REPORT

Tonkin+Taylor

Coastal Flood Hazard Assessment for Northland Region 2019-2020

Prepared for
Northland Regional Council
Prepared by
Tonkin & Taylor Ltd
Date
March 2021
Job Number
1012360.1000.v4

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Document Control

Title: Coastal Flood Hazard Assessment for Northland Region 2019-2020					
Date	**Version**	**Description**	**Prepared by:**	**Reviewed by:**	**Authorised by:**
21/08/2020	1	Draft for internal review	J.Joubert P.Knook	T. Shand	
17/09/2020	2	Draft for external review	J.Joubert P.Knook	T. Shand	R. Reinen-Hamill
6/10/2020	3	Final draft for client review	J.Joubert P.Knook	T. Shand	R. Reinen-Hamill
15/03/2021	4	Final report	P.Knook J.Joubert E.Beetham	T.Shand	R.Reinen-Hamill

Distribution:

Northland Regional Council	1 copy
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Executive summary

This study has been undertaken for Northland Regional Council (NRC) to assess areas potentially susceptible to coastal inundation for the Northland region (excluding the Kaipara Harbour and Awanui catchment). Extreme coastal water levels have been assessed for 140 output locations around the region, including both exposed (i.e. open coast) and sheltered (i.e. harbour and estuary) sites. The assessment has been carried out in accordance 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 and using similar methods to those applied in previous assessments undertaken within the Northland region (T+T, 2015, 2017).

Both ***static inundation levels*** comprising astronomical tide, storm surge, medium-term fluctuations and wave set-up and ***dynamic inundation levels*** which also include wave run-up have been assessed for each output location. Extreme levels for the open coast have been assessed using a structural extreme value method where the static or dynamic levels are calculated for every timestep using historical data and hindcast models, and analysis is undertaken on the resultant levels. This ensures all potential drivers are accounted for, while decreasing conservatism associated with traditional building block approaches and uncertainty associated with joint probability analysis.

Extreme levels for the harbour and estuary shoreline have been assessed using a combined probabilistic and building block approach where storm tide is assessed probabilistically and wave contributions due to wave set-up added separately. This was method was used due to the limited bathymetric data within the harbours and estuaries. Dynamic inundation levels have not been assessed for output locations within harbours and estuaries as run-up will be highly dependent on the local foreshore morphology and, due to the relatively small wave heights, will generally be confined to within 5-10 m of the coastal edge.

This study has assessed extreme static and dynamic inundation levels for a range of return periods (5 to 500-year ARI) for both for the present day, and future considering effects of incremental sea level rise between 0.1 m and 1.5 m. The results show present-day static inundation levels are the highest along the open coast shorelines (i.e. up to 3.5 m NZVD2016 for 100-year ARI), with the lowest levels found within estuary inlets and Whangaroa Harbour (i.e. 1.6 m NZVD2016 for 100-year ARI). This is expected as open coast shorelines are typically subject to larger breaking waves which induce large wave set-up compared to sheltered shorelines that may be subject to relatively small breaking waves.

The present-day 100-year ARI dynamic water level is largest along the exposed East Coast (i.e. up to 8.8 m NZVD2016), but lower in more protected East Coast locations (i.e. 3.2 m NZVD2016). This indicates that the exposure of the beaches along the open East Coast is highly variable. Sites along the open West Coast range from 4.6 to 7.8 m NZVD2016 indicating exposure is more consistent. The dynamic water levels for sheltered sites have not been assessed (refer to Section 3.6.2). The future coastal inundation levels show the same trend as the present-day coastal inundation levels but with level elevated based on sea level rise contribution.

Areas potentially susceptible to coastal inundation have been mapped for the entire Northland Region at 0.1 m increments between 0.5 and 5.5 m NZVD2016. The extent and depth of inundation have been assessed using 1 m DEM derived from 2019 LiDAR data and a connected bathtub model where areas are flooded only where they connect to the coastal water body. Inundation extents and depths disconnected from the shoreline have been mapped separately to show areas potentially susceptible if connected by structures to due to raised groundwater.

Wave run-up differs from static flooding as run-up is a dynamic process and should be mapped by applying an attenuation model to the maximum run-up elevation to determine the maximum inland

excursion reached by the run-up flows. However, as this is highly dependent on site-specific conditions (e.g. waves, beach slope and landward slope), the dynamic inundation extents have not been mapped for this assessment. Guidance to assess attenuation distances using site-specific information is provided.

Several sources of potential uncertainty in mapping have been noted including the LiDAR DEM accuracy, the differences in inundation levels and extents of adjacent cells and exclusion of overtopping flows.

NRC have requested that levels are assessed, and inundation extents mapped for specific combinations of static inundation and sea level rise with the resultant extents termed ***Coastal Flood Hazard Zones (CFHZ).*** These combinations are as follows with values rounded to the nearest 0.1 m.

- Coastal Flood Hazard Zone 0 (CFHZ0): Extent of 100-year ARI static water level at 2020
- Coastal Flood Hazard Zone 1 (CFHZ1): Extent of 50-year ARI static water level at 2080 including 0.6 m SLR
- Coastal Flood Hazard Zone 2 (CFHZ2): Extent of 100-year ARI static water level at 2130 including 1.2 m SLR
- Coastal Flood Hazard Zone 3 (CFHZ3): Extent of 100-year ARI static water level at 2130 including 1.5 m SLR

In addition, the MHWS-10 for the present day and future timeframes including 0.6 m and 1.2 m SLR have been assessed to the nearest 0.1 m and mapped.

This assessment has been undertaken on a regional-scale and can be superseded by a more detailed-scale assessments. This may include:

- assessment using more refined extents with more accurate values assigned to each section,
- use of more advanced methods to assess wave effects such as local-scale numerical models
- use of hydrodynamic models and/or consideration of local structures such as culverts and seawalls.

Note that this assessment considers inundation related to coastal storm processes and excludes other sources of inundation (e.g. extreme rainfall, river flows, tsunami).

1 Introduction

1.1 Background

Tonkin & Taylor Ltd (T+T) was commissioned by Northland Regional Council (NRC) in 2015 to prepare a report and maps that assessed Coastal Flood Hazard Zones (CFHZs) for 61 selected sites in the Northland region. CFHZs for each site were assessed on a local scale (i.e. 100-1000 m spatial resolution). That report was updated in 2017 to include some minor adjustments, with two sites added. In 2020, NRC commissioned T+T to undertake an assessment of areas potentially susceptible to coastal inundation, including four CFHZ scenarios, for the entire Northland region.

In 2017, CFHZs were 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 inundation is generally controlled by the maximum static water level (extreme static water level) resulting from a combination of storm tide and wave set-up. These were mapped based on a connected bathtub approach whereby all areas connected to the elevated coastal water level are flooded.

Wave run-up may extend above this static flood level. 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. Therefore, the dynamic inundation (i.e. extreme run-up) level and the inland extent of hazardous flow were evaluated separately and used to define Coastal Run-up Hazard Zones (CRHZ). However, this was 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.

This assessment follows the same method as was used by T+T (2017), however, instead of assessing 63 sites on a local-scale, coastal inundation levels have been assessed for the entire Northland region on a regional scale. Both static and dynamic inundation levels have been assessed, but only the areas potentially susceptible to static inundation have been mapped.

The assessment of CFHZs is 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 at least 50-year (i.e. 2080) and at least 100-year (i.e. 2130) timeframes.

NRC's proposed Regional Policy Statement gives effect to the policies of the NZCPS, particularly regarding 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.

1.2 Scope

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

1. Review of tide gauge data and derive MHWS-10 and extreme storm tide levels for each tide gauge location
2. Rationalise derived water levels (step 1) around entire Northland coastline using representative output locations (at maximum 10 km alongshore intervals and within harbours)
3. Assess wave set-up and wave run-up for representative output locations along open coast shorelines
4. Assess wave set-up for representative outputs locations for sheltered (e.g. harbour or estuary) shorelines

4 Undertake a high-level assessment of the variability of waves and water levels along the Northland coastline

5 Derive extreme static and dynamic water levels for open coast shorelines for a range of return periods for both present day and future timeframes adopting incremental sea level rise (SLR) values as set out in MfE (2017)

6 Derive extreme static water levels for sheltered shorelines for a range of return periods for both present day and future timeframes, adopting incremental SLR values

7 Map areas potentially susceptible to static inundation (both connected and disconnected to the shoreline) and depths at 0.1 m increments between 0.5 m and 5.5 m NZVD2016 for the entire Northland region

8 Assess and map static inundation extents for specific combinations provided by NRC and termed CFHZ0, CFHZ1, CFHZ2 and CFHZ3 for the entire Northland region

9 Assess and map present-day MHWS-10, MHWS-10 +0.6 m SLR and MHWS-10 + 1.2 m SLR for the entire Northland region using the 2019 LiDAR DEM

10 Develop guidance for site-specific assessment of wave run-up hazard

11 Summarise approach, assumptions, methods, and results in a technical report (this report).

A summary of the specific coastal inundation scenarios assessed under step (8) and (9) are set out in Table 1.1.

Table 1.1: Coastal inundation scenarios

Scenario	**Name**	**Static water level**	**Year**	**Adopted SLR value (m)**
Present day MHWS-10	MHWS-10	MHWS-10	2020	0
Present day extreme static water level	CFHZ0	100-year ARI	2020	0
MHWS at 2080	2080 MHWS-10	MHWS-10	2080	0.6
Extreme static water level at 2080	CFHZ1	50-year ARI	2080	0.6
MHWS at 2130	2130 MHWS-10	MHWS-10	2130	1.2
Extreme static water level at 2130	CFHZ2	100-year ARI	2130	1.2
Extreme static water level at 2130 under highest SLR scenario	CFHZ3	100-year ARI	2130	1.5

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 dynamic water levels and verification of techniques. Section 4 presents results of the both the static and dynamic inundation levels for selected return periods, timeframes and SLR scenarios. A discussion on mapping extents and limitations is furthermore included in Section 4. The 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 New Zealand Vertical Datum 2016 (NZVD2016) unless otherwise specified. All coordinates are presented in terms of New Zealand Transverse Mercator (NZTM).

2 Background data

2.1 Previous assessments

A number of previous assessments of coastal hazard including the effects of coastal inundation 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
- T+T (2015) Coastal Flood Hazard Zone Assessment for Selected Northland Sites
- Barnett & MacMurray Ltd. (2016) Coastal Flood Hazard Zone Modelling for Kaihu Valley, Dargaville, and Awakino Floodplain
- T+T (2017) Coastal Flood Hazard Zone Assessment for Selected Northland Sites (2017 update)
- eCoast (2017) Coastal Flood Modelling of Ruawai, Kaihu-Dargaville and Awanui
- DHI (2020) Coastal Inundation Modelling for Northern Kaipara Harbour.

2.2 Topographic and bathymetric data

The 2019 LiDAR data for the entire Northland region was flown between January and November 2019. The data was provided by NRC in the form of a 1x1 m digital elevation model (DEM) in NZVD2016. The vertical accuracy of the 2019 DEM is 0.15 m and horizontal accuracy is 1 m. An example of LiDAR data available is shown for Oneroa Bay in Figure 2.1.

In addition to the topographic data, bathymetric data was sourced from LINZ nautical charts that are available for the Northland region (i.e. nautical charts NZ 41, 42, 51, 5112, 521 and 5219).

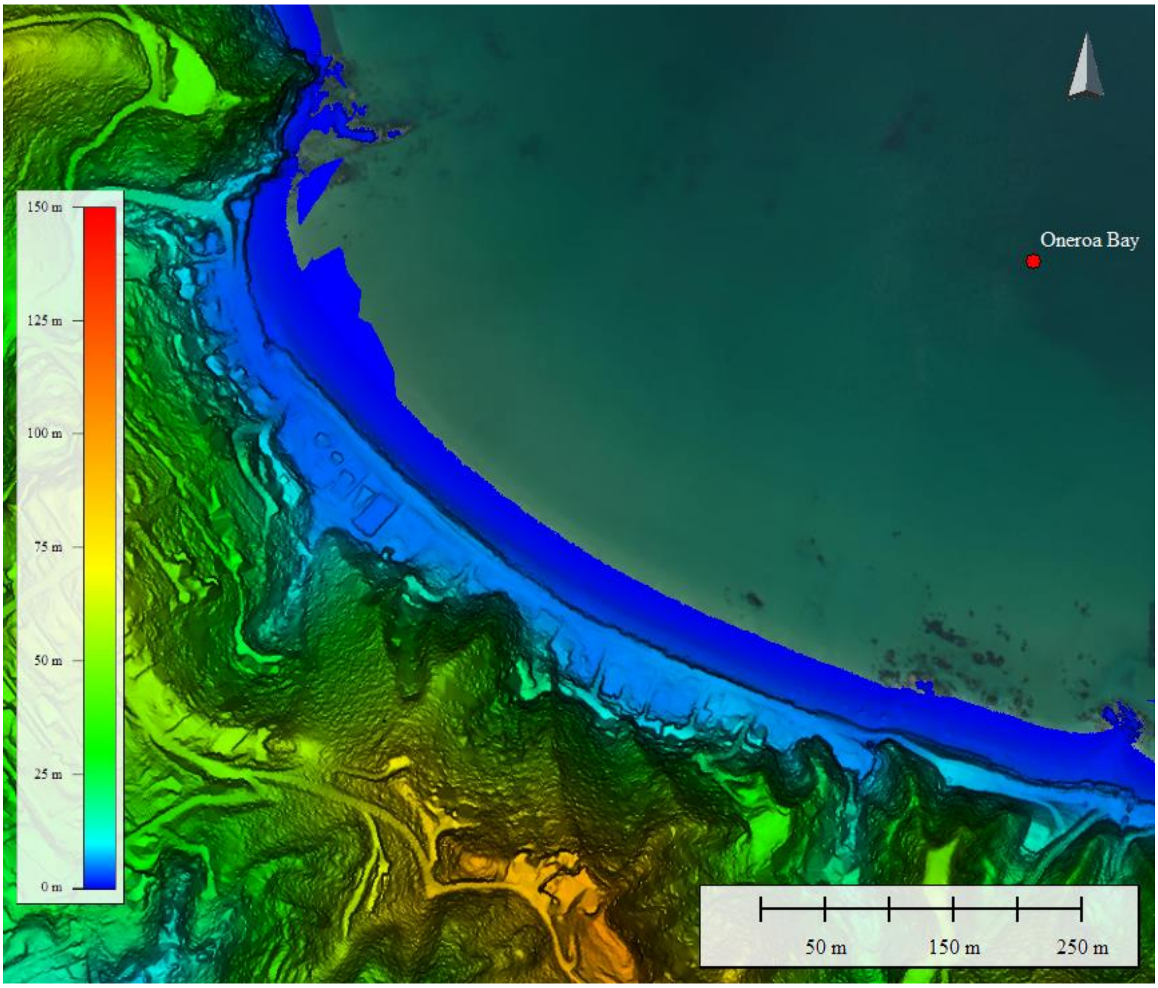

Figure 2.1: Example of 1 m DEM derived from 2019 LiDAR data for Oneroa Bay (Long Beach)

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 (Figure 2.2):

- Astronomical tides (e.g. mean sea level, mean high water spring)
- 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 including wave set-up and wave run-up.

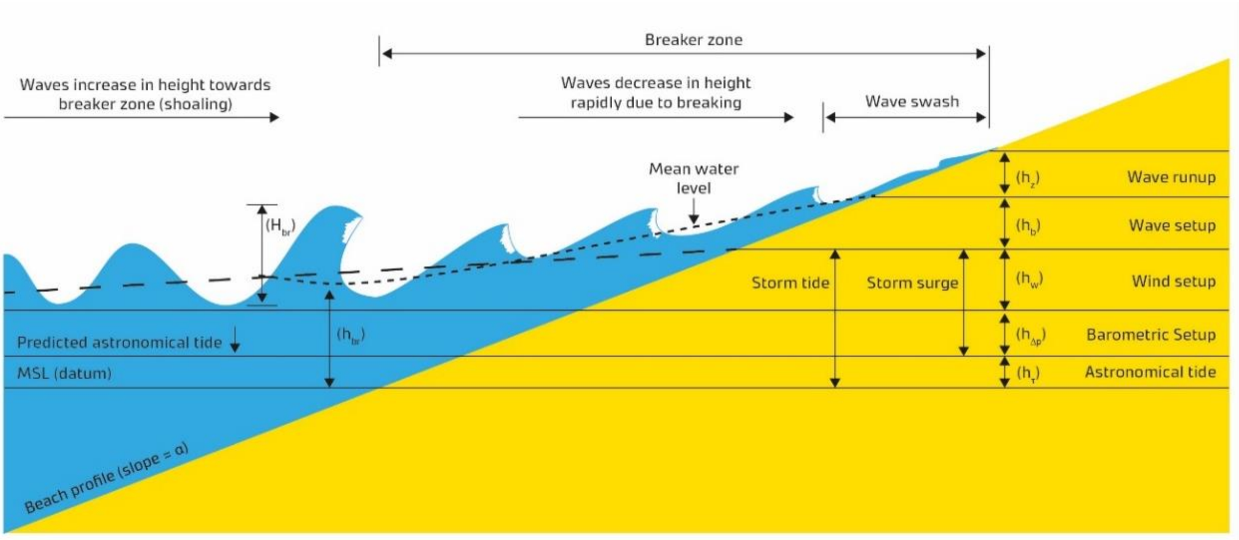

Figure 2.2: Key components that determine water level

2.3.1 Mean sea level

NIWA (2020) analysed available tide gauge records to derive MSL levels for each gauge within the study area. Table 2.1 shows the record dates and length, and analysed MSL relative to OTP64 and NZVD2016. 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: Mean sea level information based on Northland tide gauges analysis

Gauge site	Tide gauge record dates	Record length (years)	Levels (m)		
			MSL relative to OPT64[1]	Offset between OTP64 and NZVD2016[2]	MSL relative to NZVD2016
Marsden Point	1975-2020	55	-0.05	-0.085	-0.135
Opua Wharf	1990-2020	30	-0.03	-0.075	-0.105
Whangaroa Harbour	2008-2020	12	-0.07	0	-0.07
Pouto Point	2001-2020	19	+0.2	-0.290	-0.09

[1]Source: NIWA (2020), calculated over 2010-2019

[2]Source: NRC (pers. comm. 19/05/2020)

2.3.2 Mean high water springs

MHWS-10 (Mean high water springs levels exceeded by 10% of high tides) levels relative to MSL = 0 around Northland that were previously modelled by NIWA (2015) are presented in Figure 2.3. This shows MHWS-10 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-10 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. The present day MHWS-10 levels may slightly vary compared to the MHWS-10 derived by NIWA (2015), however, the relative differences between MHWS-10 around the Northland region shoreline are expected to be the same.

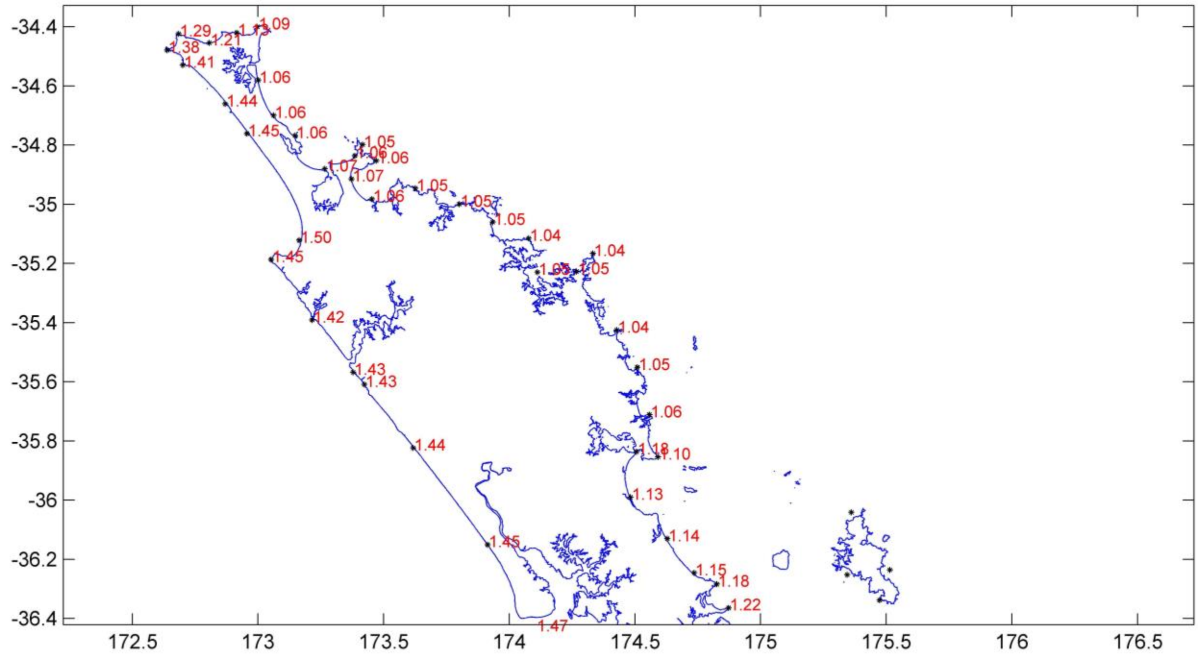

Figure 2.3: Plot of the mean high water springs level exceeded by 10% of tide (MHWS-10) level relative to MSL = 0 (Source: NIWA,2015)

NIWA (2020) have derived MHWS levels for five tide gauges based on records up to 2020, with the MHWPS (Mean High Water Perigean Spring) and MHWS-10 shown in Table 2.2. Note that he MHWS levels for Town Basin have been based on the difference in MHWS levels at Marsden Point and Town Basin with respect to MSL=0.

Table 2.2: MHWS levels for Northland tide gauges analysed by NIWA (2020)

Gauge site	MHWPS (m NZVD2016)	MHWS-10 (m NZVD2016)
Marsden Point	1.08	1.02
Town Basin[1]	1.25	1.15
Opua Wharf	1.03	0.97
Whangaroa Harbour	1.06	0.99
Pouto Point	1.54	1.42

[1]Based on difference in MHWS levels at Marsden Point and Town Basin with respect to MSL=0.

NIWA (2015) modelled the MHWS-10 levels for the Northland open coast only, excluding harbours and estuaries. MHWS levels for harbours and estuaries are set out by LINZ (2020) in Table 2.3 in terms of Chart Datum (CD) including open coast sites for reference.

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	Russell	2.5	PORT TARANAKI	3.5
Mangonui	2.6	Waitangi	2.3	Ahipara Bay	3.6
North Cape (Otou)	2.3	Pukenui Wharf	2.7	Cape Maria v. Diemen	2.4
Portland Wharf	3.1	Houhora Harbour Ent	2.6	Opononi	3.0
Tutukaka Harbour	2.3	Waiiti Bay	2.2	Omapere	2.9
Whangamumu Harbour	2.1	Ngatehe Point	2.5	Rawene	3.5
Whangarei	3	Kotiatia Point	2.5	Kohukohu	3.6
Doves Bay	2.4	Ben Gunn Wharf	2.4	Pouto Point	3.2
Kerikeri	2.3	Whangaroa	2.5		
Opua	2.6	Rocky Point	2.2		

Source: LINZ (2020)

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 2.4). 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).

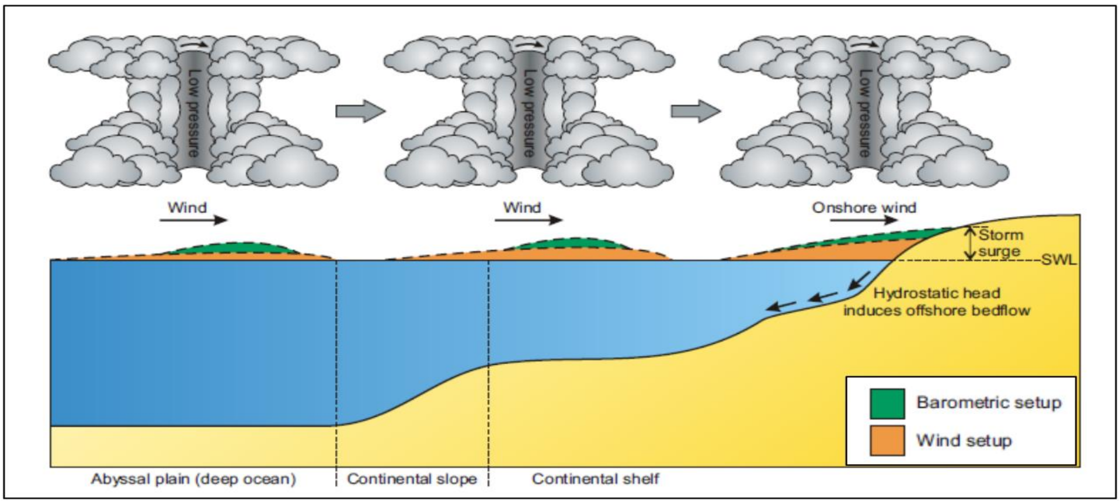

Figure 2.4: Processes driving storm surge

NIWA have undertaken an updated analysis of extreme storm tide levels by extending their previous analysis to include data up to 2020 (refer to Appendix A). The updated analysis used the skew-surge joint-probability method (SSJPM) (Batstone, Lawless et al., 2013) to determine extreme storm tide frequency and magnitude. NIWA included analysis for relatively short records (i.e. Town Basin and Whangaroa Harbour) as they rationalised that storm tide return periods can be estimated from relatively short records because all skew surges are considered and not just those that lead to extreme levels. NIWA (2020) note that a limitation of the SSJPM and other joint-probability methods is that it assumes tide and skew surge are independent, which has been shown to be true in the UK, but has not been fully investigated in NZ. Although comparisons with direct maxima methods for >50-year long records give similar results for return periods >10-years and also match observed maxima well, and thus support the validity of the independence assumption for long return period events (refer to NIWA, 2020).

In order to verify the results for each tide gauge, NIWA plotted the SSJPM results against the annual maxima (AM) using the Gringorten (1963) plotting positions, a generalised extreme value distribution fitted to the AM, and an empirical distribution of the observed peak sea levels at high tide. An example for Marsden Point is shown in Figure 2.5.

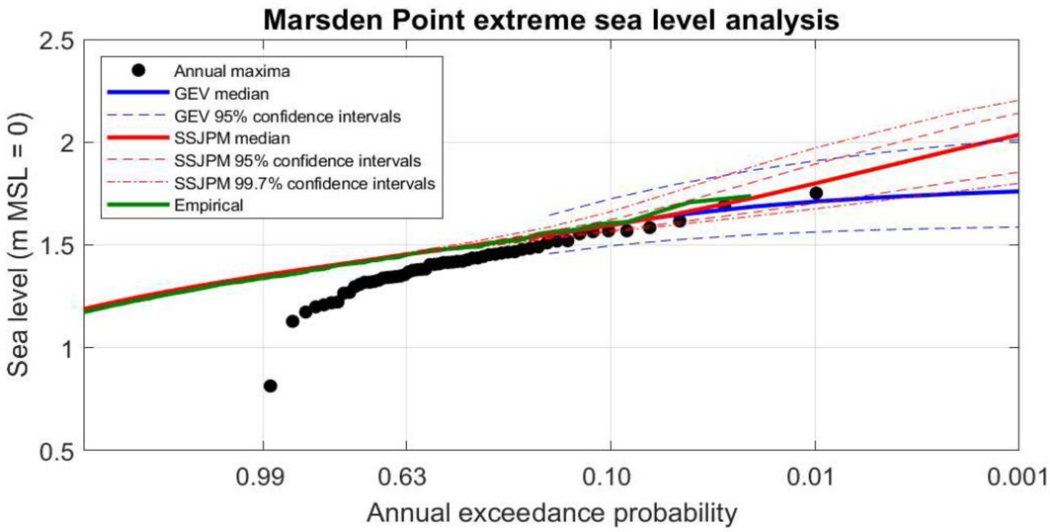

Figure 2.5: Extreme sea-level at Marsden Point relative to MSL = 0. The skew-surge joint-probability method (SSJPM) has been compared to the annual maxima (AM) plotted in their Gringorten (1963) plotting positions, a generalised extreme value distribution fitted to the AM, and an empirical distribution of the observed peak sea levels at high tide(source: NIWA, 2020)

Resulting extreme water levels for a range of return periods for the five gauges are shown in Figure 2.4. These results were provided by NIWA with respect to MSL (2010-2019) and were corrected to NZVD2016 using offsets included in NIWA (2020) and offset levels provided by NRC. Values at Marsden Point are generally higher than other east coast values except for at Town Basin within the Whangarei Harbour where local tidal amplification may be occurring. Values on the west coast are in the order of 0.5 m higher than values on the east coast.

Table 2.4: Extreme water levels (m NZVD2016) for Northland tide gauges

Site	Record length (years)	5-year ARI	10-year ARI	20-year ARI	50-year ARI	100-year ARI	200-year ARI	500-year ARI
Marsden Point	57	1.42	1.46	1.52	1.60	1.67	1.71	1.84
Town Basin	12	1.68	1.73	1.79	1.89	1.96	2.01	2.14
Opua Wharf	30	1.36	1.39	1.42	1.47	1.50	1.53	1.59
Whangaroa Harbour	12	1.39	1.42	1.45	1.49	1.52	1.53	1.58
Pouto Point	18	1.98	2.02	2.05	2.10	2.14	2.16	2.22

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). Guidance on sea level fluctuation suggests that fluctuations of up to 0.25 m (±0.15 m) should be taken into account in predicting future water levels (refer to Figure 2.6).

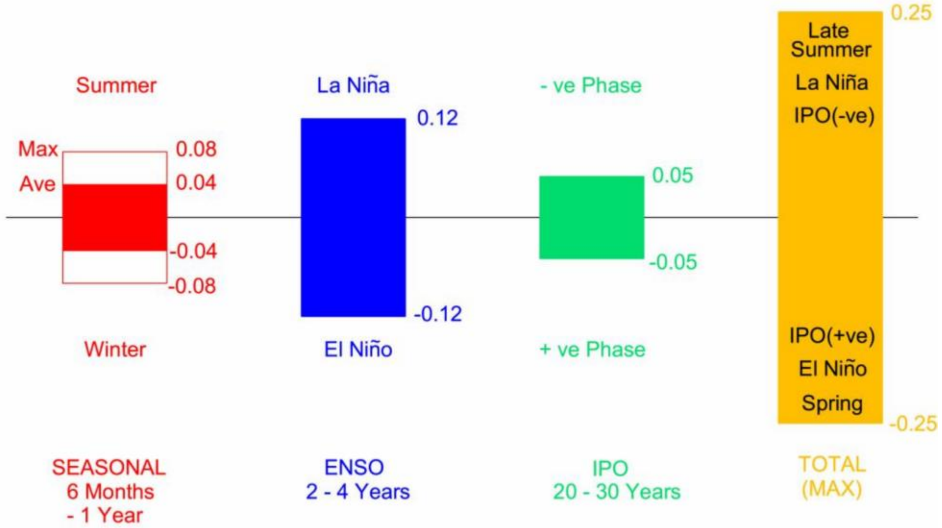

Figure 2.6: Variability in mean level of the sea due to climate cycles (source: Stephens and Bell, 2012)

2.3.5 Long-term sea level change

2.3.5.1 Historical sea level changes

Historical 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, as shown in Figure 2.7. Therefore, vertical land movements appear to have not affected the historical sea level rise. The higher historic sea level rise rate and wider uncertainty in the Northland region may be due to the short record length (i.e. ~40 years) compared to the datasets used to calculate the New Zealand average rate (i.e. >70 years).

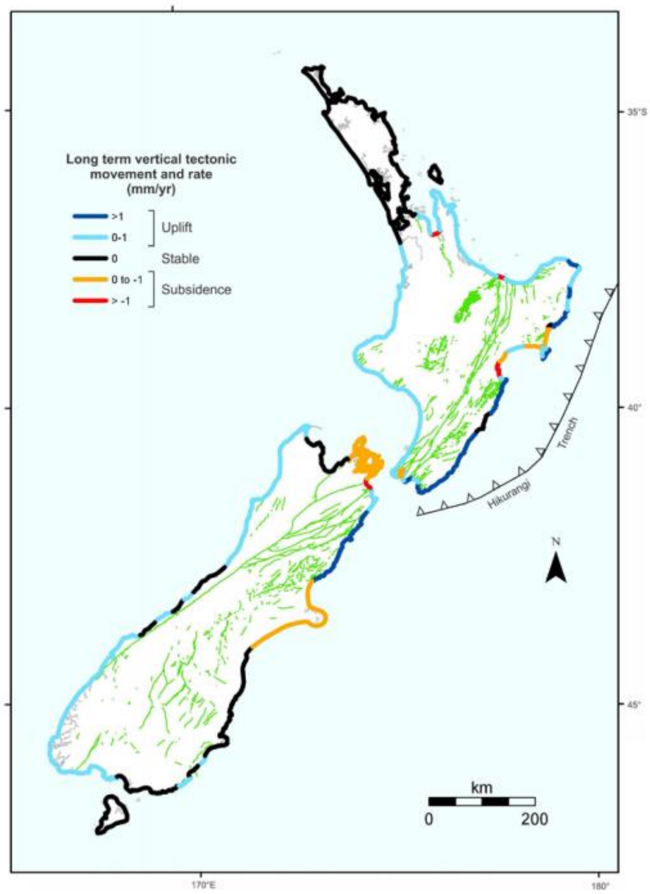

Figure 2.7: Long-term vertical land movement expected for New Zealand (Beavan & Litchfield, 2012)

2.3.5.2 Future sea level changes

Climate change is predicted to accelerate this rate of sea level rise into the future. 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 timeframe is likely to significantly alter the coastal hazard risk.

The most recent guideline released by the Ministry for the Environment (MfE, 2017) recommends that sea level rise occurring under four future emission scenarios (Representative Concentration Pathway or RCP) are considered. These scenarios are based on the most recent IPCC report (IPCC, 2013) (Figure 2.8).

1. Low to eventual net-zero emission scenario (RCP2.6 median projection)
2. Intermediate-low scenario (RCP4.5 median projection)
3. High-emissions scenario (RCP8.5 median projection)
4. Higher extreme H+ scenario, based on the RCP8.5 83rd percentile projection from Kopp et al. (2014).

