NIWA
Taihoro Nukurangi

Joint-probability of storm tide and waves on the open coast of Wellington

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Executive summary

Hindcasts of wave and storm surge conditions during the 45-year period from October 1957 through September 2002 have previously been carried out (under the NIWA "Waves And Storm Surge Projections" research programme). Both hindcasts use the same meteorological forcing from the ERA-40 re-analysis dataset of the European Centre for Medium Range Weather Forecasts. Outputs from these hindcasts, combined with tidal sea levels from the NIWA tide model, form the basis for the present study.

Marginal and joint probability extreme value analyses for storm tides and wave heights were undertaken for nine offshore locations around the coastline of the Greater Wellington Region. The results are both plotted and reported in tables.

All plotted and tabulated data in this report are relative to the mean sea level measured at the Queen's Wharf tide gauge in Wellington over the 7-year period 2005–2011, described in this report as MSL05–11. The datum used is Wellington Vertical Datum 1953 (WVD-53). Note that the International Panel for Climate Change (IPCC) provides long-term sea-level rise scenarios relative to base sea level 1980–1999. 5.6 cm should be subtracted from the values in this report (which are specified relative to MSL05–11), in order to adjust them to 1980–1999 base sea level.

The joint-probability analyses show that on the western Kapiti coast of the Wellington region, hazardous events are most likely to involve a combination of large waves coinciding with a high storm tide, because storm tide and waves are highly correlated. The exposure increases toward the north along this coast, due to increasing tidal range and exposure to larger waves from the west.

On the south and east Wairarapa coasts, large waves and swell are more likely to occur in isolation from large storm tides. The wave climate is also considerably more energetic than on the west coast, with larger extreme significant wave heights.

The probability analyses are valid for the deep-water locations where they were produced. For any storm tide and wave combination, the sea level and waves could be transformed onshore using detailed nearshore bathymetry and beach topography to quantify wave setup and run-up hazards. The results in this report don't include the effects of climate change.

The wave hindcasts were calibrated against the Baring Head wave buoy and a higher-resolution wave model of Greater Cook Strait that NIWA uses for operational forecasting. The wave hindcast under-predicts extreme significant wave heights, so a linear adjustment was applied. The cause of the under-prediction is the spatial resolution of the ERA-40 wind fields that don't fully resolve storm systems adequately to impart sufficient energy to the waves. Conversely, storm surges operate over wider spatial scales, so the hindcast results were used directly.

1 Introduction

Greater Wellington Regional Council contracted NIWA to produce estimates of the potential coastal inundation caused by combined storm-tide and waves for the Wellington Region for both the current climate and projected climate change. The areas of specific interest are Wellington City, Lower Hutt, Eastbourne, Porirua and Kapiti Coast.

Hindcasts of wave and storm surge conditions during the 45-year period from October 1957 through September 2002 have previously been determined (under the NIWA "Waves And Storm Surge Projections" research programme). Both hindcasts use the same meteorological forcing from the ERA-40 re-analysis dataset of the European Centre for Medium Range Weather Forecasts. Results from the wave and storm-tide hindcasts are used to develop the scenarios for this modelling.

This report presents results of joint-probability analyses for storm tides and waves at selected sites on the open coast of the Greater Wellington Region based on the modelling from the hindcasts; quantifying the present-day hazard.

1.1 An overview of the processes contributing to coastal inundation

There are a number of meteorological and astronomical phenomena involved in the development of a combined extreme sea level and wave event. These processes can combine in a number of ways to inundate low-lying coastal margins. The processes involved are:

- Mean level of the sea (MLOS), which can vary up or down from months up to decades.
- Astronomical tides.
- Storm surge.
- Wave setup (and run-up).
- Climate-change affects including sea-level rise.

The mean level of the sea describes the variation of the non-tidal sea level on longer time scales ranging from a monthly basis up to decades due to climate variability, including the effects of El Niño–Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO) patterns on sea level, winds and sea temperatures, and seasonal effects.

The astronomical tides are caused by the gravitational attraction of solar-system bodies, primarily the Sun and the Earth's moon. In New Zealand the astronomical tides have by far the largest influence on sea level, followed by storm surge (in most locations).

Low-pressure weather systems and/or adverse winds cause a rise in water level known as storm surge. Storm surge results from two processes: 1) low-atmospheric pressure causes the sea-level to rise, and 2) wind stress on the ocean surface pushes water down-wind and to the left of a persistent wind field, piling up against any adjacent coast.

Storm tide is defined as the sea-level peak reached during a storm event, from a combination of MLOS + tide + storm surge. It is the storm tide that is measured by sea-level gauges such as in Wellington Harbour. In this report, we refer to storm tide as the sea-level quantity relevant to coastal inundation. Climate change will also cause acceleration in long-term trends of sea-level rise and minor increases in the drivers (winds, barometric pressure) that produce storm surges.

Waves also raise the effective sea level at the coastline. **Wave setup** is the increase in mean sea level at the coast, pushed up inside the surf zone from the release of wave energy as waves break in shallow water (Figure 1-1). The term wave setup describes an average raised elevation of sea level when breaking waves are present. **Wave run-up** is the maximum vertical extent of wave "up-rush" on a beach or structure above the still water level (that would occur without waves), and thus constitutes only a short-term fluctuation in water level relative to wave setup and storm surge time scales (Figure 1-1).

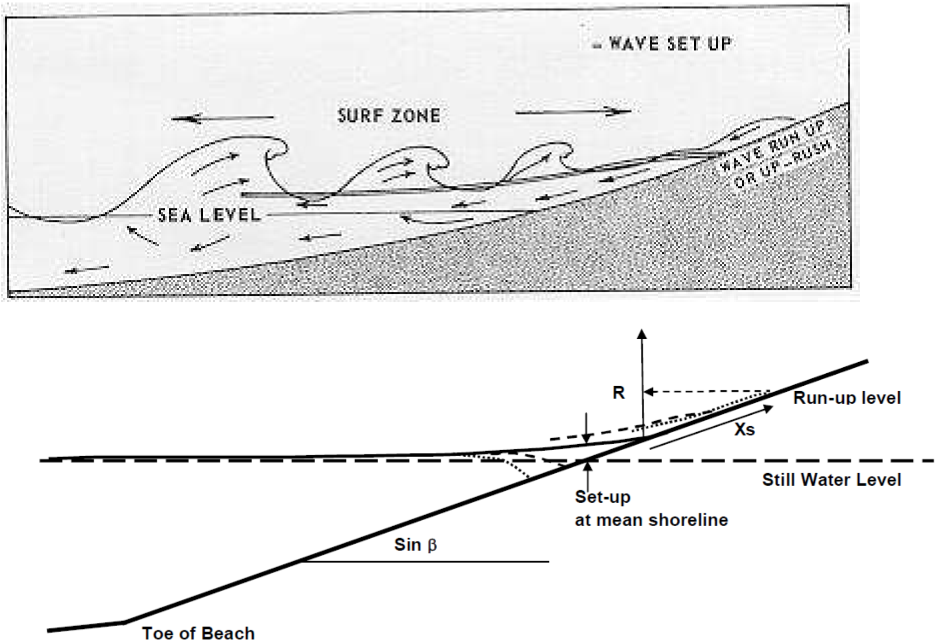

Figure 1-1: Illustration of wave setup and run-up.

Where waters are sufficiently deep adjacent to the shoreline, waves may break right at the shoreline, causing wave overtopping e.g., at rock revetments and seawalls. Wave-overtopping volumes comprise green water (flowing seawater), wave splash and wind drift.

Flooding, from rivers, streams and stormwater, is another contributor to coastal inundation when the flood discharge is constrained inside narrower sections of estuaries. This process is not considered in this report, which focuses on the joint effects of waves and storm tides on the open coast, where riverine flooding has negligible effect.

1.2 Explanation of extreme event probabilities

This report combines wave and storm tide information in a **joint-probability** analysis, which calculates the likelihoods of high storm tides and large waves coinciding. Coastal inundation, or other hazards such as erosion or structural damage to coastal defences, roads or buildings, is worse when high storm tides and large waves occur together. This report shows how these processes can be accounted for simultaneously, and quantified by an average joint-recurrence interval or joint exceedance probability.

The likelihoods associated with extreme storm tides and/or waves, are reported in terms of their probability of occurrence. The **annual exceedance probability** (AEP) describes the chance of an event reaching or exceeding a certain water level in any given year. For example, if a storm tide of 1.57 m (WVD-53) has a 5% AEP, then there is a 5% chance of a storm tide this high, or higher, occurring in any 1-year period. So it is unlikely, but could still happen and should be planned for. Furthermore, although the occurrence probability is only 5%, more than one storm tide this high or higher could occur in any given year.

Alongside AEP, the likelihood of extreme events can also be described in terms of their **average recurrence interval** (ARI), which is the average time interval between events of a specified magnitude (or larger), when averaged over many occurrences. Table 1-1 shows the relationship between AEP and ARI; small relatively common events have a high annual exceedance probability and a low average recurrence interval, and *vice versa* for large, rare events.

Table 1-1: Relationship between annual exceedance probability (AEP) and average recurrence interval (ARI). $AEP = 1 - e^{(-1/ARI)}$.

AEP (%)	99%	86%	63%	39%	18%	10%	5%	2%	1%	0.5%
ARI (years)	0.2	0.5	1	2	5	10	20	50	100	200

ARI (or its often used surrogate “return period”) is an easily misinterpreted term, with the public often assuming that because one large event has just occurred, then the average recurrence interval will pass before another such event. It is also prone to confusion with planning lifetimes, which, like ARI, are also expressed in years. We therefore prefer the term AEP, because it conveys the continuous probability that large events could occur at any time.

This report provides occurrence likelihoods for extreme storm tide and wave height magnitudes. This knowledge is only one aspect of the planning process. Another essential planning component is to consider the planning timeframe, or lifetime, of interest. This is particularly relevant in the context of rising sea levels, which will change the base level for future storm tide inundation (Bell and Hannah, 2012). For example, a typical planning lifetime for residential housing is about 100 years. Table 1-2 presents the likelihood that events with various occurrence probabilities will occur within a specified planning lifetime. The likelihoods are shaded according to their chance of occurring in the specified timeframe:

- > 85% Almost certain
- 60%–84% Likely
- 36%–59% Possible
- 16%–35% Unlikely
- < 15% Rare

For example, a relatively common (smaller) event with a 39% AEP, is *almost certain* to occur over a 20-year lifetime. However, a rare (larger) 2% AEP event is *unlikely* to occur over the same 20-year lifetime. 1% AEP's are a commonly used planning event magnitude, and 100-year planning lifetimes are common for affected infrastructure; Table 1-2 shows that a 1% AEP event is *likely* to occur over a 100-year planning lifetime.

Table 1-2: Likelihood of an event with a specified probability of occurrence (AEP / ARI), occurring within planning lifetimes. $P = 1 - e^{-L/ARI}$, where L = planning lifetime and P = probability of occurrence within planning lifetime.

		Planning lifetime (years)						
AEP (%)	ARI (years)	2	5	10	20	50	100	200
39%	2	63%	92%	99%	100%	100%	100%	100%
18%	5	33%	63%	86%	98%	100%	100%	100%
10%	10	18%	39%	63%	86%	99%	100%	100%
5%	20	10%	22%	39%	63%	92%	99%	100%
2%	50	4%	10%	18%	33%	63%	86%	98%
1%	100	2%	5%	10%	18%	39%	63%	86%
0.5%	200	1%	2%	5%	10%	22%	39%	63%

2 Methods

2.1 Data output locations

Sea level and wave data were output from the storm surge and wave models at nine sites along the open coast of the Greater Wellington region Figure 2-1. Sites 1–3 were located on the western Kapiti coast in the South Taranaki Bight, sites 4, 5, 8 and 9 were located on the southern coast in Cook Strait, and sites 6 and 7 on the eastern Wairarapa coast. The various locations have different wave exposures and tide ranges, which will result in significant differences in the joint probabilities of extreme sea levels and waves.

The model simulations produced hourly wave and storm tide estimates for a 44-year period 1958–2001 inclusive.

The data at the 9 sites come from the set of standard hindcast output locations on the 20 m isobath as defined in the Waves And Storm Surge Projections (WASP) research programme, selecting those adjacent to the coast around the Greater Wellington Region.

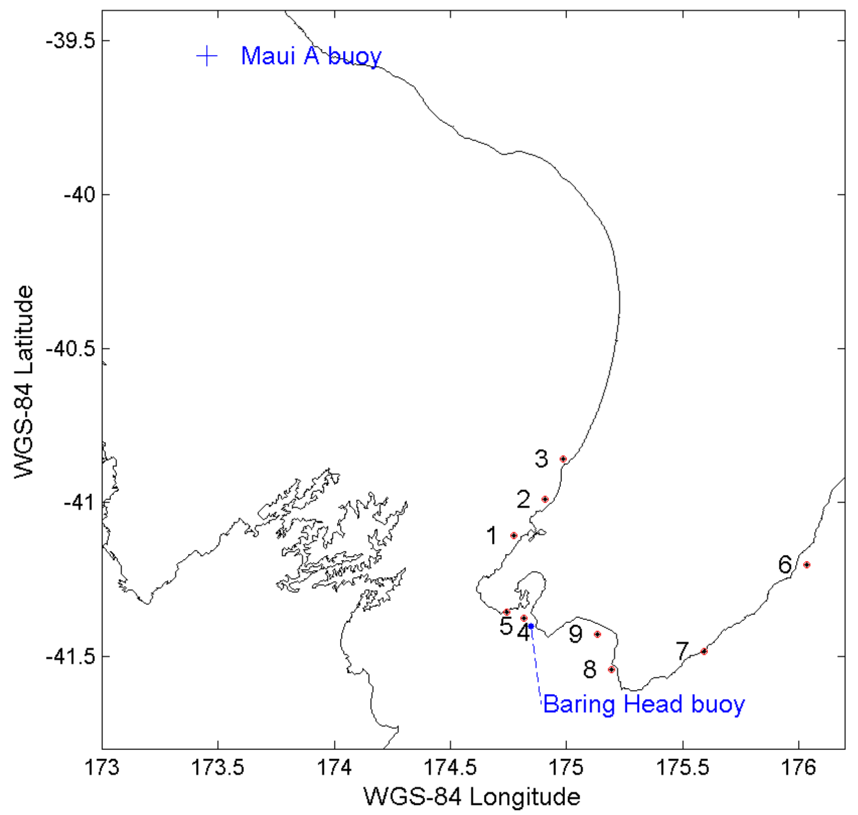

Figure 2-1: Model output site locations 1-9, and wave buoy locations.

Table 2-1: Model output site details.

Site	Locality	Longitude	Latitude	Water Depth (m)
1	Kapiti coast	174.773	-41.11	219
2	Kapiti coast	174.909	-40.99	128
3	Kapiti coast	174.985	-40.861	82
5	South Wellington	174.744	-41.358	166
4	South Wellington	174.817	-41.376	231
9	Palliser Bay	175.134	-41.43	363
8	Palliser Bay	175.192	-41.543	379
7	Wairarapa	175.594	-41.486	800
6	Wairarapa	176.032	-41.203	415

2.2 The wave model

The wave hindcast was carried out under the Waves And Storm Surge Projections programme, using the Wavewatch III spectral wave generation model (Tolman 2009). Meteorological forcing was provided by the ERA-40 re-analysis (Uppala et al. 2005) data set developed by the European Centre for Medium Range Weather Forecasts. This re-analysis provides meteorological fields on a global grid at 1.125° resolution in both latitude and longitude, at 6 hour intervals from October 1957 to September 2002.

