Coastal hazards and sea-level rise in Wellington City

Supporting the 2020-2021 district plan process

Prepared for Wellington City Council

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Climate, Freshwater & Ocean Science

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Executive summary

This study has evaluated coastal hazards (excluding tsunami) around the Wellington City district shorelines, including the effects of climate change, to inform and support the current revision cycle of the District Plan for Wellington City Council (WCC).

The scope of this study included assessment of the sea-level rise projections for the 100-year timeframe (2120), assessment of coastal erosion hazards and assessment of coastal inundation hazards at the end of this timeframe.

Maps and data from the coastal hazard assessments have been provided directly to WCC as digital files. All assessments were undertaken using the latest LiDAR mapping of the district (released 2020/2021). Updated nearshore bathymetric were also created for the South Coast and Mākara Beach to enable the high-resolution numerical modelling.

Climate change effects

The effects of climate change have been incorporated through the inclusion of relative sea-level rise (RSLR, which is the addition of slow land subsidence to a rise in ocean level) and 10% increases to the secondary climate change effects (storm-tide, wave height and wind speed) recommended by the Ministry for the Environment guidance manual for coastal hazards and climate change (MfE 2017)[1]. The RSLR levels are based on two climate change scenarios from MfE(2017); RSLR=1.43 m under RCP8.5M (50th centile) and RSLR=1.73 m RCP8.5H+ (83rd centile).

See the accompanying report Bell and Allis (2021) for details on the RSLR allowances and climate change projections for Wellington City.

Coastal erosion hazard

Nearly all coastal shorelines around Wellington City are protected to some extent by man-made coastal defences (e.g. seawalls, revetments, jetties, beach replenishment, fences etc) or natural defences (e.g. rocky shore platforms, reefs, vegetation, sand dunes) which have undetermined extents, varied designs, unspecified maintenance history, and unknown performance during large storms.

We introduced a high-level screening approach to overcome the uncertainties regarding coastal defences. A "low-lying near-coast zone" was created to illustrate areas that are potentially exposed to coastal erosion hazards *irrespective* of coastal defences, i.e. areas behind coastal defences are included in the low-lying near-coast zone. This zone is defined as land within 30 m inland from and less than 3.04 m above the present-day mean high-water springs shoreline (MHWS-10[2]). The definition of the zone is intentionally simple as a robust assessment of erosion potential for the multitude of coastal defences around Wellington was beyond the scope of this project required for the District Plan.

The intention of this zone is that development within this zone should require a detailed site-specific assessment of the erosion hazard potential taking into account engineering details, site characteristics, effectiveness during storms and history of the coastal defences. Such a study would also include assessment of the coastal inundation hazard.

[1] https://environment.govt.nz/publications/coastal-hazards-and-climate-change-guidance-for-local-government/

[2] The MHWS-10 shoreline is the intersection of the high tide exceeded by only 10% of all high tides with the land.

Coastal inundation

Coastal inundation hazards have been assessed at shorelines around Wellington City. This includes the City shorelines (Wellington Harbour and South Coast) and Mākara Beach, but excludes the shoreline around Cape Terawhiti Head from Red Rocks to Mākara beach and north of Mākara Beach.

The inundation assessments exclude the presence of buildings and small-footprint coastal defences (except where large features are resolved in the LiDAR, such as coastal revetments). This allows the simulated inundation to spread across the land and underneath buildings indicating the maximum potential inundation extent during, say, an extreme storm with failure of defence structures or for water flowing beneath the piles of a house.

Coastal inundation has been assessed using two methods tailored to the physical exposure to coastal processes:

- Harbour shorelines, from Point Dorsett at Wellington Harbour Entrance around to Horokiwi including Evans Bay and Wellington Central, have been assessed using a multivariate extreme value analysis for storm-tide[3] and wave setup[4] conditions determined from numerical modelling of wind, waves and tides throughout the harbour (but also forced by swell from outside the Harbour) and validated against historic observations and other studies. The analysis was then re-run under climate change scenarios (RSLR and +10% storminess).

  The extreme sea level elevations at 1% Annual Exceedance Probability (AEP) are then mapped onto the land using static inundation (i.e. bathtub) mapping around the harbour shorelines. This static inundation mapping technique assumes that all land areas lower than the extreme water levels at the shoreline are flooded to the same height as the shoreline water level. Only areas that have a direct hydraulic connection to the sea are mapped as inundation, including areas connected via culverts. It was beyond the scope of this work to assess the capacity of culverts, or presence of floodgates/valves which would limit the inland extend of sea-water inundation. Inundation due to groundwater where storm-tide affects groundwater level causing increased inundation is also excluded from this study.

- Mākara Beach and Wellington South Coast shorelines from Point Dorsett to Red Rocks area, were assessed for coastal inundation hazard using a detailed hydrodynamic numerical model (XBeach-GPU). This dynamic modelling accounts for the complex interactions of waves, currents, and water levels with the intricate bathymetric and topographic features in the surf zone (e.g. Moa Point Reefs, Taputeranga Island, The Sirens Rocks and other rock platforms, and sand and gravel beaches). Notably, for the purposes of inundation assessments, the model resolves wave-groups and determines how the mean sea level (averaged over multiple wave periods) is increased by wave setup in addition to extreme storm-tides. The model was calibrated against a suite of storms (which are less than 1% AEP) which have historically impacted the shorelines. The model was then re-run for the storms after adjusted the forcing conditions to an

[3] The combination of astronomical tides and storm-surge caused by low-pressure weather systems.
[4] The additional rise in sea-level cause by the release of wave energy when waves break at the coast effectively 'piling up' water against the shoreline.

equivalent 1% AEP by increasing the storm-tide elevation, and the inclusion of climate change effects (RSLR and +10% storminess).

