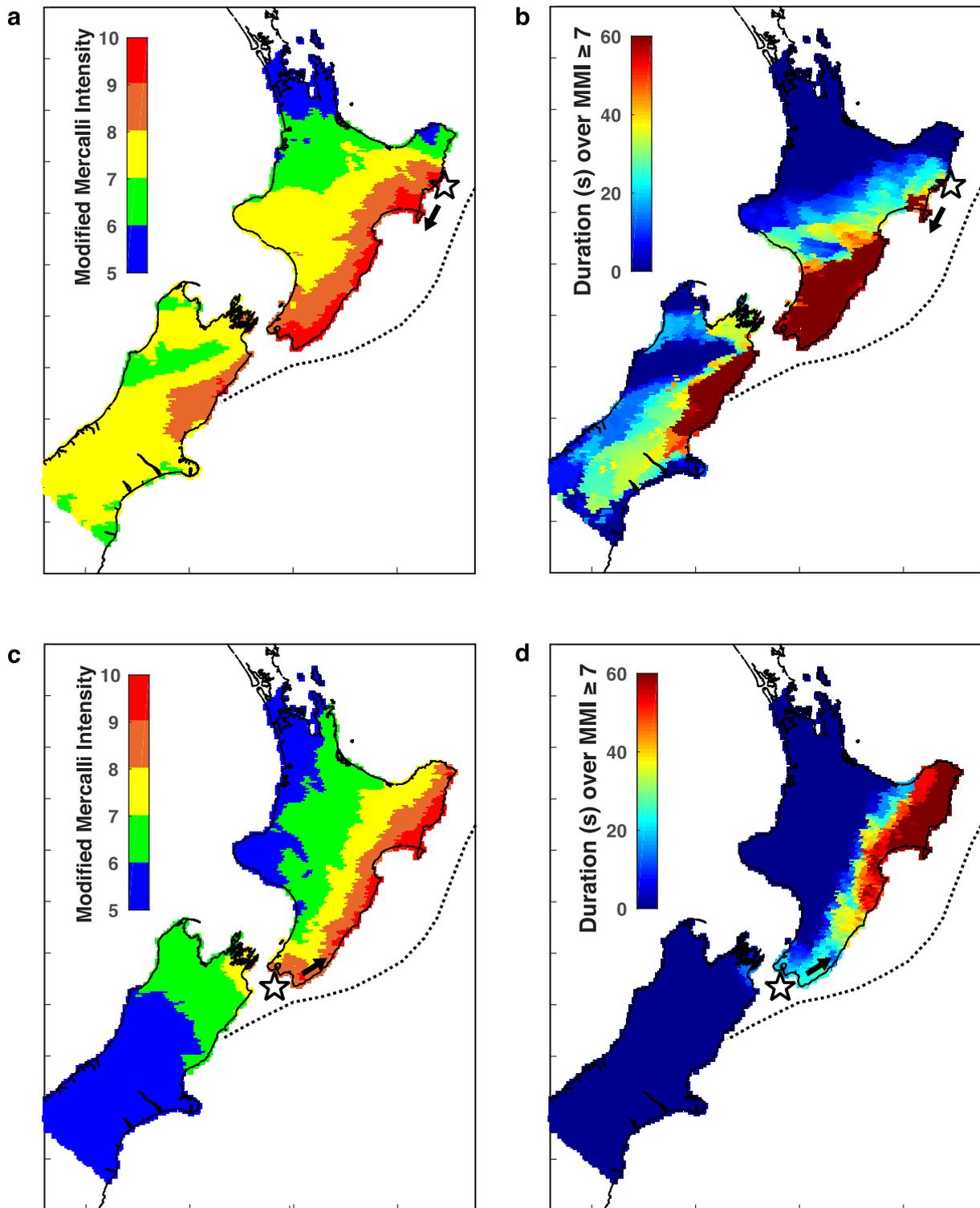


Figure 3.2 Synthetic ground motions from a potential M8.9 Hikurangi subduction earthquake with the hypocentre located at (a, b) the northern and (c, d) southern ends of the rupture zone. (a, c) A map of Modified Mercalli Intensity (MMI) derived from the magnitude of long-period (>2 seconds) peak ground velocity. The hypocentre is indicated by a star. Dashed line corresponds to the Hikurangi trench. Arrow shows the predominant direction of rupture propagation. (b, d) Duration of severe ground shaking.

4.0 PRELIMINARY IMPACTS SCENARIO

The following scenario was developed through a series of ‘expert panel’ meetings between William Power, Julia Becker and ShengLin Lin. It was informed by the tsunami inundation model and earthquake shaking model results presented in Section 2 and 3, and by the ‘Hazard Scenario Workshop Notes’ (HBRC, 2018).

Development of the scenario was entirely qualitative and based solely on the judgment of the expert panel. No additional research or literature review was undertaken. It must be assumed that quantitative loss analysis, or qualitative loss analysis by experts in more specific fields (e.g. landslides or fire risk) will yield significant changes to this preliminary scenario.

Where specific impact locations, or numbers of affected properties or people, are presented in this scenario, the choice is essentially arbitrary within the plausible range of possibilities as judged by the panel. For example, we expect fire to be one of the issues to be faced after a large earthquake, but the specific choice of Newtown in Wellington as the location of a fire is an arbitrary choice.

This approach to developing the scenario, whereby apparently specific details are provided without specific motivations for the choices made, has been used for the purpose of developing an exercise scenario. In particular we stress that the choices of particular locations or quantities must **not** be used as the basis for assessing the risk to any particular property or person and must **not** be used as the basis for any site-specific engineering work.

