Mapping New Zealand's exposure to coastal flooding and sea-level rise

NIWA internal report

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Executive summary

This report describes the scientific methodology underpinning a New Zealand national scale assessment of coastal flooding as sea level rises. The coastal flooding assessment identifies areas of land exposed to coastal flooding due to extreme sea level plus future relative sea-level rise (RSLR).

This report is intended to supplement the peer-reviewed publication *Paulik, R., Wild, A., Stephens, S., Welsh, R., Wadhwa, S. (2023) National assessment of extreme sea-level driven inundation under rising sea levels. Frontiers in Environmental Science, 10, 2633, https://doi.org/10.3389/fenvs.2022.1045743*.

Extreme sea-level elevations for nine scenarios corresponding to annual exceedance probabilities (AEP) of 39, 18, 10, 5, 2, 1, 0.5, 0.2 and 0.1 %, were determined by combining estimates of tide, storm-surge, wave setup, and mean sea-level (MSL). These nine AEP scenarios have equivalent average recurrence intervals (ARI), or return periods of: 2, 5, 10, 20, 50, 100, 200, 500 and 1000-years. The extreme sea-level estimates were derived from analysis of tide gauges, tide and wave modelling. In places where detailed studies of extreme sea levels had been previously undertaken by NIWA, the results of these detailed studies were substituted and used in place of the national assessment—in Nelson/Golden Bay/Tasman, Gisborne, Bay of Plenty, Auckland, and Canterbury.

Coastal flooding was mapped for low-lying coastal land by projecting the extreme storm-tide + wave-setup elevations onto digital elevation models (DEM) derived from a composite topographical dataset comprised of Airborne Light Detection and Ranging (LIDAR) and bias corrected Shuttle Radar Topography Mission (SRTM). Flooding was mapped using a static ("bathtub") methodology. For each of the nine AEP scenarios, additional exposure to relative sea-level rise (RSLR) was mapped by adding 0.1 m increments of RSLR up to +2 m above present-day MSL.

Two outputs were produced for each of the scenarios above: (1) GIS polygons of flooding extent, and (2) GIS rasters of flooding depth. These cover the entire coastline of Aotearoa-New Zealand, representing several horizontal resolutions down to 2 m in major urban areas.

The Aotearoa-New Zealand extreme sea level flooding maps are compatible with new sea-level rise projections for NZ and with the guidance on how to use those projections. This report includes an example of how the Aotearoa-New Zealand extreme sea level flooding maps can be used with sea-level rise projections.

Many New Zealand Councils have undertaken coastal flood mapping, some using hydrodynamic models calibrated using local measurements of sea levels, waves and wave runup. The Aotearoa-New Zealand extreme sea level flooding maps and data were produced at a whole of Aotearoa-New Zealand scale and were not designed to replace more detailed regional or local data where this is available for planning purposes. There may be a mismatch between the two products. No wave runup data were used to verify the model on NZ's west coast leading to higher uncertainty there.

Nevertheless, the Aotearoa-New Zealand extreme sea level flooding maps are uniquely useful because they provide coverage where none previously existed. They also provide a comprehensive suite of scenarios including 21 RSLR scenarios for each of 9 AEP scenarios at a national scale. This comprehensive coverage enables a graduated risk profile that can be used by, for example, local and regional councils, to identify where to conduct more detailed investigations in the process of developing adaptation strategies to protect our coastal communities. The maps may also help the financial industry or national infrastructure or service providers to assess risk to their portfolios.

1 Outputs produced—access and use

When using the coastal flood maps or data, please acknowledge or cite this source publication as appropriate: Paulik, R., Wild, A., Stephens, S., Welsh, R., Wadhwa, S. (2023) National assessment of extreme sea-level driven inundation under rising sea levels. Frontiers in Environmental Science, 10, 2633, *https://doi.org/10.3389/fenvs.2022.1045743*.

NIWA has mapped 39, 18, 10, 5, 2, 1, 0.5, 0.2 and 0.1 % AEP coastal-flooding scenarios (equivalent to return periods of 2, 5, 10, 20, 50, 100, 200, 500 and 1000-years). All of these scenarios have additional RSLR increments added up to 2 m above present-day mean sea level. There are nine AEP × twenty-one RSLR scenarios = 189 scenarios available in total. An example of the mapping is shown in Figure 1-1.

The 1% AEP scenario is available under a Creative Commons Attribution-NoDerivatives 4.0 International Public License and can be accessed here.

The other scenarios are available on request and may have different licensing requirements—details on how to request this information are available here.

When planning, a more frequent AEP scenario (e.g., 10% AEP) may be suitable for decisions with shorter time horizons, e.g., is this building likely to flood over the mortgage period? Alternatively, a large and rare AEP scenario may be appropriate for major infrastructure works, e.g., for Ultimate Limit State Bridge Design the AEP is 0.04% (2,500-year return period).

Some New Zealand Councils have created coastal flood maps for their regions and, where available, these maps should be used. The Aotearoa-New Zealand extreme sea level flooding maps provide coverage for regions where no such products exist.

They also provide a unique and comprehensive suite of nine extreme sea level AEP and twenty-one RSLR scenarios at a national scale.

Coastal-flooding scenarios were modelled at time independent 0.1 m RSLR increments. This differs from a common practice of defining future years and or RSLR scenarios (e.g., Heberger et al., 2011; Breili et al., 2020; Amadio et al., 2022). Time independent coastal-flooding maps represent Global Mean Sea Level (GMSL) projections over the next century from several shared socioeconomic pathway scenarios each with sea level height and timing uncertainties. Decision makers are often bound to coastal-flood hazard and risk assessment and reporting for prescribed RSLR heights or timeframes set by statutory and non-statutory instruments (Lawrence et al. 2018). For instance, Aotearoa-New Zealand regional and territorial authorities must investigate and implement resource management plans to mitigate coastal hazards and risks within their jurisdictional boundaries over a minimum 100-year period (Minister of Conservation 2010). Financial institutes manage these risks across spatial scales from individual properties to national portfolios and over short annual timeframes based on mortgage lending or insurance policies e.g., <10-years (Storey et al. 2020). National coastal-flood map coverage representing different AEPs and time independent of projected RSLR then facilities hazard and risk management decision making across different spatial and temporal scales.

Figure 1-1: Example of the Aotearoa-New Zealand extreme sea level flooding maps. Mission Bay, Auckland. Pink = present-day 1% AEP coastal flood exposure. Yellow = +1 m RSLR. Blue = +2 m RSLR.

1.1 Working with relative sea-level rise projections

New Zealand Ministry for the Environment has released Interim guidance on the use of new sea-level rise projections for NZ. The interim guidance will be included in an upcoming revision of the Coastal hazards and climate change guidance for local government (MfE 2017). The new sea-level rise projections combine the 2021 IPCC Sixth Assessment Report (AR6) sea-level data (downscaled to New Zealand), with localised rates of vertical land movement (VLM) around the coast. The result is estimates of relative sea-level rise (RSLR), or sea-level rise relative to the local landmass. RSLR varies around the coastline of New Zealand.

The Aotearoa-New Zealand extreme sea level flooding maps are compatible with the sea-level rise projections for NZ and with the Interim guidance. The Aotearoa-New Zealand extreme sea level flooding maps are provided in regular 0.1 m increments of RSLR, from 0 to 2 m above present-day MSL. Table 2 of the MfE Interim guidance on the use of new sea-level rise projections (which is reproduced in Table 1-1 of this report) provides the approximate years when various national sea-level rise increments could be reached. Simply match the correct RSLR increment from the maps to the SLR increment in Table 1-1 to determine the potential timing of that scenario being reached. This excludes any regional and local factors including VLM.

Table 1-1: Approximate years when various national sea-level rise increments could be reached. Source: adapted from MfE Interim guidance on the use of new sea-level rise projections (2022).

SLR (m)	Year achieved for SSP5-8.5 H+ (83rd percentile)	Year achieved for SSP5-8.5 (median)	Year achieved for SSP3-7.0 (median)	Year achieved for SSP2-4.5 (median)	Year achieved for SSP1-2.6 (median)
0.3	2050	2055	2060	2060	2070
0.4	2060	2065	2070	2080	2090
0.5	2065	2075	2080	2090	2110
0.6	2070	2080	2090	2100	2130
0.7	2080	2090	2100	2115	2150
0.8	2085	2100	2110	2130	2180
0.9	2090	2105	2115	2140	2200
1.0	2095	2115	2125	2155	>2200
1.2	2105	2130	2140	2185	>2200
1.4	2115	2145	2160	>2200	>2200
1.6	2130	2160	2175	>2200	>2200
1.8	2140	2180	2200	>2200	>2200
2.0	2150	2195	>2200	>2200	>2200

To account for VLM, first download the RSLR projections from the nearest location of interest from the sea-level rise projections website. An example is provided in Table 1-2 for site 2494 near Hutt City in Wellington. For year and RSLR scenario of interest, round the RSLR to the nearest 0.1 m increment and matching layer from Aotearoa-New Zealand extreme sea level flooding maps.

Table 1-2: Decadal increments for "medium confidence" projections of RSLR (SLR + VLM) applied at site 2494 near Hutt City in Wellington.

Year	SSP1-2.6 (median)	SSP2-4.5 (median)	SSP3-7.0 (median)	SSP5-8.5 (median)	SSP5-8.5 H+ (83rd percentile)
2005	0	0	0	0	0
2020	0.1	0.1	0.1	0.11	0.14
2030	0.18	0.18	0.18	0.18	0.22
2040	0.25	0.26	0.27	0.27	0.34
2050	0.33	0.35	0.37	0.39	0.47
2060	0.4	0.44	0.47	0.5	0.6
2070	0.48	0.54	0.59	0.63	0.77
2080	0.56	0.64	0.72	0.77	0.95
2090	0.63	0.74	0.85	0.94	1.16
2100	0.71	0.85	1.01	1.11	1.38
2110	0.8	0.96	1.14	1.26	1.61
2120	0.88	1.07	1.29	1.42	1.83
2130	0.95	1.17	1.44	1.59	2.05
2140	1.02	1.27	1.59	1.74	2.26

Year	SSP1-2.6 (median)	SSP2-4.5 (median)	SSP3-7.0 (median)	SSP5-8.5 (median)	SSP5-8.5 H+ (83rd percentile)
2150	1.09	1.38	1.73	1.89	2.46

The sea-level rise projections for NZ are zeroed to the average MSL over the 1995–2014 period (mid-point 2005) to be consistent with IPCC AR6 projections. Whereas the average mid-point of the sea level measurements used to create the Aotearoa-New Zealand extreme sea level flooding maps was the year 2010, although there is some variability (Table A-1). The ~5-year difference equates to only a few cm and could be ignored for practical purposes. If required, the RSLR (e.g., Table 1-2) can be zeroed to the year 2010 by interpolating the RSLR values to year 2010 using a spline function and subtracting the RSLR difference between 2010 and 2005.