The maximum inland reach of the runup for individual storms is then combined into an inundation envelope across all storms. The envelope represents the maximum extent of inundation across all modelled scenarios at the 1% AEP level.

Not every property within the mapped inundation areas will be affected under a 1% AEP storm because the natural variability of waves on a storm-by-storm basis means that some areas will be exposed and others not depending on the unique storm characteristics. E.g. the April 2020 storm, which damaged Ōwhiro Bay, was not particularly large compared to others, but the unique wave direction (approximately 10 degrees west of 'normal' storms) and longer wave periods (16+ seconds) exacerbated the damage in Ōwhiro Bay but other South Coast bays were relatively unaffected.

Results

The assessments show that, as expected for the present-day, only land which has the lowest elevation or is nearest to the coast are exposed to coastal hazards. This includes the coastal roads, small pockets of the harbour shorelines, some of the historically reclaimed port areas and wharfs of Wellington Central and Evans Bay, as well as low-lying coastal areas within the bays on the South Coast (e.g. Ōwhiro Bay, Lyall Bay).

The assessments including climate change effects show an escalation of coastal hazards for low-lying areas of encircling Lambton Harbour and coastal suburbs such as Seatoun, Shelley Bay, Wellington Central, Pipitea and CentrePort. Not all inundated areas are situated directly at the coast, with coastal storm inundation possible via stormwater connections to inland Kilbernie, Seatoun, Mirimar and Wellington Central. The additional wave exposure around South Coast from Breaker Bay to Ōwhiro Bay increases considerably with climate change as the current roadways and landforms (engineered and natural defences) are overwhelmed by the wave processes on top of a higher sea level. Inundation reaches several hundred metres inland at Ōwhiro Bay, Island Bay and western Lyall Bay as the overland wave flow follows the alignment of the stream bed channels, the roadways and low-lying former backshore areas. Areas where houses are situated between the coast road and the steep hillside (e.g. Breaker Bay, The Sirens, eastern/western flank of Ōwhiro Bay) are shown to be overwhelmed during storms under climate change scenarios with waves reaching behind houses and only being held back by the rising hillside.

Next steps

The hazard information from this investigation could be used to provide information that enables Wellington City Council and residents to manage and adapt to SLR. Refining the model work to include smaller increments of sea-level rise (such as increments of 0.2 m) would show the emergence of coastal hazards, and allow incremental stress-testing and advance warning of when a hazard may become intolerable, and thus when adaptive decisions are needed.

1 Introduction

Wellington City Council (WCC) is embarking on a review and update of the District Plan, which has been operative since 2000, with 83 completed plan changes. The District Plan, a mandatory planning document under the Resource Management Act 1991, sets out the objectives, policies and rules and associated map overlays that the WCC uses to manage development of the city's natural and built environment.

In relation coastal hazards in Wellington, the revised District Plan needs to consider a planning timeframe of at least 100-years to give effect to the NZ Coastal Policy Statement (NZCPS). Under Policy 24 of the NZCPS, this includes "*taking into account national guidance*" on coastal hazards and climate change (MfE, 2017), and "*the best available information on the likely effects of climate change on the region or district*". The likely effects of coastal hazards and climate change will be seen predominantly on low-lying coastal/harbour land and coastal fronting property/assets.

The latest national guidance, MfE (2017), provides sea-level rise (SLR) projections generally for Aotearoa-NZ for the next ~150 years. MfE (2017) also recommends inclusion of locally specific information on vertical land movement to SLR projections. In Wellington, new information shows a trend of subsidence which will exacerbate SLR in Wellington.

1.1 Scope of the project

WCC has engaged NIWA to provide expertise on coastal hazards (excluding tsunami), including the effects of future SLR, to inform and support the revision of the District Plan.

The scope of NIWA's input is to provide:

- Sea-level rise projections for the 100-year timeframe (2120).
- Three sea-level rise values from the MfE Guidance scenarios; present day, NZ RCP 8.5 (median) and NZ RCP 8.5 H^+ (83rd centile), where the future scenarios include tectonic subsidence affecting relative sea-level rise.
- Assessment of Coastal Erosion hazards.
- Assessment of Coastal Inundation hazard at the 1% AEP level including SLR projections.
- Maps and data from the coastal hazard assessment for inclusion to WCC planning layers.
- A methodology report covering the analysis and mapping.

The Project involves 4 analysis tasks tailored to the relevant processes in each area of the Wellington District coastline (Figure 1-1):

1. Sea-level rise projections (all areas).
2. Coastal erosion (all areas).
3. Coastal Inundation (Harbour shorelines).
4. Coastal Inundation (South Coast and Mākara Beach shorelines).

