REPORT

Tonkin+Taylor

Coastal Flood Hazard Zones for Select Northland Sites

2017 Update

Prepared for
Northland Regional Council

Prepared by
Tonkin & Taylor Ltd

Date
December 2017

Job Number
1001049

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Document Control

Title: Coastal Flood Hazard Zones for Select Northland Sites					
Date	Version	Description	Prepared by:	Reviewed by:	Authorised by:
05-2016	1	Final Report	P. Knook	T. Shand	R. Reinen-Hamill
12-2017	2	2017 Update report	P. Knook	T. Shand	R. Reinen-Hamill

Updates included in the 2017 report

The following updates from T+T (2016) have been included in this report and maps:

- Two sites have been added to the original 61 sites:
  - 62 - Whangarei Harbour North
  - 63 - Ocean Beach
- New LiDAR data (2016) has been used for Marsden Point (6), Marsden Cove (7) and Whangarei Harbour North sites (10, 11, 62 and 63). A resolution of 1 m was used to create the new DEMs
- The CFHZ GIS layers have been smoothed
- Revised methods where used to assess CFHZ and CRHZ along Paihia CBD foreshore including effects of ponding by wave overtopping and the influence of the rock protection structures
- The following sites have been split into open coast and estuary sites (previously adopted as open coast only) to more adequately allow for potentially lower inundation levels within the estuaries of these sites:
  - 19 Teal Bay
  - 27 Paihia
  - 31 Tauranga Bay
  - 32A Mahinepua
  - 32C Te Ngaere
  - 37 Taupo Bay
- CFHZ maps for higher volumes sites include Ruawai (59), Dargaville (58) and Awanui (44) have not been included as these are being assessed separately.

Distribution:

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Executive summary

Tonkin & Taylor Ltd (T+T) have been commissioned by Northland Regional Council (NRC) in 2015 to prepare a report and maps that assessed *Coastal Flood Hazard Zones* (CFHZs) for selected sites in the Northland region. In 2017 NRC requested T+T to revise this report to include some adjustments (refer Document control for list) and these have been included in the present report.

The hazard zones are consistent with NZCPS Policy 24 which requires identification of areas in the coastal environment that are potentially affected by coastal hazards over at least 100 years and having regard to cumulative effects of sea level rise, storm surge and wave height under storm conditions.

This assessment has considered the drivers of coastal flooding and run-up in the Northland region to derive extreme static water levels and run-up levels. These processes are driven by astronomical tide, storm surge, and medium term fluctuations in sea level, wave processes and long-term changes in mean sea level. Calculated run-up levels have been validated against measurements of run-up debris after a substantial storm event in January 2008. Several methods were tested with adopted method generally calculating values within 10% of observed values.

This assessment has presented extreme static and dynamic (run-up) levels corresponding to the present day, 2065 (50 years) and 2115 (100 years). These have been used to map coastal flood hazard zones (CFHZ) and coastal run-up hazard zones (CRHZ) for the following scenarios:

- Coastal Flood Hazard Zone 0 (CFHZ0): Extent of 1% AEP static water level at 2015
- Coastal Flood Hazard Zone 1 (CFHZ1): Extent of 2% AEP static water level at 2065
- Coastal Flood Hazard Zone 2 (CFHZ2): Extent of 1% AEP static water level at 2115
- Coastal Run-up Hazard Zone (CRHZ): Extent of 1% AEP dynamic wave run-up at 2115.

Coastal flood hazard zones have been mapped using a connected bathtub model where areas are flooded only where they connect to the coastal water body (or by a structure such as a drainage channel or culvert). This provides more realistic flooding extents by accounting for natural and human influenced topography.

Run-up differs from static flooding as run-up is a dynamic process. Coastal run-up hazard zones have been mapped by applying an attenuation model to the maximum run-up elevation to determine the maximum inland excursion reached by the run-up flows.

Flood mapping has only been undertaken for areas where LiDAR data is available. Where flooding reaches the boundary of the LiDAR, flooding may continue outside area but is not able to be mapped. In these cases, and where LiDAR is missing, the derived static levels at the coast should be used to determine exposure to coastal flooding hazard.

Several sources of potential uncertainty have been noted including the LiDAR extents, the current landform adopted and inclusion of human induced changes, the merging of adjacent cells and exclusion of overtopping flows. The most significant, however, is the flooding of large, low lying areas such as the Ruawai, Dargaville and Awanui areas. In these area, the connected bathtub approach may result in conservative flood extents due to the limited duration of the maximum flood and frictional losses across the land. Dynamic (hydrodynamic) modelling for these sites is being undertaken separately and maps for these sites have therefore not been included in this report.

1 Introduction

1.1 Background

Tonkin & Taylor Ltd (T+T) have been commissioned by Northland Regional Council (NRC) in 2015 to prepare a report and maps that assessed *Coastal Flood Hazard Zones* (CFHZs) for selected sites in the Northland region. In 2017 NRC requested to revise this report to include minor adjustments and these have been included in the present report.

The hazard zones are consistent with NZCPS Policy 24 which requires identification of areas in the coastal environment that are potentially affected by coastal hazards over at least 100 years and having regard to cumulative effects of sea level rise, storm surge and wave height under storm conditions. Hazard zones have been developed for 50 year and 100 year time frames.

NRC's proposed Regional Policy Statement gives effect to the policies of the NZCPS, particularly with regard to their natural hazard policies 7.1.1 to 7.1.10. Both policies require assessments to be undertaken using the best available information and techniques resulting in outputs suitable for informing risk-based assessments, but also require that where there is uncertainty in the likelihood or consequences of a natural hazard event, decision-makers will adopt a precautionary approach.

CFHZs have been assessed for 63 sites including 34 *open coast sites* (defined as being exposed to ocean swell) and 29 *sheltered sites* (within harbours, estuaries and waterways). Coastal flooding is generally controlled by the maximum static water level (*extreme static water level*) resulting from a combination of storm tide and wave set-up (refer Section 3.1). These have been mapped based on a connected bathtub approach whereby all areas connected to the elevated coastal water level are flooded. Areas protected by stopbanks or natural topography are not flooded unless there is a structure which allows inflow from the coast.

However, wave run-up may extend above this static flood level (see Figure 2-1). While this run-up may be hazardous near the coastal edge, the momentum of the flow is quickly dissipated on land and the intermittent nature means that it does not generally contribute significantly to coastal flooding. The *extreme run-up level* and the inland extent of hazardous flow has been evaluated separately and used to define *Coastal Run-up Hazard Zones* (CRHZ). This has, however, been assessed for open coasts only with insufficient data available to define run-up levels and inland extents for sheltered sites. Run-up levels are expected to be low in these areas due to the limited wave height.

These CFHZs and CRHZs have been derived and mapped in coastal areas where the Regional Council holds LIDAR data (63 sites). Figure 1-1 shows the location of these 63 sites.

1.2 Scope

The scope of works for this project has been as follows:

a Review of tidal gauge data and derivation of extreme values for each tide gauge site. Use to rationalise storm tide levels at selected locations around the Northland region.

b Assess wave set-up and run-up effects on open coast sites using wave models and data previously constructed by T+T for the coastal erosion hazard assessment.

c Assess potential wave effects within Northland sheltered estuary and harbour sites.

d Derive extreme static and run-up levels for both open coast and sheltered sites.

e Develop guidelines for site-specific assessment of wave run-up hazard.

f Map extents of CFHZ0, CFHZ1 and CFHZ2 for open coast sites using Council LiDAR data.

g Map extents of CRHZ2 (termed CRHZ in the maps) for open coast sites using Council LiDAR data.

h Map CFHZ0, CFHZ1 and CFHZ2 areas for sheltered harbour/estuary sites using Council LiDAR data.

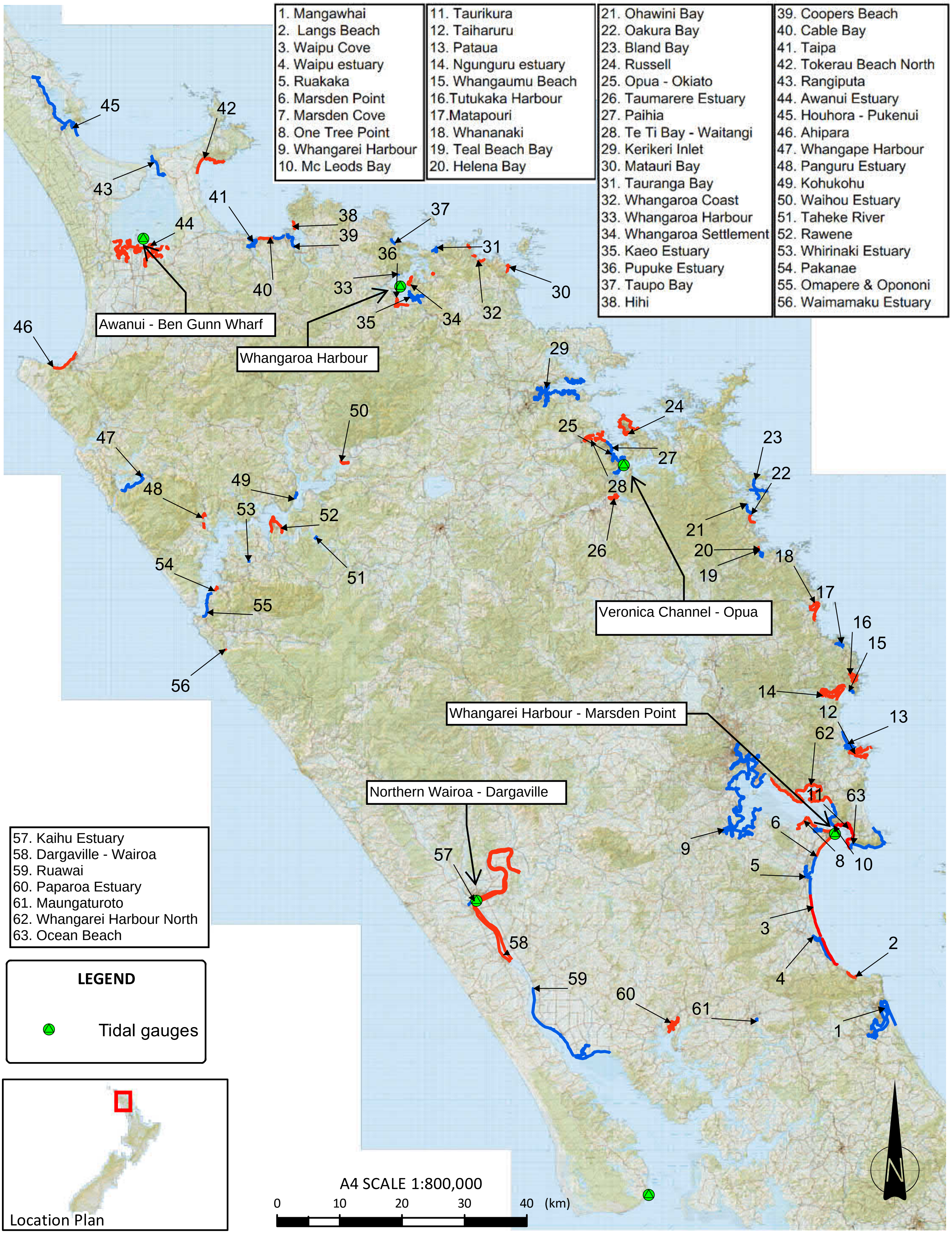
1.3 Report outline

Section 2 presents background data used in the present assessment including wave and water level data and topographic data. Section 3 presents the methodology used to derive extreme static and run-up levels and verification of techniques. Section 4 presents results of the CFHZ and CRHZ assessment in terms of tabulated levels. Study conclusions and recommendations are presented within Section 5.

1.4 Datums and coordinates

All elevations (levels) within this report are presented in terms of One Tree Point Vertical Datum 1964 (OTP64 or Reduced Level). Mean sea level varies with respect to OTP64 around the Northland coast (refer Section 2, Table 2-1) resulting in slightly different inundation levels, even where exposure is similar.

All coordinates are presented in terms of New Zealand Transverse Mercator (NZTM).



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NRC Coastal Inundation

Site Location Plan

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2 Background data

2.1 Previous assessments

A number of previous assessments of coastal hazard including the effects of coastal flooding have been undertaken within the Northland region. The following reports have been reviewed and used as background information for this study where appropriate:

- Bell and Gorman (2003) Overview of Weather and Coastal Hazards in the Northland Region – Part II: Coastal Hazards.
- Gibb (1988) Northland Regional Council 1988 Coastal Hazard Identification. Whangarei County.
- Gibb (1998) Review of Coastal Hazard Zones for Eleven Selected beaches in Whangarei District Northland Region.
- Gibb (1998) Coastal Hazard Zone Assessment for the One Tree Point Marsden Bay Area Whangarei Harbour.
- Gibb (1999) Coastal Hazard Risk Zone Assessment for Patau and Matapouri Bay, Whangarei District.
- NRC (1991) Coastal Hazard Identification in Former Mangonui County Area.
- NRC (2005) Coastal Inundation Hazard Assessment for Selected Far North Settlements.
- Tonkin & Taylor (2014) Coastal Erosion Hazard Zone Assessment for Selected Northland Sites.

2.2 Topography

Topographic data collected by Light Detection and Ranging (LiDAR) methods was provided by NRC in post processed xyz format for all 63 sites. The LiDAR data was captured between 2003 and 2016, depending on the site with available data shown in Appendix A. The data was converted from NZGD2000 ellipsoidal heights into One Tree Point 1964 Vertical Datum using the Land Information New Zealand (LINZ) NZGeiod05 separation and offset model.

2.3 Water levels

The water level at any time is determined by the combination of several components including both deterministic and stochastic components.

Key components that determine water level are:

- Mean sea level
- Astronomical tides
- Barometric and wind effects, generally referred to as storm surge
- Medium term fluctuations, including ENSO and IPO effects
- Long-term changes in relative sea level due to climatic or geological changes
- Nearshore wave effects (refer Section 2.4).

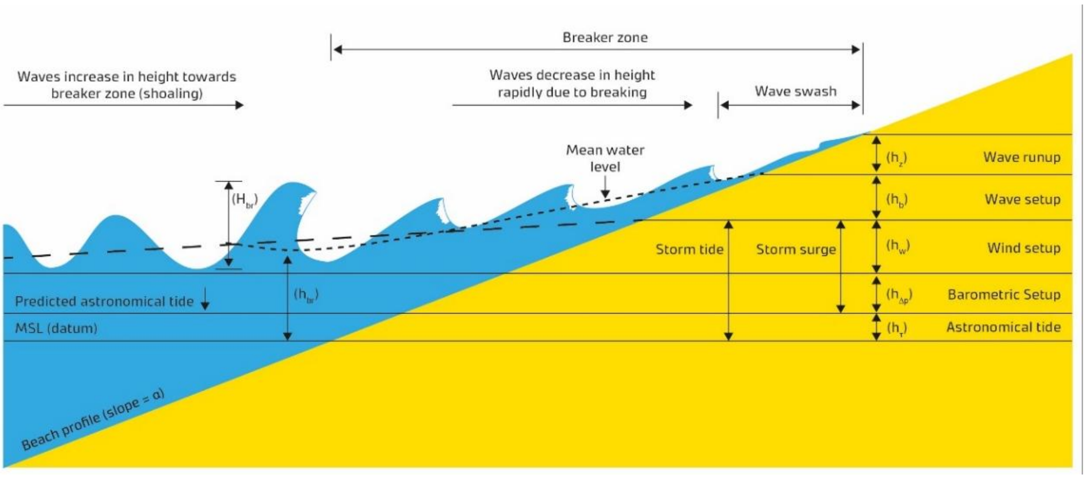

Figure 2-1: Key components that determine water level

2.3.1 Mean sea level

Six tide gauges are situated around Northland coastline. Figure 1-1 shows the location of these tide gauge sites. Table 2-1 shows, for each tidal gauge, the record duration and length, and gauge zero offsets relative to OTP64. Tide gauge locations tend to be in sheltered and/or deep water environments meaning that records will include storm tide effects but not the effects of wave set-up.

Table 2-1: Tide gauge information

Gauge site	Tide gauge record dates	Record length (years)	Levels (mm)		
			MSL relative gauge datum	Gauge datum relative OTP64	MSL relative OTP64
Marsden Point (One Tree Point)	1984-2014	30	1571	-1677	-106
Opua Wharf	1998-2014	16	1478	-1560	-82
Whangaroa Harbour	2008-2014	6	1587	-1555	32
Ben Gunn Wharf	2004-2014	10	3500	-3530	-30
Pouto Point	2001-2014	13	153	0	153
Dargaville	1981-2013	32	3248	-3090	158

2.3.2 Astronomical tide

Tidal levels for primary and secondary ports of New Zealand are provided by LINZ (2013) based on the average predicted values over the 18.6 year tidal cycle. Values for Marsden Point in terms of local Chart Datum and One Tree Point Vertical Datum 1964 (OTP64) are presented within Table 2-2. MHWS value for other Secondary Ports around the Northland region given by LINZ (2013) are presented in Table 2-3.

Mean High Water Springs (MHWS) levels relative to MSL = 0 around Northland calculated by NIWA (2015) based on analysis of tide gauges records (refer to Table 2-1) are presented in Figure 2-2. This shows MHWS on the east coast to range by up to 0.18 m (1.04 – 1.22 m MSL) with largest values in the south. MHWS on the west coast is larger by comparison (1.38 – 1.47 m MSL), increases slightly to the south and is amplified within Shipwreck Bay near Ahipara.

Table 2-2: Tidal levels determined for Marsden Point (LINZ, 2013)

Tide state	Chart Datum (m)	OTP64 (m)
Highest Astronomical Tide (HAT)	2.98	1.30
Mean High Water Springs (MHWS)	2.74	1.06
Mean High Water Neaps (MHWN)	2.32	0.64
Mean Sea Level (MSL)	1.57	-0.111
Mean Low Water Neaps (MLWN)	0.83	-0.85
Mean Low Water Springs (MLWS)	0.40	-1.28
Lowest Astronomical Tide (LAT)	-0.05	-1.73

Source: LINZ Nautical Almanac 2012 – 13

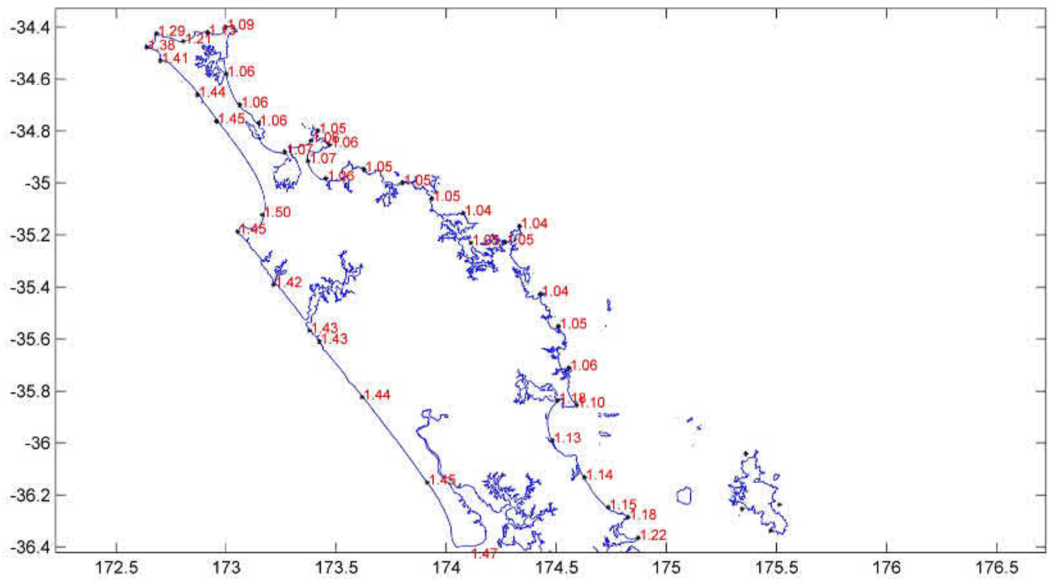

Figure 2-2: Plot of the mean high water spring level exceeded by 10% of tide (MHWS-10) level relative to MSL = 0 (Source: NIWA, 2015)

Table 2-3: Mean High Water Spring levels for secondary ports around Northland

East Coast MHWS (m CD)				West Coast MHWS (m CD)	
MARSDEN POINT	2.7	Ben Gunn Wharf	2.4	PORT TARANAKI	3.5
Mangonui	2.6	Dairy Factory Wharf	2.3	Ahipara Bay	3.6
North Cape (Otou)	2.3	Unahi Jetty	2.3	Opononi	2.9
Portland Wharf	3.1	Kerikeri	2.3	Rawene	3.2
Tutukaka Harbour	2.3	Opua	2.5	Pouto Point	3.2

East Coast MHWS (m CD)				West Coast MHWS (m CD)	
Whangamumu Harbour	2.1	Russell	2.4	Tinopai	3.8
Whangarei	3	Waitangi	2.3		
Houhora Harbour Ent	2.2	Pukenui Wharf	2.1	Source: LINZ (2013)	

2.3.3 Storm surge

Storm surge results from the combination of barometric set-up from low atmospheric pressure and wind stress from winds blowing along or onshore which elevates the water level above the predicted tide (Figure 2-3). Storm surge applies to the general elevation of the sea above the predicted tide across a region but excludes nearshore effects of storm waves such as wave set-up and wave run-up at the shoreline.