A global wave model grid was established at the same resolution, along with a nested New Zealand regional grid covering longitudes 162.000°E to 185.625°E (174.375°W) at 0.125° resolution, and latitudes 51.750°S to 32.625°S at 0.09375° resolution. The latter grid was used to provide more accurate representation of nearshore wave conditions, but both models were forced with the same ERA-40 wind fields in hindcasts from October 1957 to September 2002. The global wave model also accounted for varying sea ice cover, included in the ERA-40 data. Outputs of wave statistics computed at each model grid cell, including significant wave height, peak and mean wave period, peak and mean wave direction, directional spread and wave energy transport were archived at 3 hour intervals for the global model, and hourly intervals for the regional model.

For the present work, wave statistics were extracted from the archived regional model hindcast at cells in the vicinity of the output locations. The desired output locations on the 20 m isobath are generally closer to the coast than the 10 km resolution of the regional model grid. This creates a problem in that the model effectively represents land and sea as being made up of rectangular cells, so this is inevitably of limited accuracy in "sea" cells adjacent to land, where it will generally under-predict wave heights. For this reason, rather than interpolate from the cells immediately surrounding the intended output location, we took data from the nearest "wet" cell with no "dry" cells adjacent on its north, south, east or west sides.

2.2.1 Wave height calibration

Wave statistics derived from the hindcast have been validated against data from 7 available wave buoy records. Of these, deployments at off Baring Head east of Wellington Harbour (41.4022°S, 174.8467°E), are the most relevant for the present study. Good agreement has generally been obtained at most open coast sites, but at Baring Head in particular the hindcast was found to significantly under-predict wave heights during severe storm events (Figure 2-2). This region is well known for strong topographic funnelling of winds through Cook Strait, producing strong northerlies and southerlies. The spatial resolution of the ERA-40 topography is insufficient to properly represent this local intensification in its wind fields, and hence the wave model subsequently under-predicts significant wave heights in these conditions.

The scatter plot (Figure 2-3) also illustrates this under-prediction. The overlaid quantile-quantile plot maps a given percentile value of significant wave height H_{m0} from the hindcast record against the corresponding value from the buoy record. It shows that the highest measured values are on average approximately 1.5 times the corresponding hindcast values.

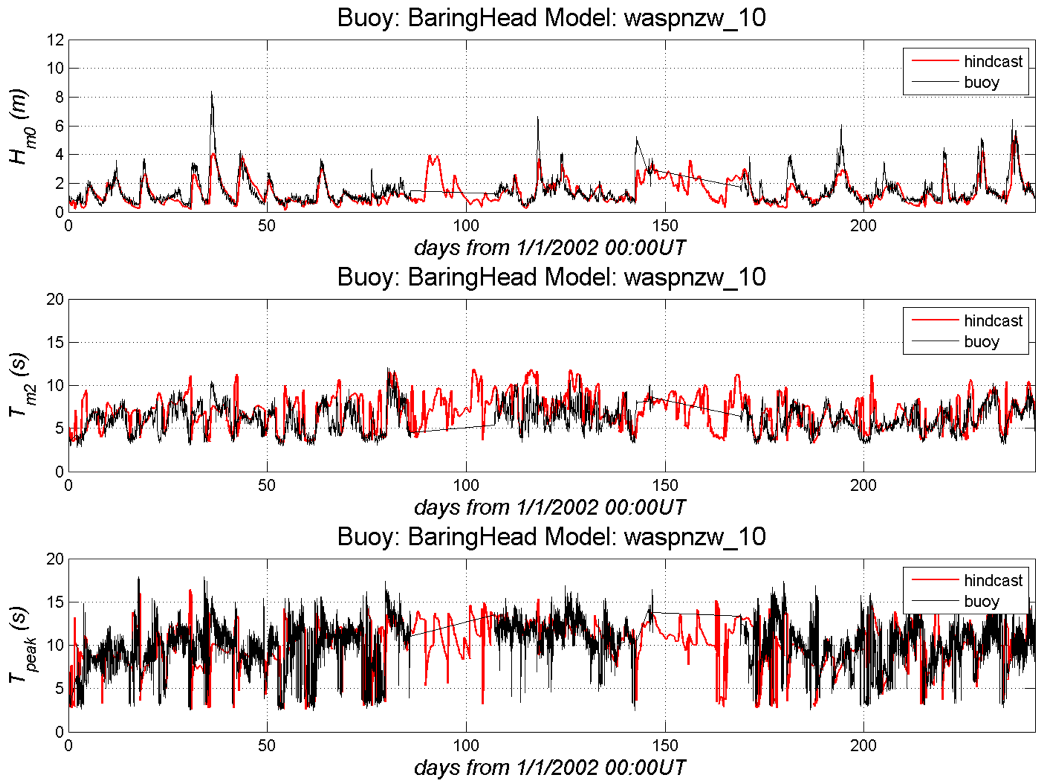

Figure 2-2: Comparison of measured and hindcast wave statistics at Baring Head, during 2002. (top panel) significant wave height, (middle panel) second-moment mean period, (bottom panel) peak period.

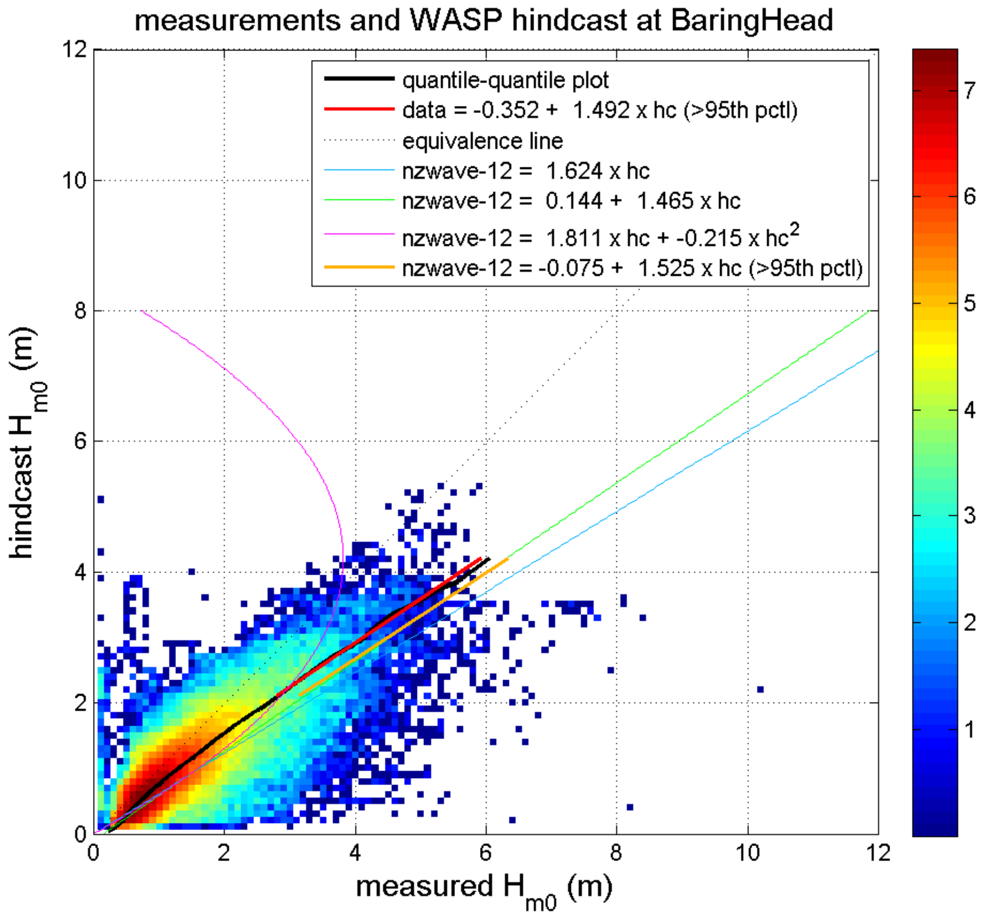

Figure 2-3: Scatter plot of measured and hindcast significant wave height at Baring Head. The colour scale is proportional to the log of the number of occurrences of measured and hindcast wave heights in each range. The solid black line is a quantile-quantile plot. The solid red line is a linear fit to quantile values above the 95th percentile, while other coloured lines represent fitting curves derived from comparing the WASP and NZWAVE models.

This comparison offers the possibility of calibrating the hindcast with the buoy record. A possible approach for extreme value analysis would be to compute a linear fit to the higher range of the quantile-quantile plot, and apply this to correct the longer hindcast record. For example the solid red line in Figure 2-3 shows the fit to values above the 95th percentile. This can only be expected to apply locally, however, to waters in the vicinity of the Wellington Harbour entrance.

In order to explore correction factors over a wider domain, we made use of another model simulation, namely the NZWAVE-12 forecast system used operationally by NIWA to produce twice daily 48-hour forecasts for the New Zealand region. This operates on a grid of approximately 12 km resolution, with input from the NZLAM-12 weather prediction model. Critically, this provides a more accurate representation of topographic effects on the local wind fields than is available from the ERA40 winds, so produces a more accurate estimate of extreme wave conditions in the Cook Strait.

The occurrence distribution of significant wave height was derived for each grid cell of both simulations, using the full 45 year record of the WASP simulation, and a three year record from the NZWAVE-12 forecasts. Comparing quantile values of H_{m0} from the WASP record with corresponding values ($H_{m0}^{'}$) from the nearest cell of the NZWAVE-12 record, several fitting functions were tested:

1. $H_{m0}^{'} = b_0 H_{m0}$, fitted over the full range of data.
2. $H_{m0}^{'} = a_1 + b_1 H_{m0}$, fitted over the full range of data.
3. $H_{m0}^{'} = b_2 H_{m0} + c_2 H_{m0}^{2}$, fitted over the full range of data.
4. $H_{m0}^{'} = a_{95} + b_{95} H_{m0}$, fitted over values above the 95th percentile.

The first and third options are constrained to pass through the origin, which is a desirable property for handling low wave heights (avoiding mapping positive to negative values). The various fitting parameters were obtained throughout the WASP domain (except for a small section of the eastern Wairarapa coast not overlapped by the NZWAVE-12 domain). Spatial smoothing was applied in order to moderate some nearshore artefacts.

Fitting curves from this analysis, using parameters for the grid cell corresponding to the Baring Head site, are included in Figure 2-3. We see that fitting to model data above the 95th percentile produces quite similar results to the corresponding analysis with buoy data, and the linear methods fitting all data are also reasonably close. The quadratic fit, optimistically included in the hope of matching the curve of the quantile-quantile plot, was not suitable.

The Figure 2-4 shows a closer agreement between hindcast and measured wave heights at the Maui-A platform, at (39.55°S, 173.45°E) than at Baring Head, but still with some under-prediction. The cross-comparison with the NZWAVE-12 forecasts produces regression lines that lie close to the buoy-hindcast quantile-quantile plot.

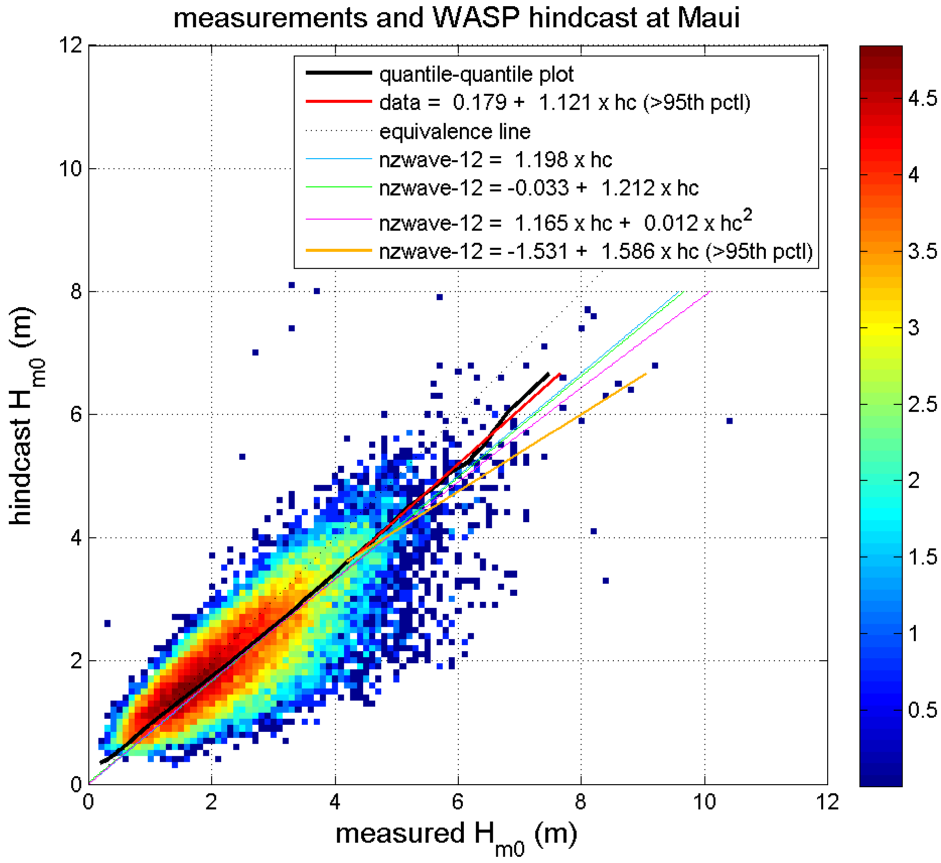

Figure 2-4: Scatter plot of measured and hindcast significant wave height at the Maui-A platform. The colour scale is proportional to the log of the number of occurrences of measured and hindcast wave heights in each range. The solid black line is a quantile-quantile plot. The solid red line is a linear fit to quantile values above the 95th percentile, while other coloured lines represent fitting curves derived from comparing the WASP and NZWAVE models.

These results indicate that this method of cross-calibrating the long-term WASP hindcast against a shorter simulation with finer resolution wind fields can produce spatially-dependent correction factors that can improve the wave height statistics of the WASP hindcast, particularly for extreme value analysis. As an example, the spatial variation of the linear scaling factor b_0 defined above is shown in Figure 2-5. As should be expected this is close to 1 in most of the open water part of the domain, but increases where topography produces disturbances in the wind field that are not well represented in a low-resolution model wind field. This is particularly the case in the vicinity of Cook Strait, but also generally to the east of the New Zealand landmass, which is the lee side for the prevailing westerlies.

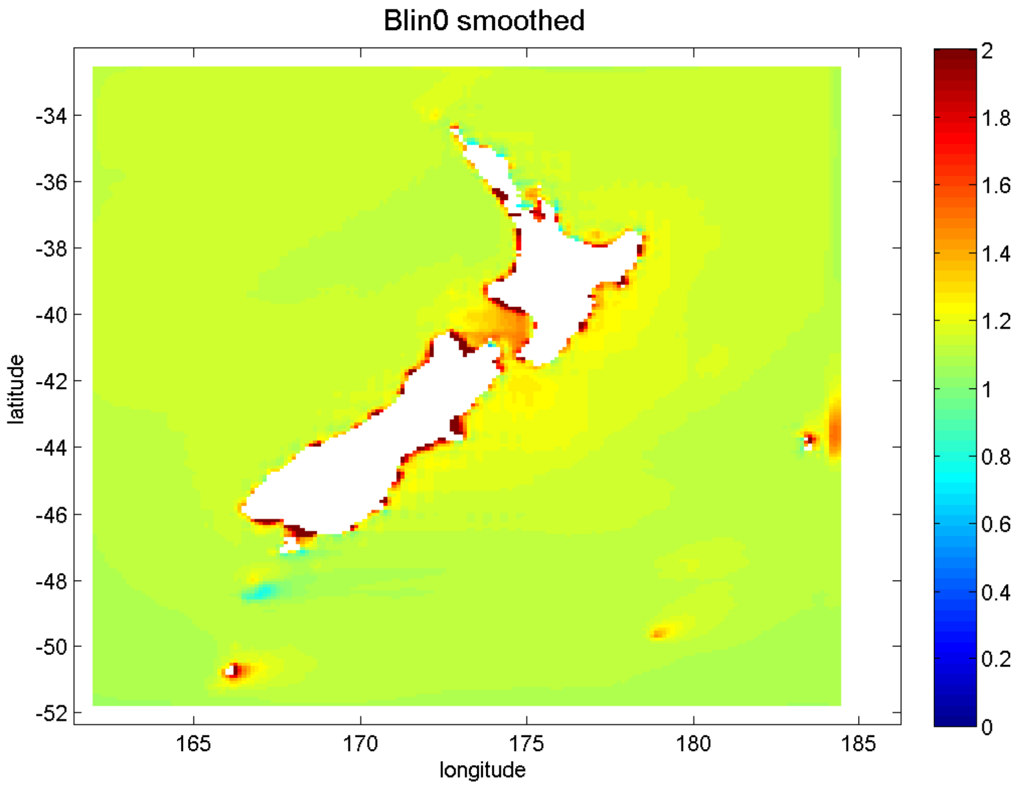

Figure 2-5: Spatial variation of the linear scaling factor *b_0* between significant wave heights derived from the WASP and NZWAVE-12 models. Note: b_0 > 1 indicates WASP wave heights require scaling up.