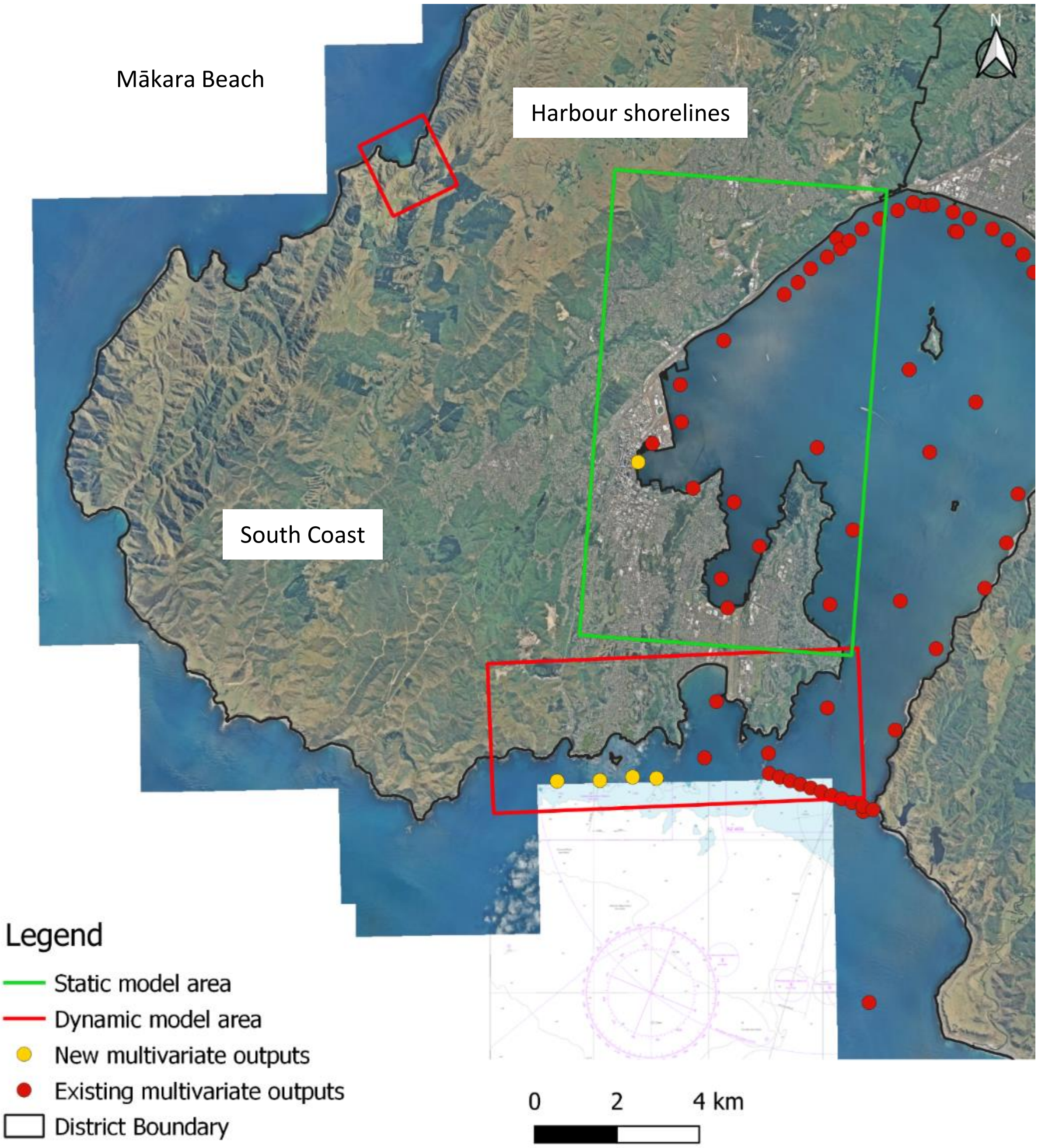


Figure 1-1: Analysis areas for the present study. Model areas indicative only.

1.2 Project outputs

Two reports are to be produced for this project

- Task 1 – SLR projections report (completed March 2021, see Section 1.2.1)
- Tasks 2-4 – Coastal hazards analysis report (this report, see Section 1.2.2)

Accompanying this report are GIS shapefiles of the mapped hazard areas (see Section 1.2.3).

1.2.1 Task 1: SLR projections

The output from Task 1 was the report:

> *Bell, R.G., Allis. M.J. (2021) Update on sea-level rise projections for Wellington City. Supporting the 2020–2021 District Plan process. NIWA Client report 2021051HN Prepared for Wellington City Council. March 2021. 25 p.*

The Task 1 output report (Bell & Allis, 2021) outlined sea-level rise elevations for the Wellington City district, including analysis of present-day mean sea levels, of recent and future vertical land movement caused by inter-seismic (between earthquake) subsidence, and synthesis of forward projections for use in Tasks 3-4.

Section 3 of this report contains a summary of the Bell & Allis (2021) outcomes as used for the numerical modelling Tasks within this report.

1.2.2 Tasks 2-4: Coastal hazards and sea-level rise

The outputs from Tasks 2-4 are contained in this present report:

> *Allis, M.J., Rautenbach, C., Gorman, R.G., Wadwha, S. (2021) Coastal hazards and sea-level rise to 2120. Supporting the 2020-2021 District Plan process. NIWA Client report 2021250HN Prepared for Wellington City Council. August 2021. 119 p.*

This report provides the methodology behind the coastal hazard assessments.

1.2.3 Mapping and GIS shapefiles

Accompanying this report are digital copies of the analysed coastal hazards. These are provided directly to WCC for this project.

Files are provided as GIS compatible files (shapefiles or GeoTiff raster) including appropriate metadata.

1.3 Vertical datums

The vertical datum used for this study is the WVD-53 vertical datum. All inputs (LiDAR, extreme sea-level elevations) and outputs are relative to this datum. This is defined as the 0.905 m above CD by Land Information New Zealand (LINZ).

The present-day MSL is analysed by Bell and Allis (2021) and results relevant to this report are summarised in Section 3.

This datum may be converted to NZVD2016 by subtracting 0.35 m from the WVD-53 at the Wellington Tide Gauge (BM ABPB) elevation (see discussion in Section 2.2 of Bell and Allis (2021)). Note this transformation is not uniform across the Wellington Region. For all geodetic transformation grids refer to data.linz.govt.nz.

2 Processes contributing to coastal hazards over the district plan timeframe

This section provides a brief overview of the processes contributing to coastal hazards as assessed in this study.

Coastal hazards around the Wellington district[5] generally include coastal erosion of beaches, estuarine shores or cliffs, and coastal inundation flooding of low-lying land which arise during extremely-high sea levels and large wave events. These coastal hazards are a significant issue within the Wellington district and will be an increasingly important issue over the 100-year timeframe of the District Plan process as the effects of climate change intensify.

There are a number of physical, meteorological and astronomical processes which can cause coastal hazards such as coastal erosion and/or coastal inundation.

