APPENDIX 7: ADDITIONAL HAZARD MODEL INFORMATION

This appendix provides additional information on parameters and assumptions used in the tsunami hazard model.

A7.1 SUMMARY TABLE OF UNCERTAINTIES AND VARIABILITIES

The treatment of uncertainty and variability in the tsunami hazard model is quite complicated. Table A 7.1 was constructed to provide a quick summary and pointers to further information.

Table A 7.1 Summary table of uncertainties and variabilities.

	Uncertainties	**Variabilities**
Earthquake Magnitude-Frequency	Subduction zones: Maximum magnitudes, B values, coupling coefficients Crustal Faults: Characteristic magnitudes, recurrence intervals Section 6.4; Appendix 7.2	Sequence of earthquake moment magnitudes (M_W) Section 6.4; Appendix 7.2
Earthquake locations within source regions		Local subduction zones: source location Regional and Distant Subduction zones: effect of varying location is represented in σB Appendix 7.4
Geophysical properties at tsunami source	Uncertain fault geometry (e.g. dip and strike angles), uncertain material properties (e.g. rigidity). Section 6.5; Appendix 7.3	Non-uniform slip distribution, variations in rupture dimensions. Section 6.5; Appendix 7.3
Tsunami Modelling	Unknown biases in tsunami models. For crustal faults: uncertainty in equivalence of maximum ‘tsunami height’. Uncertainty/errors in bathymetric data. Appendix 7.3	

A7.2 GENERATION OF SYNTHETIC CATALOGUES

Sampling of epistemic uncertainty in Magnitude-Frequency distributions

Epistemic uncertainty in the characteristic magnitudes of local crustal faults from the New Zealand Seismic Hazard Model (NZSHM) is modelled as normally distributed with a standard deviation of 0.1 magnitude units (M_W), and the adjusted characteristic magnitude is truncated to lie between the minimum and maximum moment magnitudes MWMN and MWMX, as specified in Appendix 4.

Epistemic uncertainty in the characteristic magnitudes of tentatively identified local crustal faults (Appendix 5) is modelled as normally distributed with a standard deviation of 0.2 and truncated at ±0.4 magnitude units.

Epistemic uncertainty in the magnitude-frequency distribution of subduction zone tsunami sources is represented by sampling from the parameters in Table A 3.1. A uniform random distribution is assumed between the minimum and maximum tabulated values. The sampled values of Mmax and B-value enter directly into the equation for a truncated Guttenberg-Richter distribution. The other parameters are used to determine the A-value via a process of balancing the overall seismic moment release rate.

Variability in the magnitude of earthquakes

Variability in the magnitudes of earthquakes on local crustal faults is modelled as normally distributed with a standard deviation of 0.1 magnitude units, and the sampled magnitude is truncated to lie between minimum and maximum moment magnitudes MWMN and MWMX as specified in Appendix 4. In the NZSHM earthquakes with magnitudes below MWMN are regarded as part of the background seismicity, here it is assumed that earthquakes below MWMN make a negligible contribution to the tsunami hazard.

Variability in the magnitudes of earthquakes on tentatively identified local crustal faults (Appendix 5) is modelled as normally distributed with standard deviation of 0.1 magnitude units, and the sampled magnitude is truncated to lie within ±0.4 magnitude units of the corresponding tabulated characteristic magnitude in Appendix 5.

Variability in the magnitudes of earthquakes on subduction zones is modelled by random sampling from a truncated Gutenberg-Richter (GR) distribution, parameterised by A-value, B-Value and Maximum magnitude as described in the previous section. The truncation of the GR distribution is implemented as a sharp truncation in the incremental GR distribution, which leads to a gentle tapering off in the cumulative distribution (see Chapter 3 of McGuire, 2004). Note that this may not be a good representation of subduction zones like Cascadia (Section 5.1.1.3) that experience low seismicity in the intervals between large (M_W>8) earthquakes, many of which are whole-margin events.

