Coastal inundation and sea level rise assessment for the Hutt City District

Prepared for Hutt City Council

June 2023

Climate, Freshwater & Ocean Science

Prepared by:
Connon Andrews

For any information regarding this report please contact:

Connon Andrews
Manager: Coastal Climate Risk & Infrastructure
Coastal and Estuarine Processes Group
+64 9 375 2070
connon.andrews@niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
Private Bag 99940
Viaduct Harbour
Auckland 1010

Phone +64 9 375 2050

NIWA CLIENT REPORT No:
Report date: June 2023
NIWA Project: WCC23202

Revision	Description	Date
Version 0.1	Draft in preparation/in review	04/07/2023
Version 1.0	Final - Issued to HCC	06/07/2023

Quality Assurance Statement		
	Reviewed by:	Dr. Christo Rautenbach
	Formatting checked by:	Carole Evans
	Approved for release by:	Dr. Michael Bruce

Contents

Tables

Figures

Executive summary

Hutt City Council (HCC) is reviewing the coastal inundation hazard and future effects of sea level rise as part of the District Plan review. Prior assessments have been limited to static inundation assessments based on national scale studies (MacDonald et al., 2022) and focused on the Lower Hutt environ.

This study refines the hazard by harbour wide multi-variate analysis to establish spatial varying inundation levels including allowance for Relative Sea Level Rise (RSLR) that includes projected changes to Mean Sea Level (MSL) from climate change and vertical land motion (VLM) over a 100-year planning timeframe to the year 2130.

The multivariate analysis considers the joint probability of the effects of astronomical tide, storm surge as observed at Queens Wharf, wind, and wave effects on extreme water levels, including the potential increase in future storminess of 10% as per MfE (2017). For the Hutt City District open coast, extreme sea levels, that include wave setup as defined in a national assessment (Paulik et al., 2023), have been adopted.

The coastal inundation hazard has been assessed for two cases, permanent and intermittent. Permanent inundation is represented by Mean High Water Springs (MHWS) based on the astronomical tidal cycle and intermittent, represented by the 1% Annual Exceedance Probability (1%AEP) extreme sea level, equivalent to a 1 in 100-year event. Future impacts from RSLR have been assessed based on the SSP2-4.5 median, SSP5-8.5 median and SSP5-8.5 H^+ projections.

Inundation extent has been quantified via two methods, dynamically via numerical modelling (BG-Flood) for the low-lying Lower Hutt area that is sensitive to time dependent inundation and via static bathtub modelling for the steep foreshore and backshore areas, south of Point Howard to and including the Hutt City District open coast. Inundation hazard extents and depths, based on the dynamic and static modelling have been provided to HCC in the form of digital maps in GIS format.

The results from the inundation mapping show that the present day 1% AEP storm-tide and wave setup inundation extent is limited to the foreshore region and low-lying sections around the Hutt River margins. Elsewhere, the inland extent is limited due to the steep backshore area. When RSLR is considered, the predictions show an escalation in permanent and intermittent coastal inundation in the low-lying areas, with limited impact for steep backshore areas. Furthermore, all three RSLR projections predict that a large proportion of Lower Hutt is potentially exposed to coastal inundation with rising sea-levels.

1 Introduction

Hutt City Council (HCC) is reviewing the District Plan which includes consideration of natural hazards and climate change on existing and future land use. To inform the revision, HCC commissioned NIWA to map the potential permanent and intermittent coastal inundation hazard including allowance for sea-level rise (SLR) and vertical land motion (VLM) over a 100-year planning timeframe to the year 2130.

1.1 Project Scope

The coastal inundation assessment leverages the bathtub inundation assessment for Lower Hutt (MacDonald et al., 2022), the Wellington Region Inundation Assessment (Allis et al., 2021) and the National Inundation Assessment (Paulik et al., 2023). Furthermore, the assessment utilises the latest sea level rise projections (IPCC, 2021), estimates of vertical land movement from the NZSeaRise Programme[1] and MfE (2022) guidance on sea level rise scenarios and timeframes.

The work scope includes:

1. Assessment of extreme water levels throughout the Hutt City District based on multi-variate analysis for locations within the harbour and leveraging the national coastal inundation assessment (Paulik et al., 2023) for open coast locations.

2. Compiling relative sea level rise (RSLR) projections based on the MfE (2022) guidance with emphasis on SSP2-4.5 median, SSP5-8.5 median and SSP5-8.5 H+ climate change projections to the year 2130 including VLM.

3. Quantifying and mapping the inland extent and depth for the following scenarios:

    - Mean High Water Springs (MHWS), present day
    - MWHS in the year 2130 with SLR via SSP2-4.5 median
    - MWHS in the year 2130 with SLR via SSP5-8.5 median
    - MWHS in the year 2130 with SLR via SSP5-8.5 H+
    - 1% Annual Exceedance Probability (AEP) extreme sea level, present day
    - 1%AEP extreme sea level in the year 2130 with SLR via SSP2-4.5 median
    - 1%AEP extreme sea level in the year 2130 with SLR SSP5-8.5 median
    - 1%AEP extreme sea level in the year 2130 with SLR SSP5-8.5 H+

    MHWS is representative of permanent coastal inundation and the 1%AEP event is representative of intermittent coastal inundation, often referred to as a 1 in 100-year event. The assessment does not include riverine or groundwater flooding nor tsunami inundation or short-term inundation from wave run-up.

    Inundation extent has been quantified via two methods, dynamically via numerical modelling (BG-Flood) for the low-lying Lower Hutt area that is sensitive to time dependent inundation and via static bathtub modelling for the steep foreshore and backshore areas south of Point Howard to and including the Hutt City District open coast.

4. Integrate output from dynamic and static modelling to create spatial inundation maps that show the respective inundation extent and depth relative to NZVD 2016 in the form of GIS shape and images files.

[1] https://www.searise.nz/

1.2 Project Extent

The marine boundary of Hutt City District encompasses the northern and eastern margins of Wellington Harbour and extends along the Wainuimata open coast. Output locations used throughout the analyses are presented in Figure 1-1.

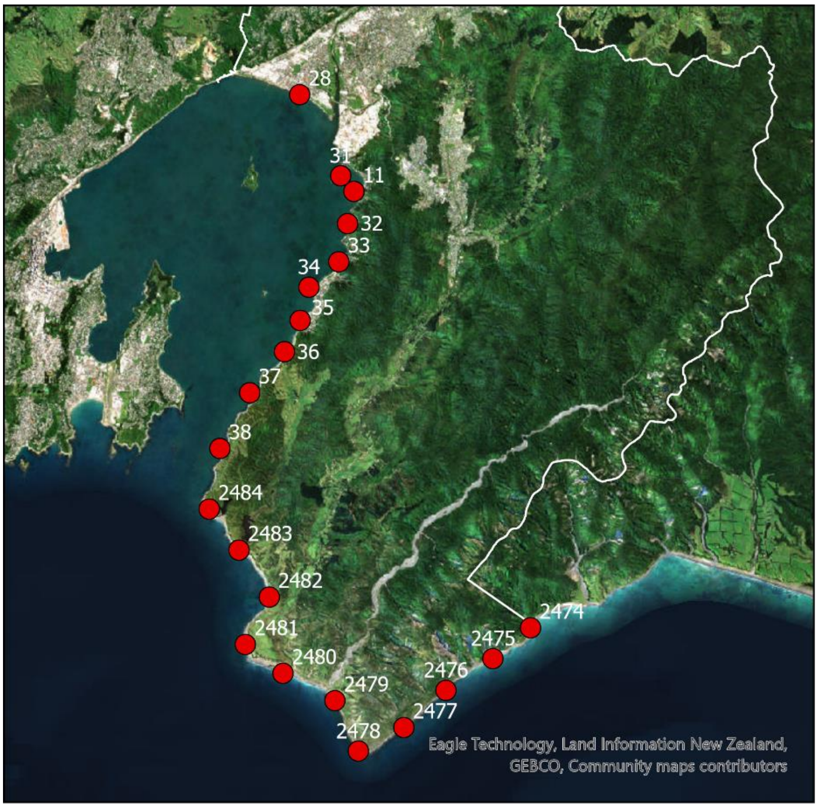

Figure 1-1: Reference locations used for extreme sea level and relative sea level rise analysis. White line is the Hutt City territorial boundary.

The naming convention for the reference locations within Wellington harbour is consistent with Allis & Gorman (2020) and the open coast locations is consistent with the NZSeaRise[1] mapping.

1.3 Vertical Datum

The vertical datum used for this study is NZVD 2016. All inputs, including LIDAR, tide levels, extreme sea levels and outputs are relative to this datum. NZVD 2016 is 1.259m above Chart Datum at Queens Wharf as defined by Land Information New Zealand (LINZ)[2,3].

[2] https://www.linz.govt.nz/guidance/marine-information/tide-prediction-guidance/standard-port-tidal-levels
[3] https://www.linz.govt.nz/guidance/marine-information/tide-prediction-guidance/standard-port-datum-descriptions

2 Background

2.1 Coastal Inundation

Coastal inundation 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 (refer to Figure 2-1). The processes involved are:

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

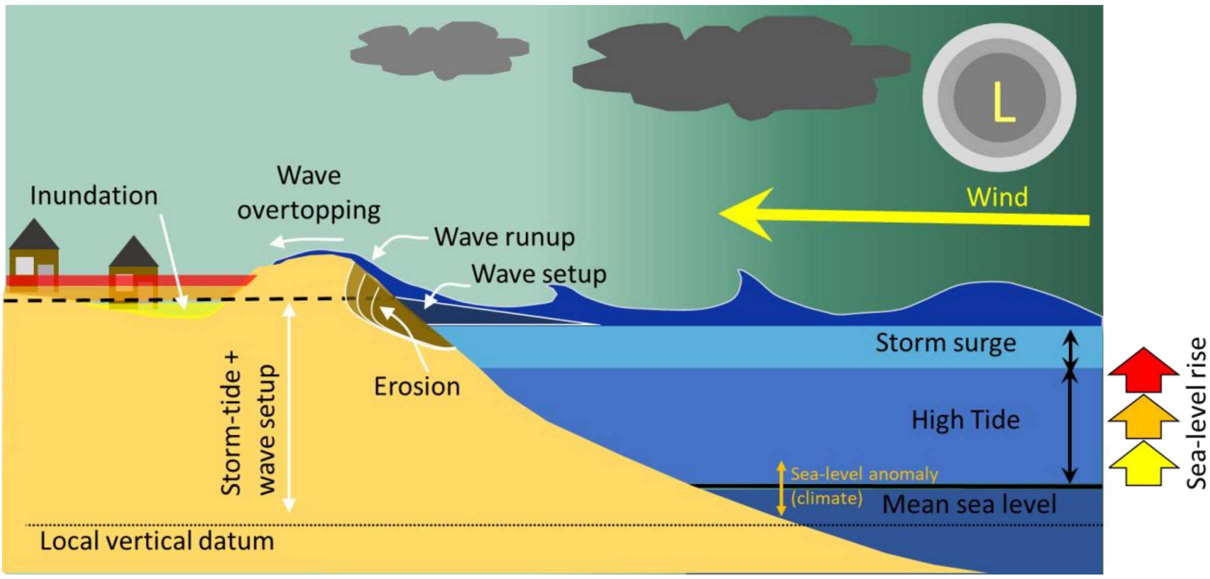

Figure 2-1: Illustration of coastal and ocean processes contributing to costal inundation.

Mean sea level (MSL) is the variation of the non-tidal sea level on longer time scales ranging from months to decades due to climate variability, including seasonal effects and the effects of El Niño–Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO) on sea level through changes or climate-regime shifts in wind patterns and sea temperatures.

Astronomical tides are tidal levels and water motion that result from Earth's rotation and gravitational effects, particularly the Earth, Sun, and Moon, without any atmospheric influences. In New Zealand astronomical tides are responsible for the semi diurnal tidal cycle and have the largest influence on sea level, followed by storm surge.

Low-pressure weather systems and/or adverse winds cause a rise in water level known as **Storm Surge**. Storm surge results from low-atmospheric pressure that causes the sea-level to rise and wind stress on the ocean surface that pushes water down-wind 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 + astronomical tide + storm surge. It is the storm-tide that is measured by sea-level gauges such as at Queens Wharf in Wellington Harbour.