4.1 Big Picture

Just after 9am on a winter school day, an Mw 8.9 earthquake occurs on the Hikurangi plate boundary. Intense shaking (MMI 8.0–10.0)⁴ occurs along the whole east coast of the North Island between Wellington and East Cape; Marlborough and parts of the Central North Island experience shaking of MMI 8.0–9.0; and most of the rest of the North Island and northern South Island experience shaking above MMI 7.0 (Figure 4.1). Between Mahia and East Cape the duration of intense shaking is very long, with a duration of severe ground shaking of more than 60 seconds (Figure 4.1; see caption for explanation of how this duration is defined).

The shaking sets off many landslides, exacerbated by typically wet winter conditions. The worst affected regions are Wellington and the East Cape, where the landslide impacts are comparable to those in Marlborough after the 2016 Kaikoura earthquake. In the Wairarapa, Hawkes Bay, and the Central North Island, the landslide impacts are not quite as intense but landslides are still widespread on steeper slopes.

The earthquake has also deformed the landscape through uplift and subsidence (Figure 4.2). Large uplifts of 3–4m have occurred along the south Wairarapa coast, meanwhile areas of Hawkes Bay have subsided by 1–2m, and the Kapiti coast has subsided by about 1m.

The deformation extends offshore, and a 50–100km wide and ~600km long strip has been uplifted by 2–3m offshore of the east coast. This deformation initiates a tsunami, which rapidly

⁴ Where MMI is stated with a decimal point this refers to the calculated MMI described in Section 3. Observationally assigned MMI is conventionally given in integer categories and written with roman numerals. The calculated MMI is calibrated to correspond with the observational definition, so that for example a calculated MMI of 8.0–9.0 corresponds to MMI VIII, however site effects are likely to result in localized areas with higher categories of impact, i.e. in this case some areas of MMI IX can be expected to occur where ground amplification is significant.

propagates to the coast. Run-up heights along the east coast are frequently in the 7–10m range, and in some localised places exceed 20 metres.

Tsunami waves batter the coast for several hours (and persist as a ‘marine threat’ for over a day); concurrently a series of large aftershocks begin that will continue for several weeks (and will include several events over Mw 7 that prompt further tsunami warnings and evacuations). The North Island has been experiencing typical winter weather, including moderate to strong northwest winds with occasional showers. A southerly storm is forecast to arrive in 4–5 days’ time.

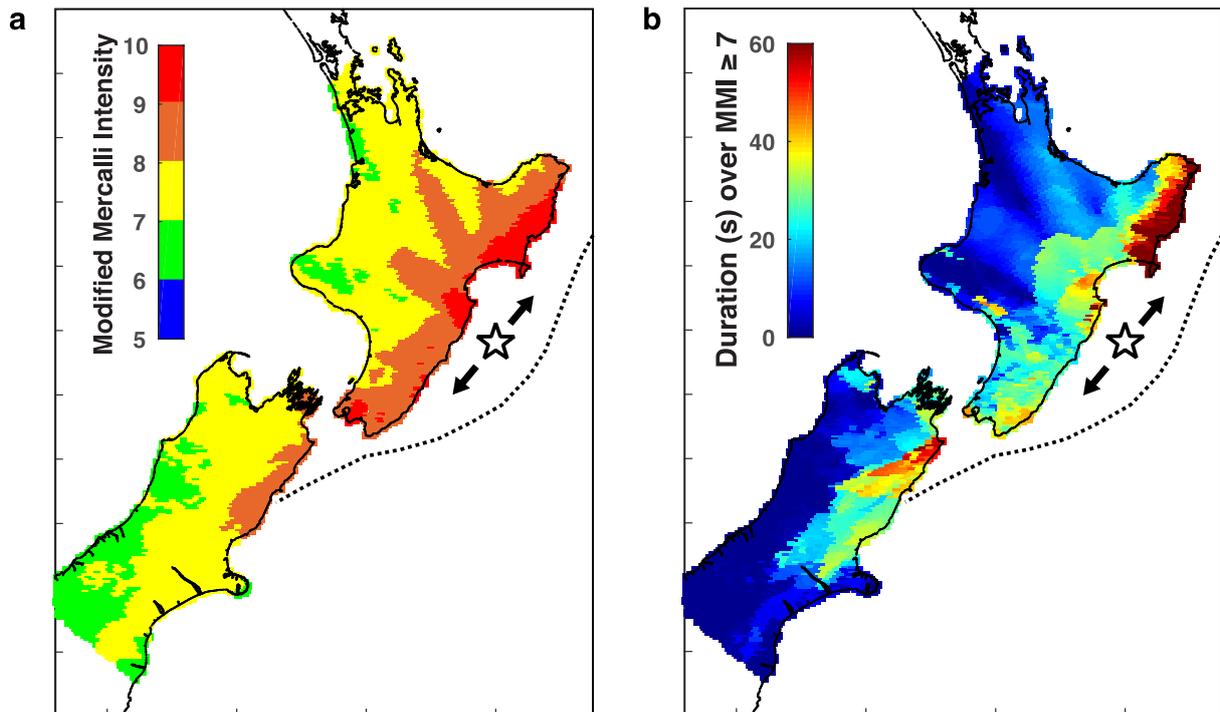


Figure 4.1 Figure 4.1: Synthetic ground motions from a potential M8.9 Hikurangi subduction earthquake with the hypocentre located at the centre of the rupture zone. (a) A map of Modified Mercalli Intensity (MMI) derived from the magnitude of long-period (>2 seconds) peak ground velocity using empirical scaling relation (Worden et al., 2012). The hypocentre is indicated by a star. Dashed line corresponds to the Hikurangi trench. Arrows show the predominant directions of rupture propagation. (b) Duration of severe ground shaking. Here the duration of ground shaking is defined as the time interval over which intensity exceeds MMI = 7 for the first time until it falls below MMI = 7 for the last time. Intense shaking (MMI 8.0–10.0) occurs along the whole east coast of the North Island between Wellington and East Cape, and the duration of the earthquake is particularly long in the East Cape region. (Figure is reproduced from Figure 3.1 for convenience).