Global maximum magnitude cut-off

In epistemic sampling of the maximum magnitude of subduction zone tsunami sources, a global upper bound on Mmax is set at M_W 9.7, slightly larger than the largest historically observed earthquake globally. This global cut-off only affects those subduction zones where Mmax-max is greater than 9.7 in Table A 3.1 (Alaska, Peru, Kuril-Kamchatka).

Minimum magnitudes for subduction zone earthquakes

In constructing the synthetic catalogues of subduction zone earthquakes we do not consider earthquakes of less than the following thresholds:

Distant earthquakes, M_W 8.5

Regional earthquakes, M_W 8.0

Local earthquakes, M_W 7.5

Below these magnitudes it is assumed that the tsunami generated are too small to significantly influence the tsunami hazard curves.

A7.3 EXPLANATION AND DERIVATION OF COEFFICIENTS DESCRIBING VARIABILITY AND UNCERTAINTY USING AN 'EFFECTIVE MAGNITUDE' APPROACH

There are several areas of uncertainty and variability that ought to be included in a tsunami hazard analysis. A complete Monte-Carlo analysis of all factors for all sources would be computationally very demanding, as well as challenging to construct. The approach taken here, which is original to this report, is to approximate the effects of these variables through an 'effective magnitude'. The idea is that variations and uncertianties in the parameters that control tsunami generation have an effect on reducing or enhancing the tsunami height which, from the point of view of an observer at one section of the coast, are approximately equivalent to an increase or decrease in the magnitude of the source earthquake relative to a baseline model.

The parameters used for this uncertainty/variability modelling are tabulated in Table A7.2. The parameters describe the standard deviations of (zero-mean) normally distributed random variables that are added to the synthetic earthquake catalogue magnitudes. The interpretation and assumed values of these parameters will be described below. It is useful to know that, when using Abe's (1979,1995) equations to estimate tsunami heights, a 0.1 increase in 'effective magnitude' is equivalent to an increase in tsunami height of 26%, a 0.2 increase is equivalent to 58%, and a 0.3 increase is equivalent to 100% (i.e., a doubling in height).

Table A 7.2 Standard deviations associated with stochastic adjustments to the synthetic catalogue to create a catalogue of 'effective magnitudes'. The fault-specific uncertainty covers uncertainties that are specific to the modelling of each fault, while the method bias covers uncertainties that cause a systematic bias across all faults. Units are in the M_W scale.

	Local Crust Fault (empirical model)	**Local Subduction Zone (numerical model)**	**Distant Subduction Zone (numerical model)**
Variability (e.g. non-uniform slip) σ_v	0.25	0.25	0.1
Modelling uncertainty (fault specific) σ_u	0.2	0.1	0.1
Modelling uncertainty (method bias) σ_b	0.14	0.05	0.05

The application of these parameters, which describe the uncertainties and variabilities that affect tsunami heights, by using them to estimate an ‘effective magnitude’ can be described as follows:

$$Mw_{ijk}(effective) = Mw_{ijk} + \sigma_v N(0,1)_{ijk} + \sigma_u N(0,1)_{jk} + \sigma_b N(0,1)_k$$ **Equation A 7.1**

where i represents individual earthquakes on fault j, described in synthetic catalogue k. N(0,1) represents a number sampled from the normal distribution with mean of zero and standard deviation of 1. The subscript to N(0,1) describes the set over which individual samples are made, e.g., $N(0,1)_{jk}$ is sampled for each fault in each catalogue, but has the same value for all earthquakes on a particular fault in a particular catalogue.

The parameters describing variability represent the effects of variations in earthquake properties, other than magnitude, that vary from event to event even in the same location. Most prominent among these is the effect of ‘variable slip’, which research by Geist (2002) and Mueller et al. (2012) have shown to have a significant effect on tsunami heights. This parameter describes a random difference to the synthetic catalogue magnitude which is independently sampled from a zero-mean normal distribution for every earthquake.