Previous studies of storm surge around New Zealand's coastline have concluded that storm surge appears to have an upper limit of approximately 1.0 m (Hay, 1991; Heath, 1979; Bell et. al, 2000). Given the perceived upper limit of storm surge for New Zealand, a standard storm surge of 0.9 m is considered representative of a return period of 80 to 100 years (MFE, 2004).

However, the actual observed water level observed depends on the superposition of storm surge on astronomical tide and is referred to as *storm tide*. Previously, storm surge values were added to a MHWS (or similar) level to obtain a storm tide level. This is known as the 'building block' approach. However, as these processes are (generally) physically and statistically independent of each other, the resulting combination are known to be conservative (Stephens et al., 2013). Methods used to evaluate storm tide which incorporate the statistical combination of these independent components are described in Section 3.

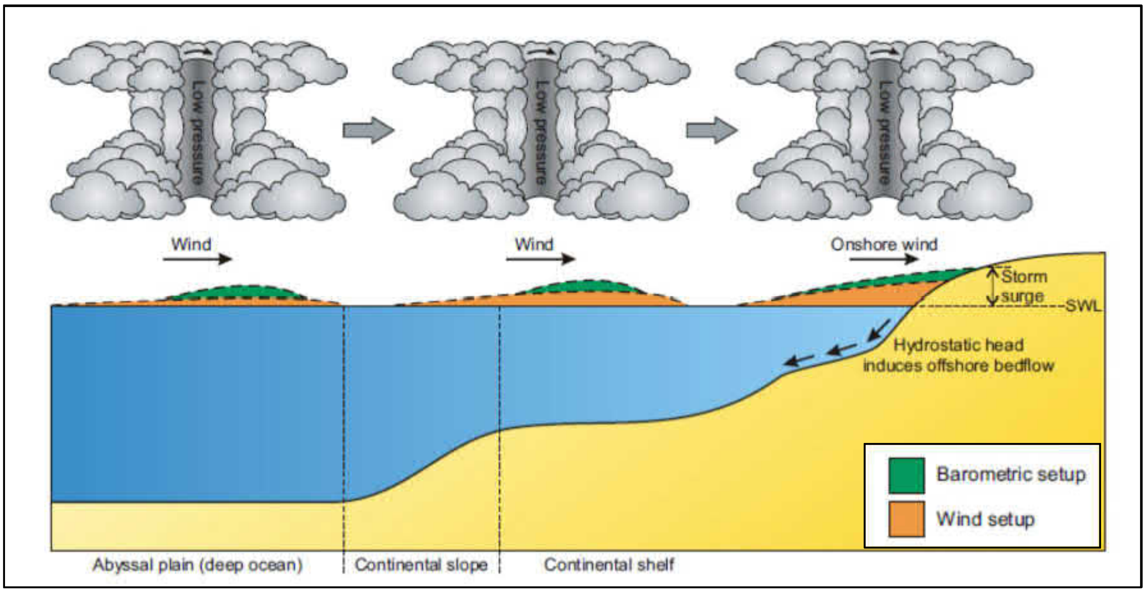

Figure 2-3: Processes driving storm surge

2.3.4 Medium term fluctuations

The long-term mean level at any particular location can fluctuate due to the influence of wider climatic variations such as the annual heating/cooling cycle, the 2–4 year El Niño—Southern Oscillation (ENSO) cycle and the 20–30 year Inter-decadal Pacific Oscillation (IPO) cycle (refer to Figure 2-4). Guidance on sea level fluctuation suggests that fluctuations of up to 0.25 m (± 0.15m) should be taken into account in predicting future water levels (MFE, 2008; Stephens's pers. comm. Dec 2014).

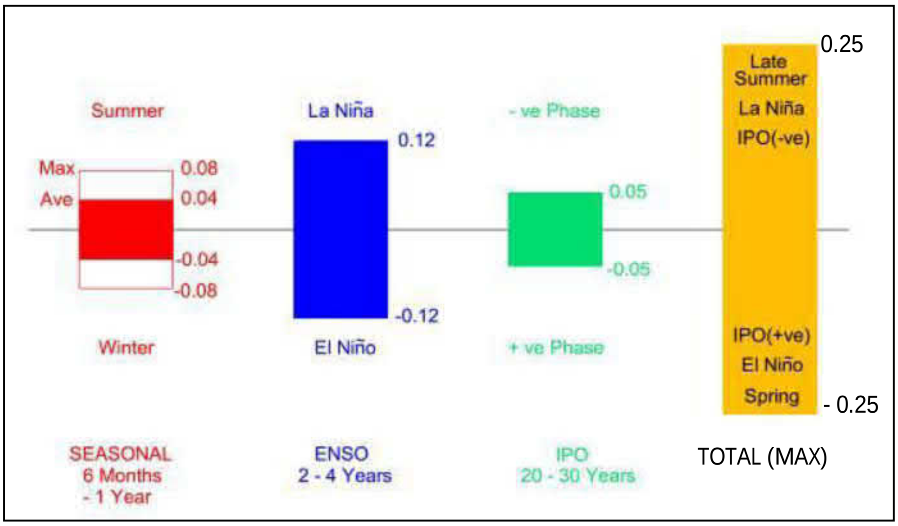

Figure 2-4: Components contributing to sea level variation over long term periods (source: MfE, 2008)

2.3.5 Long-term sea level change

Historic sea level rise in New Zealand has averaged 1.7 ± 0.1 mm/year (Hannah and Bell, 2012) with Northland exhibiting a slightly higher rate of 2.2 ± 0.6 mm/year. Beavan and Litchfield (2012) found negligible vertical land movement in Northland and this higher rate and wider uncertainty may be due to the short record length. Mulgor (2008) found mean sea levels at Dargaville had risen 81.7 mm over a 27.5 year record. While this apparently shows a higher rate of sea level rise of 3.0 mm/year, recent site datum surveys have shown lowering of the land datum by up to 22 mm over the same time period (NRC, pers. comm. April 2015) which partially explain this difference.

Climate change is predicted to accelerate this rate of sea level rise into the future. The New Zealand Coastal Policy Statement 2010 (NZCPS, 2010) requires that the identification of coastal hazards includes consideration of sea level rise over at least a 100 year planning period. Potential sea level rise over this time frame is likely to significantly alter the coastal hazard risk.

The Ministry of Environment (2008) guideline recommends a base value sea level rise of 0.5 m by 2100 (relative to the 1980-1999 average) with consideration of the consequences of sea level rise of at least 0.8 m by 2100 with an additional sea level rise of 10 mm per year beyond 2100. Bell (2013) recommends that for planning to 2115, these values are increased to 0.7 and 1.0 m respectively.

Modelling presented within the most recent IPCC report (AR5; IPCC, 2014) show predicted global sea level rise values by 2100 to range from 0.27 m, which is slightly above the current rate of rise, to 1 m depending on the emission scenario adopted. Using linear extrapolation of the 2090 to 2100 period of the RCP8.5 scenario to 2115 results in a sea level range in the order of 0.27 to 0.47 m by 2065 and 0.62 to 1.27 m by 2115 (Figure 2-5). The RCP8.5 scenario assumes emissions continue to rise in the 21st century. Adopting this scenario is considered prudent until evidence of emission stabilising justify use of a lower projection scenario (refer to Section 3.6 for adopted values).

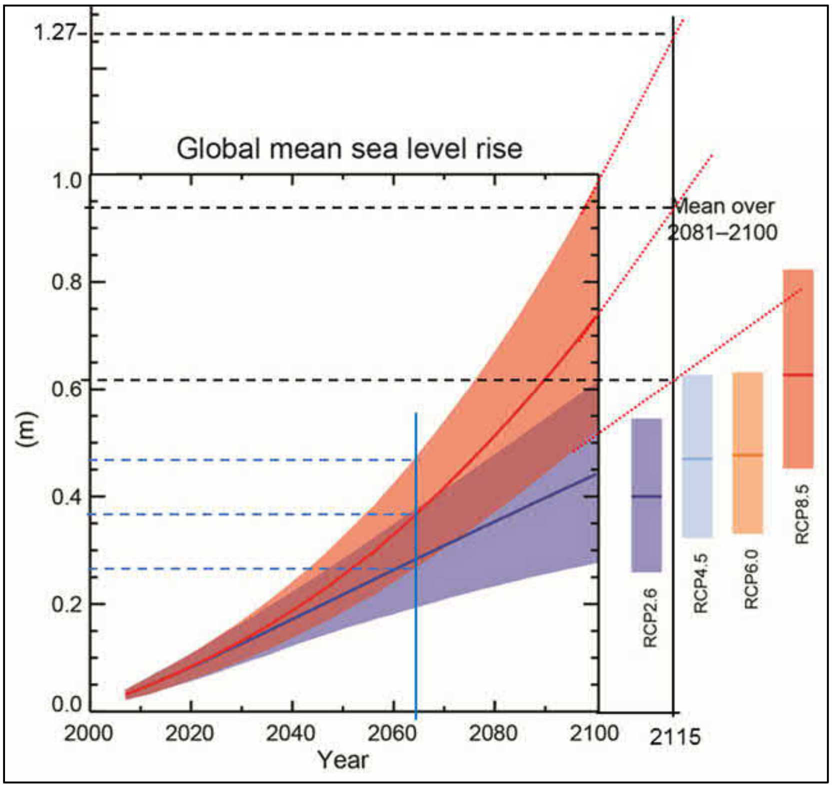

Figure 2-5: Projections of potential future sea level rise presented within IPCC AR5 (IPCC, 2014) with adopted values for this assessment at 2065 and extrapolated to 2115

2.4 Waves

Waves can both super-elevate the mean water level during the breaking process (termed wave set-up) and cause impulsive damage due to wave run-up. To evaluate the contribution of wave processes to coastal flooding, wave height at the coastline must be determined. On *open coasts* this is generally a result of open ocean swell and sea propagating into the coastline while for *sheltered coasts*, waves are generated locally within the enclosed waterway.

2.4.1 Offshore wave climate

Wave data from four offshore locations representative of the Northland Region was provided by MetOcean Solutions Ltd for this study; offshore of Ahipara, Matauri Bay, Whangaruru, and Bream Head.

The wave climates of the east and west coast of Northland differ considerably. The majority of wave energy on the west coast is generated by mid latitude low pressure systems moving from west to east beneath Australia and New Zealand. This wave energy propagates into the Tasman Sea and reaches Northland as either swell from the southwest or combined sea-swell when wind streams extend sufficiently far north. Infrequent low pressure systems forming in the Tasman Sea or further north in the tropics induce northwest to north waves and winds. The east coast is sheltered from these predominant westerly systems and waves are dominated by infrequent easterly airflows generated by subtropical low pressure systems with ex-tropical cyclones and storms descending from the tropics during summer months.

Wave roses are presented for each offshore location in Figure 2-6. These results show that offshore of Ahipara, waves arrive from a narrow directional range from the southwest. All east coast locations show similar predominantly north to northeast wave directions with less frequent southeast components. Mean significant wave height (2.5 m) and peak period (13.1 s) on the west coast is typically higher than on the east coast (1.2 to 1.5 m and 9.0 s for the mean significant wave height and peak period respectively). Refer to Table 2-4 for a summary of the characteristic wave heights for the four Northland offshore locations.

Table 2-4 Characteristic wave heights for Northland offshore locations

Location	Coordinates		Mean			1% Exceedance		
	E (°)	S (°)	Hs (m)	Tp (s)	Dp (°)	Hs (m)	Tp (s)1	Dp (°)1
Ahipara	173.02	35.24	2.5	13.1	228.7	5.0	14.0	233.1
Matauri Bay	173.99	34.84	1.5	9.1	134.3	4.4	10.8	102.2
Whangaruru	174.63	35.28	1.5	9.0	132.1	4.4	10.8	99.8
Bream Head	174.63	35.74	1.2	9.0	84.1	3.9	10.5	62.8

[1]Wave period and direction for 1% exceedance H_s conditions

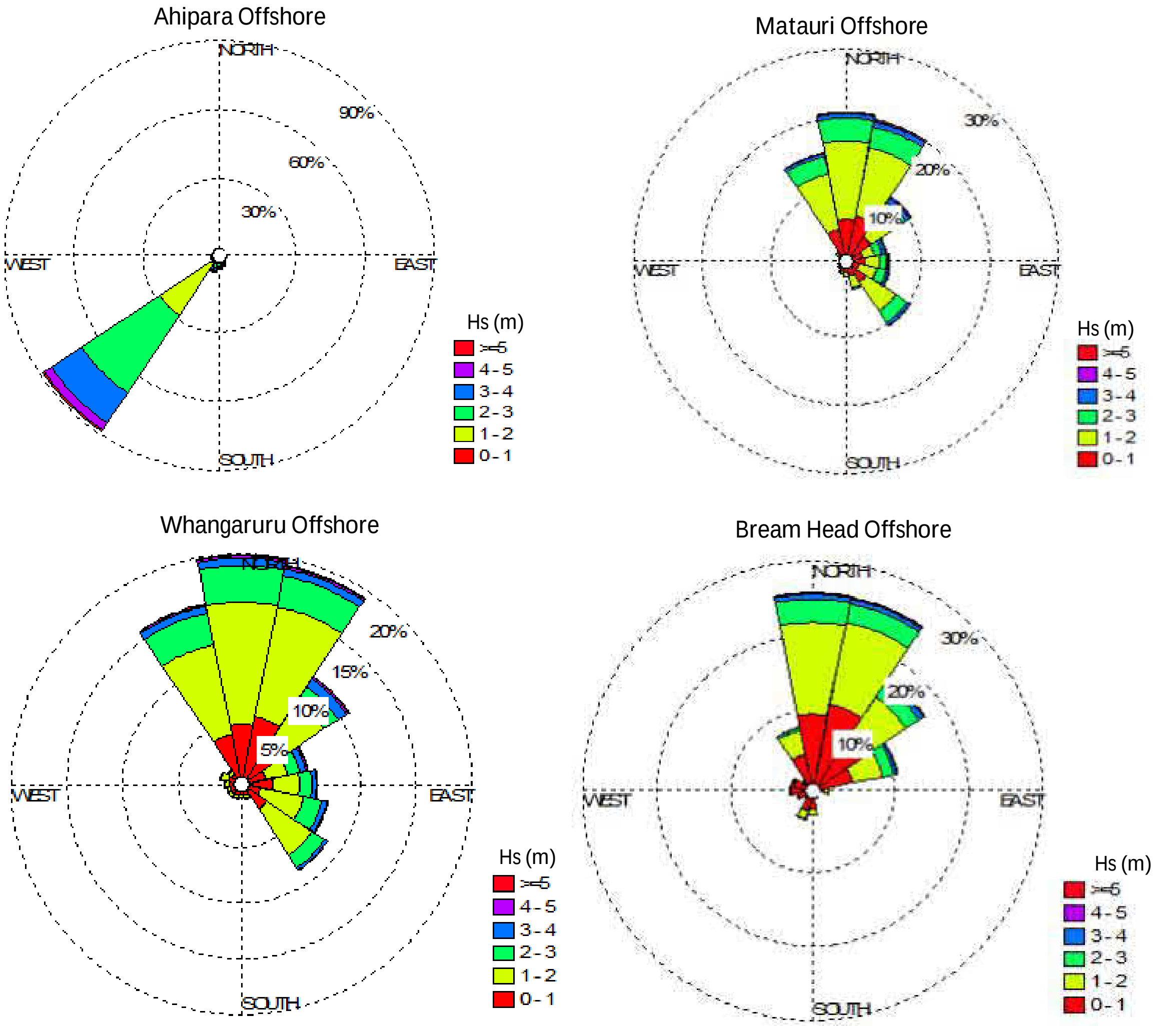

Figure 2-6: Wave roses and CDFs for each offshore buoy location showing significant wave height (H_s) and wave direction

2.4.2 Storm climatology

Northland is affected by storm events from a range of sources. On the west coast these include large mid latitude low pressure systems occurring between 50 and 60° S propagating into the Tasman Sea and low pressure systems forming off the east coast of Australia (i.e. East Coast lows). The east coast is affected by similar sub-tropical lows and by systems of tropical origin descending towards the north of New Zealand as tropical or ex-tropical cyclones (refer to T+T, 2014).

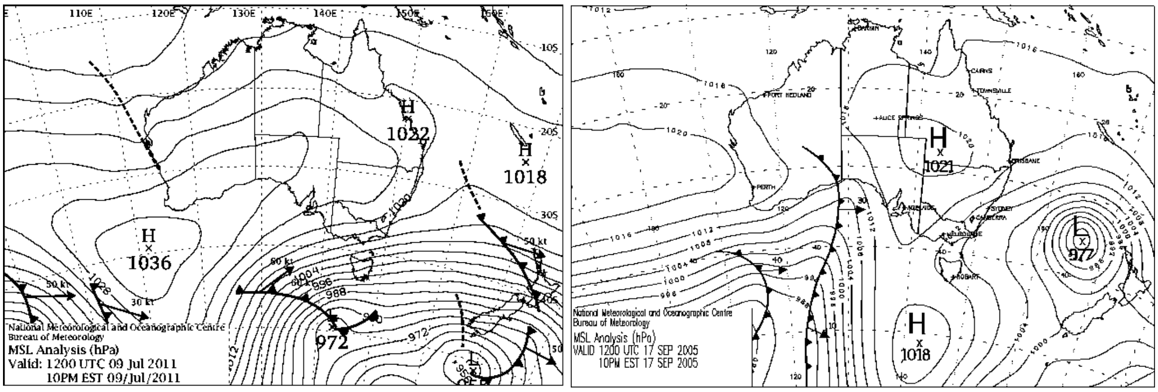

Figure 2-7: Typical storm systems affecting the west coast of Northland with a large mid-latitude cyclone in July 2011 (A) and an West coast low in September 2005 (B)

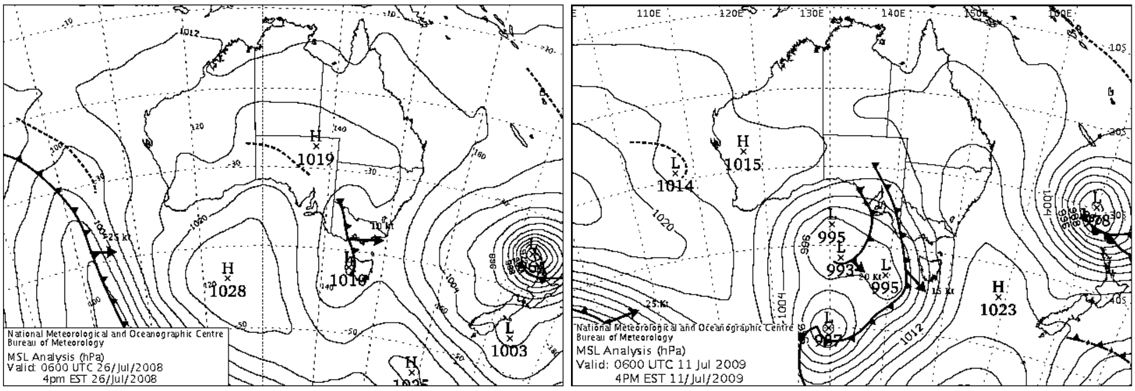

Figure 2-8: Sub-tropical storm systems causing large waves on the Northland east coast in July 2008 (A) and July 2009 (B)

Significant storm events were identified in T+T (2014) for each offshore dataset using a peaks-over-threshold (PoT) method based on a 1% exceedance height threshold and incorporating a minimum duration threshold between storms to ensure event independence. Results (Figure 2-9) presented in T+T (2014) show that for both east and west coast sites, wave period tends to increase with storm peak wave heights, although longer periods are observed for smaller waves on both coasts.

On the west coast, the largest storms may arrive from directions 220 to 280° and on the east coast from 300 to 120°. This wide directional range on the east coast means that the exposure of coastal sites will be critical to the energy received during storm events. Narrow bays will tend to be sheltered from many of the events compared to open sites exposed to a wide range of wave angles.

The relationship between Non-tidal residual (storm surge) and wave height appears highly scattered for the more frequent (lower) storm events on both coasts but the largest events do coincide with largest tidal residual indicating high dependence in extreme events. This is in agreement to findings on the east coast of Australia (Shand et al., 2011) where asymptotic dependence between the magnitude of wave height and non-tidal residual was noted.

Very large events can last upward of four days (Figure 2-10) with multiple wave height peaks. These long durations increase the likelihood of storm (wave height and storm surge) peaks coinciding with high astronomical tide.