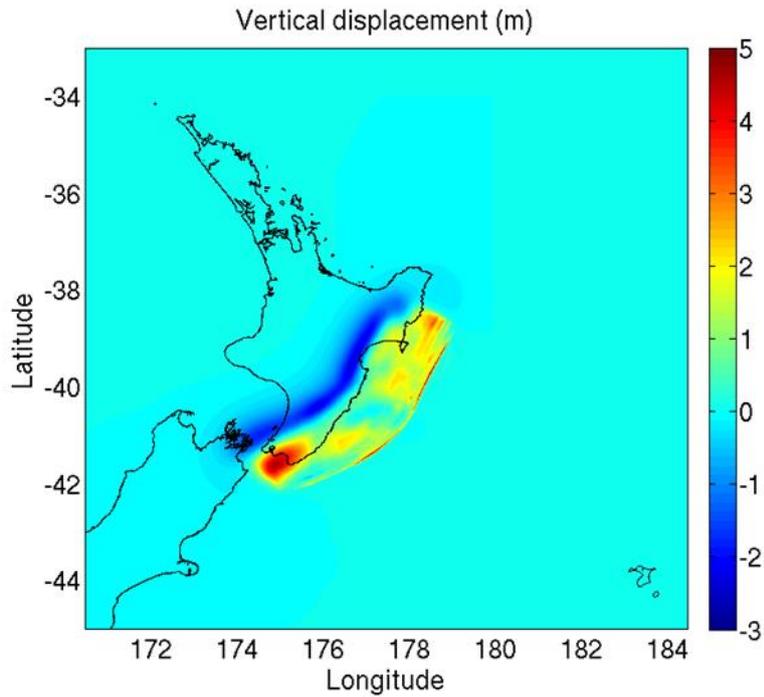


Figure 4.2 Vertical co-seismic displacement for the Mw 8.9 Hikurangi plate-interface earthquake in the base scenario (A). Large uplifts of 3–4m occur along the south Wairarapa coast. Areas of Hawkes Bay subside by 1–2m, and the Kapiti coast subsides by about 1m. (Figure is reproduced from Figure 2.20 for convenience).

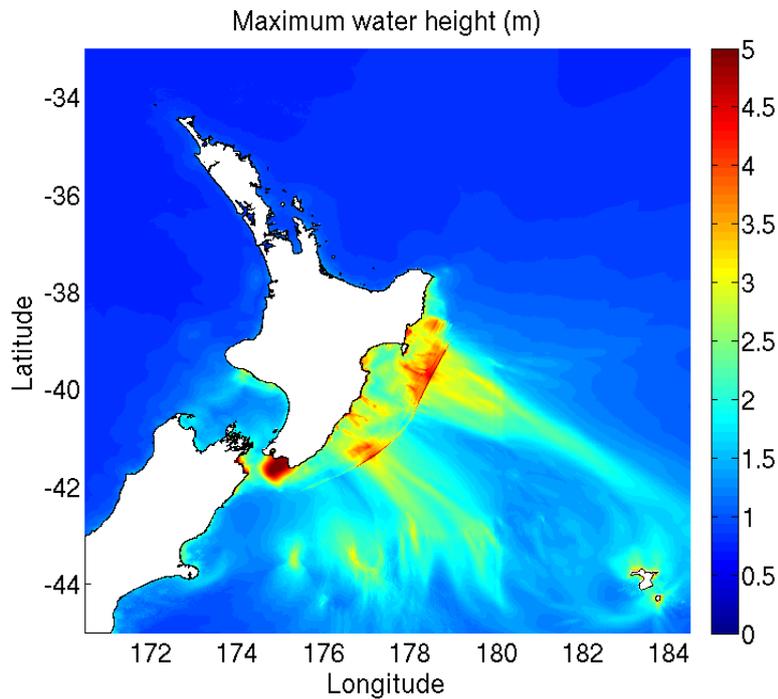


Figure 4.3 Maximum water surface elevation for the Mw 8.9 Hikurangi plate-interface earthquake in the base scenario (A). The colour scale is limited so that water heights above 5m appear as 5m (see footnote 1). (Figure is reproduced from Figure 2.3 for convenience).

4.2 Wellington

At the time of the earthquake it is the end of the rush hour, the streets are busy, and children have just been dropped off at school. The earthquake shaking in Wellington is very intense (MMI 8.0–9.0 in Wellington and the Hutt Valley, MMI 9.0–10.0 in Eastbourne and the Rimutaka Ranges). The high shaking intensity is particularly damaging to vulnerable buildings (e.g. unreinforced masonry buildings, URM), and the impact on the CBD area is comparable to that on the Christchurch CBD following the February 2011 Christchurch earthquake: almost all buildings are damaged, a significant minority (~25%) are damaged beyond the possibility of repair, and about 50 have collapsed partially or catastrophically.

Severe landslides occur in the Wellington region. A large landslide near Karori has engulfed 20 homes, and one near Days Bay has destroyed 15 houses, 10 cars on SH2 were trapped within a landslide between Wellington and Petone. Landslides have isolated Wellington from the rest of the country, as large slides that will take weeks to clear have blocked SH1 between Pukerua Bay and Paekakariki and SH2 in the Rimutakas, and the Paekakariki Hill Road and Akaterawa Hill Road are blocked by multiple smaller landslides. In addition, slips block SH2 between Wellington and Lower Hutt, the road between Petone and Eastbourne, the southbound lanes of SH1 in Nauranga Gorge, and the western portal of the Mt Victoria tunnel.

Liquefaction occurs around Petone, Wellington port and CBD (the waterfront in particular), Evans Bay and Kilbirnie. The liquefaction causes damage to the road network, the pipe network, and to underground cables.