The assumed values for these parameters are best explained starting with the case for local subduction zones. In the work of Geist (2002) the peak nearshore tsunami amplitudes varies over a factor of approximately three from lowest to highest, when local subduction zone slip distributions are randomly sampled. Assuming this variation corresponds to ±1σ of variation, we conclude that σ is approximately 0.24. In the preliminary work of Mueller et al. (2012), an increase in magnitude of 0.5 was needed to cover the total spread of inundation from 60 events with randomly varying slip. Assuming this corresponds to 2σ of variation (since ~98% of events do not exceed the inundation of an event with magnitude 0.5 units higher), we conclude that σ is approximately 0.25. Hence the value assumed for this parameter was σ_v =0.25.

In the absence of studies, we have assumed the same level of variability, i.e., 0.25 magnitude units, for other local faults; further research is required to produce a better estimate. The variability caused by non-uniform slip in distant and regional earthquakes also requires more research. It is generally assumed that the role of non-uniform slip in these events is minor or negligible, though this may perhaps not be the case if the slip distribution affects the direction of the ‘beam’ of the main tsunami energy, or if the down-dip distribution of slip affects the depth of water in which the tsunami is generated. Variations in the length and width of rupture may also have an influence, particularly if the sudbuction zone has changes in strike. For now it has been assumed that the effect is small compared to that of local events and therefore σ_v=0.1 was used.

Fault-specific uncertainty concerns fault properties that are fixed in time, but are not known with full accuracy. Examples include aspects of fault geometry, such as dip and rake angles, as well as uncertainty in elastic properties such as rigidity[23]. Titov et al. (1999) examined the sensitivity of tsunami amplitudes in Hawaii to variations in dip and rake angles of subduction earthquake tsunami sources in the Alaskan-Aleutian Arc. Over realistic ranges of uncertainty in those angles they found relatively modest variations in tsunami amplitude of 20-30%, hence our assumed value of σ_u=0.1 for these parameters as applied to distant and local subduction zones. Uncertainty in estimated tsunami heights as a consequence of fault properties is expected to be greater for tsunami generated by faults not on the subduction interface because: (a) the Abe equation used to estimate the tsunami heights does not include any variables other than magnitude and distance, and (b) there is generally a greater variation in fault properties and earthquake mechanisms among non-subduction inteface earthquakes. Hence σ_u=0.2 was assumed. These parameters describe a random difference to the synthetic catalogue magnitude which is independently sampled from a zero-mean normal distribution for every fault, but which is given the same value for every earthquake on the fault.

Modelling bias consists of systematic bias in our modelling methods that potentially affect all tsunami height estimates made with a technique. In the case of subduction zone modelling this could represent any tendency for the COMCOT model to systematically under- or over-estimate tsunami heights. Systematic deviations from the Okada method for calculating seabed displacements would fall into this category too. As these methods are not known to have strong biases, a relatively low σ_b=0.05 has been assumed. The potential bias in the Abe formula used for local non-subduction sources has two identified components: (a) the possibility that New Zealand conditions represent a systematic difference in elastic properties (see section A7.4), and (b) the uncertainty over the relationship between how the maximum tsunami height is defined where hydrodynamic modelling is used and how it is interpreted in the local source Abe equation (see Section 6.6). Each of these effects were estimated as σ_b=0.1, but as they are independent a combined value of σ_b=0.14 was assumed. These parameters describe a random difference to the synthetic catalogue magnitudes which is independently sampled for each catalogue, but which is given the same value for every event of the same category (i.e., Local crust, Local subduction zone, or Distant subduction zone) within a catalogue.

The effect of inaccurate bathymetric data could either be described as a fault-specific uncertainty, or as a modelling bias, depending on where the errors occur. Errors close to the coast for which the hazard curve is being calculated may act as a general bias, while those that are on the tsunami propagation paths only for certain sources may be fault-specific. More research is required to understand and quantify these effects.