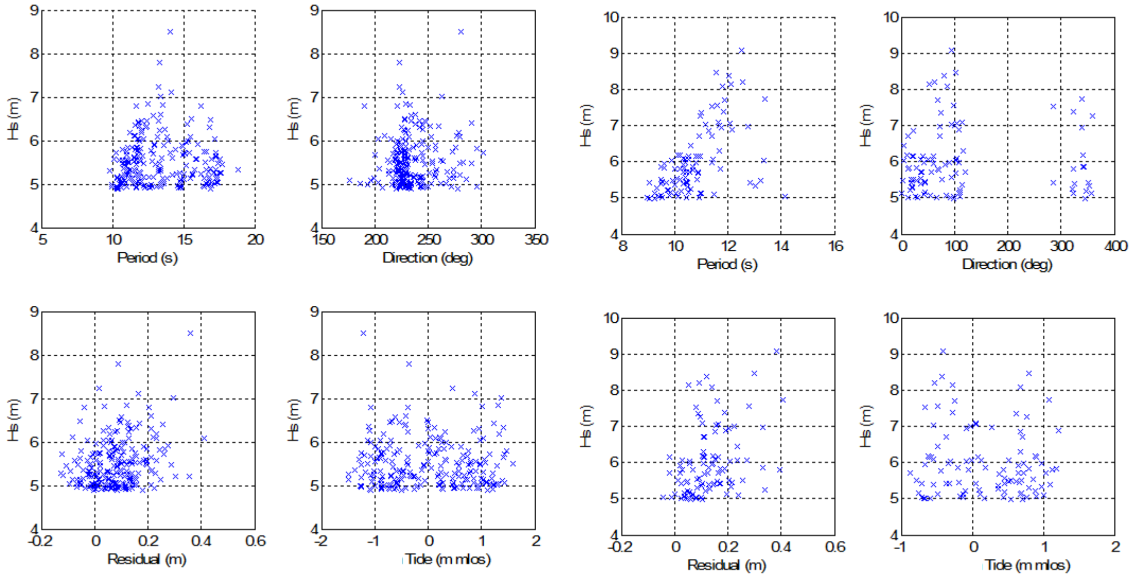

Figure 2-9: Storm peak characteristics for Ahipara (left) and Matauri (right) relating wave height to wave period, direction, non-tidal residual (storm surge) and tide

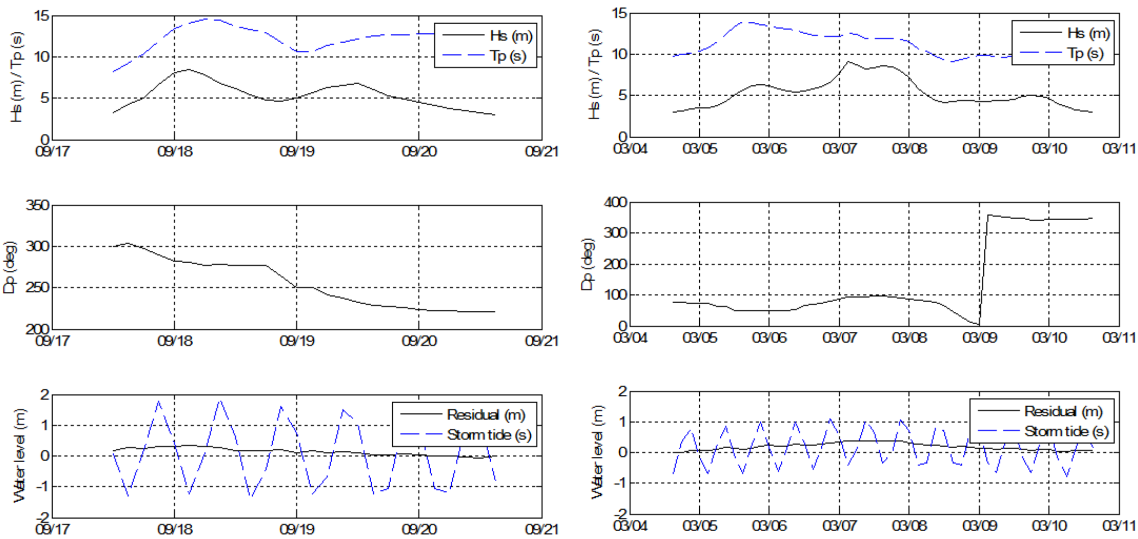

Figure 2-10: Time series of maximum storm on record for the Ahipara offshore site (September 2005) and for the Matauri site (March 1988)

3 Extreme water level assessment

3.1 Methodology

The extreme static water and run-up levels used to derive the coastal flood hazard zones (CFHZ) and coastal run-up hazard zones (CRHZ) were assessed for 63 Northland sites including both open coast and sheltered sites based on the following combinations:

$$Extreme\ static\ water\ level\ = ST\ +\ SU\ +\ SLR \qquad (3\text{-}1)$$

$$Extreme\ runup\ level\ \ = ST\ +\ RU + SLR \qquad (3\text{-}2)$$

Where:

ST = Storm tide level defined by the combination of astronomical tide, storm surge and mean sea level fluctuations

SU = Wave set-up caused by wave breaking and onshore directed momentum flux across the surf zone

RU = Wave run-up being the maximum potential vertical level reached by individual waves above the storm tide level (note this component implicitly includes wave set-up)

SLR = Sea level rise over the defined planning timeframes of 0, 50 and 100 years

The inundation components were calculated separately for the open coast environments and sheltered coastal environments. Methods used to assess and combine storm tide levels, wave set-up and run-up are described in Sections 3.2 - 3.5 and derivation of the resulting CFHZs and CRHZs presented in Section 4. Figure 3.1 shows a breakdown of the assessed extreme water levels and included components.

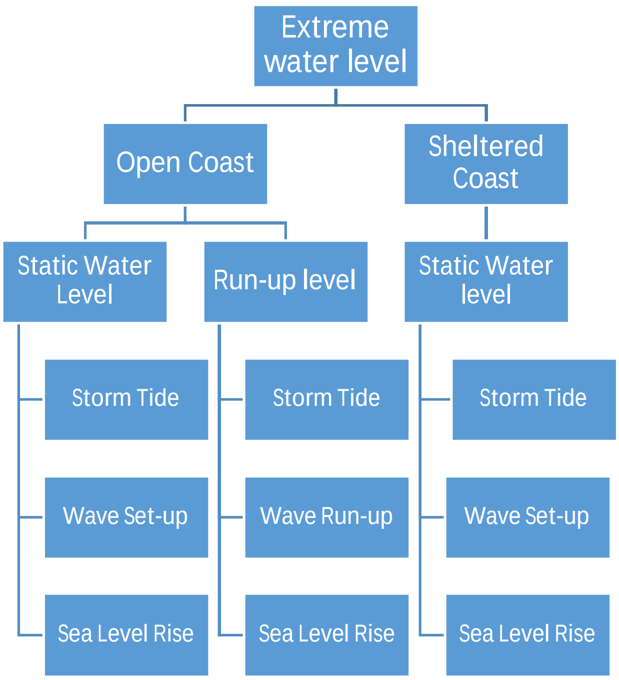

Figure 3.1: Extreme water level assessment diagram

3.2 Storm tide levels

NRC have previous undertaken extreme value (annual maxima) analysis on the water level records for six tide gauges in the Northland region; four on the east coast and two within the Kaipara Harbour. T+T engaged NIWA to undertake a supplementary analysis of extreme storm tide levels for

Northland gauges. This analysis used a monte-carlo joint probability (MCJP) technique by which the water level records are split into astronomical tide, storm surge and monthly mean level of the sea components and then recombined by a monte-carlo technique over a longer timeframe to incorporate all potential combinations. The method is described in detail by Goring et al. (2011).

Extreme values derived using this method have been found in good agreement with standard extreme value analysis techniques (i.e. annual maxima or peaks over threshold) for long-term records (i.e. Port of Auckland's 107 year record; i.e. Figure 3-2) but result in more stable values for short-term records where large records early in the record may skew the resulting analysis (Stephens pers. comm., Feb 2015). Analysis for the Dargaville record was not possible using this technique and results of a previous assessment (Mulgor, 2008) which used a similar method on a 27 year dataset have been adopted instead.

Results are presented in Table 3-1 and show reasonable agreement between NIWA or Mulgor MCJP values and NRC EVA values for the longer gauge records (Marsden and Dargaville) but increasing divergence for the shorter records. Assessment of outliers in the short records (Opua, Whangaroa and Poutu) found that extreme storm tide levels were generally a combination of a moderate storm surge (~1yr ARI) combined with very high tides resulting in an extreme combination beyond that expected when combining the two independent components during the period of record.

Values at Marsden Point are generally higher than other east coast values except for at Ben Gunn wharf within the Awanui harbour where local tidal amplification may be occurring. The mean sea level relative to OTP datum was found to increase to the north with MSL being 106 mm below OTP datum at Marsden Point, increasing to 32 mm above OTP datum at Whangaroa (refer to Section 2.3.1).

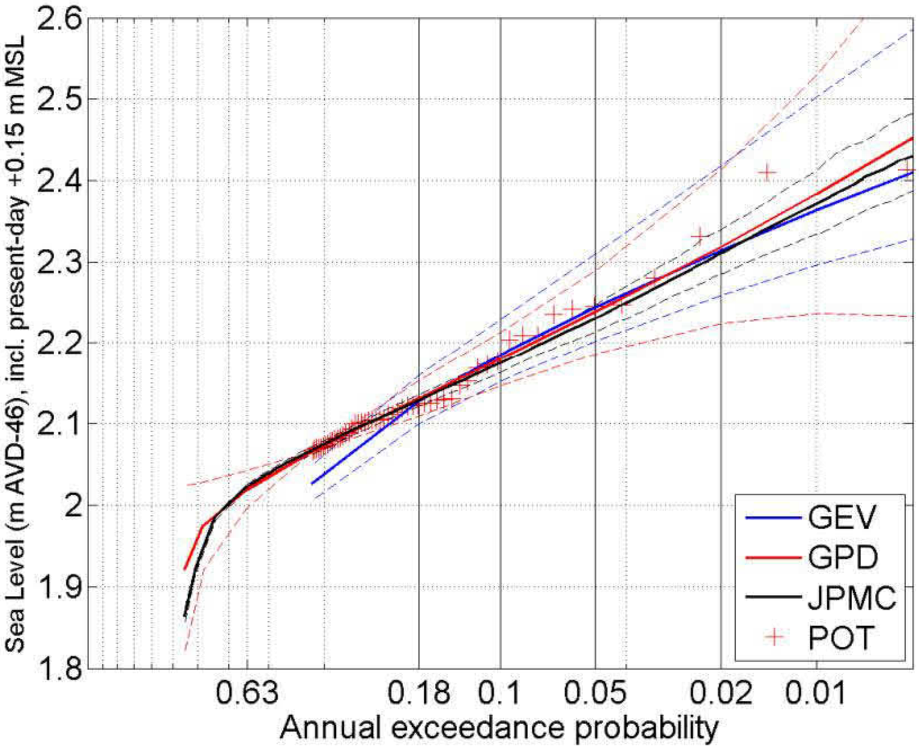

Figure 3-2: Extreme sea-level curves using Port of Auckland tide-gauge data and comparing three EVA approaches with the MCJP technique. The MCJP produces similar distribution curves but with substantially reduced confidence intervals (source: Stephens et al., 2013)

Table 3-1: Extreme values for Northland tide gauge data

Site	Record length (years)	Record max observed m OTP	NIWA 1% AEP			Mulgor 1% AEP m OTP	NRC 1% m OTP
			m MSL	m CD	m OTP		
Marsden Point (One Tree Point)	39	1.74	1.78	3.35	1.67	-	1.76
Opua Wharf	23	1.66	1.60	3.07	1.51	-	1.68
Whangaroa Harbour	6	1.63	1.58	3.17	1.61	-	1.94
Ben Gunn Wharf	10	1.68	1.79	5.29	1.76	-	1.92
Pouto Point	13	2.48	2.27	2.42	2.42	-	2.67
Dargaville	33	2.87	-	-	-	2.84	2.93

Extreme values derived for the individual gauges have been rationalised to the selected open coast and estuary sites. This rationalisation is based on gauge proximity and adjusted for tidal offsets based on NIWA models of MHWS for the Northland Region (Figure 2-2) and the MSL datum offset described in Section 2.3.1. Due to the more robust values derived from the longer gauge record at Marsden Point, these values have been used (after modification) for all open East Coast sites. The Whangaroa and Awanui values have been used for the local harbour environments. The Poutu Point values have been used for open West Coast and Kaipara Harbour sites and the Dargaville values for sites along the Dargaville River. This is because LINZ tidal offsets are not available for Dargaville meaning values could not be rationalised to other sites.

For each assessment site, the gauge extreme values applied, adopted tidal and MSL offset and resultant storm tide values in terms of OTP datum are presented in the Appendix C. The storm tide levels presented in Appendix C are based on the AEP levels derived by NIWA except for storm tide levels for sites within the Bay of Islands which are based on maximum observed level at Opua Wharf gauge. This has been adopted because the 1% AEP level derived by NIWA is 150 mm lower than the maximum observed level within the 23 year record and potentially non-conservative.

Results show that the 1% AEP storm tide values for open coast sites on the East coast are in the range 1.5 m - 1.7 m OTP64. Sites within the upper Whangarei and Rangaunu Harbours are slightly higher than the open coast due to the tidal amplification (based on LINZ tide table values). On the west coast, all sites are fairly constant with sites within the Kaipara higher due to tidal amplification (based on LINZ tide table data).

3.3 Wave height

3.3.1 Open coast wave height

Wave transformation modelling has been undertaken to transform the offshore (deep water) wave characteristics into nearshore wave conditions (10 m water depth) for each open coast site. The numerical model SWAN (Simulating WAves Nearshore) has been used to undertake wave transformation modelling using a number of model domains along the Northland Coastline. Simulations have been undertaken for each model domain for a range of relevant wave periods and directions with modelling details provided within Appendix B. This has resulted in wave height transformation coefficients being established between the offshore and nearshore positions for each relevant direction and period. An example of such a transformation table is presented in Table 3-2. Where wave height varied significantly along a particular site (i.e. at Ahipara Bay), that site was split into multiple cells with each cell having an individual transformation table. The nearshore wave heights at the 10 m contour are used as inputs for both the wave set-up and wave run-up calculations.

Table 3-2: Example wave transformation tables

Offshore point	Site	Cell	Wave transformation for offshore wave direction for T=12s							
			337.5°	0°	22.5°	45°	67.5°	90°	112.5°	135°
Matauri	Taupo Bay	23-A	0.28	0.40	0.58	0.57	0.40	0.24	0.12	0.06
		23-B	0.32	0.44	0.61	0.56	0.40	0.25	0.12	0.06
		23-C	0.38	0.54	0.76	0.74	0.46	0.28	0.13	0.07
		23-D	0.42	0.60	0.80	0.75	0.44	0.26	0.13	0.07
	Tauranga Beach	22-A	0.82	0.70	0.61	0.58	0.51	0.30	0.16	0.08
		22-B	0.64	0.61	0.63	0.62	0.52	0.28	0.14	0.07
		22-C	0.62	0.67	0.77	0.84	0.68	0.37	0.18	0.09
		22-D	0.75	0.78	0.86	0.92	0.74	0.40	0.20	0.10
		22-E	1.07	0.95	0.96	1.01	0.80	0.44	0.23	0.12
	Te Ngaere	21-A	0.29	0.51	0.79	0.63	0.32	0.19	0.14	0.10
		21-B	0.34	0.59	0.88	0.67	0.35	0.20	0.15	0.11
		21-C	0.34	0.59	0.85	0.65	0.33	0.19	0.14	0.11

3.3.2 Sheltered coast wave height

For sheltered coasts we have assumed that waves are generated locally within the enclosed water body and fetch-limited. For each coastal site, fetch distances in each direction are assessed (i.e. Figure 3 3). Where the fetch distances differ around the coastline, the sites are split into multiple cells.

Extreme three second gust wind speeds (1% and 2% AEP) are calculated for each direction according to the New Zealand Standard AS/NZS 1170.2:2011 Part 2 Wind Actions. These three second gust wind speeds have then been converted to average wind speeds of duration 10-60 minutes depending on the fetch length using procedures in the Coastal Engineering Manual (CEM) 1110-2-1100 (USACE, 2006). The growth of wind waves are limited by the minimum wind duration (10-60 minutes). Goda (2003) has estimated the required minimum wind duration (t_{min}) necessary for full wave growth for a given fetch length:

$$t_{min} = 1.0F^{0.73}U_{10}^{-0.46} \tag{3-3}$$

$$F_{min} = 1.0t^{1.37}U_{10}^{0.63} \tag{3-4}$$

Equation 3-3 calculates the required minimum wind duration for a given fetch length. Where the growth of wind waves is limited by the duration (and not limited by fetch), the fetch length (F) in Equation 3-5 and 3-6 is replaced by F_{min} (Equation 3-4). The 10 minute 1 and 2% AEP extreme wind speeds for the Northland Region are given in Table 3-3.

Table 3-3: 10 minute wind speeds for Northland

Direction	1% AEP wind speed (m/s)	2% AEP wind speed (m/s)
North	24.2	23.1
Northeast	27.1	25.8
East	28.5	27.1
Southeast	27.1	25.8
South	24.2	23.1
Southwest	27.1	25.8
West	28.5	27.1
Northwest	27.1	25.8

Fetch-limited waves are then calculated for each harbour site for all wind direction based on the methods according to Wilson (1965) and revisited by Goda (2003) with the maximum directional wave height adopted for each coastal cell. The fetch limited significant wave height and period according to Wilson (1965) are:

$$H_{1/3} = 0.3\left\{1 - \left[1 + 0.004\left(\frac{gF}{U_{10}^2}\right)^2\right]^{-2}\right\}\frac{U_{10}^2}{g} \qquad (3\text{-}5)$$

$$T_{1/3} = 8.61\left\{1 - \left[1 + 0.008\left(\frac{gF}{U_{10}^2}\right)^{1/3}\right]^{-5}\right\}\frac{U_{10}}{g} \qquad (3\text{-}6)$$

Where:

- $H_{1/3}$ = mean height of the highest one-third of waves (significant wave height)
- $T_{1/3}$ = mean period of the highest one-third of waves (significant wave period)
- F = fetch length (length over which waves are generated)
- U_{10} = wind speed 10 meters above the water surface
- g = gravitational acceleration.

Whilst wave run-up has not been mapped for harbour sites, the wave heights assessed above have been used to calculate wave set-up in Section 3.4.2

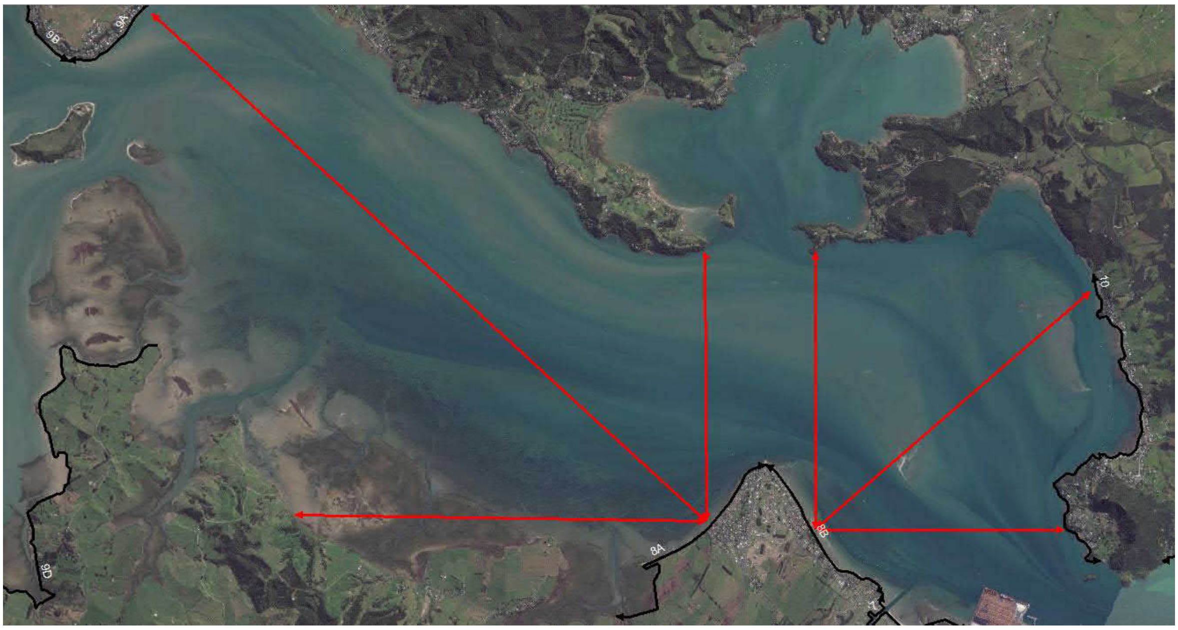

Figure 3-3: Fetch distance and resulting extreme wave is calculated for multiple directions for each sheltered coastal cell

3.4 Wave set-up

Various methods and empirical formulations to calculate wave set-up are available. The CEM provides a method to calculate wave set-up for open coast beaches based on the wave energy balance. The negative gradient in the onshore directed radiation stress is balanced by an offshore directed pressure force caused by wave set-up (refer to USACE, 2006). The CEM provides a formulation to calculate both set-up at the still water line (Equation 3-7) and the maximum set-up (Equation 3-8):

$$\overline{\eta_s} = \overline{\eta_b} + \left[\frac{1}{1+\frac{8}{3\gamma_b^2}}\right] h_b \qquad (3\text{-}7)$$

Where:

$\overline{\eta_s}$ = Set-up at still water line (SWL)

$\overline{\eta_b}$ = Set-down at still water line (SWL)

γ_b = breaker index

h_b = breaker depth

$$\overline{\eta_{max}} = \overline{\eta_s} + \frac{d\eta}{dx}\Delta x \qquad (3\text{-}8)$$

Where:

$\overline{\eta_{max}}$ = maximum set-up

$\frac{d\eta}{dx}$ = Set-up gradient between $\overline{\eta_s}$ and $\overline{\eta_{max}}$

Δx = Displacement between $\overline{\eta_s}$ and $\overline{\eta_{max}}$

This method is shown in Figure 3-4.