Clearly, the uncalibrated wave hindcast under-predicts extreme significant wave heights. The fits shown in Figure 2-3 suggest that the largest 5% of hindcast waves should be multiplied by a factor of about 1.5 to match the wave buoy at the Baring Head site. Figure 2-6 compares extreme significant wave heights predictions for the Baring Head buoy data (from a 10-year record), and for nearby model hindcast Site 4. The extreme values curves were obtained by fitting a generalised Pareto distribution (GPD) to significant wave heights exceeding the 95th percentile threshold. Before fitting the GPD, the hindcast significant wave heights were multiplied by factors of 1.0, 1.4 and 1.5, as marked in the legend on Figure 2-6. The uncalibrated hindcast (Hindcast site 4 $\times$ 1.0) under-predicts the extreme waves, for the reasons explained previously. The extreme value curve for the buoy data flattens as it approaches low annual exceedance probabilities (AEP). This is typical of environmental data where there are physical limitations to growth, but may also be influenced by the limited data record. The hindcast extreme wave height curves become increasingly less flat as the scaling factor is increased, demonstrating that the linear scaling factor is over-scaling the highest wave heights. For example, a scaling factor of 1.5 produces a good match to the buoy data at high (63–10%) AEP, but increasingly over-predicts the buoy data at low AEP, being 0.7 m higher at 1% AEP. Conversely, a scaling factor of 1.4 matches the buoy at low AEP but under-predicts at high AEP. For all subsequent extreme significant wave height and sea level–wave joint-probability analyses we have scaled all significant wave heights exceeding the 95th percentile threshold by a factor of 1.5. This adds a degree of conservatism to the extreme wave analyses, but is also reasonable because the 10-year

Baring Head buoy record is barely sufficient for accurate prediction of 1% AEP wave heights. For the rest of this report, the 1.5 times scaled significant wave heights (H_s) from the hindcast are used.

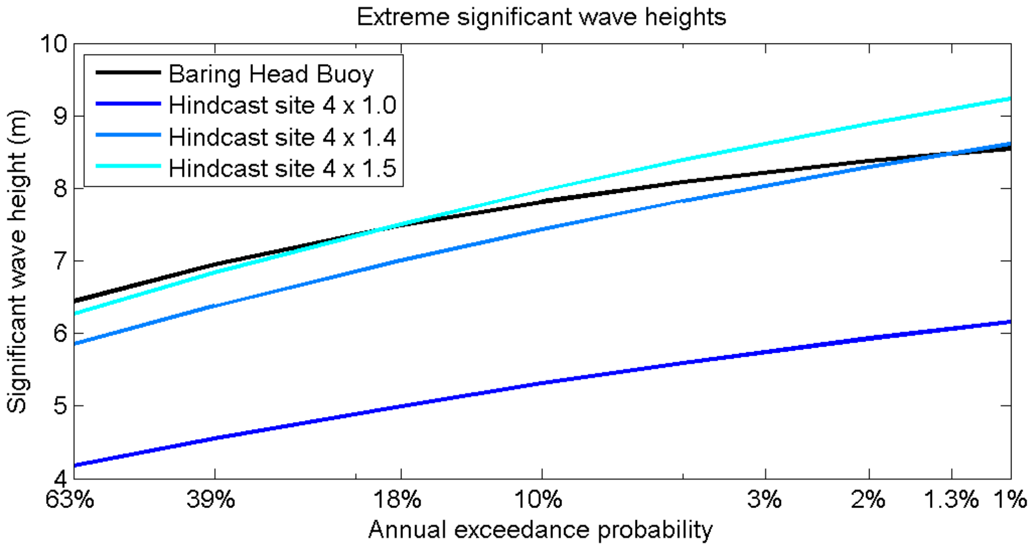

Figure 2-6: Comparison of extreme significant wave height curves at the Baring Head wave buoy and model hindcast at site 4, with various linear scaling factors applied.

2.2.2 Simulated wave heights

Histograms of significant wave height over the 45-year period at the nine sites are shown in Figure 2-7 for the western Kapiti coast and Figure 2-8 for the southern and eastern Wairarapa coasts. The southern and eastern coasts are exposed to higher wave energy than the western Kapiti coast. The histograms of wave height on the Kapiti coast have two peaks, with the frequent occurrence of small <0.5 m wave heights. These small wave events show that there are numerous locally-driven wind sea wave events in the South Taranaki Bight, whereas the south and east coasts appear to be more dominated by swell.

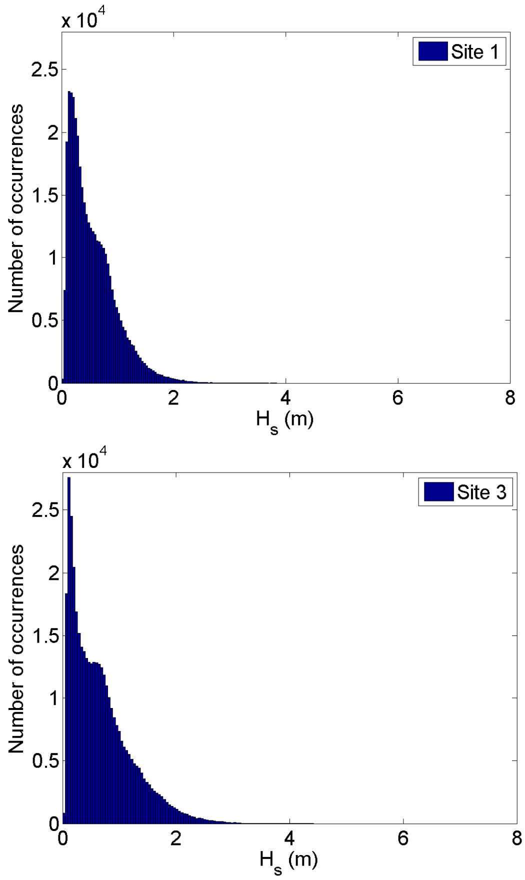

Figure 2-7: Histograms of simulated significant wave height at sites 1-3 (Kapiti coast).

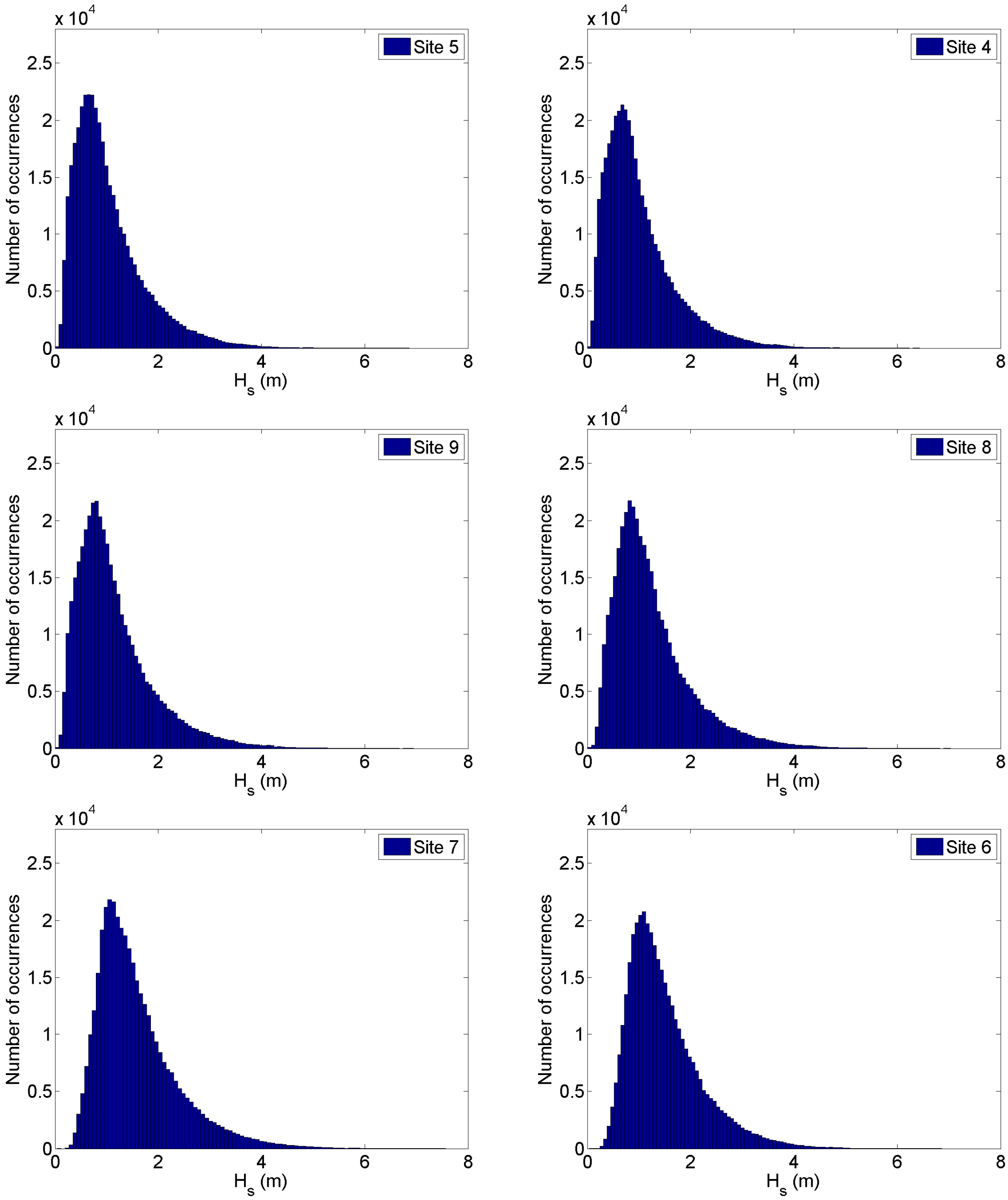

Figure 2-8: Histograms of simulated significant wave height at sites 4,5,9,8 (south Wellington coast) and sites 6,7 (Wairarapa coast).

2.3 The storm surge model

The storm surge was modelled using RiCOM (River and Coastal Ocean Model), a general purpose finite element hydrodynamic model on an unstructured grid. RiCOM has been used extensively for modelling coastal hydrodynamics including tsunami and storm surge inundation (Lane & Walters 2009; Lane et al. 2009; Walters 2004; Walters 2005; Walters et al. 2010). The unstructured grid is built up of triangular elements which allow extra resolution in places of interest, and those with complex topography or rapidly changing depth. The grid used for the hindcast modelling is the same as is used for operational storm surge forecasting within EcoConnect (Lane et al. 2009). It covers most of New Zealand's exclusive economic zone (EEZ) from 157º E to 210º E and from 22º S to 65º S. As with the wave modelling, the meteorological forcing for the storm surge modelling was taken from the ERA40 re-analysis for the time period 1957-2002.

The storm tide was calculated by adding the tidal data to the storm surge data for each 3-hour interval, and adding mean level of the sea (MLOS). The tidal data is reconstructed from constituents developed using TIDE2D, a model in frequency space, which is also calculated on an unstructured grid (Walters 2005).

The output from the storm surge hindcast is the storm surge at set points on or close to the 20 metre contour around New Zealand (Note that in some places the points are not quite on the 20 metre contour in order to provide better coverage of points or to facilitate future uses of the data).

2.3.1 Mean level of the sea

The storm tide was modelled relative to the mean sea level measured at the Queen's Wharf tide gauge in Wellington over the 7-year period 2005–2011, described in this report as MSL05–11. The storm tide was specified relative to Wellington Vertical Datum 1953 (WVD-53). All plotted and tabulated data in this report are given relative to MSL05–11 (WVD-53), unless otherwise stated.

MLOS measured in Wellington Harbour was, therefore, uniformly applied to the Greater Wellington Region. The justification for this is that MLOS tends to vary slowly around the New Zealand coastline, and is regionally quite consistent (Hannah & Bell 2012). At any given time, differences in MLOS will therefore be small (< ~ 1 cm) around the Wellington region.

The process of determining MLOS to add to the modelled tide and storm surge was:

1. Obtain MLOS at Wellington 1944–2011 (blue line Figure 2-9).
2. Find linear trend in MLOS at Wellington 1944–2011 = 2.46 mm/yr (black line Figure 2-9).
3. Find mean sea level 2005–2011 (MSL05–11) = 0.196 m WVD-53 (green line Figure 2-9).
4. Adjusted detrended MLOS to MSL05–11 base sea level (red line Figure 2-9).
5. Add adjusted, detrended MLOS to modelled tide and storm surge to get total storm tide.

Note that the International Panel for Climate Change (IPCC) provides long-term sea-level rise scenarios relative to base sea level 1980–1999. Wellington mean sea-level 1980–1999 was 0.140 m (WVD-53). Thus 5.6 cm should be subtracted from the values in this report (which are specified relative to MSL05–11), in order to adjust them to 1980–1999 base sea level.

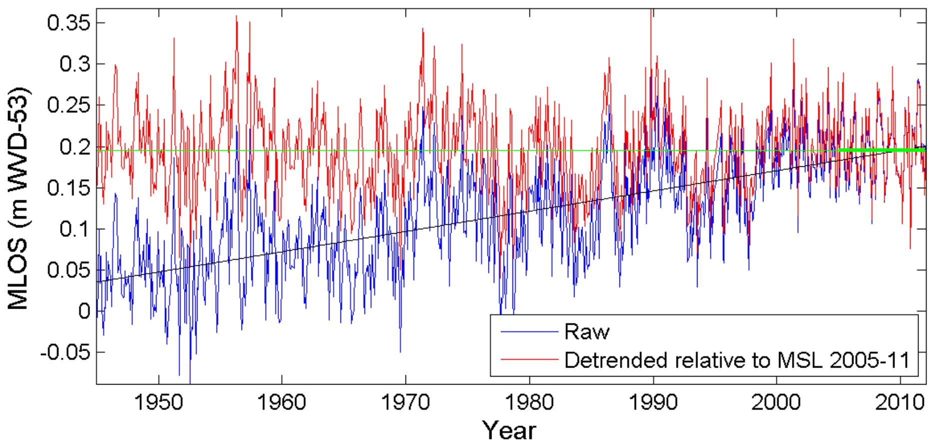

Figure 2-9: Mean level of the sea 1944-2011 at Queen's Wharf Wellington.

2.3.2 Simulated sea levels

Histograms of the astronomical tide are shown in Figure 2-10 for the western coast and Figure 2-11 for the southern and eastern coasts. The tidal range around the Greater Wellington region is relatively small compared with much of the New Zealand coastline (Walters 2005). On the western coast there is a gradient where the tidal range increases from south (site 1) toward the north (site 3).