2.1 Coastal erosion

Coastal erosion or shoreline retreat is the loss of coastal land to the sea or ocean. It is a natural process which occurs whenever the transport of material (sediments or bedrock) away from the shoreline is not balanced by new material being deposited onto the shoreline. Within a coastal compartment (e.g. a bay), this imbalance in the sediment budget leads to retreat of the shoreline (Figure 2-1). Coastal erosion is typically driven by the action of waves and currents and relative sea level on coastal deposits at beaches, estuaries and cliffs, but can also result with changes to external sediment supplies such as reduction to longshore transport, reduction river/stream sediment load, long-term environmental shifts (e.g. sea-level rise) or arising from human disturbances (e.g. dredging, some construction activities).

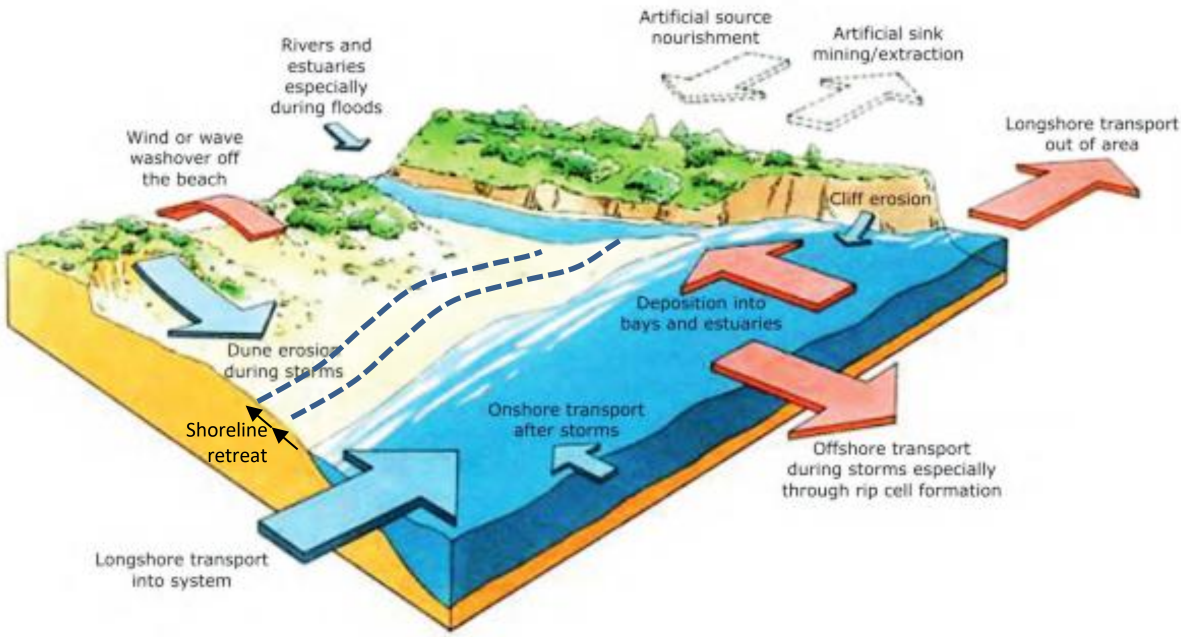


Figure 2-1: Schematic of sediment budget within a coastal compartment. A net loss of sediment on the beach face will result in erosion and shoreline retreat. [Modified from Engineers Australia (2012)].

[5] Excluding Tsunami

Coastal erosion can be either a:

- Rapid-onset hazard (occurs very quickly, a period of days to weeks), or
- Slow-onset hazard (occurring over many years, or decades to centuries).

Significant episodes of coastal erosion are often associated with extreme weather events (coastal storms, storm surge and riverine flooding), both because the waves and currents tend to have greater intensity and because the associated storm surge can allow waves and currents to attack landforms which are normally out of their reach (Figure 2-3).