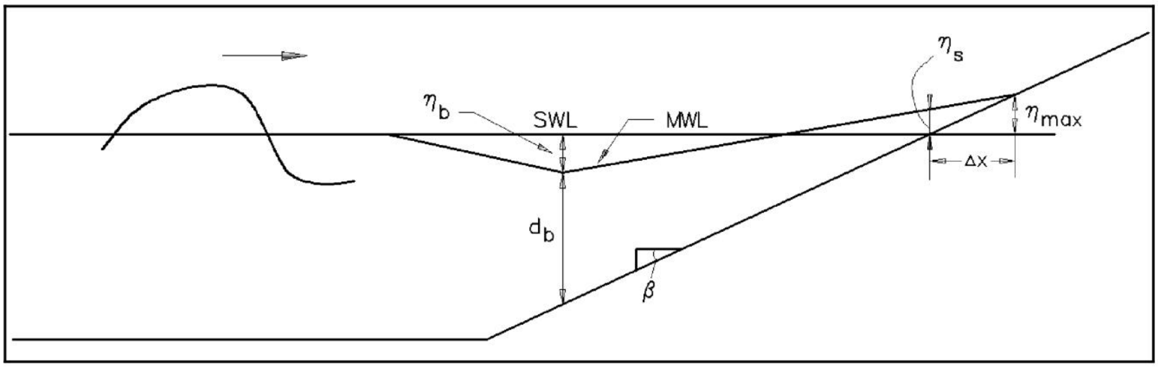

Figure 3-4: Wave set-up method (source: USACE, 2006)

Wave set-up at the still water line (SWL) is calculated based on the set-down, breaking wave height and breaker depth. The method by USACE (2006) utilises a single slope (foreshore slope) to calculate wave set-up and set-down at the SWL, and maximum wave set-up. According to Equation 3-4 maximum set-up is calculated based on the displacement and set-up gradient between set-up at SWL and maximum set-up. The CEM calculates Δx (Equation 3-4) on the foreshore slope. However, the beach slope is steeper shoreward of the still water line and applying the foreshore slope to calculate Δx would result in an unrealistic high wave set-up. We have therefore used the wave set-up at the SWL in this study.

3.4.1 Open coast wave set-up

The extreme static water level is the result of the wave set-up superimposed on the still water level or storm tide occurring at that time. Traditional *building block* approaches apply wave set-up resulting from an extreme event onto a corresponding (or lesser) extreme storm tide level. While there appears a partial dependence between wave height and storm surge, there will be less dependence between wave height and storm tide where the independent astronomical tide is a primary contributor. This is particularly true for short duration events (or sheltered coastlines exposed to only a portion of the event) where the storm peak may not coincide with a high tide.

The following approach has therefore been adopted to accurately quantify the combined water level resulting from these components:

1. Develop hourly timeseries of nearshore wave height using wave Hs transformation tables.
2. Develop equivalent hourly timeseries of water level based on the Marsden Point water level data set (east coast) adjusted for local tidal conditions and on Pouto Point (west coast) adjusted for local tidal conditions. This water level includes the effect of the astronomical tide, storm surge and any medium-term sea level fluctuations.
3. Calculate set-up for each timestep (1hr) using the CEM method described in Section 3.4 and add to water level producing a static water level timeseries.
4. Undertake an extreme value analysis (EVA) to derive the ‘structural’ or combined extreme values. Analysis was undertaken using a peaks over threshold method and a Weibull distribution which has been found to most accurately represent wave-dominated extremes (Shand et al., 2009).

This approach provides a robust measure of the joint occurrence without requiring bivariate extreme value analysis which can introduce considerable additional uncertainty (Shand, 2011) with the dependence often biased by smaller events.

Figure 3-5 compares the results of using the building block approach with the structural EVA approach. For instance the extreme water level indicated with the circled 'X' in Figure 3-5 is 2 m OTP64 using the structural EVA approach compared to 2.9 m OTP64 using the building block approach (which is nearly 50% larger). It can be seen that the extreme water level calculated using a building block approach results in extreme water levels up to 50% larger (ranging from 0 to 50%) compared to the structural EVA approach.

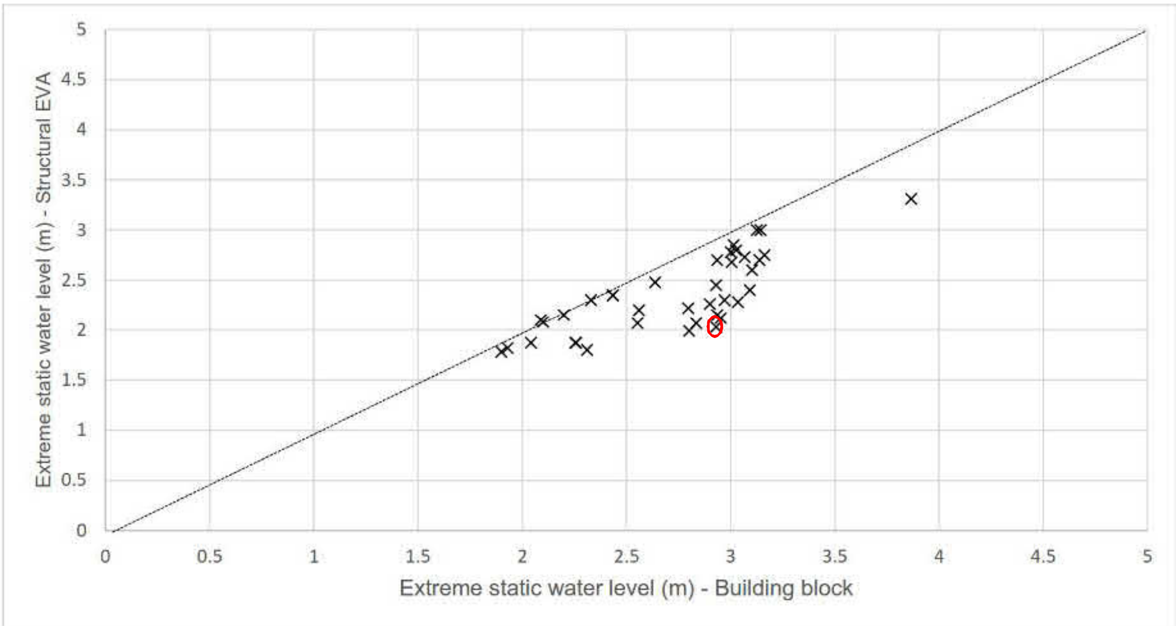

Figure 3-5: Comparison of extreme static water level calculated using the building block with the structural EVA approach

3.4.2 Sheltered coast wave set-up

The sheltered coast wave set-up is added to the storm tide following the building block approach to calculate the extreme static water level. Due to the lack of topographic and bathymetric data in sheltered coastal environments, wave set-up is calculated based on the simpler method of Thornton & Guza (1983) which does not require nearshore slope information. The expression is as follows:

$$\overline{\eta_{max}} = 0.17 H_b \quad (3\text{-}9)$$

Where:

H_b = Wave breaking height

Exceptions to this occur where open coast waves break at a harbour entrance. In these cases, open coast wave set-up will be partially developed and will contribute to the extreme water levels within the harbour. A modified version of the CEM method (Eqn 3.3) has been developed for these scenarios which includes an allowance for the harbour entrance depth resulting in a portion of the open coast set-up being developed within the waterway.

3.5 Wave run-up

Wave run-up occurs as waves travel across the surf zone and are then carried by momentum above the still water level until such forces are exceeded by gravity. A range of empirical-based formula have been developed over the past 50 years using the results of field and laboratory studies. Shand et al. (2011) reviewed several of these methods compared to field data of run-up height during extreme events and found the method of Mase (1989) to best predict extreme run-up elevation.

The run-up formula were found to be highly sensitive to assumed beach slope (or the particular part of the beach from which slope was derived) with site-specific calibration recommended where possible.

Based on those results, wave run-up for this assessment has been calculated based on the method of Mase (1989) presented in the CEM. This is a predictive equation for irregular run-up on plane, impermeable beaches based on laboratory data. The formulation by Mase (1989) is as follows:

$$R_{2\%} = H_0 \cdot 1.86 \cdot \xi_0^{0.71} \tag{3-10}$$

Where:

$R_{2\%}$ = Run-up exceeded by 2% of the run-up crests

H_0 = Significant deep water wave height

ξ_0 = Iribarren number: $\left[(\tan\alpha) / (\sqrt{H_0/L_0})\right]$

3.5.1 Run-up validation

A validation assessment has been undertaken to validate the adopted method to predict the run-up and to calibrate the appropriate beach slope. NRC have provided a summary of observed run-up debris from a storm event in January 2008 (NRC, 2008). This storm generated significant waves of 4.1 to 4.2 m offshore of Northland during a peak water level of 1.1 m OPT with a wave height peak of up to 4.65 m occurring during lower tide. While this was a large event, the return period on the significant wave height is less than one year. Observers in some locations have described a “wall of water” which is typical of infragravity motions occurring during large wave events.

Elevations of run-up debris were recorded at several beaches between Rangiputa and Te Mimiha (Figure 3-6). The debris was observed at elevations of 2.3 to 4.85 m above ‘mean sea level’ (interpreted as meaning relative to OTP vertical datum). We have assumed this debris line is the maximum run-up elevation, although if the debris line is some distance inland of the coastal edge, it is possible that the run-up reached a higher elevation near the coastal edge but reduced in height as it travelled overland before reaching the final extent at the debris line.

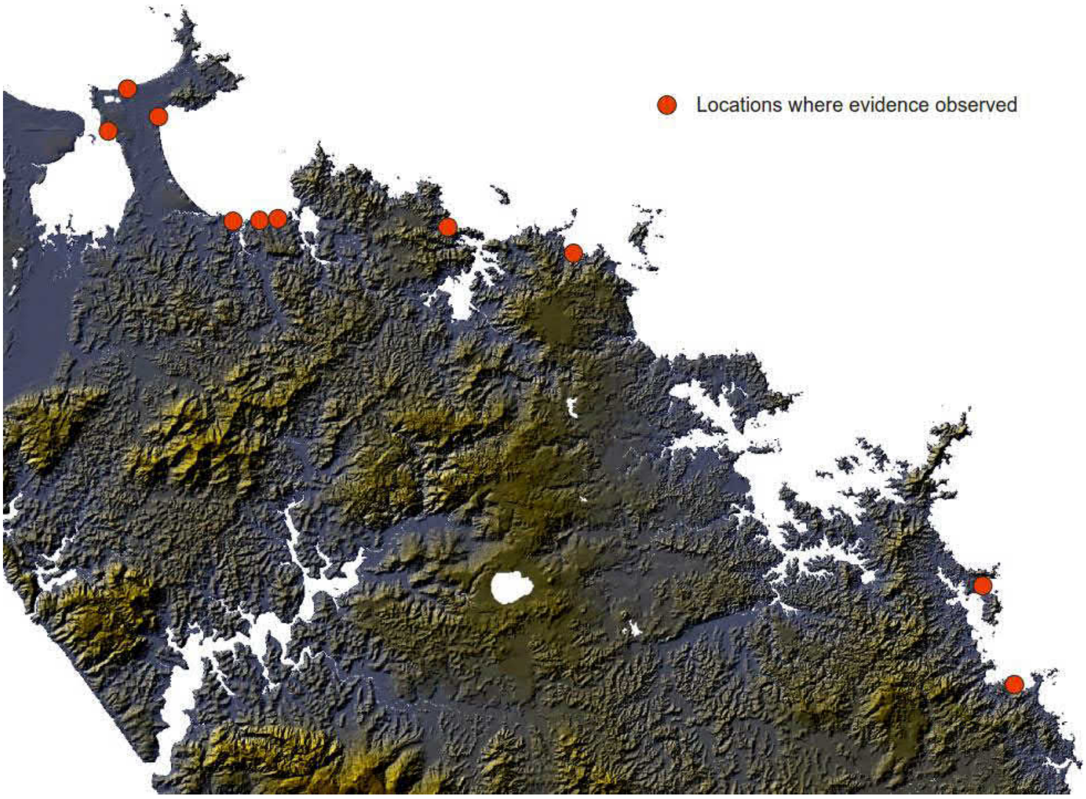

Figure 3-6: Locations where run-up evidence collected (source: NRC, 2008)

Figure 3-7: Example of wave run-up debris from the January 2008 storm identified at Te Ngarie (NRC, 2008)

While specific measurement locations were not provided, we have attempted to locate each site based on the images provided. We have then determined the local significant wave height based on nearshore wave models and the local beach geometry. Using these parameters we calculated wave run-up using two different expressions, Mase (1989) and Stockton et al. (2006), and different slope definitions (beach face and surfzone) and have compared results with site observations.

Results (Table 3-4) show that the Mase (1989) expression using the beachface slope produces results closest to the recorded levels. These results calculated using this expression are typically within ±10% of measurements, although the model over-predicted run-up at Bland Bay by around 30%. This may be due to over-prediction of the wave height in the sheltered southern corner where offshore reefs provide substantial protection but are difficult to model using spectral-type wave models. The Stockdon and Mase methods using the beachface and surfzone slope respectively resulted in under-predictions of run-up in agreement with Shand et al. (2011).

The upper beach slope has been used to calculate the Iribarren number as per recommendations by Mase (1989), findings by Shand et al. (2011) and the result of the model validation. The results show that the specific slope makes a large difference in the predicted run-up elevations. The option for site-specific assessment should remain available to update values derived within this regional assessment.

Table 3-4: Comparison of observed and modelled run-up

Sites	Observed debris line (m MSL)	Modelled run-up (m MSL)					
		Stockdon (2006) (beachface slope)		Mase (1989) (beachface slope)		Mase (1989) (surfzone slope)	
Rangiputa	3-3.2	2.05	(-34%)	2.91	(-6%)	0.97	(-69%)
Tokerau	3.2	2.15	(-33%)	3.1	(-3%)	1.76	(-45%)
Taipa	3.06	2.17	(-29%)	3.19	(4%)	1.92	(-37%)
Cable	4.85	2.7	(-44%)	4.48	(-8%)	3.62	(-25%)
Coopers	3.78	2.32	(-39%)	3.48	(-8%)	2.45	(-35%)
Hihi	3.25	2.13	(-34%)	3.05	(-6%)	2.18	(-33%)
Taupo	3.87	2.56	(-34%)	4.15	(7%)	2.94	(-24%)
Te Ngaire	3.4	2.23	(-34%)	3.36	(-1%)	1.82	(-46%)
Bland	2.27	2.03	(-11%)	2.91	(28%)	2.55	(12%)
Te Mimiha	4.5	2.81	(-38%)	4.52	(0%)	2.18	(-52%)
	RMS diff	*34%*		*10%*		*41%*	

3.5.2 Open coast wave run-up

Extreme wave run-up level is the result of the wave run-up superimposed on the still water level or storm tide occurring at that time. Similar to wave set-up, the traditional *building block* approaches apply wave run-up resulting from an extreme event onto a corresponding extreme storm tide level without taking into account the joint occurrence of these components.

The following approach has therefore been adopted to accurately quantify the wave run-up level resulting from these components:

1. Develop hourly timeseries of nearshore wave height using wave Hs transformation tables.
2. Develop equivalent hourly timeseries of water level based on the Marsden Point water level data set (east coast) adjusted for local tidal conditions and on Pouto Point (west coast) adjusted for local tidal conditions. This water level includes the effect of the astronomical tide, storm surge and any medium-term sea level fluctuations.
3. Calculate wave run-up for each timestep using the Mase (1989) method described above and add to water level producing a wave run-up timeseries.
4. Undertake an extreme value analysis to derive the ‘structural’ or combined extreme values. Analysis was undertaken using a peaks over threshold method and a Weibull distribution which has been found to most accurately represent wave-dominated extremes (Shand et al., 2009).

Figure 3-8 compares the results of the using the building block approach with the structural EVA approach. For instance the run-up indicated with the circled ‘X’ in Figure 3-8 is 3.8 m using the structural EVA approach compared to 6.6 m using the building block approach which is nearly 75%

larger. It can be seen from Figure 3-5 that wave run-up calculated using the building block approach is up to 75% larger compared to using the structural EVA approach.

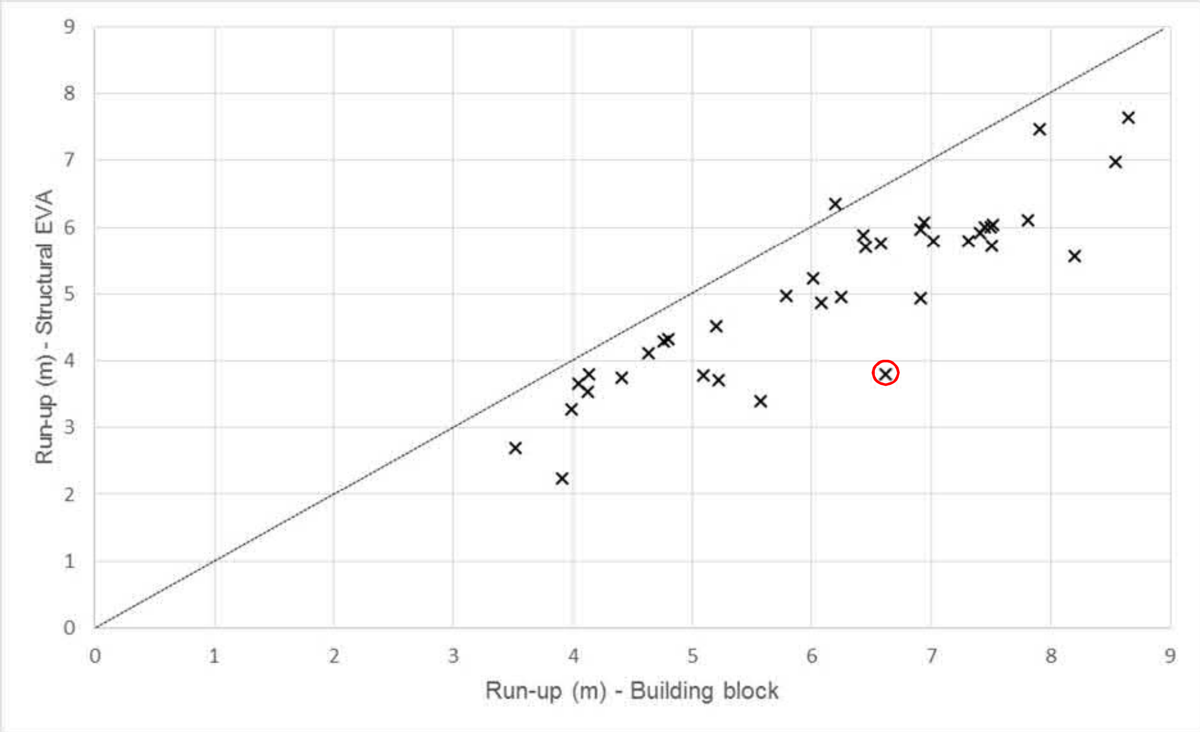

Figure 3-8: Comparison of extreme wave run-up level calculated using the building block with the structural EVA approach

3.5.3 Sheltered coast wave run-up

Due to the lack of bathymetric data in sheltered coastal environments, wave run-up was not calculated for sheltered waterways. However, given that extreme wave heights for sheltered coasts tend to be less than Hs=1 m, wave run-up will generally also be less than 1-2 m depending on shoreline type. Generic setback distances and freeboards should be implemented to allow for this unless site-specific assessment shows otherwise.