The first tsunami waves reach the south coast of Wellington after 10 minutes and inner harbour areas like Petone after about 30 minutes. The largest in the series of waves occur about 40 minutes post-earthquake at the south coast and about 60 minutes post-earthquake in the inner harbour. Tsunami wave heights reach a maximum of about 7–8 metres at the coast. The extent of inland inundation is mitigated by the 1.5–2m of uplift in the Wellington region; nonetheless the inundation extends up to about 2km inland in Petone (and about 4km up the Hutt River). The hardest hit areas are Lyall Bay and Eastbourne, though there is also significant inundation in Seatoun, Evans Bay, the CBD, Petone and Seaview. The tsunami inundates the southern end of the airport runway, depositing several cm of sand and floating debris.

The intense earthquake shaking leads to a widespread self-evacuation from the tsunami evacuation zones, although some are inevitably caught up in the tsunami. Tsunami casualties were disproportionately distributed among the less-mobile, such as elderly and disabled people, those living in areas where the tsunami arrived most quickly, such as Lyall Bay, and those trapped by rubble or injured by falling glass, for example in the CBD.

Electricity, gas, water, and wastewater are all cut off. It will take approximately 7–10 days to repair local electricity infrastructure damage. A power pylon connecting the Cook Strait cable to the Haywards substation has come down due to land-sliding on steep terrain near Makara. There is also earthquake damage to the Haywards substation and electrical equipment at Oteranga Bay. Essential equipment at both ends of the Cook Strait cable narrowly escaped tsunami damage, though some outbuildings have been swept away at both sites. It seems the cable itself was fortunate to escape damage despite submarine landslides occurring in Cook Strait. A power pylon has also come down on the Rimutaka Hills between Upper Hutt and the Wairarapa, breaking the power connection.

Gas, water and wastewater pipes have experienced widespread damage, and none of these utilities are functional. The water supply will take several months of work to fully restore, and

the wastewater system may be out for a similar length of time. Damage to gas supplies has been linked to several minor fires. In Seaview small boats from the marina have been floated onshore by the tsunami and have caused damage to oil storage tanks and pipes. There are also several minor fires in this area. The telecommunications network continues to operate, and experiences extreme demand, for about 8 hours after the earthquake, at which point the battery power supplies run out.

The Wellington port is unusable due to shaking damage and liquefaction. Two metres of uplift in the harbour heads also make the heads impassable for the largest ships except at high tide.

A large fire has broken out in Newtown. The fire is currently confined to the commercial area between Adelaide Road and Riddiford Street, but strong winds, difficulty finding water to fight the fire, and difficulty of access due to earthquake debris, means that it threatens to spread further afield.

Total casualties caused by the direct earthquake consequences (shaking damage, landslides, tsunami) number about 500 fatalities and 5000 injuries. It is not always possible to identify a single cause of death or injury, but it appears that the casualties are approximately equally divided between shaking damage, landslides and tsunami. Casualties caused by secondary consequences, such as disease and fire, will depend on the emergency response.

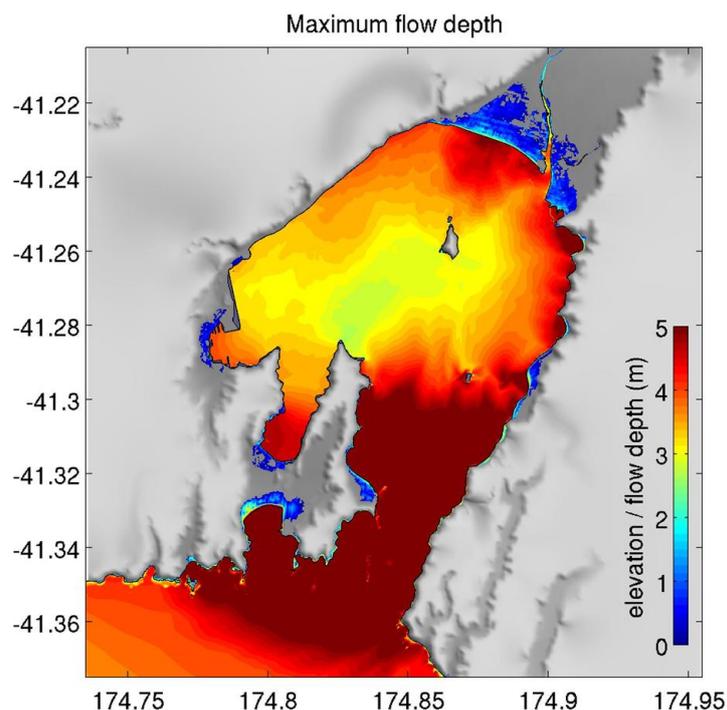


Figure 4.4 Maximum flow depth (height of water above ground level) in Wellington for the Mw 8.9 Hikurangi plate-interface earthquake in the base scenario (A). Offshore the maximum water elevation is shown. This figure is equivalent to Figure 2.4, except that the colour scale has been restricted to a maximum of 5m in order to allow easier evaluation of flow-depth correlated impacts. Flow depths and water heights greater than 5m appear here as 5m.

4.3 Napier

The earthquake shaking in Napier is intense (around MMI 9.0, more specifically MMI 8.0–9.0 to the north of the town centre, and MMI 9.0–10.0 to the south including Hastings, Figure 4.1).