2 Background

This report provides a technical background for NIWA's Aotearoa-New Zealand extreme sea level flooding maps and data. The report describes the methods used to calculate extreme sea levels around the coastline of New Zealand and used to map the depth and extent of overland flooding from those extreme sea levels. This report includes:

- Contributions to coastal flooding.
- Reference datums, and mean sea levels and tides.
- Analysis of extreme sea-level elevations around the NZ coast.
- Future sea-level rise projections.
- Mapping of flooding over the land from extreme sea-levels including increments of sea-level rise.
- Determining property risk exposure

2.1 Coastal hazards

Coastal hazards around New Zealand include:

- Coastal flooding.
- Shoreline erosion.
- Tsunami.
- Groundwater salinisation and elevation change.
- Interactions between coastal processes and other hazards, like fluvial flooding.

All of these coastal hazards are a significant issue and will be exacerbated by the effects of climate change and sea-level rise.

This study addresses coastal flooding during extreme coastal storms around New Zealand, and how it could be exacerbated by sea-level rise.

IPCC Working Group II (AR6) found global mean sea-level rise is likely to continue accelerating, even under the lower SSP1-2.6 scenario and the more strongly forced scenarios. Consequently, they determine with high confidence that coastal risks will increase by at least 10-fold over this century due to already committed sea-level rise. For New Zealand, nuisance and extreme coastal flooding have increased since 2000 because of a higher MSL (PCE 2014; PCE 2015; Stephens, Scott A. et al. 2018b). Ongoing sea-level rise will cause more frequent flooding before mid-century, with very high confidence. As sea level continues to rise, so does the scale and the frequency of adaptation interventions needed in coastal areas (MfE 2022).

Sea-level rise will greatly increase the frequency (and depth, and so the extent of the areas) of coastal storm-tide flooding (PCE 2014).

2.1.1 Coastal Flooding

Coastal flooding arises from the occurrence or combination of several meteorological and astronomical processes which may combine to elevate sea levels sufficiently to inundate low-lying coastal margins with seawater. The processes involved are:

- Mean sea level.
- Astronomical tides.
- Storm surge (winds and low barometric pressure).
- Wave setup (and runup).
- Climate-change effects including sea-level rise, stronger winds, larger waves and larger storm surges.

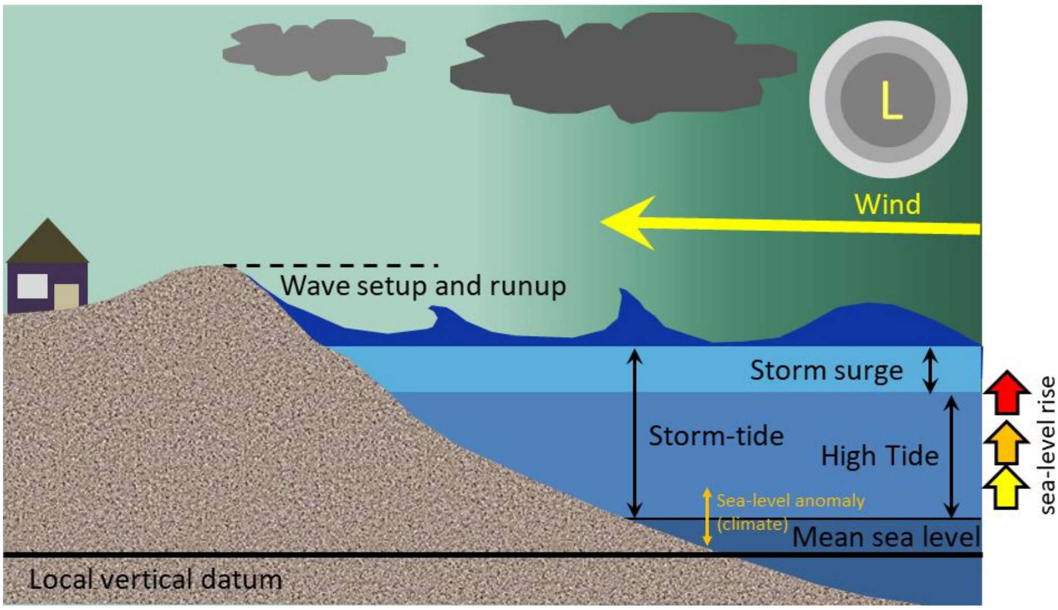

Figure 2-1: Illustration of coastal and ocean processes contributing to coastal flooding.

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

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

Storm-tide is defined as the sea-level peak reached during a storm event, from a combination of MSL + tide + storm surge. It is the storm-tide that is measured by sea-level gauges such as in Wellington Harbour. Large storm-tide events cause coastal flooding. From the sea-level gauge record, times and tidal elevation at each high water can be identified. Similarly, each peak in the total water level can be identified, allowing the storm surge to be computed as the difference (total – tide − MSL) between each high tide level and the nearest peak high-water level. The methods used to calculate storm surge include the mean sea level anomaly (e.g., the monthly mean sea level) as part of the storm surge component of sea level.

Waves also raise the sea level at the coastline higher above the offshore storm-tide levels. Wave setup is the increase in mean sea level at the coast, pushed up inside the surf zone from the release of wave energy as waves break in shallow water (Figure 2-1). The term wave setup describes an average raised elevation of sea level at the shore when breaking waves are present. In this way **wave setup** also contributes to coastal flooding during a storm event. **Wave runup** is the maximum vertical extent of wave "up-rush" on a beach or structure on the still water level (that would occur without waves). Consequently, runup constitutes only a short-term fluctuation on a wave-by-wave basis in water level (and hence water volume) compared with wave setup and storm surge. Wave runup does not contribute significantly to coastal flooding except in circumstances where the flowing "green water" in wave runup overtops a barrier and cannot readily exit back to the sea.

Where waters are sufficiently deep adjacent to the shoreline, waves may break right at the shoreline, causing wave overtopping e.g., at rock revetments and seawalls. Wave-overtopping volumes in this situation comprise green water (flowing seawater), compounded with wave splash and wind drift of the wave spray. Flooding, from rivers, streams and stormwater, is another contributor to coastal flooding when the flood discharge is constrained inside narrower sections of estuaries.

In this study, we mapped overland flooding from extreme sea levels that include the effects of MSL, astronomical tides, storm surge, wave setup and increments of sea-level rise. Neither riverine flooding nor tsunami flooding is considered.

2.2 Climate change impacts on coastal flooding

Climate change will not introduce any new coastal hazards to the coastline but it will exacerbate the existing hazards and in most cases increase their extent, creating new risks in coastal areas that have not previously been exposed (MfE 2017). Sea-level rise will greatly increase the frequency and depth of coastal storm-tide flooding (PCE 2014; PCE 2015).

Climate change effects on extreme storm surge and waves have been predicted to be quite subtle around New Zealand. A general increase in wave height and period is predicted along the south/west, together with a decrease in wave height along the north/east coasts. Likewise, extreme storm surge is predicted to increase a small amount in magnitude in the south and decrease in the north of NZ. (NIWA 2012; Cagigal et al. 2020; Albuquerque et al. 2022). Therefore, relative sea-level rise will be the main driver of increasing impact from coastal flooding.

2.3 Exceedances and return periods

The likelihoods associated with extreme storm-tides and/or waves, are reported in terms of their probability of occurrence. The <u>annual exceedance probability</u> (AEP) describes the chance of an event reaching or exceeding a certain water level in any given year. For example, if a storm-tide of 1.5 m height has a 5% AEP, then there is a 5% chance of a storm-tide this high, or higher, occurring in <u>any</u> 1-year period. Such an event is an outside chance in any year, but it can still happen and should be planned for. Furthermore, although the occurrence probability is only 5% for any year, more than one storm-tide this high or higher could occur in any given year. Integrated over a planning timeframe of say 100 years, a 5% AEP event has a 99% chance of occurring or being exceeded, i.e., it is almost certain.

The likelihood of extreme events can also be described in terms of their <u>average recurrence interval</u> (ARI), which is the average time interval between events of a specified magnitude (or larger), when averaged over many occurrences i.e., a long time. Table 2-1 shows the relationship between AEP and

ARI, small relatively common events have a high annual exceedance probability and a low average recurrence interval, and *vice versa*.

Table 2-1: Relationship between annual exceedance probability (AEP) and average recurrence interval (ARI). AEP = 1 – $e^{(-1/ARI)}$.

AEP (%)	63%	39%	18%	10%	5%	2%	1%	0.5%	0.2%	0.1%
ARI (years)	1	2	5	10	20	50	100	200	500	1000

ARI (or its often used surrogate "return period") can be misinterpreted on the assumption that because one large event has just occurred, then the average recurrence interval will pass before another such event. The term AEP is preferred for weather-related hazards, because it conveys the continuous probability that large events could occur at any time.

Another essential planning component is to consider the planning timeframe, or lifetime, of interest. For example, a planning lifetime of at least 100 years is recommended in the NZ Coastal Policy Statement (e.g., Policy 24), whereas residential mortgage lifetimes are ≤ 30-years duration. Table 2-2 presents the likelihood that events with various occurrence probabilities will occur, *at least once*, within a specified planning lifetime. The likelihoods are shaded according to their chance of occurring or being exceeded in the specified timeframe:

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

For example, a relatively common (smaller) event with a 39% AEP is *almost certain* to occur or be exceeded over a 20-year lifetime. However, a rare (larger) 2% AEP event is *unlikely* to occur or be exceeded over the same 20-year lifetime. 1% AEP is a commonly used planning or engineering design event magnitude, and 100-year planning lifetimes are common for affected infrastructure or for coastal hazard risk assessments, Table 2-2 shows that a 1% AEP event is *likely* to occur or be exceeded over a 100-year planning lifetime with a 63% probability.