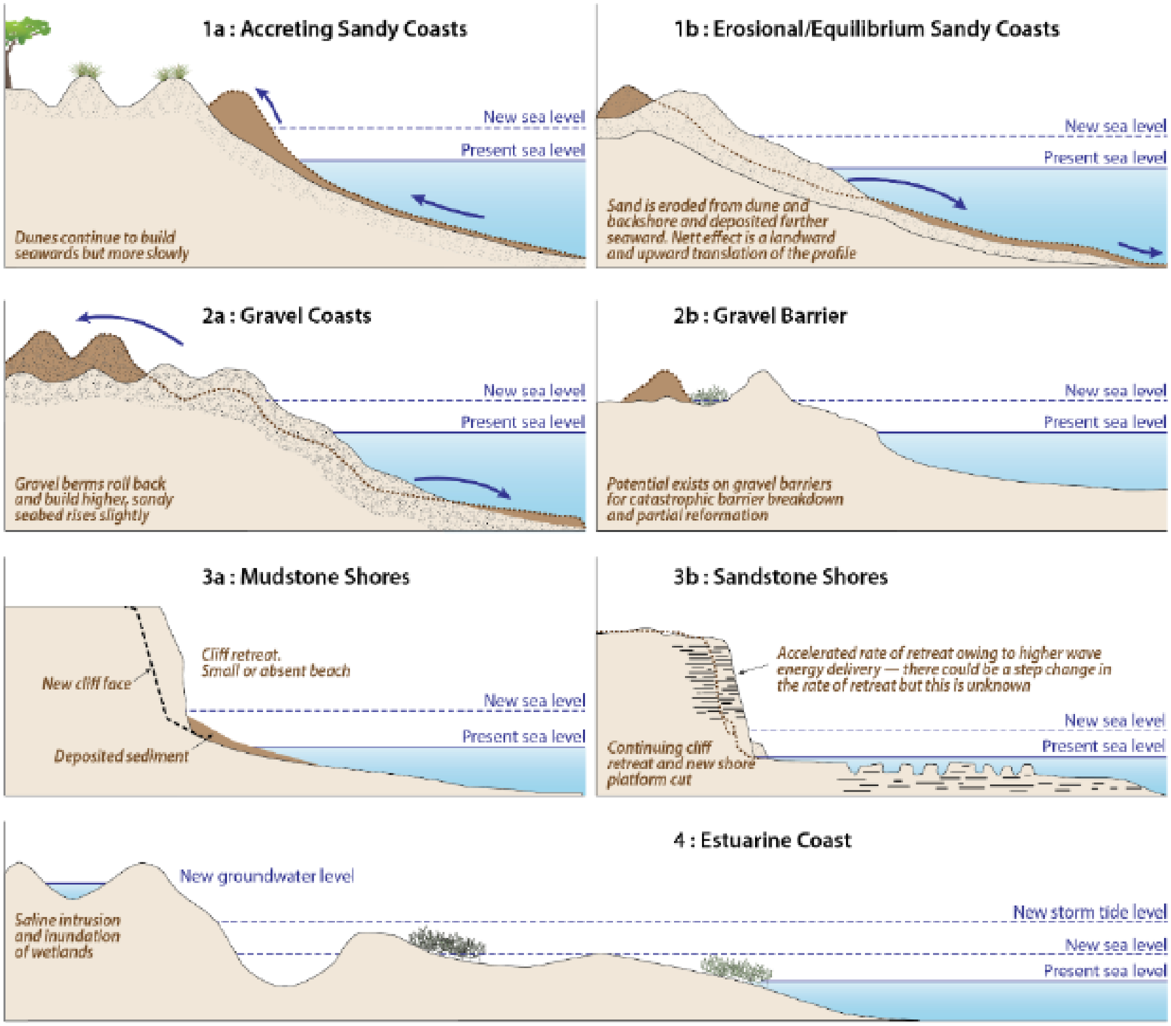
Erosion also occurs on a longer time scale as the landforms respond to changes in the balance of sediment input/loss arising from long-period fluctuations. This may include, for example, shifts in wave climate during atmospheric phenomena like the Interdecadal Pacific Oscillations (IPO) or El Niño South Oscillation (ENSO) shifts, or the slow (days to centuries) flushing of sediment from rivers following earthquakes and catchment land sliding, and slow subsidence/uplift due to inter-seismic (between earthquake) vertical land movement.

Many coastal landforms naturally undergo quasi-periodic cycles of erosion and accretion on time-scales of days to years. This is especially evident on landforms such as beaches and dunes (e.g. Lyall Bay) and along spits at river/lagoon entrances (e.g. Mākara Beach) where the coastal landform is seen to change shape and position over time, dynamically readjusting to the local conditions and often returning (temporarily) to a self-similar equilibrium position.

However, human activities can also strongly influence the susceptibility of landforms to erosion, even those activities intended to prevent erosion. For example, the construction of coastal protection structures (such as breakwaters as at Wellington Airport, or groynes and seawalls as Island Bay) can lead to changes in coastal sediment transport pathways, resulting in erosion in some areas and accretion in others. The removal of sediments from the coastal system (e.g., by dredging or sand/gravel extraction), or a reduction in the supply of sediments (e.g., by the management of river flood plains) can also be associated with unintended erosion. In Wellington, the coastline is predominantly protected by engineering structures which support the coastal roads and alleviate some of the effects of coastal erosion on people and assets.

Coastal erosion becomes a hazard when society does not adapt to its effects on people, the built environment and infrastructure. The most vulnerable coasts are those made up of unconsolidated sediments, such as beaches, dunes and sand cliffs, on open coasts that experience net longshore drift of sediment. Shorelines with protection structures, such as Wellington, have some additional defence against erosion. The defence structures such as seawalls or groynes are often designed to accommodate the short-term storm effects, but require upgrades over time to manage effects of chronic sediment supply reduction or the effects of sea-level rise.

Climate change and sea-level rise will have an effect on coasts as they respond to changes in distribution of sediment patterns and rates of sediment transport, which in turn will affect the shape and orientation of beaches (MfE 2017). Figure 2-2 outlines the generalised impacts of SLR on difference types of coastal landforms. Where engineered structures are present, the potential rate of erosion, and hence risk exposure to the hinterland, at the present day or with future sea-level rise is governed by the design, maintenance and upgrade of the structures.



These schematics are only indicative, because local geomorphology, human impacts and changes to the sediment supply may produce different responses. Graphics: adapted by Max Oulton (University of Waikato) from Ministry for the Environment (2008a)

Figure 2-2: Generalised impacts of SLR on different types of coastal morphology. [Source: Figure 32 from MfE (2017)].

2.2 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. The processes involved are:

- Mean level of the sea (MLOS),
- 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