[23] The treatment of rigidity as an uncertainty is problematic in the tsunami hazard model. For this study a rigidity of 50 GPa, typical of hard rock, has been assumed throughout. Shallow dipping subduction zones, such as Hikurangi and parts of the Kermadec Trench, may have lower rigidities at shallow depths (see Bilek and Lay, 1999). The effect of a lower rigidity on an earthquake of fixed magnitude is to increase its tsunami generation potential (this is one possible explanation for 'tsunami earthquakes', such as the 1947 Gisborne events; see Section 3.2), but it will also reduce the frequency with which such earthquakes occur in our model based on plate-rate balancing. As these two effects tend to counteract each other in the hazard curves this effect is not well described by the current uncertainty model. Ideally a location-specific rigidity model could be used—this is a topic for further research.

A7.4 ESTIMATION OF TSUNAMI HEIGHTS

Interpretation of 'maximum tsunami height'

The maximum tsunami height within a coastal section is the maximum at any offshore point in the area over the duration of the simulation. The time periods of the simulations are typically 30 hours for distant sources, 24 hours for regional sources, and 12 hours for local sources, and are intended to be sufficiently long to capture the largest waves in most situations likely to contribute to the hazard curves (the quality of simulation results degrades over time elapsed since the first wave arrivals, hence running the models for longer would not necessarily improve the results).

Faults that are partially on-shore

The following set of crustal faults, labelled with the Fault Name and NZSHM_Number (see Appendix 4), were identified as extending a significant distance onshore for at least half of their length. In the estimation of tsunami heights for earthquakes on these faults, it was assumed that only half of the seismic moment release contributes to tsunami generation, i.e., the effective magnitude was reduced by 0.2 magnitude units.

WairarapNich_345, AwatNEVerCl_379, AwatNEVer_380, Matata_163, WhakataneN_158, WaimanaN_166, Waikaremoana_165, Urewera3_162, Otaraia_368, JorKekCha_373, JorKekNeed_374, Hundalee_405

Estimation of tsunami heights – Distant and Regional subduction zones

Models from the New Zealand tsunami forecast database (Power, unpublished; an earlier version of this database is described in Power and Gale, 2011) were used to fit parameters of a semi-empirical model (Abe, 1979, 1994). The form of the empirical equation is:

$$Ht = 10^{M_W - B_{ij}}$$ **Equation A 7.2**

where the coefficients B_{ij} (and their standard deviations σB_{ij}) were estimated using the data from the forecast models. i represents each particular source region, and j represents each particular coastal zone. M_W is the moment magnitude.

Abe (1979, 1994) calculated coefficients B_{ij} using historical data, but given the sparsity of New Zealand historical data, the approach used here is to fit these coefficients using modelled scenario data.

For this purpose 312 models were used from the forecast database, which for distant sources includes simulations at M_W 8.7, 9.0, 9.3, located at intervals of 400 km around the subduction zones of the Pacific Rim. Regional events were similarly modelled at M_W 8.1, 8.4, 8.7, 9.0, 9.3 and 400 km intervals. Source models for distant earthquakes in the forecast database were based on the subduction zone unit sources given by NOAA (see for example, Tang et al., 2010). Regional earthquake sources were modelled using additional unit sources compiled within GNS Science.

Rupture dimensions were typically 1000 x 100 km for M_W9.3, 600 x 100 km for M_W9.0, 400 x 100 km for M_W8.7, 200 x 100 km for M_W8.4, and 200 x 50 km for M_W8.1. Variations around these dimensions were made for scenario events located near the ends of subduction zones. In reality, variations in the dimensions of rupture vary considerably even between earthquakes of the same magnitude, and this affects the degree of tsunami generation; this variation contributes to the variability coefficients in Table A 7.1.

Once the coefficients B_{ij} and σB_{ij} have been determined, estimation of wave heights proceeds using equation A 7.2, specifically:

$$Ht = 10^{M_W - (B_{ij} + \overline{\sigma B_{ij}})}$$ **Equation A 7.3**

where $\overline{\sigma B_{ij}}$ is randomly sampled from a normal distribution with mean of zero and standard deviation σB_{ij}. This corresponds primarily to the variability in tsunami height associated with different earthquake locations within the source region.