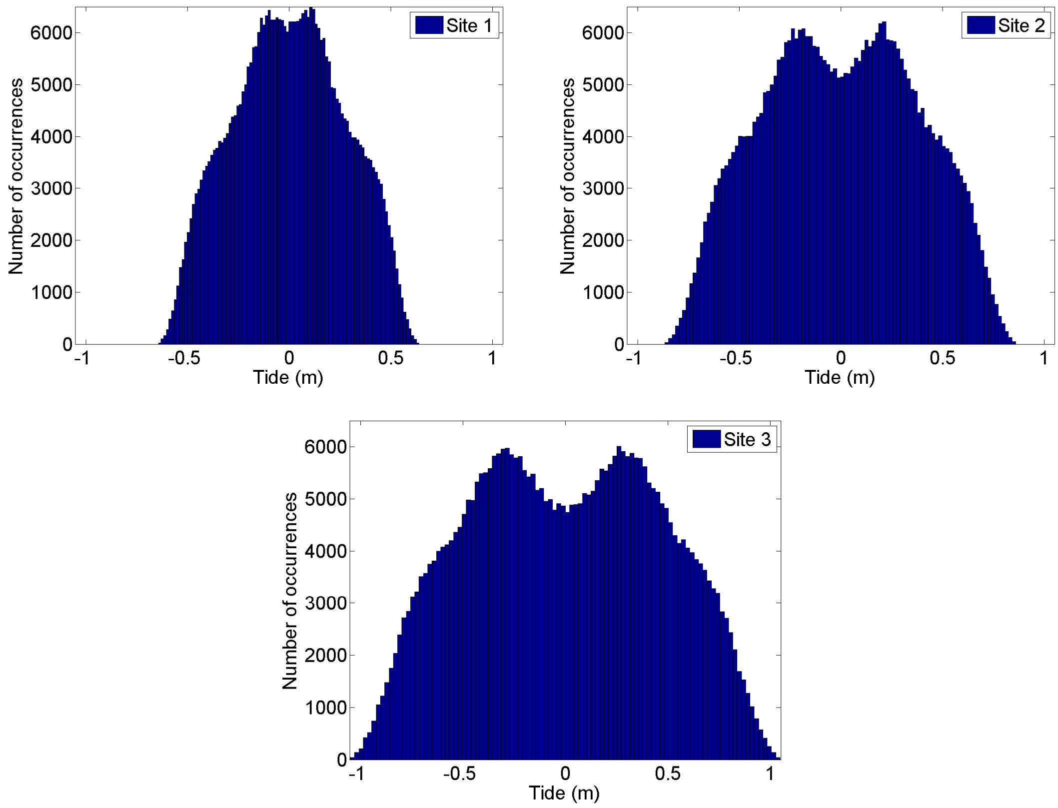

Figure 2-10: Histograms of simulated astronomical tide height at sites 1-3 (Kapiti coast, Figure 2-1), relative to instantaneous mean level of the sea.

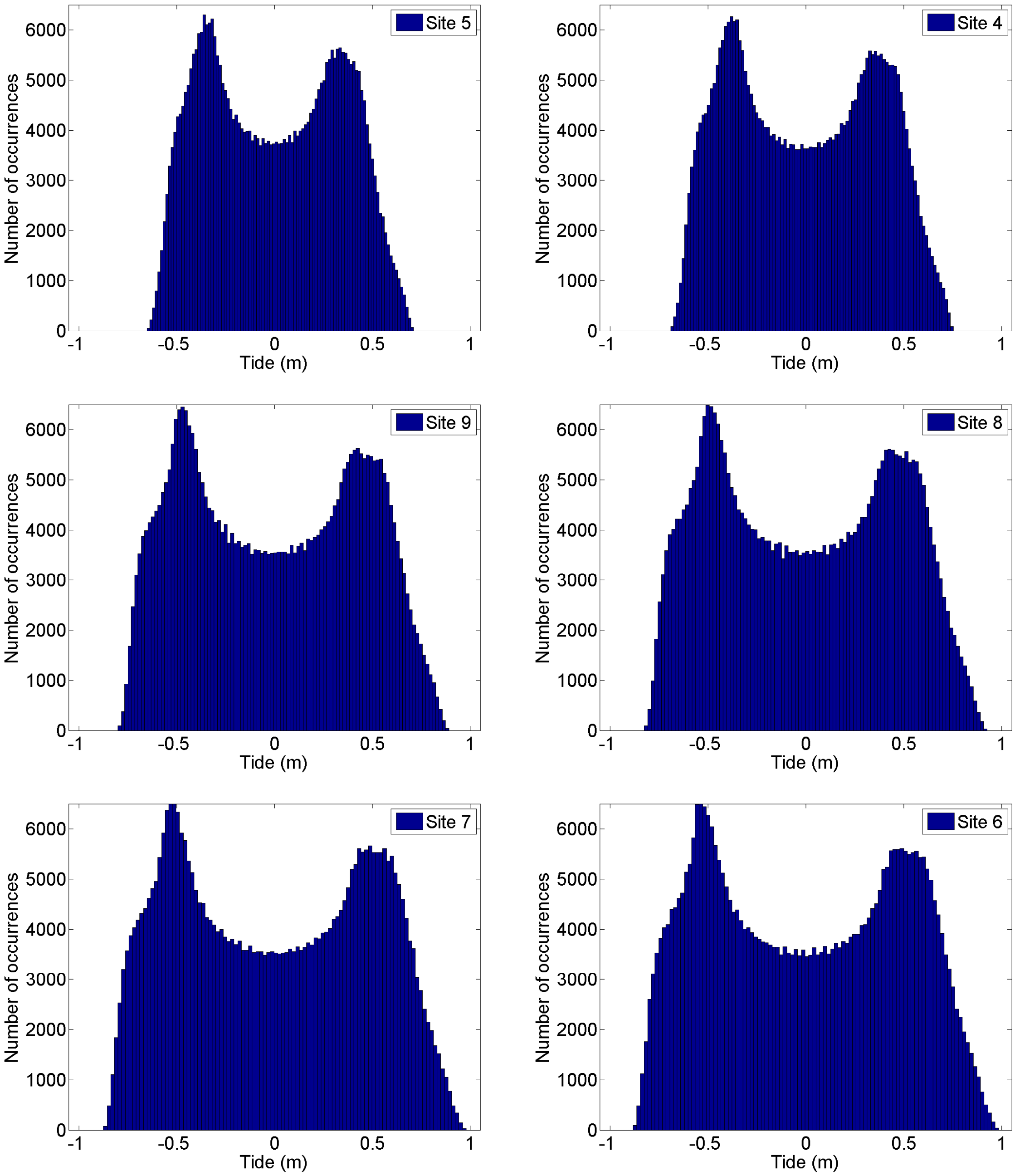

Figure 2-11: Histograms of simulated astronomical tide height at sites 4,5,9,8 (south Wellington coast) and sites 6, 7 (Wairarapa coast, Figure 2-1) , relative to instantaneous mean level of the sea.

Histograms of sea level variability due to meteorologically-induced storm surge are shown in Figure 2-12 for the western coast and Figure 2-13 for the southern and eastern coasts. Unlike the tide, the histograms of storm surge variability around the Greater Wellington region are similar at all sites. This occurs because storm surge is a weather-driven phenomenon that occurs over longer timescales (16–300 hours) than the tides (12–24 hours), and the scale of weather systems is also larger than the distance between the 9 sites.

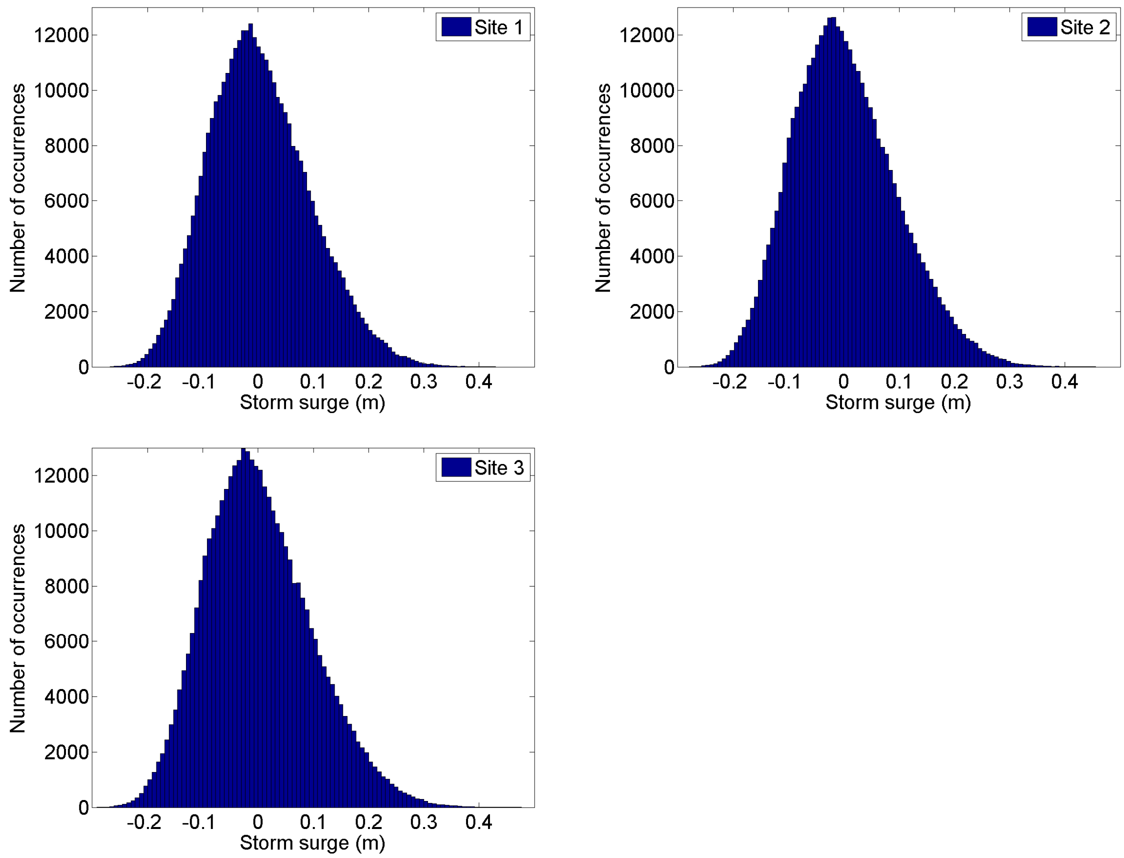

Figure 2-12: Histograms of simulated storm surge height at sites 1-3 (Kapiti coast, Figure 2-1), relative to instantaneous mean level of the sea.

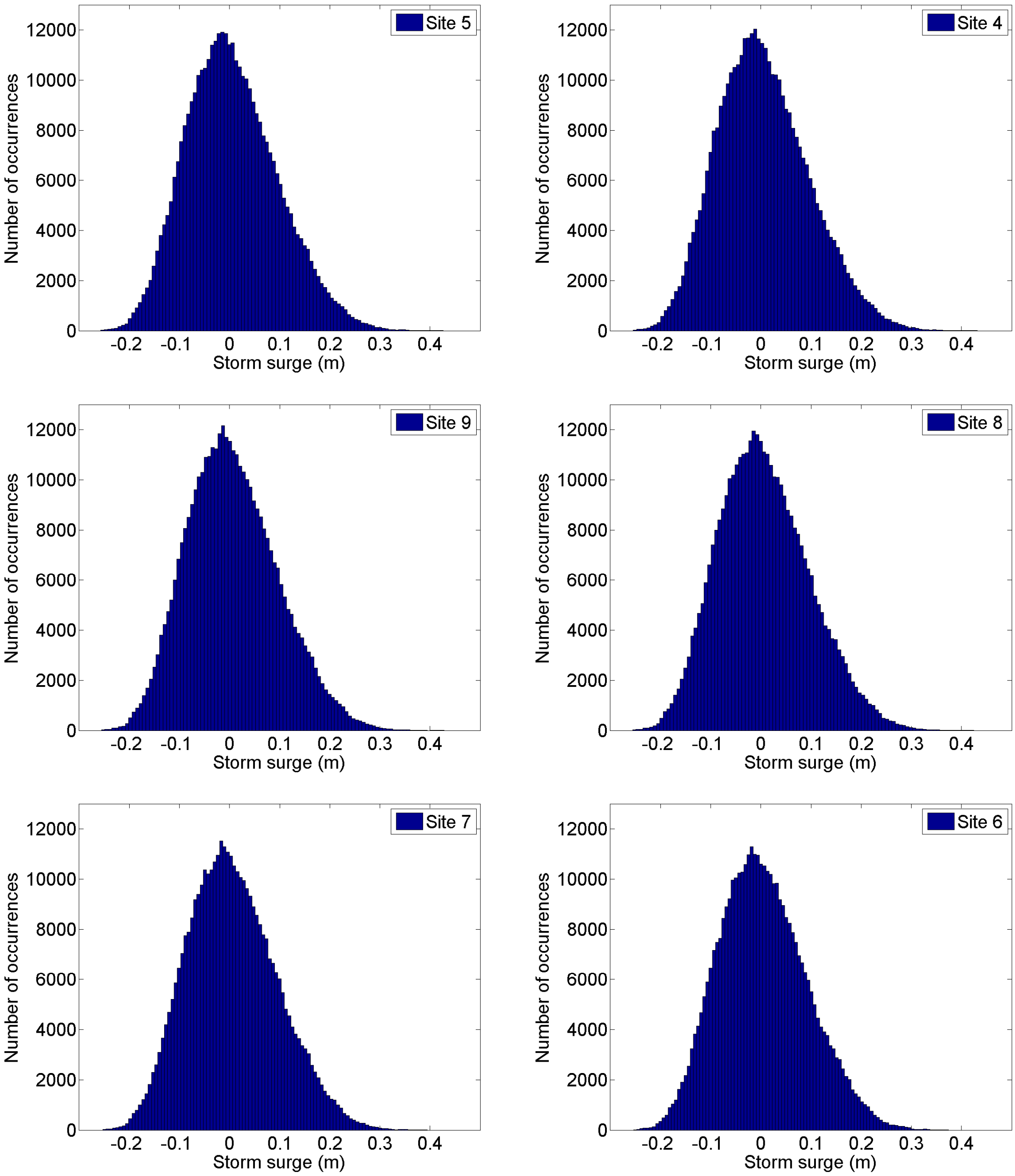

Figure 2-13: Histograms of simulated storm surge height at sites 4,5,9,8 (south Wellington coast) and sites 6, 7 (Wairarapa coast, Figure 2-1) , relative to instantaneous mean level of the sea.

Histograms of sea level variability due to the combined effect of MLOS, astronomical tide and storm surge, known as “storm tide”, are shown in Figure 2-14 for the western coast and Figure 2-15 for the southern and eastern coasts. It is apparent that the tide dominates the general shape of the short-term sea level variability, but the storm surge adds to the tide to increase the overall range in sea level variability, and occasionally results in unusually high storm tides.