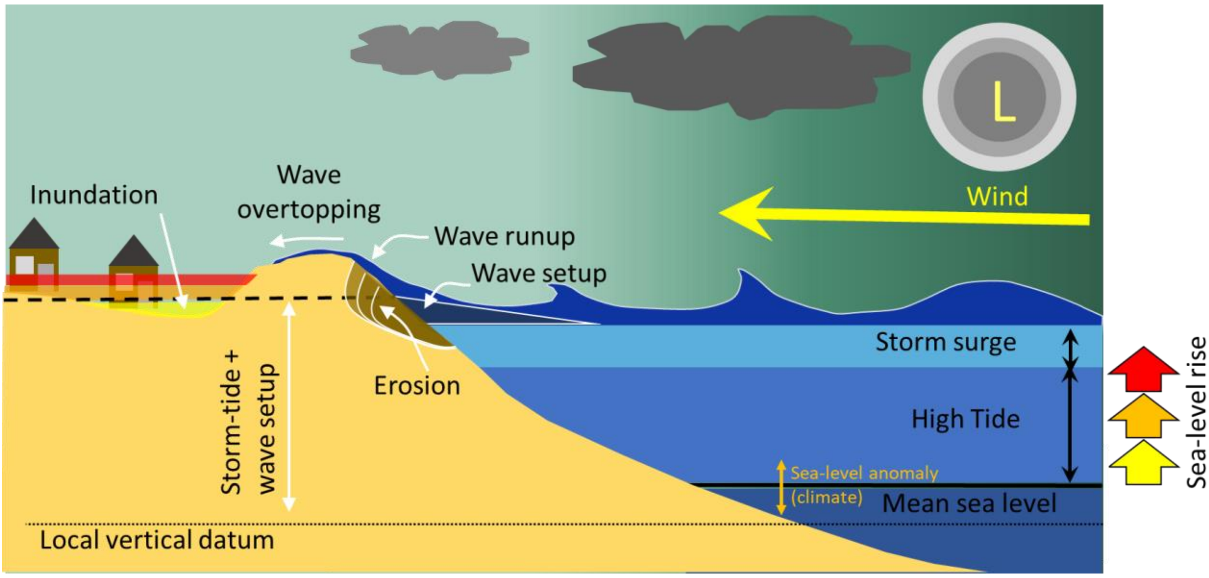


Figure 2-3: Illustration of coastal and ocean processes contributing to costal inundation and coastal hazards.

The **mean level of the sea** describes the variation of the non-tidal sea level on longer time scales ranging from monthly up 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.

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 MLOS + 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 inundation. From the sea-level gauge record, times and tidal elevation at each high water were identified. Similarly, each peak in the total water level was identified, allowing the skew surge to be computed, as the difference (total – tide) between each high tide level and the nearest peak high-water level (Figure 2-4).

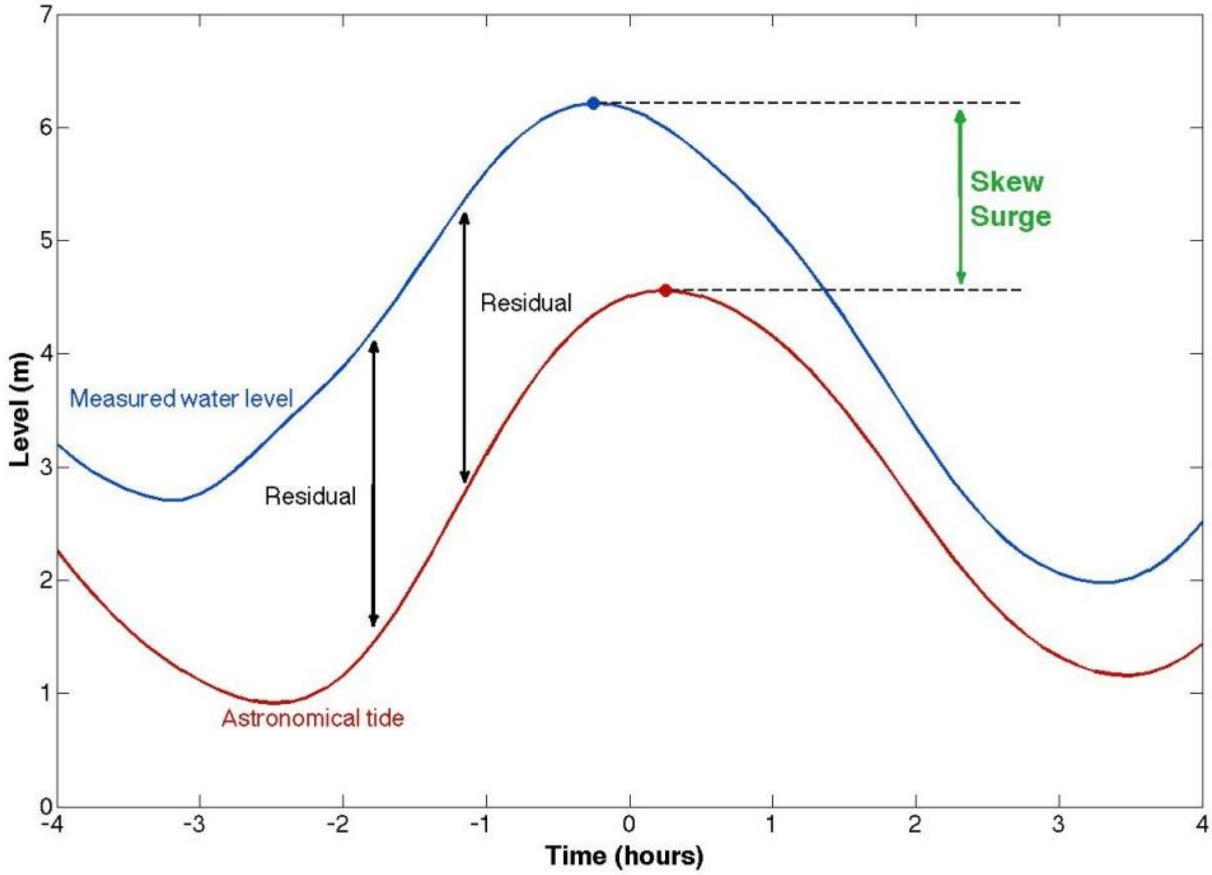


Figure 2-4: Illustration of the definition of skew surge. Skew surge is the difference between the maximum observed water level and the maximum predicted tidal level, which may occur at different times. [Source: https://www.surgewatch.org/definition/skew-surge/[Source: https://www.surgewatch.org/definition/skew-surge/].

Waves from swell and wind 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 2-3). The term wave setup describes an average raised elevation of sea level at the shore when long waves (caused by breaking waves) are present. In this way **wave setup** also contributes to coastal inundation 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 inundation 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 inundation when the flood discharge is constrained inside narrower sections of estuaries. Neither riverine flooding nor groundwater flooding nor tsunami inundation are considered in this report.