This shows that by 2130, SLR of between 0.6 and 1.5 m could be expected.

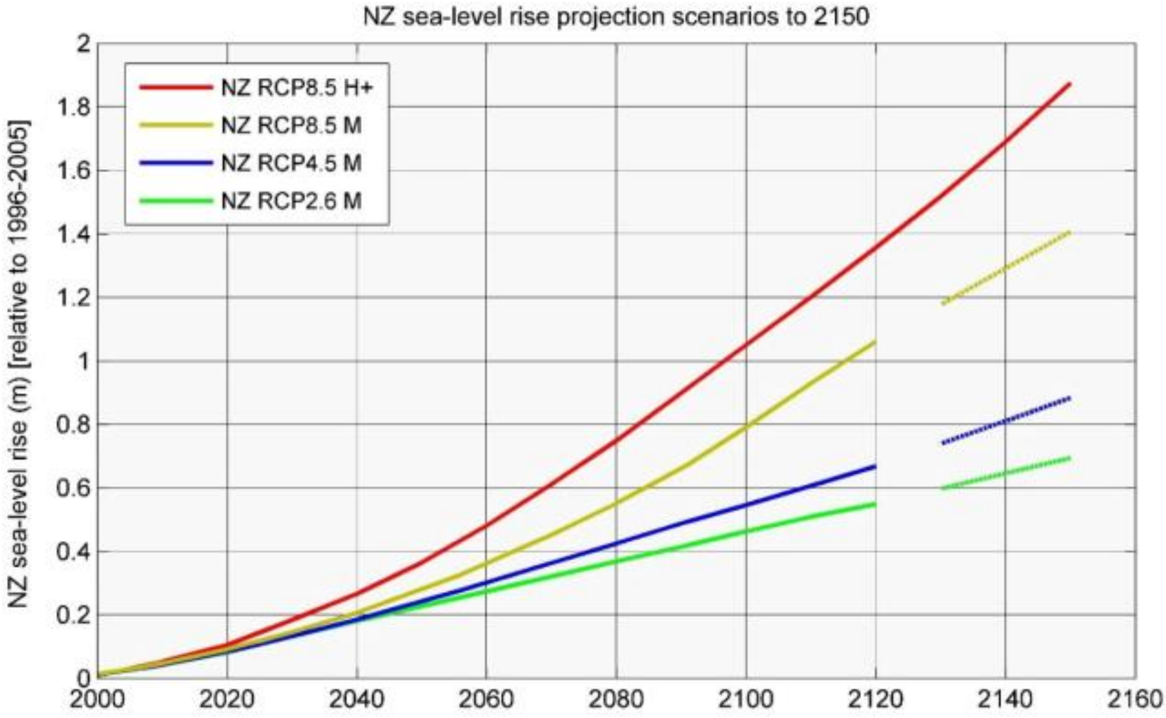

Figure 2.8: Projections of potential future sea level rise presented within MfE (2017) with adopted values for this assessment at 2080 and extrapolated to 2130

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 six offshore locations representative of the Northland Region was provided by MetOcean Solutions Ltd for this study; offshore of Baylys Beach, Ahipara, Great Exhibition Bay, Matauri Bay, Whangaruru, and Bream Bay (Figure 2.9).

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.

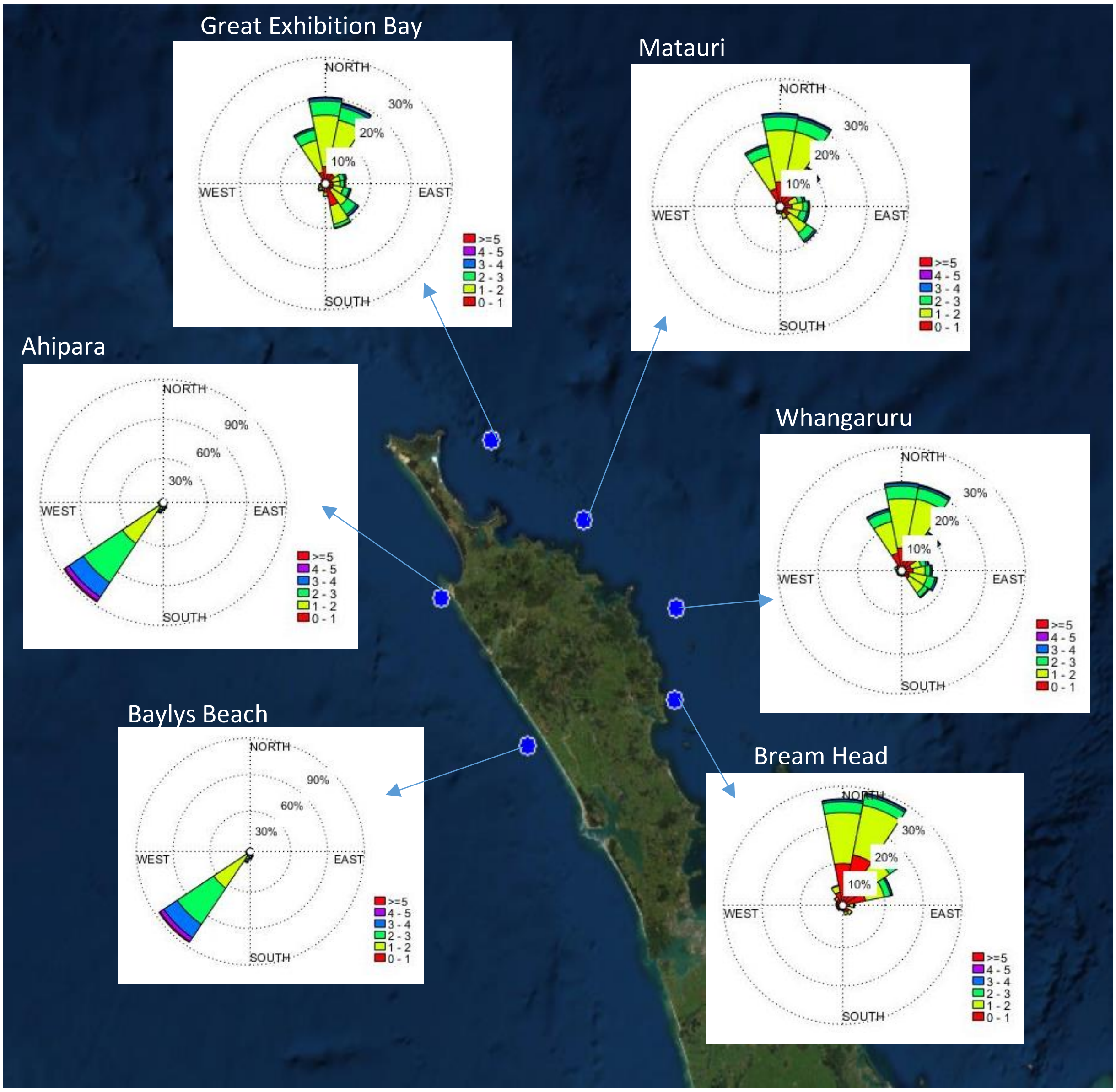

Figure 2.9: Offshore wave data locations around Northland

Wave roses are presented for each offshore location in Figure 2.9. These results show that offshore of Ahipara and Baylys Beach, 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.

Figure 2.5 shows a summary of the characteristic wave heights for the six Northland offshore locations. Mean significant wave height (2.4-2.5 m) and peak period (13.6 s) on the west coast is typically higher than on the east coast (1.3 to 1.6 m and 9-10 s for the mean significant wave height and peak period respectively). The 1% exceedance wave heights (i.e. wave heights exceeded 1% of the time) are typically larger (i.e. 5.3-5.4 m) and longer (i.e. 14.3-14.4 s) on the west coast compared to the east coast (i.e. 3.9-4.4 m and 10.6-11.1 s for the significant wave height and peak wave period respectively). The 100-year ARI wave heights follow a similar trend, with the largest waves on the West Coast (i.e. up to 10.2 m) and smallest waves offshore of Bream Bay (i.e. 8.6 m).

Table 2.5: Characteristic wave heights for Northland offshore locations

	Coordinates		50% (Median)			1% Exceedance		100-year ARI
Location	E (°)	S (°)	H_s (m)	T_p (s)	D_p (°)	H_s (m)	T_p (s)[1]	H_s (m)
Baylys Beach	173.62	35.98	2.5	13.6	231.3	5.4	14.3	10.2
Ahipara	173.02	35.24	2.4	13.6	230	5.3	14.4	10
Great Exhibition	173.36	34.44	1.6	10	147.8	4.4	11.1	9.9
Matauri Bay	173.99	34.84	1.6	9.4	130	4.4	11	9.8
Whangaruru	174.63	35.28	1.6	9.3	128.4	4.4	10.9	9.8
Bream Head	174.63	35.74	1.3	9.3	79.7	3.9	10.6	8.6

[1]Wave period and direction corresponding to mean H_s
[2]Wave period and direction for 1% exceedance H_s conditions

2.4.2 Storm climatology

Northland is affected by storm events from a range of sources. On the west coast (Figure 2.10) 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 (Figure 2.11) 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).

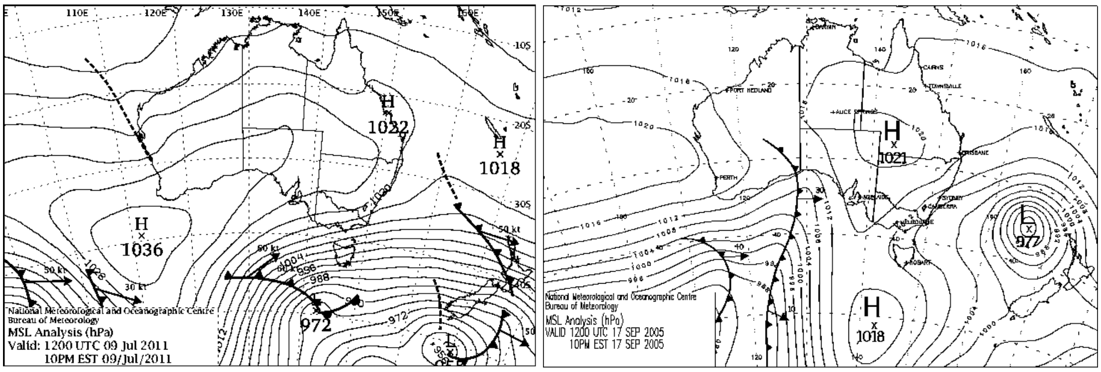

Figure 2.10: Typical storm systems affecting the west coast of Northland with a large mid-latitude cyclone in July 2011 (A) and a West coast low in September 2005 (B)

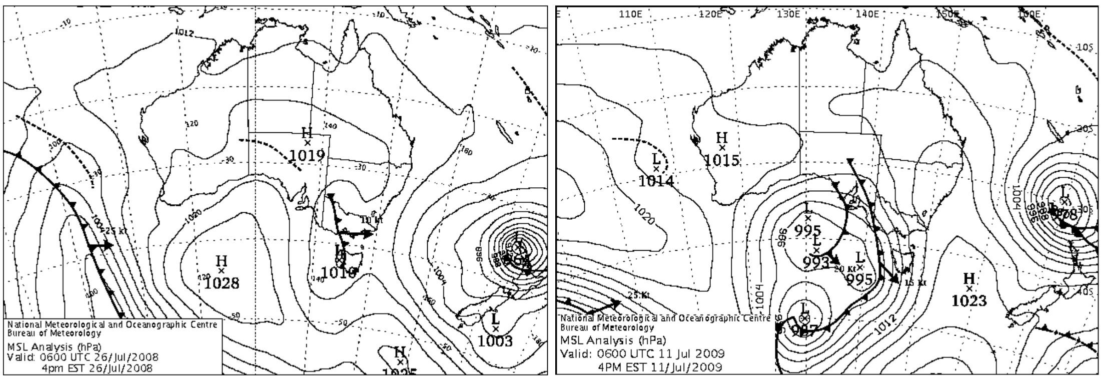

Figure 2.11: Sub-tropical storm systems causing large waves on the Northland east coast in July 2008 (A) and July 2009 (B)

An example of a recent tropical cyclone coming down along the east coast is TC Pam. Figure 2.12 shows TC Pam moving southwards towards the east coast of Northland on 15 March 2015. The offshore significant wave height exceeded 5 m with peak wave period 18 sec, which coincided with high tide. Due to the mainly southerly wind direction, beach shorelines that are facing north were typically affected. A summary of the most recent (i.e. last 20 years) storm events is included in Section 2.4.3.

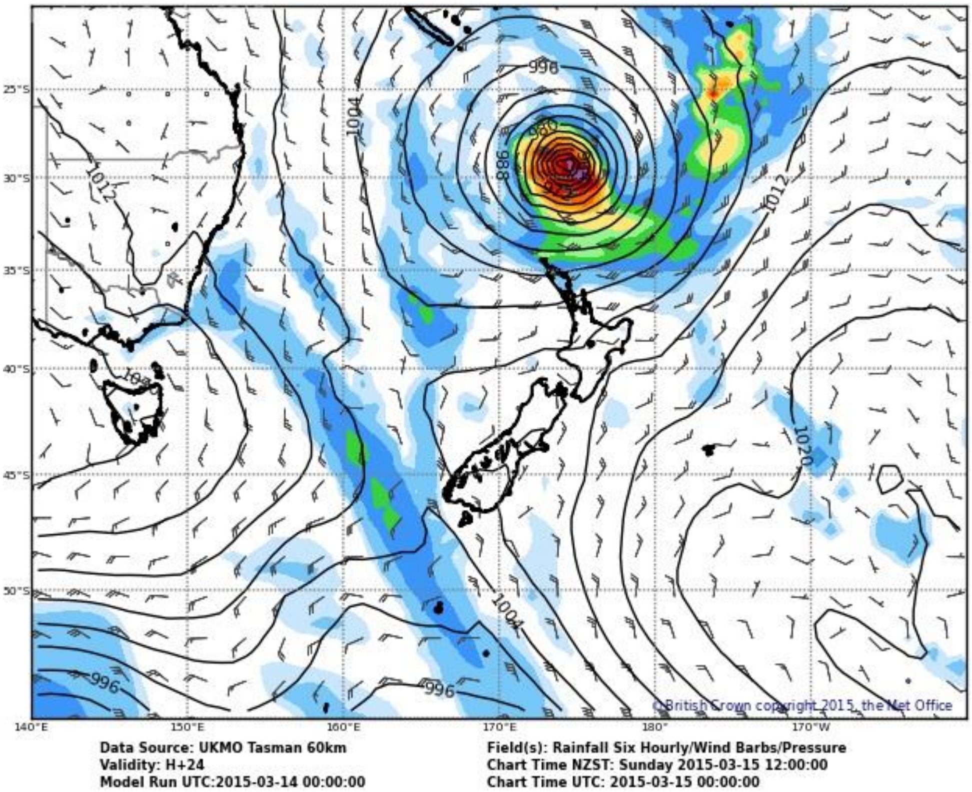

Figure 2.12: Pressure chart showing Tropical Cyclone Pam moving southwards towards the east coast of Northland

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 (refer to Figure 2.13) 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 with 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 (see Figure 2.14) with multiple wave height peaks. These long durations increase the likelihood of storm (wave height and storm surge) peaks coinciding with high astronomical tide.

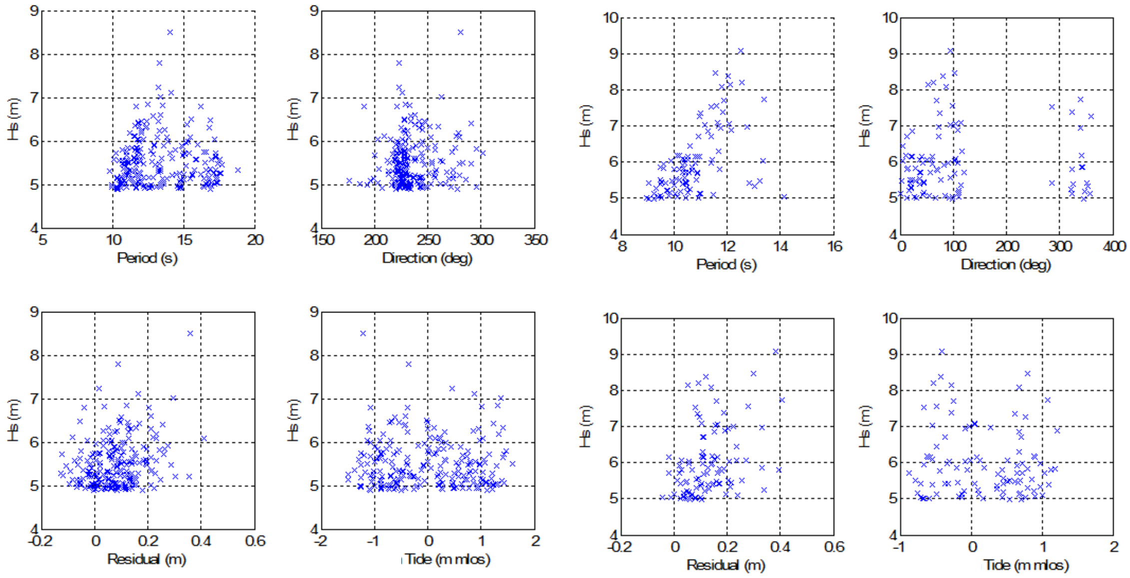

Figure 2.13: Storm peak characteristics for Ahipara (left) and Matauri (right) relating wave height to wave period, direction, non-tidal residual (storm surge) and tide

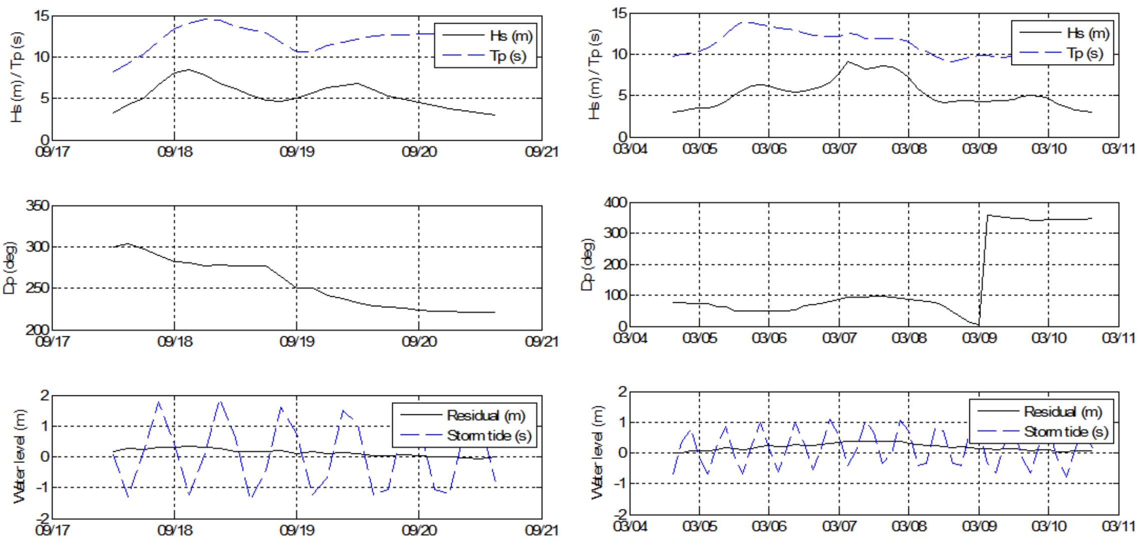

Figure 2.14: Time series of maximum storm on record for the Ahipara offshore site (September 2005) and for the Matauri site (March 1988)

2.4.3 Notable recent storm events

Recent notable storm events have had different impacts on the coastline of Northland, such as inundation from wave overtopping, erosion of the beach face and inundation from high water levels within the estuary. Several of the notable storm events which had coastal impacts are outlined below:

2.4.3.1 March 2015

Ex-tropical Cyclone Pam, debris on roads following storm surge plus waves. Erosion seen of beach dunes and coastal terraces along parts of the east coast of Northland. Inundation extent of Waipu cove is shown in Figure 2.15.

Figure 2.15: Debris line along the reserve of Waipu Cove (Sourced from NRC)

2.4.3.2 January 2008

High easterly winds coinciding with high tides and storm surge led to inundation along some eastern beach locations in the Far North (e.g. Rangiputa, Doubtless Bay beaches, Taupo Bay, Te Ngaere, Bland Bay and Te Mimiha). An example of this is shown by the resulting debris line seen at Te Ngaere (Figure 2.16).

Figure 2.16: Example of wave run-up debris from the January 2008 storm identified at Te Ngaere

2.4.3.3 September 2005

Large perigean spring tides coincided with a low-pressure system that caused storm surge and high winds. West coast sites were especially hard hit, with up to 10 m of erosion occurring near Ahipara and up to 4m near Omapere (Figure 2.17). Localised effects occurred on the east coast, with some erosion seen at Rangiputa and damage to a seawall at One Tree Point.

Figure 2.17: Erosion experienced at Ahipara (left) and Omapere (right) after the September 2005 storm

2.4.3.4 July 2000

Parts of Northland experienced heavy rain and high winds. Large storm tide coinciding with high spring tides led to coastal inundation. Significant amount of erosion occurred along dune backed beaches, shown for Whananaki North in Figure 2.18.

Figure 2.18: Erosion scarp of Whananaki North beach, July 2000 (Sourced from NRC)

2.4.3.5 March 1997

Ex-tropical Cyclone Gavin brought high winds, high storm surge and heavy rain to parts of Northland. At Paihia, 50 m the waterfront collapsed due to unusually high tides and large waves. Flooding of beachfront homes was experienced in Tutukaka.

3 Extreme water level assessment

3.1 Methodology

For this regional-scale assessment, extreme water levels have been derived as shown in the diagram in Figure 3.1, with a schematisation of the combination of water level components shown in Figure 3.2. Representative output locations have been defined along the entire Northland region shoreline for which extreme water levels have been derived. Storm tides including MSL and MHWS-10 have been analysed by NIWA (2020) using water level records from five tide gauges that are situated within the study area, with details of this analysis and levels set out in Section 3.3. The water levels derived for the individual gauges were then rationalised to the output locations by applying offsets (refer to Section 3.2). Location-specific extreme water levels have been derived for both open coast and sheltered shorelines by including storm tide, wave effects and sea level rise (SLR).

Extreme static and dynamic inundation levels have been calculated separately due to the different inundation mechanisms. Static inundation could potentially inundate large areas due to the consistently elevated water level, whereas dynamic inundation due to wave run up is temporary and restricted to the coastal edge, typically in the order of 10-30m (see schematisation in Figure 3.2). The extreme static water levels and extreme dynamic water levels for open coast and sheltered sites based on the following combinations:

$$Extreme\ static\ water\ level = ST + SU + SLR \qquad (3.1)$$

$$Extreme\ dynamic\ water\ level\ = ST + RU + SLR \qquad (3.2)$$

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** at 0.1 m increments up to 1.5 m (roughly corresponding to highest RCP scenario at 2130 as included in MfE, 2017) and selected SLR values at defined planning timeframes (i.e. present day, at least 50 and at least 100 years).

The inundation components were calculated separately for the open coast environments and sheltered coastal environments. Methods to transform offshore wave conditions (Section 2.4.1) to the nearshore for the assessment of wave effects are set out in Section 3.4. Methods used to assess and combine storm tide levels and wave set-up are described in Section 3.5, and including run-up (for open coast only) are described in Sections 3.6. Allowance for SLR and adopted levels at defined planning timeframes are set out in Section 3.7. Resulting coastal inundation levels based on this extreme water level assessment is set out in Section 4.

Figure 3.1: Extreme water level assessment diagram

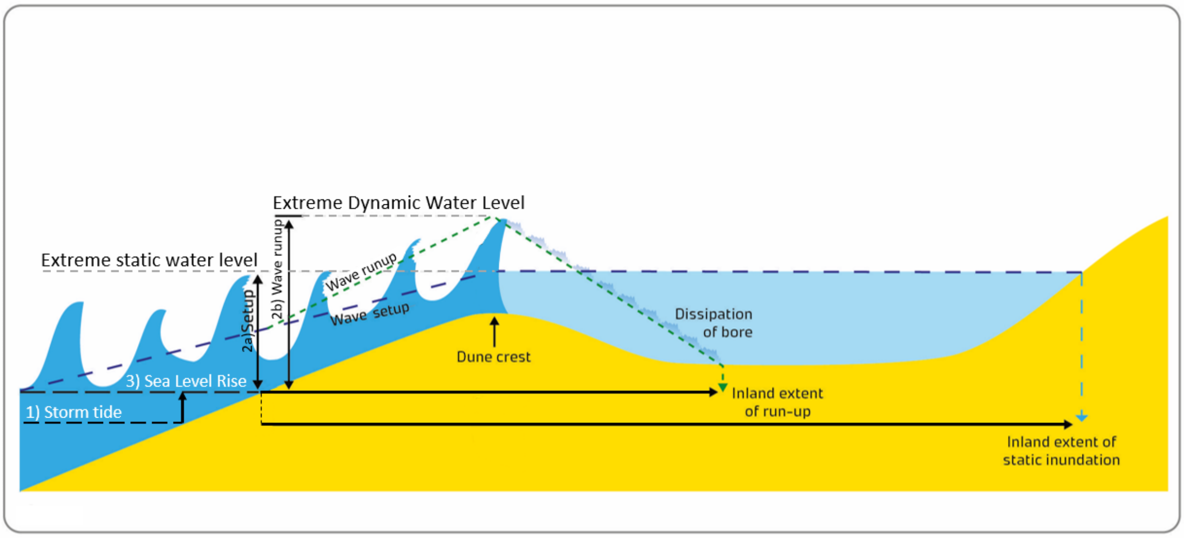

Figure 3.2: Schematisation of extreme water level components and combined extreme water levels

3.2 Output locations

Representative output locations cover the extent of the Northland region and have been defined to include townships, beaches and major estuaries, with a minimum distance between sites of 10 km along undeveloped stretches of coast. Figure 3.3 shows the output locations along the Northland shoreline with more detailed figures showing output locations included in Appendix C.

The output locations are typically representative for a section of shoreline, for instance the output location at Ocean Beach is representative for the east facing shoreline of Whangarei Heads, or the Parua Bay output location is intended to be representative for the entire bay (refer to Figure Appendix C.1; output location #30). The area extents for each output location have been indicated with polygons and are included in Appendix C.

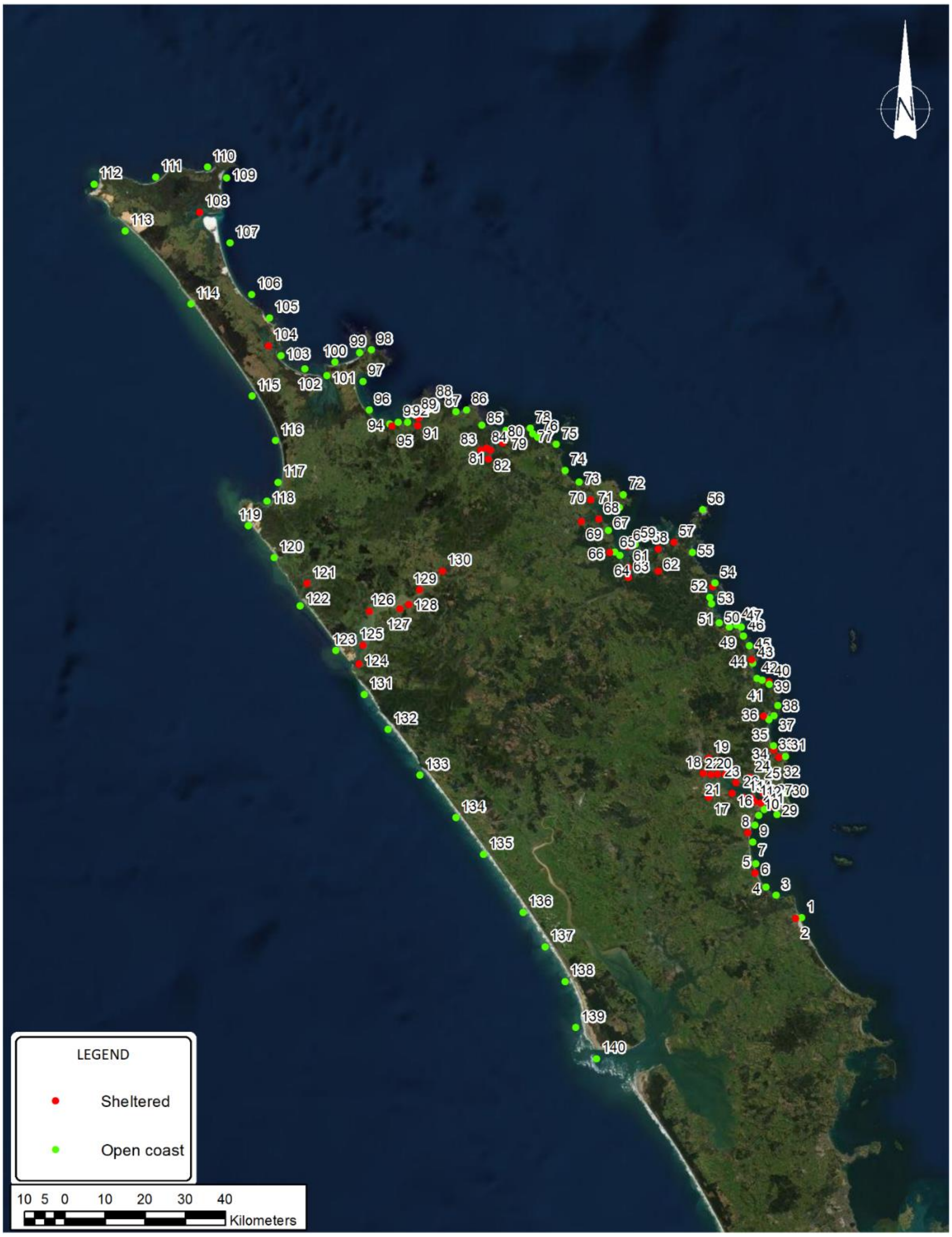

Figure 3.3: Output locations along Northland region shoreline at every township and major beach, or at <10 km alongshore intervals (aerial sourced from Esri world imagery)

3.2.1 Offset of water levels

Tidal levels vary around the Northland coastline as a result of tidal propagation and bathymetric features. Therefore, tidal levels (i.e. astronomical and storm tide levels) need to be transferred from the five tide gauges to the output locations. The following sources have been used as a basis for rationalising offsets between the main tide gauges and output locations:

- NIWA (2015) MHWS-10 model outputs
- LINZ (2020) MHWS Secondary Port values.

As the MHWS-10 values modelled by NIWA (2015) cover the entire Northland region open coast (refer to Figure 2.3), this dataset has been used for the open coast output locations. It is noted that the present day MHWS-10 levels may slightly vary from the levels derived in 2015, however, it has been assumed that the relative differences are the same and these have been used. For the output locations situated within harbours and estuaries the relative differences between the LINZ (2020) secondary ports levels have been used to rationalise the offsets between tide gauge and output locations. This approach is consistent with the approach used by T+T (2017).

Figure 3.4 shows the MHWS-10 levels derived by NIWA (2020) and rationalised MHWS-10 levels around the Northland region shoreline based on NIWA (2015) and LINZ (2020). Note that as a result of the rationalisation of MHWS-10 levels along the shoreline uncertainty in the accuracy of levels may be introduced. As we have used LINZ (2020) levels which are rounded to the nearest 0.1 m, the accuracy of the rationalised MHWS-10 levels have been estimated at ±0.1 m.

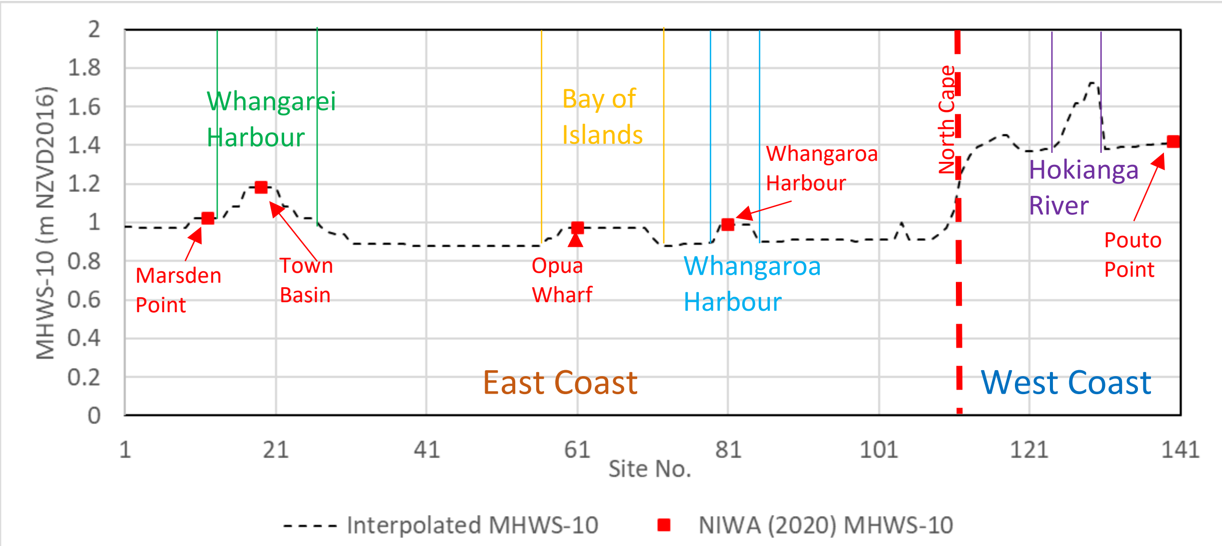

Figure 3.4: Rationalised MHWS-10 levels for output locations based on NIWA (2015) and LINZ (2020), including levels derived for tide gauges by NIWA (2020)

3.3 Storm tide levels

Extreme values derived for the individual gauges by NIWA (2020), as set out in Section 2.3.3, have been rationalised to the selected open coast and estuary sites by applying the MHWS-10 offsets (refer to Section 3.2.1). 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, except for the open coast sites within the Bay of Islands for which the local tide gauge levels have been used. The Town Basin, Whangaroa Harbour and Opua Wharf values have been used for the local harbour environments. The Pouto Point values have been used for open West Coast.