3.6 Sea level rise

The Northland Regional Policy Statement (RPS) has endorsed allowance for 1 m SLR by 2115, although no allowance has been set in RPS for 2065. For this study we have adopted the following sea level rise allowances for respective timeframes:

- 2065: 0.4 m SLR allowance
- 2115: 1.0 m SLR allowance.

These values are superimposed on the derived extreme static water or run-up level with the resultant extreme water levels shown in Appendix C.

4 Coastal inundation assessment and mapping

4.1 Assessment scenarios

Extreme static water and run-up levels have been assessed for 63 Northland sites (Appendix C). These extreme levels have been used to derive coastal flood hazard zones (CFHZ) and coastal run-up hazard zones (CRHZ) respectively for the following scenarios:

1. Coastal Flood Hazard Zone 0 (CFHZ0): Extent of 1% AEP static water level at 2015
2. Coastal Flood Hazard Zone 1 (CFHZ1): Extent of 2% AEP static water level at 2065
3. Coastal Flood Hazard Zone 2 (CFHZ2): Extent of 1% AEP static water level at 2115
4. Coastal Run-up Hazard Zone (CRHZ): Extent of 1% AEP dynamic wave run-up at 2115.

The definition sketch for mapping of these sites is provided within Figure 4-1 and described below.

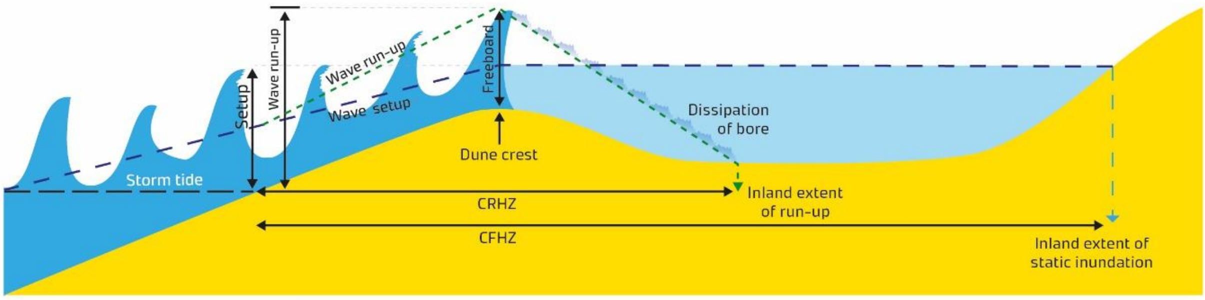

Figure 4-1: Definition sketch for CFHZ and CRHZ

4.2 Mapping CFHZ

The CFHZs have been mapped based on the extreme static water levels caused by storm tide, wave set-up and the effects of sea level rise. Digital terrain models (DEMs) were constructed for each site using NRC classified LiDAR data described in Section 2.2. DEMs have been constructed at a 2 m grid resolution and represent the bare earth (i.e. with buildings and vegetation removed). For sites 6-7, 10-11 and 62-63 1 m DEMs have been constructed at a 1 m grid resolution based on LiDAR data from 2016

The flooded extents have been mapped using a connected bathtub model where areas are flooded only where they connect to the coastal water body (or by a structure such as drainage channels or culvert as defined by NRC). This provides more realistic flooding extents by accounting for natural and human influenced topography. Results are presented within Appendix D with inundation polygons smoothed using the GIS tool PAEK (Polynomial Approximation with Exponential Kernel). A tolerance of five times the DEM resolution has been applied to smoothen the polygons (i.e. 5 m for a 1x1 m DEM and 10 m for a 2x2 m DEM).

Note that flood mapping has only been undertaken for areas where LiDAR data is available. Where flooding reaches the boundary of a DEM, flooding may continue outside the mapped area but is not able to be mapped. In these cases, and where LiDAR is missing, the derived static levels should be used to determine exposure to coastal flooding hazard.

For large areas subject to flooding (i.e. Ruawai, Dargaville-Wairoa and Awanui areas), the connected bathtub approach may result in conservative flood extents due to frictional losses occurring during flooding flows and due to the limited duration of the maximum flood elevation owing to the tidal cycle. Dynamic (hydrodynamic) modelling for these sites is being undertaken separately and maps for these sites have therefore not been included in this report. Mapping CRHZ

The CFHZs have been mapped based on the extreme static water levels caused by storm tide, wave set-up and the effects of sea level rise.

Coastal run-up hazard differs from static flooding as run-up is a dynamic process. An incident wave running up the shoreface reaches a maximum potential height at the coastal edge before decreasing with distance inland due to friction and energy loss. If a similar bathtub approach were applied for wave run-up elevation then very large areas would be flooded. This is unrealistic and instead the following approach has been adopted for open coast sites:

a The dune crest/backshore position and elevation has been digitised from local DEMs at approximately 10 m intervals.

b The extreme run-up level has been assessed for each coastal cell (Appendix C).

c If run-up level exceeds the dune crest elevation, the inland wave attenuation distance has been calculated based on relationships proposed by Cox and Machemehl (1986) and adjusted by FEMA (2005) as shown in Figure 4-2. The inland wave attenuation distance is the distance to which wave energy dissipates to zero.

d This inland distance (X) from the <u>current</u> dune crest is mapped for each transect and defines the CRHZ.

e If extreme run-up level does not exceed the dune crest elevation, the CRHZ is defined by the intersection of the maximum run-up elevation and the terrain (i.e. seaward of the dune crest).

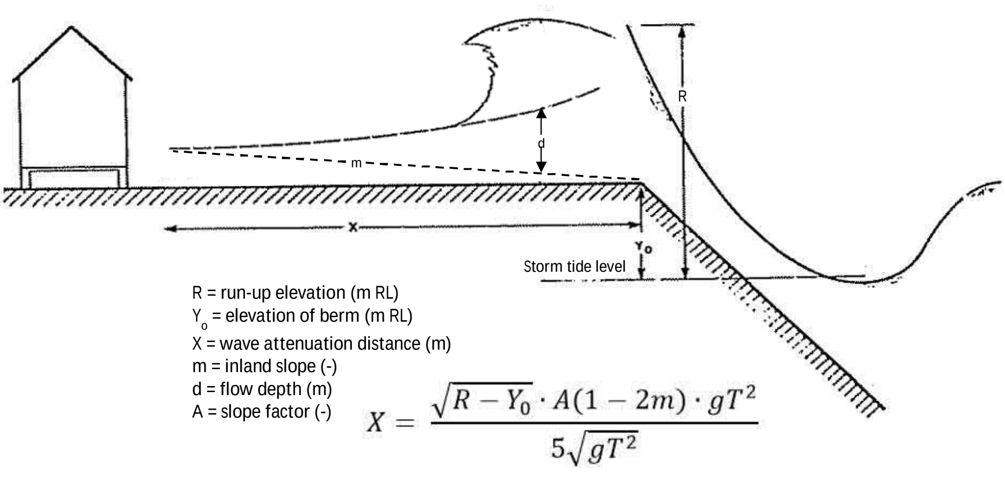

Figure 4-2: Run-up attenuation definition sketch (modified from Cox and Machemehl, 1986)

An example of using this method is shown in Figure 4-3. The dune elevation varies alongshore from a maximum of 7.9 m OTP64 to a minimum of 0.5 m OTP64 at a stream entrance. The run-up elevation is relatively consistent alongshore between 5 and 6 m OTP64. The run-up distance inland of the dune crest varies from 0 where the run-up elevation does not exceed the dune crest to 16 m where the run-up elevation significantly exceeds the dune crest elevation.

Furthermore it should be noted that the CRHZ represents the extent to where wave energy is fully dissipated. Topography induced overland flow paths may extend inland of the CRHZ and have not been considered in this assessment. The CRHZ mapping assumes that foreshore topography is as per the LIDAR survey. Shoreline retreat would result in the CRHZ migrating inland, but this is not reflected in the mapping.

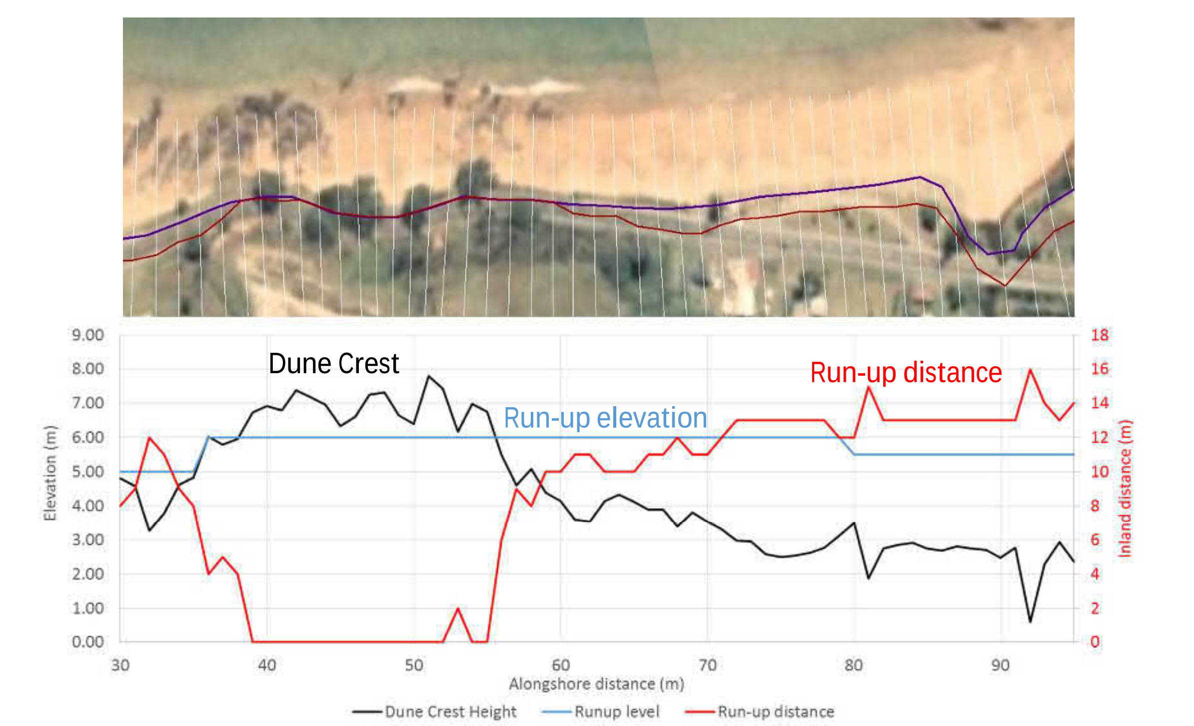

Figure 4-3: Example of wave run-up attenuation along a coastline. The dune crest height, run-up level and calculated run-up attenuation distance are shown at 10 m alongshore intervals.

4.3 Mapping CFHZ and CRHZ for Paihia CBD (site 27)

Different methods were used to assess the CFHZ and CRHZ along the Paihia CBD foreshore (site 27). This is due to the presence of a rock revetment and low-lying 'ponding-prone' areas situated several meters landward of the revetment which have been subject to flooding during large wave events (i.e. as shown in Figure 4-4Figure 4-4 during a storm event in 2014).

Figure 4-5 shows the extent of the rock revetment along the Paihia CBD foreshore.

Figure 4-4: Overtopping of the rock revetment along the Paihia CBD foreshore during a storm event in 2014 (source: R Griffin)

Figure 4-5: Extent of rock revetment along Paihia CBD foreshore (site 27) indicated with red line/arrows

4.3.1 CFHZs for Paihia CBD

CFHZs for the Paihia CBD foreshore have been re-assessed and re-mapped using a method which takes into account maximum overflow volume and backshore topography. The CFHZs have been re-assessed for the present day, 50 year and100 year time frames and include the following steps:

- Break the shoreline into representative sections
- Construct time series of water levels and wave height
- Calculate total overflow volume
- Assess maximum ponding volume (before water flows back to the sea)
- Re-mapping of CFHZs.

Three sections of rock revetment have been identified. These included partially grouted rock armour, rock armour backed by a grass bank and grouted rock armour with a grouted seawall.

Time series of water levels and significant wave heights over a characteristic tidal cycle have been constructed based on the 1% annual exceedance probability storm tide levels at 15 minute intervals across a characteristic tidal cycle. (see Figure 4-6).

The structure details and tidal conditions have been used as inputs to the EurOtop (2016) manual method for determining overtopping rates. Figure 4-6 shows the mean overtopping results for the three sections for the present day time frame.

The area of land that would be inundated by the assessed overflow was mapped by assessing the maximum level of ponding that can occur before a flow path back out to the sea is formed. Figure 4-7 shows an example of a cross-section along the Paihia CBD foreshore including the maximum level of ponding and resulting backflow that occurs when the maximum level of ponding is reached. The maximum inundated area limited by the maximum level of ponding is also shown in Figure 4-7.

Mapping of the inundated areas limited by the maximum level of ponding has been done for the present day, 50 year and 100 year timeframes. It was found that the maximum floodable volumes are limited by the coastal edge level and therefore the extent of CFHZ0, CFHZ1 and CFHZ2 are the same (see Figure 4-8).

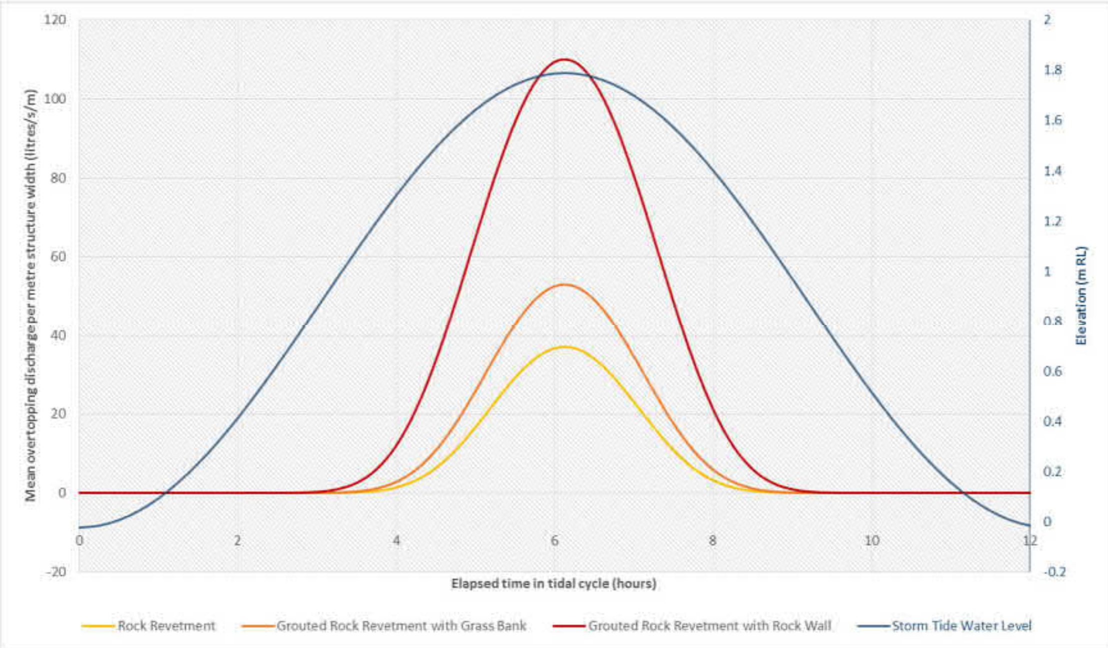

Figure 4-6: Current extreme static water levels (right axis) and mean overtopping discharge rates (left axis) for the three revetment structures over a high tide cycle.

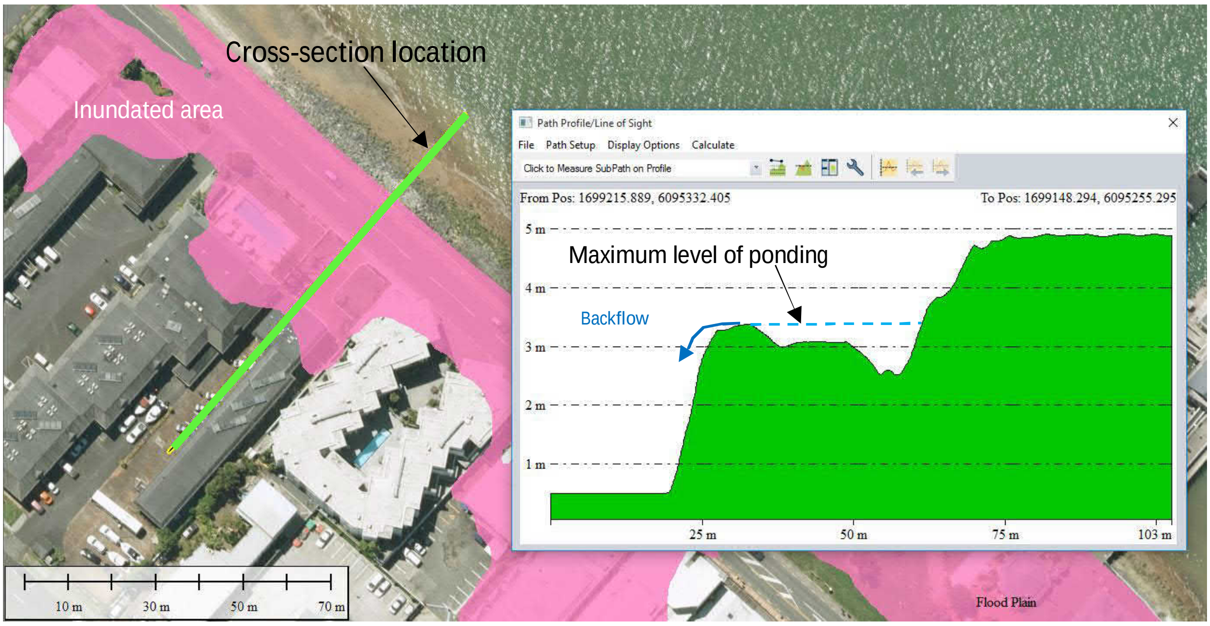

Figure 4-7: Example showing a cross-section including maximum level of ponding and backflow when maximum ponding level is reached. The map shows the inundated area limited by maximum level of ponding along the Paihia CBD foreshore.

4.3.2 CRHZ for Paihia CBD

A method to calculate wave run-up levels for sloping rock structures is presented in CIRIA (2007) The Rock Manual and was used for the Paihia CBD foreshore. This method takes into account significant wave height, peak wave period, revetment slope and roughness (see equation 3-11).

$$R_{2\%} = 1.17 \cdot \xi_0^{0.46} \cdot H_s \qquad (4\text{-}1)$$

Where:

$R_{2\%}$ = Run-up exceeded by 2% of the run-up crests

H_s = Significant wave height

ξ_m = Iribarren number: [(tan α) /(√H_s /L_{m0})]

Mapping of the CRHZ was done using the method as described in Section 0. It was found that using Equation 3-11 results in a lower run-up level compared to using Equation 3-10 for beach slopes. The run-up attenuation distance is typically 10-11 m along the rock revetment subject to the crest level, and is approximately 3-5 m less compared to using Equation 3-10 for beach slopes to assess run-up levels. Figure 4-8: Revised CFHZ0/1/2 (blue polygon) and CRHZ2 (orange line) for Paihia CBD foreshore. Figure 4-8 Figure 4-8 shows the revised CRHZ along the Paihia CBD foreshore.

Figure 4-8: Revised CFHZ0/1/2 (blue polygon) and CRHZ2 (orange line) for Paihia CBD foreshore.

4.4 Uncertainties and limitations

Uncertainty in mapping may be introduced by:

- Extent of LiDAR
- Flow transmitting or blocking structures
- Merging of adjacent cells
- Large flooded areas
- Future changes in land elevations and geomorphology
- No overtopping flows included in wave run-up.

Of these uncertainties, the first two components are limitations introduced by the LiDAR datasets. The mapping of flooded zones is limited to the extent of the LiDAR datasets where it might be flooded outside of the LiDAR extents. Structures (e.g. bridges or culverts) within the LiDAR datasets are not picked up as only surface points can be surveyed. The LiDAR DEMs need to be manually edited to include structures which may introduce uncertainty and could limit the flooded zones in case a structure has not been properly included. Where land elevation at a site is below the CFHZ level, yet no flooding is shown, a check should be made to confirm there is no hydraulic connection to the coast.

Where flood levels differ between adjacent cells, for instance a higher flood level is applied on the open coast and a lower flood level is applied to the adjacent estuary (e.g.Waitangi, Matapouri, Waipu Cove etc.), the corresponding flooded areas must be defined for each cell and merged. This may introduce some uncertainty where the flood extents overlap each other and a decision needs to be made as to where the overlapping areas are cropped. This has generally been resolved by using the closest shoreline.

For very large flooded areas, the connected bathtub approach may result in conservative flood extents (refer to Section 4.2) due to friction and a limited peak flood duration. Furthermore, flow through small openings such as stream mouths may similarly result in conservative flood extents compared to reality.