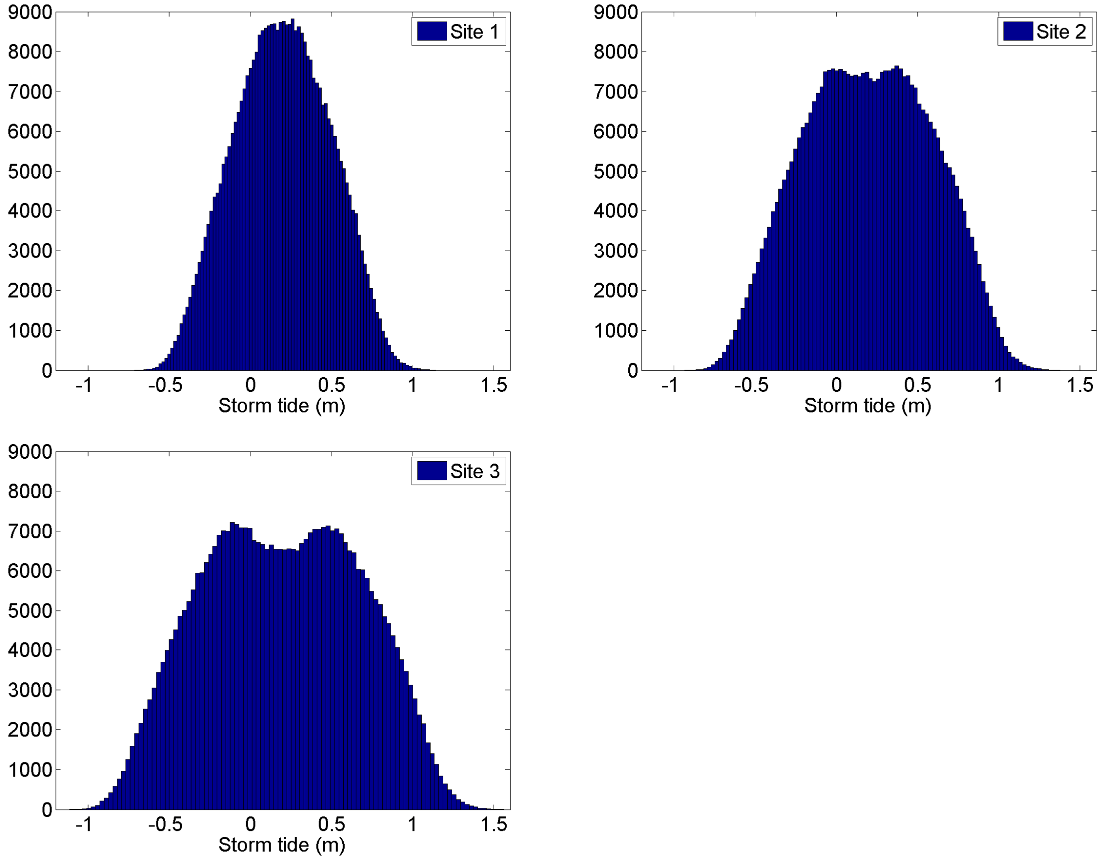

Figure 2-14: Histograms of simulated storm tide height at sites 1-3 (Kapiti coast, Figure 2-1), relative to MSL05–11 base sea level (WVD-53).

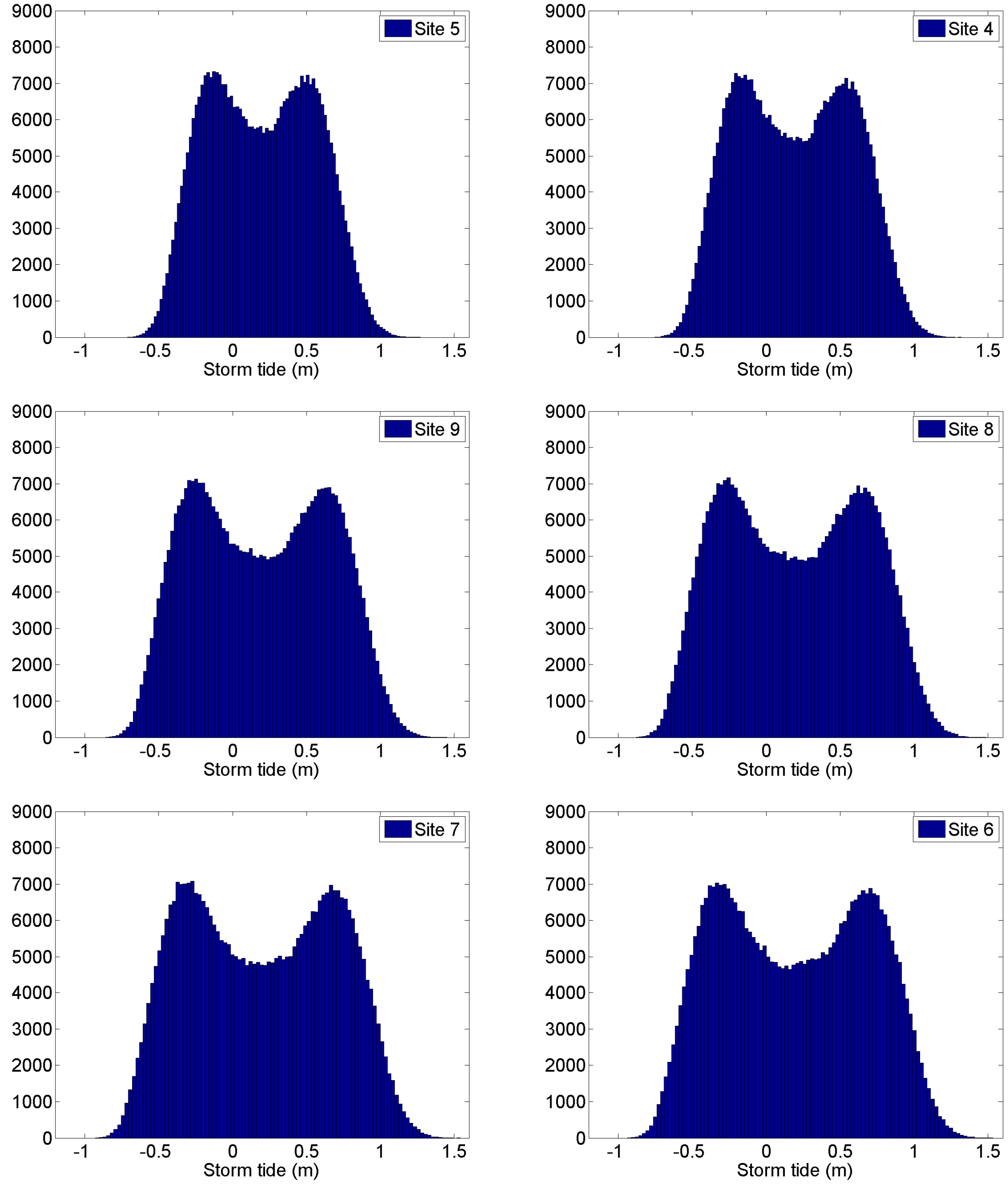

Figure 2-15: Histograms of simulated storm tide height at sites 4,5,9,8 (south Wellington coast) and sites 6, 7 (Wairarapa coast, Figure 2-1), relative to MSL05–11 base sea level (WVD-53).

2.4 Extreme value analyses

Joint-probability and marginal (individual) analyses of extreme storm tides and waves were undertaken using the JOIN-SEA software developed by HR Wallingford (Hawkes 2008; HR Wallingford 2000; HR Wallingford and Lancaster University 2000). These analyses don't include any effect of climate change. The software fits a Generalised Pareto distribution to the largest 5% of waves and storm tides to model extreme values, and samples from the empirical distribution to model more frequent event magnitudes. The software fits a bivariate normal distribution to account for any dependence between the storm tides and waves. The datasets are sampled to coincide with high tide, giving 706 values per year for storm tide and waves.

A location map for the modelled sites is reproduced in Figure 2-16.

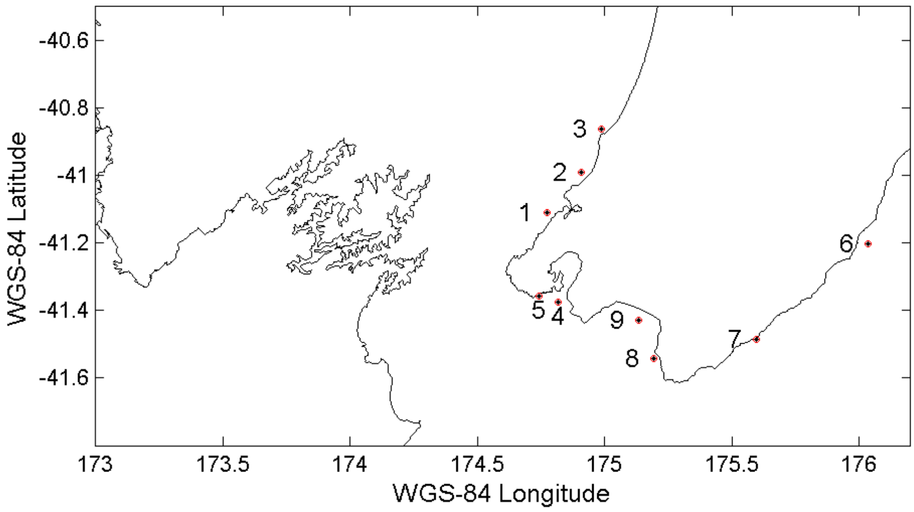

Figure 2-16:Model output site locations 1-9.

Figure 2-17 shows predicted extreme significant wave height associated with various Annual exceedance probabilities (AEP). Extreme waves are predicted to be much larger on the southern and eastern coast (sites 4–9), due to their exposure to large southerly (and easterly) swells.

Figure 2-18 shows predicted extreme storm tides. Extreme storm tides are heavily influenced by the tidal range, because, even for a large storm surge event, the high tide is the largest component of sea level variability. Thus the extreme sea levels are predicted to increase toward the north between sites 1 to 3, similarly between site 5 (South Wellington) up to site 6 (north Wairarapa).

Table 2-2 and Table 2-3 give the extreme values for significant wave height and storm tide.

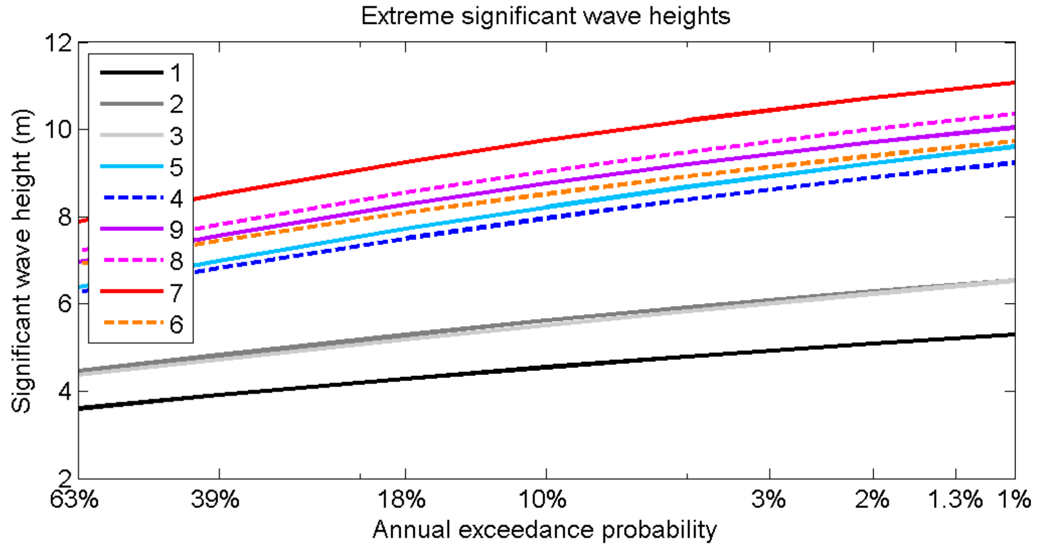

Figure 2-17: Modelled extreme significant wave height for various annual exceedance probabilities.

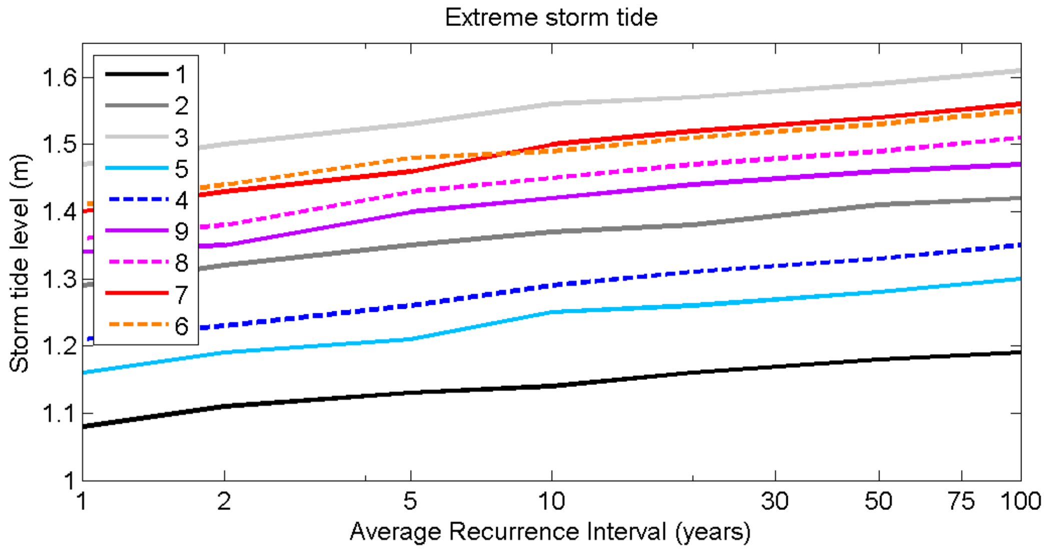

Figure 2-18: Modelled extreme storm tide for various annual exceedance probabilities. Levels are relative to Wellington Vertical Datum 1953 adjusted to 2005–2011 base sea level.

Table 2-2: Modelled extreme significant wave height for various annual exceedance probabilities.

AEP	ARI	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9
99%	0.2	2.78	3.47	3.51	4.74	4.78	5.51	6.15	5.52	5.26
86%	0.5	3.26	4.04	4.01	5.64	5.74	6.35	7.19	6.53	6.27
63%	1	3.60	4.45	4.37	6.26	6.39	6.93	7.89	7.21	6.95
39%	2	3.91	4.83	4.72	6.83	7.00	7.45	8.52	7.82	7.57
18%	5	4.28	5.29	5.18	7.50	7.72	8.09	9.26	8.55	8.29
10%	10	4.55	5.61	5.51	7.97	8.22	8.52	9.75	9.04	8.77
5%	20	4.79	5.92	5.83	8.39	8.68	8.92	10.20	9.48	9.20
2%	50	5.09	6.29	6.24	8.89	9.23	9.40	10.72	10.00	9.71
1%	100	5.29	6.55	6.53	9.24	9.61	9.73	11.08	10.36	10.05

Table 2-3: Modelled extreme storm tide for various annual exceedance probabilities. Levels are relative to Wellington Vertical Datum 1953 adjusted to 2005–2011 base sea level.

AEP	ARI	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9
99%	0.2	1.00	1.20	1.37	1.13	1.08	1.32	1.32	1.28	1.25
86%	0.5	1.05	1.25	1.43	1.17	1.13	1.37	1.37	1.33	1.30
63%	1	1.08	1.29	1.47	1.21	1.16	1.41	1.40	1.36	1.34
39%	2	1.11	1.32	1.50	1.23	1.19	1.44	1.43	1.38	1.35
18%	5	1.13	1.35	1.53	1.26	1.22	1.47	1.46	1.41	1.38
10%	10	1.14	1.36	1.55	1.29	1.24	1.49	1.48	1.44	1.41
5%	20	1.16	1.38	1.57	1.31	1.26	1.51	1.51	1.46	1.43
2%	50	1.18	1.41	1.59	1.33	1.28	1.53	1.54	1.49	1.46
1%	100	1.19	1.42	1.61	1.35	1.30	1.55	1.56	1.51	1.47

2.5 Joint-probability analyses

The relationship between storm tide and wave height is plotted in Figure 2-19 for the western Kapiti coast and Figure 2-20 for the southern and eastern coasts. The scatter of the independent storm tide and wave height event combinations shows that on the western coast there is a clear positive relationship between storm tide and wave height, but not on the southern or eastern coasts. The reasons for this are:

- The great majority of weather systems approach the Wellington region from the west of New Zealand. As low-pressure systems and fronts approach from the west, they generate wind waves and swell that propagate toward the west coast, affecting sites 1–3, but not the southern or eastern sites 4–9 that are sheltered from the west.
- The semi-enclosed nature of the South Taranaki Bight and its exposure to weather systems approaching from the west makes it the primary generation zone for storm surge around the Wellington region. Surge generated in the

Bight from wind setup and the ubiquitous inverted-barometer component affects all sites similarly.