These extreme levels are based on analyses of historical datasets and therefore may not consider variations in storm surge heights due to potential climate change effects in the future. However, Cagigal et al. (2019) assessed future storm surges around New Zealand by developing a hindcast that was validated against sea level records and using seven global climate models to assess their effect on storm surge projections. They found that the 50-year return period storm surge will decrease around the North Island based on projections until 2100. This assumes that the relationship between storm surge and atmospheric conditions will be the same in the future. Based on this we have assumed that the derived extreme levels are valid for the future timeframes considered and may only increase as a result of sea level rise (see Section 3.7).

3.4 Wave height

3.4.1 Open coast wave height

Wave transformation modelling has been undertaken to transform the offshore (deep water) wave characteristics (see Section 2.4.1) 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 shoreline.

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. The nearshore wave heights at 10 m water depth are used as inputs for both the wave set-up and wave run-up calculations. An example of an offshore wave height timeseries and the transformed nearshore wave height timeseries is shown in Figure 3.5.

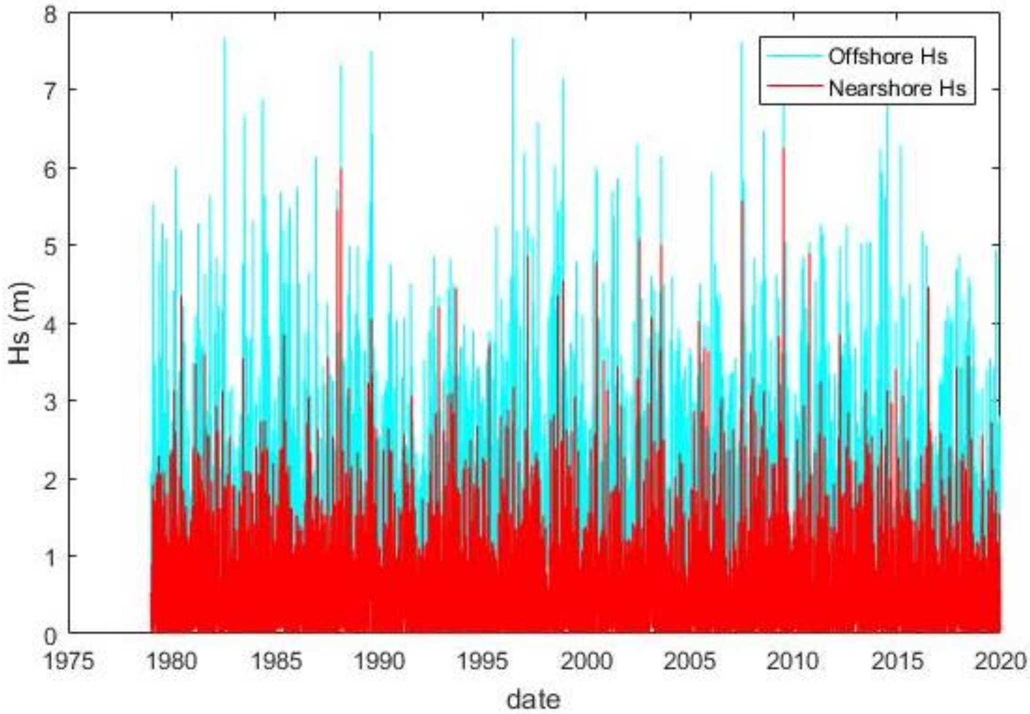

Figure 3.5: Example of offshore wave height timeseries and transformed nearshore wave height timeseries at Ruakaka

The hindcast wave height timeseries used for this study do not include any potential future climate change effects and these have not been included in this study. However, ongoing research on projected wave heights over the next 100-years suggests that extreme wave heights are projected to decrease on both the east and west coast of the North Island (pers. comm. Alberquerque, 25-8-2020). Based on this we have assumed that the hindcast wave timeseries do not require to be adjusted to take into account climate change effects.

3.4.2 Sheltered coast wave height

For sheltered coasts it is assumed that waves are generated locally within the enclosed water body and fetch-limited. For each output location, fetch distances in each direction are assessed (see example in Figure 3.6).

Extreme three second gust wind speeds for a range of recurrence intervals have been 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 10-120 minutes depending on the fetch length using procedures in the Coastal Engineering Manual (CEM) 1110-2-1100 (USACE, 2006). The growth of wind waves is limited by the minimum wind duration (10-120 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).

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 output location. The fetch limited significant wave height and period according to Wilson (1965) are:

$$H_{1/3} = 0.3\left\{1 - \left[1 + 0.004\left(\frac{gF}{U_{10}^2}\right)^2\right]^{-2}\right\}\frac{U_{10}^2}{g} \tag{3.5}$$

$$T_{1/3} = 8.61\left\{1 - \left[1 + 0.008\left(\frac{gF}{U_{10}^2}\right)^{1/3}\right]^{-5}\right\}\frac{U_{10}}{g} \tag{3.6}$$

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.

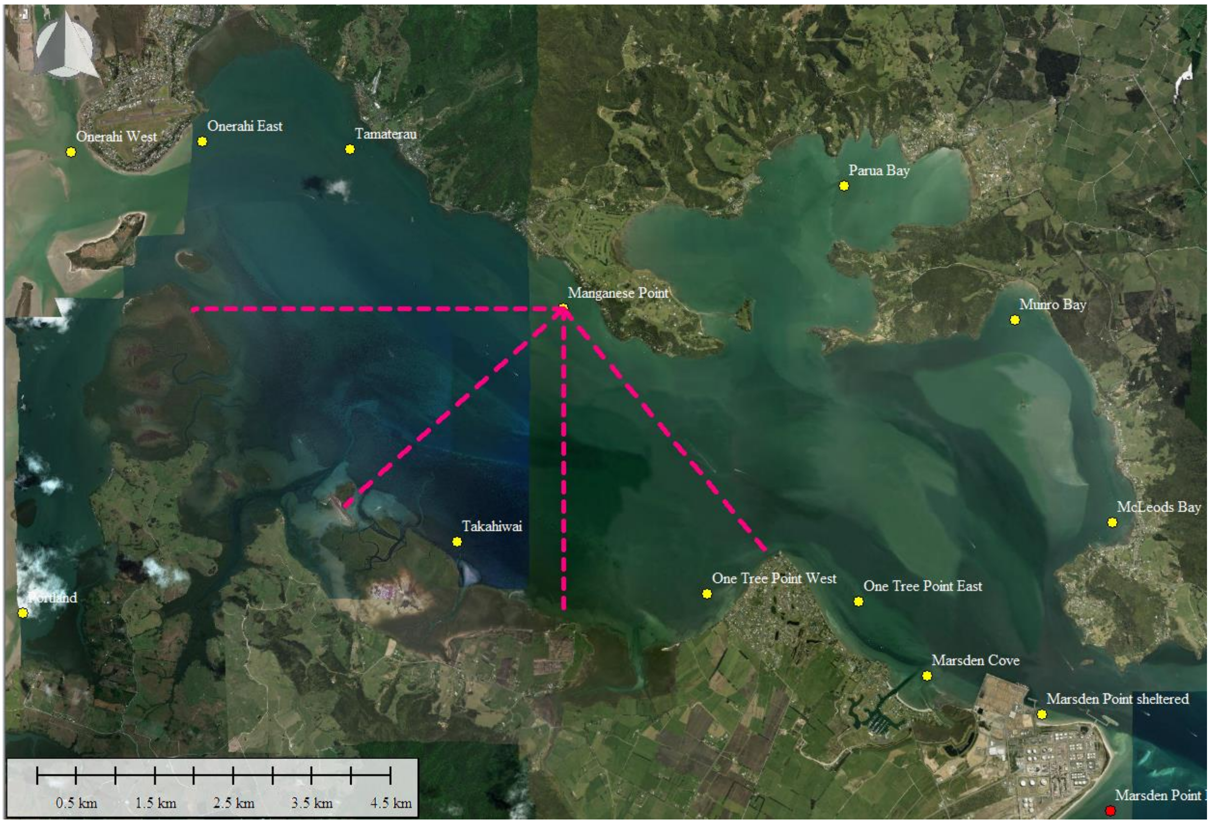

Figure 3.6: Example of fetch distances and directions (pink dashed lines) for Manganese Point situated within the Whangarei Harbour

An example of wave heights produced by 100-year ARI wind speeds for various directions is shown in Table 3.1. The wave heights have been calculated based on Equation 3.2 and one-hour extreme wind speeds derived for Northland as set out in AS/NZS 1170.2 (2011). Note that this is assuming no depth or duration limiting factors, which may limit the height of the generated wave in certain conditions.

Table 3.1: Resulting 100-year ARI wave heights for various fetch distances and wind directions

Fetch distance (km)	Wind Direction							
	N	NE	E	SE	S	SW	W	NW
<1	0.5	0.6	0.6	0.6	0.5	0.6	0.6	0.6
1-2	0.8	0.9	0.9	0.9	0.8	0.9	0.9	0.9
2-5	1.2	1.3	1.4	1.3	1.2	1.3	1.4	1.3
5-10	1.6	1.8	1.9	1.8	1.6	1.8	1.9	1.8
10-15	2.0	2.2	2.3	2.2	2.0	2.2	2.3	2.2

3.5 Wave set-up

3.5.1 Open coast wave set-up

Various methods and empirical formulations to calculate wave set-up are available including USACE (2006), Stockdon et al. (2006), Battjes (1974) and Guza & Thornton (1981). Consistent with T+T (2017), the USACE (2006) method as outlined in the Coastal Engineering Manual (CEM) was adopted. 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):

$$\overline{\eta_s} = \overline{\eta_b} + \left[\frac{1}{1+\frac{8}{3\gamma_b^2}}\right] h_b \tag{3.7}$$

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

$$\overline{\eta_{max}} = \overline{\eta_s} + \frac{d\eta}{dx}\Delta x \tag{3.8}$$

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 schematised in Figure 3.7.

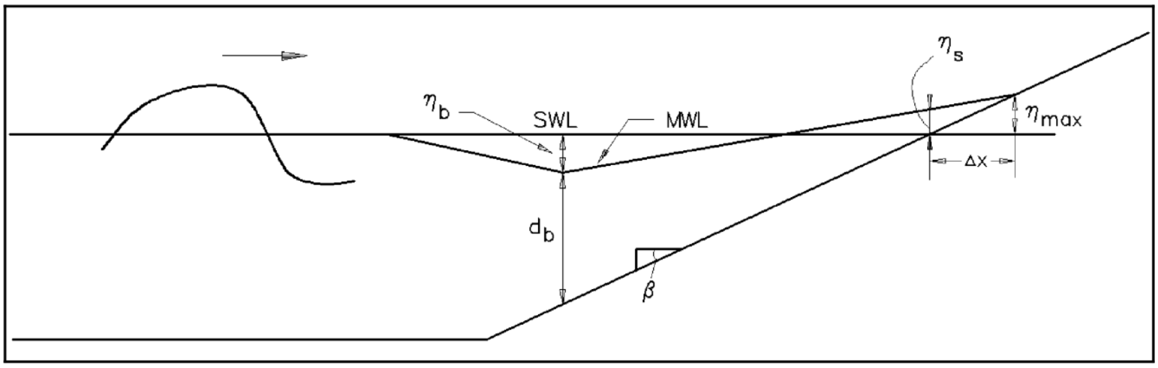

Figure 3.7: Wave set-up method (source: USACE, 2006)

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 3.8 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.

3.5.1.1 Combined storm tide and 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 H_s transformation coefficients (see Appendix B).
2. Develop equivalent hourly timeseries of water level based on the Marsden Point water level data set for the east open coast, Pouto Point data set for the west open coast and Opua Wharf data set for the Bay of Islands, each data set 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 (1 hour) using the CEM method described in Section 3.5.1 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 represent wave-dominated extremes most accurately (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 3.8 shows an example of wave height (top panel) and water level (middle panel) timeseries, and the combined water level and wave set-up timeseries (lower panel). Figure 3.9 shows an example of an extreme value analysis on extreme static inundation levels.

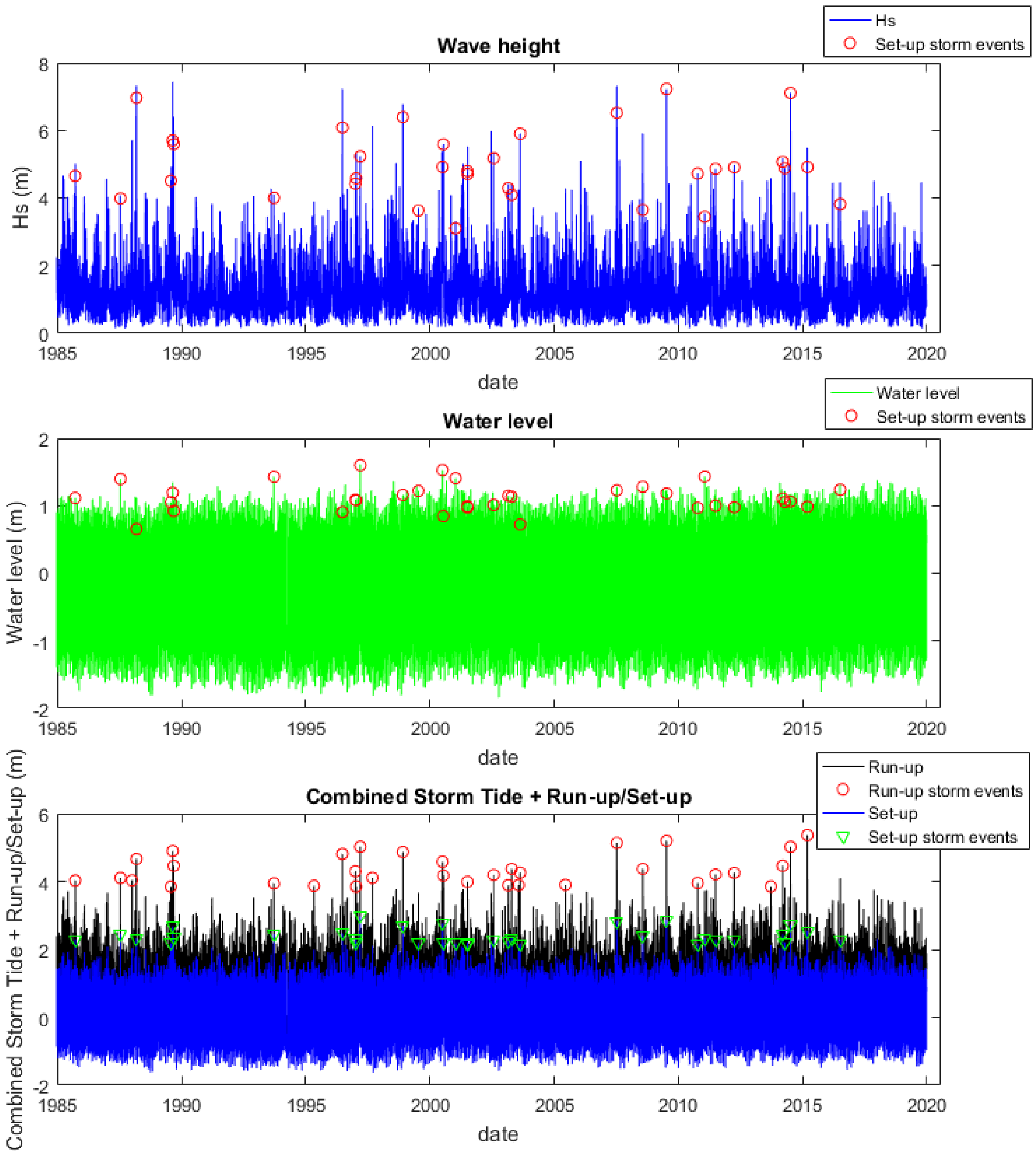

Figure 3.8: Timeseries of wave height (top panel), water level (middle panel) and combined water level + run-up and set-up (bottom panel) including identified extreme run-up and set-up events (shown as red circles and green triangles)

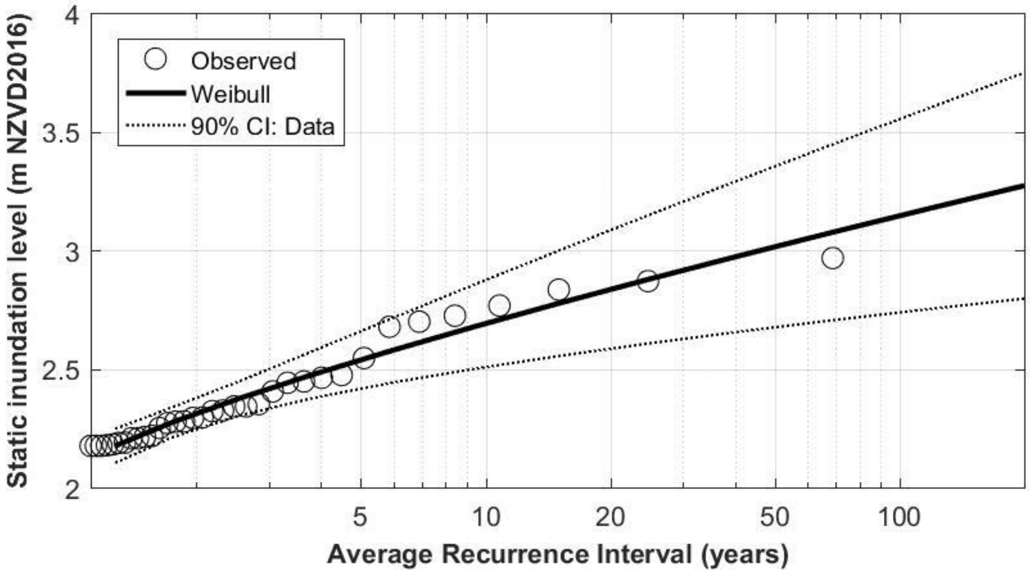

Figure 3.9: Example of extreme value analysis for static inundation level

Figure 3.10 shows a comparison of extreme static inundation levels using the building block approach and the structural EVA approach as derived by T+T (2017). This figure shows 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. For instance, the extreme water level indicated with the circled 'X' in Figure 3.10 is 2 m using the structural EVA approach compared to 2.9 m using the building block approach (which is nearly 50% larger).

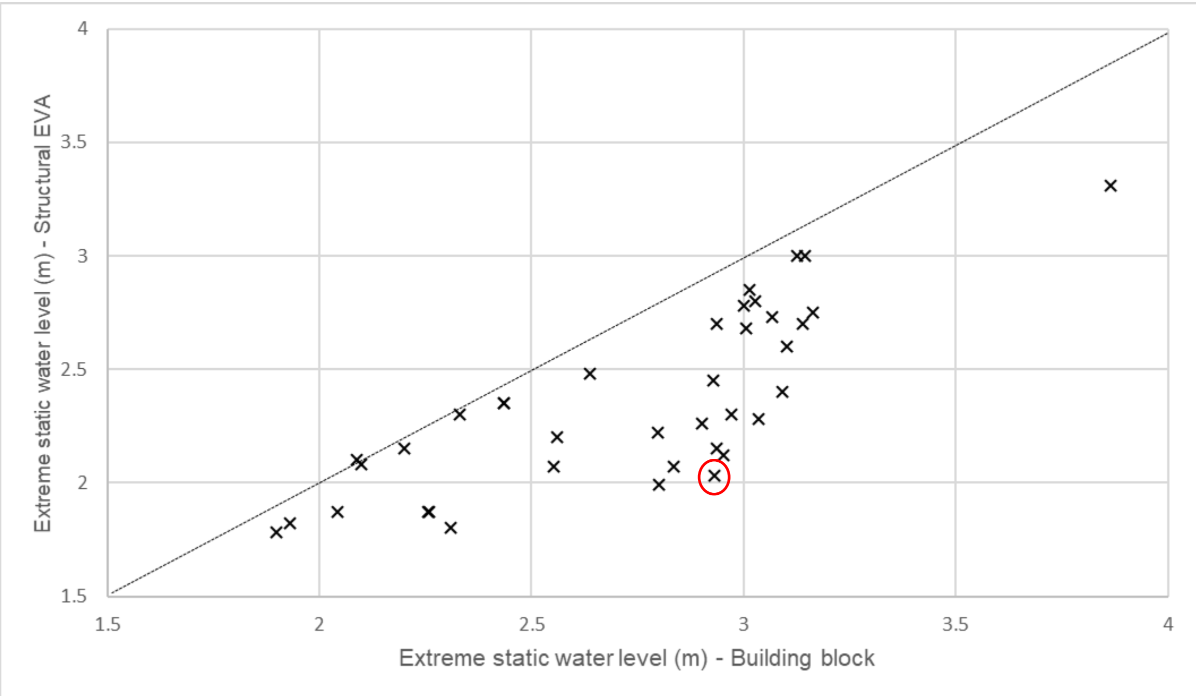

Figure 3.10: Comparison of extreme static water level calculated using the building block with the structural EVA approach based on T+T (2017)

3.5.2 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:

$$\overline{\eta_{max}} = 0.17H_b \tag{3.9}$$

Where:

H_b = Wave breaking height

Exceptions to this occur where open coast waves break at a harbour or estuary mouth entrance. In these cases, open coast wave set-up will be partially developed and will contribute to the extreme water levels within the harbour. However, this is only expected to occur at shallow estuary entrances that have a reasonable width (i.e. >50 m), such as at the Mangawhai River or Waipu Cove River. Studies such as Dodet et al. (2013), Olabarrieta et al. (2011) and Tanaka et al. (2009) found that wave set-up within estuaries are respectively 7-15%, 6% and 2-14% of offshore wave height. However, this is highly dependent on the geometry of the entrance channels, water depth and offshore wave conditions. T+T (2017) assessed the proportional wave set-up at 15 sites considering local site conditions and found proportional wave set-up between 10% and 20% of the open coast wave set-up, which is in the order of 3-4% of the offshore wave height. Therefore, for this regional-scale assessment an allowance for proportional wave set-up within estuaries connected to the open coast have been assumed being 20% of the open coast wave set-up. The proportional wave set-up is added to the wave set-up generated by local breaking waves within the estuaries.

3.6 Wave run-up

3.6.1 Open coast 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. da Silva et al. (2020) analysed several run-up methods based on various conditions and parameters and compared them to available field data. 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 formulae 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 comparing a range of run-up formulas (see Section 3.6.1.1), 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: $\left[(\tan\alpha)\,/(\sqrt{H_0/L_0})\,\right]$

3.6.1.1 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. da Silva et al. (2020) present a range of methods for predicting run-up which have been reviewed for this assessment. These formulas have been used to compare predicted run-up with observed run-up that occurred during an event in January 2008.

NRC have provided a summary of observed run-up debris levels 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 1.02 m NZVD2016 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 infra-gravity motions occurring during large wave events (see some site photographs in Figure 2.16).

Elevations of run-up debris were recorded at several beaches between Rangiputa and Te Mimiha (Figure 3.11). The debris was observed at elevations of 2.3 to 4.85 m above 'mean sea level' (interpreted as meaning relative to NZVD2016). We have assumed this debris line is the $R_{2\%}$ 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.

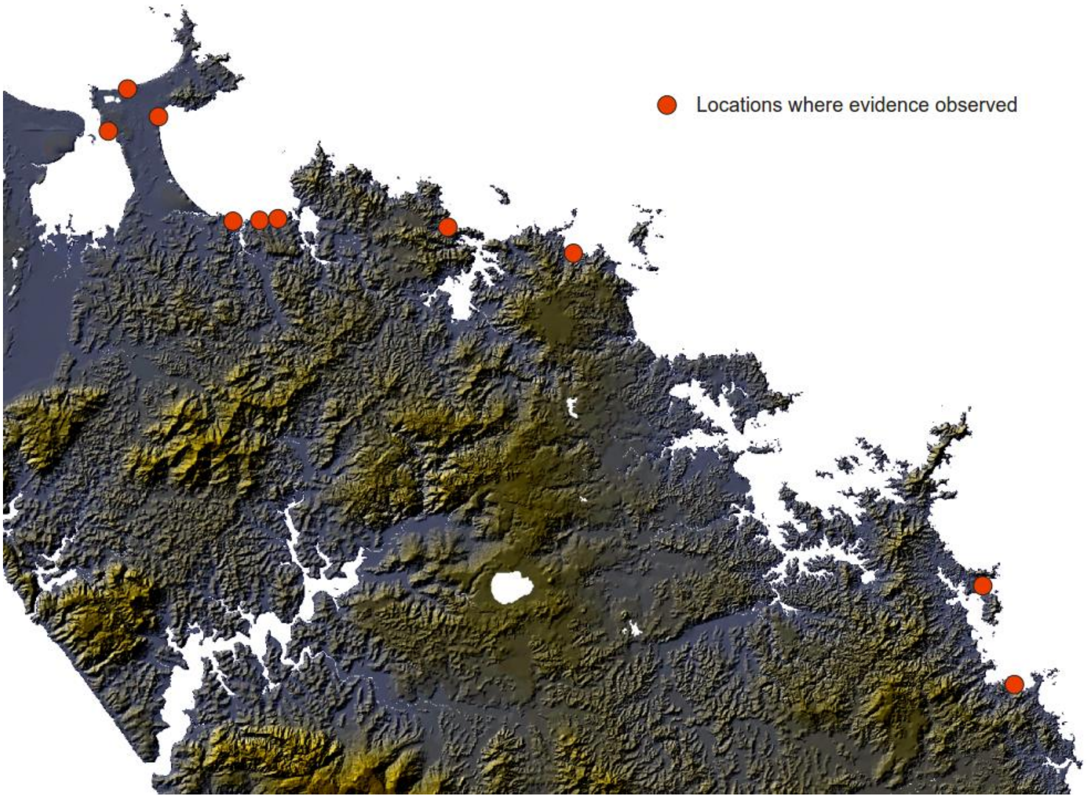

Figure 3.11: Locations where run-up evidence was collected (source NRC, 2008)

While specific measurement locations were not provided, we have attempted to locate each site based on the images provided. For these sites the local significant wave heights have been determined based on nearshore wave models and local beach geometry. Wave run-up levels have been calculated using methods defined by Mase (1989), Hedges & Mase (2004), Stockdon et al. (2006), Didier et al. (2020) and da Silva et al. (2020) (for reflective beaches). These methods predicted run-up levels close to the observed run-up levels have therefore been included in this report.

Results (Table 3.2 and visually in Figure 3.12) show that the Mase (1989) expression produces results closest to the recorded levels. The resulting levels calculated using Mase (1989) are typically within ±10% of the measurements, although the model over-predicts 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. Stockdon et al. (2006) and Hedges & Mase (2003) typically resulted in underpredicting run-up values for these test sites. Didier et al. (2020) shows reasonable correlation with values in Table 3.2, however, it was deemed inappropriate as the method did not accounting for beach slope which is considered a primary factor contributing to run-up elevations. The method by da Silva et al. (2020) shows typically over-prediction of run-up levels, however, this method calculates the maximum swash extent instead of the $R_{2\%}$ and requires a number of detailed input parameters which are not available for this regional-scale assessment.

The upper beach slope (see Figure 3.13) 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, with the surfzone slope largely underpredicting run-up shown by T+T (2017).

Table 3.2: Comparison of observed and modelled run-up

Sites	**Observed debris line [MSL]**	**Modelled run-up (m MSL)**									
		Stockdon et al. (2006)		**Mase (1989)**		**Hedges & Mase (2003)**		**Didier et al. (2020)**		**da Silva et al. (2020) (reflective)**	
Rangiputa	3.1	2.05	*-34%*	2.91	*-6%*	2.33	*-25%*	2.78	*-10%*	4.01	*29%*
Tokerau	3.2	2.15	*-33%*	3.10	*-3%*	2.45	*-23%*	3.39	*6%*	4.19	*32%*
Taipa	3.06	2.17	*-29%*	3.19	*4%*	2.51	*-18%*	3.11	*2%*	3.98	*30%*
Cable	4.85	2.70	*-44%*	4.48	*-8%*	3.40	*-30%*	3.77	*-22%*	3.59	*-41%*
Coopers	3.78	2.32	*-39%*	3.48	*-8%*	2.77	*-27%*	3.90	*3%*	4.15	*12%*
Hihi	3.25	2.13	*-34%*	3.05	*-6%*	2.46	*-24%*	2.74	*-16%*	3.87	*20%*
Taupo	3.87	2.56	*-34%*	4.15	*7%*	3.22	*-17%*	4.19	*8%*	3.87	*0%*
Te Ngaere	3.4	2.23	*-34%*	3.36	*-1%*	2.62	*-23%*	3.09	*-9%*	3.84	*14%*
Bland	2.27	2.03	*-10%*	2.91	*28%*	2.31	*2%*	2.88	*27%*	4.04	*57%*
Te Mimiha	4.5	2.81	*-38%*	4.52	*0%*	3.52	*-22%*	3.19	*-29%*	3.33	*-38%*
RMS difference		-34%		+10%		-22%		-16%		+31%	

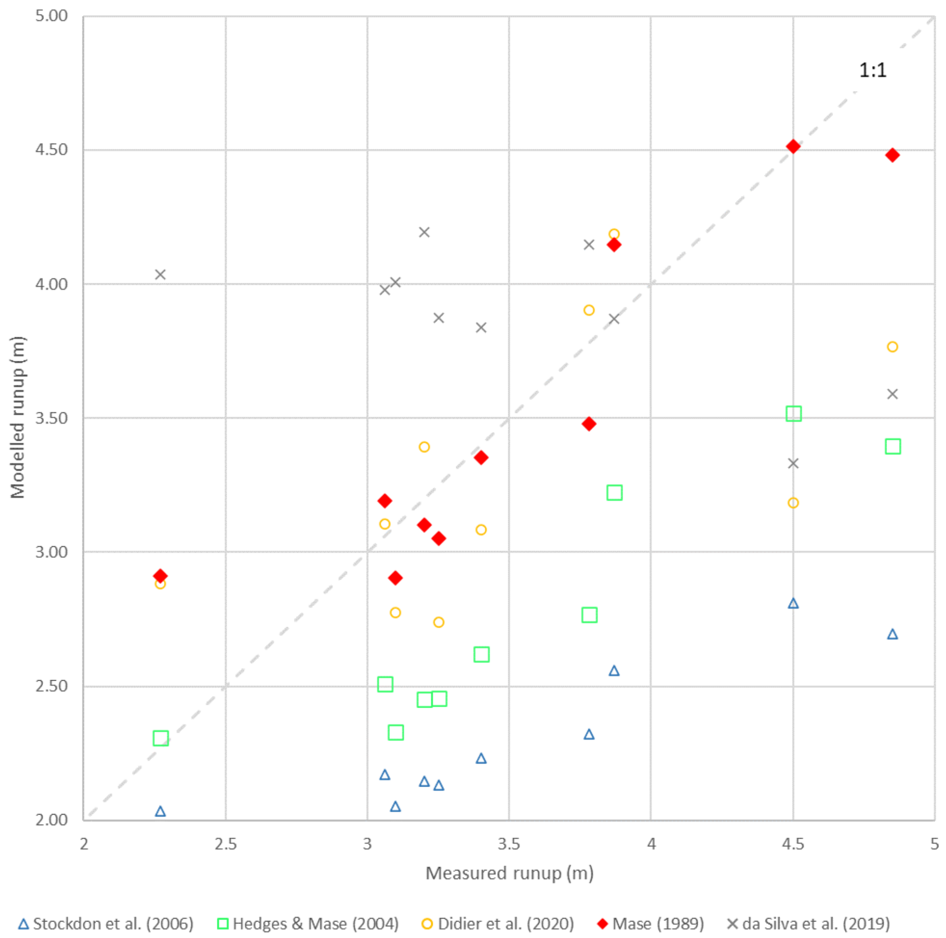

Figure 3.12: Plotted measured and modelled run-up

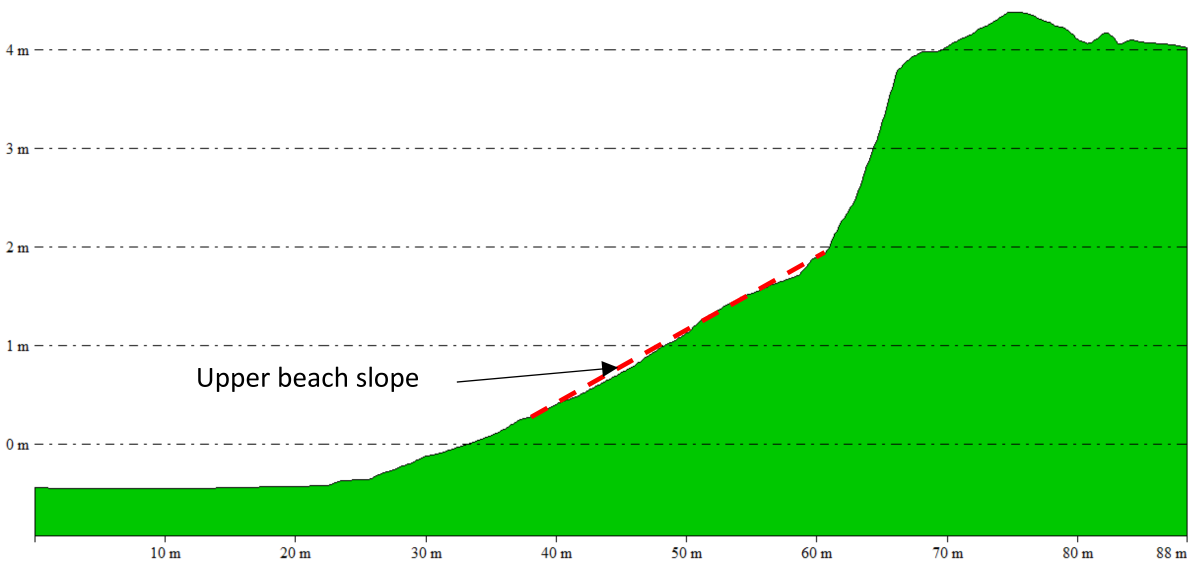

Figure 3.13: Example of beach profile with adopted beach slope

3.6.1.2 Combined storm tide and wave run-up

The extreme dynamic water 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 H_s transformation coefficients (refer to Appendix B).
2. Develop equivalent hourly timeseries of water level based on the Marsden Point water level data set for the east open coast, Pouto Point data set for the west open coast and Opua Wharf data set for the Bay of Islands, each data set 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).