In this report, we present maps of total storm inundation that include the effects of MLOS, astronomical tides, storm surge, and wave setup. We also conduct simulations that include increments of relative sea-level rise.

2.3 Climate change

Climate change does not introduce any new coastal hazards to the Wellington district but it 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).

Among the impacts from climate change, sea-level rise in future is expected to be the dominant influence on coastal hazards. Sea-level rise is expected to greatly increase the frequency (and depth, and so the extent of the areas) of coastal storm inundation (Parliamentary Commissioner for the Environment, 2015; Stephens, 2015) and the frequency and magnitude of coastal erosion, relative to the present (MfE 2017).

The effects of climate change on other drivers of coastal hazards will be secondary to ongoing sea-level rise. MfE (2017) recommends including minor increases (+10%) to storm surge, waves heights and wind speeds for assessments of future hazards over a 100-year time period.

In Wellington, SLR is compounded by a slow inter-seismic subsidence of the land leading to an additional *relative* sea-level rise (RSLR). Further details of RSLR and the projections for Wellington are found in Bell & Allis (2021) and in Section 3.

In this report we have considered both the effect of SLR combined with the +10% increases to secondary components.

3 Task 1 (summary): sea-level rise projections for Wellington City

The Bell & Allis (2021) report built on the previous SLR reports and analyses, provides a synopsis of the most recent updates in SLR trends and forward projections, including locally relevant SLR, which includes recent vertical land movement trends. The report provides:

- Present day mean sea-levels to use as the base sea level for future projections.
  - The 1986–2005 average MSL was 0.164 m WVD-53
  - Present-day (period from 2001–2019) MSL in Wellington Harbour and South Coast is 0.215 m WVD-53 (or -0.135 m NZVD–2016 using an offset of 0.35 m)
  - a +3 cm MSL offset from Wellington Harbour should be applied to the western areas at Mākara and Ōhāriu due to the prevailing westerly winds and waves from Tasman Sea persistently piling water against the west coast.
- An overview of local (relative) sea-level rise (RSLR) trends in Wellington from 121 years of average annual mean sea-level data at the Wellington Harbour tide gauge.
  - Over the entire record, the linear trend in RSLR up to the end of 2019 is 1.95 ±0.09 mm/yr.
  - Over the last six decades (1960–2019), the average RSLR trend is 2.82 ±0.19 mm/yr.
- Analysis of recent and future vertical land movement (VLM) caused by inter-seismic (between earthquake) subsidence which is prevalent across the Wellington Region.
- Synthesis of the latest national coastal guidance on SLR projections out to 100-years for New Zealand (Figure 3-1). WCC requested to use only the RCP8.5 (median) and RCP8.5 H+ (83rd percentile) from the national coastal guidance.
- Forward projections, including mean sea level offsets, of RSLR, which includes recent vertical land movement trends over the 100-year planning timeframe.

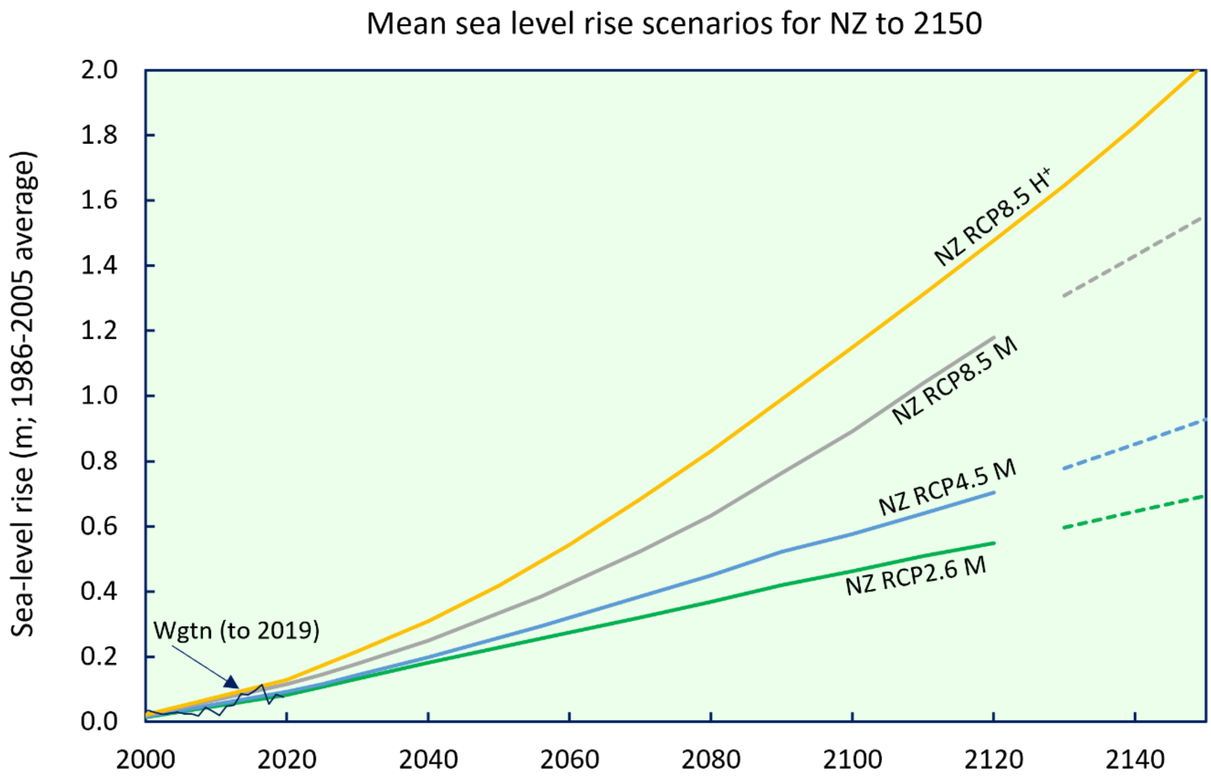


Figure 3-1: The four SLR scenarios for NZ (excluding VLM) from the MfE coastal guidance (MfE 2017) out to 2150 overlain by the annual MSL series from Wellington Harbour for 2000–2019. Note: SLR is relative to the 1986–2005 average MSL (refer Bell & Allis 2021). *Source*: Projections - MfE 2017, tide gauge data – GWRC

Bell & Allis (2021) separate the sea level analysis and projections into two regions; the Harbour shorelines of Wellington City including the South Coast, and the western coast for Mākara and Ōhāriu. Projections are also provided in two vertical datums, given the drive to convert to the national 2016 vertical datum.