A geomorphologically static landform coastline has been assumed for the mapping of all coastal flood hazard zones. Future changes in topography, or changes which have occurred since the time of LIDAR survey, due to natural (i.e. accretion or erosion) or artificial causes (e.g. earthworks) may affect the predicted flood extents. Any changes should be reviewed in future updates of the CFHZ. Furthermore, the CRHZ has been mapped relative to the existing dune crest. This approach has been adopted because of the uncertainty in future dune crest position and likewise should be reviewed in future updates.

No overtopping flows have been included in the wave run- up mapping. Overtopping has the potential to cause flooding in areas not connected to the marine area by low topography. However, overtopping is highly site-specific and not feasible to assess on a regional scale. Such overtopping should be considered further on a site-specific basis as required. The assessment referred to above for Paihia in Section 4.3.1 considered wave overtopping in deriving CFHZ extent, however as with other sites, the flow paths resulting from wave run-up have not been mapped.

4.5 Discussion of results

4.5.1 CFHZ and CRHZ levels

The assessed open coast CFHZ0 levels as presented in Appendix C vary from 1.8 m to 3.2 m OTP64 on the east coast and from 2.8 m to 3.3 m OTP64 on the west coast. The highest CFHZ0 are found at exposed open coast beaches with the highest CFHZ levels on the east coast at Ocean Beach, and on the west coast at Ahipara. The lowest CFHZ levels are reached at the sheltered Bay of Islands / Whangaroa sites on the east coast and at the Hokianga sites on the west coast.

For the estuary sites the CFHZ0 levels vary from 1.7 m to 2.2 m OTP64 on the east coast and from 2.4 m to 3.3 m OTP64 on the west coast. The highest CFHZ0 levels on the east coast are reached in the Upper Whangarei Harbour, Tauranga Bay, Te Ngaere and Taupo Bay, and on the west coast at Ruawai and Paparoa. The higher estuary sites CFHZ levels on the west coast exist because of the higher astronomical tidal levels (refer to Section 2.3.2 for MHWS levels around Northland).

The highest wave run-up levels (CRHZ2) are reached at Waipu (8.5 m OTP64), Russell (8.6 m OTP64) and Ocean Beach (8.8 m and 9.6 m OTP64) due to large waves and steep foreshores. The largest run-up attenuation distance is reached at Tauranga Bay (19 m) due to the relatively low dune crest.

Average run-up attenuation distances are 10 - 12 m for exposed beaches with steep beach slopes and/or relatively low dune crests.

4.5.2 CFHZ and CFHZ maps

The extents of the CFHZs for each site as mapped in Appendix D using a connected bathtub approach vary from small areas (e.g. Long Reach, Russell) to very large areas (e.g. Ruawai – not mapped). For sites with a steep rising topography (e.g. Long Reach, Russell) the static inundation extent is limited to the coastal edge. This is evident along most open coast beaches of the east coast of Northland, and Ahipara and Omapere on the west coast.

An exception to this are streams and inlets interrupting the coastline that could result in inundation behind the higher fore dunes through the stream or inlet. For instance at Taipa, Pataua and Matapouri coastal inundation occurs via the estuary.

5 Conclusions and recommendations

This assessment has considered the drivers of coastal flooding and run-up in the Northland region to derive extreme static water levels and run-up levels that have been used to map Coastal Flooding and Run-up Hazard for select sites where LIDAR survey was available.

These processes are driven by astronomical tide, storm surge, and medium term fluctuations in sea level, wave processes and long-term changes in mean sea level. These processes can be independent or partially-dependent on one another and analysis methods have been used which allow for this level of dependence. This has resulted in less conservative outputs that would be obtained using traditional 'building block' approaches whereby complete dependence is assumed.

Calculated run-up levels have been validated against measurements of run-up debris after a substantial storm event in January 2008. Several methods were tested with adopted method generally calculating values within 10% of observed values.

This assessment has presented extreme static and dynamic (run-up) levels corresponding to the present day, 2065 (50 years) and 2115 (100 years). These have been used to map coastal flood hazard zones (CFHZ) and a coastal run-up hazard zone (CRHZ) for the following scenarios:

- Coastal Flood Hazard Zone 0 (CFHZ0): Extent of 1% AEP static water level at 2015
- Coastal Flood Hazard Zone 1 (CFHZ1): Extent of 2% AEP static water level at 2065
- Coastal Flood Hazard Zone 2 (CFHZ2): Extent of 1% AEP static water level at 2115
- Coastal Run-up Hazard Zone (CRHZ): Extent of 1% AEP dynamic wave run-up at 2115.

Coastal flood hazard zones have been mapped using a connected bathtub model where areas are flooded only where they connect to the coastal water body (or by a structure such as a drainage channel or culvert). This provides more realistic flooding extents by accounting for natural and human influenced topography.

Run-up differs from static flooding as run-up is a dynamic process. Coastal run-up hazard zones have been mapped by applying an attenuation model to the maximum run-up elevation to determine the maximum inland incursion reached by wave run-up.

Flood mapping has only been undertaken for areas where LiDAR data is available. Where flooding reaches the boundary of a DEM, flooding may continue outside the mapped area but is not able to be mapped. The extent of the mapping is generally represented by a straight edge to the CFHZ extent. In these cases, and where LiDAR is missing, the derived static levels at the coast should be used to determine exposure to coastal flooding hazard.

Several sources of potential uncertainty have been noted including the LiDAR extents, the current landform adopted and inclusion of human induced change, the merging of adjacent cells and exclusion of overtopping flows. The most significant, however, is the flooding of large, low lying areas such as the Ruawai, Dargaville and Awanui areas. In these area, the connected bathtub approach may result in conservative flood extents due to the limited duration of the maximum flood and frictional losses across the land. Dynamic (hydrodynamic) modelling for these sites is being undertaken separately and maps for these sites have therefore not been included in this report.

6 Applicability

This report has been prepared for the benefit of Northland Regional Council with respect to the particular brief given to us and it may not be relied upon in other contexts or for any other purpose without our prior review and agreement.

Tonkin & Taylor Ltd

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8 Glossary

Chart Datum:	Marine based datum corresponding to a very low astronomical tide
Gauge datum:	Arbitrary zero datum on a tide gauge
One Tree Point Vertical Datum 1964 (OTP64):	Land datum generally based on a historic mean
Reduced Level (RL):	Land based datum (see OTP64)
Mean Sea Level (MSL):	Time-averaged water level
Astronomical tide:	Cyclic fluctuation in water levels induced by astronomical (sun and moon) processes and shallow water resonance. Independent of climatic and synoptic events
Mean High Water Spring (MHWS):	Defined as the high tide level averaged over a certain number of percentage of tides (i.e. MHWS10 is the high tide level exceeded by 10% of tides)
Storm Surge (SS):	Elevated water level resulting from the effects of barometric pressure and wind shear
Storm Tide (ST):	Total water level resulting from the combination of astronomical tide and storm surge
Wave set-up:	Quasi-static elevated water level at the coastline resulting from wave dissipation in the surf zone
Wave run-up:	Water level fluctuations above the static level caused by residual (non-dissipated) wave energy reaching the shoreline
Sea Level Rise (SLR):	Long-term change in relative mean sea level. May be caused by changes in global sea level and/or local land level
Offshore:	The seaward zone extending from the shoreface to the edge of the continental shelf.
Open coast:	Defined as coastline exposed to non-fetch-limited swell and sea. Typically non-consolidated sandy beaches.
Sheltered coast:	Defined as coastline exposed to locally generated fetch-limited waves
Extreme static water level:	Maximum vertical 'static' water elevation caused by a combination of mean sea level fluctuations, astronomical tide, storm surge, wave set-up and, in the future, sea level rise
Extreme run-up level:	Maximum vertical elevation of wave run-up processes superimposed on storm tide (includes wave set-up)

Coastal Flood Hazard Zone (CFHZ):	Area inundated by an extreme static water level
Coastal Run-up Hazard Zone (CRHZ):	Area subject to wave run-up flows

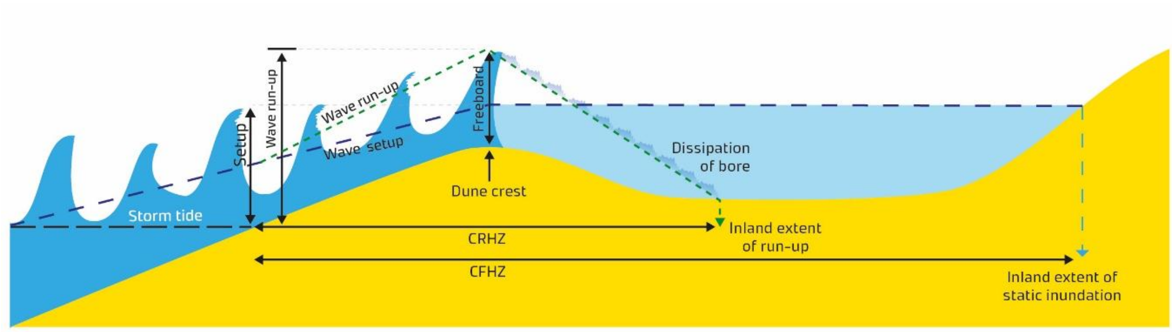

Figure 8-1: Definition sketch for CFHZ and CRHZ

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Appendix A: Available LiDAR data

Table A-1: LiDAR data user for each site/cell

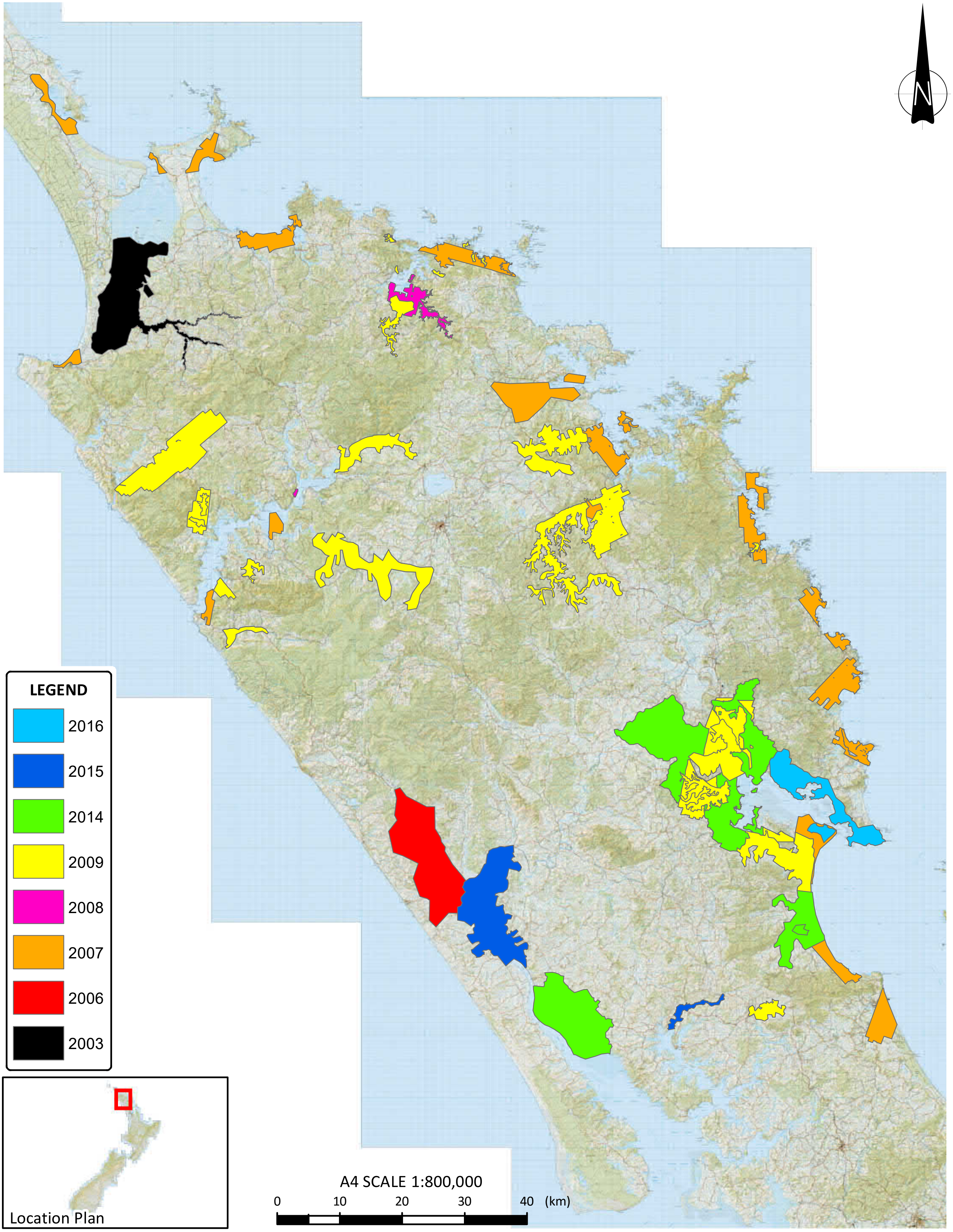
Site				LiDAR year
No	Name	Type	Cell	
1	Mangawhai estuary	Open coast	A	2007
		Sheltered	B	2007
2	Langs Beach	Open coast		2007
3	Waipu Cove	Open coast	A	2014
		Open coast	B	2007
		Estuary	C	2007
4	Waipu Estuary	Sheltered		2007/ 2014
5	Ruakaka	Open coast	A	2007/ 2009
		Sheltered	B	2009
6	Marsden Point	Sheltered	A	2007/2 016
		Open coast	B	2007/2 016
		Open coast	C	2007/2 016
7	Marsden Cove	Sheltered		2007/2 016
8	One Tree Point	Sheltered	A	2007
		Sheltered	B	2007
9	Whangarei Harbour West	Sheltered	A	2014
		Sheltered	B	2014
		Sheltered	C	2009/ 2014
		Sheltered	D	2009/ 2014
10	Mc Leods Bay	Sheltered		2009/2 016
11	Taurikura - Urquarts Bay	Open coast	A	2009/2 016
		Sheltered	B	2009/2 016
12	Taiharuru	Open coast	A	2007
		Sheltered	B	2007
13	Pataua Estuary and Pataua North	Open coast	A	2007
		Sheltered	B	2007
14	Ngunguru Estuary	Open coast	A	2007
		Sheltered	B	2007
15	Whangaumu Beach	Open coast		2007

Site				LiDAR year
No	Name	Type	Cell	
16	Tutukaka Harbour	Open coast		2007
17	Matapouri Estuary and Bay	Open coast	A	2007
		Sheltered	B	2007
18	Whananaki	Open coast	A	2007
		Open coast	B	2007
		Sheltered	C	2007
19	Teal Beach Bay (Ngawai Bay)	Open coast		2007
20	Helena Bay (Te Mimiha)	Open coast		2007/ 2009
21	Ohawini Bay (& Parutahi Beach)	Open coast		2007
22	Oakura Bay	Open coast		2007
23	Bland Bay	Open coast	A	2007
		Sheltered	B	2007
24	Russell	Open coast	A1	2007
		Open coast	A2	2007
		Sheltered	B	2007
25	Opua - Okiato	Sheltered	A	2007
		Sheltered	B	2007
		Sheltered	C	2007
		Sheltered	D	2007
26	Taumarere Estuary	Sheltered		2007/ 2009
27	Paihia	Sheltered		2007
28	Te Ti Bay - Waitangi Estuary	Open coast		2007
		Sheltered		2007/ 2009
29	Kerikeri Inlet	Sheltered	A	2007
		Sheltered	B	2007
30	Matauri Bay	Open coast	A	2007
		Open coast	B	2007
31	Tauranga Bay	Open coast		2009
32	Whangaroa Coast	Open coast	A	2009
32		Open coast	B	2009
		Open coast	C	2007/ 2009

Site				LiDAR year
No	Name	Type	Cell	
33	Whangaroa Harbour (Totara North)	Sheltered		2009
34	Whangaroa Settlement	Sheltered	A	2008
		Sheltered	B	2009
35	Kaeo Estuary	Sheltered		2008
36	Pupuke Estuary	Sheltered		2009
37	Taupo Bay	Open coast		2007/ 2009
38	Hihi	Open coast	A	2007
		Sheltered	B	2007
39	Coopers Beach	Open coast	A	2007
		Sheltered	B	2007
40	Cable Bay	Open coast		2007
41	Taipa	Open coast	A	2007
		Sheltered	B	2007
42	Tokerau Beach North	Open coast		2007
43	Rangiputa	Sheltered		2007
44	Awanui Estuary	Sheltered		2003
45	Houhora - Pukenui	Open coast	A	2007
		Sheltered	B	2007
46	Ahipara	Open coast		2007
47	Whangape Harbour	Sheltered		2009
48	Panguru Estuary	Sheltered		2009

Site				LiDAR year
No	Name	Type	Cell	
49	Kohukohu	Sheltered		2008
50	Waihou Estuary	Sheltered		2009
51	Taheke River estuary	Sheltered		2009
52	Rawene	Sheltered		2007
53	Whirinaki Estuary	Sheltered		2009
54	Pakanae (Awapokoui estuary)	Sheltered		2009
55	Omapere & Opononi	Open coast	A	2007
		Sheltered	B	2007
56	Waimamaku Estuary	Sheltered		2009
57	Kaihu Estuary	Sheltered		2006/ 2015
58	Dargaville - Wairoa	Estuary		2015
59	Ruawai	Estuary	A	2014
		Estuary	B	2014
60	Paparoa estuary	Estuary		2015
61	Maungaturo-to	Estuary		2009
62	Whangarei Harbour North	Estuary	A	2016
		Estuary	B	2016
		Estuary	C	2016
63	Ocean Beach	Open coast	A	2016
		Open coast	B	2016

Note that the latest LiDAR data has been used in preference of older LiDAR data for each site/cell



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APPROVED	RRH	Dec.17

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PROJECT No.
1001049

NRC Coastal Inundation

LiDAR extents

FIGURE No.
Figure A

Rev.
2

Appendix B: Wave transformation using numerical SWAN model

Open coast

Numerical wave transformation modelling has been undertaken to transform offshore waves into the shoreline for each open coast site.

B1 Model description

The numerical model SWAN (Simulating Waves Nearshore) has been used to undertake wave transformation modelling. SWAN is a third-generation wave model that computes random, short-crested wind-generated waves in coastal regions and inland waters by solving the spectral action balance equation without any restrictions on the wave spectrum evolution during growth or transformation. The SWAN model accommodates the process of wind generation, white capping, bottom friction, quadruplet wave-wave interactions, triad wave-wave interactions and depth induced breaking. SWAN is developed at Delft University of Technology in the Netherlands and is widely used by government authorities, research institutes and consultants worldwide. Further details of SWAN can be found in Booij et al. (1999).

B2 Model domains

The regional model domain encompassing all of Northland was constructed using bathymetry sourced from the LINZ Nautical Charts (Figure B-2). A total of six local model domains (see Table B-1) have been generated incorporating all coastal cells being assessed except for Omapere. Omapere is subject to only limited offshore wave energy due to the presence of the Hokianga Bar and the narrow inlet throat.

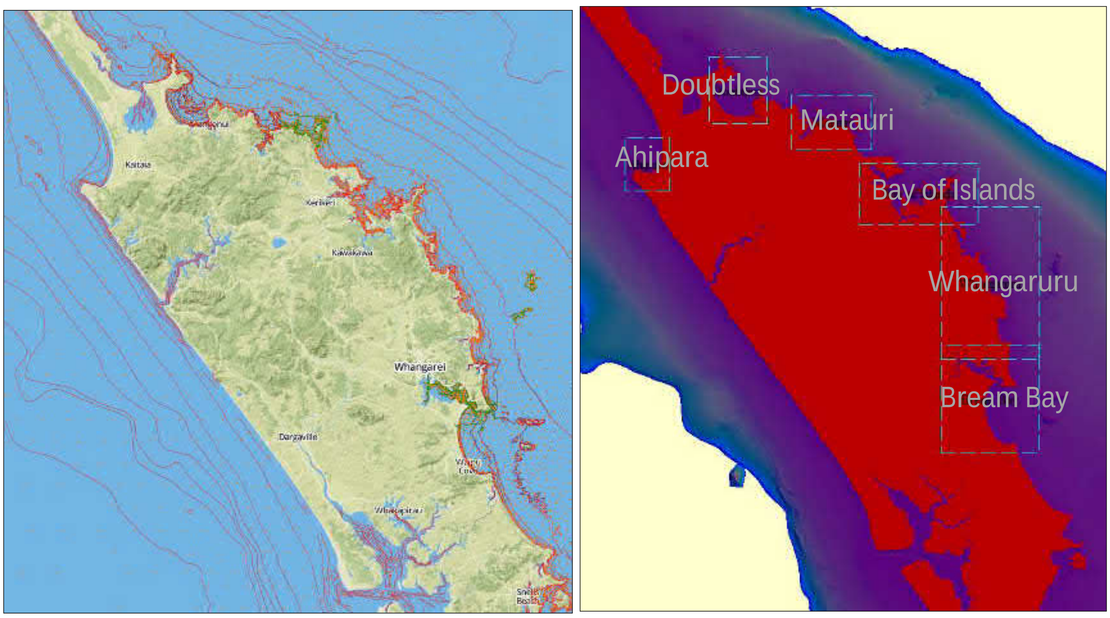

Figure B-2: Bathymetric contours and spot heights from LINZ database (A) and derived bathymetry map model (B) used to construct SWAN model domains (dashed boxes)

Table B-1 Model domains

Model domain	Coordinates (lower left corner) [X,Y] NZTM2000	Domain size [X,Y]	Grid resolution
Ahipara	(1602000,6101000)	20 x 20 km2	50 m x 50 m
Doubtless	(1632500,6125000)	20 x 25 km2	50 m x 50 m
Matauri	(1662000,6116000)	30 x 20 km2	50 m x 50 m
Bay of Islands	(1687000,6086500)	40 x 25 km2	50 m x 50 m
Whangaruru	(1716100,6040500)	35 x 55 km2	50 m x 50 m
Bream Bay	(1716000,6005500)	35 x 40 km2	50 m x 50 m

B3 Storm event modelling

Wave modelling was undertaken to transform wave conditions offshore to the nearshore where they are used to drive beach erosion models. The peak significant wave height during the design events (10 and 100 year ARI from multiple directions) are transformed from offshore to 10 m water depth using the local SWAN models while applying a corresponding extreme wind (i.e. 100 year ARI wind during the 100 year ARI wave event). This check ensures that wave energy gained by wind forcing is allowed for as well as losses due to refraction, friction and breaking. Figure B-1 shows example results of the significant wave height during a 100 year ARI storm from the west (west coast) and figures B-2 to B-6 show example results for a storm from the northeast (east coast) for each model domain.