3.6.2 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 H_s=1 m, wave run-up will generally also be less than 1-2 m depending on shoreline type with run-up generally dissipated within 5-10 m of the coastal edge. Generic setback distances and freeboards should be implemented to allow for this unless site-specific assessment shows otherwise.

3.7 Sea level rise

For assessing areas susceptible to coastal inundation, SLR values have been considered at 0.1 m increments up to 1.5 m. The upper bound 1.5 m SLR corresponds roughly to the 2130 RCP8.5H+ scenario as defined in MfE (2017). The 1.5 m SLR is the most extreme scenario recommended to consider by MfE (2017) to 'stress test' dynamic adaptive pathways and new greenfield and major infrastructure developments.

For defining Coastal Flood Hazard Zones (CFHZs) the following SLR values have been adopted as requested by NRC:

- CFHZ1 = 0.6 m
- CFHZ2 = 1.2 m
- CFHZ3 = 1.5 m.

The CFHZ1 roughly corresponds to the 2080 RCP8.5M, with the CFHZ2 and CFHZ3 roughly corresponding to the RCP8.5M and RCP8.5H+ respectively for 2130 as set out in MfE (2017). Table 3.3 shows the SLR values at 10-year intervals as included in MfE (2017) with respect to the 1986-2005 MSL baseline.

It should be noted that for a more detailed assessment the values are suggested to be adjusted to a more recent MSL if available (e.g. 2020 MSL). This adjustment is suggested as the sea level has risen since 1986-2005 and is suggested to be subtracted from future projections. For instance, for the RCP8.5M scenario 0.09 m SLR has been projected to occur between 1985-2005 and 2020, and is suggested to be subtracted if a 2020 MSL baseline is considered.

Table 3.3: Decadal increments for projections of sea level rise based on MfE (2017) with respect to a 1985 – 2005 baseline level

SLR scenario Year	RCP2.6M[1] (m)	RCP4.5M[1] (m)	RCP8.5M[1] (m)	RCP8.5H+[2] (m)
2020	0.08	0.08	0.09	0.11
2030	0.13	0.13	0.15	0.18
2040	0.18	0.19	0.21	0.27
2050	0.23	0.24	0.28	0.37
2060	0.27	0.3	0.36	0.48
2070	0.32	0.36	0.45	0.61
2080	0.37	0.42	0.55[3]	0.75
2090	0.42	0.49	0.67	0.9
2100	0.46	0.55	0.79	1.05
2110	0.51	0.61	0.93	1.2
2120	0.55	0.67	1.06	1.36
2130	0.6	0.74	1.18[3]	1.52[3]

[1]Median

[2]83rd percentile

[3]Values approximately corresponding to adopted CFHZ1, 2 and 3 values

4 Results and mapping

4.1 Coastal inundation levels

Coastal inundation levels (i.e. static and dynamic inundation levels) have been assessed by combining individual component values as set out in Section 3. These have been assessed for a range of return periods (i.e. ARI), timeframes and SLR scenarios for 140 output location around the Northland region shoreline. The derived levels have been rounded to the nearest 0.1 m due to accuracy in interpolation between gauges and the LiDAR DEM used for mapping. Appendix C sets out the present-day static and dynamic inundation levels for a range of return periods and the MHWS-10 and CFHZ0-3 levels for each output location. The adopted return period, timeframe and SLR value for CFHZ0-3 are set out in Table 1.1.

A summary of the extreme static and dynamic water levels (i.e. 100-year ARI), and the CFHZ0-3 for both east and west open coast shorelines, the major harbours and the remaining inlet estuaries is shown in Table 4.1. Figure 4.1 and Figure 4.2 show maps of the Northland region with the shoreline coloured for ranges in present-day 100-year static inundation and dynamic inundation levels respectively. These show that the present-day static inundation levels are the highest along the open coast shorelines (i.e. up to 3.5 m NZVD2016), with the lowest levels found within estuary inlets and Whangaroa Harbour (i.e. 1.6 m NZVD2016). This is expected as open coast shorelines are typically subject to larger breaking waves which induce large wave set-up compared to sheltered shorelines that may be subject to relatively small breaking waves.

Table 4.1: Summary of coastal inundation levels (m NZVD2016)

Timeframe/ Return period/ SLR value	Water level component	Open East Coast	Open West Coast	Whangarei Harbour	Bay of Islands	Whangaroa Harbour	Hokianga Estuary	Estuary inlets
Present-day 100-year ARI	Static [1]	1.7-3.5	2.9-3.5	1.8-2.2	2.5-2.7	1.6-1.7	2.3-2.5	1.6-2.4
	Dynamic	3.2-8.8	4.6-7.8	-	4.3-6.4	-	-	-
2080 50-year ARI 0.6 m SLR	Static [2]	2.2-4.0	3.4-4.0	2.3-2.7	3.0-3.2	2.1-2.1	2.8-3.0	2.0-2.9
	Dynamic	3.7-9.2	5.1-8.3	-	4.7-6.9	-	-	-
2130 100-year ARI 1.2 m SLR	Static [3]	2.8-4.6	4.0-4.6	2.9-3.3	3.6-3.8	2.7-2.8	3.5-3.7	2.7-3.5
	Dynamic	4.3-9.9	5.7-8.9	-	5.4-7.6	-	-	-
2130 100-year ARI 1.5 m SLR	Static [4]	3.2-4.9	4.4-5.0	3.3-3.7	4.0-4.1	3.1-3.1	3.8-4.0	3.0-3.8
	Dynamic	4.6-10.2	6.0-9.3	-	5.7-7.9	-	-	-

[1]CFHZ0 [2]CFHZ1 [3]CFHZ2 [4]CFHZ3

The present-day 100-year ARI dynamic water level is largest along the exposed East Coast (i.e. up to 8.8 m NZVD2016), but lower in more protected East Coast locations (i.e. 3.2 m NZVD2016). This indicates that the exposure of the beaches along the open East Coast is highly variable. Sites along the open West Coast range from 4.6 to 7.8 m NZVD2016 indicating exposure is more consistent. The dynamic water levels for sheltered sites have not been assessed (refer to Section 3.6.2). The future coastal inundation levels show the same trend as the present-day coastal inundation levels, but with level elevated based on sea level rise contribution.

For each output location, extreme static and dynamic water levels have been tabulated for a range of return periods (i.e. 5-year ARI to 500-year ARI) for the present day and including future water levels for SLR values at 0.1 m increments (i.e. 0.1 m to 1.5 m). These tables have been provided in digital format as part of Appendix C.

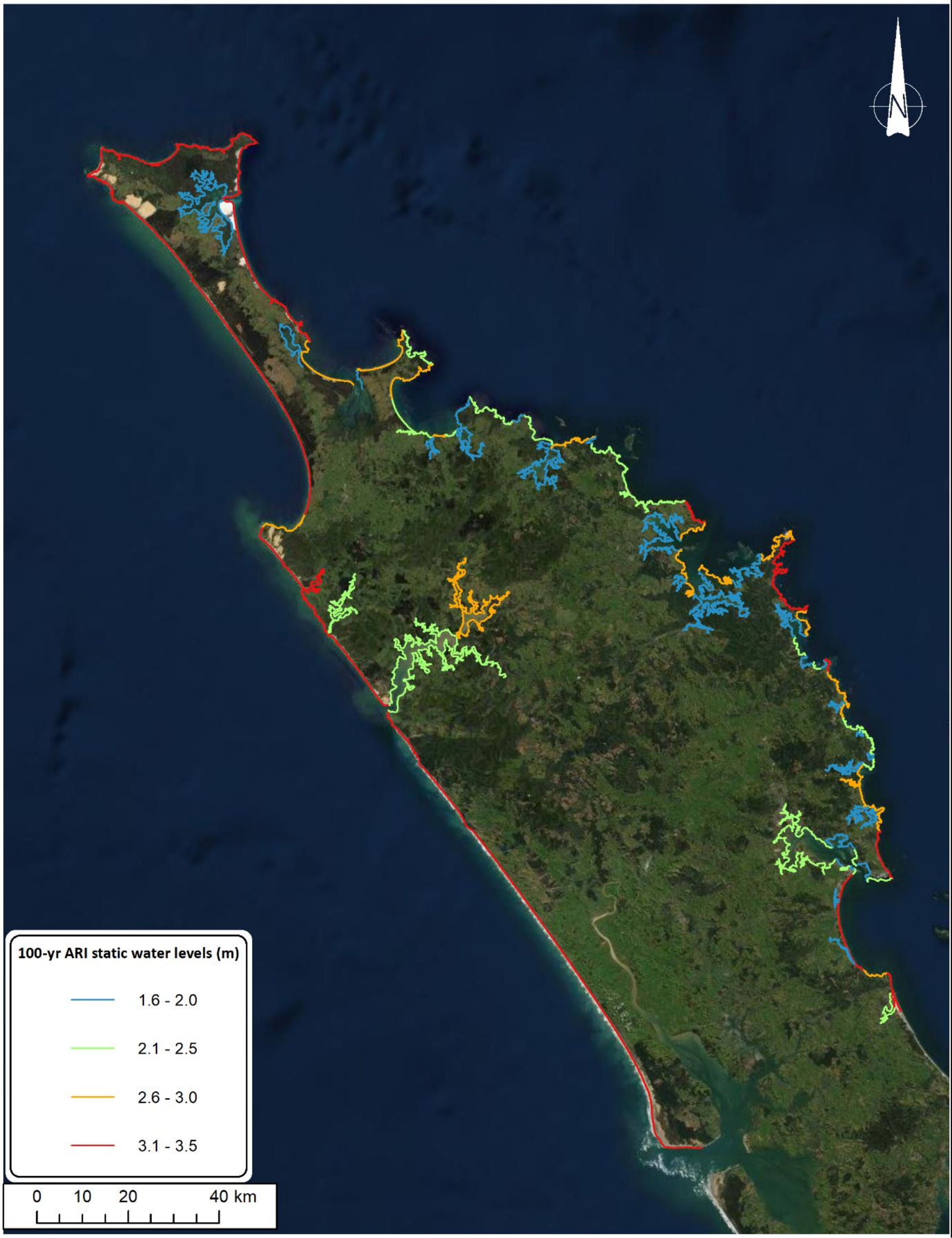

Figure 4.1: Present-day 100-year ARI static inundation levels (m NZVD2016) for Northland region

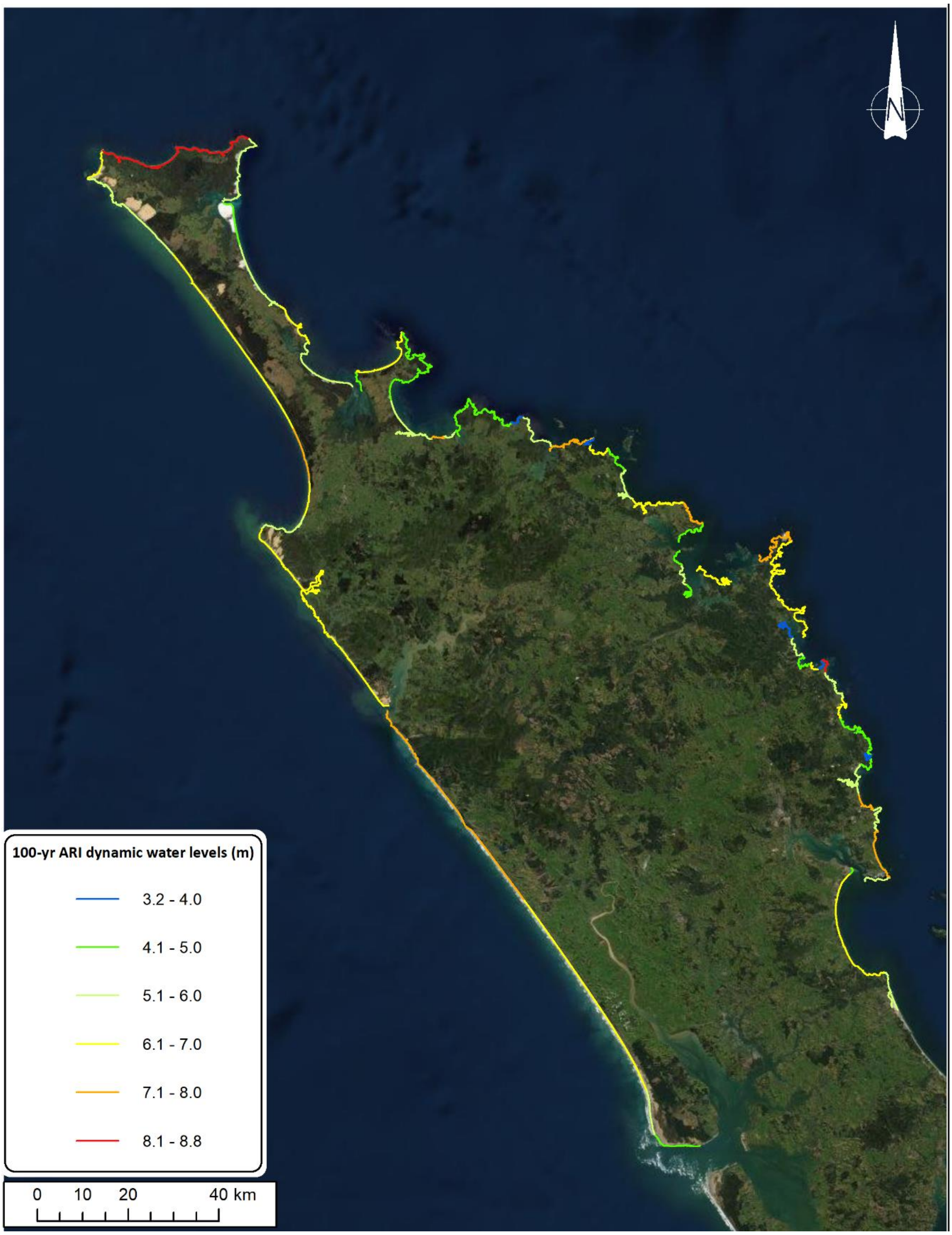

Figure 4.2: Present-day 100-year ARI dynamic inundation levels (m NZVD2016) for Northland region

4.2 Mapping

4.2.1 Method

The areas potentially susceptible to static inundation have been mapped using the connected bathtub model. This model differentiates areas below a specified inundation level that are connected to the coastal water body from those that are disconnected (Figure 4.3). A 1 m digital elevation model (DEM) created and provided by NRC for the entire Northland region (refer to Section 2.2) was used. This model represents bare earth (i.e. with buildings and vegetation removed) was used, and does not include structures such as seawalls and culverts.

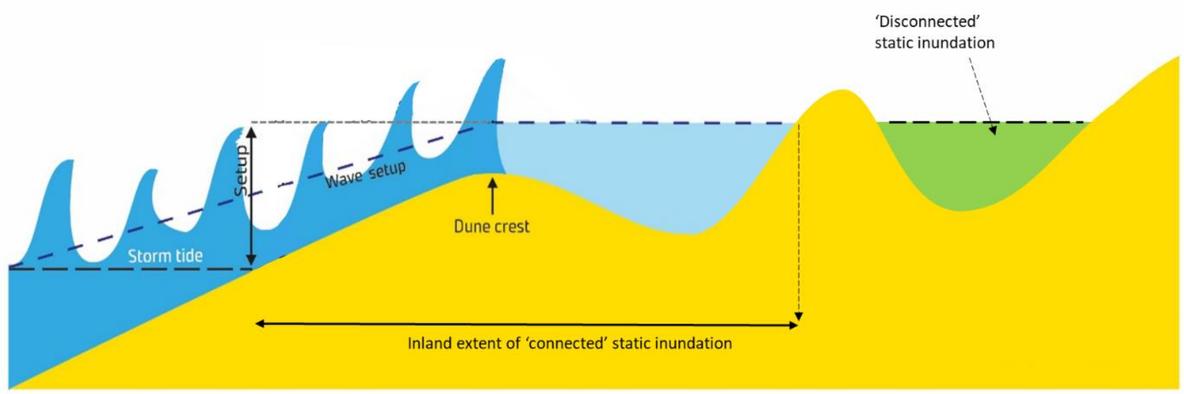

Figure 4.3: Connected and disconnected bathtub approach sketch

Both connected and non-connected areas have been assessed at 0.1m increments between 0.5 and 5.5m NZVD2016 for the entire Northland Region. For each increment both the extent and depth of inundation is assessed with results provided as polygons and raster depth maps. Figure 4.4 shows and example of connected and non-connected areas susceptible to coastal inundation at Pataua and Figure 4.5 shows an example of the depth of inundation for a static inundation level of 2.9 m NZVD2016 (100-year ARI) at Pataua.

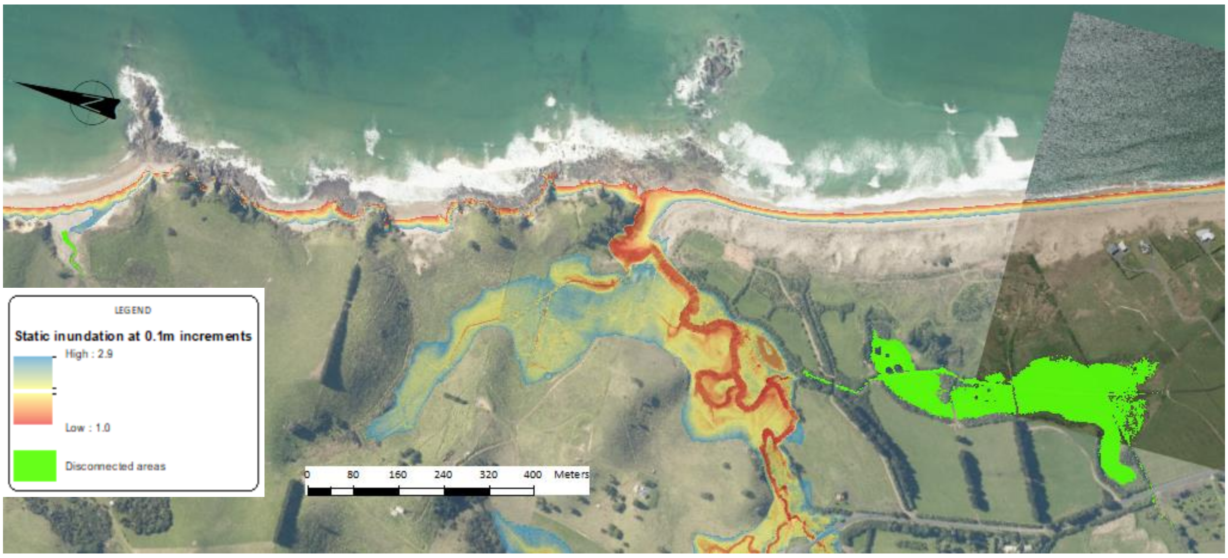

Figure 4.4: Example of inundation extents at 0.1 m increments at Pataua, with disconnected area shown for 2.9 m NZVD2016 level

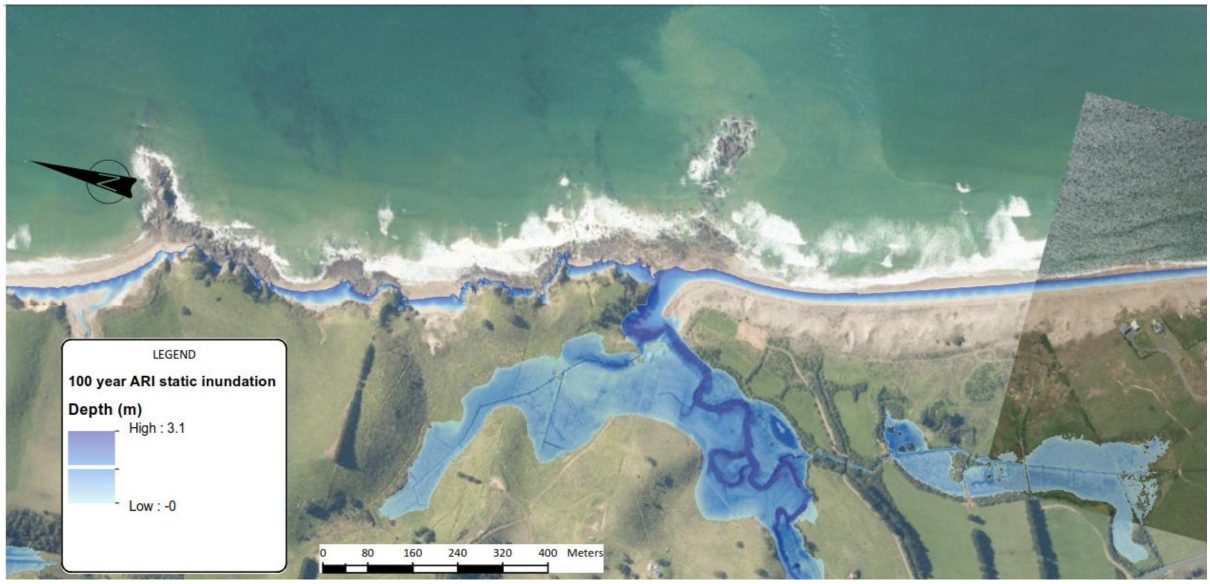

Figure 4.5: Example of inundation depths for a static inundation level of 2.9 m NZVD2016 at Pataua

4.2.2 MHWS-10 mapping

The present day MHWS-10 has been mapped for the entire Northland region except for the Kaipara Harbour and Awanui Estuary. The MHWS-10 levels for each output point as set out in Appendix C have been mapped by using the respective contour levels (assessed at the closest 0.1 m). Where MHWS-10 levels change between output locations transitions have typically been applied approximately midway between the output locations over 100 m per mm or at a geomorphic feature (e.g. cliff headland separating two beaches).

The present day MHWS has been mapped in the form of a polyline. The future MHWS-10 at 2080 allowing for 0.6 m SLR and at 2130 allowing for 1.2 m SLR have been mapped without transitions between adjacent cells. Both polygons and depth rasters (i.e. polygons including depth to ground level at each grid point) have been created for the future MHWS-10 scenarios clipped to the present-day MHWS-10 at the offshore boundary. An example of the mapped MHWS-10 line and polygons is shown in Figure 4.6.

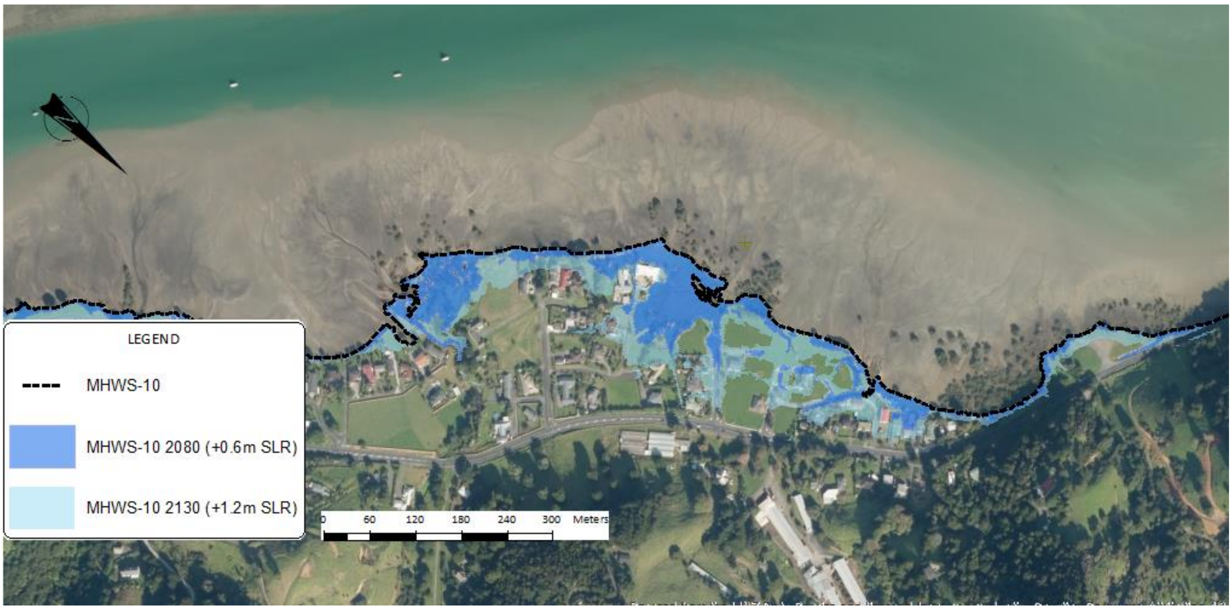

Figure 4.6: Example of present day MHWS-10 and future MHWS-10 polygon at Tamaterau

As the 2019 DEM that was used for mapping has a vertical accuracy of 0.15 m, the same vertical accuracy applies to the mapped MHWS-10, with the horizontal accuracy in order of metres where the foreshore slope is relatively flat or due to potential errors in DEM (e.g. due to point cloud classification). Therefore, the MHWS-10 lines should not be utilised for cadastral or survey purposes.

4.2.3 CFHZ mapping

In addition to mapping of incremental levels across the region, the following specific inundation scenarios have been mapped:

- CFHZ0 (Present-day 100-year ARI)
- CFHZ1 (2080 50-year ARI + 0.6 m SLR)
- CFHZ2 (2130 100-year ARI + 1.2 m SLR)
- CFHZ3 (2130 100-year ARI + 1.5 m SLR).

The inundation extents of CFHZs have been mapped based on the CFHZ level derived at each output location. This means that the inundation level for each scenario may differ across the Northland region. Where inundation levels between adjacent output points differ, for instance a higher inundation level may occur on an open coast shoreline than with an adjacent estuarine shoreline, and the inundated area overlaps, the largest inundation extents have been mapped. An example of this is shown in Figure 4.7, with an example of the CFHZ0-3 mapped for Pataua shown in Figure 4.8.

Both the inundation extents and depth have been provided for each CFHZ. It should be noted that CFHZ values have mapped at the nearest 0.1m due to the regional scale of the assessment and the vertical accuracy of the LiDAR DEM. Therefore while inundation depths have been provided down to 1 cm, depth less than 0.1 m may not be reliable and furthermore are unlikely to be hazardous. This could be reviewed for a more detailed assessment by considering a lower bound threshold for inundation depths.

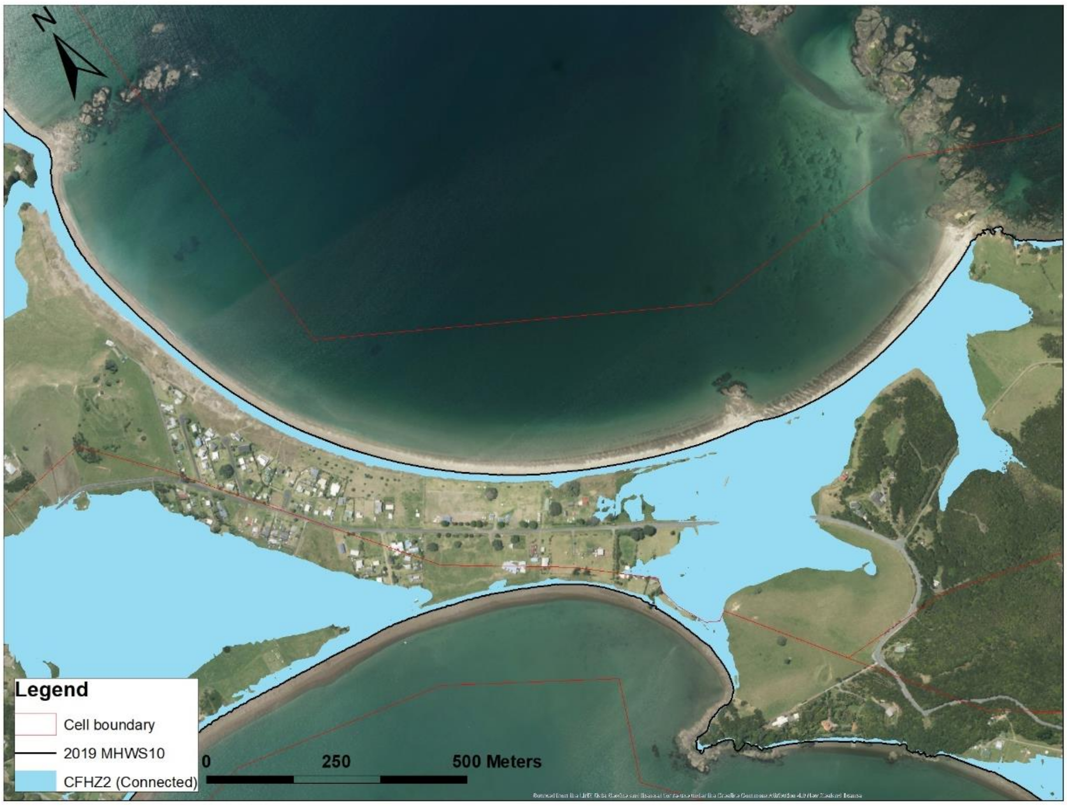

Figure 4.7: Example of merged inundation extents

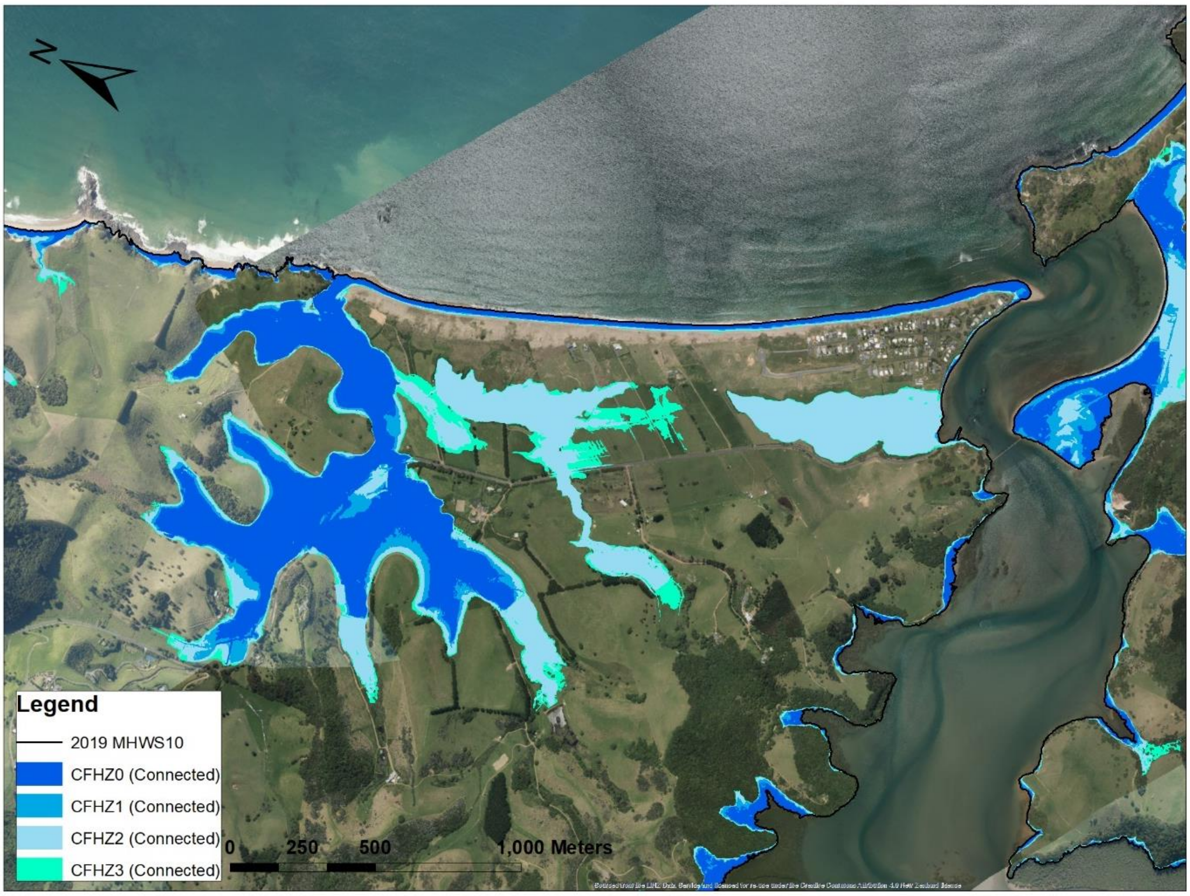

Figure 4.8: Example of CFHZs

4.2.4 Extreme dynamic inundation extents

Extreme dynamic inundation 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. Dynamic run-up levels are generally substantially higher than static levels and therefore if a similar bathtub approach were applied, then very large areas may be flooded. Therefore, run-up extents should be mapped by assessing the attenuation distance from the coastal edge. Mapping of the CRHZs is outside of the scope for this assessment, however, guidance to assess site-specific run-up hazard, including calculating attenuation distances, is set out below.

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 4.9). A site-specific self-assessment of wave run-up attenuation distance and flow depth can be undertaken following these steps:

i Determine dynamic inundation (wave run-up) level based on Appendix C or calculate wave run-up according to Equation 3.10 for a specific location and add to relevant storm tide level.