Wave processes can also elevate sea levels at the coast with the effects more pronounced in swell dominated shallow water environments. **Wave setup** is the increase in mean sea level at the coast, elevated inside the surf zone from the release of wave energy as waves break in shallow water. During storm events wave setup can be pronounced generating a persistent average raised sea level at the shoreline that can result in direct coastal inundation. **Wave runup** is the maximum vertical extent of wave up-rush on a beach or structure above the still water level in the absence of 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. Typically, wave run-up does not contribute significantly to coastal inundation except in circumstances where wave run-up overtops a barrier and cannot readily escape back to the sea.

Inundation from freshwater sources such as rivers, streams and stormwater are potential contributors to coastal inundation. Should periods of intense rainfall and therefore high river levels coincide with extreme sea levels, coastal inundation is likely to be exacerbated. This is certainly relevant to Lower Hutt where considerable development has occurred over the original Hutt River floodplain.

2.2 Baseline Periods

Future projections of mean sea level as a result of climate change are referenced to baseline periods, with the latest AR6 IPCC (2021) projections relative to the 1995 to 2014 period. Two baseline periods are utilised in this assessment:

- 1995 – 2014: IPCC (2021) AR6 assessment mean sea level.
- 2022: representative present day MSL from 1/1/2022 to 31/12/2022.

MSL for each period based on data recorded at Queens Wharf and assumed to be spatially uniform throughout the district is provided in Table 2-1.

Table 2-1: Mean sea level (MSL) at Queens Wharf - Wellington.

Tidal Level	MSL m NZVD
Present day MSL (2022)	-0.13
1995-2014 MSL	-0.17

2.3 Tidal Levels

Tidal levels are monitored at Queens Wharf and selected published tidal levels with an emphasis on Mean High Water Springs (MHWS) and Mean Low Water Springs (MLWS) relative to NZVD 2016 for 2022 are presented in Table 2-2.

MHWS and MLWS are defined as the average of the levels of each pair of successive high waters, and of each pair of successive low waters, during that period of about 24 hours in each semi-lunation (approximately every 14 days), when the range of the tide is greatest (spring range).

LINZ further provides a "Cadastral MHWS" for cadastral and engineering purposes based on an 18.6-year period as opposed to the typical published nautical levels that are based on predictions for the next 12 months. The 18.6-year period captures the full range of oscillation of the orbital surface of the moon around the earth which causes long-term modulation of oceanic tides. The current LINZ 18.6-year duration is 1 January 2000 to 31 December 2018[4]. For this assessment the Cadastral MHWS (MHWS-C) has been used.

Table 2-2: Selected astronomical tidal levels for Queens Wharf, Wellington.

Tidal Level	Tide level m NZVD
Highest Astronomical Tide (HAT)	0.64
Mean High Water Springs (MHWS)	0.56
Mean High Water Springs Cadastral (MHWS-C)	0.51
Mean Sea Level (MSL)	-0.13
Mean Low Water Springs (MLWS)	-0.75
Mean Low Water Springs Cadastral (MLWS-C)	-0.81
Lowest Astronomical Tide (LAT)	-0.84
Chart Datum (CD)	-1.26

Source: https://www.linz.govt.nz/guidance/marine-information/tide-prediction-guidance/standard-port-tidal-levels (12 June 2023)

To delineate MHWS-C at each of the project reference locations (refer to Figure 1-1) MHWS7% as presented in Paulik et al. (2023) which is equivalent to MHWS-C for the Wellington region was adopted. MHWS-C is assumed to be spatially uniform throughout Wellington Harbour (locations 11 to 38). Along the open coast (locations 2474 to 2484) MHWS-C has been derived via spatial interpolation from the underlying NIWA national tide model that informs the Paulik et al. (2023) assessment. Table 2-3 presents MHWS-C for the baseline periods referenced to NZVD 2016.

Table 2-3: Mean High Water Springs Cadastral (MHWS-C) for project reference locations (m NZVD)

Location	MHWS-C (m) Present Day	MHWS-C (m) 1995-2014
11 to 38	0.51	0.47
2474	0.58	0.54
2475	0.56	0.52
2476	0.54	0.50
2477	0.53	0.49
2478	0.51	0.47
2479	0.51	0.47
2480	0.50	0.46
2481	0.49	0.45
2482	0.51	0.47
2483	0.50	0.46
2484	0.50	0.46

[4] https://www.linz.govt.nz/guidance/geodetic-system/coordinate-systems-used-new-zealand/vertical-datums/tidal-level-information-surveyors accessed 22 June 2023.

2.4 Vertical Land Movement

Vertical land movement throughout the Hutt City District has been quantified via the NZSeaRise project based on satellite measurements, albeit over a short duration. Estimates are presented in Figure 2-2 for the district in mm/year, with negative values showing subsidence.

The NZSeaRise estimates show a trend of overall subsidence with a range of -2.16 to -5.27 mm/year with an overall district average of -3.76mm/year. The NZSeaRise estimates show spatial variability as follows:

- Lower Hutt shoreline, an average subsidence of -3.00mm/year
- Eastern shoreline of Wellington Harbour, an average subsidence of -3.47mm/year
- Exposed open coast of the district, an average subsidence of -4.25mm/year.

The NZSeaRise estimates are consistent with ongoing landmass subsidence trend of -3mm/year based on GNSS inter-seismic ground motion over the past decade for Wellington Harbour (Allis et al., 2021).

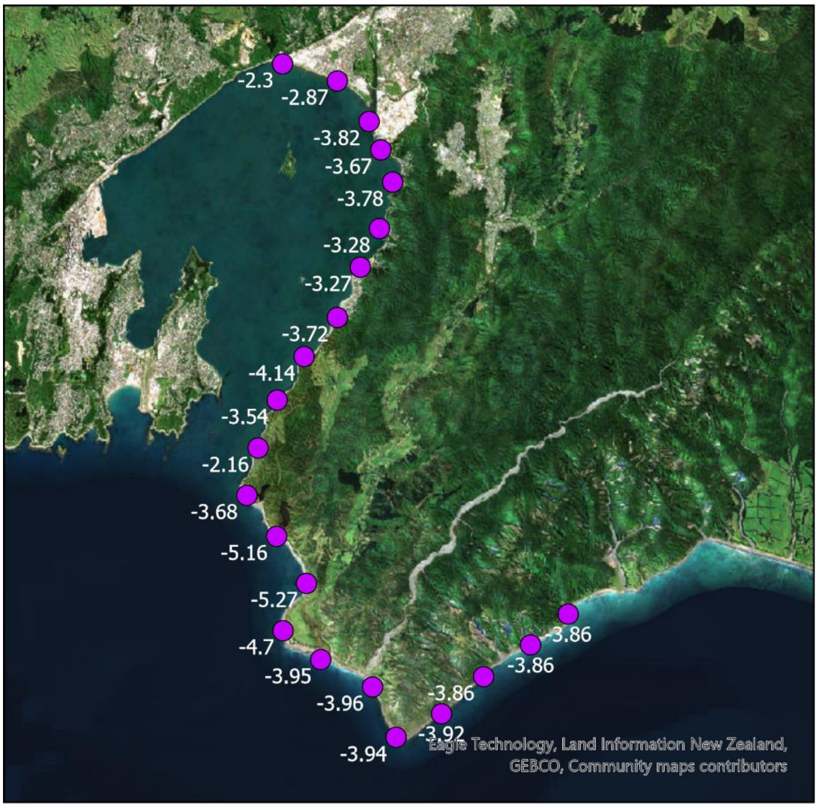

Figure 2-2: NZSeaRise Vertical Land Movement Estimates (mm/year).

2.5 Sea Level Rise

Future absolute SLR projections (excluding VLM) for Shared Socioeconomic Pathway (SSP) scenarios, out to the year 2150 are presented in Figure 2-3. MfE (2022) recommends the use of selected SSP scenarios, a timeframe out to 2130 and the use of SSP5-8.5H^{+} + VLM scenario for coastal subdivision, greenfield development, major new infrastructure and changes in land use and development including intensification.

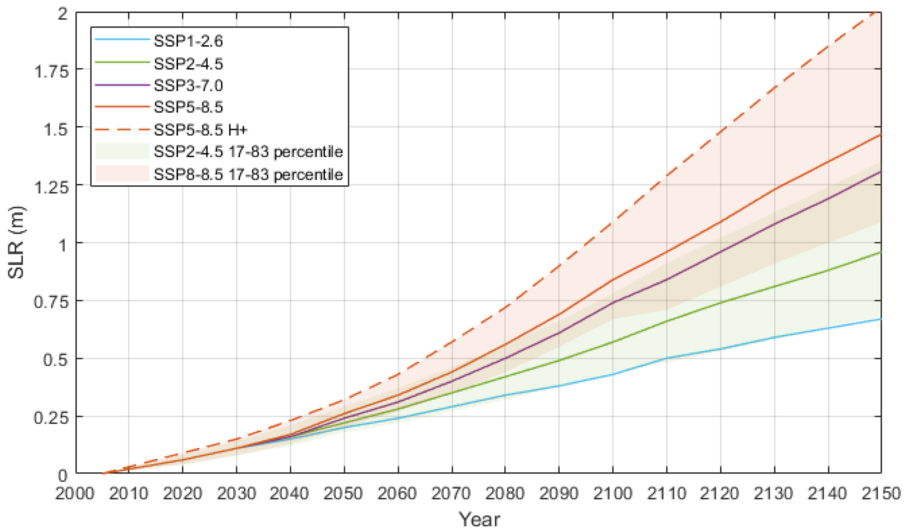

Figure 2-3: Absolute RSLR projections for Hutt City District w.r.t 1995-2014 baseline.

Consistent with MfE (2022) the SSP2-4.5, SSP5-8.5 and SSP5-8.5 H+ projections have been adopted for this study. Table 2-4 presents the magnitude of relative sea level rise at 2130 for each projection, including VLM derived from spatial interpolation of the NZSeaRise data for each reference location.

Table 2-4: Vertical land motion (mm/year) and relative sea level rise magnitude at the year 2130.

Location [c]	Longitude (deg)	Latitude (deg)	VLM (mm/year)	SSP2-4.5 (m) [a]	SSP5-8.5 (m) [a]	SSP5-8.5H+ (m) [a]
11	174.9078	-41.2609	-3.77	1.28	1.70	2.14
28	174.8844	-41.2307	-3.00 [b]	1.18	1.60	2.04
31	174.9023	-41.2561	-3.61	1.26	1.68	2.12
32	174.9056	-41.2711	-3.49	1.25	1.67	2.11
33	174.9023	-41.2832	-3.29	1.22	1.64	2.08
34	174.8900	-41.2913	-3.35	1.23	1.65	2.09
35	174.8866	-41.3020	-3.64	1.26	1.68	2.12
36	174.8803	-41.3119	-3.93	1.30	1.72	2.16
37	174.8662	-41.3251	-3.76	1.28	1.70	2.14
38	174.8543	-41.3428	-2.18	1.08	1.50	1.94
2474	174.9858	-41.3972	-3.86	1.29	1.71	2.15
2475	174.9704	-41.4072	-3.86	1.29	1.71	2.15
2476	174.9510	-41.4175	-3.86	1.29	1.71	2.15
2477	174.9337	-41.4295	-3.92	1.3	1.72	2.16
2478	174.9149	-41.4373	-3.94	1.3	1.72	2.16
2479	174.9047	-41.4215	-3.96	1.3	1.72	2.16
2480	174.8827	-41.4133	-3.95	1.3	1.72	2.16
2481	174.8667	-41.4044	-4.7	1.4	1.82	2.26
2482	174.8762	-41.3893	-5.27	1.47	1.89	2.33
2483	174.8632	-41.3747	-5.16	1.45	1.87	2.31
2484	174.8503	-41.362	-3.68	1.27	1.69	2.13

a Projections refenced to 1995-2014 baseline.
b VLM based on average of estimated VLM along Petone foreshore from NZSeaRise
c Locations refer to Figure 1-1.

3 Extreme sea levels

Extreme sea levels were assessed for the Hutt City District via two separate approaches, the national inundation assessment for the open coast (Paulik et al., 2023) and a numerical model based multivariate assessed for Wellington Harbour. The following sections presents the methodology used to assess the 1%AEP sea levels.