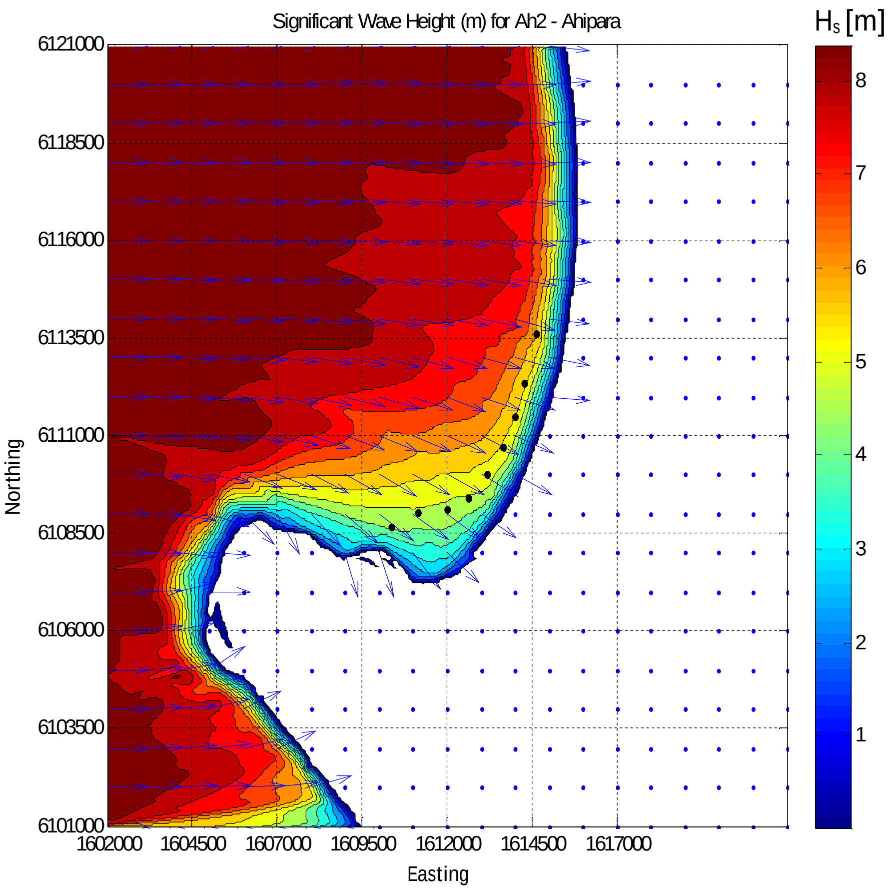

Figure B-1: SWAN model results for the Ahipara domain – Significant wave height and direction during a 100 year ARI storm from the west

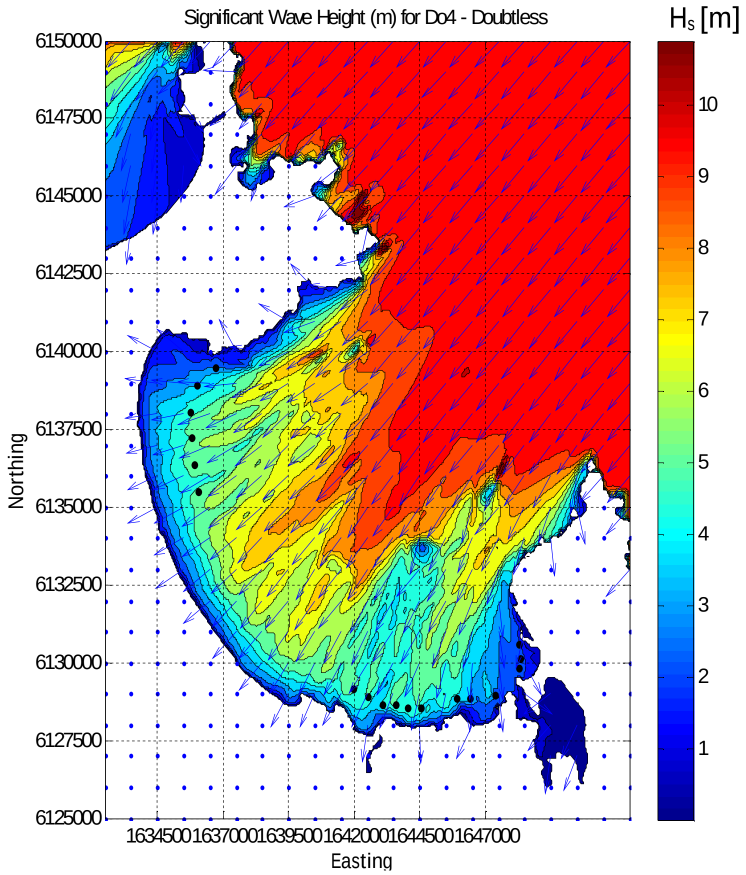

Figure B-2: SWAN model results for the Doubtless model domain – Significant wave height and direction during a 100 year ARI storm from the Northeast

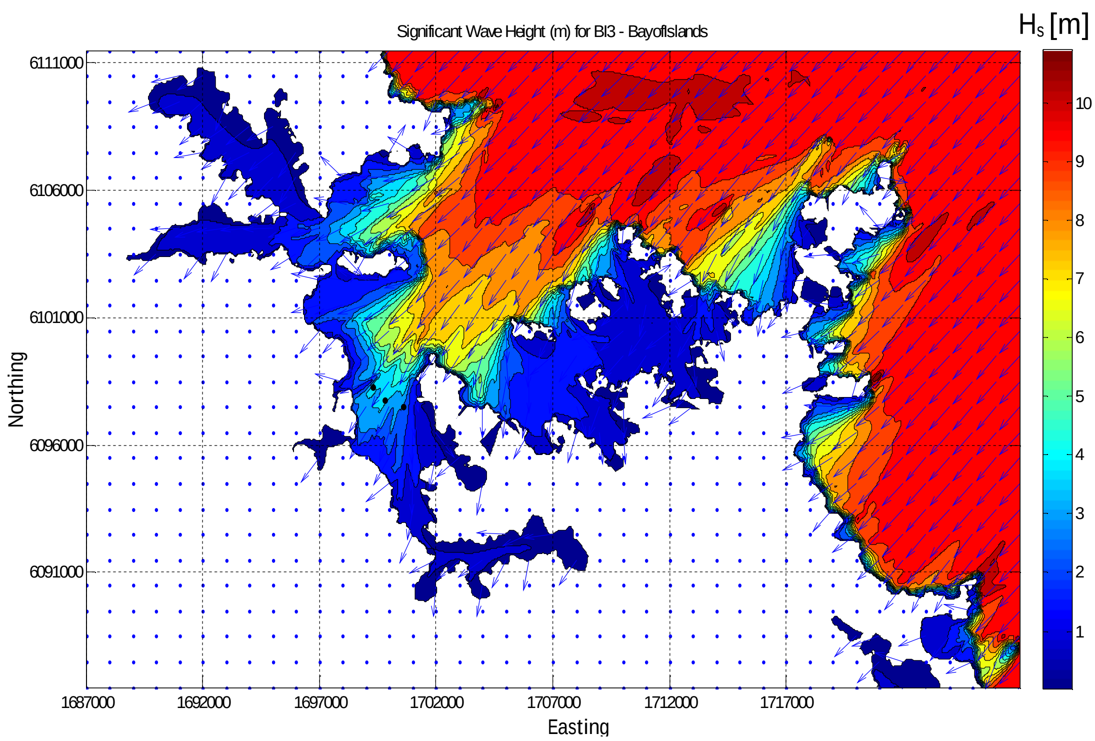

Figure B-3: SWAN model results for the Bay of Islands model domain – Significant wave height and direction during a 100 year ARI storm from the Northeast

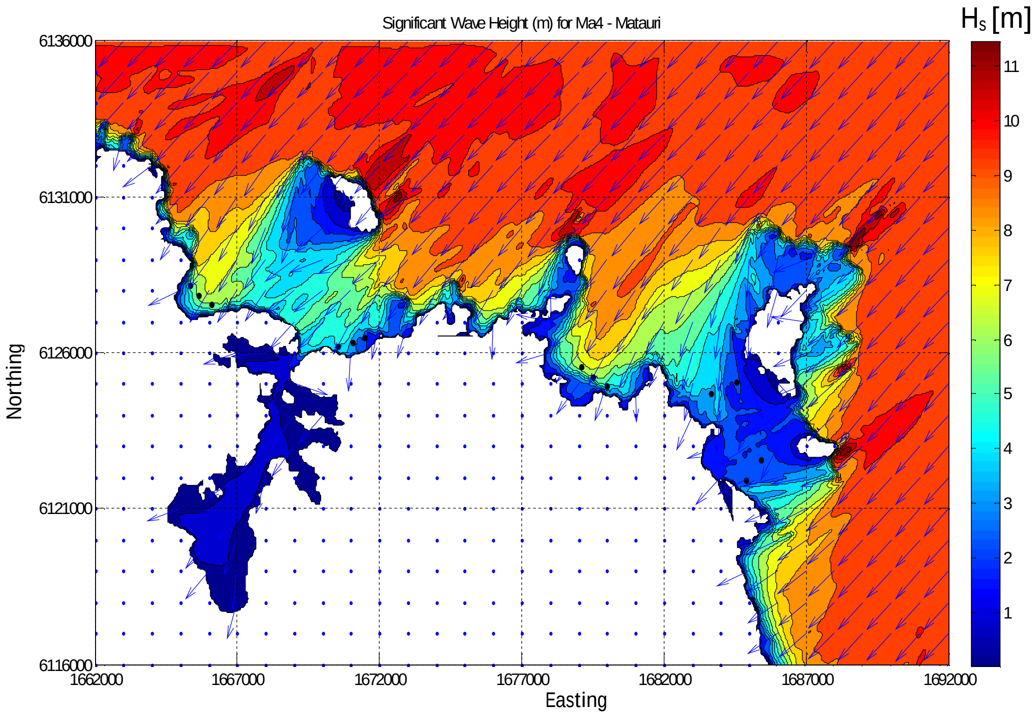

Figure B-4: SWAN model results for the Matauri model domain – Significant wave height and direction during a 100 year ARI storm from the Northeast

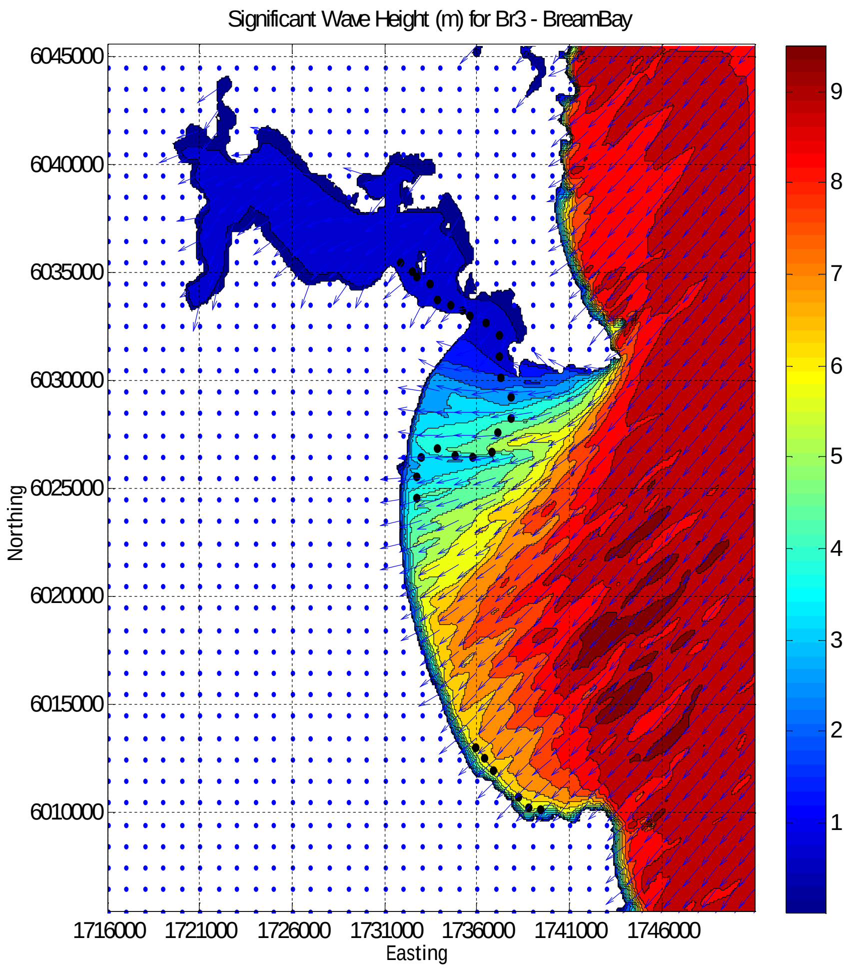

Figure B-5: SWAN model results for the Bream Bay model domain – Significant wave height and direction during a 100 year ARI storm from the northeast

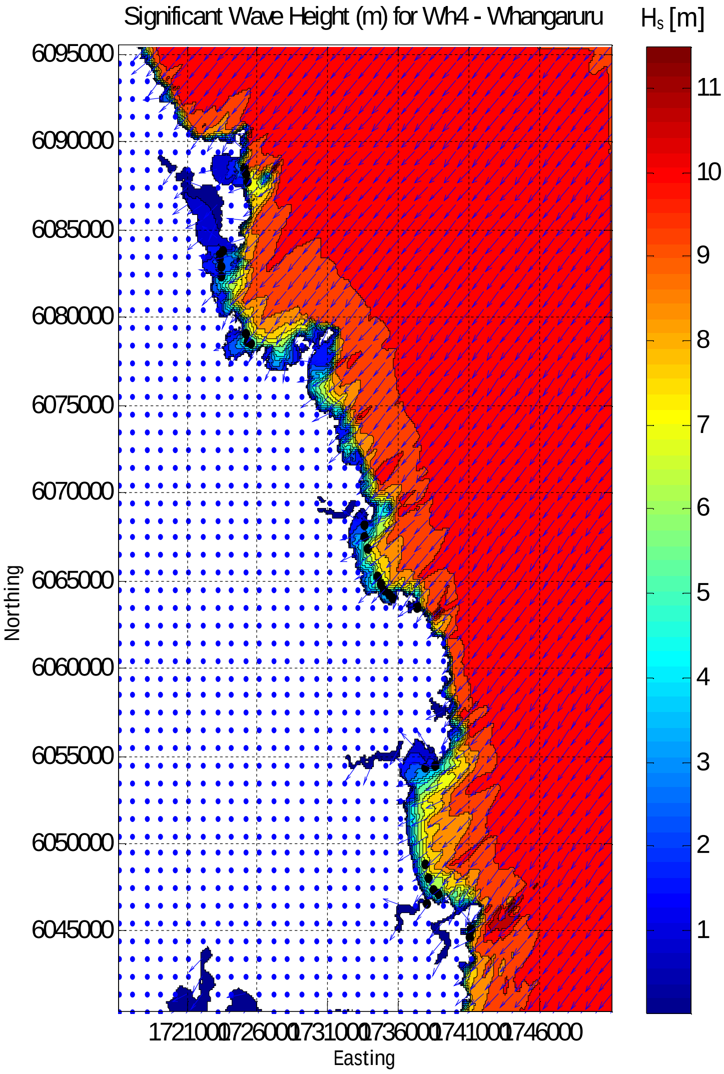

Figure B-6: SWAN model results for the Whangaruru model domain – Significant wave height and direction during a 100 year ARI storm from the northeast

B4 Wave transformation modelling

Wave transformation modelling has been undertaken to transform the offshore wave characteristics into nearshore wave conditions for each open coast site. Simulations have been undertaken for each model domain for a range of relevant wave periods and directions. This has resulted in wave height transformation coefficients being established between the offshore and nearshore positions for each relevant direction and period. Example of transformation tables are included for Ahipara, Matauri and Bream Bay in Table B.1, B.2 and B.3 respectively. Shorter-period wind-wave have been excluded from analysis as they do not significantly contribute to the extreme wave climate (i.e. in the largest 30-40 storms).

Table B.1: Wave transformation table for Ahipara offshore

	Site	Wave H transformation for offshore wave direction for T=12 s								
		Cell	180	202.5	225	247.5	270	292.5	315	337.5	360
Ahipara	Ahipara	30-A	0.04	0.08	0.13	0.22	0.40	0.59	0.73	1.02	1.01
		30-B	0.04	0.09	0.14	0.25	0.46	0.67	0.82	1.06	0.98
		30-C	0.05	0.10	0.15	0.27	0.49	0.71	0.85	1.06	0.97
		30-D	0.05	0.12	0.18	0.31	0.56	0.80	0.89	1.03	0.94
		30-E	0.07	0.15	0.22	0.36	0.60	0.75	0.96	1.13	0.96
		30-F	0.09	0.19	0.29	0.48	0.77	0.92	1.04	1.09	0.94
		30-G	0.10	0.22	0.34	0.56	0.85	0.98	1.10	1.12	0.91
		30-H	0.09	0.21	0.32	0.52	0.74	0.89	1.08	1.11	0.90
		30-I	0.11	0.24	0.36	0.57	0.79	0.93	0.98	0.89	0.58
		30-J	0.12	0.26	0.43	0.70	0.99	1.20	1.08	1.01	0.73
		30-K	0.11	0.26	0.44	0.67	0.89	0.93	0.98	0.97	0.81

Table B.2: Wave transformation table for Matauri offshore

	Site	Wave H transformation for offshore wave direction for T=12 s							
		Cell	337.5	0	22.5	45	67.5	90	112.5	135
Matauri	*Taupo Bay*	23-A	0.28	0.40	0.58	0.57	0.40	0.24	0.12	0.06
		23-B	0.32	0.44	0.61	0.56	0.40	0.25	0.12	0.06
		23-C	0.38	0.54	0.76	0.74	0.46	0.28	0.13	0.07
		23-D	0.42	0.60	0.80	0.75	0.44	0.26	0.13	0.07
	Tauranga Beach	22-A	0.82	0.70	0.61	0.58	0.51	0.30	0.16	0.08
		22-B	0.64	0.61	0.63	0.62	0.52	0.28	0.14	0.07
		22-C	0.62	0.67	0.77	0.84	0.68	0.37	0.18	0.09
		22-D	0.75	0.78	0.86	0.92	0.74	0.40	0.20	0.10
		22-E	1.07	0.95	0.96	1.01	0.80	0.44	0.23	0.12
	Te Ngaere	21-A	0.29	0.51	0.79	0.63	0.32	0.19	0.14	0.10
		21-B	0.34	0.59	0.88	0.67	0.35	0.20	0.15	0.11
		21-C	0.34	0.59	0.85	0.65	0.33	0.19	0.14	0.11
	Matauri	20-A	0.27	0.25	0.25	0.33	0.42	0.50	0.61	0.41
		20-B	0.24	0.22	0.23	0.32	0.40	0.46	0.47	0.34
		20-C	0.22	0.22	0.26	0.39	0.50	0.52	0.54	0.40

Table B.3: Wave transformation table for Bream Bay offshore

	Site	Wave H transformation for offshore wave direction for T=12 s							
		Cell	337.5	0	22.5	45	67.5	90	112.5	135
Bream Bay	Taiharuru	7	0.14	0.23	0.53	0.83	0.88	0.72	0.78	0.72
	One Tree Point	6-B	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		6-C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
		6-C_2	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02
		6-D	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02
	Marsden Cove	5-C	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02
		5-D	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02
	Marsden Point	4-A	0.00	0.00	0.01	0.01	0.03	0.08	0.15	0.19
		4-B	0.01	0.01	0.02	0.03	0.08	0.22	0.40	0.52
		4-C	0.01	0.02	0.04	0.08	0.21	0.52	0.84	0.91
		4-D	0.02	0.04	0.06	0.15	0.37	0.78	1.06	0.91
		4-E	0.04	0.06	0.11	0.24	0.53	0.83	0.87	0.73
	Ruakaka	3-A	0.08	0.13	0.21	0.47	0.77	0.75	0.62	0.49
		3-B	0.04	0.06	0.11	0.26	0.51	0.73	0.75	0.55
		3-D	0.03	0.05	0.09	0.26	0.57	0.86	0.78	0.63
	Waipu	2-A	0.07	0.16	0.51	0.95	1.10	1.06	0.85	0.40
		2-B_1	0.07	0.19	0.57	1.04	1.14	0.97	0.63	0.28
		2-B_2	0.10	0.26	0.69	1.10	1.09	0.84	0.52	0.20
	Langs Beach	1-A	0.15	0.41	0.98	1.18	0.90	0.68	0.44	0.17
		1-B	0.15	0.42	0.95	1.07	0.82	0.61	0.39	0.15
		1-C	0.15	0.40	0.89	1.01	0.83	0.61	0.39	0.15
		1-D	0.15	0.40	0.86	0.96	0.75	0.52	0.32	0.13
		1-E	0.17	0.44	0.86	0.91	0.63	0.39	0.23	0.09
		1-F	0.17	0.43	0.79	0.75	0.49	0.29	0.16	0.06

Appendix C: Storm tide and extreme water levels

This Appendix presents extreme water levels at present day (current), in 50 years (2065) and in 100 years (2115) including:

- Storm tide level resulting from the combination of astronomical tide and storm surge
- Extreme static water level used to derive Coastal Flood Hazard Zone (CFHZ)
- Extreme run-up level used to derive Coastal Run-up Hazard Zone (CRHZ).