- Thus the waves at western sites 1–3 are often generated by the same weather systems that generate the storm surge.
- Conversely, the southern and eastern sites 4–9 are exposed to waves and swell generated in the south and east of New Zealand that are often uncorrelated with the weather systems generating storm surge.
- Tidal amplitudes are small. For example, the median high tide level is 0.37 m at Site 1, which is similar to a moderate storm surge. This means that correlation between storm tide and waves on the western coast is not masked by large tides.

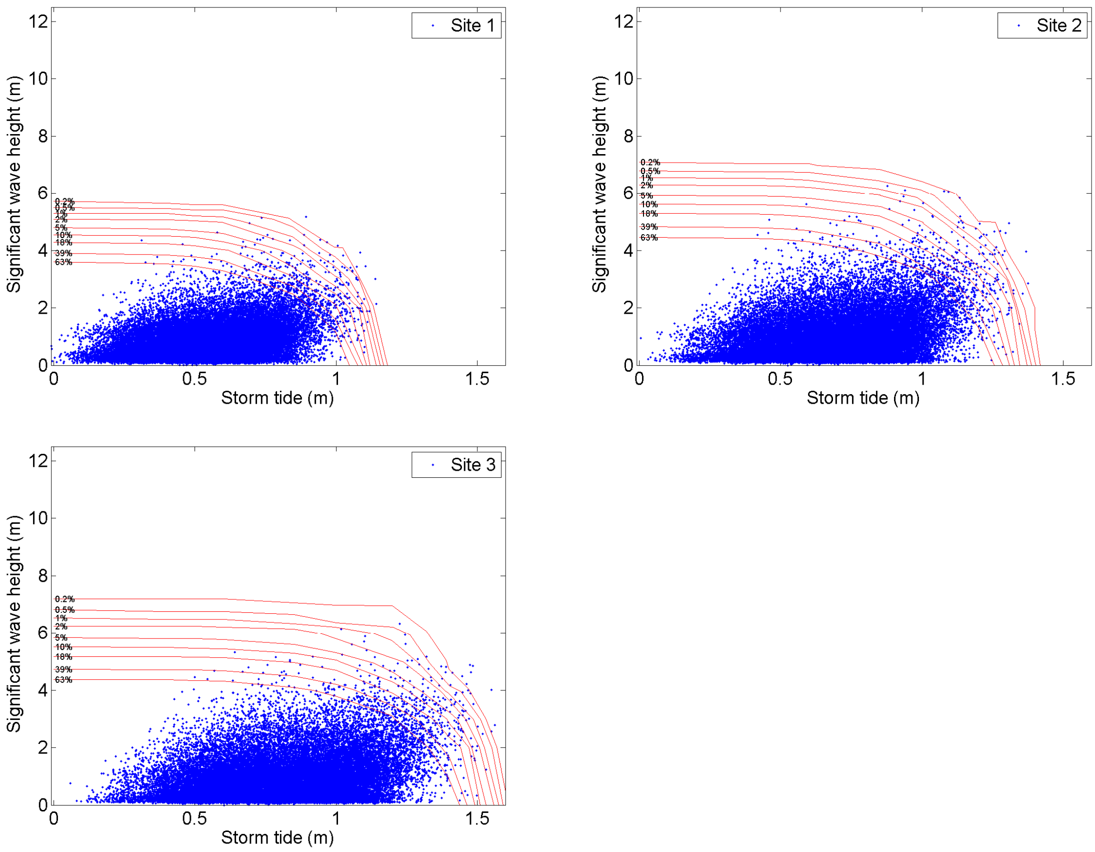

Figure 2-19: Scatter plot of significant wave height against storm tide level at sites 1-3 (western Kapiti coast, Figure 2-1). Storm tide levels are relative to Wellington Vertical Datum 1953 adjusted to 2005–2011 base sea level.

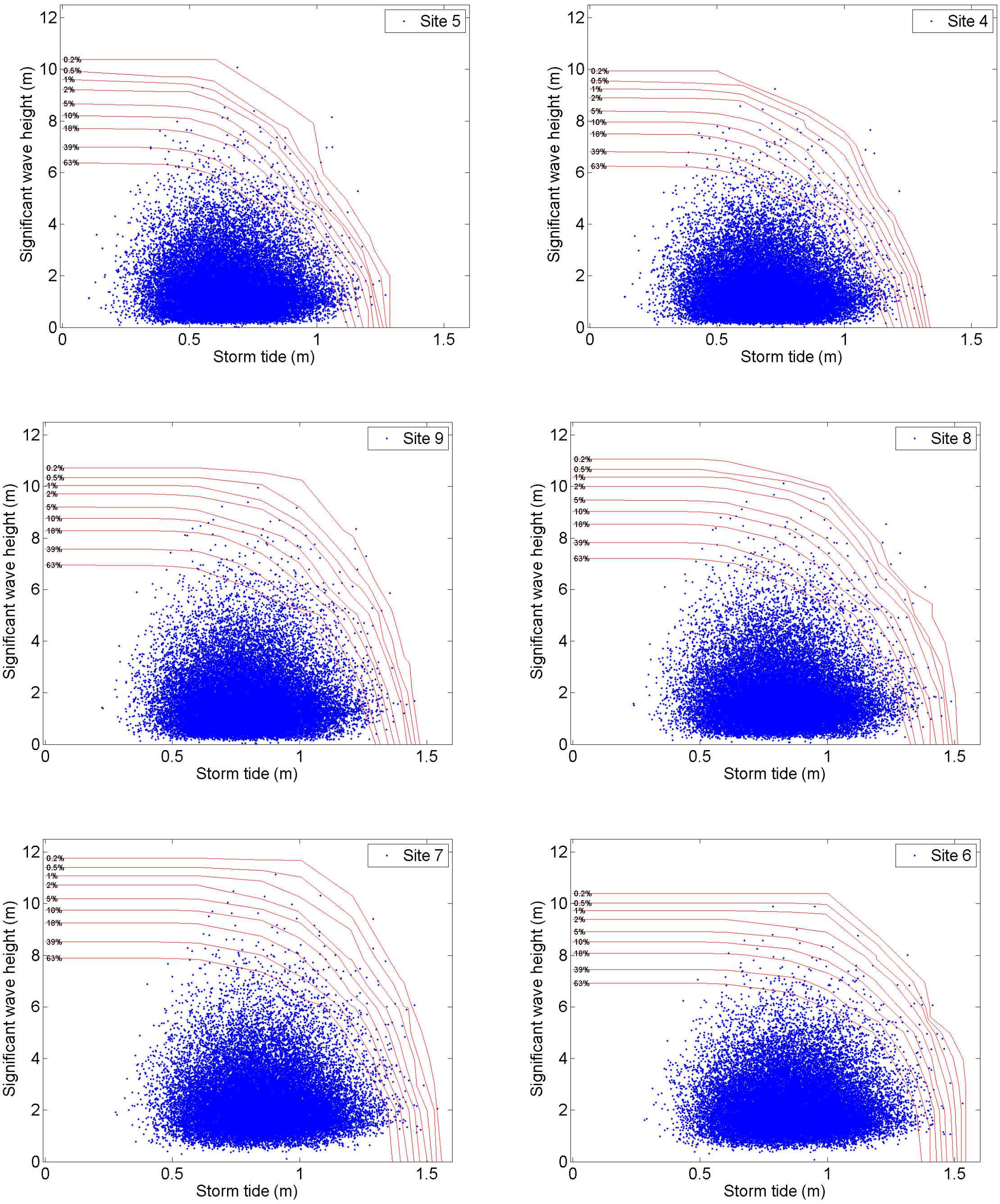

Figure 2-20: Scatter plot of significant wave height against storm tide level at sites 5,4,9,8 (south Wellington coast) and 6,7 (Wairarapa coast). Storm tide levels are relative to Wellington Vertical Datum 1953 adjusted to 2005–2011 base sea level.

Joint-probability contours for storm tide and wave height coinciding with various Annual exceedance probabilities (AEP) are plotted in Figure 2–19 for the western coast and Figure 2–20 for the southern and eastern coasts. At any location on a given contour line, the storm tide / wave combination has an equal likelihood of occurring. There is a difference in the shape of the contours between the western and south / eastern coasts, arising from the difference in correlation between waves and storm tides on each coast. At sites 1–3 on the west coast the joint-probability contours are comparatively “square”, with the contours simultaneously approaching both high storm tide and significant wave height values. This reflects the relatively high likelihood of the largest wave heights and storm tides occurring together. The difference in storm tide range at sites 1–3 reflects the increasing tidal range toward the north.

At sites 4–9 on the southern and eastern coasts the joint-probability contours are more “rounded”, with high storm tides more likely to occur in isolation from high significant wave heights and *vice versa*. This is because waves and storm tides are not highly correlated on the south and east coasts.

To highlight the shape difference between contours, the joint-probability contours for a joint 1% AEP event are overlaid in Figure 2-21. The joint-probability analyses show that on the west coast of the Wellington region, hazardous events are most likely to involve a combination of large waves coinciding with a high storm tide. On the south and east coasts, large waves are more likely to occur in isolation from large storm tides, and the wave climate is also more extreme due to exposure to long-fetch ocean swell.

Joint probabilities are given in Table 2-4–Table 2-12 for each site. Values for annual exceedance probabilities down to and including 1% are reliable for the techniques and data used in this study. Values for 0.5% and 0.2% annual exceedance probabilities are presented, but are less reliable due to modelling uncertainties; these values require more detailed analysis and assessment of risk.

In the past, annual exceedance probabilities were often calculated separately for both sea levels and waves, but there was no information on the likelihood of high sea levels and large waves coinciding. Without this information it is tempting, for example, to design for a 1% AEP wave event to coincide with a 1% AEP sea level; an event which is actually highly unlikely, having a much lower AEP. The joint probability analyses solve this problem and provide a realistic probability of occurrence for the joint occurrence of high sea level and waves, which can be applied over realistic design timeframes.

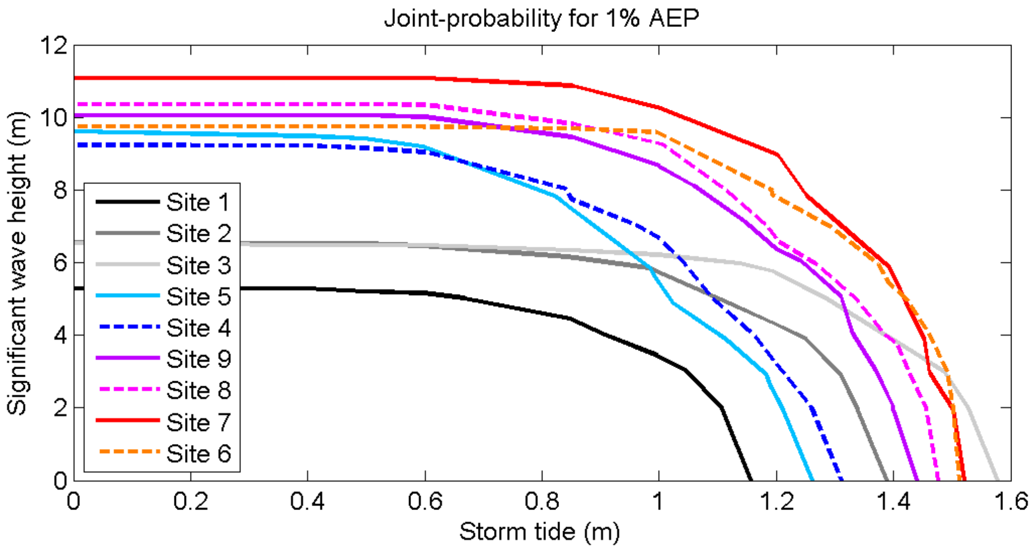

Figure 2-21: Joint-probability contours of storm tide and wave height at all sites for a joint 1% annual exceedance probability (AEP). Storm tide levels are relative to Wellington Vertical Datum 1953 adjusted to 2005–2011 base sea level.

Table 2-4: Joint-probability of storm tide sea level (SL metres) and significant wave height (Hs metres) for various annual exceedance probabilities (AEP) at site 1. Site 1 is located on western Kapiti coast (Figure 2-1). Storm tide levels are relative to Wellington Vertical Datum 1953 adjusted to 2005–2011 base sea level.

AEP	SL	H_s	AEP	SL	H_s	AEP	SL	H_s
63%	0.00	3.60	39%	0.00	3.91	18%	0.00	4.28
63%	0.40	3.54	39%	0.40	3.85	18%	0.40	4.23
63%	0.50	3.48	39%	0.50	3.80	18%	0.50	4.18
63%	0.60	3.38	39%	0.60	3.70	18%	0.60	4.09
63%	0.79	2.91	39%	0.85	2.97	18%	0.85	3.43
63%	0.85	2.61	39%	0.86	2.93	18%	0.93	2.95
63%	1.00	1.46	39%	1.00	1.87	18%	1.00	2.38
63%	1.08	0.00	39%	1.11	0.00	18%	1.13	0.00
AEP	SL	H_s	AEP	SL	H_s	AEP	SL	H_s
10%	0.00	4.55	5%	0.00	4.79	2%	0.00	5.09
10%	0.39	4.52	5%	0.39	4.75	2%	0.39	5.07
10%	0.49	4.49	5%	0.49	4.72	2%	0.48	5.04
10%	0.49	4.47	5%	0.58	4.67	2%	0.58	4.98
10%	0.58	4.40	5%	0.68	4.49	2%	0.80	4.53
10%	0.82	3.79	5%	0.83	4.07	2%	0.82	4.41
10%	0.95	2.98	5%	0.97	3.14	2%	0.97	3.59
10%	0.97	2.76	5%	0.99	2.99	2%	1.03	3.02
10%	1.14	0.00	5%	1.16	0.00	2%	1.16	0.82
						2%	1.18	0.00
AEP	SL	H_s	AEP	SL	H_s	AEP	SL	H_s
1%	0.00	5.29	0.5%	0.00	5.48	0.2%	0.00	5.72
1%	0.39	5.26	0.5%	0.39	5.34	0.2%	0.39	5.72
1%	0.48	5.25	0.5%	0.48	5.32	0.2%	0.48	5.66
1%	0.58	5.20	0.5%	0.58	5.25	0.2%	0.56	5.63
1%	0.82	4.59	0.5%	0.82	4.66	0.2%	0.58	5.56
1%	0.86	4.49	0.5%	0.90	4.41	0.2%	0.82	4.94
1%	0.97	3.89	0.5%	0.96	3.97	0.2%	0.94	4.22
1%	1.07	2.99	0.5%	1.09	2.94	0.2%	0.97	4.04
1%	1.16	1.29	0.5%	1.16	1.69	0.2%	1.14	2.82
1%	1.19	0.00	0.5%	1.20	0.00	0.2%	1.16	1.89
						0.2%	1.22	0.00

Table 2-5: Joint-probability of storm tide sea level (SL metres) and significant wave height (Hs metres) for various annual exceedance probabilities (AEP) at site 2. Site 2 is located on western Kapiti coast (Figure 2-1). Storm tide levels are relative to Wellington Vertical Datum 1953 adjusted to 2005–2011 base sea level.