Table 2-2: Likelihood of *at least one exceedance* event occurring within planning lifetimes The likelihood of occurrence is described by AEP and/or ARI. $P = 1 - e^{-L / ARI}$, where L = planning lifetime and P = probability of occurrence within planning lifetime.

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

3 Methods

3.1 Overview of methodology

The present study estimated storm-tide-driven sea levels (ESLs) along the New Zealand coastline. ESL elevations were calculated for each coastal segment incorporating each coastal process from Figure 2-1 applied as the formula:

ESL = MSL + ST + WS + RSLR (1)

where: MSL is mean sea level relative to local vertical datum calculated from sea-level gauge records over (approximately) a recent decade, ST is the storm-tide combination of high tide, meteorological effects (storm-surge) and monthly sea-level anomaly, affected by both seasonal heating and cooling and interannual and inter-decadal climate variability such as the El Niño Southern Oscillation (ENSO), and WS is the additional wave setup (over and above ST) at the shoreline where breaking waves are present.

The following list provides the sequence of steps undertaken:

1. Choose the locations for which to calculate extreme sea levels. This was done by hand with sites chosen to represent both wave-exposed open coast and wave-sheltered estuarine locations, and chosen to capture the transition between high and low energy environments. There were 788 model output locations.

2. Ascertain mean sea level for the region (Section 3.2).

3. Calculate the storm-tide (ST) elevation (Section 3.3.1) using sea-level gauge records where available and elsewhere using tidal predictions and linear relationships between tidal and storm-tide heights.

4. Calculate the wave setup (WS) elevation (Section 3.4) for locations outside estuaries, based on wave height with the wave height/setup factor derived from comparisons with regional study information (the regional studies contain detailed calculations of extreme storm-tide and wave conditions offshore from the coastline, where undertaken by NIWA. They were created for several NZ Councils in several locations around New Zealand: for Tasman (Stephens, Scott A. et al. 2018c), Bay of Plenty (Stephens, Scott A. et al. 2018a), Canterbury (Stephens, Scott A et al. 2015a), Gisborne (Stephens, Scott A et al. 2014) and Wellington (Stephens, Scott A. et al. 2012)). Inside estuaries a constant WS = 0.2 m was used.

5. Combine the storm-tide and wave-setup elevations (Section 3.3.1).

6. Calculate ESL including RSLR increments up to 2 m (Section 3.6).

7. Where regional study information was available, replace the ESL's with results from the regional studies.

8. Map extreme storm-tide + wave setup + SLR increments onto the land around New Zealand using available LiDAR data sets (Section 3.7).

3.2 Vertical datums and mean sea level

3.2.1 Vertical datums

The data underpinning the Aotearoa-New Zealand extreme sea level flooding maps have been determined relative to a mean sea level averaged between years 2001 and 2019 (midpoint 2010), although this did vary in places due to data coverage. The MSL includes the offsets to local vertical datums with evaluation against LiDAR in the same vertical datum.

3.2.2 Mean sea level

The level of the sea is recorded at a number of tide gauges around New Zealand. These are located at or near Ports and Harbours, and are operated by Port companies, Regional Councils or NIWA. Tide gauges record the level of the sea and are sheltered from the waves or rely on filtering to eliminate the temporary rise and fall in sea level with the passing of a wave.

MSL offset relative to local vertical datum were calculated, based on available sea-level records with a known relationship to vertical datum. These are presented in Table A-1.

3.2.3 Tides

Sea-level records, supplemented by NIWA's tidal model predictions (Walters et al. 2001), were used to calculate the mean high-water springs 7% elevation (MHWS-7) at locations around New Zealand. MHWS-7 is the level equalled or exceeded by the largest 7% of all high tides. MHWS-7 was adopted on the basis that it provides a nationally consistent estimate of mean high-water springs that is unaffected by regional changes in individual tidal harmonic constituents. It equates to the average of approximately 50 of the highest high tides per year.

In regions with no sea-level gauge record, tide elevations were estimated as follows:

1. Along the open coast, outside of estuaries, MHWS-7 was calculated from a tidal model (Walters et al. 2001).
2. Inside estuaries MHWS-7 was calculated using a scaling factor of 1.1 × [MHWS-7 outside the estuary]. This approximation accounts for observations from New Zealand gauged estuaries that the tide usually amplifies inside estuaries (Stephens, Scott A. et al. 2013).

This method of deriving MHWS differs from the LINZ method based on summing $M_2 + S_2 + N_2$ tidal constituents, but gives results that are close to the LINZ method while providing a consistent measure around NZ in terms of the percent of high tides that exceed MHWS.

3.3 Extreme sea level analysis

3.3.1 Extreme sea level estimates from available regional studies

Several regional studies using detailed investigations on the joint probabilities of coincident storm-tides and waves offshore from the coast (e.g., Figure 3-1) have been drawn on for this assessment.

The regional studies were undertaken by NIWA in the Auckland (Stephens, Scott A. et al. 2013), Bay of Plenty (Stephens, Scott A. et al. 2018a), Tasman/Golden Bay/Nelson (Stephens, Scott A. et al. 2018c) and Canterbury (Stephens, Scott A et al. 2015a) regions. Verification of extreme sea level calculations were based on beach slope and historical wave-runup observations.

Extreme sea level data from the regional studies were used for areas of coastline where they had been produced.

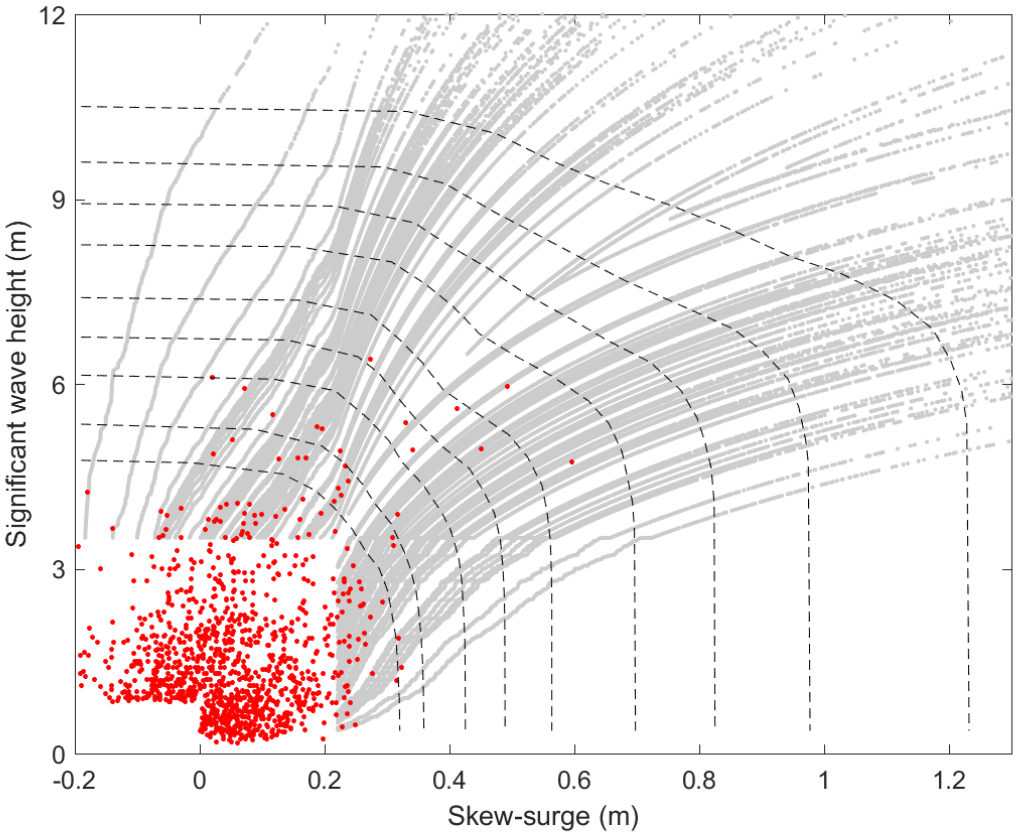

Figure 3-1: Joint-probability analysis of skew-surge and significant wave height at Mount Maunganui. Red dots represent measured data; grey dots represent data 10,000-years of simulated data, and dashed lines represent joint-probability contours for 63, 39, 18, 10, 5, 2, 1, 0.5, 0.2%, from largest (most frequent) AEP on the inside to smallest (least frequent) AEP on the outside. There is a naturally-strong dependence between skew-surge and wave height observed in both the measured and simulated data—both tend to grow extreme together. Analysis based on Heffernan,Tawn (2004).

3.3.2 Extreme storm-tides

In regions with a sea-level gauge record, extreme storm-tide levels were calculated by fitting extreme-value models to the measured sea levels, as described by Stephens, S. A. et al. (2020). Storm-tide estimates were available from Stephens et al. (2020) for 30 locations with sea-level records. Stephens et al. (2020) applied a skew-surge joint-probability method (Batstone et al. 2013) to calculate ST frequency and magnitude distributions for NZ.

In regions with no sea-level gauge record, storm-tide elevations were calculated using linear relationships between MHWS-7 (see Section 3.2.3) and extreme storm-tide elevations (Figure 3-2) using methods described in Stephens, S. A. et al. (2020).

Table 3-1 illustrates the linear fit coefficients and Figure 3-2 provides examples.