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

If run-up level exceeds the dune crest, calculate run-up attenuation according to Equation 3.11, modified from FEMA (2005).

$$X = \frac{\sqrt{R-Y_0}\cdot A(1-2m)\cdot gT^2}{5\sqrt{gT^2}} \quad (3.11)$$

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 2.5 for relevant location)

g = 9.81 m/s^2

A = Inland slope friction factor (default = 1, can be adjusted if calibration data available)

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

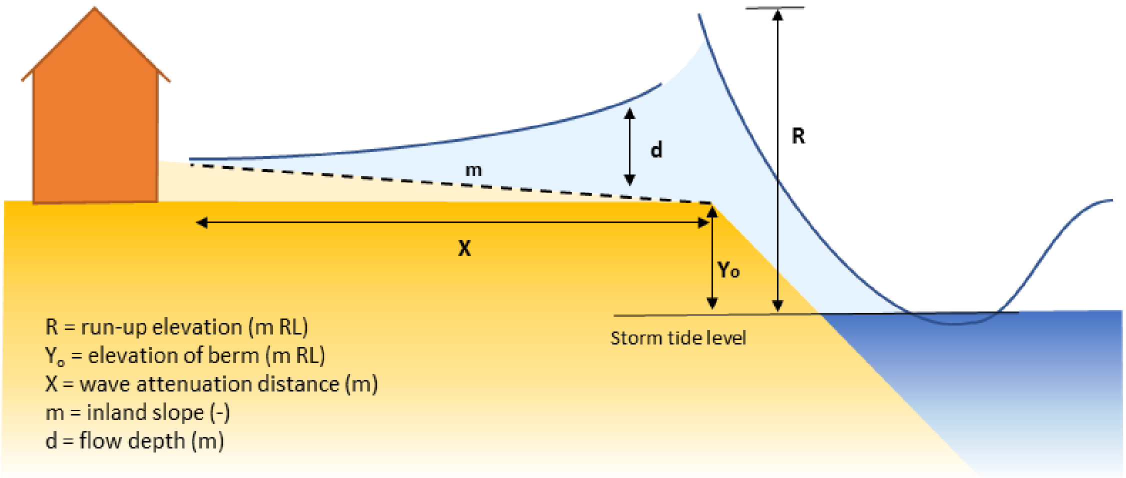

Figure 4.9: Run-up attenuation definition sketch (modified from Cox and Machemehl, 1986)

iii 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.

iv (optional) If the flow depth at a certain wave run-up attenuation distance (X) is required, calculate the flow depth according to Equation 3.12

$$d = \left[\sqrt{R - Y_0} - \frac{5X}{A(1-2m)\sqrt{gT^2}}\right]^2 \tag{3.12}$$

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 2.5 for relevant location)

g = 9.81 m/s^2

A = Inland slope friction factor (default = 1, can be adjusted if calibration data available)

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

As a first estimate, Figure 4.10 shows the wave run-up attenuation distance (X) as a function of run-up height above the crest (R-Y_o) for both East Coast and West Coast sites. A peak wave period of 11 sec and 14 sec have been adopted for the East Coast and West Coast respectively. The landward attenuation distance is based on a water depth less than 0.1 m. For instance, for a wave run-up height exceeding the crest by 1.5 m along the West Coast, the wave run-up attenuation distance is 8 m, beyond which the water depth is less than 10 cm.

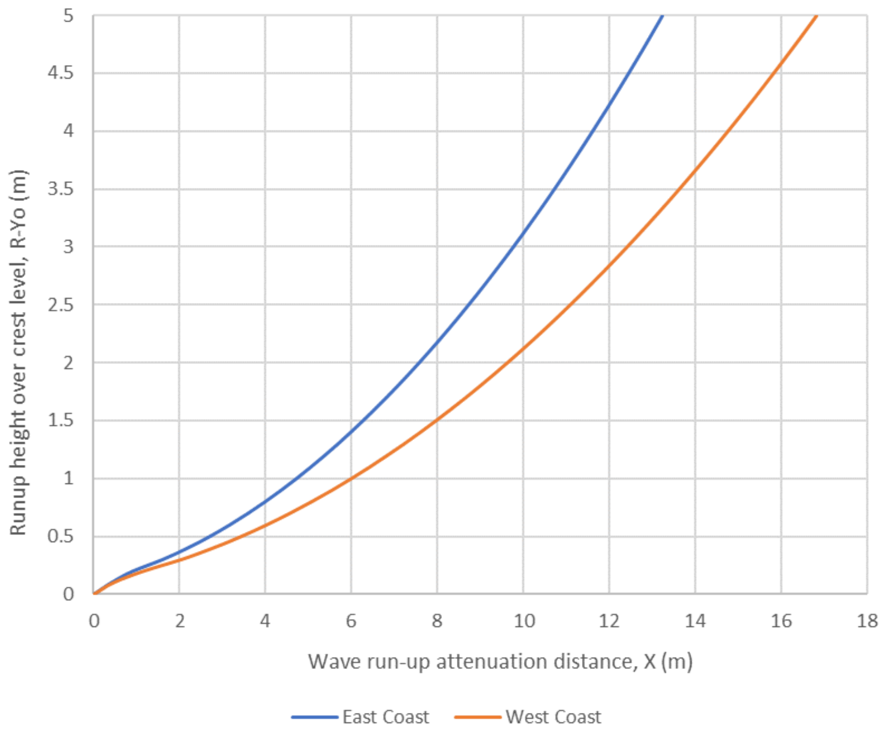

Figure 4.10: Run-up inland inundation extent to 10 cm water depth

4.3 Comparison with T+T (2017)

T+T (2017) undertook an assessment of coastal inundation levels for 63 sites across the Northland region on a local-scale, with 34 sites along the open coast. The 100-year static inundation levels for the 34 open coast sites have been compared with the levels derived in this regional-scale assessment. Figure 4.11 shows the present-day 100-year ARI static inundation levels for the 34 sites open coast sites derived by T+T (2017) and the static inundation levels for all open coast sites derived in this study.

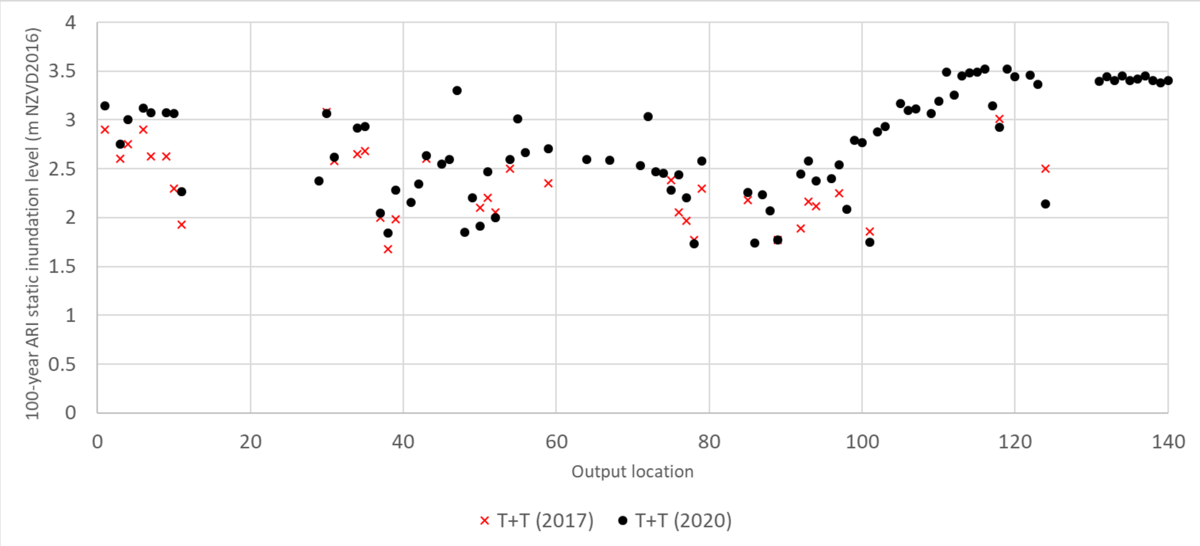

Figure 4.11: 100-year ARI static inundation levels derived by T+T (2017) and T+T (2020) for open coast sites

This shows that in general the static inundation levels derived for this regional-scale assessment are slightly higher (i.e. in the order of 0.1 m), with differences up to 0.5 m. These differences are primarily due to differences in scale of assessment and/or the more recent wave and water level data used for this study.

For this regional-scale study, the output locations have been selected such that it represents a larger section of the shoreline, with surfzone slope, beachface slope and wave conditions applicable for the entire section. T+T (2017) undertook a local-scale assessment with refined parameters adopted that are applicable for smaller-scale sections. Therefore, the surfzone slope and wave conditions may slightly vary due to the difference in scale and result in slightly different static inundation levels.

T+T (2017) used water level and wave timeseries up to 2014 for their assessment, whereas for this assessment these timeseries have been extended to the start of 2020. The extended timeseries may increase or decrease the extreme values as a result of storms that occurred between 2014 and 2020. However, the most significant storm that occurred after 2014 was ex-tropical cyclone Pam that caused minor damage to some beaches (refer to Section 2.4.3). It should also be noted that the wave conditions timeseries provided by MetOcean are slightly different, which also explains the difference in wave set-up heights.

4.4 Uncertainties and limitations

Uncertainty may be introduced by:

- Flow transmitting or blocking structures
- Difference in inundation levels and extents of adjacent cells
- Large flooded areas
- Future changes in land elevations and geomorphology
- No overtopping flows included in this study
- Scale of assessment.

Of these uncertainties, the first component is a limitation introduced by the LiDAR dataset. Structures (e.g. bridges or culverts) within the LiDAR datasets are not picked up as only surface points can be surveyed. The 2019 DEM would need to be manually edited to include structures which may introduce uncertainty and could limit the inundation extents in case a structure has not been properly included. However, by providing unconnected inundation extents, these could be added to the connected inundation extents on a site-specific basis.

Where inundation levels for the same CFHZ differ between adjacent cells, the corresponding inundation extents must be defined for each cell and merged. This may introduce some uncertainty where the inundation extents overlap each other, and a decision needs to be made as to where the overlapping areas are cropped. In general, we have utilised the larger value and inundated extent.

For large inundated extents, the connected bathtub approach may result in conservative extents due to friction and limited peak flood duration. Flow through small openings such as stream mouths may similarly result in conservative inundation extents compared to reality. An example of this is the stream near Aurere (i.e. Awapoko River), which show relatively large inundation extents in the vicinity of the stream that has a relatively small opening to the coast.

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 inundation extents. However, provided that the static inundation levels remain the same, using the bathtub model would result in the same flood extents. This approach is consistent with current best practice, although we are aware research projects have been recently initiated to investigate the possibility and implication of methods that consider both. This research is still three to five years from completion, with the outcome currently unknown. Attempting to map inundation extents using future shoreline position could potentially combine the uncertainties in predicted future shoreline position and future extreme water levels, and this would result in even greater uncertainty in future inundation extents or larger range of possible scenarios. It is not recommended to consider this for a regional scale assessment but to assess this on a site-specific basis using models that confidently model the combined future coastal morphology and inundation.

No overtopping flows have been included in this study. 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. An example of a site-specific overtopping assessment is included in T+T (2017) undertaken for the Paihia township, which considers maximum overflow volumes and backshore topography. Figure 4.12 shows the revised coastal inundation extents for Paihia that were mapped by assessing the maximum level of ponding that could occur before a flow path back out to the sea is formed.

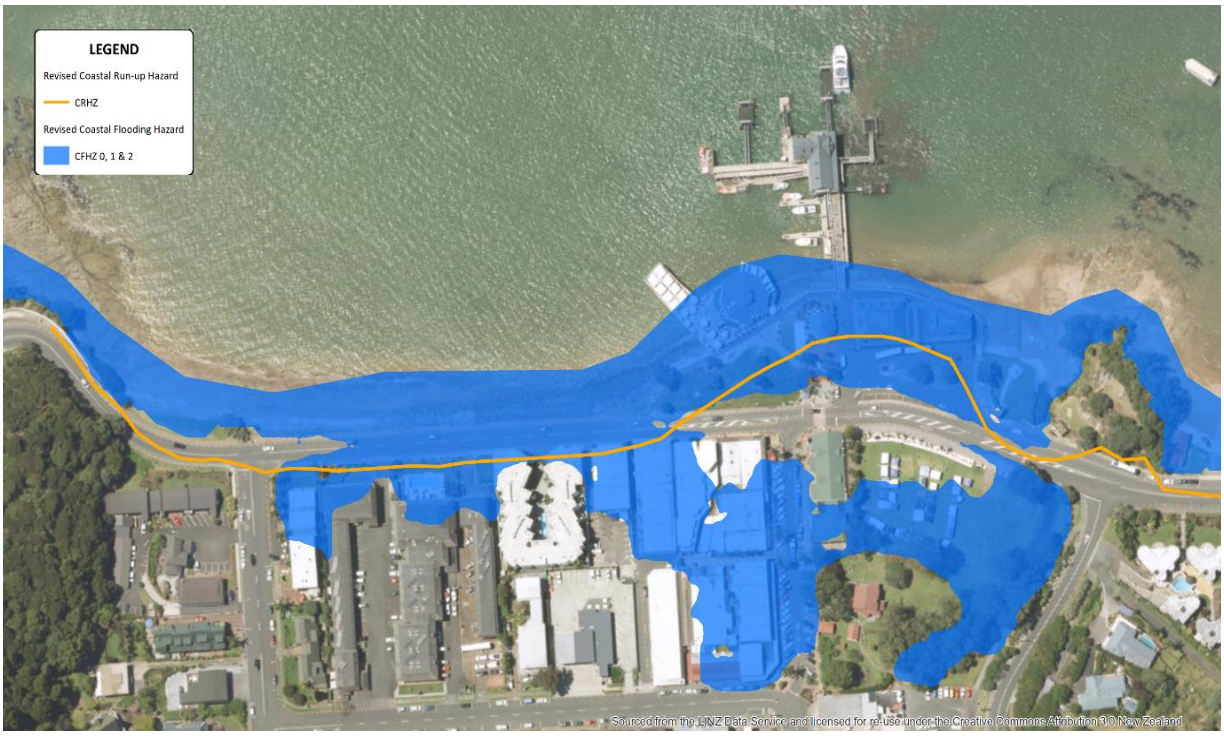

Figure 4.12: Site-specific coastal inundation extents at Paihia (source: T+T, 2017)

This assessment has been undertaken on a regional-scale and can be superseded by a more detailed-scale assessments. This may include:

- assessment using more refined extents with more accurate values assigned to each section,
- use of more advanced methods to assess wave effects such as local-scale numerical models
- use of hydrodynamic models and/or consideration of local structures such as culverts and seawalls.

Note that this assessment considers inundation related to coastal storm processes and excludes other sources of inundation (e.g. extreme rainfall, river flows, tsunami).

5 Summary and recommendations

This study has been undertaken for Northland Regional Council (NRC) to assess areas potentially susceptible to coastal inundation for the Northland region (excluding the Kaipara Harbour and Awanui catchment). Extreme coastal water levels have been assessed for 140 output locations around the region, including both exposed (i.e. open coast) and sheltered (i.e. harbour and estuary) sites.

Both ***static inundation levels*** comprising astronomical tide, storm surge, medium-term fluctuations and wave set-up and ***dynamic inundation levels*** which also include wave run-up have been assessed for each output location. Extreme levels for the open coast have been assessed using a structural extreme value method where the static or dynamic levels are calculated for every timestep using historical data and hindcast models, and analysis is undertaken on the resultant levels. This ensures all potential drivers are accounted for, while decreasing conservatism associated with traditional building block approaches and uncertainty associated with joint probability analysis.

Extreme levels for the harbour and estuary shoreline have been assessed using a combined probabilistic and building block approach where storm tide is assessed probabilistically and wave contributions due to wave set-up added separately. This was method was used due to the limited bathymetric data within the harbours and estuaries. Dynamic inundation levels have not been assessed for output locations within harbours and estuaries as run-up will be highly dependent on the local foreshore morphology and, due to the relatively small wave heights, will generally be confined to within 5-10 m of the coastal edge.

This assessment has assessed a range of return periods (i.e. 5 to 500-year ARI) for both extreme static and dynamic levels for the present day, and have considered SLR between 0.1 m and 1.5 m at 0.1 m increments. The results show present-day static inundation levels are the highest along the open coast shorelines (i.e. up to 3.5 m NZVD2016 for 100-year ARI), with the lowest levels found within estuary inlets and Whangaroa Harbour (i.e. 1.6 m NZVD2016 for 100-year ARI). This is expected as open coast shorelines are typically subject to larger breaking waves which induce large wave set-up compared to sheltered shorelines that may be subject to relatively small breaking waves.

The present-day 100-year ARI dynamic water level is largest along the open East Coast (i.e. up to 8.8 m NZVD2016), but lower in more protected East Coast locations (i.e. 3.2 m NZVD2016). This indicates that the exposure of the beaches along the open East Coast is highly variable The ranges for sites along the open West Coast range from 4.6-7.8 m NZVD2016) indicating that exposure is more consistent. The dynamic water levels for sheltered sites have not been assessed (refer to Section 3.6.2). The future coastal inundation levels show the same trend as the present-day coastal inundation levels but with level elevated based on sea level rise contribution.

Areas potentially susceptible to coastal inundation have been mapped for the entire Northland Region at 0.1 m increments between 0.5 and 5.5 m NZVD2016. The extent and depth of inundation have been assessed using 1 m DEM derived from 2019 LiDAR data and a connected bathtub model where areas are flooded only where they connect to the coastal water body. Inundation extents and depths disconnected from the shoreline have been mapped separately to show areas potentially susceptible if connected by structures to due to raised groundwater.

Wave run-up differs from static flooding as run-up is a dynamic process and should be mapped by applying an attenuation model to the maximum run-up elevation to determine the maximum inland excursion reached by the run-up flows. However, as this is highly dependent on site-specific conditions (e.g. waves, beach slope and landward slope), the dynamic inundation extents have not been mapped for this assessment. Guidance to assess attenuation distances using site-specific information is provided.

Several sources of potential uncertainty in mapping have been noted including the LiDAR DEM accuracy, the difference in inundation levels and extents between adjacent cells and exclusion of overtopping flows.

NRC have requested that levels are assessed, and inundation extents mapped for specific combinations of static inundation and sea level rise with the resultant extents termed ***Coastal Flood Hazard Zones (CFHZ).*** These combinations are as follows with values rounded to the nearest 0.1 m.

- Coastal Flood Hazard Zone 0 (CFHZ0): Extent of 100-year ARI static water level at 2020
- Coastal Flood Hazard Zone 1 (CFHZ1): Extent of 50-year ARI static water level at 2080 including 0.6 m SLR
- Coastal Flood Hazard Zone 2 (CFHZ2): Extent of 100-year ARI static water level at 2130 including 1.2 m SLR
- Coastal Flood Hazard Zone 3 (CFHZ3): Extent of 100-year ARI static water level at 2130 including 1.5 m SLR

In addition, the MHWS-10 for the present day and future timeframes including 0.6 m and 1.2 m SLR have been assessed to the nearest 0.1 m and mapped.

Recommendations for future refinement of coastal inundation levels and extents are listed below.

- **Continue water level monitoring at existing tide gauges and install new tide gauge**

  The water level records from the existing tide gauges is a useful dataset that has been used to derive extreme water levels and we strongly recommend monitoring to be continued and preferably enhanced with additional gauges. By continuing to record water levels at these gauges, the timeseries length will extend and would provide a better understanding of the historical water levels. The installation of additional tide gauges around the region would provide more certainty as the variation in tidal and extreme levels in different parts of the region. These could be long-term gauges used for future analysis or shorter-term deployments used to confirm differences in levels. For instance, installing a tide gauge at Ahipara would provide more information on levels at the northern extent of the West Coast rather than relying on data from the Pouto Point gauge.
- **Undertake more detailed-scale assessment**

  More detailed, local-scale assessments could be undertaken to refine static and dynamic inundation levels and extents where results from this study show risks to be unacceptable. For a local-scale or site-specific scale the shoreline could be subdivided into smaller sections using specific data for each section. For instance, a site-specific cross-section could be used to assess wave effects by using a 1D or 2D model (e.g. XBeach). If empirical formulas are used, site-specific parameters such as beachface slope or landward slope can be used to assess wave run-up level and landward attenuation distance. As wave run-up is highly site specific, different empirical run-up formulas (e.g. refer to formulas included in Section 3.6.1.1) could be tested if calibration data is available to refine the wave run-up level and landward extent.
- **Coupled wave-hydrodynamic modelling for large flood extents**

For low-lying areas that are subject to static inundation the inundation extents may be large as a result of using the bathtub approach. However, coastal inundation is typically limited to the peak flood durations. For these areas it is recommended to use a hydrodynamic model which takes into account the duration of the high tides. An example of this is the stream near Aurere (i.e. Awapoko River), which show relatively large inundation extents in the vicinity of the stream that has a relatively small opening to the coast. Furthermore, it is recommended to couple the hydrodynamic model with a wave model as wave conditions may vary alongshore or within large estuaries and would result in varying wave set-up heights.

- **Assess combined effected of future morphological changes and coastal inundation**

  The areas potentially susceptible to coastal inundation for future timeframes have been mapped using the 2019 LiDAR DEM. However, this ignores the potential land changes due to morphological evolution and other coastal processes. In particular in estuarine environments the evolution of the bed levels in the vicinity of the estuary mouth could have an effect on the upstream propagation of wave set-up generated by breaking waves on the open coast. Local or site-specific studies could be undertaken to numerically model the morphological changes as a result of the rising sea level. Although numerical model results may not be calibrated or validated, they would provide insights on what could potentially occur.

6 Applicability

This report has been prepared for the exclusive use of our client 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, or by any person other than our client, without our prior written agreement.

Tonkin & Taylor Ltd

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7 References

Batstone, C., Lawless, M., Tawn, J., Horsburgh, K., Blackman, D., McMillan, A., Worth, D., Laeger, S., Hunt, T. (2013) A UK best-practice approach for extreme sea-level analysis along complex topographic coastlines. Ocean Engineering, 71: 28-39. http://dx.doi.org/10.1016/j.oceaneng.2013.02.003

Battjes, J.A., 1974. Copmputation of set-up, longshore currents, run-up and overtopping due to wind-generated waves. Delft University of Technology.

Barnett & MacMurray Ltd. (2016). Coastal Flood Hazard Zone Modelling for Kaihu Valley, Dargaville, and Awakino floodplain. Report prepared for Northland Regional Council.

Beaven R.J. and Litchfield, N.J. (2012). Vertical land movement around the New Zealand coastline: implications for sea-level ri9se, GNS Science Report 2012/29. 41p.

Bell, R.G., Goring, D.G. and de Lange, W.P. (2000). Sea-level change and storm surges in the context of climate change. IPENZ Transactions, v. 27, no. 1/Gen, p. 1-10.

Bell, R.G. and Gorman, R.M. (2003). Overview of Weather and Coastal Hazards in the Northland Region – Part II: Coastal Hazards. Report prepared for Northland Regional Council, HAM2003-114.

Cox, J.C. and Machemehl, J. (1986). Overload bore propagation due to an overtopping wave. Journal of Waterway, Port, Coastal and Ocean Engineering, Vol. 112, No. 1.

da Silva, P.G, Medina, R., González, M., Garnier, R., 2019. Wave reflection and saturation on natural beaches: The role of the morphodynamic beach state in incident swash. Coast. Eng. 153, 103540. https://doi.org/10.1016/j.coastaleng.2019.103540

da Silva, P. G., Coco, G., Garnier, R., Klein, A. H. F., On the prediction of run-up, setup and swash on beaches, Earth-Science Reviews (2019) (Journal Pre-Proof), https://doi.org/10.1016/j.earscirev.2020.103148

DHI (2020) Coastal inundation Modelling for Northern Kaipara Harbour. Technical report prepared for Northland Regional Council.

Didier, D., Caulet, C., Bandet, M., Bernatchez, P., Dumont, D., Augereau, E., Floc'h, F., Delacourt, C., 2020. Wave run-up parameterization for sandy, gravel and platform beaches in a fetch-limited, large estuarine system. Cont. Shelf Res. 192, 104024. https://doi.org/10.1016/j.csr.2019.104024

Dodet, G., Bertin, X., Bruneau, N., Fortunato, F.B., Nahon, A. and Roland, A. (2013). Wave-current interactions in a wave-dominated tidal inlet. Journal of Geophysical Research Oceans, Vol. 118, 1587-1605.

eCoast (2017) Coastal Flood Modelling of Ruawai, Kaihu-Dargaville and Awanui. Report prepared for Northland Regional Council.

FEMA (2005). Guidelines and Specifications for Flood Hazard Mapping Partners. Section D.4.5.

Gibb (1988). Northland Regional Council 1988 Coastal Hazard Identification. Whangarei County Technical Publication No 1988/1.

Gibb (1998). Review of Coastal Hazard Zones for Eleven Selected beaches in Whangarei District Northland Region. Technical Report Prepared for Northland Regional Council, CR98/4.

Gibb (1998). Coastal Hazard Zone Assessment for the One Tree Point Marsden Bay Area Whangarei Harbour. Technical Report Prepared for Whangarei District Council, CR98/8.

Gibb (1999). Coastal Hazard Risk Zone Assessment for Patau and Matapouri Bay, Whangarei District. Report prepared for Whangarei District Council. C.R. 99/7.

Goda, Y. (2003). Revisiting Wilson's formulas for simple wind-wave prediction. J. Waterway, Port, Coastal, and Ocean Engrg. 129(2), pp. 93-95.

Gringorten, I. I. (1963), A plotting rule for extreme probability paper, J. Geophys. Res., 68(3), 813–814, doi:10.1029/JZ068i003p00813.

Guza, R.T., Thornton, E.B., 1981. Wave set-up on a natural beach. J. Geophys. Res. 86, 4133–4137. https://doi.org/10.1029/JC086iC05p04133

Hannah, J. and Bell, R.G. (2012). Regional sea level trends in New Zealand. J. Geophys. Res. 117: C01004.

Hay, D.N. (1991). Storm and oceanographic databases for the Western Bay of Plenty. Unpublished MSc Thesis, Depth. Of Earth Sciences, University of Waikato.

Heath, R.A. (1979). Significance of storm surges on the New Zealand coast. New Zealand Journal of Geology and Geophysics, v. 22, p. 259-266.

Hedges, T & Mase, H. (2004). Modified Hunt's Equation Incorporating Wave Setup. Journal of Waterway Port Coastal and Ocean Engineering 130, 109-113.

IPCC (2013). Working Group I contribution to the IPCC 5th Assessment Report "Climate Change 2013: The Physical Science Basis". Report by Intergovernmental Panel on Climate Change. June, 2013.

LINZ (2020). Tidal Level Information for Surveyors. http://www.linz.govt.nz/geodetic/datums-projections-heights/vertical-datums/tidal-level-information-for-surveyors.

Mase, H (1989). Random Wave Run-up Height on Gentle Slopes, Journal of the Waterway, Port, Coastal and Ocean Engineering Division, American Society of Civil Engineers, pp 593-609.

Ministry for the Environment (2004). Climate Change Effects and Impacts Assessment: A Guidance Manual for Local Government in New Zealand. Wratt D, Mullan B, Salinger J, Allen S, Morgan T, Kenny G. with MfE. Ministry for the Environment, Wellington, 153 p.

Ministry for the Environment (2008). Coastal Hazards and Climate Change. A Guidance Manual for Local Government in New Zealand. 2nd edition. Revised by Ramsay, D, and Bell, R. (NIWA). Prepared for Ministry for the Environment. Viii+127 p.

Ministry for the Environment (2017) Coastal Hazards and Climate Change: Guidance for Local Government in New Zealand. 3rd edition. Prepared for the Ministry for the Environment.

Mulgor (2008). Extreme Sea Levels at Dargaville. Draft Report prepared for Barnett & MacMurray Ltd. Client Report 2008/5.

NIWA (2015). Extreme sea-level plots for Northland gauges. Prepared for Tonkin & Taylor Ltd.

NIWA (2020). Extreme sea-level plots for Northland gauges. Prepared for Tonkin & Taylor Ltd.

NRC (1991). Coastal Hazard Identification in Former Mangonui County Area. Technical Publication 1991/3.

NRC (2005). Coastal Inundation Hazard Assessment for Selected Far North Settlements.

NRC (2008). 21 January 2008 – What was it? Internal presentation.

Olabarrieta, M., Warner, J.C. and Kumar, N. (2011). Wave-current interaction in Willapa Bay. Journal of Geophysical Research Oceans, Vol. 116, C12014.

Shand, R., Shand, T.D., McComb, P. and Johnson, D. (2011). Evaluation of empirical predictors of extreme run-up using field data. 20th Australasian Coasts and Ports Conference Sept 2011.

Shand, T., D., Wasko, C., D., Westra, S., P., Smith, G., Carley, J., T., Peirson, W., L. (2012). Joint Probability Assessment of NSW Extreme Waves and Water Levels, Water Research Laboratory, School of Civil and Environmental Engineering UNSW, Manly Vale, WRL Technical Report, WRL TR2011/29

Shand, T. D., Goodwin, I. D., Mole, M. A., Carley, J. T., Coghlan, I. R., Harley, M. D. and Peirson, W. L. (2010), NSW Coastal Inundation Hazard Study: Coastal Storms and Extreme Waves, WRL Technical Report 2010/16.

Stephens, S. and Bell, R. (2012). Toolbox 2.2.2: Causes of sea level variability. Impacts of Climate Change on Urban Infrastructure & the Built Environment – A Toolbox.

Stephens et al. (2013). Coastal Storm-tide levels in the Auckland Region. Report prepared for Auckland Council.

Stockdon, H.F., Holman, R.A., Howd, P.A. and Sallenger, Jr., A.H. (2006). Empirical parameterization of set-up, swash, and run-up. Coastal Eng. 53(7), pp 573-588.

Tanaka, S., Nagabayashi, H. and Tinh, N.X. (2009). Wave setup at different river entrance morphologies. Conference Paper May 2009

Thornton, E.B. and Guza, R.T. (1983). Transformation of Wave Height Distribution. Journal of Geophysical Research 88.

Tonkin & Taylor (2014). Coastal Erosion Hazard Zone Assessment for Selected Northland Sites. Technical report prepared for NRC.

Tonkin & Taylor (2017). Coastal Erosion Hazard Zone Assessment for Selected Northland Sites, 2017 update. Technical report prepared for NRC.

USACE (2006). Coastal Engineering Manual. Engineer Manual 1110-2-1100, U.S. Army Corps of Engineers, Washington, D.C.

Wilson, B.W. (1965). Numerical prediction of ocean waves in the North Atlantic for December, 1959. Deutsche Hydrographische Zeit 18(3), pp. 114-130.

Appendix A: Northland sea-level analysis (NIWA, 2020)

Memo

From	**Chris Eager and Scott Stephens**
To	Patrick Knook
CC	
Date	05 June 2020
Subject	Northland sea-level analysis
File path *(right click to update)*	*O:\CAVA2004\Working\NorthlandSL_T&T\Final\Memo v5_CAE.docx*

NIWA quality-analysed sea-level data from 7gauges from the beginning of 2014 (Table 1). The quality-control (QC) was undertaken relative to National Environmental Monitoring Standards (NEMS) http://www.nems.org.nz/assets/Documents/NEMS-14/Water-Level-v3.0.pdf. Data was assigned one of three QC codes: 100 = missing data, 200= data that was shifted in time to align with data either side (daylight-saving adjustment), 300 = synthetic data (sections of length ≤ 3 hours were filled by linear interpolation, sections of lengths between 3 and 24-hours=were filled using linear interpolation of residuals plus predicted astronomical tide), 500 = good-quality original data. The excel file distinguishes between data replacement due to missing data (no raw data), or bad data that was removed and then replaced.

The QC records were combined with older 1-hourly spaced datasets before subsequent calculation of mean sea level (MSL, Table 2), tidal harmonic (Table 3) and extreme sea-level analysis (Table 4). The QC datasets were sampled at 1−5 minute intervals. Before combining with the older records, a 15-minute running average was applied to remove the effects of infragravity waves and the data was decimated to 1-hourly intervals.

MSL was calculated over three epochs (Table 2): recent 10 and 20-year epochs to the end of 2019, and the 1986–2005 epoch used as baseline for sea-level rise projections by the IPCC AR5 assessment and for NZ (MfE 2017). MSL was unable to be calculated for all these epochs due to the variable sea-level record lengths.

Tidal harmonic analyses were undertaken with 69 constituents including the solar annual and semi-annual tidal constituents, using UniTide (Foreman, Cherniawsky et al. 2009). This software does a good job of fitting tides even in highly frictional environments such as shallow river systems where the tides can be highly non-linear.

Extreme sea-level analyses used the skew-surge joint-probability method (SSJPM) (Batstone, Lawless et al. 2013) to determine extreme storm-tide frequency and magnitude. Joint-probability methods provide more robust low-frequency magnitude estimates for short-duration records than direct maxima methods because they overcome the main theoretical limitations of extreme value theory application to measured sea level maxima—splitting the sea level into its deterministic (predictable) tidal and stochastic (e.g., unpredictable, storm-driven) non-tidal components, and analysing the two components separately before recombining. Storm-tide return periods can be estimated from relatively short records because all skew surges are considered, not just those that lead to extreme levels. A limitation of the SSJPM and other joint-probability methods is that it assumes tide and skew surge are independent, which has been shown to be true in the UK (Williams, Horsburgh et al. 2016) but has not been fully investigated in NZ, although

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comparisons with direct maxima methods for > 50-year-long records give similar results for return periods ≥10 years and also match observed maxima well, and thus support the validity of the independence assumption for long-return-period events (Stephens, Bell et al. 2020). To verify the results we have plotted the SSJPM results against the annual maxima (AM) plotted in their Gringorten (1963) plotting positions, a generalised extreme-value distribution fitted to the AM, and an empirical distribution of the observed peak sea-levels at high tide (Figure 1–Figure 7).

We were unable to complete the Marsden Point gauge analysis within the allocated budget so are awaiting T&T approval to proceed. We have QC'd the Town Basin record from 2014 onward but there is older data that could be QC'd and combined. At the other sites we already held older 1-hourly data to combine with the data from 2014 on.

Table 1: List of sea-level records analysed and the start and finish dates.

SL gauge	Start date of combined 1-hourly dataset	Start date of Quality Controlled data	End date of Quality Controlled data
Marsden Point	Feb 1963	1 January 2014	29 April 2020
Pouto Point	01 May 2002	1 January 2014	29April 2020
Town Basin	22 Oct 2008	1 January 2014	29 April 2020
Opua Veronica Channel	26 Apr 1990	1 January 2014	29 April 2020
Whangaroa Harbour	21 Aug 2008	1 January 2014	29 April 2020
Awanui Ben Gunn Wharf	30 Jul 2004	1 January 2014	30 April 2020
Northern Wairoa Dargaville	16 Jan 1981	1 January 2014	30 April 2020

Table 2: Mean sea level. Elevations are provided in metres relative to OTP-64 (with exception Awanui Ben Gunn, Unahi Datum).