AEP	SL	H_s	AEP	SL	H_s	AEP	SL	H_s
63%	0.00	4.45	39%	0.00	4.83	18%	0.00	5.29
63%	0.40	4.43	39%	0.40	4.81	18%	0.40	5.28
63%	0.50	4.41	39%	0.50	4.78	18%	0.50	5.23
63%	0.61	4.35	39%	0.60	4.73	18%	0.60	5.20
63%	0.63	4.33	39%	0.85	4.42	18%	0.85	4.92
63%	0.86	4.02	39%	0.87	4.38	18%	1.00	4.46
63%	1.01	3.45	39%	1.00	3.91	18%	1.01	4.40
63%	1.10	2.89	39%	1.14	2.92	18%	1.20	3.02
63%	1.21	1.83	39%	1.20	2.38	18%	1.21	2.93
63%	1.29	0.00	39%	1.32	0.00	18%	1.35	0.00
AEP	SL	H_s	AEP	SL	H_s	AEP	SL	H_s
10%	0.00	5.61	5%	0.00	5.92	2%	0.00	6.29
10%	0.39	5.60	5%	0.39	5.87	2%	0.39	6.26
10%	0.49	5.56	5%	0.46	5.84	2%	0.49	6.24
10%	0.59	5.50	5%	0.49	5.83	2%	0.59	6.23
10%	0.84	5.29	5%	0.59	5.80	2%	0.84	5.93
10%	0.98	4.85	5%	0.84	5.52	2%	0.89	5.78
10%	1.07	4.42	5%	0.99	5.17	2%	0.98	5.48
10%	1.18	3.42	5%	1.13	4.38	2%	1.18	4.37
10%	1.23	2.95	5%	1.18	3.78	2%	1.19	4.34
10%	1.36	0.00	5%	1.27	2.92	2%	1.30	2.89
			5%	1.38	0.00	2%	1.38	1.23
						2%	1.41	0.00
AEP	SL	H_s	AEP	SL	H_s	AEP	SL	H_s
1%	0.00	6.55	0.5%	0.00	6.79	0.2%	0.00	7.09
1%	0.39	6.49	0.5%	0.39	6.69	0.2%	0.40	7.04
1%	0.49	6.49	0.5%	0.49	6.69	0.2%	0.50	7.04
1%	0.59	6.46	0.5%	0.59	6.69	0.2%	0.59	7.04
1%	0.83	6.30	0.5%	0.84	6.54	0.2%	0.84	6.79
1%	0.98	5.95	0.5%	0.99	6.35	0.2%	0.99	6.59
1%	0.99	5.82	0.5%	1.06	5.89	0.2%	1.14	5.95
1%	1.18	4.76	0.5%	1.18	5.04	0.2%	1.19	5.46
1%	1.22	4.36	0.5%	1.25	4.42	0.2%	1.33	4.47
1%	1.33	2.91	0.5%	1.36	2.95	0.2%	1.39	2.98
1%	1.37	1.95	0.5%	1.38	2.52	0.2%	1.39	2.90
1%	1.42	0.00	0.5%	1.44	0.00	0.2%	1.46	0.00

Table 2-6: Joint-probability of storm tide sea level (SL metres) and significant wave height (Hs metres) for various annual exceedance probabilities (AEP) at site 3. Site 3 is located on western Kapiti coast (Figure 2-1). Storm tide levels are relative to Wellington Vertical Datum 1953 adjusted to 2005–2011 base sea level.

AEP	SL	H_s	AEP	SL	H_s	AEP	SL	H_s
63%	0.00	4.37	39%	0.00	4.72	18%	0.00	5.18
63%	0.40	4.37	39%	0.40	4.72	18%	0.40	5.18
63%	0.50	4.36	39%	0.50	4.71	18%	0.50	5.16
63%	0.61	4.33	39%	0.60	4.70	18%	0.60	5.13
63%	0.61	4.33	39%	0.85	4.56	18%	0.85	5.00
63%	0.86	4.17	39%	0.98	4.39	18%	1.00	4.78
63%	1.01	3.94	39%	1.00	4.34	18%	1.14	4.42
63%	1.21	3.20	39%	1.20	3.67	18%	1.20	4.22
63%	1.26	2.89	39%	1.31	2.93	18%	1.37	2.95
63%	1.41	1.41	39%	1.40	2.05	18%	1.40	2.70
63%	1.47	0.00	39%	1.50	0.00	18%	1.53	0.00
AEP	SL	H_s	AEP	SL	H_s	AEP	SL	H_s
10%	0.00	5.51	5%	0.00	5.83	2%	0.00	6.24
10%	0.40	5.51	5%	0.40	5.83	2%	0.40	6.24
10%	0.49	5.51	5%	0.50	5.83	2%	0.50	6.24
10%	0.59	5.49	5%	0.60	5.81	2%	0.59	6.16
10%	0.84	5.39	5%	0.84	5.72	2%	0.84	6.09
10%	0.99	5.12	5%	0.99	5.44	2%	0.92	5.98
10%	1.19	4.60	5%	1.19	4.90	2%	0.99	5.89
10%	1.22	4.48	5%	1.28	4.49	2%	1.19	5.16
10%	1.38	3.28	5%	1.39	3.74	2%	1.36	4.49
10%	1.40	2.98	5%	1.45	3.00	2%	1.39	4.31
10%	1.54	0.00	5%	1.57	0.00	2%	1.50	2.99
						2%	1.59	0.00
AEP	SL	H_s	AEP	SL	H_s	AEP	SL	H_s
1%	0.00	6.53	0.5%	0.00	6.82	0.2%	0.00	7.19
1%	0.40	6.53	0.5%	0.40	6.82	0.2%	0.40	7.19
1%	0.50	6.53	0.5%	0.50	6.82	0.2%	0.50	7.19
1%	0.60	6.52	0.5%	0.60	6.82	0.2%	0.60	7.19
1%	0.85	6.41	0.5%	0.84	6.73	0.2%	0.85	7.05
1%	1.00	6.19	0.5%	0.99	6.59	0.2%	1.00	7.05
1%	1.07	6.04	0.5%	1.16	6.13	0.2%	1.20	6.46
1%	1.19	5.61	0.5%	1.19	5.87	0.2%	1.24	6.34
1%	1.39	4.65	0.5%	1.39	5.00	0.2%	1.40	5.59
1%	1.41	4.53	0.5%	1.47	4.60	0.2%	1.53	4.75
1%	1.52	3.02	0.5%	1.55	3.07	0.2%	1.57	3.17
1%	1.61	0.00	0.5%	1.63	0.00	0.2%	1.65	0.00

Table 2-7: Joint-probability of storm tide sea level (SL metres) and significant wave height (Hs metres) for various annual exceedance probabilities (AEP) at site 4. Site 4 is located on southern Wellington coast close to the Baring Head wave buoy (Figure 2-1). Storm tide levels are relative to Wellington Vertical Datum 1953 adjusted to 2005–2011 base sea level.

AEP	SL	H_s	AEP	SL	H_s	AEP	SL	H_s
63%	0.00	6.26	39%	0.00	6.83	18%	0.00	7.50
63%	0.40	6.25	39%	0.40	6.81	18%	0.40	7.49
63%	0.50	6.18	39%	0.50	6.76	18%	0.50	7.44
63%	0.60	6.05	39%	0.60	6.61	18%	0.54	7.40
63%	0.70	5.74	39%	0.80	5.82	18%	0.60	7.30
63%	0.85	4.93	39%	0.84	5.53	18%	0.84	6.32
63%	0.92	4.31	39%	0.97	4.37	18%	0.89	5.92
63%	1.00	3.43	39%	0.99	4.06	18%	0.99	4.93
63%	1.04	2.87	39%	1.07	2.91	18%	1.03	4.44
63%	1.20	0.85	39%	1.19	1.44	18%	1.13	2.96
63%	1.21	0.00	39%	1.23	0.00	18%	1.19	2.03
						18%	1.26	0.00
AEP	SL	H_s	AEP	SL	H_s	AEP	SL	H_s
10%	0.00	7.97	5%	0.00	8.39	2%	0.00	8.89
10%	0.40	7.94	5%	0.40	8.37	2%	0.40	8.89
10%	0.50	7.91	5%	0.50	8.34	2%	0.50	8.80
10%	0.60	7.82	5%	0.60	8.19	2%	0.60	8.73
10%	0.73	7.47	5%	0.83	7.50	2%	0.85	7.85
10%	0.85	6.87	5%	0.85	7.32	2%	0.92	7.45
10%	0.96	5.98	5%	1.00	6.06	2%	1.00	6.57
10%	1.00	5.56	5%	1.01	6.00	2%	1.07	5.96
10%	1.08	4.48	5%	1.12	4.50	2%	1.17	4.47
10%	1.17	2.99	5%	1.19	3.00	2%	1.20	3.41
10%	1.20	2.45	5%	1.20	2.88	2%	1.23	2.98
10%	1.29	0.00	5%	1.31	0.00	2%	1.33	0.00
AEP	SL	H_s	AEP	SL	H_s	AEP	SL	H_s
1%	0.00	9.24	0.5%	0.00	9.55	0.2%	0.00	9.93
1%	0.40	9.24	0.5%	0.40	9.55	0.2%	0.40	9.93
1%	0.50	9.21	0.5%	0.50	9.54	0.2%	0.50	9.89
1%	0.60	9.19	0.5%	0.60	9.52	0.2%	0.60	9.89
1%	0.67	8.94	0.5%	0.77	8.89	0.2%	0.85	9.04
1%	0.85	8.23	0.5%	0.85	8.62	0.2%	0.85	8.95
1%	0.96	7.45	0.5%	1.00	7.41	0.2%	1.00	7.84
1%	1.00	6.94	0.5%	1.00	7.21	0.2%	1.05	7.46
1%	1.11	5.96	0.5%	1.15	5.93	0.2%	1.18	5.96
1%	1.19	4.47	0.5%	1.20	4.81	0.2%	1.20	5.44
1%	1.21	3.78	0.5%	1.22	4.44	0.2%	1.26	4.47
1%	1.27	2.98	0.5%	1.28	2.96	0.2%	1.30	2.98
1%	1.35	0.00	0.5%	1.36	0.00	0.2%	1.37	0.00

Table 2-8: Joint-probability of storm tide sea level (SL metres) and significant wave height (Hs metres) for various annual exceedance probabilities (AEP) at site 5. Site 5 is located on southern Wellington coast (Figure 2-1). Storm tide levels are relative to Wellington Vertical Datum 1953 adjusted to 2005–2011 base sea level.

AEP	SL	H_s	AEP	SL	H_s	AEP	SL	H_s
63%	0.00	6.39	39%	0.00	7.00	18%	0.00	7.72
63%	0.40	6.36	39%	0.40	6.97	18%	0.40	7.69
63%	0.50	6.28	39%	0.50	6.87	18%	0.50	7.63
63%	0.60	6.09	39%	0.60	6.68	18%	0.59	7.41
63%	0.69	5.72	39%	0.78	5.81	18%	0.61	7.35
63%	0.85	4.61	39%	0.85	5.21	18%	0.84	6.02
63%	0.89	4.29	39%	0.93	4.35	18%	0.86	5.88
63%	1.00	2.95	39%	1.00	3.50	18%	0.98	4.41
63%	1.01	2.86	39%	1.05	2.90	18%	0.99	4.24
63%	1.16	0.00	39%	1.19	0.00	18%	1.09	2.94
						18%	1.19	1.41
						18%	1.21	0.00
AEP	SL	H_s	AEP	SL	H_s	AEP	SL	H_s
10%	0.00	8.22	5%	0.00	8.68	2%	0.00	9.23
10%	0.40	8.19	5%	0.40	8.68	2%	0.40	9.23
10%	0.50	8.09	5%	0.50	8.59	2%	0.50	9.18
10%	0.60	7.85	5%	0.60	8.35	2%	0.60	8.85
10%	0.75	7.37	5%	0.82	7.38	2%	0.63	8.83
10%	0.85	6.56	5%	0.86	7.10	2%	0.85	7.73
10%	0.92	5.89	5%	0.97	5.90	2%	0.89	7.36
10%	1.00	4.76	5%	1.01	5.28	2%	1.00	5.96
10%	1.02	4.42	5%	1.07	4.43	2%	1.00	5.89
10%	1.14	2.95	5%	1.18	2.95	2%	1.10	4.42
10%	1.20	1.97	5%	1.21	2.48	2%	1.20	3.05
10%	1.24	0.00	5%	1.26	0.00	2%	1.21	2.94
						2%	1.28	0.00
AEP	SL	H_s	AEP	SL	H_s	AEP	SL	H_s
1%	0.00	9.61	0.5%	0.00	9.96	0.2%	0.00	10.37
1%	0.40	9.61	0.5%	0.40	9.96	0.2%	0.40	10.37
1%	0.50	9.46	0.5%	0.50	9.96	0.2%	0.51	10.37
1%	0.60	9.28	0.5%	0.60	9.39	0.2%	0.59	10.17
1%	0.73	8.81	0.5%	0.82	8.62	0.2%	0.61	9.92
1%	0.85	8.23	0.5%	0.86	8.35	0.2%	0.86	9.11
1%	0.93	7.34	0.5%	1.00	7.18	0.2%	0.92	8.72
1%	1.00	6.61	0.5%	1.01	6.95	0.2%	1.01	8.03
1%	1.06	5.88	0.5%	1.10	5.75	0.2%	1.06	7.26
1%	1.14	4.41	0.5%	1.16	4.31	0.2%	1.13	5.81
1%	1.21	3.47	0.5%	1.21	3.63	0.2%	1.19	4.36
1%	1.23	2.94	0.5%	1.24	2.87	0.2%	1.21	4.04
1%	1.30	0.00	0.5%	1.31	0.00	0.2%	1.26	2.91

Table 2-9: Joint-probability of storm tide sea level (SL metres) and significant wave height (Hs metres) for various annual exceedance probabilities (AEP) at site 6. Site 6 is located on Wairarapa coast just south of Riversdale (Figure 2-1). Storm tide levels are relative to Wellington Vertical Datum 1953 adjusted to 2005–2011 base sea level.

AEP	SL	H_s	AEP	SL	H_s	AEP	SL	H_s
63%	0.00	6.93	39%	0.00	7.45	18%	0.00	8.09
63%	0.40	6.93	39%	0.40	7.45	18%	0.40	8.09
63%	0.50	6.93	39%	0.50	7.44	18%	0.50	8.09
63%	0.60	6.90	39%	0.60	7.44	18%	0.60	8.07
63%	0.85	6.67	39%	0.82	7.28	18%	0.85	7.88
63%	1.00	6.24	39%	0.85	7.22	18%	1.01	7.43
63%	1.09	5.76	39%	1.00	6.81	18%	1.05	7.27
63%	1.20	4.91	39%	1.17	5.82	18%	1.21	6.28
63%	1.25	4.32	39%	1.20	5.55	18%	1.26	5.82
63%	1.35	2.88	39%	1.30	4.37	18%	1.37	4.36
63%	1.40	1.51	39%	1.39	2.91	18%	1.41	3.67
63%	1.41	0.00	39%	1.40	2.56	18%	1.44	2.91
			39%	1.44	0.00	18%	1.48	0.00
AEP	SL	H_s	AEP	SL	H_s	AEP	SL	H_s
10%	0.00	8.52	5%	0.00	8.92	2%	0.00	9.40
10%	0.40	8.52	5%	0.40	8.92	2%	0.40	9.40
10%	0.50	8.52	5%	0.50	8.92	2%	0.50	9.40
10%	0.60	8.52	5%	0.59	8.91	2%	0.60	9.37
10%	0.85	8.33	5%	0.84	8.73	2%	0.84	9.26
10%	0.99	7.93	5%	0.89	8.62	2%	0.99	8.95
10%	1.12	7.25	5%	0.99	8.29	2%	1.06	8.66
10%	1.19	6.80	5%	1.19	7.25	2%	1.19	7.97
10%	1.29	5.80	5%	1.20	7.18	2%	1.27	7.22
10%	1.39	4.36	5%	1.33	5.75	2%	1.39	5.78
10%	1.39	4.35	5%	1.39	4.93	2%	1.39	5.70
10%	1.44	2.90	5%	1.42	4.31	2%	1.45	4.33
10%	1.48	0.00	5%	1.47	2.87	2%	1.50	2.89
			5%	1.51	0.00	2%	1.53	0.00
AEP	SL	H_s	AEP	SL	H_s	AEP	SL	H_s
1%	0.00	9.73	0.5%	0.00	10.03	0.2%	0.00	10.39
1%	0.40	9.73	0.5%	0.40	10.03	0.2%	0.40	10.39
1%	0.50	9.73	0.5%	0.50	10.03	0.2%	0.50	10.39
1%	0.60	9.71	0.5%	0.60	10.03	0.2%	0.60	10.39
1%	0.85	9.70	0.5%	0.85	9.93	0.2%	0.85	10.26
1%	1.00	9.38	0.5%	0.99	9.50	0.2%	1.00	10.12
1%	1.18	8.76	0.5%	1.19	8.85	0.2%	1.15	10.08
1%	1.20	8.66	0.5%	1.22	8.56	0.2%	1.20	9.00
1%	1.32	7.30	0.5%	1.37	7.13	0.2%	1.28	8.64
1%	1.40	6.30	0.5%	1.39	6.61	0.2%	1.40	7.23
1%	1.42	5.84	0.5%	1.44	5.71	0.2%	1.41	7.20
1%	1.48	4.38	0.5%	1.50	4.28	0.2%	1.48	5.76
1%	1.53	2.92	0.5%	1.54	2.85	0.2%	1.53	4.32
1%	1.55	0.00	0.5%	1.56	0.00	0.2%	1.56	2.88

Table 2-10: Joint-probability of storm tide sea level (SL metres) and significant wave height (Hs metres) for various annual exceedance probabilities (AEP) at site 7. Site 7 is located on Wairarapa coast near Manurewa Point (Figure 2-1). Storm tide levels are relative to Wellington Vertical Datum 1953 adjusted to 2005–2011 base sea level.