3.1 Open Coast

The methodology employed is fully described in Paulik et al. (2023). In summary the national assessment included quantification of extreme sea levels and spatial inundation extent under current climatic sea conditions, plus relative sea level rise up to 2m above present-day mean sea level.

The national assessment is based on analysis of sea-level measurements and numerical models and was verified against sea-level runup observations collected after large storm-tide events. For the Hutt City District, extreme levels were based on storm tide observed at Queens Wharf and adjusted for tidal range amplification and included the effects of wave setup (refer to Paulik et al., 2023). The location of the national output points for the Wellington Harbour environ is shown in Figure 3-1.

Utilising the national assessment data, which was subsequently converted to NZVD 2016 and adjusted for the project baseline durations, 1%AEP inundation levels for the open coast locations were derived via spatial interpolation from the national inundation dataset. 1%AEP inundation levels for the present day (refer to Figure 3-1) and at 2130 for each of the RSLR projections are presented in Table 3-1.

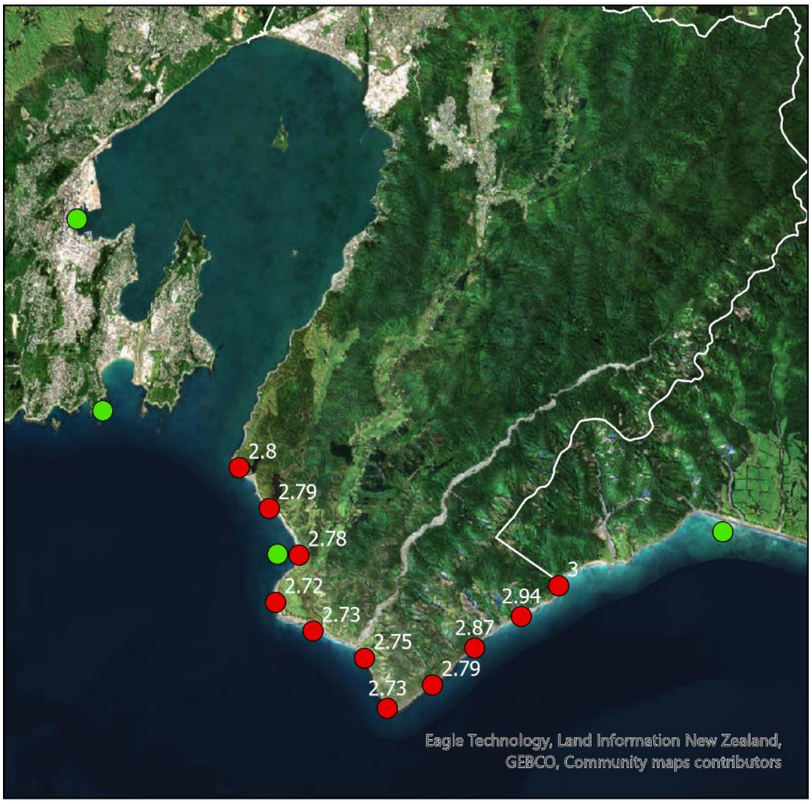

Figure 3-1: National inundation assessment locations and present-day 1%AEP inundation level (m NZVD). National assessment locations shown in green.

Table 3-1: 1%AEP sea level (m) relative to NZVD 2016 for present day and at 2130 for SSP2-4.5, SSP5-8.5 and SSP5-8.5H+ SLR projections.

Site ID	Present day	SSP2-4.5	SSP5-8.5M	SSP5-8.5H+
2474	3.00	4.25	4.67	5.11
2475	2.94	4.19	4.61	5.05
2476	2.87	4.12	4.54	4.98
2477	2.79	4.05	4.47	4.91
2478	2.73	3.99	4.41	4.85
2479	2.75	4.02	4.44	4.88
2480	2.73	3.99	4.41	4.85
2481	2.72	4.07	4.49	4.93
2482	2.78	4.21	4.63	5.07
2483	2.79	4.21	4.63	5.07
2484	2.80	4.03	4.45	4.89

3.2 Wellington Harbour

The analysis of extreme storm-tide plus wave setup elevations for this study is based on a numerical wave model and extreme value analysis developed for Wellington Harbour by NIWA (Allis & Gorman 2020). The Allis & Gorman (2020) study performed a multivariate-probability analysis of tide, storm surge, wave height/period and wind speed/direction based on a 20-year 2000-2019 period to produce an extreme value distribution at multiple locations within Wellington Harbour focussed on the north-western shoreline.

For this study the Allis & Gorman (2020) methodology was adopted, refined, and applied to the Hutt City District. A full description of the numerical modelling process is described in the following sections. In summary, the modelling approach collates records of concurrent environmental conditions covering the period 1998-2019 (wind, waves, tides, sea level) which contribute to the sea state and coastal hazards within Wellington Harbour. Using multivariate probability statistics from the 20-year record, a 1,000-year long *synthetic* record of extreme conditions is simulated using numerical modelling of 500 disparate scenarios from the 20-year record. A multivariate analysis follows the approach of Heffernan and Tawn (2004) and the multi-year synthetic record is expanded to include wave setup at the shoreline.

Given the length of the resulting simulated record, it becomes possible to compute return values for intermediate return periods by a direct 'countback' method, rather than by extrapolating a fitted extreme value distribution, fitted to a shorter record. For example, the 10th highest event of a 1,000-year synthetic record represents the 1% AEP (100-year return period) value.

Results and extreme value statistics are provided at 10 output locations spaced around the Hutt City harbour shoreline (refer to Figure 1-1) for the present day MSL and considering RSLR to 2130 (refer to Section 2.5).

The secondary effects of climate change were accounted for by increasing the storm surge elevation, winds speeds and offshore waves by 10% following MfE (2017) guidance. Overall, three 1% AEP storm-tide + wave setup and climate change scenarios were assessed with results presented in Section 3.2.10.

3.2.1 Numerical modelling approach

The numerical modelling approach involves collating and synthesising a long record of concurrent environmental conditions that contribute to the sea state and coastal hazards within Wellington Harbour. The parameters include winds throughout the region (speed and direction), waves throughout the harbour and Cook Strait (height, period, and direction), water level elevation and currents (tides, storm surges). A record of these parameters in the vicinity of the coast, in conjunction with seabed profile parameters, can then be used to estimate the additional effects of wave setup expected to arise in storm conditions.

The key elements of the approach consist of:

1. given available measurements of limited duration (e.g., measured winds, water levels and offshore wave conditions at single locations), derive sufficiently long *synthetic* records of extreme conditions to enable robust extreme value statistics to be established for the joint occurrence of parameters, and

2. deriving values of necessary environmental parameters (wind, waves, water levels) at the required locations within the harbour from the newly created synthetic records.

3. derive the extreme value statistics of the output variables (waves, water levels) at the required locations within the harbour.

3.2.2 Multi-variate time series simulation

The joint-occurrence technique described by Heffernan and Tawn (2004) was applied. This methodology recognises that the various contributors to extreme conditions, e.g., tides, storm surge and waves, very rarely achieve their individual extreme values simultaneously. For example, the storm surge, tidal level, and wave height values that individually have a 1% AEP would be expected to occur simultaneously with a much lower AEP than 1%, which would only be the case if they were perfectly correlated. However, they have *some* correlation, as, for example, large storm surge and high waves can tend to occur during intense storms, while higher water levels also allow larger waves to reach a given nearshore location. Hence, they cannot be treated as completely independent, in which case the joint AEP would be 1% × 1% × 1% = 0.0001%, which is too low in reality.

Instead, the Heffernan and Tawn (2004) approach quantifies the actual interdependence between extreme values of several variables, based on available records. This then allows a statistical model to be developed to simulate extreme values of these “dependent” variables over a longer time period. Secondary variables can also be simulated, where they either have a known dependency on the original “dependent” variables, or to be completely independent.

Given the length of the resulting simulated record, it becomes possible to compute return values for intermediate return periods by a direct ‘countback’ method, rather than by extrapolating a fitted extreme value distribution fitted to a shorter record.

3.2.3 Wind

Spatially variable wind fields over Wellington Harbour were derived based on correlation of measured data at the Wellington airport and ~1.5 km resolution New Zealand Convective Scale Model (NZSCM), which NIWA has been running for operational weather forecasting since 2014. A regression analysis between simultaneous wind records from the airport and the wind fields from NZCSM was completed providing a spatial transformation matrix of the form:

$$\begin{bmatrix} u' \\ v' \end{bmatrix} = \begin{bmatrix} \lambda_{11} & \lambda_{12} \\ \lambda_{21} & \lambda_{22} \end{bmatrix} \begin{bmatrix} u \\ v \end{bmatrix} = A \begin{bmatrix} u \\ v \end{bmatrix} \quad (1)$$

where *u* and *v* respectively denote eastward and northward wind velocity components at the Airport, and the primed quantities denote velocities at any given cell of the NZCSM model grid. The transformation matrix *A* (defined separately for each grid cell) can alternatively be represented (by singular value decomposition) as a product:

$$A = \begin{bmatrix} \cos\theta_2 & \sin\theta_2 \\ -\sin\theta_2 & \cos\theta_2 \end{bmatrix} \begin{bmatrix} a & 0 \\ 0 & b \end{bmatrix} \begin{bmatrix} \cos\theta_1 & \sin\theta_1 \\ -\sin\theta_1 & \cos\theta_1 \end{bmatrix} \quad (2)$$

which illustrates that this relationship can account for a combination of rotation of the wind direction by an angle θ_1 (e.g., by topographic steering) to a "principal" orientation, with respect to which parallel and transverse velocities are scaled by different factors (*a* and *b*), followed by a second rotation to the output axes. The lambda (λ) parameters in Equation (1) were adjusted to minimise a mean square error function

$$\chi^2_{wind} = \frac{1}{N} \sum_{i=1}^{N} \left(u'(t_i) - u(t_i)\right)^2 + \left(v'(t_i) - v(t_i)\right)^2 \quad (3)$$

summing over all times t_i with matching records.

This method allows a synthetic 1.5 km resolution spatial wind field to be derived for any time in the 1960-2019 airport wind record.

3.2.4 Tides and storm-surge

Water levels $Z(t)$ at Queen's Wharf recorded at 5-minute intervals between 31/8/1994 and 10/5/2019 (apart from some gaps) were adopted. Water levels in this record were referenced to local Chart Datum and converted to NZVD 2016. A tidal decomposition allowed the sea level record to be represented as tidal and non-tidal components, i.e.,

$$Z(t) = Z_{tidal} + Z_{residual} = \sum_{i=1}^{N} A_n \cos\left(2\pi t/T_n - \phi_n\right) + Z_{residual} \quad (4)$$

where A_n and $\phi_n$are the amplitude and phase, respectively, of the tidal constituent with period T_n, out of *N* constituents considered in the analysis. The residual term includes the effect of storm surge and longer-term variability, as well as the fixed datum offset.

Spatial and temporal water level and depth-averaged currents throughout Wellington Harbour are required as inputs for wave modelling (refer to Section 3.2.5). The spatially variable tidal contribution to water level and currents at any required time was derived from the New Zealand tide model, while the Queen's Wharf sea level record was used to derive the non-tidal contribution to sea level (assumed spatially uniform).

The largest tidal constituents identified from the Queen's Wharf record are listed in Table 3-2. The tidal signal in the measured record is dominated by the two leading semi-diurnal constituents, M2 and N2. This means that a satisfactory representation of water level and currents throughout the Harbour can be obtained using only the first two components, i.e., with *N*=2 in Eq. 4.

Table 3-2: Tidal constituents identified in the Queen's Wharf sea level record. The seven largest constituents are listed in decreasing order by amplitude.