Table 3-1: Linear fit scalars and coefficients. 1) storm-tide (ST) relationship to MHWS-7, 2) wave-setup (WS) estimation wave model parameters (WS = *w* × Hs99), and 3) observed and predicted ST + WS heights

AEP (%)	ST			WS		ST + WS	
	y-intercept	Scalar (× MHWS-7 (m))	r fit coefficient	Linear fit scalar (*w*)	r fit coefficient	Linear fit scalar (m)	r fit coefficient
39	0.21	1.17	0.99	0.33	0.55	0.97	0.47
18	0.23	1.2	0.98	0.39	0.58	0.97	0.47
10	0.25	1.23	0.98	0.44	0.59	0.97	0.49
5	0.26	1.25	0.97	0.48	0.59	0.97	0.52
2	0.28	1.29	0.97	0.53	0.61	0.97	0.59
1	0.28	1.32	0.96	0.56	0.62	0.96	0.63
0.5	0.28	1.35	0.96	0.6	0.62	0.96	0.69
0.2	0.29	1.39	0.95	0.66	0.60	0.95	0.73
0.1	0.29	1.42	0.94	0.70	0.58	0.95	0.79

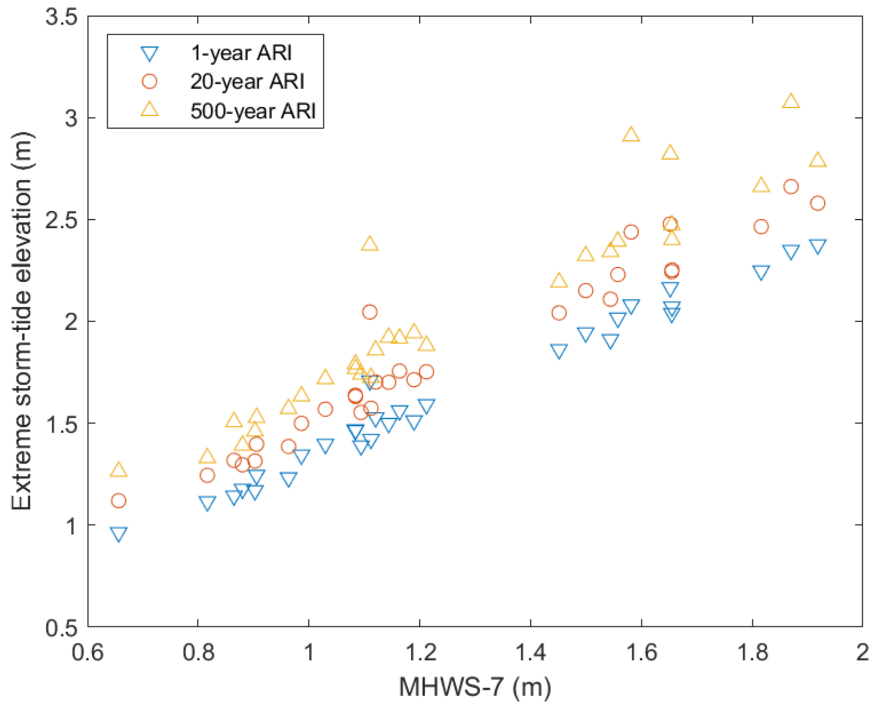

Figure 3-2: Linear relationship of storm tide and MHWS-7. For shown ARI.

3.4 Wave setup

Waves contribute to the elevated water level at the coast through a process of wave breaking leading to wave setup. This is an additional increase in the water level cause by the energy released due to wave breaking continually 'pushing water up' at the coast.

Two methods were used to derive wave setup:

1. Using data from available regional studies conducted by NIWA.
2. Using modelled wave heights around NZ to estimate wave setup as a proportion of wave height, after calibration against regional study information.

At other locations without more detailed information we reasoned that wave setup would be proportional to wave energy around New Zealand. We used a 45-year (1957–2002) wave hindcast of wave conditions around New Zealand (Gorman et al. 2010; Godoi et al. 2016) to extract the 99th percentile significant wave height (H_s^{99}) (Figure 3-3). We extracted H_s^{99} at 13 locations where we had regional data available (Figure 3-4) to develop linear relationships between H_s^{99} and wave setup corresponding to various ARI/AEP, at the regional study sites (Figure 3-5, Figure 3-6). The linear relationships were then used to calculate wave setup around NZ, based on H_s^{99} (Table 3-1).

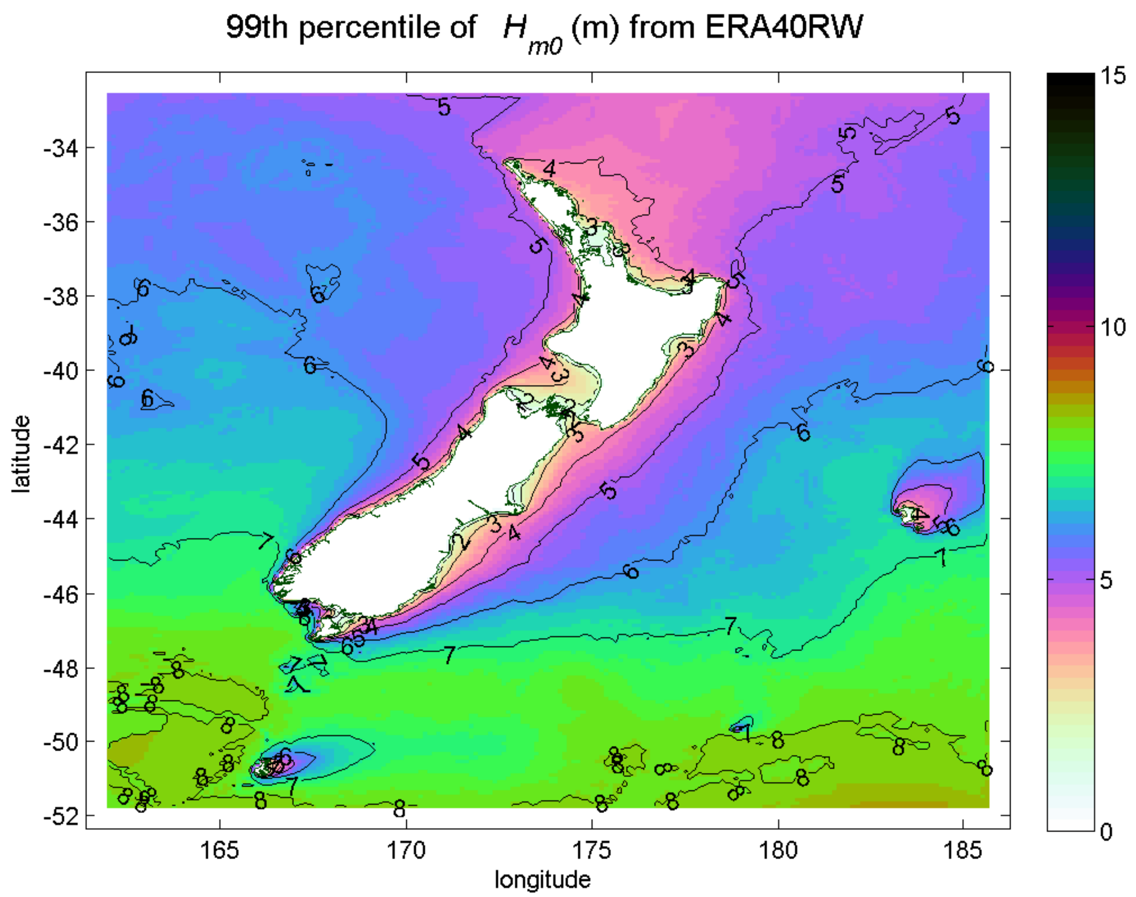

Figure 3-3: 99th percentile significant wave height (H_{m0}) around New Zealand. Derived from 45-year (1957–2002) wave hindcast.

A notable limitation is that there are no verification sites on the west coast (Figure 3-4). We are reasonably confident in the storm-tide elevation predictions on the west coast because the tides are highly predictable and there were sea level records available. But there is much greater uncertainty in the wave setup component. If the west coast beaches are more highly dissipative (of wave energy) than those on the east coast then a logical consequence is to overpredict the wave setup component on the west coast due to the higher wave energy and underpredicted dissipation (Figure 3-3).

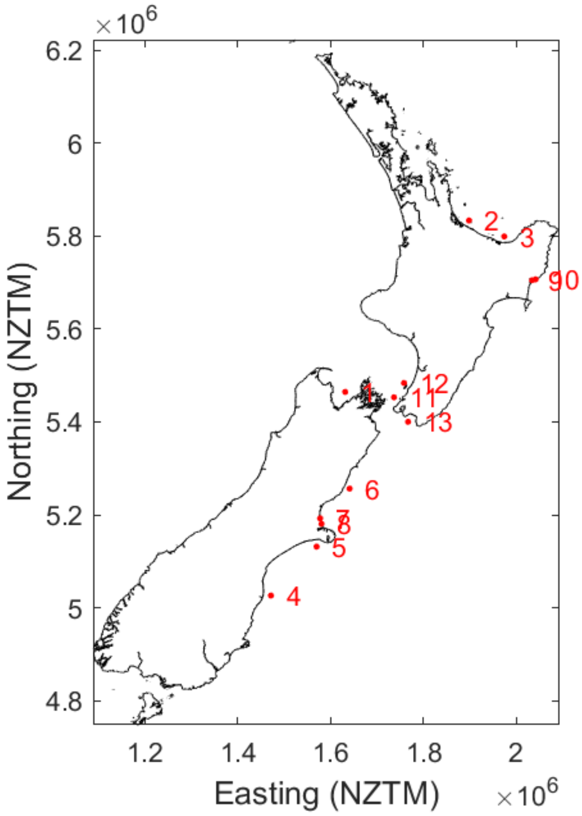

Figure 3-4: Location of Coastal Calculator extraction sites used to estimate wave setup. Sites 7,8 (Christchurch) and 9,10 (Gisborne) are close together.

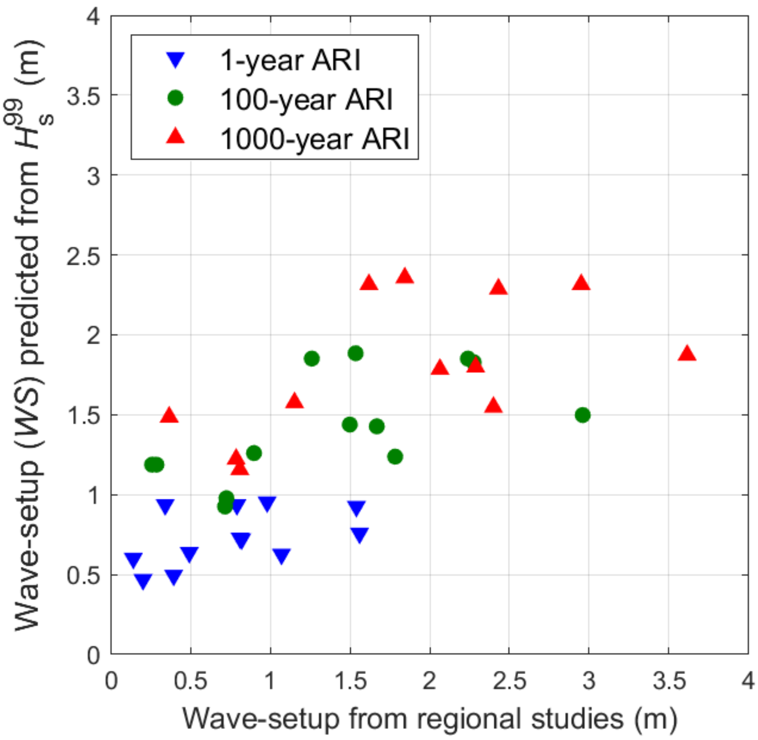

Figure 3-5: Comparison of wave-setup predictions (using linear fits to wave height, Table 3-1) and observations (from regional studies) for three ARI scenarios.