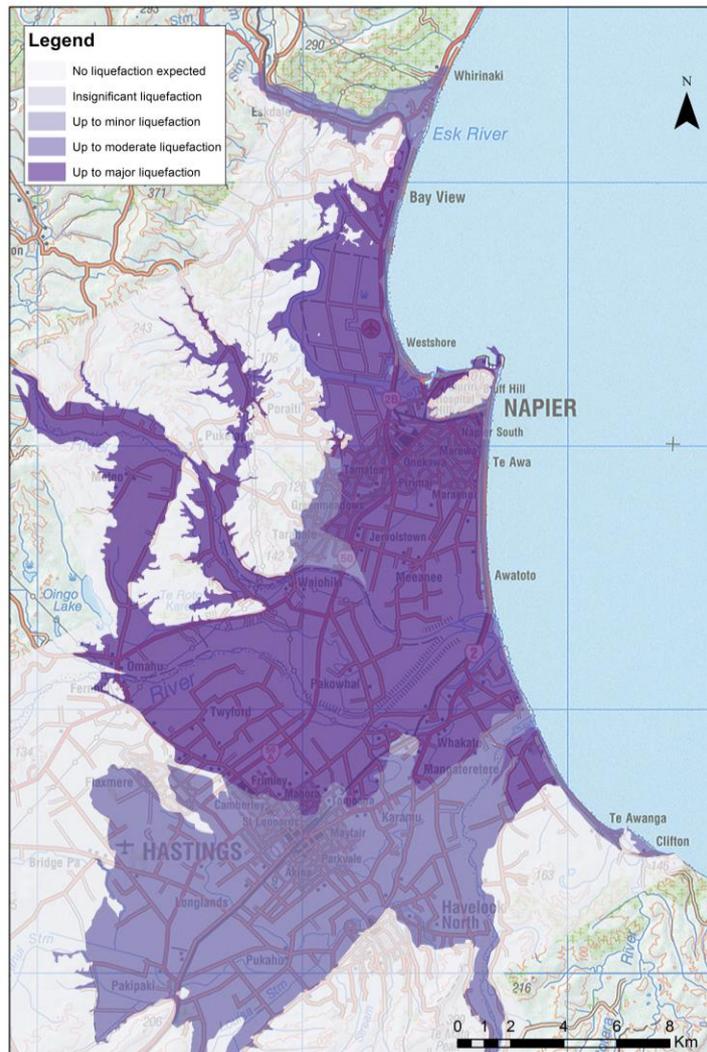


Figure 4.5 Liquefaction severity map for the scenario. Figure is from the 500-year return period liquefaction severity map in Rosser and Dellow (2017), we assume an approximately similar impact for the Hikurangi scenario. The impacts fall into the following categories: **None-to-minor** - no observed liquefaction related land damage through to minor observed ground cracking but with no observed ejected liquefied material at the ground surface; **minor-to-moderate** - observed ground surface undulation and minor-to-moderate quantities of observed ejected liquefied material at the ground surface but with no observed lateral spreading; **moderate-to-major** - large quantities of observed ejected liquefied material at the ground surface and severe ground surface undulation and/or moderate-to-severe lateral spreading.

Within the CBD 10 buildings collapse, and there is minor to moderate damage to most others. Damage to residential buildings is less - they typically remain liveable but still costly to repair.

Liquefaction is widespread in Hawkes Bay (Figure 4.5), there are moderate to very high levels of liquefaction in the CBD and Meanee areas, and to the north around the airport, and minor to moderate liquefaction affects the whole valley floor around Napier, Hastings and Havelock North. There is widespread tilting of buildings on their foundations, and some road damage.

A metre and a half of subsidence occurs in the marshland areas around the airport, and almost immediately strong currents start flowing through the Ahuriri lagoon trying to fill the deficit now that much of this area is below sea level. The subsidence also extends south into Onekawa. Meanwhile, offshore there is widespread uplift of 2–2.5m extending right out to the Hikurangi Trench, and this initiates a series of tsunami waves. Strong and unusual currents start to flow into the Ahuriri lagoon and other tidal river mouths after about 15 minutes. The first major wave starts to arrive at the coast after about 20 minutes, and reaches a peak around 30–50 minutes

after the earthquake⁵ - it causes widespread flooding north and south of Napier. A second wave, which is even more severe to the south of Napier peaks around 140–160 minutes after the earthquake.

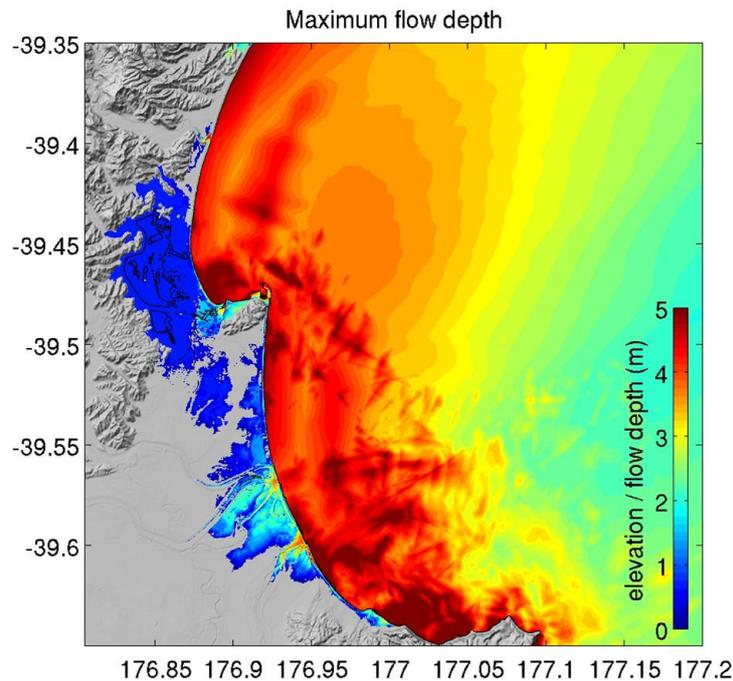


Figure 4.6 Maximum flow depth (height of water above ground level) in Napier for the Mw 8.9 Hikurangi plate-interface earthquake in the base scenario (A). Offshore the maximum water elevation is shown. This figure is equivalent to Figure 2.5, except that the colour scale has been restricted to a maximum of 5m in order to allow easier evaluation of flow-depth correlated impacts. Flow depths and water heights greater than 5m appear here as 5m.