AEP	SL	H_s	AEP	SL	H_s	AEP	SL	H_s
63%	0.00	7.89	39%	0.00	8.52	18%	0.00	9.26
63%	0.40	7.89	39%	0.40	8.52	18%	0.40	9.26
63%	0.50	7.89	39%	0.50	8.50	18%	0.50	9.24
63%	0.60	7.86	39%	0.60	8.49	18%	0.60	9.21
63%	0.85	7.49	39%	0.85	8.12	18%	0.85	8.87
63%	0.92	7.27	39%	1.00	7.49	18%	0.88	8.80
63%	1.00	6.84	39%	1.03	7.32	18%	1.00	8.32
63%	1.13	5.82	39%	1.19	5.85	18%	1.13	7.33
63%	1.20	4.93	39%	1.20	5.69	18%	1.20	6.59
63%	1.23	4.36	39%	1.28	4.39	18%	1.24	5.87
63%	1.32	2.91	39%	1.36	2.93	18%	1.32	4.40
63%	1.40	1.34	39%	1.40	2.06	18%	1.39	2.93
63%	1.40	0.00	39%	1.43	0.00	18%	1.39	2.93
						18%	1.46	0.00
AEP	SL	H_s	AEP	SL	H_s	AEP	SL	H_s
10%	0.00	9.75	5%	0.00	10.20	2%	0.00	10.72
10%	0.40	9.75	5%	0.40	10.20	2%	0.40	10.72
10%	0.50	9.75	5%	0.50	10.20	2%	0.50	10.72
10%	0.60	9.74	5%	0.57	10.17	2%	0.60	10.71
10%	0.84	9.39	5%	0.60	10.14	2%	0.85	10.51
10%	0.99	8.80	5%	0.85	9.85	2%	1.00	10.23
10%	1.00	8.76	5%	1.00	9.33	2%	1.01	10.19
10%	1.18	7.30	5%	1.09	8.72	2%	1.18	8.73
10%	1.19	7.17	5%	1.20	7.90	2%	1.20	8.63
10%	1.28	5.84	5%	1.23	7.26	2%	1.30	7.28
10%	1.36	4.38	5%	1.32	5.81	2%	1.38	5.82
10%	1.39	3.66	5%	1.40	4.36	2%	1.40	5.21
10%	1.42	2.92	5%	1.40	4.29	2%	1.43	4.37
10%	1.48	0.00	5%	1.45	2.91	2%	1.47	2.91
			5%	1.51	0.00	2%	1.54	0.00
AEP	SL	H_s	AEP	SL	H_s	AEP	SL	H_s
1%	0.00	11.08	0.5%	0.00	11.39	0.2%	0.00	11.77
1%	0.40	11.08	0.5%	0.40	11.39	0.2%	0.40	11.77
1%	0.50	11.08	0.5%	0.50	11.39	0.2%	0.50	11.77
1%	0.60	11.08	0.5%	0.60	11.35	0.2%	0.61	11.77
1%	0.85	10.89	0.5%	0.85	11.26	0.2%	0.86	11.45
1%	1.00	10.53	0.5%	1.00	10.99	0.2%	0.95	11.45
1%	1.12	10.02	0.5%	1.19	10.11	0.2%	1.01	11.41
1%	1.21	9.13	0.5%	1.20	9.99	0.2%	1.21	10.34
1%	1.24	8.59	0.5%	1.27	8.66	0.2%	1.31	10.02
1%	1.33	7.16	0.5%	1.36	7.22	0.2%	1.33	8.59
1%	1.41	5.74	0.5%	1.40	6.44	0.2%	1.41	7.16
1%	1.41	5.72	0.5%	1.43	5.78	0.2%	1.41	6.97
1%	1.46	4.29	0.5%	1.46	4.33	0.2%	1.46	5.73
1%	1.51	2.86	0.5%	1.50	2.89	0.2%	1.48	4.29
1%	1.56	0.00	0.5%	1.57	0.00	0.2%	1.53	2.86

Table 2-11: Joint-probability of storm tide sea level (SL metres) and significant wave height (Hs metres) for various annual exceedance probabilities (AEP) at site 8. Site 8 is located in Palliser Bay (Te Humenga Point) (Figure 2-1). Storm tide levels are relative to Wellington Vertical Datum 1953 adjusted to 2005–2011 base sea level.

AEP	SL	H_s	AEP	SL	H_s	AEP	SL	H_s
63%	0.00	7.21	39%	0.00	7.82	18%	0.00	8.55
63%	0.40	7.21	39%	0.40	7.82	18%	0.40	8.55
63%	0.50	7.19	39%	0.50	7.81	18%	0.50	8.53
63%	0.60	7.13	39%	0.60	7.75	18%	0.60	8.47
63%	0.85	6.56	39%	0.81	7.32	18%	0.85	7.99
63%	0.98	5.79	39%	0.84	7.22	18%	0.98	7.38
63%	1.00	5.64	39%	0.99	6.36	18%	1.00	7.16
63%	1.13	4.34	39%	1.05	5.86	18%	1.14	5.91
63%	1.20	3.40	39%	1.17	4.39	18%	1.21	5.11
63%	1.23	2.89	39%	1.19	4.15	18%	1.25	4.43
63%	1.36	0.00	39%	1.27	2.93	18%	1.34	2.95
			39%	1.38	0.00	18%	1.41	1.67
						18%	1.43	0.00
AEP	SL	H_s	AEP	SL	H_s	AEP	SL	H_s
10%	0.00	9.04	5%	0.00	9.48	2%	0.00	10.00
10%	0.40	9.04	5%	0.40	9.48	2%	0.40	10.00
10%	0.50	9.02	5%	0.50	9.47	2%	0.50	9.99
10%	0.60	8.96	5%	0.60	9.42	2%	0.60	9.95
10%	0.67	8.87	5%	0.85	9.04	2%	0.85	9.65
10%	0.85	8.50	5%	0.90	8.83	2%	1.00	9.08
10%	1.00	7.82	5%	1.00	8.29	2%	1.04	8.81
10%	1.05	7.40	5%	1.12	7.36	2%	1.19	7.35
10%	1.19	5.92	5%	1.20	6.46	2%	1.20	7.29
10%	1.20	5.77	5%	1.24	5.89	2%	1.30	5.88
10%	1.29	4.44	5%	1.33	4.42	2%	1.39	4.41
10%	1.36	2.96	5%	1.39	2.94	2%	1.40	3.79
10%	1.40	2.16	5%	1.40	2.68	2%	1.42	2.94
10%	1.44	0.00	5%	1.46	0.00	2%	1.49	0.00
AEP	SL	H_s	AEP	SL	H_s	AEP	SL	H_s
1%	0.00	10.36	0.5%	0.00	10.68	0.2%	0.00	11.05
1%	0.40	10.36	0.5%	0.40	10.68	0.2%	0.40	11.05
1%	0.50	10.36	0.5%	0.50	10.57	0.2%	0.51	10.95
1%	0.60	10.36	0.5%	0.60	10.57	0.2%	0.61	10.95
1%	0.68	10.24	0.5%	0.85	10.43	0.2%	0.86	10.65
1%	0.85	10.02	0.5%	0.93	10.31	0.2%	1.01	10.49
1%	1.00	9.52	0.5%	1.00	10.03	0.2%	1.03	10.39
1%	1.10	8.78	0.5%	1.16	8.84	0.2%	1.21	9.30
1%	1.20	8.00	0.5%	1.20	8.51	0.2%	1.26	8.90
1%	1.25	7.31	0.5%	1.29	7.36	0.2%	1.40	7.42
1%	1.35	5.85	0.5%	1.38	5.89	0.2%	1.42	6.94
1%	1.40	4.73	0.5%	1.40	5.74	0.2%	1.43	5.94
1%	1.41	4.39	0.5%	1.43	4.42	0.2%	1.47	4.45
1%	1.45	2.93	0.5%	1.46	2.95	0.2%	1.51	2.97
100	1.51	0.00	0.5%	1.53	0.00	0.2%	1.55	0.00

Table 2-12: Joint-probability of storm tide sea level (SL metres) and significant wave height (Hs metres) for various annual exceedance probabilities (AEP) at site 9. Site 9 is located in Palliser Bay of Lake Ferry (Figure 2-1). Storm tide levels are relative to Wellington Vertical Datum 1953 adjusted to 2005–2011 base sea level.

AEP	SL	H_s	AEP	SL	H_s	AEP	SL	H_s
63%	0.00	6.95	39%	0.00	7.57	18%	0.00	8.29
63%	0.40	6.94	39%	0.40	7.57	18%	0.40	8.29
63%	0.50	6.94	39%	0.50	7.57	18%	0.50	8.27
63%	0.60	6.88	39%	0.60	7.49	18%	0.60	8.23
63%	0.85	6.26	39%	0.73	7.32	18%	0.85	7.68
63%	0.94	5.78	39%	0.84	6.91	18%	0.92	7.38
63%	1.00	5.31	39%	0.99	6.00	18%	1.00	6.84
63%	1.09	4.34	39%	1.01	5.85	18%	1.09	5.91
63%	1.20	2.89	39%	1.13	4.39	18%	1.21	4.49
63%	1.20	2.83	39%	1.19	3.57	18%	1.22	4.43
63%	1.34	0.00	39%	1.23	2.93	18%	1.29	2.95
			39%	1.35	0.00	18%	1.40	0.00
AEP	SL	H_s	AEP	SL	H_s	AEP	SL	H_s
10%	0.00	8.77	5%	0.00	9.20	2%	0.00	9.71
10%	0.40	8.77	5%	0.40	9.20	2%	0.40	9.71
10%	0.50	8.75	5%	0.50	9.19	2%	0.50	9.71
10%	0.59	8.71	5%	0.60	9.08	2%	0.60	9.49
10%	0.84	8.18	5%	0.79	8.82	2%	0.85	8.98
10%	0.99	7.44	5%	0.85	8.66	2%	0.98	8.59
10%	1.00	7.38	5%	1.00	7.89	2%	1.01	8.33
10%	1.13	5.90	5%	1.06	7.35	2%	1.13	7.16
10%	1.19	5.14	5%	1.19	5.88	2%	1.21	6.36
10%	1.23	4.43	5%	1.20	5.70	2%	1.25	5.73
10%	1.31	2.95	5%	1.28	4.41	2%	1.34	4.30
10%	1.39	1.30	5%	1.35	2.94	2%	1.39	2.86
10%	1.41	0.00	5%	1.40	1.85	2%	1.41	2.45
			5%	1.43	0.00	2%	1.46	0.00
AEP	SL	H_s	AEP	SL	H_s	AEP	SL	H_s
1%	0.00	10.05	0.5%	0.00	10.35	0.2%	0.00	10.71
1%	0.40	10.05	0.5%	0.40	10.35	0.2%	0.40	10.71
1%	0.50	10.05	0.5%	0.50	10.35	0.2%	0.51	10.71
1%	0.60	9.80	0.5%	0.60	10.30	0.2%	0.61	10.54
1%	0.67	9.75	0.5%	0.85	9.77	0.2%	0.86	10.36
1%	0.85	9.10	0.5%	0.86	9.66	0.2%	0.93	9.83
1%	1.00	8.54	0.5%	1.01	8.78	0.2%	1.01	9.13
1%	1.04	8.36	0.5%	1.12	8.37	0.2%	1.15	8.42
1%	1.16	6.97	0.5%	1.21	7.05	0.2%	1.21	7.85
1%	1.20	6.58	0.5%	1.23	6.98	0.2%	1.32	7.02
1%	1.30	5.57	0.5%	1.35	5.58	0.2%	1.40	5.62
1%	1.36	4.18	0.5%	1.39	4.19	0.2%	1.42	5.22
1%	1.40	2.88	0.5%	1.41	3.70	0.2%	1.44	4.21
1%	1.40	2.79	0.5%	1.43	2.79	0.2%	1.45	2.81
1%	1.47	0.00	0.5%	1.49	0.00	0.2%	1.51	0.00

3 Glossary of abbreviations and terms

Annual exceedance probability (AEP)	The probability of a given (usually high) sea level being equalled or exceeded in elevation, in any given calendar year. AEP can be specified as a fraction (e.g., 0.01) or a percentage (e.g., 1%).
Average recurrence interval (ARI)	The average time interval (averaged over a long time period and many "events") that is expected to elapse between recurrences of an infrequent event of a given large magnitude (or larger). A large infrequent event would be expected to be equalled or exceeded in elevation, once, on average, every "ARI" years.
Future cast	A numerical simulation (representation) of *future* conditions. Differs from a *forecast*; whereas a forecast aims to predict the exact time-dependent conditions in the immediate future, such as a weather forecast a *future cast* aims to simulate a time-series of conditions that would be typical of the future (from which statistical properties can be calculated) but does not predict an exact time-sequence.
GPD	Generalised Pareto distribution: a statistical distribution suitable for modelling the extreme values of a dataset above a high threshold. Used in this study to extrapolate extreme significant wave heights by fitting to the largest 5% of modelled and measured significant wave heights, and modelled joint-probabilities.
H_0	Significant wave height: the average of the largest 33% of wave heights.
Hindcast	A numerical simulation (representation) of *past* conditions. As opposed to a forecast or future cast that simulates the future.
H_s	Scaled hindcast significant wave height.
Joint-probability	The probability of two separate processes occurring together (e.g., large waves and high storm tide).
Marginal variable	Refers to a single variable (e.g., wave height, or storm tide) representing one axis, or "margin", of a joint-probability plot.
Mean level of the sea (MLOS)	The variation of the non-tidal sea level on time scales ranging from a monthly basis to decades, due to climate variability. This includes ENSO and IPO patterns on sea level, winds and sea temperatures, and seasonal effects.
SL	Storm-tide level.
Storm surge	The rise in sea level due to storm meteorological effects. Low-atmospheric pressure causes the sea-level to rise, and wind stress on the ocean surface pushes water down-wind and to the left up against any adjacent coast.
Storm tide	Storm tide is defined as the sea-level peak around high tide reached during a storm event, resulting from a combination of MLOS + tide + storm surge.

WASP	The NIWA Waves And Storm Surge Projections research programme to produce a model, validated by 40 years of historic data, to project future wave and storm surges at a nationally consistent scale off the New Zealand coast <http://www.niwa.co.nz/our-science/coasts/research-projects/all/wasp>
Wave run-up	The maximum vertical extent of wave "up-rush" on a beach or structure above the still water level, and thus constitutes only a short-term upper-bound fluctuation in water level relative to wave setup.
Wave setup	The increase in mean still-water sea level at the coast, resulting from the release of wave energy in the surf zone as waves break.

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