All the wave setup elevations shown in Figure 3-5 are from open coast sites, outside of estuaries. Estuaries are relatively sheltered environments where waves tend to be internally generated by wind of limited fetch and duration. Swell propagation into estuaries tends to be limited by wave breaking on the offshore bar. We applied a constant WS height of 0.2 m at locations inside estuaries and for all ARI's. This simplification was thought to be reasonable for a national-scale analysis and is based on calculations of wave setup inside Tauranga Harbour during extreme wind conditions (Reeve et al. 2019).

3.5 Storm tide + wave setup elevations

Figure 3-5 shows scatter plots of regional studies versus predicted storm-tide + wave setup, for 1, 100 and 1000-year ARI. The linear *r* fit coefficients for the prediction of *WS* averaged 0.59 across all AEP and thus were considerably weaker than for the prediction of *ST* (Table 3-1). Lower predictability for *WS* was expected and reflects the considerable influence of site-specific factors influencing the across-shore translation of breaking waves into wave setup at the shoreline. When *WS* is added to *ST*, the linear relationships between the predictions and the regional studies averaged 0.60 across all ARI. These relationships provide a method of predicting storm-tide + wave setup around NZ based objectively on wave energy exposure and tide.

Extreme sea levels were calculated around New Zealand for average recurrence intervals of 2, 5, 10, 20, 50, 100, 200, 500 and 1000 years.

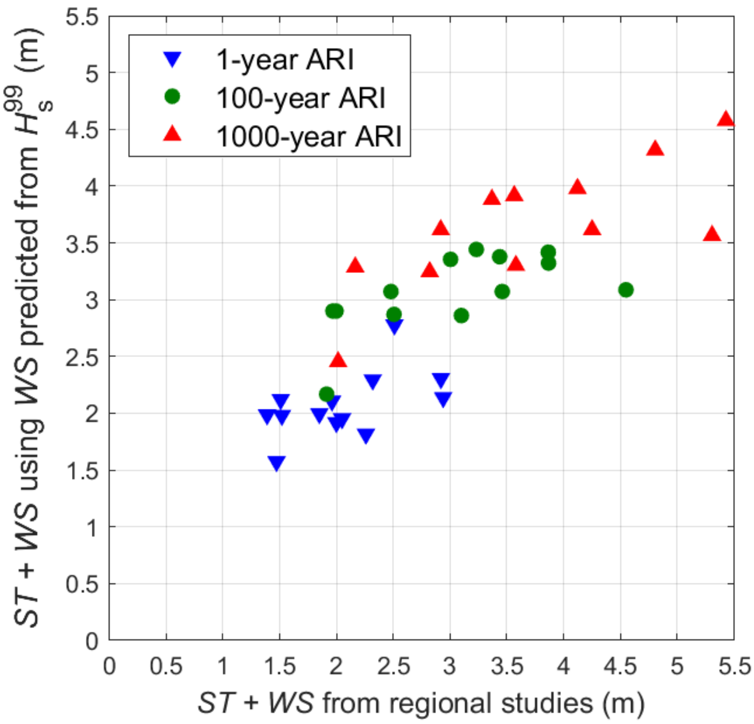

Figure 3-6: Comparison of storm-tide + wave-setup predictions (including wave-setup predictions, Table 3-1) and observations (from regional studies) for three ARI scenarios.

3.6 Extreme sea levels around New Zealand

Figure 3-7 and Figure 3-8 illustrate the final storm-tide + wave setup elevations for New Zealand.

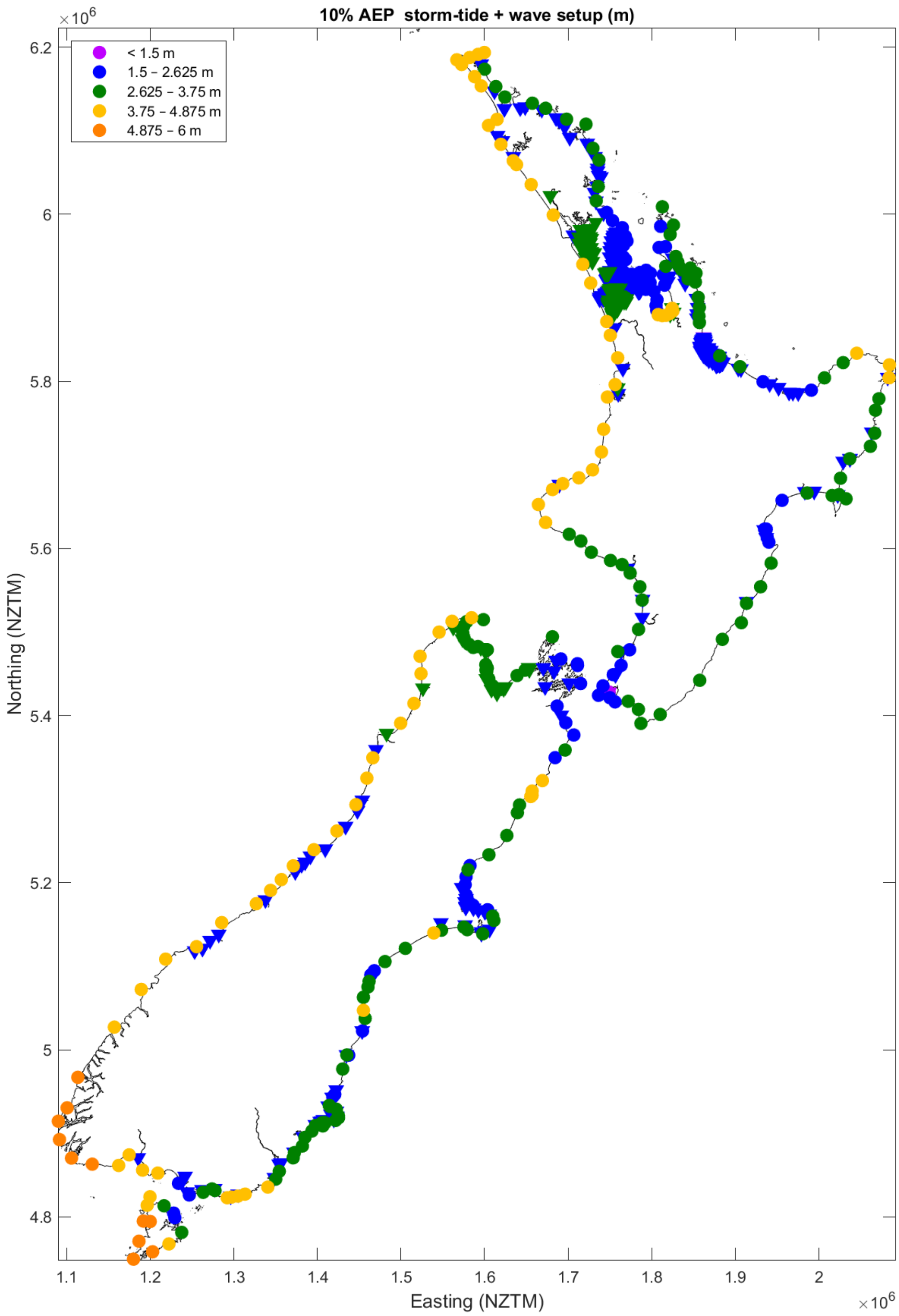

Figure 3-7: 10% AEP storm-tide + wave-setup elevations around New Zealand. ▽ = estuarine location, ○ = open coast location.