The tsunami waves (particularly the first and second ones) cause severe damage to residential houses in Westshore, Ahuriri, Clive, Haumoana and Te Awanga. There is severe damage to the port, and debris from the port in the form of logs and containers exacerbates the damage to Westshore and Ahuriri. The SH2 bridge at Ahuriri has been badly damaged by the tsunami and the debris within it and cannot be quickly repaired. The SH2B bridge has light damage and can reopen within a few hours of the tsunami abating (i.e. the following day). However, the road itself needs clearing of tsunami debris and frequently experiences flooding at high tides. The SH2 road bridge at Clive is badly damaged and cannot be quickly repaired.

Napier is temporarily cut-off by road. Large slips that will take weeks to clear block the SH5 Napier-Taupo road and the SH2 Napier-Wairoa road. Smaller slips block SH2 between Hastings and Woodville, but these can be cleared in a couple of days. The Pahiataua hill road also has minor slips that can be cleared in a couple of days, opening a route through to Palmerston North.

The railway line to Woodville is badly damaged and will take weeks to repair. The Napier airport is unusable due to tsunami damage, liquefaction and subsidence. The subsidence problem may put the airport out of action permanently as it now floods at every high tide. Smaller planes and helicopters can land at other smaller airfields in Hawkes Bay. No fuel can come in through the damaged port.

⁵ The wave timings, like many other properties of the earthquake and tsunami, are specific to this scenario.

There is extensive damage to water pipes and electricity cables. Telecommunications remain in operation for a few hours (~8 hours) using batteries. An exchange house has been damaged.

Power connections to the national grid have been damaged due to landslides brining down power pylons in the Kawekas between Napier and Taupo and the Rimutakas between the Wairarapa and Wellington. The connection to Palmerston North remains serviceable. There is some damage to an electric substation in Napier that may take some time to repair.

There was a large-scale tsunami evacuation from the CBD to Bluff Hill after the earthquake. Despite some minor landslides on Bluff Hill it was possible for people to get there and find suitable shelter. Westshore residents faced a difficult evacuation, as many were reluctant to cross the SH2 bridge to get to Bluff Hill due to earthquake damage and the strong currents flowing through the river channel before the arrival of the main tsunami, others tried to drive north instead but found the road difficult to travel on due to liquefaction and debris. Residents of Clive and Haumoana also faced a difficult evacuation due to very high levels of liquefaction making movement very slow. Despite widespread evacuation, there are still some casualties, mostly in the Westshore and Clive areas. Emergency vehicle access to both Westshore and Clive is severely limited by tsunami damage to bridges and roads.

In total there are about 200 fatalities, with a majority caused by the tsunami, and about 700 injuries fairly equally split between tsunami and earthquake. About 2000 people cannot return to their homes in the Napier region, most others can return for basic shelter but lack most utilities. In Hastings there is some liquefaction (less than Napier) and there are some collapsed buildings (similar to Napier), but the town is mostly liveable and has intermittent electricity and water supply to most neighbourhoods. Many Napier residents relocate to Hastings once the roads are cleared, to avoid repeated tsunami evacuations caused by aftershocks and to have better access to utilities.

Three days after the earthquake a gastroenteritis outbreak occurs in Hawkes Bay due to unsanitary conditions and the lack of mains water for many people.

4.4 Gisborne

The strength of shaking in Gisborne is very intense (MMI 9.0–10.0). The strength of shaking causes 10–20 buildings to collapse, these are equally split between commercial and residential. Parapet damage is a particular problem. There is widespread moderate to severe damage in commercial areas.

A series of tsunami waves follow the earthquake, initiated by widespread uplift offshore. The first large wave starts to rise after about 10 minutes, and peaks 20–40 minutes after the earthquake. A second larger wave peaks 80–100 minutes after the earthquake. There is widespread tsunami damage to the commercial and residential areas on the south side of the CBD, which has been greatly exacerbated by large numbers of floating logs from the port (which is itself very badly damaged and cannot be used without lengthy and extensive repairs). Further south there is widespread inundation of farmland and marshland around the Waipaoa River, including houses on the outskirts of Manutuke and Muriwai. Commercial sawmills in the area near the Waipaoa River are severely damaged.

Gisborne is physically cut-off from the rest of the country by large landslides on all highways leaving the town, these will all need heavy equipment to clear and several weeks to repair damage. The SH35 road bridge in central Gisborne has been destroyed by the tsunami, as

has the bridge over the Waikanae Creek, however, other bridges in Gisborne remain intact. The airport remains physically usable (but lacks fuel supplies and communications).

The water and wastewater networks are badly damaged by the shaking, and will take weeks to restore these utilities. Local electricity infrastructure is similarly badly damaged, and the connection to the national grid has been severed by a landslide taking down a power pylon between Gisborne and Napier. Communications infrastructure is only lightly damaged, but communications fail from lack of power after about 8 hours running on batteries.

The earthquake has caused about 20 fatalities, and 200 injuries. The tsunami causes about 70 fatalities and 300 injuries, disproportionately distributed among people with reduced mobility. Hospitals and medical centres just about manage to cope. About 1000 people are permanently displaced, mostly due to tsunami damage. Schools in the tsunami zone managed to evacuate in time.

The surrounding countryside is very badly affected by landslides. Several small communities are completely isolated and lacking all utilities. Many landslide dams have been formed.