Constituent	Period (hours)	Amplitude (m)	Phase in NZST (°)
M2	12.42	0.490	149.9
N2	12.66	0.127	113.2
O1	25.82	0.033	221.3
SA	8766.23	0.028	5.1
S2	12.00	0.026	353.2
K1	23.93	0.025	269.1
L2	12.19	0.025	175.4

3.2.5 Waves

A SWAN (Simulating WAves Nearshore) model (Booij et al. 1999, Ris et al. 1999) covering Wellington Harbour and Entrance from Cook Strait (refer to Figure 3-2) was developed to predict the evolution of wave conditions within Wellington Harbour in response to forcing by:

- Wind speed and direction varying in both time and space including spatial variability of winds over the harbour arising from topographic influences.
- Water level and depth averaged currents varying in time and space within the model domain.
- Incident swell on the domain boundary, from directional wave records outside the harbour entrance.

Data sources for the wind, water level and current forcing are described in Sections 3.2.3 to 3.2.5. For wave boundary conditions, measurements from the Baring Head wave buoy (1998-present) located outside of Wellington Harbour were utilised.

The Baring Head buoy, however, only has directional records since 2015. Consequently, measured significant wave height and peak wave period from the buoy record were used with fixed values for peak wave direction (θ_{peak} =190°) and directional spread (θ_{spread}=30°). This assumption is justified based on peak wave direction statistics from the Baring Head wave buoy record (Figure 3-3). This shows a predominance of southerly waves, with a mean value of $\theta_{peak} = 190.3°$, averaged over the southern quadrant (135°-225°). Directional spread data were not available from the Baring Head buoy, so we adopted the findings of Young et al. (1996) that, over a large number of wave observations, directional spread at the peak of the spectrum typically averages 30°.

A scaling factor of 1.2 on the measured significant wave height was applied to represent wave conditions at the model boundary, based on preliminary simulations to quantify the mean reduction in wave height between the boundary and the wave buoy site (refer Figure 3-2).

The model is implemented on an unstructured mesh (Zijlema, 2010) to provide high resolution in nearshore areas, typically 20 m mesh size within 500 m of shoreline (refer to Figure 3-2). Deepwater locations, where wave conditions have less spatial variability, have reduced spatial resolution, typically 50 m in the central harbour and up to 1 km near the offshore boundary to improve computational time.

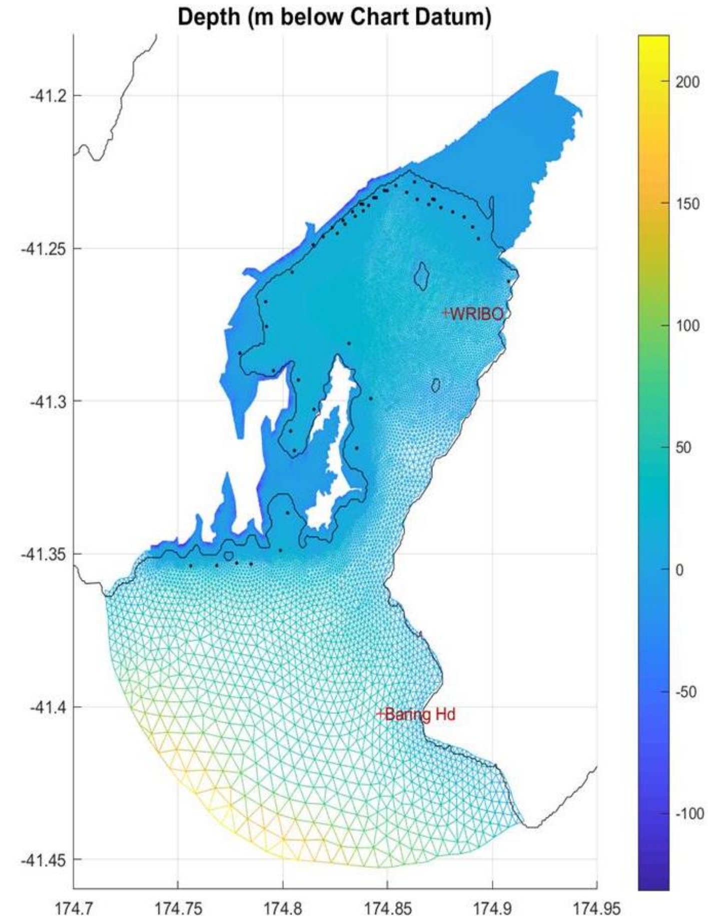

Figure 3-2: Map of Wellington Harbour showing the triangular mesh used for SWAN model simulations. The colour scale represents water depth (m CD). Wave measurement locations (red+).

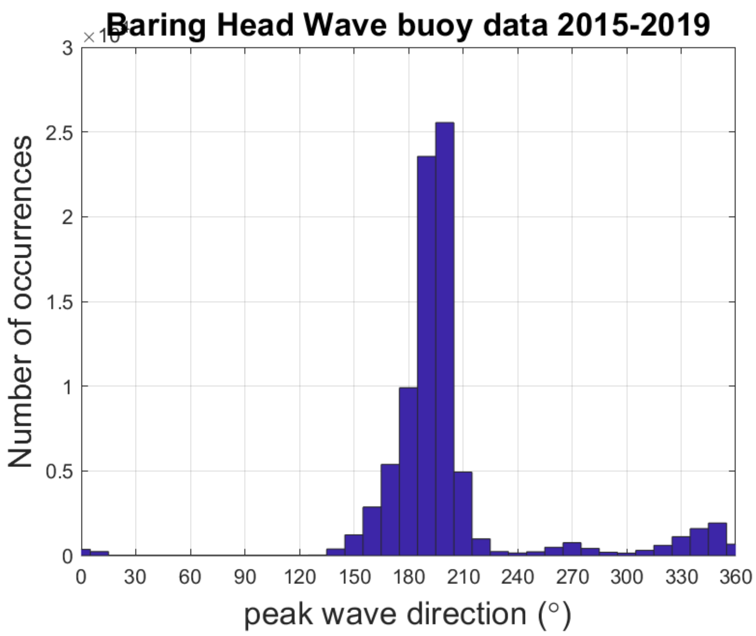

Figure 3-3: Occurrence distribution of peak wave direction from the Baring Head wave buoy record. Data is taken from the 2015-2019 period in which directional data were available. Peak wave direction is FROM where waves travel, in degrees clockwise from North and occurrences are x 10^4.

3.2.6 Synthesis of 20-year concurrent timeseries

For relatively short simulation periods (a few weeks, or months) it is feasible to run direct non-stationary SWAN simulations, forced by the historical records of environmental conditions throughout the simulation period. The computational requirements of a high-resolution model mean that direct multi-year simulations are, however, not feasible to complete within the project timeframe. For our purposes much longer multi-year simulations were required, so instead we used an “Emulator” technique (Camus et al. 2011a, b). This method assumes that the model forcing can be derived from a small set of input parameters, which for the Hutt City district includes:

1. Wind speed at Wellington Airport.
2. Wind direction at Wellington Airport.
3. Significant wave height at Baring Head wave buoy site.
4. Peak wave period at Baring Head wave buoy site.
5. M2 phase at Queen’s Wharf.
6. N2 phase at Queen’s Wharf.
7. Residual water level at Queen’s Wharf (i.e., non-tidal storm surge).

From these, all required wave model inputs could be derived.

Rather than run the SWAN model with the full time series of the input variables from the simulation period, a finite set of representative conditions was selected based on the historic record, using a Maximum Dissimilarity Algorithm to cover the *7*-dimensional parameter space of all possible input conditions as efficiently as possible. For this study a set of 500 samples were used.

SWAN stationary simulations were then carried out for each of these 500 sample parameter sets, the outputs of which provides a “lookup table” of the wave conditions within the Harbour that arises from each of these sets of input parameters. This allows a statistical model to be built from which the nearshore conditions arising from *any* combination of input parameters can be derived.

We applied this “Emulator” approach using input values for each parameter taken from the historic records described above, to simulate nearshore wave conditions for which all these inputs were available. This resulted in a simulation covering the years 1998-2019, less any gaps in the Baring Head, Queen’s Wharf or Wellington Airport records.

The “Emulator” was subsequently calibrated and verified against wave measurements from the WRIBO[5] data buoy moored approximately 2 km southeast of Matiu/Somes Island, as well as data from the Baring Head buoy used to provide model inputs. This calibration and validation are illustrated in Figure 3-4, which shows scatter plots of modelled significant wave height against corresponding measurements values. In these plots, each red dot shows a measured value plotted against the simulation output for the corresponding location and time. A quantile-quantile plot is overlaid on the scatter plots.

[5] Wellington Regional Integrated Buoy Observations (WRIBO). Operated by NIWA in conjunction with the Greater Wellington Regional Council. http://www.gw.govt.nz/wellington-harbour-buoy/

a) b)

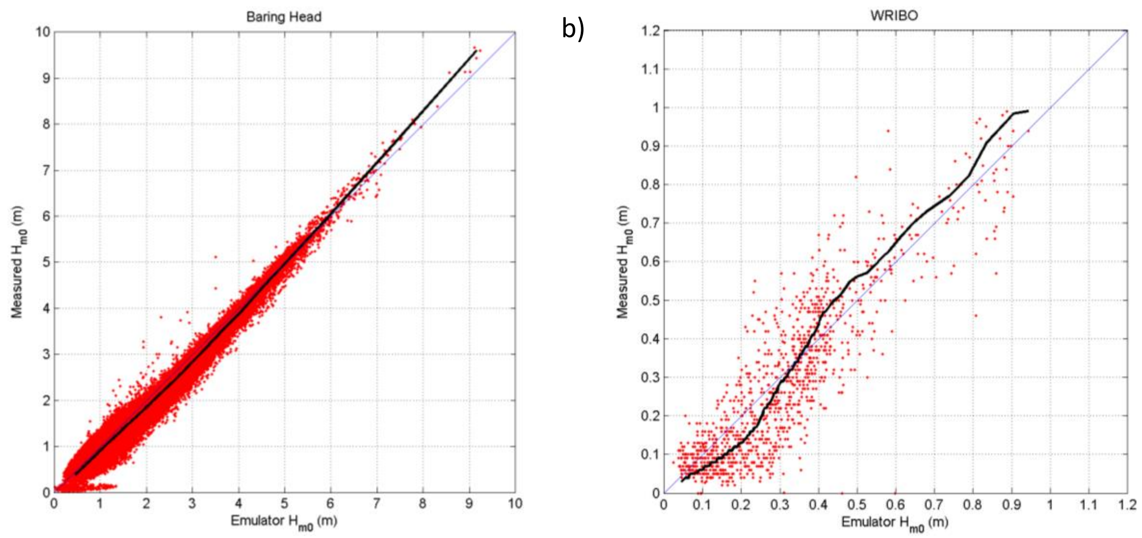

Figure 3-4: Scatter plots, overlaid with quantile-quantile plots, comparing significant wave height measurements with corresponding simulation outputs. Locations: (a) Baring Head Waverider, (b) WRIBO, SE of Matiu/Somes Island. An equivalence line (blue) for matching agreement is also shown.

The Baring Head record (Figure 3-4a), with significant wave height scaled up by a factor 1.2, was used to provide boundary conditions to the SWAN wave model. The close agreement, with small scatter, shows that the scaling factor is appropriate to represent the relationship between wave height at the offshore boundary and at the buoy location.

At the WRIBO buoy, south-east of Matiu/Somes Island (Figure 3-4b), there is a higher degree of scatter, but the quantile-quantile plot lies close to the equivalence line, particularly for the higher-energy conditions, indicating that the simulation gives a satisfactory representation of extreme-value statistics at this location.

3.2.7 Multi-century emulator

The simulations described in Section 3.2.6 provides a 20-year record of nearshore wave and storm tide conditions, from which extreme statistics can be derived by developing a much longer synthesised record as outlined in Section 3.2.2.

For greater computational efficiency, we reversed the order of this process, and

1. Compiled a historic record of high-water values of our seven input parameters.
2. Developed a multivariate statistical model for the extreme values of this record level at Queen's Wharf, and offshore significant wave height and peak period.
3. Applied that statistical model to derive a multi-century synthetic record of extreme values of the input variables.
4. Used this as input to the "Emulator" to derive multi-century synthetic time series of nearshore wave and storm tide conditions at the reference locations (refer to Figure 1-1) within Wellington Harbour.

3.2.8 Climate change scenarios

In addition to applying the methodology described in Section 3.2.7 to conditions derived from historic records, we also considered scenarios in which various combinations of climate change scenarios will result in changes to the extreme conditions out to 2130.