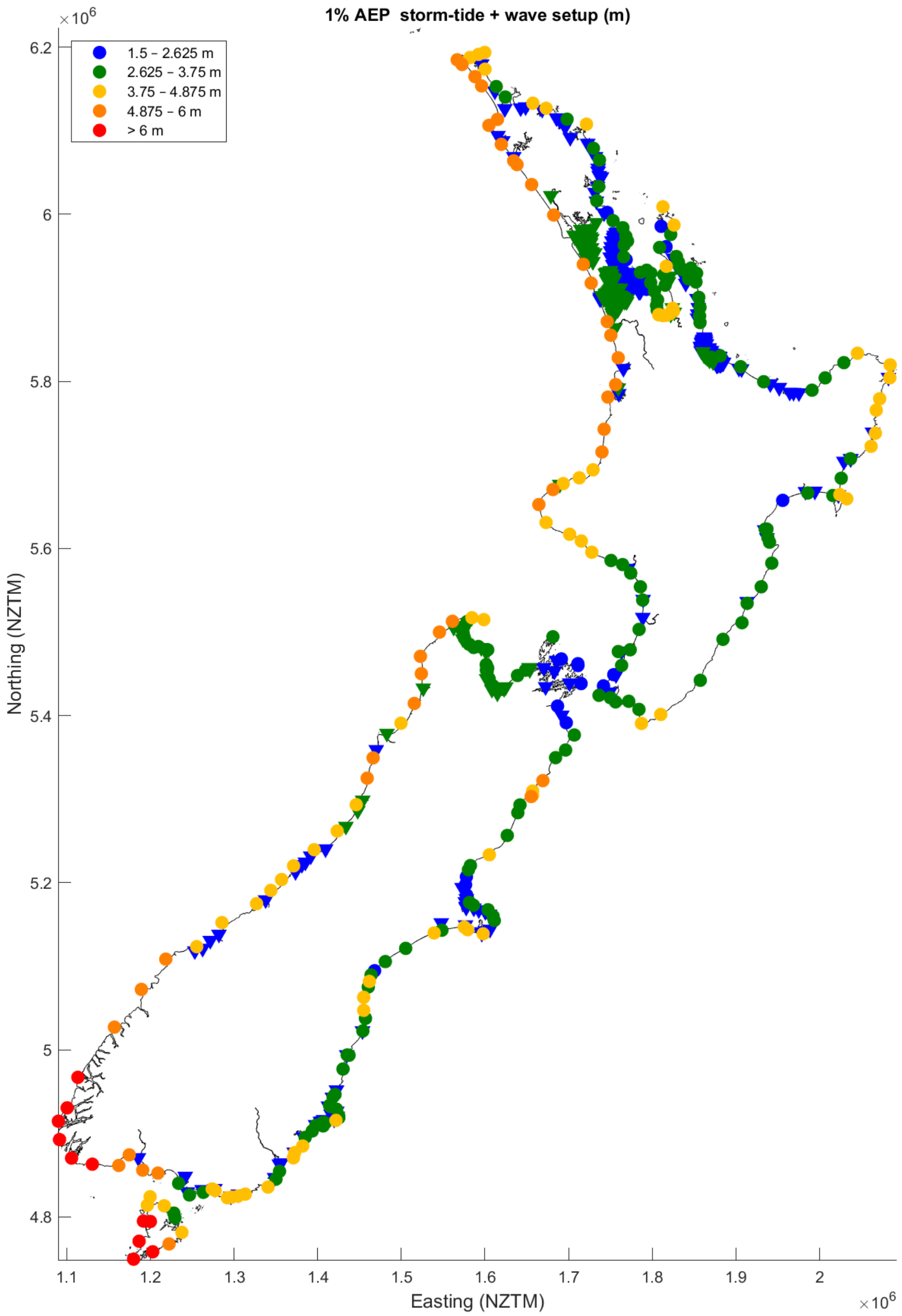

Figure 3-8: 1% AEP storm-tide + wave-setup elevations around New Zealand. ▽ = estuarine location, ○ = open coast location.

3.7 GIS mapping of coastal flooding

3.7.1 Digital elevation model

Coastal-flood mapping requires high resolution DEMs (Gesch 2018). Airborne light detection and ranging (LiDAR) topography surveys are managed by LINZ[1]. LiDAR DEMs represent 71% of New Zealand's mainland coastlines, with six regions exceeding 90% coverage in 2022 (Figure 3-9). Regional coverage is variable as LiDAR DEMs are acquired by regional or territorial authorities for coastal and resource management purposes. These organizations have routinely conducted LiDAR surveys since 2003, sampling at point density rates ranging from 1–4 per 1 m^2 (urban land) to 1 per 25 m^2 (rural land) (Paulik et al. 2020). Higher densities for urban land have higher vertical accuracies ranging between ±0.05 m to ±0.25 m at 1 standard deviation or ±0.07 m to ±0.10 m at the 95% confidence interval. 'Bare-earth' DEMs are created for horizontal grids with 1 m representing most urban land. Here, vertical and horizontal LIDAR DEM resolutions were considered sufficient for coastal-flood mapping at 0.1 m RSLR increments.

LINZ has a programme to complete coverage of LiDAR around New Zealand's coastal areas and plans to have all coastal areas covered by 2024[2].

LiDAR was acquired or converted to the local vertical datums (LVD) for each region where the LVD corresponded to the extreme sea-level analysis for each region via MSL offset to datum (Table A-1).

National coastal-flood mapping in this study required a composite DEM formed from LiDAR and satellite derived topographic data. Here, we applied a fully convolutional neural network (FCN) model based on Meadows,Wilson (2021) to correct vertical biases in the Shuttle Radar Topography Mission (SRTM) (Farr et al. 2007) for coastal land without LiDAR DEM coverage. Using the SRTM DEM from EarthExplorer (http://earthexplorer.usgs.gov/) at a resolution of 1 arc-second (30 m) (JPL/NASA 2021), the FCN model was trained to correct the DEM over land up to 20 m elevation above MHWS-10. SRTM DEM vertical error reduction for regions with partial LiDAR coverage were evaluated for land overlapping local LIDAR DEMs resampled to 30 m.

Topographic elevation data often lacks the resolution to represent mitigation structures acting as barriers to coastal flooding. In large-scale coastal-flood mapping studies, mitigation structures are treated in several ways including parameterization of inundation grids as protected land (Vousdoukas, M. I. et al. 2016) and setting uniform levee crest level heights (Scussolini et al. 2016). Here, we adopt the latter approach using the New Zealand Inventory of Stopbanks (NZIS) to represent linear mitigation structures i.e., levees (Crawford-Flett et al. 2022). Structure design levels for ESL protection were absent therefore we implemented 1) a 10 m buffer around polyline features representing the protection structure crest, 2) raster clip of LiDAR and SRTM DEM grid cells within the buffered area polygon, 3) increase grid cell elevation heights up to a minimum 1% AEP ESL for the corresponding coastline segment, and 4) merge elevation height adjusted grid cells into the original LiDAR and SRTM DEM. This approach assumes land protection up to 1% AEP ESL heights, consistent with regulatory requirements to manage adverse ESL and RSLR effects over a future 100-year period (Minister of Conservation 2010). We note individual mitigation structure design levels vary, affording land protection less than or exceeding 1% AEP ESL heights.

[1] https://data.linz.govt.nz/
[2] https://linz.maps.arcgis.com/apps/MapSeries/index.html?appid=2552c3a5cee24f7b87806b085c3fee8a

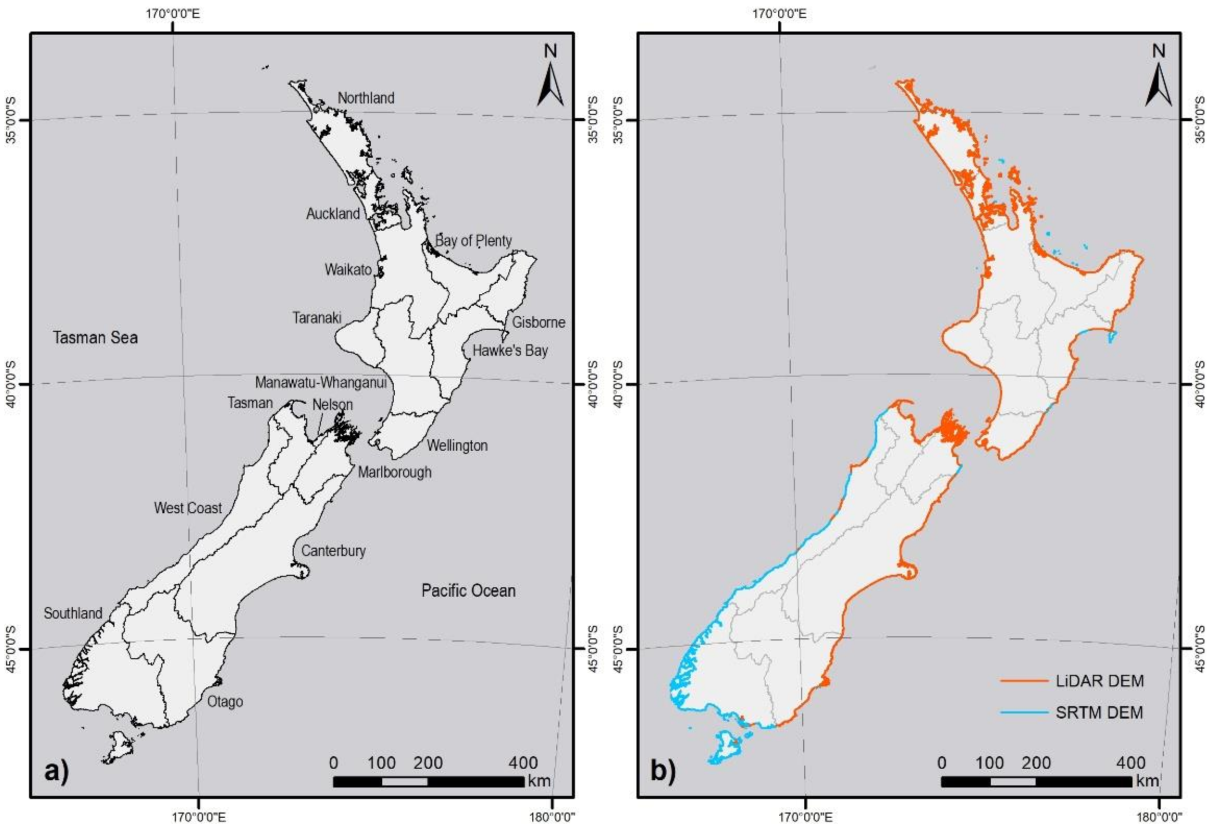

Figure 3-9: (a) New Zealand regional authority boundaries, and (b) coastline coverage represented by LiDAR and SRTM DEMs.

3.7.2 Coastal-flood mapping

Coastal flooding was mapped using a static approach as described by Breilh et al. (2013) and Stephens, Scott A. et al. (2021). This has several advantageous for nationwide coastal-flood mapping being 1) implementation in a GIS environment using geoprocessing and spatial interpolation functions; 2) low computational demand for operation on a standard personal computer. The static approach was implemented in two phases 1) ESL water surface model and 2), coastal-flood grid development.

ESL heights for coastline segments were converted into space-varying water surface grids prior to coastal-flood mapping. Firstly, ESL height points are converted into polylines with z values forming a connected ESL water surface between points. Polylines were split into 100 m segments, creating 53,000 ESL height points for New Zealand's mainland coastline. Water surface grids for land above MHWS were produced for ESL heights using a spline interpolation. Several coastal environment areas represented as polygons were created to spatially confine water surfaces which included 1) a WS zone limited to 100 m inland of MHWS, and 2) small (e.g., tidal lagoons, tidal river mouth, freshwater river mouths) and large (e.g., shallow drowned valley, deep drowned valley, fjord) estuaries (Hume et al. 2016). This simplified approach limits WS inland influence, assuming land inundation beyond the WS zone and opposite small estuaries is primarily driven by ST.