MSL epoch (years)	Sea-level gauge						
	Marsden Point	Pouto Point	Town Basin	Opua	Whangaroa Hbr	Awanui Ben Gunn	Dargaville
2010–2019 (10-years)	-0.05	0.2	-0.25	-0.03	-0.07	0.19	0.25
2000–2019 (20-years)	-0.06	0.23	NA	-0.06	NA	NA	0.22
1986–2005 (IPCC AR5)	-0.12	NA	NA	NA	NA	NA	NA

Table 3: **Tidal elevations.** Elevations are provided in metres relative to MSL = 0. They require a datum offset to convert them to a known datum such as OTP-64 (e.g., Table 2). HAT = highest astronomical tide. MHWPS = mean high-water perigean springs. MHWS6 = elevation exceeded by highest 6% of all high tides. MHWS10 = elevation exceeded by highest 10% of all high tides. MHWSn = mean high-water springs nautical. LAT = lowest astronomical tide. M_2 = amplitude of M_2 tidal constituent. S_2 = amplitude of S_2 tidal constituent. N_2 = amplitude of N_2 tidal constituent.

High-tide elevation	Sea-level gauge						
	Marsden Point	Pouto Point	Town Basin	Opua	Whangaroa Hbr	Awanui Ben Gunn	Dargaville
HAT	1.41	1.83	1.59	1.33	1.32	1.39	2.33
MHWPS	1.21	1.63	1.34	1.13	1.12	1.13	1.82
MHWS6	1.20	1.58	1.34	1.12	1.11	1.17	1.92
MHWS10	1.15	1.51	1.28	1.07	1.06	1.13	1.84
MHWSn	1.07	1.42	1.19	0.98	0.97	0.98	1.60
LAT	-1.48	-1.85	-1.67	-1.36	-1.36	-1.30	-2.08
M_2	0.89	1.14	0.99	0.82	0.81	0.83	1.32
S_2	0.18	0.28	0.20	0.17	0.16	0.15	0.28
N_2	0.14	0.21	0.15	0.14	0.15	0.14	0.22

Table 4: **Extreme sea-level estimates.** Elevations are provided relative to MSL = 0. They require a datum offset to convert them to a known datum such as OTP-64. Values were calculated using the SSJPM method.

	Average recurrence interval (years)	5	10	20	50	100	200	500
Marsden Point	Lower 99.7% confidence interval	1.53	1.56	1.60	1.64	1.68	1.70	1.76
	Lower 95% confidence interval	1.53	1.57	1.61	1.66	1.70	1.73	1.81
	Lower 68% confidence interval	1.54	1.57	1.61	1.67	1.72	1.75	1.83
	Median	1.55	1.59	1.65	1.73	1.80	1.84	1.97
	Upper 68% confidence interval	1.56	1.60	1.66	1.76	1.83	1.88	2.01
	Upper 95% confidence interval	1.57	1.62	1.69	1.81	1.89	1.94	2.08
	Upper 99.7% confidence interval	1.59	1.66	1.75	1.88	1.97	2.02	2.15
Pouto Point	Lower 99.7% confidence interval	2.05	2.08	2.11	2.14	2.16	2.17	2.20
	Lower 95% confidence interval	2.05	2.09	2.12	2.16	2.18	2.20	2.24
	Lower 68% confidence interval	2.06	2.10	2.13	2.17	2.20	2.22	2.26
	Median	2.07	2.11	2.14	2.19	2.23	2.25	2.31
	Upper 68% confidence interval	2.08	2.12	2.17	2.23	2.27	2.30	2.38
	Upper 95% confidence interval	2.09	2.14	2.20	2.28	2.33	2.36	2.46
	Upper 99.7% confidence interval	2.16	2.25	2.36	2.50	2.62	2.68	2.88

	Average recurrence interval (years)	5	10	20	50	100	200	500
Town Basin	Lower 99.7% confidence interval	1.73	1.76	1.79	1.82	1.83	1.85	1.88
	Lower 95% confidence interval	1.74	1.77	1.80	1.84	1.86	1.88	1.91
	Lower 68% confidence interval	1.75	1.79	1.83	1.88	1.91	1.93	1.99
	Median	1.78	1.83	1.89	1.99	2.06	2.11	2.24
	Upper 68% confidence interval	1.87	1.98	2.08	2.20	2.29	2.32	2.42
	Upper 95% confidence interval	1.96	2.08	2.18	2.30	2.37	2.39	2.47
	Upper 99.7% confidence interval	2.13	2.23	2.32	2.40	2.44	2.46	2.51
Opua Veronica Channel	Lower 99.7% confidence interval	1.44	1.47	1.49	1.52	1.54	1.55	1.58
	Lower 95% confidence interval	1.45	1.47	1.50	1.53	1.55	1.57	1.61
	Lower 68% confidence interval	1.45	1.48	1.51	1.54	1.57	1.59	1.64
	Median	1.46	1.49	1.52	1.57	1.60	1.63	1.69
	Upper 68% confidence interval	1.47	1.50	1.54	1.60	1.65	1.68	1.76
	Upper 95% confidence interval	1.48	1.52	1.57	1.65	1.71	1.75	1.86
	Upper 99.7% confidence interval	1.52	1.59	1.67	1.81	1.92	1.99	2.20
Whangaroa Harbour	Lower 99.7% confidence interval	1.44	1.46	1.48	1.51	1.53	1.53	1.55
	Lower 95% confidence interval	1.45	1.47	1.50	1.53	1.54	1.55	1.58
	Lower 68% confidence interval	1.45	1.48	1.50	1.54	1.56	1.57	1.60
	Median	1.46	1.49	1.52	1.56	1.59	1.60	1.65
	Upper 68% confidence interval	1.47	1.51	1.55	1.60	1.63	1.65	1.71
	Upper 95% confidence interval	1.49	1.54	1.59	1.66	1.71	1.74	1.83
	Upper 99.7% confidence interval	1.56	1.64	1.74	1.87	1.97	2.03	2.21
Awanui Ben Gunn Wharf	Lower 99.7% confidence interval	1.54	1.57	1.59	1.63	1.65	1.67	1.71
	Lower 95% confidence interval	1.54	1.57	1.61	1.64	1.67	1.69	1.74
	Lower 68% confidence interval	1.55	1.59	1.62	1.67	1.70	1.72	1.78
	Median	1.56	1.61	1.65	1.71	1.75	1.78	1.86
	Upper 68% confidence interval	1.58	1.63	1.68	1.76	1.82	1.85	1.95
	Upper 95% confidence interval	1.60	1.67	1.74	1.83	1.91	1.95	2.08
	Upper 99.7% confidence interval	1.65	1.73	1.83	1.96	2.07	2.13	2.33
Northern Wairoa Dargaville	Lower 99.7% confidence interval	2.52	2.56	2.60	2.65	2.68	2.70	2.75
	Lower 95% confidence interval	2.53	2.57	2.61	2.67	2.70	2.73	2.79
	Lower 68% confidence interval	2.53	2.57	2.62	2.68	2.72	2.74	2.82
	Median	2.53	2.58	2.63	2.70	2.76	2.79	2.90
	Upper 68% confidence interval	2.54	2.59	2.65	2.72	2.79	2.84	2.97
	Upper 95% confidence interval	2.55	2.61	2.67	2.77	2.86	2.92	3.10
	Upper 99.7% confidence interval	2.57	2.64	2.74	2.92	3.09	3.20	3.54

Extreme sea-level plots

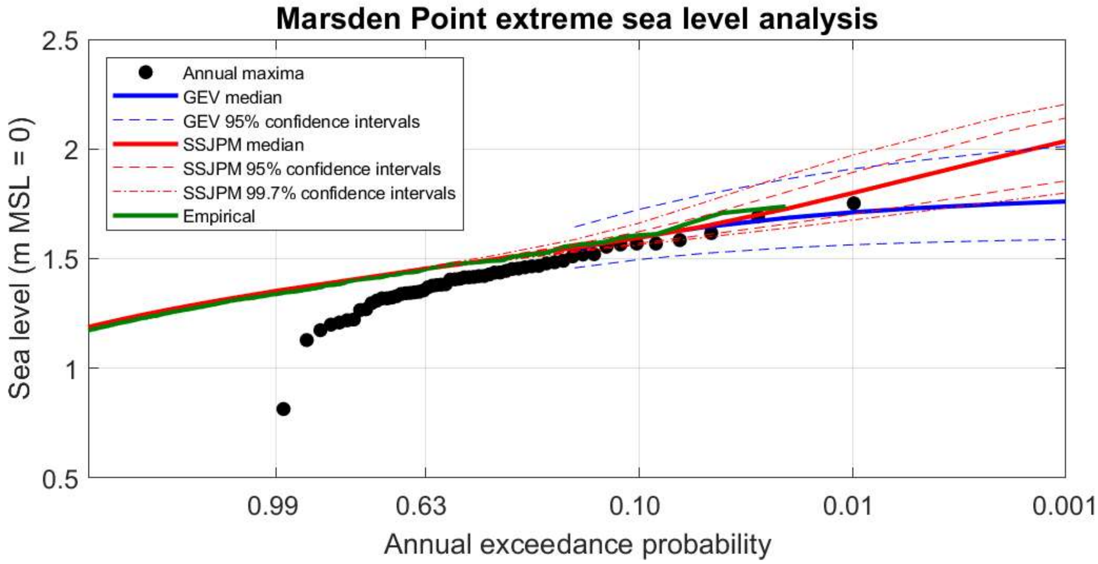

Figure 1: **Extreme sea level at Marsden Point.** Elevations are plotted in metres relative to MSL = 0. They require a datum offset to convert them to a known datum such as OTP-64 (e.g., Table 2). The skew-surge joint-probability method (SSJPM) has been compared to the annual maxima (AM) plotted in their Gringorten (1963) plotting positions, a generalised extreme-value distribution fitted to the AM, and an empirical distribution of the observed peak sea-levels at high tide.

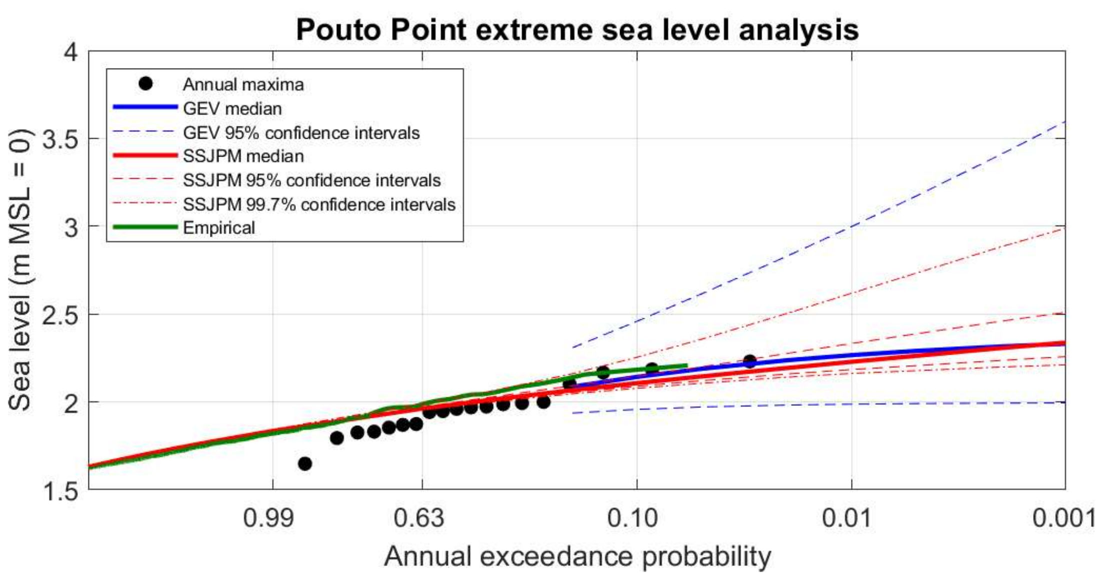

Figure 2: **Extreme sea level at Pouto Point.** Elevations are plotted in metres relative to MSL = 0. They require a datum offset to convert them to a known datum such as OTP-64 (e.g., Table 2). The skew-surge joint-probability method (SSJPM) has been compared to the annual maxima (AM) plotted in their Gringorten (1963) plotting positions,

a generalised extreme-value distribution fitted to the AM, and an empirical distribution of the observed peak sea-levels at high tide. (e.g., Table 2).

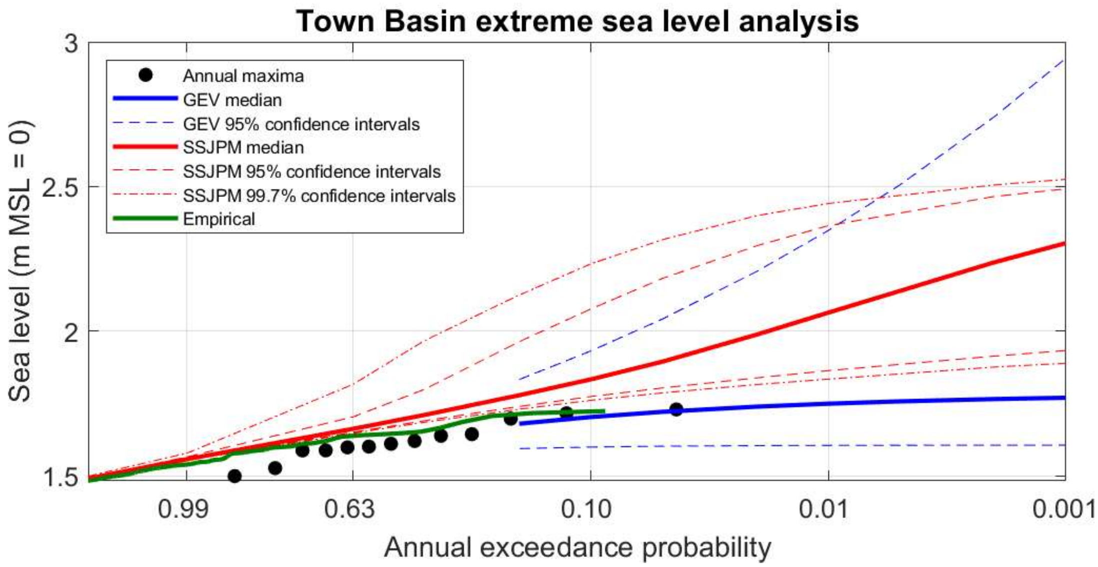

Figure 3: **Extreme sea level at Town Basin.** Elevations are plotted in metres relative to MSL = 0. They require a datum offset to convert them to a known datum such as OTP-64 (e.g., Table 2). The skew-surge joint-probability method (SSJPM) has been compared to the annual maxima (AM) plotted in their Gringorten (1963) plotting positions, a generalised extreme-value distribution fitted to the AM, and an empirical distribution of the observed peak sea-levels at high tide. (e.g., Table 2).

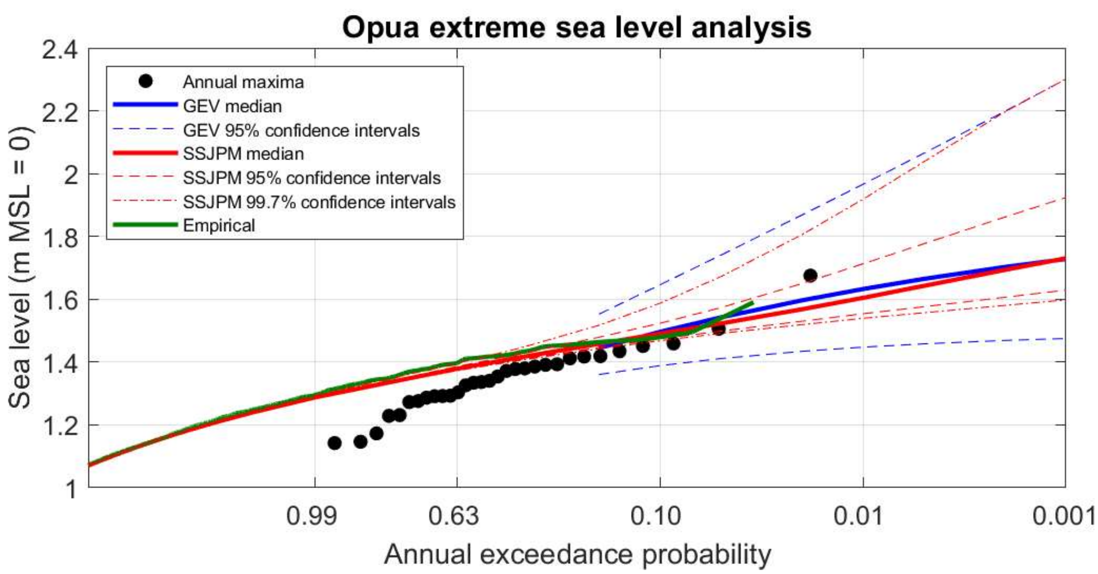

Figure 4: **Extreme sea level at Opua.** Elevations are plotted in metres relative to MSL = 0. They require a datum offset to convert them to a known datum such as OTP-64 (e.g., Table 2). The skew-surge joint-probability method (SSJPM) has been compared to the annual maxima (AM) plotted in their Gringorten (1963) plotting positions, a

generalised extreme-value distribution fitted to the AM, and an empirical distribution of the observed peak sea-levels at high tide. (e.g., Table 2).

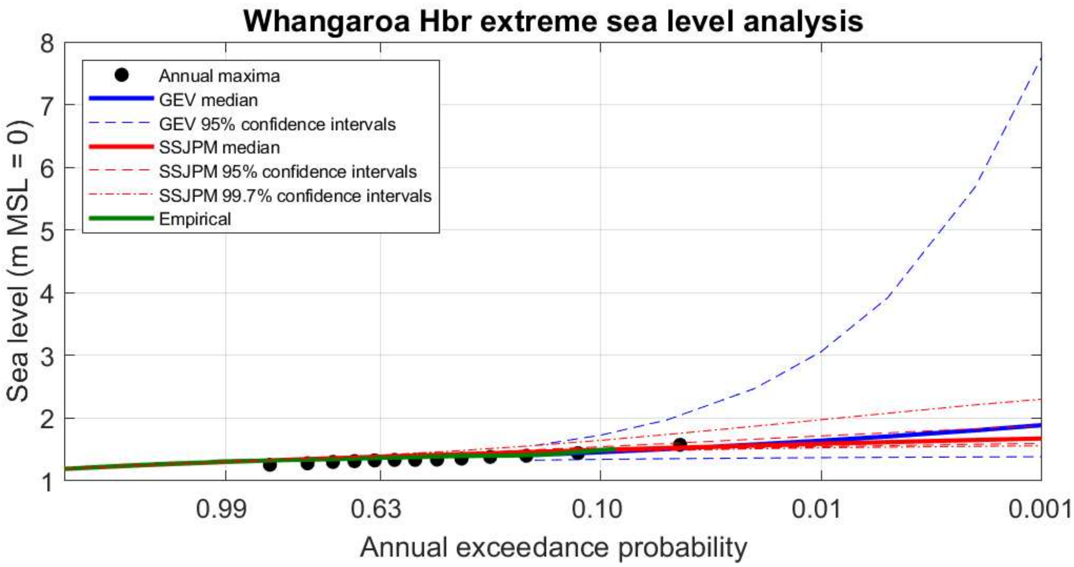

Figure 5: Extreme sea level at Whangaroa. Elevations are plotted in metres relative to MSL = 0. They require a datum offset to convert them to a known datum such as OTP-64 (e.g., Table 2). The skew-surge joint-probability method (SSJPM) has been compared to the annual maxima (AM) plotted in their Gringorten (1963) plotting positions, a generalised extreme-value distribution fitted to the AM, and an empirical distribution of the observed peak sea-levels at high tide. (e.g., Table 2).

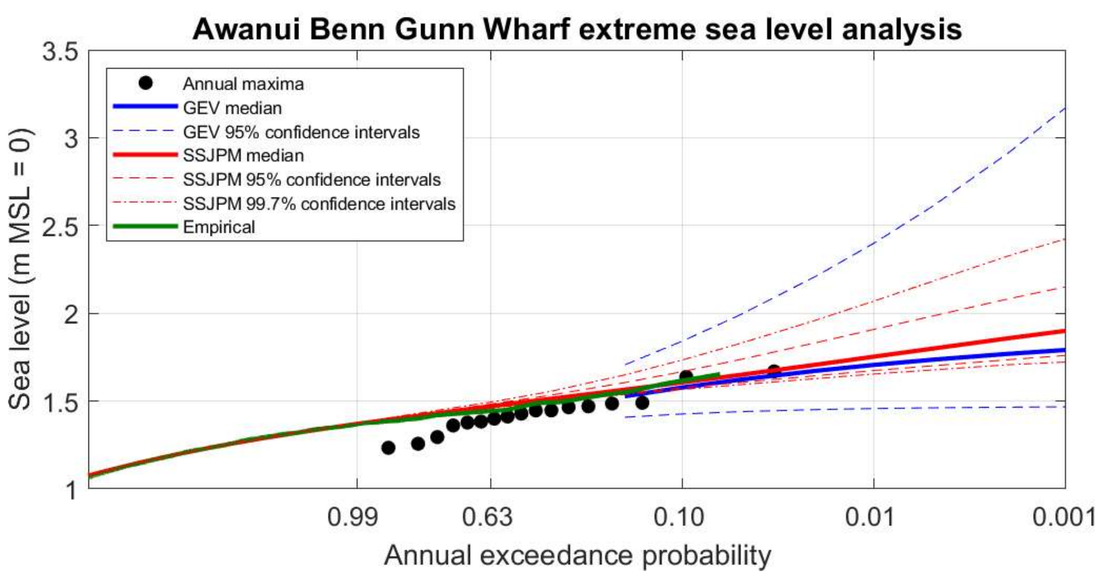

Figure 6: Extreme sea level at Awanui Ben Gunn Wharf. Elevations are plotted in metres relative to MSL = 0. They require a datum offset to convert them to a known datum such as OTP-64 (e.g., Table 2). The skew-surge joint-probability method (SSJPM) has been compared to the annual maxima (AM) plotted in their Gringorten (1963) plotting

positions, a generalised extreme-value distribution fitted to the AM, and an empirical distribution of the observed peak sea-levels at high tide. (e.g., Table 2).

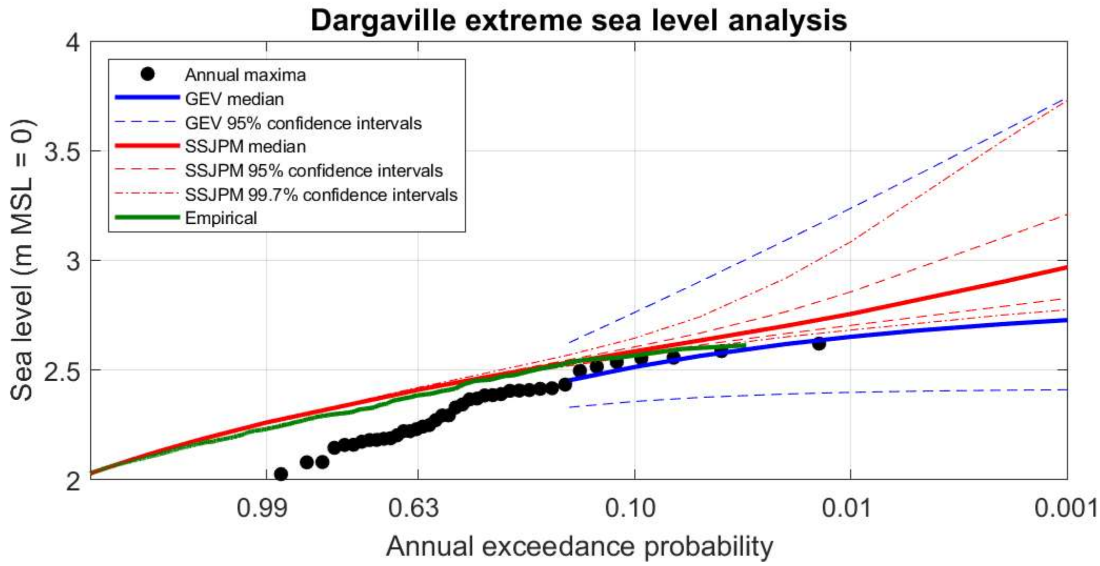

Figure 7: Extreme sea level at Dargaville. Elevations are plotted in metres relative to MSL = 0. They require a datum offset to convert them to a known datum such as OTP-64 (e.g., Table 2). The skew-surge joint-probability method (SSJPM) has been compared to the annual maxima (AM) plotted in their Gringorten (1963) plotting positions, a generalised extreme-value distribution fitted to the AM, and an empirical distribution of the observed peak sea-levels at high tide. (e.g., Table 2).

References

Batstone, C., Lawless, M., Tawn, J., Horsburgh, K., Blackman, D., McMillan, A., Worth, D., Laeger, S., Hunt, T. (2013) A UK best-practice approach for extreme sea-level analysis along complex topographic coastlines. *Ocean Engineering*, 71: 28-39. http://dx.doi.org/10.1016/j.oceaneng.2013.02.003

Foreman, M.G.G., Cherniawsky, J.Y., Ballantyne, V.A. (2009) Versatile Harmonic Tidal Analysis: Improvements and Applications. *Journal of Atmospheric and Oceanic Technology*, 26(4): 806-817. 10.1175/2008jtecho615.1

Gringorten, I.I. (1963) A plotting rule for extreme probability paper. *Journal of Geophysical Research*, 68(3): 813-814.

MfE (2017) *Coastal hazards and climate change: Guidance for local government. Ministry for the Environment Publication ME1341. Wellington, Ministry for the Environment. 279 p. + Appendices http://www.mfe.govt.nz/publications/climate-change/coastal-hazards-and-climate-change-guidance-local-government*. Ministry for the Environment, Wellington.

Stephens, S.A., Bell, R.G., Haigh, I.D. (2020) Spatial and temporal analysis of extreme storm-tide and skew-surge events around the coastline of New Zealand. *Nat. Hazards Earth Syst. Sci.*, 20(3): 783-796. 10.5194/nhess-20-783-2020
https://www.nat-hazards-earth-syst-sci.net/20/783/2020/

Williams, J., Horsburgh, K.J., Williams, J.A., Proctor, R.N.F. (2016) Tide and skew surge independence: New insights for flood risk. *Geophysical Research Letters*, 43(12): 6410-6417. 10.1002/2016gl069522.

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 Appendix B.1). A total of eight local model domains (see Appendix B Table 1) have been generated incorporating the majority of the output locations. For output locations that are outside of the SWAN model domains, model results from nearby output locations (i.e. inside model domains) with similar exposure and geometry have been used.

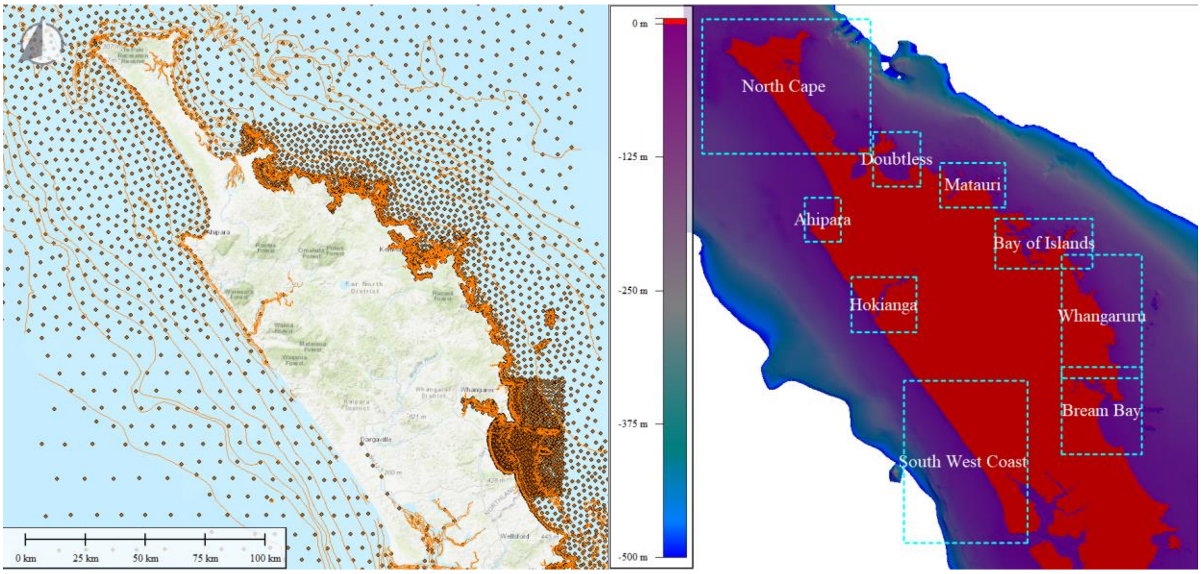

Figure Appendix B.1: Bathymetric contours and spot heights from LINZ database (A) and derived bathymetry map model (B) used to construct SWAN model domains (dashed boxes)

Appendix B Table 1: Model domains

Model domain	Coordinates (lower left corner) [X,Y] NZTM2000	Domain size [X,Y]	Grid resolution
South West Coast	(1646000,5967500)	55x70km²	50mx50m
Ahipara	(1602000,6101000)	20x20km²	50mx50m
North Cape	1556750,6140000)	75x60km²	100mx100m
Doubtless	(1632500,6125000)	20x25km²	50mx50m
Matauri	(1662000,6116000)	30x20km²	50mx50m
Bay of Islands	(1687000,6086500)	40x25km²	50mx50m
Whangaruru	(1716100,6040500)	35x55km²	50mx50m
Bream Bay	(1716000,6005500)	35x40km²	50mx50m

B3 Wave transformation modelling

Wave transformation modelling has been undertaken to transform the offshore wave characteristics into nearshore wave conditions where they are used to calculate wave effects (i.e. set-up and run-up). 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. 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).

Examples of SWAN model results for the 100-year ARI events showing the wave transformation are shown in Figure Appendix B.2 to Figure Appendix B.9. Figure Appendix B.2 to Figure Appendix B.3 show example results of the significant wave height during a 100-year ARI storm from the west (west coast) and Figure Appendix B.4 to Figure Appendix B.9 show example results for a storm from the northeast (east coast) for each model domain.