Table C-1: Storm tide and extreme water levels

Site				MHWS (m OTP)	Current 1% AEP (m OTP)			2065 2% AEP (m OTP)			2115 1% AEP (m OTP)		
No.	Name	Type	Cell		Storm tide	Static WL	Run-up level	Storm tide	Static WL	Run-up level	Storm tide	Static WL	Run-up level
1	Mangawhai estuary	Open coast	A	1.07	1.6	3.0	5.8	2.0	3.2	6.1	2.6	4.0	6.8
		Sheltered	B	1.07	1.6	1.9		2.0	2.3		2.6	2.9	
2	Langs Beach	Open coast		1.06	1.6	2.7	6.0	2.0	3.0	6.1	2.6	3.7	7.0
3	Waipu Cove	Open coast	A	1.06	1.6	3.0	7.5	2.0	3.2	7.7	2.6	4.0	8.5
		Open coast	B	1.06	1.6	2.9	6.1	2.0	3.1	6.4	2.6	3.9	7.1
		Estuary	C	1.06	1.6	2.0		2.0	2.3		2.6	3.0	
4	Waipu Estuary	Sheltered		1.06	1.6	2.0		2.0	2.3		2.6	3.0	
5	Ruakaka	Open coast	A	1.06	1.6	2.7	4.9	2.0	3.0	5.1	2.6	3.7	5.9
		Sheltered	B	1.06	1.6	1.9		2.0	2.3		2.6	2.9	
6	Marsden Point	Sheltered	A	1.11	1.7	1.9		2.0	2.2		2.7	2.9	
		Open coast	B	1.11	1.7	2.0	3.4	2.0	2.3	3.6	2.7	3.0	4.4
		Open coast	C	1.11	1.7	2.4	3.8	2.0	2.7	4.1	2.7	3.4	4.8

Site				MHWS (m OTP)	Current 1% AEP (m OTP)			2065 2% AEP (m OTP)			2115 1% AEP (m OTP)		
No.	Name	Type	Cell		Storm tide	Static WL	Run-up level	Storm tide	Static WL	Run-up level	Storm tide	Static WL	Run-up level
7	Marsden Cove	Sheltered		1.11	1.7	1.9		2.0	2.2		2.7	2.9	
8	One Tree Point	Sheltered	A	1.11	1.7	1.9		2.0	2.2		2.7	2.9	
		Sheltered	B	1.11	1.7	1.9		2.0	2.3		2.7	2.9	
9	Whangarei Harbour West (9A Onerahi East; 9B Onerahi South; 9C Whangarei / Onerahi West; 9D Otaika / Portland	Sheltered	A	1.11	1.9	2.1		2.2	2.5		2.9	3.1	
		Sheltered	B	1.11	1.9	2.0		2.2	2.4		2.9	3.0	
		Sheltered	C	1.11	1.9	1.9		2.2	2.3		2.9	2.9	
		Sheltered	D	1.11	1.9	2.1		2.2	2.4		2.9	3.1	
10	Mc Leods Bay	Sheltered		1.11	1.7	2.0		2.0	2.3		2.7	3.0	
11	Taurikura - Urquarts Bay	Open coast	A	1.11	1.7	1.8	2.2	2.0	2.2	2.5	2.7	2.8	3.2
		Sheltered	B	1.11	1.7	1.9		2.0	2.2		2.7	2.9	
12	Taiharuru	Open coast	A	0.98	1.5	2.7	6.0	1.9	2.9	6.3	2.5	3.7	7.0
		Sheltered	B	0.98	1.5	1.9		1.9	2.2		2.5	2.9	
13	Pataua Estuary and Pataua North	Open coast	A	0.98	1.5	2.8	7.0	1.9	3.0	7.2	2.5	3.8	8.0
		Sheltered	B	0.98	1.5	1.8		1.9	2.1		2.5	2.8	
14	Ngunguru Estuary	Open coast	A	0.98	1.5	2.8	5.9	1.9	3.0	5.9	2.5	3.8	6.9
		Sheltered	B	0.98	1.5	1.9		1.9	2.2		2.5	2.9	
15	Whangaumu Beach	Open coast		0.98	1.5	2.1	4.3	1.9	2.4	4.5	2.5	3.1	5.3
16	Tutukaka Harbour	Open coast		0.97	1.5	1.8	2.7	1.9	2.1	2.9	2.5	2.8	3.7
17	Matapouri Estuary and Bay	Open coast	A	0.97	1.5	2.1	3.8	1.9	2.4	4.0	2.5	3.1	4.8
		Sheltered	B	0.97	1.5	1.9		1.9	2.2		2.5	2.9	
18	Whananaki	Open coast	A	0.97	1.5	2.7	5.0	1.9	3.0	5.2	2.5	3.7	6.0
		Open coast	B	0.97	1.5	2.8	5.2	1.9	3.1	5.4	2.5	3.8	6.2

Site				MHWS (m OTP)	Current 1% AEP (m OTP)			2065 2% AEP (m OTP)			2115 1% AEP (m OTP)		
No.	Name	Type	Cell		Storm tide	Static WL	Run-up level	Storm tide	Static WL	Run-up level	Storm tide	Static WL	Run-up level
		Sheltered	C	0.97	1.5	1.8		1.9	2.1		2.5	2.8	
19	Teal Beach Bay (Ngawai Bay)	Open coast	A	0.97	1.5	2.1	6.0	1.9	2.4	6.3	2.5	3.1	7.0
		Sheltered	B	0.97	1.5	1.9		1.9	2.2		2.5	2.9	
20	Helena Bay (Te Mimiha)	Open coast		0.97	1.5	2.2	6.1	1.9	2.5	6.4	2.5	3.2	7.1
21	Ohawini Bay (& Parutahi Beach)	Open coast		0.97	1.5	2.2	3.7	1.9	2.4	3.8	2.5	3.2	4.7
22	Oakura Bay	Open coast		0.97	1.5	2.3	4.3	1.9	2.5	4.5	2.5	3.3	5.3
23	Bland Bay	Open coast	A	0.97	1.5	2.6	5.7	1.9	2.8	5.9	2.5	3.6	6.7
		Sheltered	B	0.97	1.5	1.7		1.9	2.0		2.5	2.7	
24	Russell	Open coast	A1	1.00	1.6	2.5	7.6	1.9	2.8	7.7	2.6	3.5	8.6
		Open coast	A2	1.00	1.6	1.8	6.4	1.9	2.1	6.6	2.6	2.8	7.4
		Sheltered	B	1.00	1.6	1.7		1.9	2.1		2.6	2.7	
25	Opua - Okiato (25A Okiato South; 25B Okiato East / North; 25C Opua South; 25D Opua North)	Sheltered	A	1.00	1.7	1.8		2.0	2.2		2.7	2.8	
		Sheltered	B	1.00	1.7	1.7		2.0	2.1		2.7	2.7	
		Sheltered	C	1.00	1.7	1.7		2.0	2.1		2.7	2.7	
		Sheltered	D	1.00	1.7	1.8		2.0	2.1		2.7	2.8	
26	Taumarere Estuary	Sheltered		1.00	1.7	1.7		2.0	2.1		2.7	2.7	
27	Paihia	open coast	A	1.00	1.7	2.3	4.7	2.0	2.6	4.9	2.7	3.3	5.7
		Sheltered	B	1.00	1.7	1.8		2.0	2.1		2.7	2.8	
28	Te Ti Bay - Waitangi Estuary	Open coast		1.00	1.7	1.9	4.5	2.0	2.2	4.8	2.7	2.9	5.5

Site				MHWS (m OTP)	Current 1% AEP (m OTP)			2065 2% AEP (m OTP)			2115 1% AEP (m OTP)		
No.	Name	Type	Cell		Storm tide	Static WL	Run-up level	Storm tide	Static WL	Run-up level	Storm tide	Static WL	Run-up level
		Sheltered		1.00	1.7	1.7		2.0	2.1		2.7	2.7	
29	Kerikeri Inlet	Sheltered	A	1.00	1.7	1.8		2.0	2.2		2.7	2.8	
		Sheltered	B	1.00	1.7	1.8		2.0	2.1		2.7	2.8	
30	Matauri Bay	Open coast	A	0.98	1.5	2.5	3.8	1.9	2.7	4.0	2.5	3.5	4.8
		Open coast	B	0.98	1.5	2.1	5.6	1.9	2.4	5.9	2.5	3.1	6.6
31	Tauranga Bay	Open coast	A	0.99	1.6	2.4	7.3	1.9	2.7	7.5	2.6	3.4	8.3
		Sheltered	B	0.99	1.6	2.2		1.9	2.5		2.6	3.2	
32	Whangaroa Coast (32A Mahinepua; 32B Wainui; 32C Te Ngaere)	Open coast	A1	0.98	1.5	1.9	3.3	1.9	2.2	3.6	2.5	2.9	4.3
		Sheltered	A2	0.98	1.5	1.7		1.9	2.0		2.5	2.7	
		Open coast	B	0.98	1.5	2.1	4.9	1.9	2.4	5.2	2.5	3.1	5.9
		Open coast	C1	0.98	1.5	2.2	5.9	1.9	2.5	6.0	2.5	3.2	6.9
		Sheltered	C2	0.98	1.5	2.0		1.9	2.3		2.5	3.0	
33	Whangaroa Harbour (Totara North)	Sheltered		1.13	1.6	1.8		2.0	2.1		2.6	2.8	
34	Whangaroa Settlement (34A Whangaroa Settlement; 34B Matangirau)	Sheltered	A	1.13	1.6	1.8		2.0	2.1		2.6	2.8	
		Sheltered	B	1.13	1.6	1.7		2.0	2.0		2.6	2.7	
35	Kaeo Estuary	Sheltered		1.13	1.6	1.8		2.0	2.1		2.6	2.8	
36	Pupuke Estuary	Sheltered		1.13	1.6	1.8		2.0	2.2		2.6	2.8	
37	Taupo Bay	Open coast	A	0.99	1.6	2.3	5.0	1.9	2.6	5.2	2.6	3.3	6.0
		Sheltered	B	0.99	1.6	2.2		1.9	2.5		2.6	3.2	
38	Hihi	Open coast	A	1.00	1.6	1.9	3.8	1.9	2.2	4.0	2.6	2.9	4.8

Site				MHWS (m OTP)	Current 1% AEP (m OTP)			2065 2% AEP (m OTP)			2115 1% AEP (m OTP)		
No.	Name	Type	Cell		Storm tide	Static WL	Run-up level	Storm tide	Static WL	Run-up level	Storm tide	Static WL	Run-up level
		Sheltered	B	1.00	1.6	1.7		1.9	2.1		2.6	2.7	
39	Coopers Beach	Open coast	A	1.00	1.6	2.0	3.7	1.9	2.3	4.0	2.6	3.0	4.7
		Sheltered	B	1.00	1.6	1.7		1.9	2.1		2.6	2.7	
40	Cable Bay	Open coast		1.00	1.6	2.3	5.8	1.9	2.6	6.0	2.6	3.3	6.8
41	Taipa	Open coast	A	1.00	1.6	2.2	5.7	1.9	2.5	5.8	2.6	3.2	6.7
		Sheltered	B	1.00	1.6	1.8		1.9	2.1		2.6	2.8	
42	Tokerau Beach North	Open coast		1.00	1.6	2.4	4.1	1.9	2.6	4.3	2.6	3.4	5.1
43	Rangiputa	Sheltered		1.08	1.6	2.0	3.3	1.9	2.3	3.6	2.6	3.0	4.3
44	Awanui Estuary	Sheltered		1.08	1.8	2.0		2.1	2.3		2.8	3.0	
45	Houhora - Pukenui	Open coast	A	1.08	1.6	2.4	3.5	1.9	2.6	3.7	2.6	3.4	4.5
		Sheltered	B	1.08	1.6	1.7		1.9	2.1		2.6	2.7	
46	Ahipara	Open coast		1.66	2.4	3.3	5.8	2.7	3.6	6.0	3.4	4.3	6.8
47	Whangape Harbour	Sheltered		1.66	2.4	2.5		2.7	2.9		3.4	3.5	
48	Panguru Estuary	Sheltered		1.66	2.4	2.5		2.7	2.8		3.4	3.5	
49	Kohukohu	Sheltered		1.66	2.4	2.5		2.7	2.9		3.4	3.5	
50	Waihou Estuary	Sheltered		1.66	2.4	2.5		2.7	2.8		3.4	3.5	
51	Taheke River estuary	Sheltered		1.66	2.4	2.4		2.7	2.8		3.4	3.4	
52	Rawene	Sheltered		1.66	2.4	2.5		2.7	2.9		3.4	3.5	
53	Whirinaki Estuary	Sheltered		1.66	2.4	2.4		2.7	2.8		3.4	3.4	
54	Pakanae (Awapokoui estuary)	Sheltered		1.66	2.4	2.6		2.7	2.9		3.4	3.6	

Site				MHWS (m OTP)	Current 1% AEP (m OTP)			2065 2% AEP (m OTP)			2115 1% AEP (m OTP)		
No.	Name	Type	Cell		Storm tide	Static WL	Run-up level	Storm tide	Static WL	Run-up level	Storm tide	Static WL	Run-up level
55	Omapere & Opononi	Open coast	A	1.66	2.4	2.8	5.1	2.7	3.2	5.5	3.4	3.8	6.1
		Sheltered	B	1.66	2.4	2.6		2.7	3.0		3.4	3.6	
56	Waimamaku Estuary	Sheltered		1.67	2.4	2.9		2.7	3.2		3.4	3.9	
57	Kaihu Estuary	Sheltered		1.68	2.8	2.9		3.2	3.3		3.8	3.9	
58	Dargaville - Wairoa	Sheltered		1.72	2.8	2.9		3.2	3.3		3.8	3.9	
59	Ruawai	Sheltered	A	1.71	2.9	3.3		3.3	3.7		3.9	4.3	
		Sheltered	B	1.71	3.0	3.2		3.4	3.5		4.0	4.2	
60	Paparoa estuary	Sheltered		1.71	3.1	3.3		3.5	3.7		4.1	4.3	
61	Maungaturoto	Sheltered		1.71	3.1	3.1		3.5	3.5		4.1	4.1	
		Sheltered	A	1.11	1.8	2.0		2.1	2.4		2.8	3.0	
		Sheltered	B	1.11	1.8	2.0		2.1	2.3		2.8	3.0	
62	Whangarei Harbour North	Sheltered	C	1.11	1.7	2.0		2.0	2.3		2.7	3.0	
		Open Coast	A	1.11	1.6	3.2	8.8	1.9	3.5	9.0	2.6	4.2	9.8
63	Ocean Beach	Open Coast	B	1.11	1.6	3.1	9.6	1.9	3.4	9.7	2.6	4.1	10.6

Run-up has not been calculated for sheltered sites due to lack of, and variable, bathymetry data

Appendix D: CFHZ and CRHZ Maps

Appendix E: Guidance for assessing site-specific run-up hazard

The attenuation of wave run-up with distance inland is highly site-specific and is dependent on the run-up elevation, dune height and backshore slope (i.e. Figure E-1). This appendix sets out how to undertake a site specific self-assessment of wave run-up attenuation distance and flow depth.

Wave attenuation with distance from the coastal edge can be assessed following the following steps:

i Determine extreme run-up level based on Appendix C or calculate wave run-up according to Equation 3-10 and add to relevant storm tide level.

ii Assess the dune crest or backshore elevation using Council LiDAR or site-specific topographic survey

iii If run-up level exceeds the dune crest, calculate run-up attenuation according to Equation E-1, modified from FEMA (2005).

$$X = \frac{\sqrt{R-Y_0} \cdot A(1-2m) \cdot gT^2}{5\sqrt{gT^2}} \qquad \text{(E-1)}$$

Where:

X = Wave run-up attenuation distance (m)

R = Wave run-up level including the storm tide (m RL)

Y_0 = Dune crest elevation (m RL)

T = Wave period (use T_p (s) for 1% exceedance event in Table 2-4 for relevant location)

g = 9.81 m/s^2

A = Inland slope factor (default = 1, can be adjusted at own preference)

m = Positive upward inland slope valid for -0.5 < m < 0.25 (e.g. for 1(V):10(H), m = 0.1)

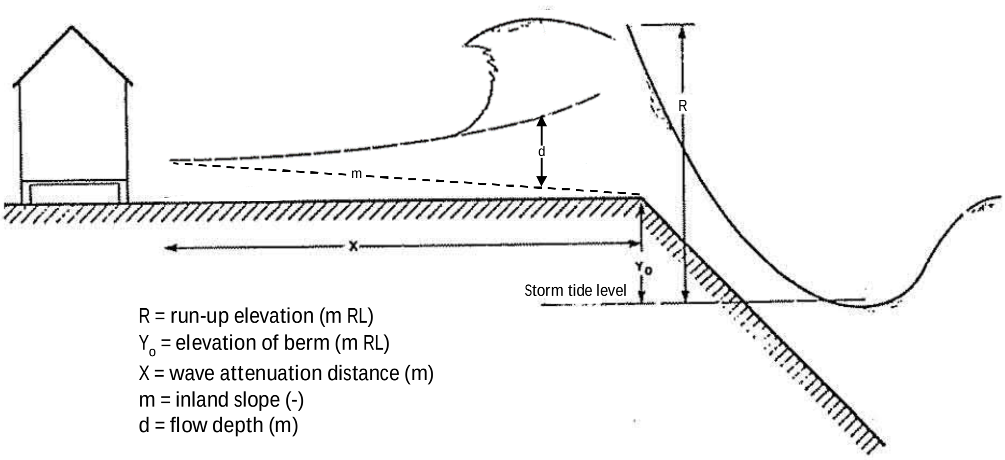

Figure E-1 Run-up attenuation definition sketch (modified from Cox and Machemehl, 1986)

iv Offset the calculated distance from the dune crest/coastal edge.

The distance between the coastal edge and the offset line represents the coastal run-up hazard zone. These steps should be repeated if the beach slope, wave conditions or dune crest level vary alongshore.

v (optional) If the flow depth at a certain wave run-up attenuation distance (X) is required, calculate the flow depth according to Equation E-2

$$d = \left[\sqrt{R - Y_0} - \frac{5X}{A(1-2m)\sqrt{gT^2}}\right]^2 \quad \text{(E-2)}$$

Where:

d = Flow depth (in meters) at certain wave run-up attenuation distance (X)

X = Wave run-up attenuation distance (m)

R = Wave run-up level including the storm tide (m RL)

Y_0 = Dune crest elevation (m RL)

T = Wave period (use T_p (s) for 1% exceedance event in Table 2-4 for relevant location)

g = 9.81 m/s^2

A = Inland slope factor (default = 1, can be adjusted at own preference)

m = Positive upward inland slope valid for -0.5 < m < 0.25 (e.g. for 1(V):10(H), m = 0.1)