Water surface grids were applied in a static "bathtub" approach for coastal-flood mapping. Horizontal inundation is determined where grid cells at least one of its cardinal neighbours are inundated and hydraulically connected to the coastline (Yunus et al. 2016). Inundation depth above ground can also be computed for DEM grid cells from the difference between ESL water surface height and underlying terrain elevation. Inundation grids for LiDAR DEM coverage were resampled to 2 m in medium to major urban areas, 10 m outside these areas and 30 m for the STRM DEM areas. Variable grid resolution considers the need to represent potential topographical barriers affording land protection from coastal flooding.

4 Assumptions and limitations

Many New Zealand Councils have undertaken coastal flood mapping, some using hydrodynamic models calibrated using local measurements of sea levels, waves and wave runup. The Aotearoa-New Zealand extreme sea level flooding maps and data were produced at a whole of Aotearoa-New Zealand scale and were not designed to replace more detailed regional or local data where this is available for planning purposes. There may be a mismatch between the two products. We will endeavour to continually upgrade the Aotearoa-New Zealand extreme sea level flooding maps to match regional studies.

Various NZ Councils have used regional joint-probability studies to drive simulations of coastal flooding, using either dynamic or static (bathtub) models. Despite matching offshore storm-tide + wave setup conditions, where dynamic models were used by Councils, this may result in a mis-match between Council dynamically mapped products and the Aotearoa-New Zealand extreme sea level flooding maps, which used a static (bathtub) mapping method.

Dynamic models often determine coastal-flooding more reliably than static models, particularly on flat terrain where frictional effects strongly influence the horizontal extent of inundation (e.g., Ramirez et al. 2016; Didier et al. 2019; Kumbier et al. 2019; Stephens, Scott A. et al. 2021). Static flood mapping usually results in an over estimation of coastal flood extents from storm-tide levels. This is demonstrated by the comparative flooding extents from 'static' and 'dynamic' models in Figure 4-1 and Figure 4-2. The static models show that more flooding (depth and extent) is indicated when the dynamics of the flooding process (e.g., depth, velocity, duration) are not included. This is illustrated in Figure 4-2 where the static model overestimates flooding north of the main river feature where the topography is relatively lower with distance from the coast. Little difference in flooding occurs south of the river where topography is steeper.

Coastal flooding overestimation is unquantified though likely, particularly where the static model combined with coarser DEM vertical and horizontal resolutions does not sufficiently represent mitigation structures impeding flood flows (Breilh et al. 2013; Gesch 2018; Paprotny, D. et al. 2019). Incomplete information on mitigation structure geometries and design levels in NZIS (Crawford-Flett et al. 2022) further reduces capacity for the static model to limit inundation over flat terrains where land is protected. This is identified in several large-scale coastal-flooding investigations (Vousdoukas, Michalis I. et al. 2018b; Bates et al. 2021), emphasizing detailed mitigation structure design as a critical input dataset for accurate coastal-flooding and uncertainty quantification using either static or dynamic model approaches. Despite these limitations, our model approach provides national coastal-flooding scenarios that identify hazard exposure across different spatial and temporal scales. This information can be used to signal where dynamic models are required to conduct detailed investigations of coastal-flood hazards and risk.

Dynamic inundation approaches based on hydraulic models were not considered here due to their complexity and computational expense. While complex processes driving episodic inundation (e.g., nearshore waves, erosion, wave run-up) are simplified by static-based models (Vousdoukas, M. I. et al. 2018a), efficient and scalable inundation mapping approaches can outbalance a need for higher resolution maps. Such models hold practical appeal for decision makers with statutory or non-statutory requirements for disclosure of climate hazard and adaptation trends (e.g., United Nations International Strategy for Disaster Reduction, 2015). In this case, static models can suitably inform both national and jurisdictional level ESL inundation hazard exposure and risk 'hotspot' identification, monitoring of socio-economic exposure and hazard risk changes in response to land use policy settings or analyse mitigation structure design-level performance requirements for risk avoidance (Mechler et al. 2014; Paprotny, Dominik and Terefenko 2017). However, users must critically assess inundation map accuracy and limitations to determine appropriateness for statutory hazard and risk management. In the New Zealand context this knowledge requires ongoing research on ESL inundation hazard variability caused by DEM accuracy and resolution, hydrodynamic processes mitigation structure design, static and dynamic model types applied in different coastal settings (Vousdoukas, M. I. et al. 2018a; Stephens, Scott A. et al. 2021).

Figure 4-1: Comparison of dynamic model of flooding (blue) with static model (red). The scenario modelled was a 1% AEP storm-tide + 1.25 m SLR in Tauranga. Source: Reeve et al. (2019).

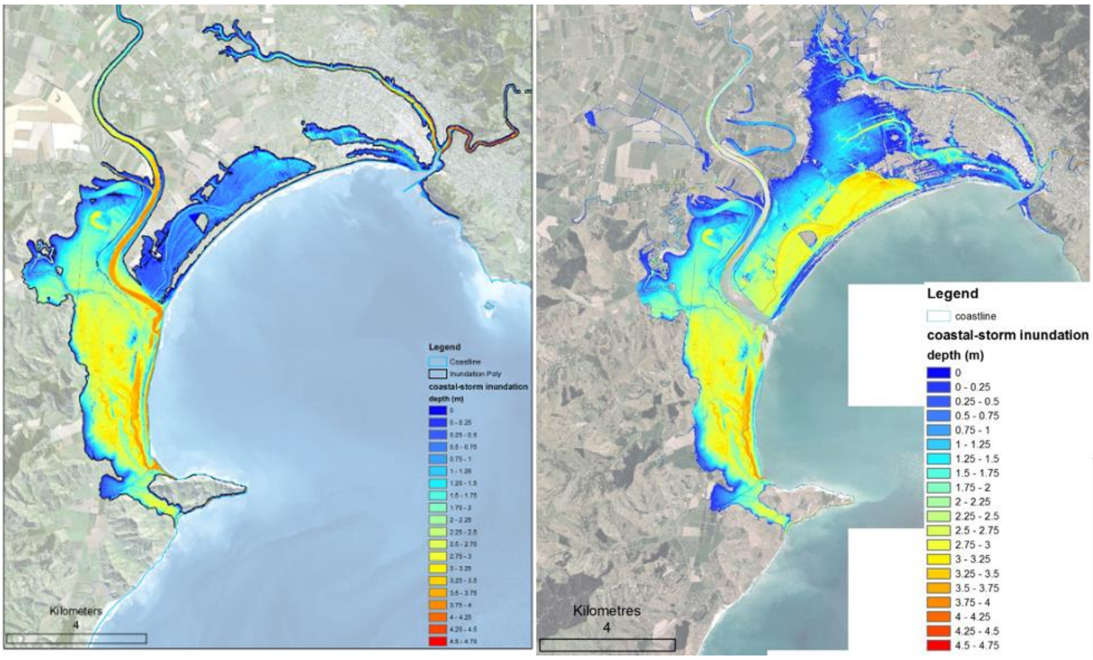

Figure 4-2: Comparison of dynamic model of coastal flooding (left) with bathtub model (right). Note the larger coastal flood extent created by the bathtub model. Source: Stephens, Scott A et al. (2015b).

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The authors gratefully acknowledge provision of sea-level data from various port companies and regional councils in New Zealand and from National Institute of Water and Atmospheric Research.

6 Glossary of abbreviations and terms

Annual Exceedance Probability	Annual Exceedance Probability (AEP) refers to the probability of a flood event occurring in any year. The probability is expressed as a percentage. For example, a storm-tide level which may be calculated to have a 1% chance to occur in any one year, is described as 1% AEP.
Average recurrence interval	Average recurrence interval (ARI) which is the average time interval between events of a specified magnitude (or larger), when averaged over many occurrences.
Coastal flooding	Coastal flooding occurs when normally dry, low-lying land is flooded by seawater.
DEM	Digital elevation model
Exposure	A feature is exposed (true/false) to the hazard layer.
GIS	Geographic information system.
LiDAR	Airborne Light Detection and Ranging (LiDAR), is a remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth.
MHWS	Mean high-water springs.
MHWS–7	MHWS–7 is the level equalled or exceeded by the highest 7% of all high tides
MSL	MSL is the mean level of the sea relative to a vertical datum over a defined epoch, usually of several years.
MSLA	Sea-level anomaly (MSLA) is the variation of the non-tidal sea level about the longer term MSL on a monthly to inter-annual timescale. Causes include ENSO patterns on sea level, winds and sea temperatures, and seasonal effects.
Present-day MSL	The best estimate of mean sea level for a region at time of writing, relative to local vertical datum.
RCP	Representative Concentration Pathways. IPCC and researchers world-wide base their projections for sea-level rise on four Representative Pathway Concentrations (RCPs). These 4 scenarios are representative of four different groupings of future radiative forcing (warming) by greenhouse gas emissions and associated social, economic, population and land-use projections.
Significant wave height	The average height of the highest one-third of waves in the wave record

RSLR	Relative sea-level rise—the sea level that is observed with respect to a land-based reference frame. This includes effects of vertical land motion as well as sea-level rise.
SLR	Sea-level rise. The rise in mean sea level over time. The main contributors to the global rise in sea level since the 1900 are 1) Warming of ocean waters causing expansion in seawater volume 2) Melting or break-up of land-based ice stores such as glaciers and polar ice sheets (particularly Greenland and West Antarctica), 3) changes in water properties or flowpaths of the main ocean currents, and 4) changes in the net storage of terrestrial freshwater e.g., groundwater/river extraction, reservoirs, changes in rainfall and evaporation from climate variability e.g., El Niño/La Niña. Local processes also contribute to SLR on a local scale, including, for example: subsidence of large river-delta systems or from pumping of underground aquifers or oil/gas reservoirs, tectonic effects (slow regional uplift/subduction).
Storm surge	The temporary rise in sea level due to storm meteorological effects. Low atmospheric pressure causes the sea-level to rise, and wind stress on the ocean surface pushes water down-wind and to the left up against any adjacent coast.
Storm-tide	Storm-tide is defined as the sea-level peak during a storm event, resulting from a combination of MSL + SLA + tide + storm surge. In New Zealand this is generally reached around high tide.
VLM	Vertical land motion—may occur due to tectonic movements, ice mass loading, glacial isostatic adjustment), or local site instabilities due to, for example, compaction, sedimentation, or water, oil, or gas extraction (Denys et al. 2020)
Wave runup	The maximum vertical extent of wave "up-rush" on a beach or structure above the still water level, and thus constitutes only a short-term upper-bound fluctuation in water level relative to wave setup
Wave setup	A sustained increase in the mean water level at the shore compared to the level further offshore beyond the surf zone that is induced by the transfer of momentum from waves as they break over a sloping foreshore. Setup is localised to the surf zone but is a meaningful addition to the extreme storm-tide levels at the coast

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Appendix A Mean sea level around New Zealand

Table A-1: Mean sea level offsets from vertical datum. Includes notes on derivation. Analysis by Dr Rob Bell. The average MSL epoch centre is the year 2010.