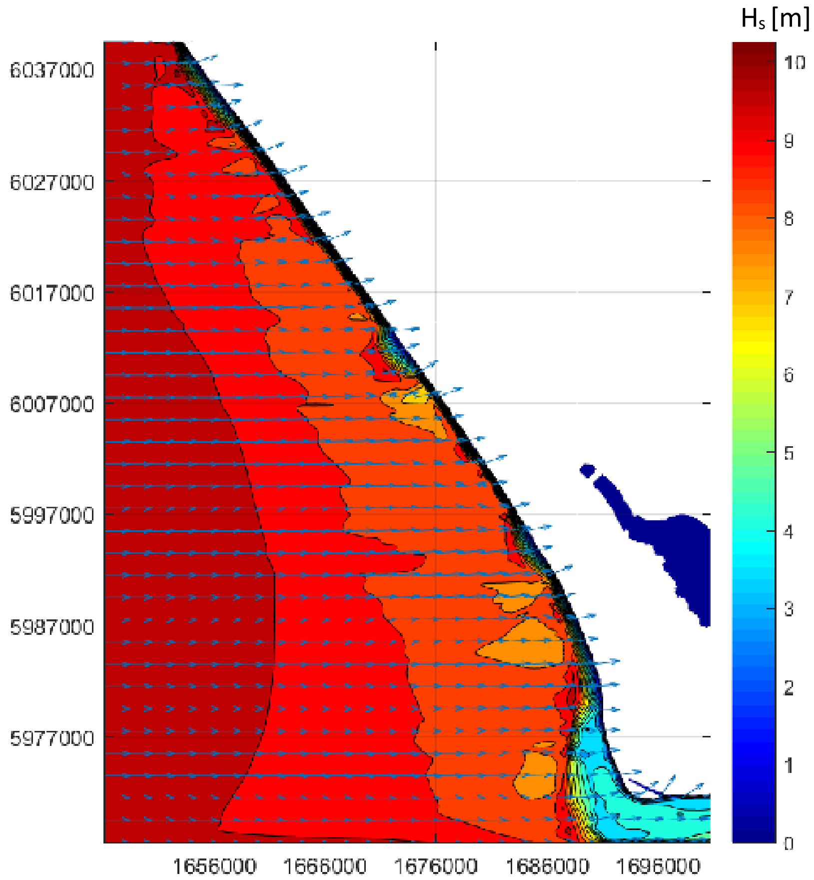

Figure Appendix B.2: SWAN model results for the South West Coast domain – Significant wave height and direction during a 100-year ARI storm from the west

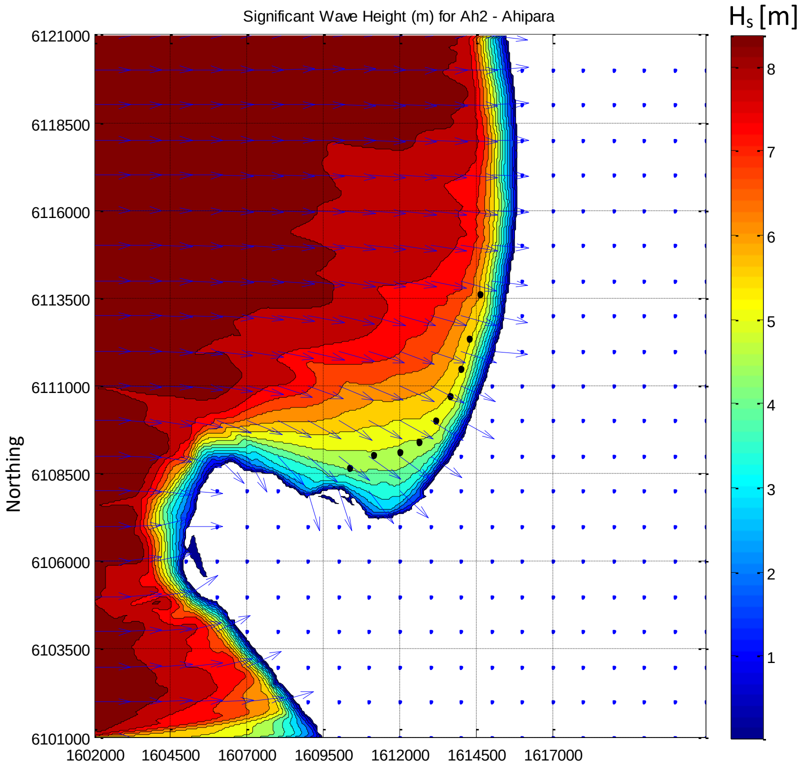

Figure Appendix B.3: SWAN model results for the Ahipara domain – Significant wave height and direction during a 100-year ARI storm from the west

Easting

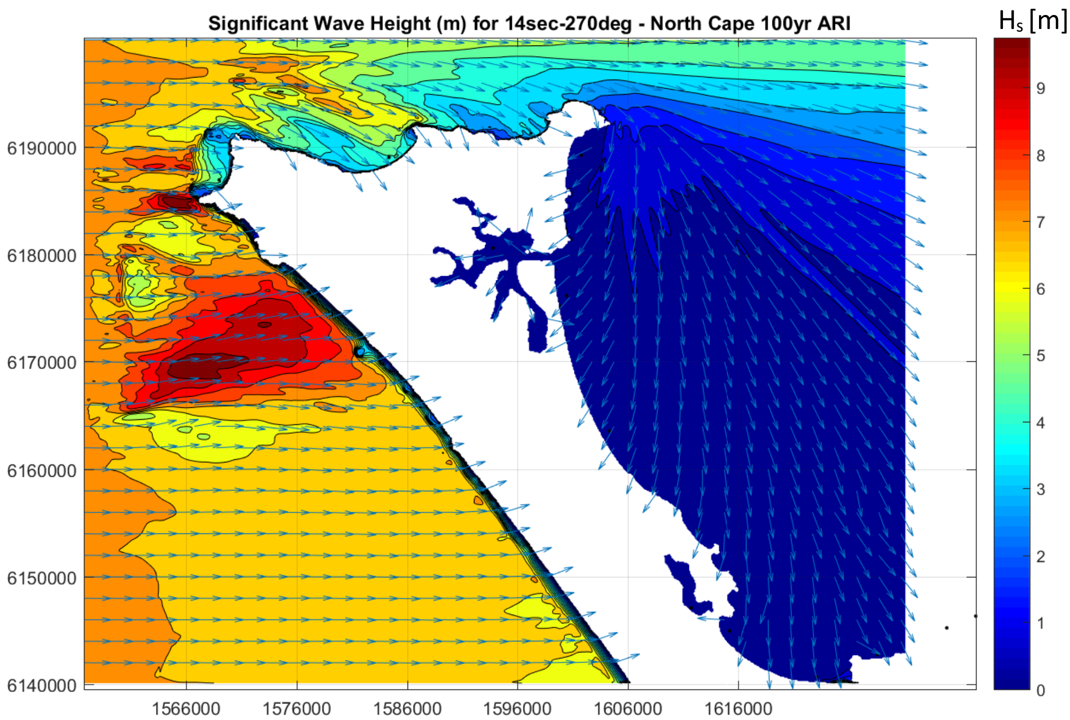

Figure Appendix B.4: SWAN model results for the North Cape domain – Significant wave height and direction during a 100-year ARI storm from the northeast

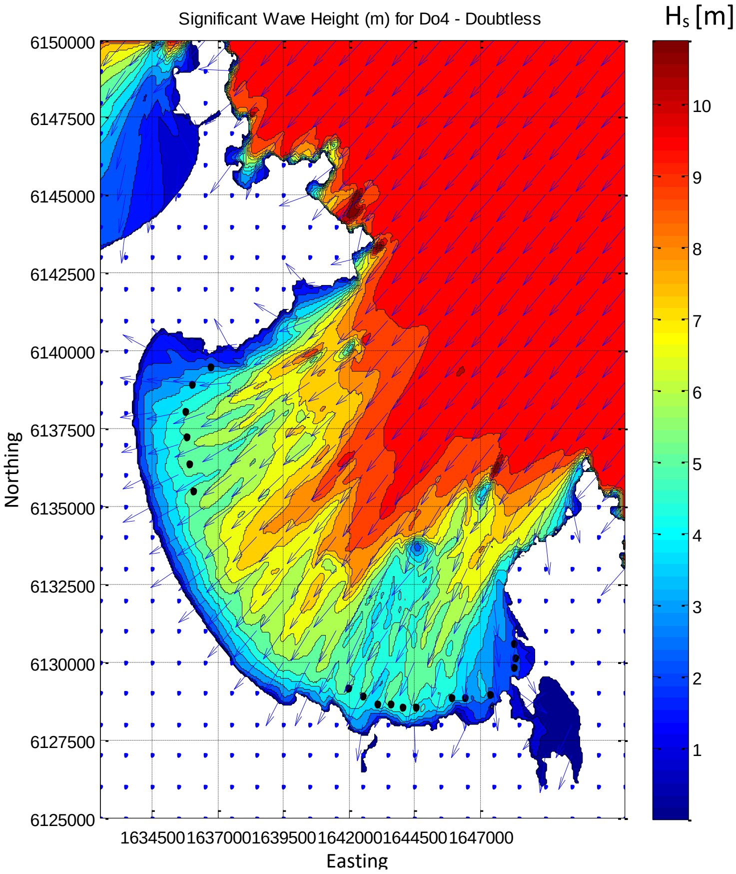

Figure Appendix B.5: SWAN model results for the Doubtless model domain – Significant wave height and direction during a 100-year ARI storm from the northeast

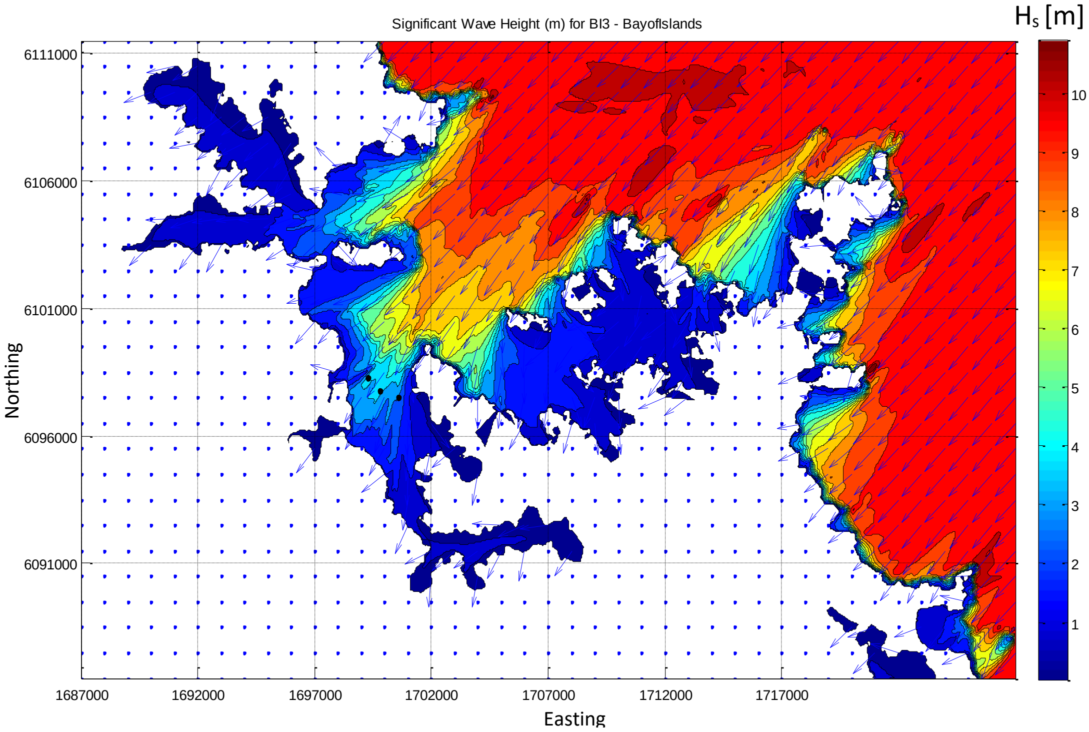

Figure Appendix B.6: SWAN model results for the Bay of Islands model domain – Significant wave height and direction during a 100-year ARI storm from the Northeast

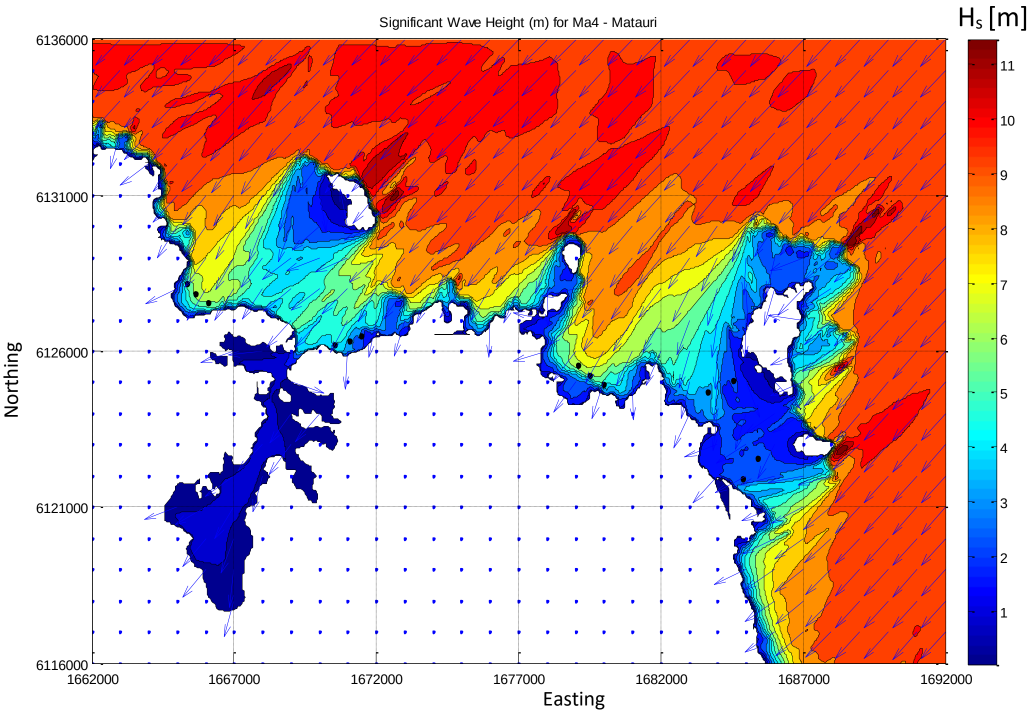

Figure Appendix B.7: SWAN model results for the Matauri model domain – Significant wave height and direction during a 100-year ARI storm from the Northeast

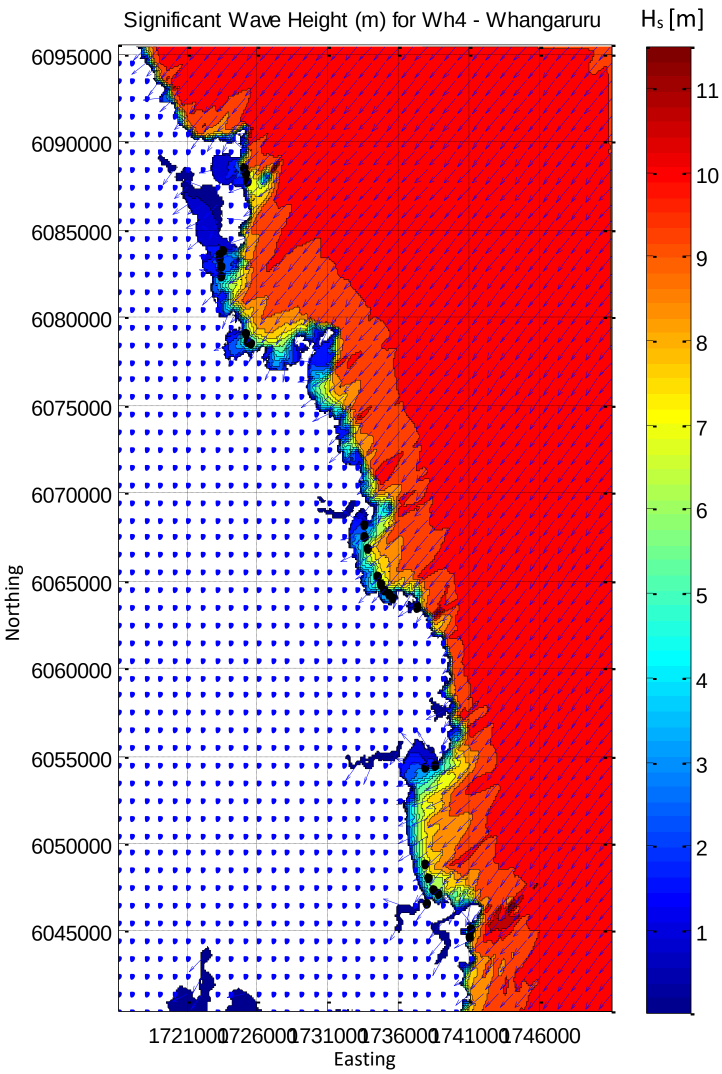

Figure Appendix B.8: SWAN model results for the Whangaruru model domain – Significant wave height and direction during a 100-year ARI storm from the northeast

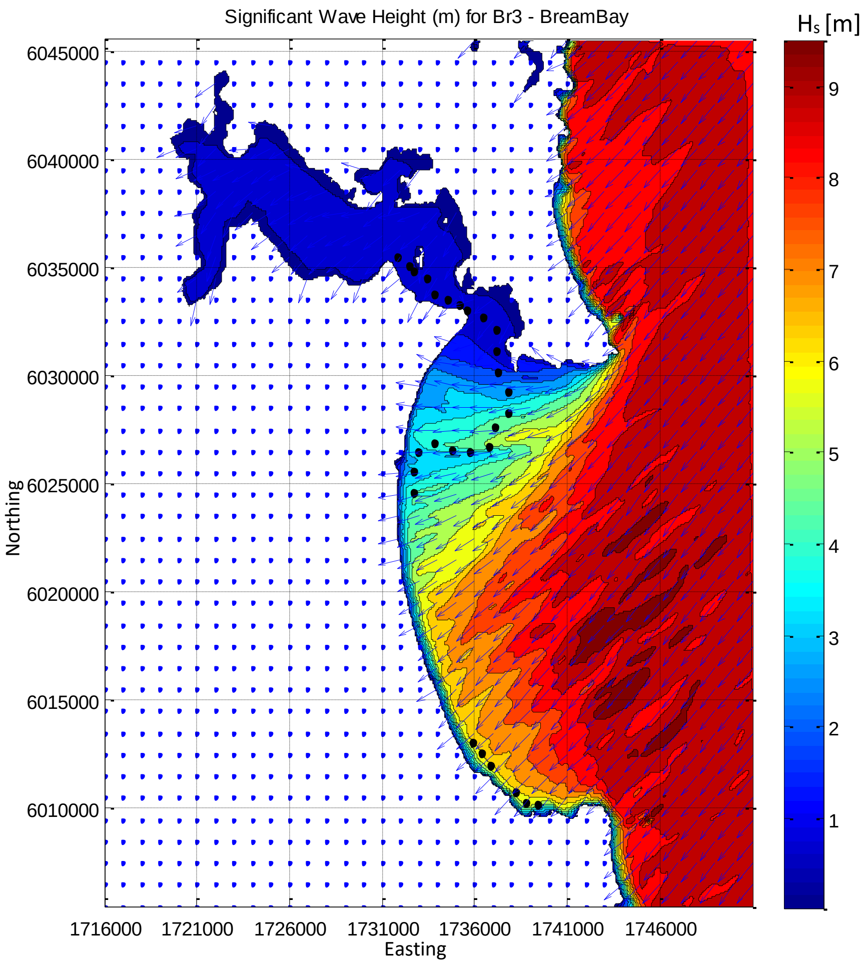

Figure Appendix B.9: SWAN model results for the Bream Bay model domain – Significant wave height and direction during a 100-year ARI storm from the northeast

Appendix C: Storm tide and extreme water levels

- **Figure Appendix C.1-6: Cell extents corresponding to output locations**
- **Appendix C Table 1: Extreme water levels**
- **Appendix C Table 2: CFHZs**
- **Digitally: Output tables for each output location including 5-500 year ARI static and dynamic water levels, and SLR increments 0.1-1.5 m**

Figure Appendix C.1: Cell extents corresponding to output locations (in green) around Whangarei Harbour. Refer to Appendix C Table 1 & Appendix C Table 2 below for site name and inundation values

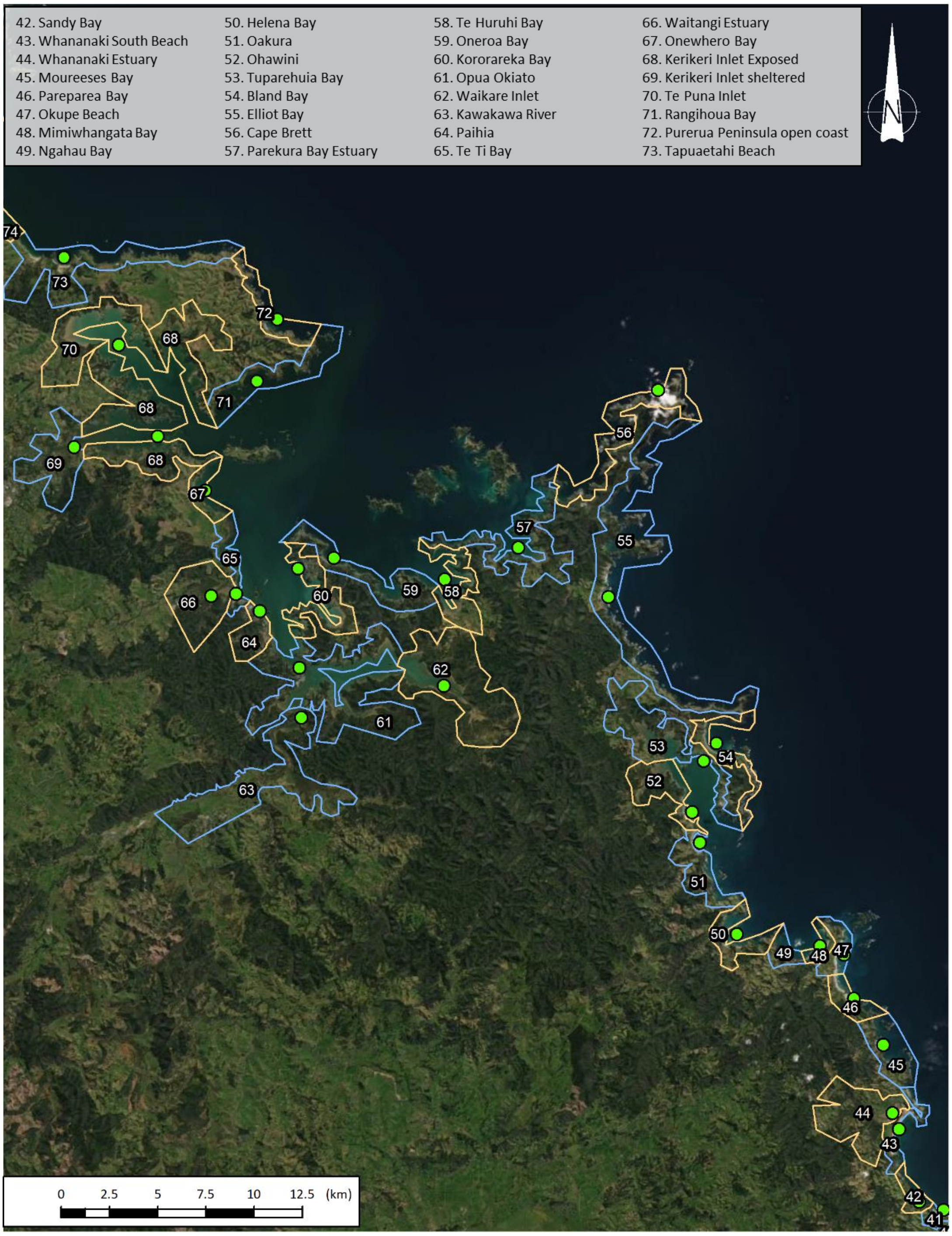

Figure Appendix C.2: Cell extents corresponding to output locations (in green) around Bay of Islands. Refer to Appendix C Table 1 & Appendix C Table 2 below for site name and inundation values

Figure Appendix C.3: Cell extents corresponding to output locations (in green) around Whangaroa. Refer to Appendix C Table 1 & Appendix C Table 2 below for site name and inundation values

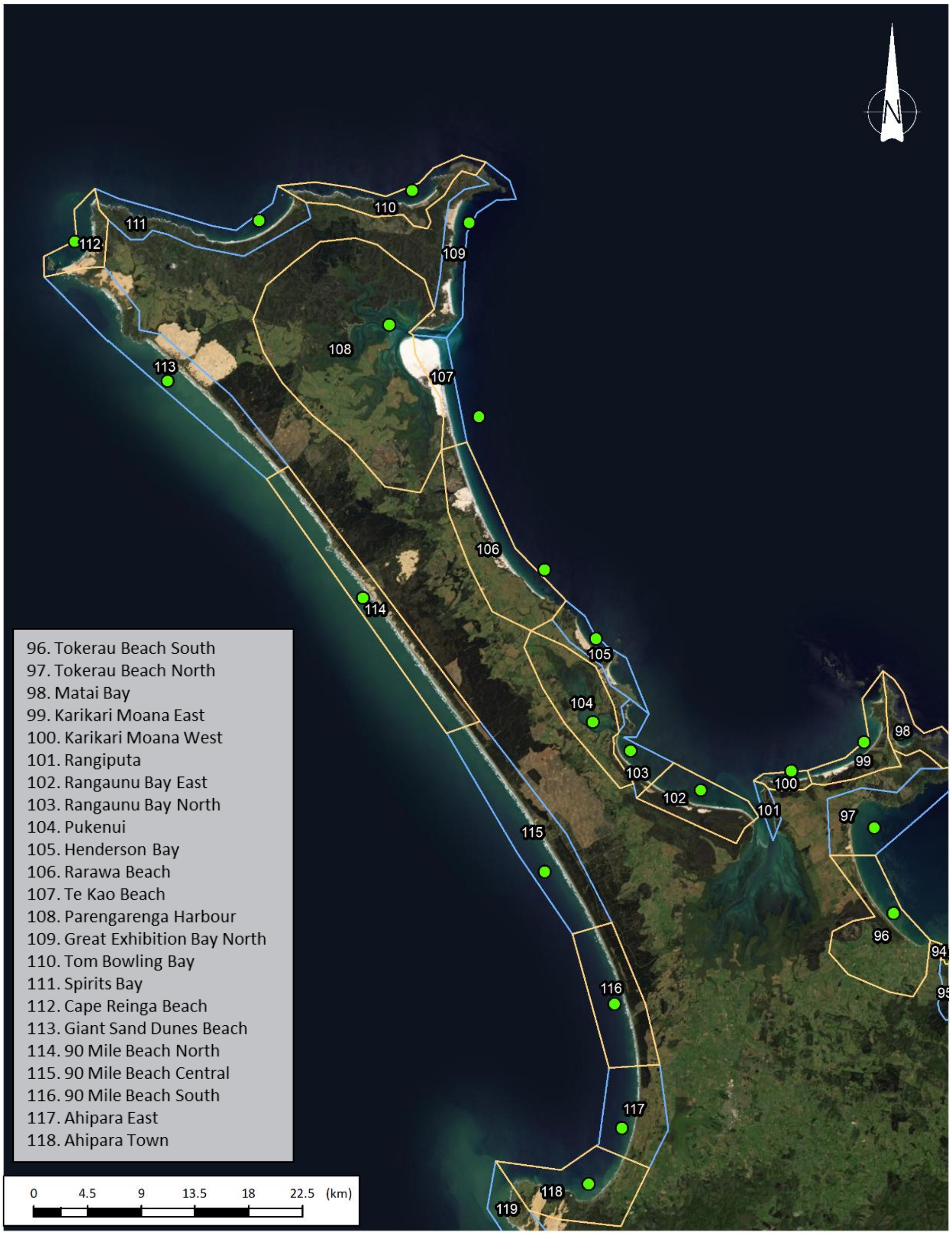

Figure Appendix C.4: Cell extents corresponding to output locations (in green) around North Cape. Refer to Appendix C Table 1 & Appendix C Table 2 below for site name and inundation values

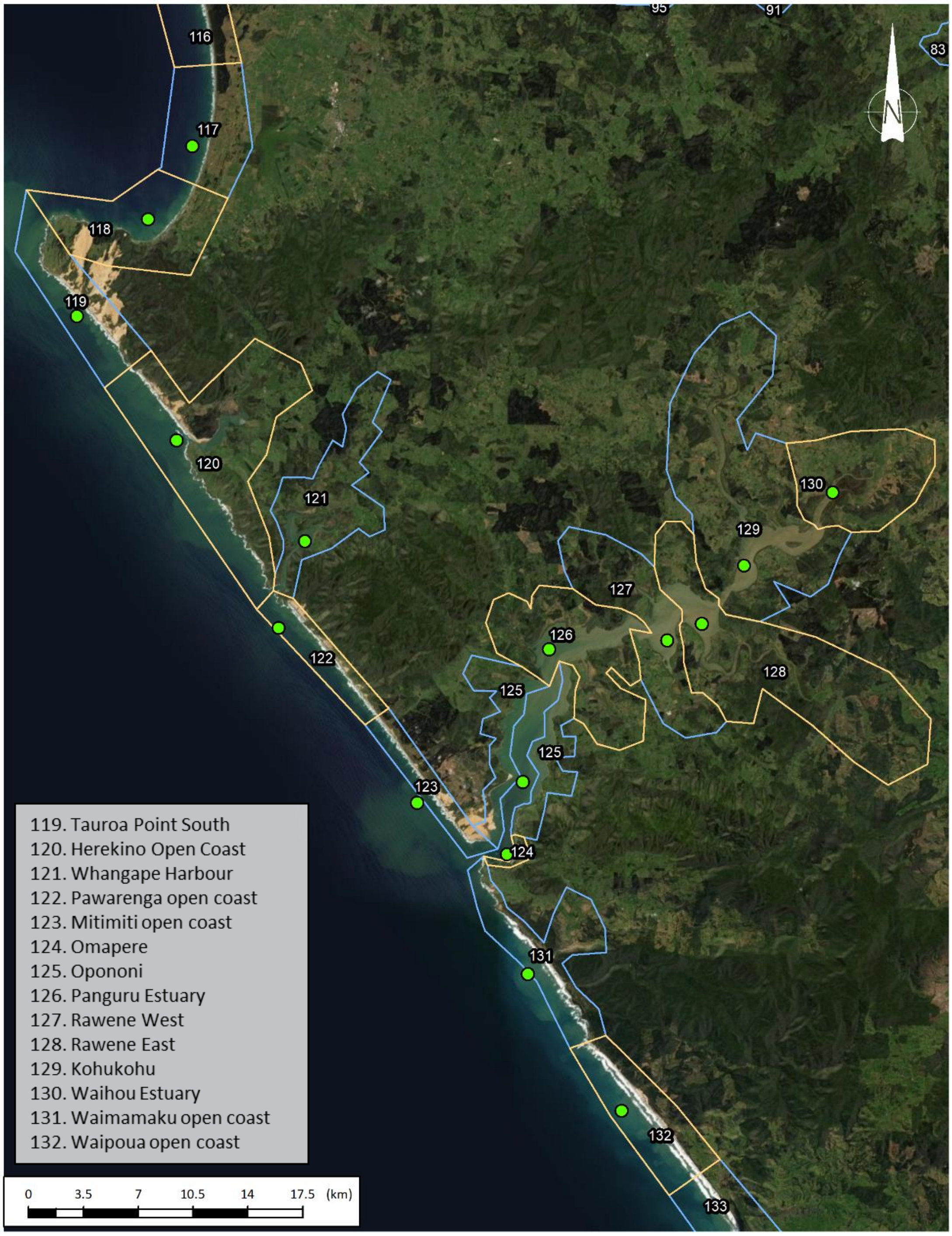

Figure Appendix C.5: Cell extents corresponding to output locations (in green) around Ahipara. Refer to Appendix C Table 1 & Appendix C Table 2 below for site name and inundation values

Figure Appendix C.6: Cell extents corresponding to output locations (in green) around Baylys Beach. Refer to Appendix C Table 1 & Appendix C Table 2 below for site name and inundation values

Appendix C Table 1: Extreme water levels (m NZVD2016)

Number	Name	MHWS-10 (m NZVD2016)	Storm tide (m NZVD2016)							Static inundation (m NZVD2016)							Dynamic inundation (m NZVD2016)						
			5 yr	10 yr	20 yr	50 yr	100 yr	200 yr	500 yr	5 yr	10 yr	20 yr	50 yr	100 yr	200 yr	500 yr	5 yr	10 yr	20 yr	50 yr	100 yr	200 yr	500 yr
1	Mangawhai open coast	1.0	1.4	1.4	1.5	1.6	1.6	1.7	1.8	2.5	2.7	2.8	3.0	3.1	3.3	3.4	4.7	4.9	5.2	5.5	5.7	5.9	6.1
2	Mangawhai Estuary	1.0	1.4	1.4	1.5	1.6	1.6	1.7	1.8	1.7	1.8	1.8	1.9	2.0	2.1	2.2							
3	Langs Beach	1.0	1.4	1.4	1.5	1.5	1.6	1.7	1.8	2.3	2.4	2.5	2.7	2.8	2.8	2.9	4.5	4.9	5.3	5.8	6.3	6.7	7.4
4	Waipu Cove	1.0	1.4	1.4	1.5	1.5	1.6	1.7	1.8	2.5	2.6	2.7	2.9	3.0	3.1	3.2	5.6	5.9	6.1	6.4	6.6	6.8	7.0
5	Waipu Estuary	1.0	1.4	1.4	1.5	1.5	1.6	1.7	1.8	1.6	1.7	1.8	1.9	1.9	2.0	2.1							
6	Waipu North	1.0	1.4	1.4	1.5	1.5	1.6	1.7	1.8	2.5	2.6	2.8	3.0	3.1	3.3	3.4	5.5	5.8	6.1	6.4	6.7	6.9	7.2
7	Ruakaka South	1.0	1.4	1.4	1.5	1.5	1.6	1.7	1.8	2.3	2.5	2.7	2.9	3.1	3.2	3.4	4.8	5.1	5.4	5.8	6.1	6.4	6.7
8	Ruakaka Estuary	1.0	1.4	1.4	1.5	1.5	1.6	1.7	1.8	1.6	1.7	1.8	1.9	2.0	2.0	2.2							
9	Ruakaka North	1.0	1.4	1.4	1.5	1.5	1.6	1.7	1.8	2.3	2.5	2.7	2.9	3.1	3.2	3.4	4.9	5.3	5.6	6.0	6.2	6.5	6.9
10	Marsden Point open coast exposed	1.0	1.4	1.5	1.5	1.6	1.7	1.7	1.8	2.3	2.5	2.7	2.9	3.1	3.2	3.5	5.0	5.4	5.7	6.1	6.4	6.7	7.1
11	Marsden Point Partly sheltered	1.0	1.4	1.5	1.5	1.6	1.7	1.7	1.8	1.7	1.8	1.9	2.1	2.3	2.4	2.6	3.3	3.5	3.8	4.1	4.3	4.6	4.9
12	Marsden Point sheltered	1.0	1.4	1.5	1.5	1.6	1.7	1.7	1.8	1.6	1.6	1.7	1.8	1.8	1.9	2.0							
13	Marsden Cove	1.0	1.3	1.3	1.4	1.5	1.6	1.6	1.7	1.4	1.5	1.6	1.7	1.8	1.8	1.9							
14	One Tree Point East	1.0	1.3	1.3	1.4	1.5	1.6	1.6	1.7	1.4	1.5	1.5	1.6	1.7	1.8	1.9							
15	One Tree Point West	1.1	1.3	1.4	1.4	1.5	1.6	1.7	1.8	1.5	1.6	1.6	1.8	1.9	1.9	2.1							
16	Takahiwai	1.1	1.3	1.4	1.4	1.5	1.6	1.7	1.8	1.5	1.6	1.6	1.8	1.9	1.9	2.0							
17	Portland	1.2	1.4	1.5	1.5	1.6	1.7	1.8	1.9	1.6	1.6	1.7	1.8	1.9	1.9	2.0							
18	Otaika	1.2	1.4	1.5	1.5	1.6	1.7	1.8	1.9	1.6	1.6	1.7	1.8	1.9	1.9	2.1							
19	Whangarei	1.2	1.4	1.5	1.5	1.6	1.7	1.8	1.9	1.5	1.6	1.6	1.7	1.8	1.9	2.0							
20	Onerahi West	1.2	1.4	1.5	1.5	1.6	1.7	1.8	1.9	1.5	1.5	1.6	1.7	1.8	1.8	1.9							
21	Onerahi East	1.2	1.4	1.5	1.5	1.6	1.7	1.8	1.9	1.6	1.7	1.8	1.9	2.0	2.0	2.2							
22	Tamaterau	1.1	1.3	1.4	1.4	1.5	1.6	1.7	1.8	1.5	1.6	1.6	1.8	1.8	1.9	2.1							
23	Manganese Point	1.1	1.3	1.4	1.4	1.5	1.6	1.7	1.8	1.5	1.6	1.6	1.7	1.8	1.9	2.0							
24	Parua Bay	1.0	1.3	1.3	1.4	1.5	1.6	1.6	1.7	1.4	1.4	1.5	1.6	1.7	1.8	1.9							
25	Munro Bay	1.0	1.3	1.3	1.4	1.5	1.6	1.6	1.7	1.4	1.5	1.5	1.6	1.7	1.8	1.9							
26	McLeods Bay	1.0	1.3	1.3	1.4	1.5	1.6	1.6	1.7	1.5	1.5	1.6	1.7	1.8	1.9	2.0							
27	Taurikura Bay	1.0	1.2	1.3	1.3	1.4	1.5	1.6	1.7	1.4	1.4	1.5	1.6	1.7	1.7	1.9							
28	Urquharts Bay	1.0	1.2	1.3	1.3	1.4	1.5	1.5	1.7	1.3	1.4	1.4	1.6	1.6	1.7	1.8							
29	Smugglers Bay	0.9	1.3	1.4	1.4	1.5	1.6	1.6	1.8	1.8	2.0	2.1	2.2	2.4	2.5	2.7	4.0	4.3	4.6	4.9	5.1	5.4	5.6
30	Ocean Beach	0.9	1.3	1.4	1.4	1.5	1.6	1.6	1.8	2.5	2.6	2.8	2.9	3.1	3.2	3.4	5.8	6.1	6.4	6.8	7.0	7.3	7.6
31	Taiharuru	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	2.1	2.2	2.3	2.5	2.6	2.7	2.9	4.6	4.8	5.1	5.4	5.6	5.8	6.0
32	Taiharuru River	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	1.5	1.6	1.7	1.8	1.9	1.9	2.1							
33	Pataua Estuary	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	1.4	1.5	1.5	1.6	1.7	1.7	1.9							
34	Pataua open coast	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	2.4	2.5	2.6	2.8	2.9	3.0	3.2	6.3	6.7	7.0	7.3	7.6	7.8	8.1
35	Ngunguru open coast	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	2.1	2.3	2.5	2.7	2.9	3.1	3.4	4.6	4.9	5.2	5.6	5.9	6.1	6.5