Relative sea-level rise was included as described in Section 2.5 and the secondary effects of climate change were accounted for increasing the storm surge elevation, winds speeds and offshore waves following MfE (2017) guidance. These were included as single "storm" scenarios which included:

- Wind speed increased by 10%.
- Offshore significant wave height increased by 10%.
- Storm surge increased by 10%.

And were combined with the RSLR values.

A 1,000-year synthetic record was computed for selected combinations of climate change scenarios, allowing Annual Exceedance Probabilities as low as 0.995% (100-year ARI) to be estimated along with confidence interval.

3.2.9 Wave setup

Wave setup was included following methods outlined in Chapter II-4-3 of the Coastal Engineering Manual (USACE 2012), which estimate the setup at the still-water shoreline as

$$\bar{\eta}_s = \bar{\eta}_b + \bar{\eta}_{sz} \tag{5}$$

which is a combination of the set down $\eta_b$at the break point and the subsequent setup η_{sz} across the surf zone shoreward of the break point. The first term is estimated as

$$\bar{\eta}_b = -\frac{1}{8}\frac{H_b^2 \frac{2\pi}{L_m}}{\sinh\left(\frac{4\pi}{L_m} d_b\right)} \tag{6}$$

where H_b is the breaking wave height, d_b is the breaking wave depth, and L_m is the mean length of waves in deep water, related to the mean wave period $T_{m-1,0}$ (derived from spectral moments) by

$$L_{m-1,0} = \frac{g}{2\pi} T_{m-1,0}^2 \tag{7}$$

Where, as in our case, the peak wave period T_p is more directly available than the mean period, an empirical relationship

$$T_p = 1.1 T_{m-1,0} \tag{8}$$

is used.

The breaking wave height is estimated (using Equation II-4-8) as

$$H_b = 0.56 H_{rmso} (H_{rmso}/L_m)^{-0.2} \tag{9}$$

using the root-mean-square offshore wave height, related to the offshore significant wave height by

$$H_{rmso} = 0.7H_{m0} \quad (10)$$

The breaking wave depth d_b is related to the breaking wave height H_b by a ratio

$$\gamma_b = \frac{H_b}{d_b} \quad (11)$$

which in turn depends on wave height, wavelength, and the local seabed slope $\tan\beta$, through the empirical relationships

$$\gamma_b = b - a\frac{H_b}{gT_m^2} \quad (12)$$

with

$$a = 43.8\left(1 - \backslash exp\left(-19\tan\beta\right)\right) \quad (13)$$

$$b = 1.56/\left(1 + exp(-19.5\tan\beta)\right) \quad (14)$$

The setup shoreward of the breakpoint can then also be estimated as

$$\eta_{sz} = \frac{d_b}{\left[1 + \frac{8}{3\gamma_b^2}\right]} \quad (15)$$

In selecting appropriate values of the bed slope parameter $\tan\beta$, we note that the Wellington harbour coastline is nearly all rocky revetments, vertical seawalls, steep rocky beaches, or bedrock outcrops. In the absence of sufficiently reliable bathymetric data to justify a site-by-site selection of the slope parameter, we applied a uniform 1(V):2(H) slope as a balance between the flatter beaches and the steeper structures.

3.2.10 Extreme sea levels

The 1%AEP extreme sea levels estimated by the countback method from the 1,000-year synthetic records are presented in Table 3-3.

Table 3-3: 1%AEP sea level (m) relative to NZVD 2016 for present day and at 2130 for SSP2-4.5, SSP5-8.5 and SSP5-8.5H+ SLR projections.

Site ID	Present day	SSP2-4.5	SSP5-8.5	SSP5-8.5H+
11	1.08	2.46	2.89	3.34
28	1.05	2.32	2.75	3.19
31	1.07	2.43	2.85	3.30
32	1.10	2.44	2.87	3.31
33	1.09	2.40	2.83	3.28
34	1.15	2.48	2.90	3.34
35	1.18	2.55	2.98	3.43
36	1.18	2.58	3.01	3.46
37	1.32	2.73	3.15	3.61
38	1.61	2.83	3.26	3.73

The tabulated results show that storm-tide elevation increases towards the harbour mouth as a function on higher wave energy and hence corresponding wave setup.

4 Inundation extents

Inundation extent has been quantified via two methods, dynamically via numerical modelling (BG-Flood) for the low-lying Lower Hutt area that is sensitive to time dependent inundation and via static bathtub modelling for the steep foreshore and backshore areas south of Point Howard to and including the Hutt City District open coast. The approach enables the delineation of the inundation hazard while considering the varying RSLR magnitudes along the Hutt City District shoreline. The following sections present the methods and results of the mapping.

4.1 Inundation Scenarios

The following scenarios have been simulated to define current and future permanent and intermittent inundation extent and depth.

- Mean High Water Springs Cadastral (MHWS-C), present day
- MWHS-C in the year 2130 with SLR via SSP2-4.5
- MWHS-C in the year 2130 with SLR via SSP5-8.5
- MWHS-C in the year 2130 with SLR via SSP5-8.5 H+
- 1% Annual Exceedance Probability (AEP) extreme sea level, present day
- 1%AEP extreme sea level in the year 2130 with SLR via SSP2-4.5
- 1%AEP extreme sea level in the year 2130 with SLR SSP5-8.5
- 1%AEP extreme sea level in the year 2130 with SLR SSP5-8.5 H+

MfE (2022) recommends that the 1%AEP extreme sea level at the year 2130 with SLR via the SSP5-8.5 H+ projection be adopted for future land use planning. Inundation extents utilising the SSP2-4.5 projection, an intermediate emissions scenario that closely aligns with the current global emission reduction commitments via the Paris Agreement and the SSP5-8.5 projection, a high emission scenario, have been included to demonstrate the range of potential outcomes.

4.2 Topography

All mapping utilised the Hutt City 2021 1m LINZ LIDAR that captured Lower Hutt to and including Muritai (location 37 on Figure 1-1). South of Muritai including the open coast areas the 2013/2014 LINZ LIDAR datasets were utilised.

4.3 Static Mapping Assessment

In this study a "bathtub" model was used to produce inundation maps that show the spatial extent and inundation depths. The inundation maps are generated by projecting a sea-level value across land, any land that lies below the sea-level is deemed to be inundated. However, this somewhat simplified approach does come with caveats. Storm-tide peaks typically last for only 1–3 hours around the time of high tide. This duration may not provide sufficient time to inundate large land areas, particularly if seawater ingress rates are affected by narrow constrictions, such as drainage channels and culverts. Therefore, bathtub type models do not fully capture the dynamic and time-variant processes that occur during an inundation event.

The bathtub models often predict greater inundation (depth and extent) when the dynamics of the inundation process (e.g., depth, velocity, duration) are ignored. Overestimation is more pronounced in flat low-lying areas compared to steep backshore areas where is often little difference compared to more detailed dynamic numerical approaches. The difference between dynamic and bathtub models becomes less relevant when long timeframes and potentially large RSLR are being considered (Stephens et al. 2021).

Static inundation mapping has been completed for the shoreline south of Point Howard to and including the open coast (Locations 31 to 2474). Summarised inundation levels used for the mapping are provided in Appendix A. To allow for varying magnitudes of RSLR along the coast, inundation extent and depth were derived via spatial linear interpolation from the calculated levels at the reference locations.

4.4 Dynamic Inundation Assessment

Due to the extent of the low-lying area within Lower Hutt that has high exposure to future sea level rise (MacDonald et al., 2022) a dynamic numerical model approach was adopted. The numerical model BG-Flood (Block-Adaptive GPU-capable Flood model) was adopted and each scenario (refer to Section 4.1) was simulated.

4.4.1 BG-Flood model

BG-Flood is a GPGPU-enabled shallow water hydrodynamic model based on a block-uniform adaptive quadtree structure. It can model tsunamis, storm-surge, and fluvial and pluvial flooding (Bosserelle et al., 2021). BG-Flood has been developed within NIWA since 2018 and is built off the open-source finite volume solver of the full non-linear shallow water equations taken from the Basilisk modelling suite. These equations have been implemented within a CUDA GPGPU framework which speeds up the modelling time dramatically with the memory model modified to follow the Block-Uniform Quadtree implementation used in Vacondio et al., (2017) which allows a compromise between the rapid adaptation of the quadtree formulation but with a layout that leverages off the speed of cartesian grids within the GPU framework.

4.4.2 Model grids and resolutions

BG-Flood uses an adaptive block mesh to simulate hydrodynamics at a range of scales. The model mesh therefore can change throughout the model domain to capture topographic and bathymetric features that can affect tidal propagation at a high resolution as well as ensuring high resolution for the inundation area of interest. For this study the model resolution on land was 10m, 5m in the Hutt River and 2.5m for the smaller rivers. The model only resolves open channel flow and does not incorporate piped networks or channels that are not defined in the LIDAR survey.

4.4.3 Roughness

Ground roughness can impact flow and how far inland the tidal wave can propagate. For all the simulations a Manning's n roughness map was used with water 0.011, built environment 0.06, urban parks 0.04, river 0.011 and forest 0.06 (Scheele et al., 2023).

4.4.4 Boundary conditions

Boundary conditions as derived for location 28 (refer to Figure 1-1) were applied to the model boundary. MHWS-C was simulated based on measured spring tide level from Queens Wharf (refer to Figure 4-1) and the 1%AEP level was derived from scaling the 22/03/2023 0.73m NZVD 2016 storm tidal level recorded at Queens Wharf to the 1%AEP level as derived from the multivariate analysis (refer to Figure 4-2).

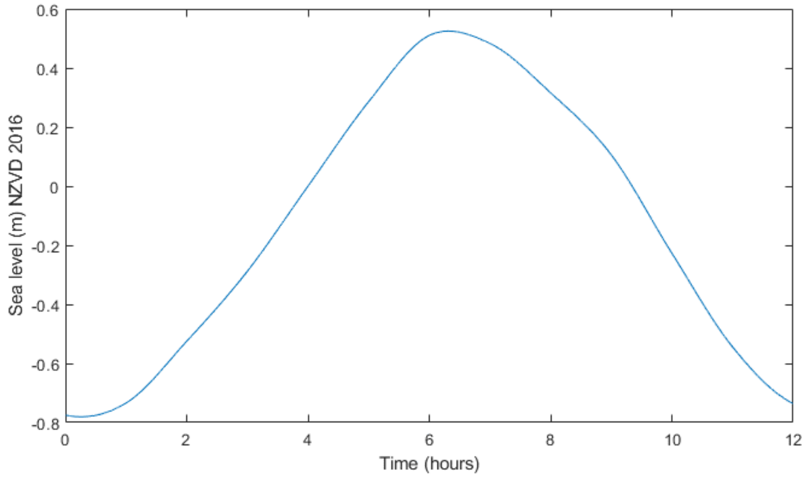

Figure 4-1: MHWS-C boundary condition (based on signal from Queens Wharf).

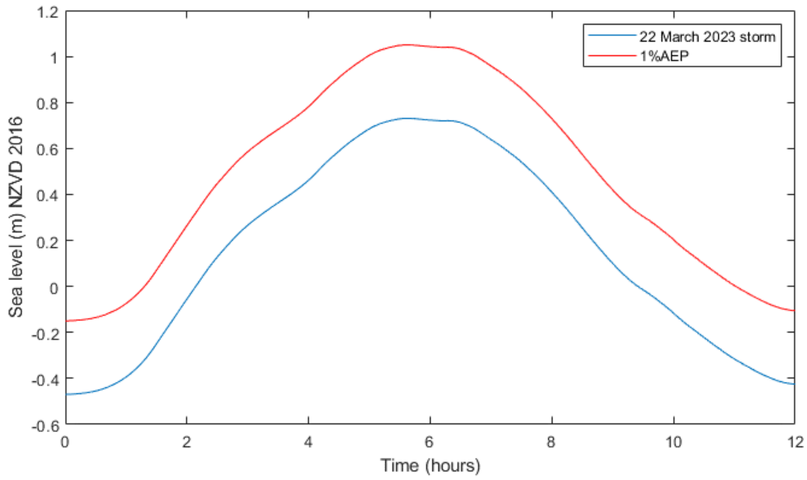

Figure 4-2: 1%AEP model boundary condition and reference 22 March 2023 storm.