Tide gauge site	Longitude E (WGS-84)	Latitude N (WGS-84)	MSL (CD or TG0) [m]	MSL epoch	No. of yrs	LVD name	Ref BM	BM above TG0 [m]	BM (LVD) [m]	BM (NZVD16) [m]	Offset: TG0 to LVD	Offset: TG0 to NZVD-2016	MSL (LVD) [m]	MSL (NZVD-16) [m]	Notes:
Opua - Bay of Islands	174.1211	-35.3122	1.50	2001–2019 (est)	19	OTP-64	A1DG (9)	4.681	3.1231	3.0494	1.558	1.632	-0.058	-0.132	Using 1993-94 Opua data (1.389 m), for same period Marsden Pt was 1.485 m and 1.60 m for 2001-2019 - so factor increase is 1.0774 - so for Opua factor * 1.389 m = 1.50 m. TGzero (CD) is rel to A1DG (9) BM - and used adjacent BM A1E6 for NZVD2016 offset
Whangarei Port	174.35	-35.767	1.85	2001–2019 (est)	19	OTP-64	A2Q9	5.182	3.27	3.1400	1.912	2.042	-0.062	-0.192	MSL for Sept 1999 to Jun 2007 from Hannah & Bell (2012) - pro-rat'd with same period at Marsden Pt (1.598 m) to estimate 2001-2019 MSL (needed a x factor of 1.01 or a 15 mm increase
Marsden Point	174.5	-35.842	1.610	2001–2019	19	OTP-64	DJM9	4.8160	3.1378	3.0700	1.678	1.746	-0.068	-0.136	
Port Auckland	174.76938	-36.8436	1.910	2001–2019	19	AVD-46	DD1N	5.2330	3.4878	3.1370	1.745	2.096	0.165	-0.186	
Tararu - Thames	175.52159	-37.12802		1998–2017	20	MVD-53	A6BM						0.170		<---- -0.370 m NZVD from JLAS!! JLAS file states MSL = 3.03 m below BM, which means MSL = 2.66 - 3.03 = -0.37 m. Equivalent MVD-53 level on BM = 3.050 m meaning MSL = +0.02 m

Tide gauge site	Longitude E (WGS-84)	Latitude N (WGS-84)	MSL (CD or TG0) [m]	MSL epoch	No. of yrs	LVD name	Ref BM	BM above TG0 [m]	BM (LVD) [m]	BM (NZVD16) [m]	Offset: TG0 to LVD	Offset: TG0 to NZVD-2016	MSL (LVD) [m]	MSL (NZVD-16) [m]	Notes:
															MVD-53 !!! Doesn't tie with Moturiki record and that MTL is set-up in Firth (from modelling). Instead used the 0.17 m MSL value for 1998--2017 in Table 2-1 of the Stephens (2018) NIWA report 2018289HN for Waikato RC on storm-tide analysis of Tararu record, which has been adjusted for vertical land movement and this relates to the more recent LiDAR
Whitianga	175.70884	-36.83258				MVD-53	BUGN			1.7530			0.164	-0.127	MSL of 1.88 m below BM - LINZ offsets for JLAS file. Used NZVD datum conversion tool for MVD-53. Confirmed by MSL in latter 5 yrs up to end of 2020 from Whitianga Gauge being 0.18 m relative to gauge zero (=MVD-53). Whitianga has known setup thru the ebb delta, so reduce general east Coromandel coast MSL offset to be 0.14 m and use 0.16 m inside Whitianga Harbour.
Moturiki	176.18547	-37.63097	1.604	2001–2019	19	MVD-53	AB5A	7.1000	5.6129	5.4201	1.487	1.680	0.117	-0.076	
Tauranga (Tug Whf)	176.18227	-37.64056	1.100	2000–2019	19	MVD-53	B309	4.1030	3.1368	2.9400	0.966	1.163	0.134	-0.063	

Tide gauge site	Longitude E (WGS-84)	Latitude N (WGS-84)	MSL (CD or TG0) [m]	MSL epoch	No. of yrs	LVD name	Ref BM	BM above TG0 [m]	BM (LVD) [m]	BM (NZVD16) [m]	Offset: TG0 to LVD	Offset: TG0 to NZVD-2016	MSL (LVD) [m]	MSL (NZVD-16) [m]	Notes:
Lottin Point	178.1586	-37.5501	3.200	2008–2020	12	MVD-53	F4V2	6.3700		3.0400			0.123	-0.160	Older TG0 used BM ECPK: - 4.59 m below ECPK in LINZ Get Data site. Calculated MVD-53 level from LINZ Conv page
Gisborne Port	178.0263	-38.67356	1.260	2004–2019	15	GVD-26	ACVP	4.0910	3.0364	2.6920	1.055	1.399	0.205	-0.139	
Napier Port	176.9201	-39.476	0.970	2001–2019	19	NVD-62	B3XM	4.8370	3.9057	3.7195	0.931	1.118	0.039	-0.148	
Wairarapa coast						WVD-53							0.226		Interpolate between Napier and Wgtn. Offset between NVD-62 and WVD-53 at Kairakau (A3Y4) using online converter is 0.187 m -so Napier MSL is ~0.039+0.187 = 0.226 m WVD-53. Wgtn below is 0.228 m. So approximately the same as Wellington value
Wellington Port	174.77694	-41.2853	1.130	2001–2019	19	WVD-53	ABPC	3.5650	2.6625	2.3063	0.903	1.259	0.228	-0.129	
Porirua Hbr at Mana Cruising Club	174.866	-41.1	1.100	2010–2020	11	WVD-53	C1K1	2.5500							From GWRC monitoring site: http://graphs.gw.govt.nz/ Porirua Mana gauge has an average of 1.105 m above CD from 2010-2020 (incl) - rounded down to 1.10 m as most other sites cover 19 yrs. From DML 13 Feb 2015 hydro survey report for Porirua Hbr, CD is 2.55 m

Tide gauge site	Longitude E (WGS-84)	Latitude N (WGS-84)	MSL (CD or TG0) [m]	MSL epoch	No. of yrs	LVD name	Ref BM	BM above TG0 [m]	BM (LVD) [m]	BM (NZVD16) [m]	Offset: TG0 to LVD	Offset: TG0 to NZVD-2016	MSL (LVD) [m]	MSL (NZVD-16) [m]	Notes:
															below BM C1K1 - BUT no level on this??
Port Taranaki	174.033	-39.055	1.960	2000–2019	19	TVD-70	AGMH	6.7090	4.8972	4.6077	1.812	2.101	0.148	-0.141	
Kawhia	174.8232	-38.0659		2008–2020	12	MVD-53	EW67		2.3080	2.0200			0.278	-0.010	Used recent JLAS levelling - no MVD-53 level directly available. Estimate using LINZ Coord Transform for same BM gives 2.308 m MVD-53
Manukau Entr	174.5117	-37.0466	3.650	2010–2020	10	AVD-46	EW4T			3.5500			0.187	-0.100	Older TG0 used BM EFYL: - 5.209 m below EFYL in LINZ get data page. Calculated AVD-46 from LINZ Conv site
Onehunga	174.7841	-36.933	2.430	2001–2019	17	AVD-46	ADLT	5.5930	3.3890	3.1000	2.204	2.493	0.226	-0.063	
Port Albert - mid Kaipara Hbr						AVD-46	F4C1		3.0630	2.7500			0.270	-0.040	Used recent JLAS levelling - no AVD-46 level directly available. Estimate using LINZ Coord Transform for same BM gives 3.063 m AVD-46 (so offset between datums is 0.313 m
Pouto Point - Kaipara	174.1816	-36.3626	2.301	2004–2019	15	OTP-64	B5R9	5.3270	3.1700	2.8800	2.157	2.447	0.144	-0.146	From Tideda file held by NIWA for NRC data from Pouto
Nelson Port			2.350	2001–2019	19	NVD-55	AC4T	5.733	3.490	3.1546	2.243	2.578	0.107	-0.228	
Picton			0.870	2005–2019	6	NVD-55	BQFK	2.716	2.039	1.7200	0.677	0.996	0.193	-0.126	
Lyttelton	172.7222	-43.6058	1.420	2001–2019	18	LVD-37	B40V	4.478	3.237	2.8300	1.241	1.648	0.179	-0.228	
Timaru Port	171.254	-44.392	1.480	2002–2019	18	LVD-37	B2Y9	5.759	4.460	4.1294	1.299	1.630	0.181	-0.150	

Tide gauge site	Longitude E (WGS-84)	Latitude N (WGS-84)	MSL (CD or TG0) [m]	MSL epoch	No. of yrs	LVD name	Ref BM	BM above TG0 [m]	BM (LVD) [m]	BM (NZVD16) [m]	Offset: TG0 to LVD	Offset: TG0 to NZVD-2016	MSL (LVD) [m]	MSL (NZVD-16) [m]	Notes:
Port Chalmers	170.6249	-45.8095	1.130	2001–2019	19	DVD-58	DR0F	3.816	2.800		1.016		0.114		
Dunedin Wharf			1.110	2001–2019	19	DVD-58	AFEQ	3.728	2.732	2.3700	0.996	1.358	0.114	-0.248	
Bluff Port			1.750	2001–2019	19	BVD-55	ABCC	8.620	7.009	6.6919	1.611	1.928	0.139	-0.178	
Westport			2.040	1999–2019	18	LVD-37	DJMC	7.327	5.548	5.1900	1.779	2.137	0.261	-0.097	Email of 12 Jan 2021 from Glen Rowe has MSL = 2.04 m above CD (not 1.75 m) and pre-Kaikoura CD was 7.327 m below BM