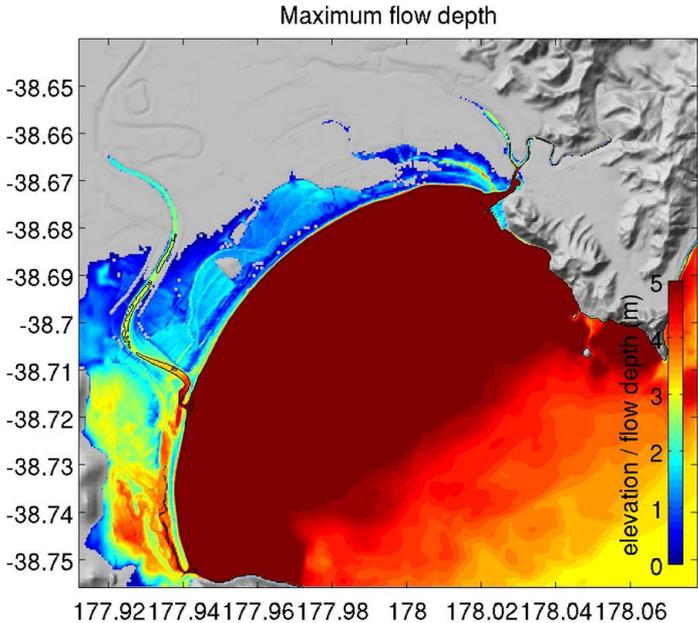


Figure 4.7 Maximum flow depth (height of water above ground level) in Gisborne for the Mw 8.9 Hikurangi plate-interface earthquake in scenario A. Offshore the maximum water elevation is shown. This figure is equivalent to Figure 2.6, except that the colour scale has been restricted to a maximum of 5m in order to allow easier evaluation of flow-depth correlated impacts. Flow depths and water heights greater than 5m appear here as 5m.

4.5 Tauranga

The intensity of earthquake shaking in Tauranga is fairly intense (MMI 7.0–8.0). This is enough to cause some minor structural damage, but no buildings collapse. There is also light liquefaction damage around Mt Maunganui and Papamoa. Lateral spreading is observed along the coastline and the riverbank of Kaituna River. In total there are about 50 injuries and no deaths.

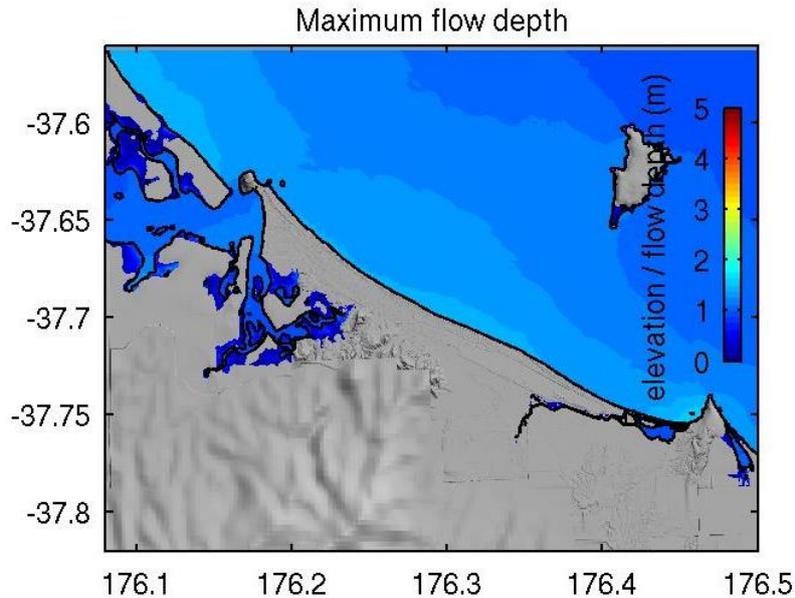


Figure 4.8 Maximum flow depth (height of water above ground level) in Tauranga for the Mw 8.9 Hikurangi plate-interface earthquake in scenario A. Offshore the maximum water elevation is shown. This figure is equivalent to Figure 2.6, except that the colour scale has been restricted to a maximum of 5m in order to allow easier evaluation of flow-depth correlated impacts. Flow depths and water heights greater than 5m appear here as 5m.

A small series of tsunami waves follow, starting about one hour after the earthquake, but these mainly affect areas closest to the shoreline (e.g. dune areas) and damage is light. There is damage to small boats in the marinas, and very minor damage to the port and to railway bridges. The airport is unaffected and operational.

Damage to water, power and communications infrastructure is light and fairly easily repaired over the following few days. Power is out for a few hours everywhere, but restored to 90% of properties within 3 days. There are occasional blackouts as the national grid struggles to balance supply and demand.

There are minor landslides on the roads connecting to Auckland via the Kaimai ranges, but these can be cleared in a few hours.

4.6 Rest of the Country

In Auckland, which experienced shaking of MMI 7.0–8.0, there has been some damage to URM buildings, in particular there are chimney collapses and facades have come down. In total about 200 people have been injured by building damage, there are no deaths.

Power was cut for about 3 hours in the Auckland region, and most other parts of the North Island, while the Huntly power station and the geothermal stations in the Taupo Volcanic Zone were checked for damage. Since then there have been intermittent blackouts as the national grid struggles to balance supply and demand, particularly due to lack of power coming from the South Island.

Ports and airports in Auckland, Tauranga, Palmerston North and Christchurch, must cope with additional flights and ships that are no longer able to land or dock at their original destinations.

The ferry service between the North and South Islands has been suspended due to the damage to the port at Wellington. In the South Island SH1 in Marlborough has been closed by slips.

Helicopter operators are very busy with ferrying vulnerable people as well as helping to restore damaged infrastructure.

Within the area with widespread tsunami evacuations many people are struggling to re-unite with other family members, and wishing to re-enter the tsunami zones to look for pets.

In total the casualties from direct impacts (shaking, tsunami, landslides) number about 1000, with about ten times as many injuries. Secondary impacts such as fire and disease threaten to significantly add to these totals.

5.0 SUMMARY

We have presented modelling results for an Mw 8.9 southern Hikurangi earthquake and tsunami. In addition to the results describing the base scenario chosen at the 'Hikurangi Response Plan Hazard Scenario Workshop', we also present results of tsunami modelling for a range of alternative scenarios, demonstrating that there is a broad spectrum of possible impacts at our coastal cities in future Hikurangi earthquakes of this magnitude. The sensitivity of shaking intensity and duration to the earthquake hypocentre location is also demonstrated.