Abe (1979) successfully calibrated and applied equation A 7.2 in the context of earthquakes spanning a wide range of magnitudes (large events such as the 1960 M_W9.5 Chile earthquake and the 1960 M_W9.2 Alaska tsunami were among those used for calibration), suggesting that A7.2 is suitable for use over a broad range of tsunamigenic magnitudes.

Estimation of tsunami heights – Local subduction zones

Tsunami heights from the local subduction zone sources, i.e., Hikurangi, Kermadec and Puysegur, were estimated by searching for the closest analogue in a pre-calculated catalogue and scaling the results to accommodate the difference between the synthetic catalogue earthquake magnitude and the magnitude of the closest analogue scenario.

The pre-calculated catalogue of tsunami scenarios consisted of a scenario for rupture of the whole subduction margin, two half margin scenarios, and three one-third margin scenarios. Due to the length of the Kermadec Trench, six scenarios, each spanning one-sixth of the trench, were also used for that source. The magnitudes of these scenarios are tabulated in Table A7.3

Table A 7.3 Magnitudes of scenario events used for modelling of local subduction zones.

	Hikurangi	**Kermadec**	**Puysegur**
Whole margin	9.0	9.3	9.0
Half margin	8.6	9.0	8.6
Third of margin	8.3	8.7	8.3
Sixth of margin	-	8.3	-

For any given local subduction zone earthquake in the synthetic catalogue, the earthquake location was uniformly randomly distributed across the margin, i.e., if the magnitude was closest to that of a one-third of margin event, the wave heights were equally likely to be modelled by scaling any one of the three corresponding scenarios. This amounts to an assumption that the subduction zones are homogeneous in the spatial distribution of earthquakes. The Hikurangi margin, however, is known to have strong variations in geophysical properties along its length, which may well correlate with the distribution of large earthquakes; if so, this would be in contradiction to this assumption used here. Further research is therefore required to better understand and quantify these relationships, and to incorporate the heterogeneity of the local subduction zones into the tsunami hazard model.

Once the appropriate scenario is selected the estimation of tsunami heights proceeds using:

$$Ht = 10^{M_W - (B_{ij} + \overline{\sigma B_{ij}})}$$ **Equation A 7.4**

where B_{ij} are estimated using only the results from the chosen analogue scenario. As σB_{ij} cannot be estimated from a single scenario, a fixed value of 0.1 has been assumed (this is approximately the average value of σB_{ij} found for the distant and regional sources), further research is needed to better quantify this parameter.

Note that this scaling is consistent with Abe's (1979, 1995) empirical equations for local and distant source tsunami.

The approach to estimating tsunami heights for local subduction events by scaling the catalogue is not without limitations. In particular, the discretization of events in the catalogue into adjacent equal size ruptures may produce inconsistencies around the borders between the modelled events. Improvements to this methodology should probably accompany research into the variation in geophysical properties along the length of the subduction zones.

Estimation of tsunami heights – Local crustal and outer rise faults

Estimation of tsunami heights from the local non-subduction zone faults follows the methods of Abe (1995). The tsunami height is estimated as:

$$Ht = 10^{M_W - \log D - 5.55 + C}$$ **Equation A 7.5**

where M_W is the earthquake moment magnitude, D is the distance between the fault and the coastal section, and C is a constant.

If $D < 10^{\frac{M_W}{2} - 2.25}$ (when the coastal section is approximately above the fault plane) then

$$Ht = 10^{\frac{M_W}{2} - 3.3 + C}$$ **Equation A 7.6**

is used instead.

The constant C is taken here to be 0.1; in Abe's work C is either 0.0 or 0.2 according to the specific geophysical properties of the location, here this uncertainty is instead expressed using the 'effective magnitude' approach described in the next section.