Based on the MHWS-C and 1%AEP tidal signals, boundary conditions for each scenario were compiled by vertically shifting each signal to achieve peak tidal levels as presented in Table 4-1.

Table 4-1: Simulated peak tidal level for study scenarios.

Tidal Scenario	Sea level (m) NZVD 2016
MHWS-C present day	0.51
MHWS-C at 2130 via SSP2-4.5	1.66
MHWS-C at 2130 via SSP5-8.5	2.08
MHWS-C at 2130 via SSP5-8.5 H+	2.52
1%AEP present day	1.05
1%AEP at 2130 via SSP2-4.5	2.32
1%AEP at 2130 via SSP5-8.5	2.75
1%AEP at 2130 via SSP5-8.5 H+	3.19

4.4.5 Simulations

Two-dimensional tidal hydrodynamics were simulated over a 12-hour period for each scenario on the New Zealand eScience Infrastructure (NESI) specialised platform for high performance computing. For each scenario time series water level and depth were recorded and used for subsequent GIS Mapping (refer to Section 4.5). Example model output from BG-Flood for the 1%AEP inundation level at 2130 via SSP5-8.5 H^+ RSLR projection is presented in Figure 4-3.

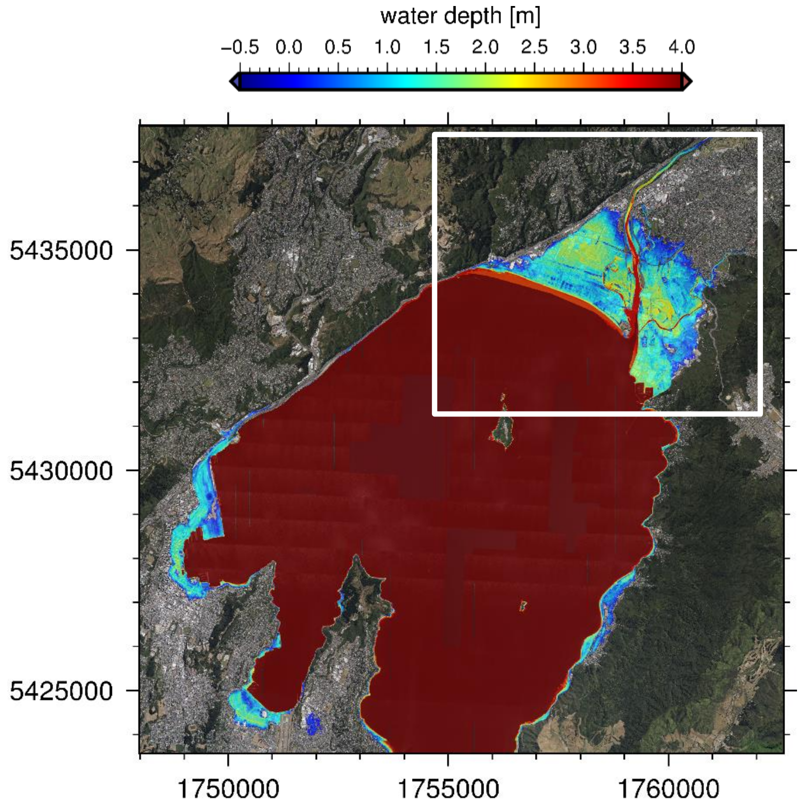

Figure 4-3: 1%AEP inundation depth (m) at 2130 via SSP5-8.5 H+. White box defines the Lower Hutt sub domain.

Due to varying RSLR throughout the district only the simulated results for the Lower Hutt sub-domain (refer to Figure 4-3) are applicable for each scenario and were retained for inundation mapping.

4.5 Inundation Mapping

The results for both the static and dynamic assessment were integrated into single GIS files showing peak inundation depth and extent while incorporating varying RSLR throughout the district. To allow for localised geographic features such and curb and channel that are not resolved in the LIDAR and LIDAR vertical accuracy of ~0.1m, areas that had an inundation depth less than 10cm were excluded from the mapping.

District inundation maps are presented in Appendix B and inundation maps of the Lower Hutt environ are presented in Appendix C for each scenario.

Digital spatial inundation maps that show the respective inundation extent and depth relative to NZVD 2016 in the form of GIS shape and images files have been provided to HCC.

5 Summary

In this study a static and dynamic inundation mapping assessment was completed to produce maps of potential exposure to inundation (extent and depth) from present-day MHWS and 1% AEP storm-tide + wave-setup event, plus projected relative sea-level rise over a 100-year planning timeframe to 2130.

Inundation extent has been quantified via dynamic modelling for the Lower Hutt environ to capture time dependent inundation. The remainder of the Hutt City District and has been assessed via static modelling. The results have been compiled into GIS layers that delineate inundation extent and depth.

The 1% AEP storm-tide and wave setup within the harbour has been assessed via multivariate analysis whereas the open coast has been assessed via the NIWA national assessment (Paulik et al., 2023).

Future effects from RSLR have been assessed via the SSP2-4.5, SSP5-8.5 and SSP5-8.5H+ projections and include ongoing landmass subsidence rates estimated as part of the NZSeaRise project (www.searise.nz/maps).

The results from the inundation mapping show that the present day 1% AEP storm-tide and wave setup inundation extent is limited to the foreshore region and low-lying sections around the Hutt River margins. Elsewhere, the inland extent is limited due to the steep backshore area. When RSLR is considered, the predictions show an escalation in permanent and intermittent coastal inundation in the low-lying areas, with limited impact for steep backshore areas. Furthermore, all three RSLR projections predict that a large proportion of Lower Hutt is potentially exposed to coastal inundation with rising sea-levels.

Maps and data (GIS files) from the inundation mapping have been provided directly to HCC as digital files.

6 References

Allis, M.J., Gorman, R.G., 2020: Te Ara Tupua - Ngauranga to Petone Shared Path. Technical report: multivariate analysis of extreme coastal conditions for design. *NIWA Client Report* 2020087HN. Prepared for New Zealand Transport Agency April 2020: 72.

Allis, M.J., Gorman, R.G., Rautenbach, C., Wadhwa, S., 2021: Coastal hazards and sea-level rise in Wellington City - Supporting the 2020-2021 district plan process. NIWA Client Report 2021250HN. Prepared for Wellington City Council.

Booij, N.; Ris, R.C.; Holthuijsen, L.H., 1999: A third-generation wave model for coastal regions 1. Model description and validation. *Journal of Geophysical Research 104(C4)*: 7649-766.

Bosserelle C, Lane EM, Harang, A. BG-Flood, 2021: A GPU adaptive, open-source, general inundation hazard model. Australasian Coasts & Ports 2021 Conference – Christchurch. https://www.coastsandports.org/papers/2021/150_bosserelle_finalpaper.pdf

Camus, P., Mendez, F.J., Medina, R., 2011a: A hybrid efficient method to downscale wave climate to coastal areas. Coastal Engineering, 58(9): 851-862. https://doi.org/10.1016/j.coastaleng.2011.05.007

Camus, P., Tomas, A., Vidal, C., Mendez, F.J., Medina, R., Losada, I.J., 2011b: Downscaling wave energy resources to coastal areas. *OCEANS 2011 IEEE - Spain*, 2011: 1-8. doi: 10.1109/Oceans-Spain.2011.6003590.

Heffernan, J.E., Tawn, J.A., 2004: "A conditional approach for multivariate extreme values (with discussion)." *Journal of the Royal Statistical Society: Series B (Statistical Methodology),* 66(3): 497-546.

IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, doi:10.1017/9781009157896.

MacDonald, I., Wadhwa, S., 2022: Coastal Inundation mapping for Hutt City. NIWA Client Report No: 2022195HN. Prepared for Hutt City Council

Ministry for the Environment (MfE), 2017: Coastal Hazards and Climate Change: guidance for local government. Available at: http://www.mfe.govt.nz/sites/default/files/media/Climate Change/coastal-hazards-guide-final.pdf.

Ministry for the Environment, 2022: Interim guidance on the use of new sea-level rise projections. Wellington: Ministry for the Environment.

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.

Ris, R.C.; Holthuijsen, L.H.; Booij, N., 1999: A third-generation wave model for coastal regions 2. Verification. *Journal of Geophysical Research 104(C4)*: 7667-768

Scheele FR, Uma SR, Wang X, Syed Y, Inglis S, William S, Lane, EM, Horspool NH, Burbidge D, Power W, Xu Z, Paulik R, Welsh R, Porter H., 2023: National tsunami exposure assessment for Toka Tu Ake EQC building portfolio. GNS Consultancy Report 2022/124.

USACE (2012). Coastal Engineering Manual Part II: Coastal Hydrodynamics (EM 1110-2-1100). Books Express Publishing.

Vacondio, R., Dal Palu, A., Ferrari, A., Mignosa, P., et al., 2017: A non-uniform efficient grid type for GPU parallel Shallow Water Equations models, Environmental Modelling & Software, Vol. 88, pp. 119-137 DOI: 10.1016/j.envsoft.2016.11.012

Young, I.R., and Holland, G.R., 1996: Atlas of the Oceans: Wind and Wave Climate. Oxford, Pergamon Press, Elsevier Science Inc., 241pp.

Zijlema, M., 2010: Computation of wind-wave spectra in coastal waters with SWAN on unstructured grids. *Coastal Engineering 57(3)*: 267-27

Appendix A MHWS and 1%AEP Levels

Table A-1: Present day MHWS and MHWS at 2130 for RSLR projections (m NZVD 2016).

Location	MHWS-C (m) Present Day	MHWS-C (m) at 2130 - SSP2-4.5	MHWS-C (m) at 2130 - SSP5-8.5	MHWS-C (m) at 2130 - SSP5-8.5H+
11	0.51	1.75	2.17	2.61
28	0.51	1.65	2.07	2.51
31	0.51	1.73	2.15	2.59
32	0.51	1.72	2.14	2.58
33	0.51	1.69	2.11	2.55
34	0.51	1.70	2.12	2.56
35	0.51	1.73	2.15	2.59
36	0.51	1.77	2.19	2.63
37	0.51	1.75	2.17	2.61
38	0.51	1.55	1.97	2.41
2474	0.58	1.83	2.25	2.69
2475	0.56	1.81	2.23	2.67
2476	0.54	1.79	2.21	2.65
2477	0.53	1.79	2.21	2.65
2478	0.51	1.77	2.19	2.63
2479	0.51	1.77	2.19	2.63
2480	0.50	1.76	2.18	2.62
2481	0.49	1.85	2.27	2.71
2482	0.51	1.94	2.36	2.80
2483	0.50	1.91	2.33	2.77
2484	0.50	1.73	2.15	2.59

Table A-2: Present day 1%AEP sea level and 1%AEP sea level at 2130 for RSLR projections (m NZVD 2016).

Location	1%AEP (m) Present Day	1%AEP (m) At 2130 - SSP2-4.5	1%AEP (m) At 2130 - SSP5-8.5	1%AEP (m) At 2130 - SSP5-8.5H+
11	1.08	2.46	2.89	3.34
28	1.05	2.32	2.75	3.19
31	1.07	2.43	2.85	3.30
32	1.10	2.44	2.87	3.31
33	1.09	2.40	2.83	3.28
34	1.15	2.48	2.90	3.34
35	1.18	2.55	2.98	3.43
36	1.18	2.58	3.01	3.46
37	1.32	2.73	3.15	3.61
38	1.61	2.83	3.26	3.73
2474	3.00	4.25	4.67	5.11
2475	2.94	4.19	4.61	5.05
2476	2.87	4.12	4.54	4.98
2477	2.79	4.05	4.47	4.91
2478	2.73	3.99	4.41	4.85
2479	2.75	4.02	4.44	4.88
2480	2.73	3.99	4.41	4.85
2481	2.72	4.07	4.49	4.93
2482	2.78	4.21	4.63	5.07
2483	2.79	4.21	4.63	5.07
2484	2.80	4.03	4.45	4.89

Appendix B District Inundation Maps

Figure B-1: Present day MHWS inundation level (m NZVD 2016).

Figure B-2: MHWS inundation level at 2130 via SSP2-4.5 (m NZVD 2016).

Figure B-3: MHWS inundation level at 2130 via SSP5-8.5 (m NZVD 2016).