A preliminary impact assessment was developed for the base scenario, assumed to occur at 9am on a school day in winter. This qualitative assessment considered the tsunami and shaking impacts, as well as other related hazards such as landsliding. The assessment was developed at a series of 'expert panel' meetings, and takes the form of an 'impact scenario' to be used for planning exercises. There are important limitations to the method of assessment used, and the results generated in this way must **not** be used as the basis for assessing the risk to any particular property or person and must **not** be used as the basis for any site-specific engineering work.

A striking feature of the scenario is the wide geographical spread of damage than can occur in such a large earthquake, which will present serious challenges for how to restore normal living conditions.

6.0 ACKNOWLEDGEMENTS

The tsunami scenarios presented in this work are a re-use of tsunami modelling results from a study previously conducted for the Earthquake Commission (Horspool, 2016). We acknowledge the use in the EQC study of bathymetric data for Wellington Harbour surveyed by NIWA and co-funded by Greater Wellington Regional Council and the Department of Conservation. We also acknowledge Xiaoming Wang for his help in preparing the tsunami modelling figures, and David Burbidge and Finn Scheele for reviewing this document.

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APPENDICES

A1.0 APPENDIX 1: NINE DIFFERENT RANDOMISED SLIP DISTRIBUTIONS

The earthquake and tsunami scenarios presented in Section 2.0 were chosen to highlight specific features. In order to give a more representative sample of the range of effects that non-uniform slip can give, in Figure A1.1 we show maximum water elevation plots for nine different randomly sampled slip distributions, all are possible scenarios for an Mw 8.9 southern Hikurangi earthquake. Scenario A, the base scenario is the middle scenario, and Scenario C is the top right scenario.

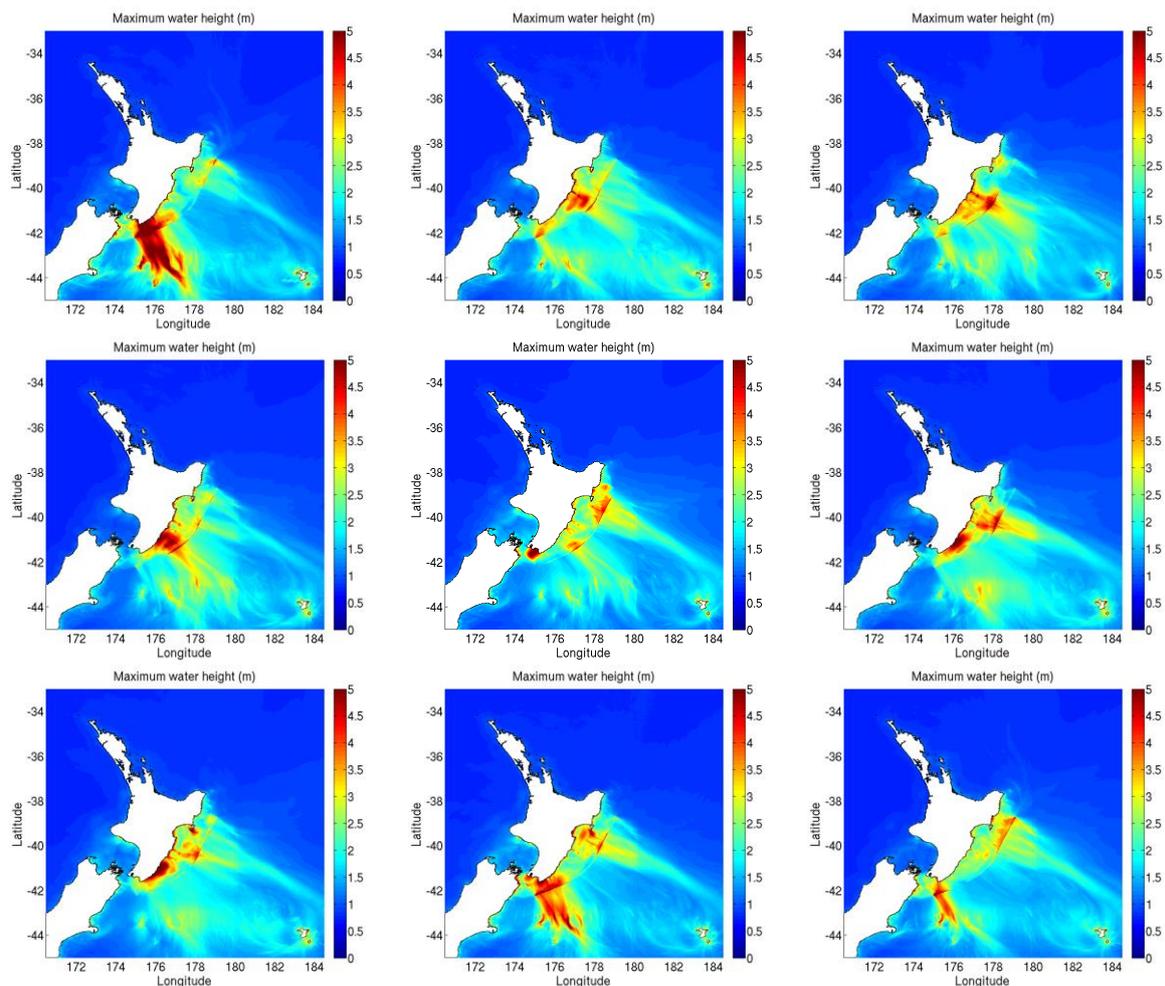


Figure A1.1 Maximum water surface elevation for nine different randomly-sampled slip distributions, all represent possible variations on an Mw 8.9 southern Hikurangi earthquake. Scenario A, the base scenario is the middle scenario, and Scenario C is the top right scenario.