Number	Name	MHWS-10 (m NZVD2016)	Storm tide (m NZVD2016)							Static inundation (m NZVD2016)							Dynamic inundation (m NZVD2016)						
			5 yr	10 yr	20 yr	50 yr	100 yr	200 yr	500 yr	5 yr	10 yr	20 yr	50 yr	100 yr	200 yr	500 yr	5 yr	10 yr	20 yr	50 yr	100 yr	200 yr	500 yr
36	Ngunguru Estuary	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	1.5	1.6	1.7	1.8	1.9	2.0	2.2							
37	Whangaumu Beach	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	1.5	1.6	1.7	1.9	2.0	2.2	2.4	3.1	3.3	3.5	3.9	4.1	4.4	4.7
38	Tutukaka Harbour	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	1.4	1.5	1.6	1.7	1.8	2.0	2.1	2.5	2.7	2.9	3.2	3.4	3.7	4.0
39	Matapouri open coast	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	1.7	1.8	1.9	2.1	2.3	2.4	2.6	3.3	3.5	3.7	4.0	4.3	4.5	4.8
40	Matapouri Estuary	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	1.4	1.4	1.5	1.6	1.7	1.8	1.9							
41	Woolleys Bay	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.2	2.4	3.6	3.8	4.0	4.3	4.5	4.7	4.9
42	Sandy Bay	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	2.0	2.0	2.1	2.3	2.3	2.4	2.5	3.4	3.6	3.8	4.1	4.3	4.5	4.7
43	Whananaki South Beach	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	2.1	2.2	2.3	2.5	2.6	2.8	2.9	5.4	5.7	5.9	6.2	6.4	6.6	6.9
44	Whananaki Estuary	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	1.5	1.6	1.7	1.8	1.9	1.9	2.1							
45	Moureeses Bay	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	2.1	2.2	2.3	2.5	2.5	2.6	2.7	4.9	5.2	5.4	5.7	5.9	6.1	6.4
46	Pareparea Bay	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	2.1	2.2	2.3	2.5	2.6	2.7	2.8	4.8	5.1	5.4	5.7	5.9	6.1	6.4
47	Okupe Beach	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	2.5	2.7	2.9	3.1	3.3	3.5	3.7	6.8	7.2	7.5	7.9	8.2	8.5	8.9
48	Mimiwhangata Bay	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	1.5	1.6	1.7	1.8	1.9	1.9	2.0	2.4	2.6	2.9	3.2	3.4	3.7	4.0
49	Ngahau Bay	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	4.4	4.8	5.2	5.8	6.3	6.8	7.5
50	Helena Bay	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	1.6	1.7	1.8	1.8	1.9	2.0	2.1	3.6	3.8	4.0	4.2	4.4	4.6	4.8
51	Oakura	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	1.9	2.0	2.1	2.3	2.5	2.6	2.8	4.6	4.8	5.1	5.4	5.6	5.8	6.1
52	Ohawini	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	1.5	1.6	1.7	1.9	2.0	2.1	2.3	2.4	2.6	2.8	3.0	3.2	3.4	3.6
53	Tuparehuia Bay	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	1.4	1.4	1.5	1.6	1.7	1.7	1.9							
54	Bland Bay	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	2.0	2.1	2.3	2.4	2.6	2.7	2.9	5.3	5.5	5.8	6.1	6.2	6.4	6.6
55	Elliot Bay	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	2.2	2.4	2.6	2.8	3.0	3.2	3.5	5.0	5.4	5.7	6.1	6.3	6.6	7.0
56	Cape Brett	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	1.9	2.1	2.2	2.5	2.7	2.9	3.1	4.4	5.0	5.6	6.4	7.2	7.9	9.0
57	Parekura Bay Estuary	0.9	1.3	1.3	1.4	1.4	1.4	1.5	1.5	1.4	1.5	1.5	1.6	1.6	1.6	1.7							
58	Te Huruhi Bay	0.9	1.3	1.3	1.4	1.4	1.4	1.5	1.5	1.5	1.6	1.6	1.7	1.7	1.8	1.8							
59	Oneroa Bay	1.0	1.4	1.4	1.4	1.5	1.5	1.5	1.6	2.4	2.5	2.6	2.6	2.7	2.8	2.8	5.1	5.4	5.7	6.1	6.4	6.8	7.2
60	Kororareka Bay	1.0	1.4	1.4	1.4	1.5	1.5	1.5	1.6	1.5	1.5	1.6	1.6	1.7	1.7	1.8							
61	Opua Okiato	1.0	1.4	1.4	1.4	1.5	1.5	1.5	1.6	1.5	1.5	1.5	1.6	1.6	1.7	1.7							
62	Waikare Inlet	1.0	1.4	1.4	1.4	1.5	1.5	1.5	1.6	1.5	1.5	1.6	1.6	1.6	1.7	1.7							
63	Kawakawa River	1.0	1.4	1.4	1.4	1.5	1.5	1.5	1.6	1.4	1.5	1.5	1.6	1.6	1.6	1.7							
64	Paihia	1.0	1.4	1.4	1.4	1.5	1.5	1.5	1.6	2.3	2.4	2.5	2.5	2.6	2.7	2.7	3.8	4.0	4.2	4.4	4.6	4.8	5.0
65	Te Ti Bay	1.0	1.4	1.4	1.4	1.5	1.5	1.5	1.6	2.4	2.4	2.5	2.6	2.7	2.8	2.9	4.1	4.4	4.6	4.9	5.1	5.3	5.6
66	Waitangi Estuary	1.0	1.4	1.4	1.4	1.5	1.5	1.5	1.6	1.4	1.5	1.5	1.5	1.6	1.6	1.7							
67	Onewhero Bay	1.0	1.4	1.4	1.4	1.5	1.5	1.5	1.6	2.3	2.4	2.4	2.5	2.6	2.6	2.7	3.6	3.8	3.9	4.2	4.3	4.4	4.6
68	Kerikeri Inlet Exposed	1.0	1.4	1.4	1.4	1.5	1.5	1.5	1.6	1.5	1.5	1.6	1.6	1.7	1.7	1.8							
69	Kerikeri Inlet sheltered	1.0	1.4	1.4	1.4	1.5	1.5	1.5	1.6	1.5	1.5	1.5	1.6	1.6	1.6	1.7							
70	Te Puna Inlet	1.0	1.4	1.4	1.4	1.5	1.5	1.5	1.6	1.5	1.6	1.6	1.7	1.7	1.8	1.9							

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			5 yr	10 yr	20 yr	50 yr	100 yr	200 yr	500 yr	5 yr	10 yr	20 yr	50 yr	100 yr	200 yr	500 yr	5 yr	10 yr	20 yr	50 yr	100 yr	200 yr	500 yr
71	Rangihoua Bay	0.9	1.3	1.3	1.4	1.4	1.4	1.5	1.5	2.3	2.3	2.4	2.5	2.5	2.6	2.7	3.3	3.5	3.7	4.0	4.3	4.5	4.9
72	Purerua Peninsula open coast	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	2.2	2.4	2.6	2.8	3.0	3.2	3.5	5.9	6.3	6.7	7.1	7.4	7.7	8.1
73	Tapuaetahi Beach	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	2.0	2.2	2.3	2.4	2.5	2.6	2.7	4.8	5.2	5.6	6.1	6.5	6.9	7.4
74	Takou Bay	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	2.0	2.1	2.2	2.4	2.5	2.5	2.6	3.9	4.2	4.5	4.9	5.1	5.4	5.8
75	Matauri Bay	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	1.8	1.9	2.0	2.2	2.3	2.4	2.5	3.5	3.8	4.1	4.5	4.8	5.1	5.5
76	Te Ngaere	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	2.0	2.1	2.2	2.3	2.4	2.5	2.6	4.9	5.4	5.8	6.3	6.7	7.1	7.7
77	Wainui	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	1.9	2.0	2.0	2.1	2.2	2.3	2.4	5.0	5.3	5.7	6.2	6.5	6.9	7.3
78	Mahinepua	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	1.4	1.5	1.6	1.7	1.7	1.8	1.9	2.7	2.8	2.9	3.1	3.2	3.3	3.5
79	Tauranga Bay	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	2.1	2.2	2.3	2.5	2.6	2.7	2.8	5.1	5.6	6.2	7.0	7.7	8.4	9.3
80	Touwai Bay	1.0	1.4	1.4	1.5	1.5	1.5	1.5	1.6	1.5	1.5	1.6	1.6	1.7	1.7	1.7							
81	Whangaroa Harbour	1.0	1.4	1.4	1.5	1.5	1.5	1.5	1.6	1.5	1.5	1.6	1.6	1.7	1.7	1.7							
82	Pupuke Estuary	1.0	1.4	1.4	1.5	1.5	1.5	1.5	1.6	1.5	1.5	1.6	1.6	1.6	1.6	1.7							
83	Saies	1.0	1.4	1.4	1.5	1.5	1.5	1.5	1.6	1.5	1.5	1.6	1.6	1.6	1.6	1.7							
84	Totara North	1.0	1.4	1.4	1.5	1.5	1.5	1.5	1.6	1.5	1.5	1.5	1.6	1.6	1.7	1.7							
85	Taupo Bay	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	1.9	2.0	2.1	2.2	2.3	2.3	2.4	4.5	4.8	5.1	5.6	5.9	6.2	6.6
86	Topou Bay	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	1.5	1.5	1.6	1.7	1.7	1.8	1.9	2.9	3.0	3.2	3.4	3.5	3.7	3.8
87	Motukahakaha Bay	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	1.9	2.0	2.1	2.2	2.2	2.3	2.4	3.3	3.5	3.7	3.9	4.1	4.2	4.5
88	Taemaro Bay	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	1.7	1.8	1.9	2.0	2.1	2.2	2.3	3.4	3.7	3.9	4.2	4.4	4.6	4.8
89	Hihi Beach	0.9	1.3	1.3	1.4	1.5	1.6	1.6	1.7	1.5	1.5	1.6	1.7	1.8	1.8	1.9	3.1	3.5	3.8	4.4	4.8	5.2	5.9
90	Butler Bay	0.9	1.3	1.3	1.4	1.5	1.6	1.6	1.7	1.4	1.4	1.5	1.5	1.6	1.6	1.8							
91	Mangonui Harbour	0.9	1.3	1.3	1.4	1.5	1.6	1.6	1.7	1.4	1.4	1.5	1.5	1.6	1.6	1.8							
92	Coopers Beach	0.9	1.3	1.3	1.4	1.5	1.6	1.6	1.7	1.8	2.0	2.1	2.3	2.4	2.6	2.8	3.4	3.8	4.1	4.7	5.1	5.5	6.2
93	Cable Bay	0.9	1.3	1.3	1.4	1.5	1.6	1.6	1.7	2.0	2.1	2.3	2.4	2.6	2.7	2.9	5.0	5.5	6.0	6.7	7.3	8.0	8.8
94	Taipa Bay	0.9	1.3	1.3	1.4	1.5	1.6	1.6	1.7	1.9	2.0	2.1	2.3	2.4	2.5	2.7	3.7	4.0	4.4	4.9	5.3	5.7	6.3
95	Taipa River	0.9	1.3	1.3	1.4	1.5	1.6	1.6	1.7	1.5	1.5	1.6	1.7	1.8	1.8	2.0							
96	Tokerau Beach South	0.9	1.3	1.3	1.4	1.5	1.6	1.6	1.7	2.1	2.1	2.2	2.3	2.4	2.5	2.5	4.4	4.6	4.9	5.3	5.5	5.8	6.1
97	Tokerau Beach North	0.9	1.3	1.3	1.4	1.5	1.6	1.6	1.7	1.8	2.0	2.1	2.4	2.5	2.7	3.0	3.1	3.3	3.6	3.8	4.0	4.2	4.5
98	Matai Bay	0.9	1.3	1.3	1.4	1.5	1.5	1.6	1.7	1.7	1.8	1.9	2.0	2.1	2.2	2.3	3.2	3.4	3.6	3.9	4.1	4.3	4.5
99	Karikari Moana East	0.9	1.3	1.3	1.4	1.5	1.6	1.6	1.7	2.3	2.4	2.5	2.7	2.8	2.9	3.0	4.9	5.3	5.7	6.2	6.6	7.0	7.4
100	Karikari Moana West	0.9	1.3	1.3	1.4	1.5	1.6	1.6	1.7	2.2	2.4	2.5	2.7	2.8	2.9	3.0	4.7	5.0	5.4	5.9	6.3	6.6	7.1
101	Rangiputa	0.9	1.3	1.3	1.4	1.5	1.6	1.6	1.7	1.5	1.5	1.6	1.7	1.7	1.8	1.9	3.2	3.5	3.9	4.4	4.9	5.3	6.0
102	Rangaunu Bay East	0.9	1.3	1.3	1.4	1.5	1.6	1.6	1.7	2.3	2.4	2.6	2.7	2.9	3.0	3.2	4.0	4.4	4.7	5.2	5.5	5.9	6.3
103	Rangaunu Bay North	0.9	1.3	1.3	1.4	1.5	1.6	1.6	1.7	2.2	2.3	2.5	2.8	2.9	3.1	3.4	4.0	4.3	4.5	4.8	5.1	5.3	5.6
104	Pukenui	1.0	1.4	1.4	1.5	1.6	1.6	1.7	1.8	1.5	1.6	1.6	1.7	1.8	1.8	2.0							
105	Henderson Bay	0.9	1.3	1.3	1.4	1.5	1.6	1.6	1.7	2.5	2.6	2.8	3.0	3.2	3.3	3.5	5.2	5.6	6.0	6.5	6.9	7.3	7.8

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			5 yr	10 yr	20 yr	50 yr	100 yr	200 yr	500 yr	5 yr	10 yr	20 yr	50 yr	100 yr	200 yr	500 yr	5 yr	10 yr	20 yr	50 yr	100 yr	200 yr	500 yr
106	Rarawa Beach	0.9	1.3	1.3	1.4	1.5	1.6	1.6	1.7	2.4	2.6	2.7	2.9	3.1	3.3	3.5	4.4	4.7	4.9	5.3	5.5	5.7	6.0
107	Te Kao Beach	0.9	1.3	1.3	1.4	1.5	1.6	1.6	1.7	2.4	2.6	2.7	3.0	3.1	3.3	3.5	3.3	3.5	3.7	3.9	4.1	4.3	4.5
108	Parengarenga Harbour	0.9	1.3	1.3	1.4	1.5	1.6	1.6	1.7	1.3	1.3	1.4	1.5	1.6	1.6	1.7							
109	Great Exhibition Bay North	0.9	1.3	1.4	1.4	1.5	1.6	1.6	1.8	2.4	2.5	2.7	2.9	3.1	3.2	3.4	4.1	4.4	4.7	5.0	5.2	5.4	5.7
110	Tom Bowling Bay	1.0	1.4	1.4	1.5	1.5	1.6	1.7	1.8	2.3	2.5	2.7	3.0	3.2	3.4	3.7	5.4	6.0	6.7	7.5	8.1	8.7	9.5
111	Spirits Bay	1.1	1.5	1.5	1.6	1.6	1.7	1.7	1.9	2.5	2.7	3.0	3.3	3.5	3.7	4.0	5.8	6.5	7.2	8.1	8.8	9.4	10.2
112	Cape Reinga Beach	1.3	1.8	1.9	1.9	1.9	2.0	2.0	2.1	2.4	2.6	2.8	3.1	3.3	3.4	3.6	4.4	4.8	5.2	5.8	6.2	6.7	7.2
113	Giant Sand Dunes Beach	1.4	1.9	2.0	2.0	2.0	2.1	2.1	2.2	2.8	2.9	3.1	3.3	3.4	3.6	3.8	4.9	5.1	5.4	5.7	5.9	6.2	6.5
114	90 Mile Beach North	1.4	2.0	2.0	2.0	2.1	2.1	2.1	2.2	2.8	3.0	3.1	3.3	3.5	3.6	3.8	5.5	5.8	6.1	6.4	6.7	7.0	7.3
115	90 Mile Beach Central	1.4	2.0	2.0	2.0	2.1	2.1	2.2	2.2	2.9	3.0	3.1	3.3	3.5	3.6	3.9	5.5	5.7	6.0	6.3	6.6	6.8	7.2
116	90 Mile Beach South	1.4	2.0	2.0	2.1	2.1	2.2	2.2	2.2	2.9	3.0	3.2	3.4	3.5	3.7	3.9	6.2	6.4	6.7	7.1	7.4	7.7	8.0
117	Ahipara East	1.5	2.0	2.1	2.1	2.1	2.2	2.2	2.3	2.5	2.7	2.8	3.0	3.1	3.3	3.5	5.2	5.5	5.9	6.3	6.7	7.0	7.5
118	Ahipara Town	1.5	2.0	2.1	2.1	2.1	2.2	2.2	2.3	2.2	2.4	2.5	2.7	2.9	3.1	3.4	3.8	4.2	4.5	5.0	5.3	5.7	6.2
119	Tauroa Point South	1.4	2.0	2.0	2.0	2.1	2.1	2.1	2.2	2.9	3.0	3.2	3.4	3.5	3.7	3.9	5.7	5.9	6.2	6.6	6.8	7.1	7.5
120	Herekino Open Coast	1.4	1.9	2.0	2.0	2.1	2.1	2.1	2.2	2.8	2.9	3.1	3.3	3.4	3.6	3.8	5.3	5.5	5.8	6.1	6.4	6.6	7.0
121	Whangape Harbour	1.4	1.9	2.0	2.0	2.1	2.1	2.1	2.2	2.1	2.1	2.2	2.3	2.3	2.4	2.5							
122	Pawarenga open coast	1.4	1.9	2.0	2.0	2.1	2.1	2.1	2.2	2.8	3.0	3.1	3.3	3.5	3.6	3.8	5.4	5.7	5.9	6.3	6.5	6.8	7.1
123	Mitimiti open coast	1.4	1.9	2.0	2.0	2.1	2.1	2.1	2.2	2.8	2.9	3.1	3.2	3.4	3.5	3.7	5.6	5.8	6.0	6.3	6.6	6.8	7.1
124	Omapere	1.4	1.9	2.0	2.0	2.1	2.1	2.1	2.2	2.1	2.2	2.2	2.3	2.3	2.4	2.4							
125	Opononi	1.4	2.0	2.0	2.1	2.1	2.1	2.2	2.2	2.1	2.2	2.2	2.3	2.3	2.4	2.5							
126	Panguru Estuary	1.5	2.1	2.1	2.2	2.2	2.2	2.3	2.3	2.2	2.3	2.3	2.4	2.4	2.5	2.5							
127	Rawene West	1.6	2.2	2.2	2.3	2.3	2.3	2.4	2.4	2.3	2.3	2.4	2.4	2.5	2.5	2.6							
128	Rawene East	1.6	2.2	2.2	2.3	2.3	2.3	2.4	2.4	2.3	2.3	2.4	2.4	2.4	2.5	2.5							
129	Kohukohu	1.7	2.3	2.3	2.4	2.4	2.4	2.5	2.5	2.4	2.4	2.5	2.5	2.5	2.6	2.6							
130	Waihou Estuary	1.7	2.3	2.3	2.4	2.4	2.4	2.5	2.5	2.4	2.4	2.5	2.5	2.5	2.6	2.6							
131	Waimamaku open coast	1.4	1.9	2.0	2.0	2.1	2.1	2.1	2.2	2.8	2.9	3.1	3.3	3.4	3.5	3.7	6.4	6.6	6.9	7.2	7.5	7.7	8.0
132	Waipoua open coast	1.4	1.9	2.0	2.0	2.1	2.1	2.1	2.2	2.9	3.0	3.1	3.3	3.4	3.6	3.8	6.7	7.0	7.2	7.6	7.8	8.1	8.4
133	Aranga Beach	1.4	2.0	2.0	2.0	2.1	2.1	2.1	2.2	2.8	3.0	3.1	3.3	3.4	3.5	3.7	6.7	7.0	7.2	7.6	7.8	8.1	8.4
134	Omamari Beach	1.4	2.0	2.0	2.0	2.1	2.1	2.1	2.2	2.9	3.0	3.1	3.3	3.4	3.6	3.8	6.3	6.5	6.8	7.1	7.3	7.6	7.9
135	Baylys Beach	1.4	2.0	2.0	2.0	2.1	2.1	2.1	2.2	2.8	3.0	3.1	3.3	3.4	3.5	3.7	5.9	6.2	6.4	6.7	7.0	7.2	7.5
136	Glinks Gully	1.4	2.0	2.0	2.0	2.1	2.1	2.1	2.2	2.8	3.0	3.1	3.3	3.4	3.6	3.7	5.5	5.7	5.9	6.2	6.4	6.6	6.9
137	Pouto North	1.4	2.0	2.0	2.0	2.1	2.1	2.1	2.2	2.9	3.0	3.1	3.3	3.5	3.6	3.8	5.9	6.2	6.4	6.7	7.0	7.2	7.5
138	Pouto Central	1.4	2.0	2.0	2.0	2.1	2.1	2.2	2.2	2.8	3.0	3.1	3.3	3.4	3.5	3.7	6.0	6.2	6.4	6.7	7.0	7.2	7.5
139	Pouto South	1.4	2.0	2.0	2.0	2.1	2.1	2.2	2.2	2.8	2.9	3.1	3.2	3.4	3.5	3.7	4.4	4.6	4.8	5.0	5.2	5.4	5.6
140	Kaipara Harbour Entrance (Pouto Point)	1.4	2.0	2.0	2.1	2.1	2.1	2.2	2.2	2.8	2.9	3.1	3.3	3.4	3.5	3.7	3.9	4.1	4.2	4.4	4.6	4.8	5.0

Appendix C Table 2: CFHZs

Number	Name	2020	2080 (+0.6m SLR)	2130 (+1.2m SLR)	2130 (+1.5 m SLR)
		CFHZ0	CFHZ1	CFHZ2	CFHZ3
1	Mangawhai open coast	3.1	3.6	4.3	4.6
2	Mangawhai Estuary	2.0	2.5	3.2	3.5
3	Langs Beach	2.8	3.3	4.0	4.3
4	Waipu Cove	3.0	3.5	4.2	4.5
5	Waipu Estuary	1.9	2.5	3.1	3.4
6	Waipu North	3.1	3.6	4.3	4.6
7	Ruakaka South	3.1	3.5	4.3	4.6
8	Ruakaka Estuary	2.0	2.5	3.2	3.5
9	Ruakaka North	3.1	3.5	4.3	4.6
10	Marsden Point open coast exposed	3.1	3.5	4.3	4.6
11	Marsden Point Partly sheltered	2.3	2.7	3.5	3.8
12	Marsden Point sheltered	1.8	2.4	3.0	3.3
13	Marsden Cove	2.0	2.5	3.2	3.5
14	One Tree Point East	2.0	2.5	3.2	3.5
15	One Tree Point West	2.1	2.6	3.3	3.6
16	Takahiwai	2.1	2.6	3.3	3.6
17	Portland	2.1	2.6	3.3	3.6
18	Otaika	2.1	2.7	3.3	3.6
19	Whangarei	2.1	2.6	3.3	3.6
20	Onerahi West	2.0	2.5	3.2	3.5
21	Onerahi East	2.2	2.7	3.4	3.7
22	Tamaterau	2.1	2.6	3.3	3.6
23	Manganese Point	2.1	2.6	3.3	3.6
24	Parua Bay	1.9	2.5	3.1	3.4
25	Munro Bay	2.0	2.5	3.2	3.5
26	McLeods Bay	2.1	2.6	3.3	3.6
27	Taurikura Bay	1.9	2.4	3.1	3.4
28	Urquharts Bay	1.9	2.4	3.1	3.4
29	Smugglers Bay	2.4	2.8	3.6	3.9
30	Ocean Beach	3.1	3.5	4.3	4.6
31	Taiharuru	2.6	3.1	3.8	4.1
32	Taiharuru River	1.9	2.4	3.1	3.4
33	Pataua Estuary	1.7	2.2	2.9	3.2
34	Pataua open coast	2.9	3.4	4.1	4.4
35	Ngunguru open coast	2.9	3.3	4.1	4.4
36	Ngunguru Estuary	1.9	2.4	3.1	3.4
37	Whangaumu Beach	2.0	2.5	3.2	3.5
38	Tutukaka Harbour	1.8	2.3	3.0	3.3
39	Matapouri open coast	2.3	2.7	3.5	3.8
40	Matapouri Estuary	1.7	2.2	2.9	3.2
41	Woolleys Bay	2.2	2.7	3.4	3.7
42	Sandy Bay	2.3	2.9	3.5	3.8
43	Whananaki South Beach	2.6	3.1	3.8	4.1
44	Whananaki Estuary	1.9	2.4	3.1	3.4
45	Moureeses Bay	2.5	3.1	3.7	4.0
46	Pareparea Bay	2.6	3.1	3.8	4.1
47	Okupe Beach	3.3	3.7	4.5	4.8
48	Mimiwhangata Bay	1.9	2.4	3.1	3.4
49	Ngahau Bay	2.2	2.7	3.4	3.7
50	Helena Bay	1.9	2.4	3.1	3.4
51	Oakura	2.5	2.9	3.7	4.0
52	Ohawini	2.0	2.5	3.2	3.5
53	Tuparehuia Bay	1.7	2.2	2.9	3.2
54	Bland Bay	2.6	3.0	3.8	4.1
55	Elliot Bay	3.0	3.4	4.2	4.5
56	Cape Brett	2.7	3.1	3.9	4.2
57	Parekura Bay Estuary	1.6	2.2	2.8	3.1
58	Te Huruhi Bay	1.7	2.3	2.9	3.2
59	Oneroa Bay	2.7	3.2	3.9	4.2
60	Kororareka Bay	1.7	2.2	2.9	3.2
61	Opua Okiato	1.6	2.2	2.8	3.1
62	Waikare Inlet	1.6	2.2	2.8	3.1
63	Kawakawa River	1.6	2.2	2.8	3.1
64	Paihia	2.6	3.1	3.8	4.1
65	Te Ti Bay	2.7	3.2	3.9	4.2
66	Waitangi Estuary	1.6	2.1	2.8	3.1
67	Onewhero Bay	2.6	3.1	3.8	4.1
68	Kerikeri Inlet Exposed	1.7	2.2	2.9	3.2
69	Kerikeri Inlet sheltered	1.6	2.2	2.8	3.1
70	Te Puna Inlet	1.7	2.3	2.9	3.2
71	Rangihoua Bay	2.5	3.1	3.7	4.0
72	Purerua Peninsula open coast	3.0	3.4	4.2	4.5
73	Tapuaetahi Beach	2.5	3.0	3.7	4.0
74	Takou Bay	2.5	3.0	3.7	4.0

Number	Name	2020 CFHZ0	2080 (+0.6m SLR) CFHZ1	2130 (+1.2m SLR) CFHZ2	2130 (+1.5 m SLR) CFHZ3
75	Matauri Bay	2.3	2.8	3.5	3.8
76	Te Ngaere	2.4	2.9	3.6	3.9
77	Wainui	2.2	2.7	3.4	3.7
78	Mahinepua	1.7	2.3	2.9	3.2
79	Tauranga Bay	2.6	3.1	3.8	4.1
80	Touwai Bay	1.7	2.2	2.9	3.2
81	Whangaroa Harbour	1.7	2.2	2.9	3.2
82	Pupuke Estuary	1.6	2.2	2.8	3.1
83	Saies	1.6	2.2	2.8	3.1
84	Totara North	1.6	2.2	2.8	3.1
85	Taupo Bay	2.3	2.8	3.5	3.8
86	Topou Bay	1.7	2.3	2.9	3.2
87	Motukahakaha Bay	2.2	2.8	3.4	3.7
88	Taemaro Bay	2.1	2.6	3.3	3.6
89	Hihi Beach	1.8	2.3	3.0	3.3
90	Butler Bay	1.6	2.1	2.8	3.1
91	Mangonui Harbour	1.6	2.1	2.8	3.1
92	Coopers Beach	2.4	2.9	3.6	3.9
93	Cable Bay	2.6	3.0	3.8	4.1
94	Taipa Bay	2.4	2.9	3.6	3.9
95	Taipa River	1.8	2.3	3.0	3.3
96	Tokerau Beach South	2.4	2.9	3.6	3.9
97	Tokerau Beach North	2.5	3.0	3.7	4.0
98	Matai Bay	2.1	2.6	3.3	3.6
99	Karikari Moana East	2.8	3.3	4.0	4.3
100	Karikari Moana West	2.8	3.3	4.0	4.3
101	Rangiputa	1.7	2.3	2.9	3.2
102	Rangaunu Bay East	2.9	3.3	4.1	4.4
103	Rangaunu Bay North	2.9	3.4	4.1	4.4
104	Pukenui	1.8	2.3	3.0	3.3
105	Henderson Bay	3.2	3.6	4.4	4.7
106	Rarawa Beach	3.1	3.5	4.3	4.6
107	Te Kao Beach	3.1	3.6	4.3	4.6

Number	Name	2020 CFHZ0	2080 (+0.6m SLR) CFHZ1	2130 (+1.2m SLR) CFHZ2	2130 (+1.5 m SLR) CFHZ3
108	Parengarenga Harbour	1.6	2.1	2.8	3.1
109	Great Exhibition Bay North	3.1	3.5	4.3	4.6
110	Tom Bowling Bay	3.2	3.6	4.4	4.7
111	Spirits Bay	3.5	3.9	4.7	5.0
112	Cape Reinga Beach	3.3	3.7	4.5	4.8
113	Giant Sand Dunes Beach	3.4	3.9	4.6	4.9
114	90 Mile Beach North	3.5	3.9	4.7	5.0
115	90 Mile Beach Central	3.5	3.9	4.7	5.0
116	90 Mile Beach South	3.5	4.0	4.7	5.0
117	Ahipara East	3.1	3.6	4.3	4.6
118	Ahipara Town	2.9	3.3	4.1	4.4
119	Tauroa Point South	3.5	4.0	4.7	5.0
120	Herekino Open Coast	3.4	3.9	4.6	4.9
121	Whangape Harbour	2.3	2.9	3.5	3.8
122	Pawarenga open coast	3.5	3.9	4.7	5.0
123	Mitimiti open coast	3.4	3.8	4.6	4.9
124	Omapere	2.3	2.9	3.5	3.8
125	Opononi	2.3	2.9	3.5	3.8
126	Panguru Estuary	2.4	3.0	3.6	3.9
127	Rawene West	2.5	3.0	3.7	4.0
128	Rawene East	2.4	3.0	3.6	3.9
129	Kohukohu	2.5	3.1	3.7	4.0
130	Waihou Estuary	2.5	3.1	3.7	4.0
131	Waimamaku open coast	3.4	3.9	4.6	4.9
132	Waipoua open coast	3.4	3.9	4.6	4.9
133	Aranga Beach	3.4	3.9	4.6	4.9
134	Omamari Beach	3.4	3.9	4.6	4.9
135	Baylys Beach	3.4	3.9	4.6	4.9
136	Glinks Gully	3.4	3.9	4.6	4.9
137	Pouto North	3.5	3.9	4.7	5.0
138	Pouto Central	3.4	3.9	4.6	4.9
139	Pouto South	3.4	3.8	4.6	4.9
140	Kaipara Harbour Entrance (Pouto Point)	3.4	3.9	4.6	4.9

# Appendix D:	Peer review letter

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8 October 2020

Review of "Coastal Flood Hazard Assessment for Northland Region 2019-2020"

I have reviewed the report describing the analysis and assessment of coastal flooding for the Northland region. Based on my experience in the field, I would like to make a number of comments about the report.

- The report is well-written and details the large amount of work underpinning the analysis. The figures are clear and insightful. I commend the authors for providing a number of sketches that exemplify the processes in action and how they have been modelled.
- The methodology is state-of-the-art and certainly results in a robust and reliable assessment of future flood hazards. There are many aspects that need to be mentioned:
  a) A large number of locations is analysed and the methodology accounts for the differences between open and sheltered coastlines.
  b) I particularly liked the approach combining the evaluation of *static* and *dynamic* inundation levels. This is new, sensible and useful to coastal managers.
  c) The use of different approaches, probabilistic and "building block", for the evaluation of extremes is a strong point of the work and helps reduce uncertainty.
  d) The study also considers a range of realistic scenarios of sea level rise. The scenarios are in line with the most recent available projections and the use of maps to present results allows to visualize and better understand the extent of areas susceptible to flooding.
- The analysis is extremely detailed in all components. For example, to choose the runup formula, the authors perform an analysis of which available runup formula best describes the Northland coast. I also found some of the hypotheses on future wave and storm surge climate in line with the most recent findings for New Zealand and certainly reasonable.
- The recommendations presented are sensible, relevant and worth attention. I subscribe to each of the arguments brough forward.
- Finally, I should also point out that following an initial review of the report, I discussed some changes with Tonkin & Taylor. All changes requested have been addressed in this final version of the report.

Yours sincerely,

Giovanni Coco
Associate Professor

Giovanni Coco

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