Figure B-4: MHWS inundation level at 2130 via SSP5-8.5 H+ (m NZVD 2016).

Figure B-5: Present day 1%AEP inundation level (m NZVD 2016).

Coastal Inundation mapping - Hutt City

Figure B-6: 1%AEP inundation level at 2130 via SSP2-4.5 (m NZVD 2016).

Figure B-7: 1%AEP inundation level at 2130 via SSP5-8.5 (m NZVD 2016).

Figure B-8: 1%AEP inundation level at 2130 via SSP5-8.5 H+ (m NZVD 2016).

Appendix C Lower Hutt Inundation Maps

Figure C-1: Present day MHWS inundation level (m NZVD 2016).

Coastal Inundation mapping - Hutt City

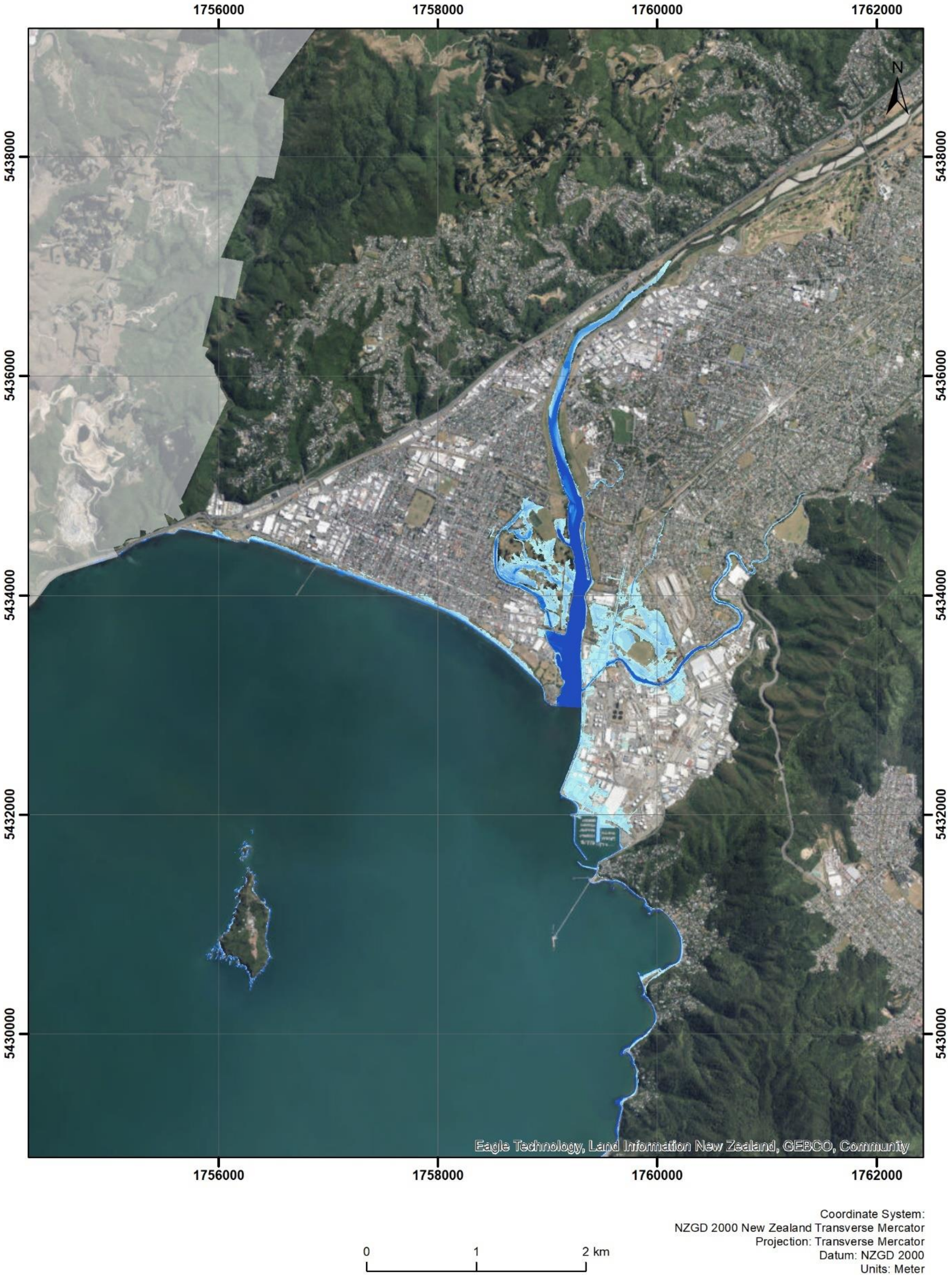

Figure C-2: MHWS inundation level at 2130 via SSP2-4.5 (m NZVD 2016).

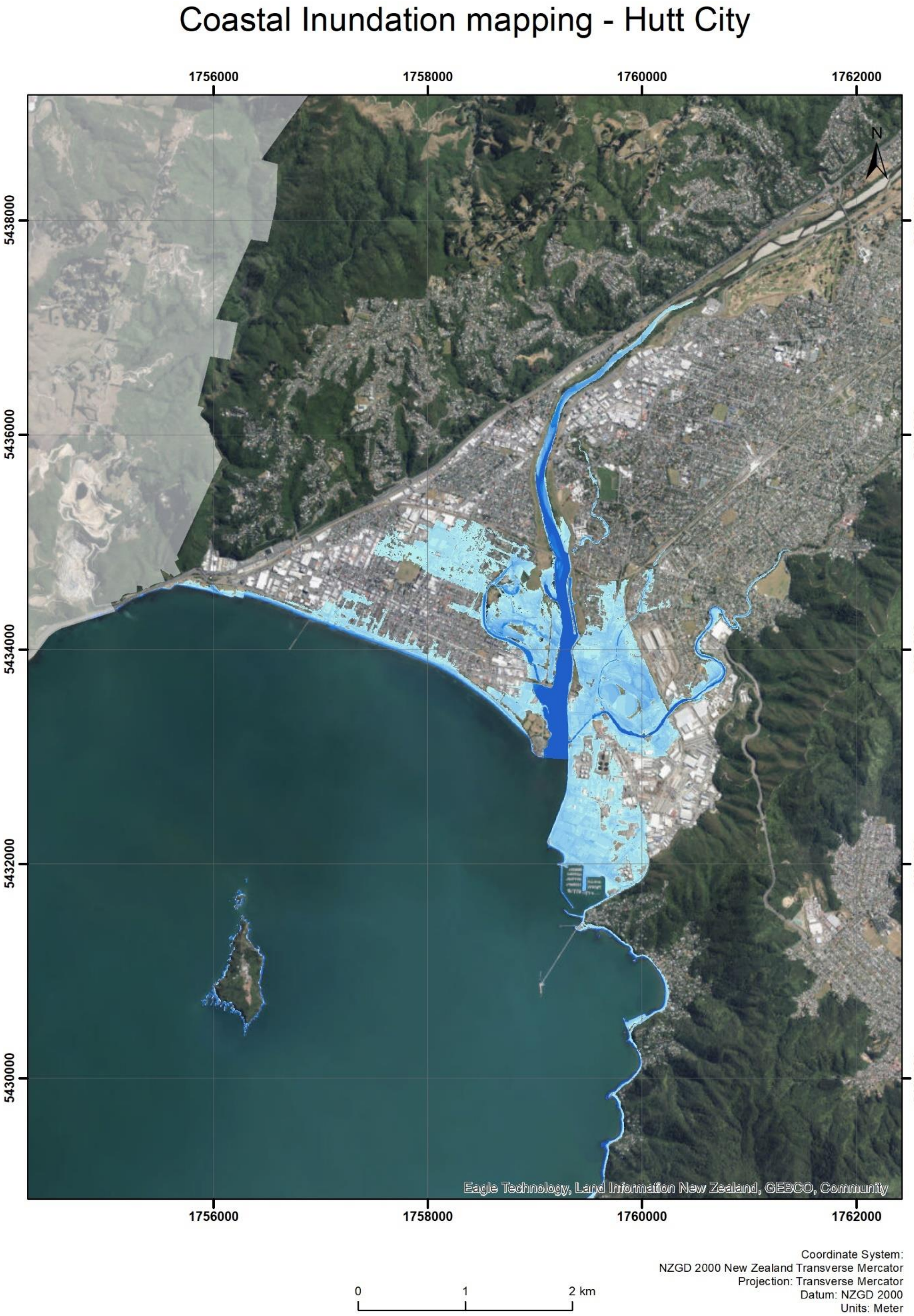

Figure C-3: MHWS inundation level at 2130 via SSP5-8.5 (m NZVD 2016).

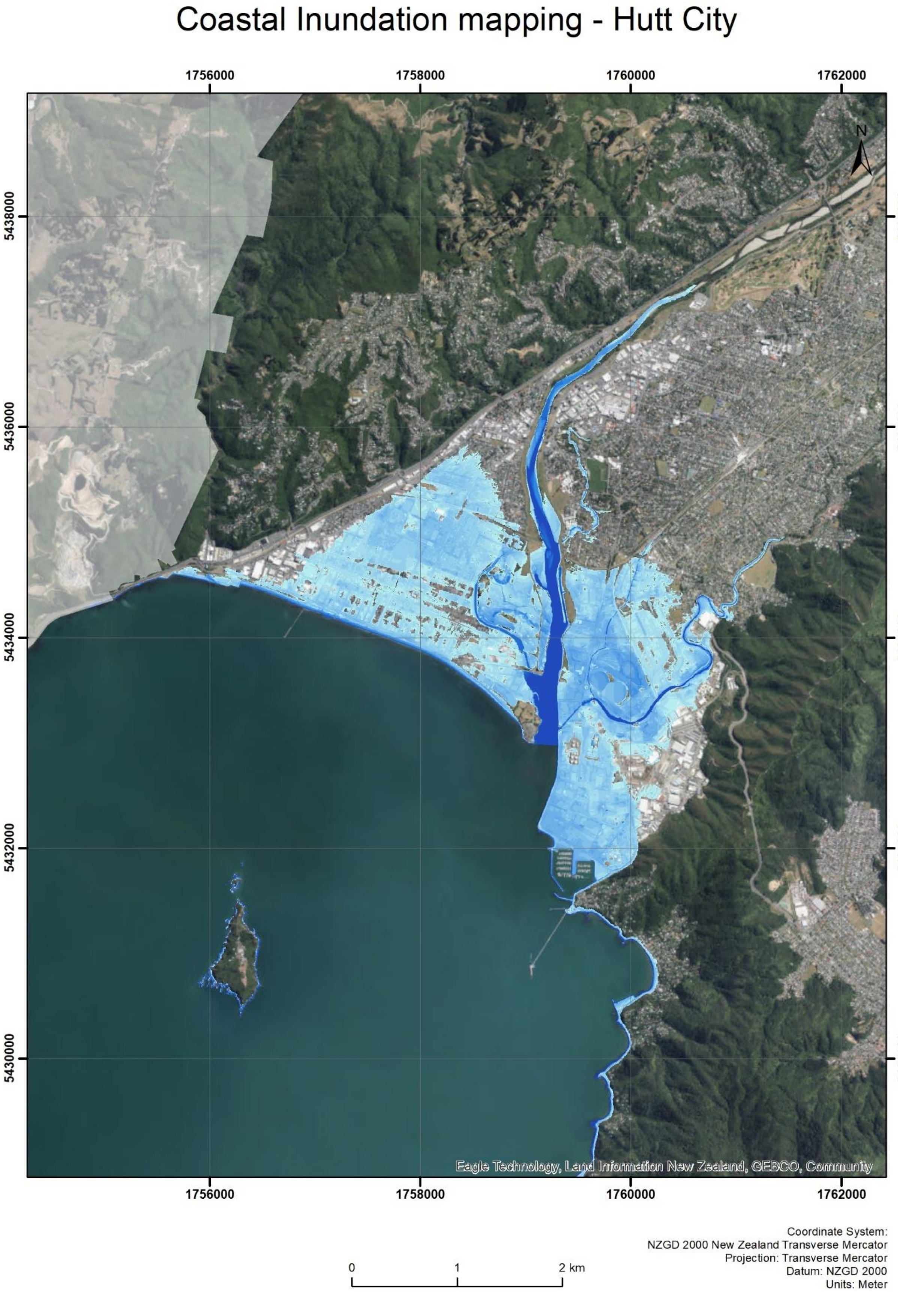

Figure C-4: MHWS inundation level at 2130 via SSP5-8.5 H+ (m NZVD 2016).