Because equation A 7.5 uses only magnitude and distance from the fault to determine tsunami height, it can give poor results in situations where the bathymetry is unfavourable for tsunami propagation. For instance, equation A 7.5 may overestimate tsunami heights at the Kapiti coast caused by earthquakes near the Wairarapa coast, since the throttling effect of the narrow part of Cook Strait is not taken into account.

Construction of hazard curves

Hazard curves are constructed from the synthetic catalogues of tsunami heights in the following way:

For a chosen 20 km coastal section, the catalogue of tsunami heights is sorted into descending order. Within a catalogue covering N years, the tsunami with return period RP is expected to occur at least N/RP times. The (N/RP)th entry in the sorted synthetic catalogue of tsunami heights is therefore the estimated tsunami height at the desired return period.

This process is repeated for several different return periods to construct a single hazard curve.

Epistemic uncertainty is accounted for by creating a different hazard curve for each set of the sampled epistemically-uncertain parameters. The distribution of different hazard curves can then be used to quantify the uncertainty in the hazard curves. In our results this is achieved by identifying the 16th and 84th percentile from the distribution of curves at each return period.

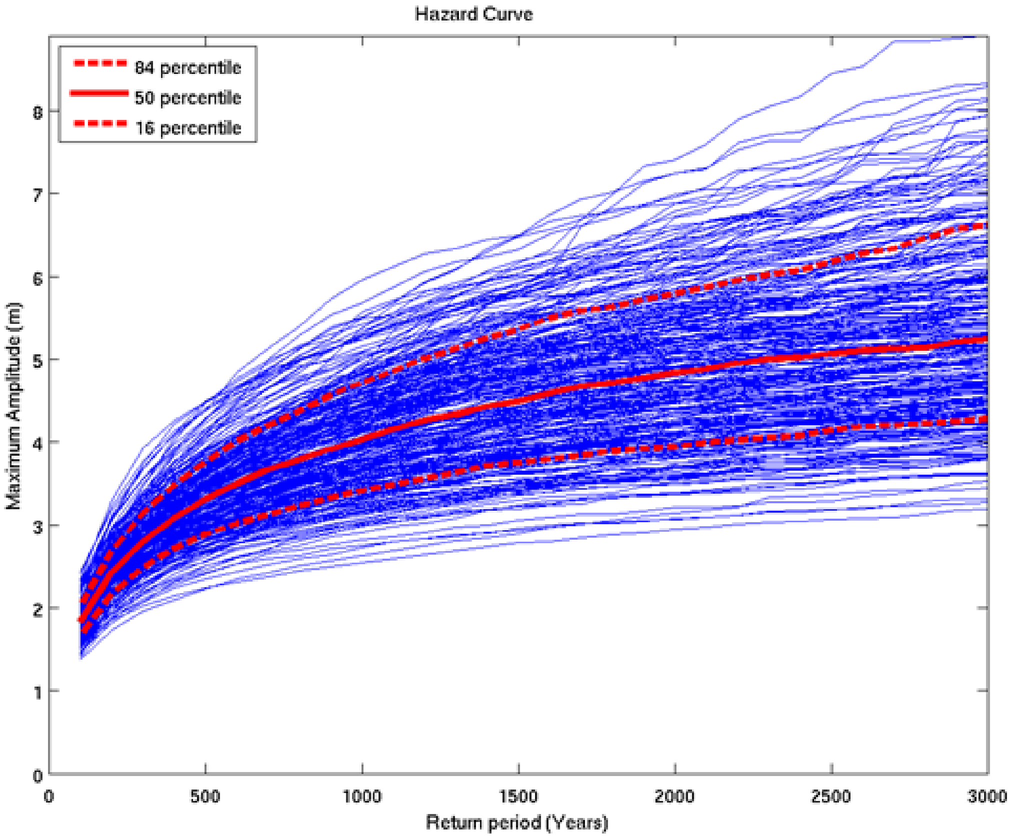

Figure A 7.1 Hazard curves for 300 samples of epistemic uncertainty, illustrating how the 16th, 50th and 84th percentiles of uncertainty are calculated.

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