Figure C-5: Present day 1%AEP inundation level (m NZVD 2016).

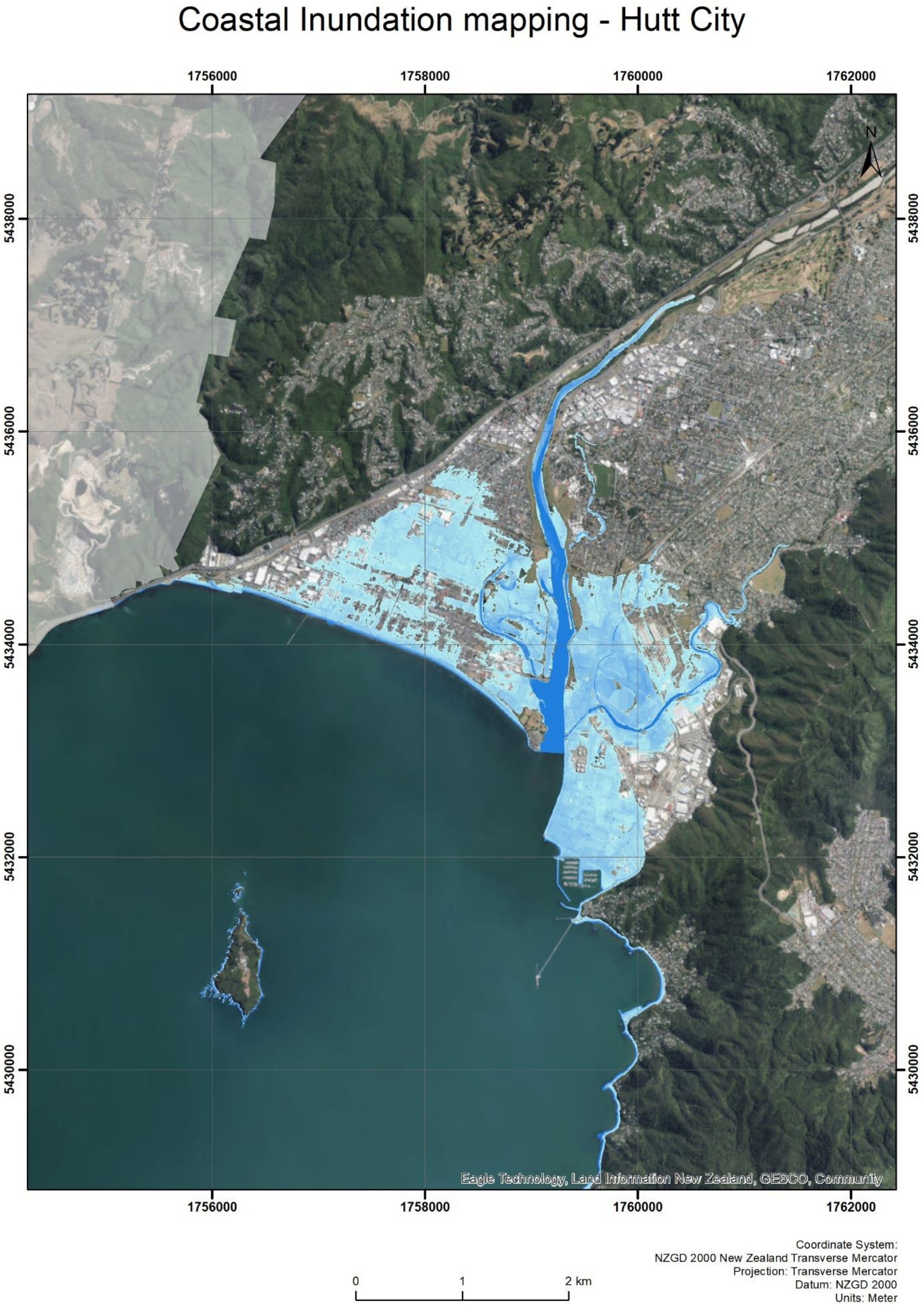

Figure C-6: 1%AEP inundation level at 2130 via SSP2-4.5 (m NZVD 2016).

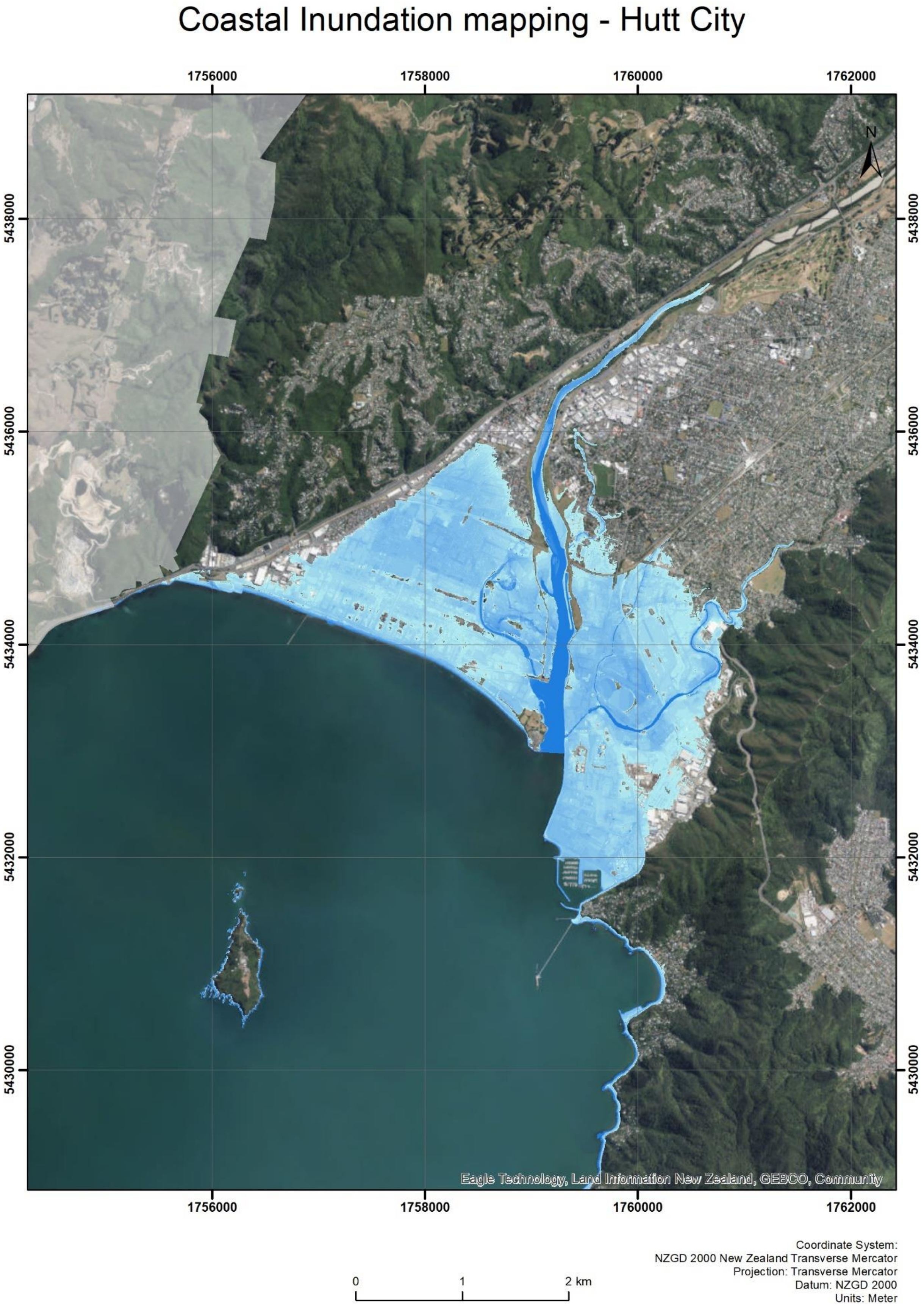

Figure C-7: 1%AEP inundation level at 2130 via SSP5-8.5 (m NZVD 2016).

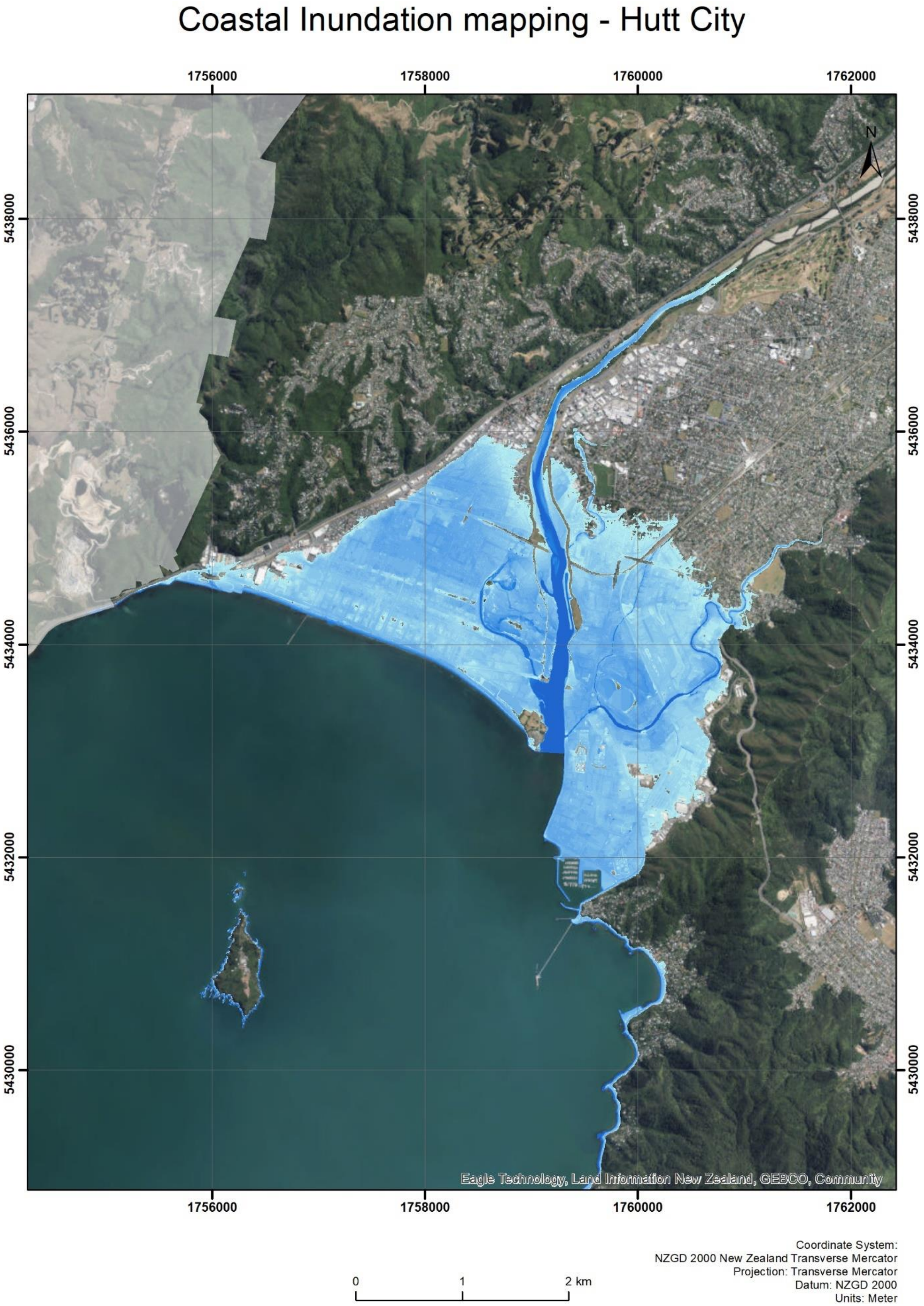

Figure C-8: 1%AEP inundation level at 2130 via SSP5-8.5 H+ (m NZVD 2016).