The RLSR projections at 2120 recommended for use in coastal flood mapping for the present District Plan revision are 1.43 m and 1.73 m above the 1985–2006 local baseline MSL (a baseline period also used by IPCC and the national coastal guidance MfE, 2017). These projected RSLR heights for Wellington Harbour also include an ongoing landmass subsidence trend of 3 mm/year, based on monitoring trends of inter-seismic ground motion over the past decade (but excludes any major seismic rupture event that could occur over the planning timeframe).

Bell & Allis (2021) provide Table 3-1 for future projections around Wellington City.

Table 3-1: Summary of RSLR projections of future MSL in 2120 for use in coastal flood mapping for the present District Plan revision. Values based on two selected RCP scenarios from MfE(2017) specifically requested by WCC and a -3 mm/yr VLM allowance that both extend out approximately 100-years from now (2120).

Scenario (incl. VLM = 3 mm/yr subsidence)	MSL elevation (relative to 1985–2006 local MSL baseline) [m]	MSL elevation (WVD-53) [m]	MSL elevation (NZVD-2016) [m]
	Wellington Harbour and South Coast		
NZ RCP8.5M (median) + VLM	**1.43**	**1.59** [= 1.43 + 0.164]	**1.24** [= 1.43 - 0.186]
NZ RCP8.5 H+ (83rd percentile) + VLM	**1.73**	**1.89** [= 1.73 + 0.164]	**1.54** [= 1.73 - 0.186]
	West coast (Mākara and Ōhāriu)		
NZ RCP8.5M (median) + VLM	**1.43**	**1.62** [= 1.43 + 0.194]	**1.27** [= 1.43 - 0.156]
NZ RCP8.5 H+ (83rd percentile) + VLM	**1.73**	**1.92** [= 1.73 + 0.194]	**1.57** [= 1.73 - 0.156]

Adjusted to local RLSR projections for Wellington City and South Coast, the 2120 projections equate to 1.59 m (NZ RCP8.5 M) and 1.89 m (NZ RCP8.5 H+) in Wellington Vertical Datum 1953 (WVD-53)[6]. For the west coast areas of Mākara and Ōhāriu, Table 3-1 includes the +3 cm MSL offset from Wellington Harbour which is due to the prevailing westerly winds and waves from Tasman Sea persistently piling water against the west coast.

[6] To convert to the new recommended nation-wide NZ Vertical Datum 2016 (NZVD-2016), subtract 0.347 m from WVD-53 value.

4 Task 2: Coastal Erosion hazard

The physical processes contributing to coastal erosions hazards at the shoreline are described in Section 2.2 and illustrated in Figure 2-1 to Figure 2-3.

4.1 Existing coastal protection structures

Existing data about coastal structures was provided by WCC, this include the following layers:

- *WCC seawalls* (email from Pam Brown at WCC, 23-Dec-2020), including asset types shown in Figure 4-1.
- *WCC Assets T1* (provided March 2021) viewable at gis.wcc.govt.nz[7] the following layers were included and filtered to include only those near the coast which are likely to provide an element of protection or resistance to coastal erosion processes:
  - WCC Boardwalks/Boardwalks polygon
  - WCC Boat Ramp
  - WCC Jetty
  - WCC Breakwater
  - WCC Walls
  - WCC Fences and Rails

These layers are mapped in Figure 4-2 and Figure 4-1 and show that the majority of the Wellington City coastline is protected by engineered structures and there are a broad variety of seawall protection types. These coastal structures are seen to generally support the coastal roads (e.g. Moa Pt Road, The Esplanade, Karaka Bay Road, Queens Drive, Oriental Bay), with existing urban development usually inland of these roads (except for the approximately 13 properties on Queens Drive to the west of the Lyall Bay beach, and some boat sheds within the Harbour, and the Port).

However, these WCC GIS layers are non-exhaustive as they are missing some WCC coastal structure assets as well as a number of large private coastal structures. Missing features include, for example:

- The revetment protecting Wellington Airport and Moa Point road
- The WCC revetment along Cobham Drive
- Centreport areas (e.g. Thorndon Wharf, Aotea Quay, Lambton Harbour, Mirimar Wharf and Burham wharf)
- The Kiwirail revetment structures alongside Wellington Harbour extending from Kaiwharawhara to Petone.
- Shelly Bay wharf and coastal structures.
- Private seawalls in front of the 13 properties on Queens Drive to the west of the Lyall Bay beach.

[7] http://gis.wcc.govt.nz/arcgis/rest/services/Asset/WCC_Assets_T1/MapServer

- Various lengths of seawall around the coast (E.g. 200 m missing in SW Island Bay)

We recommend WCC collate information about all WCC and other private seawall assets in the district. This information would enable WCC to create risk and vulnerability maps to show where development is protected by private assets but with an unknown level of protection. This would show where risk is potentially heightened due to unknown condition of the private asset and also demonstrate where assets (WCC or private) are potentially more vulnerability to coastal hazards because WCC cannot build/maintain private seawalls.

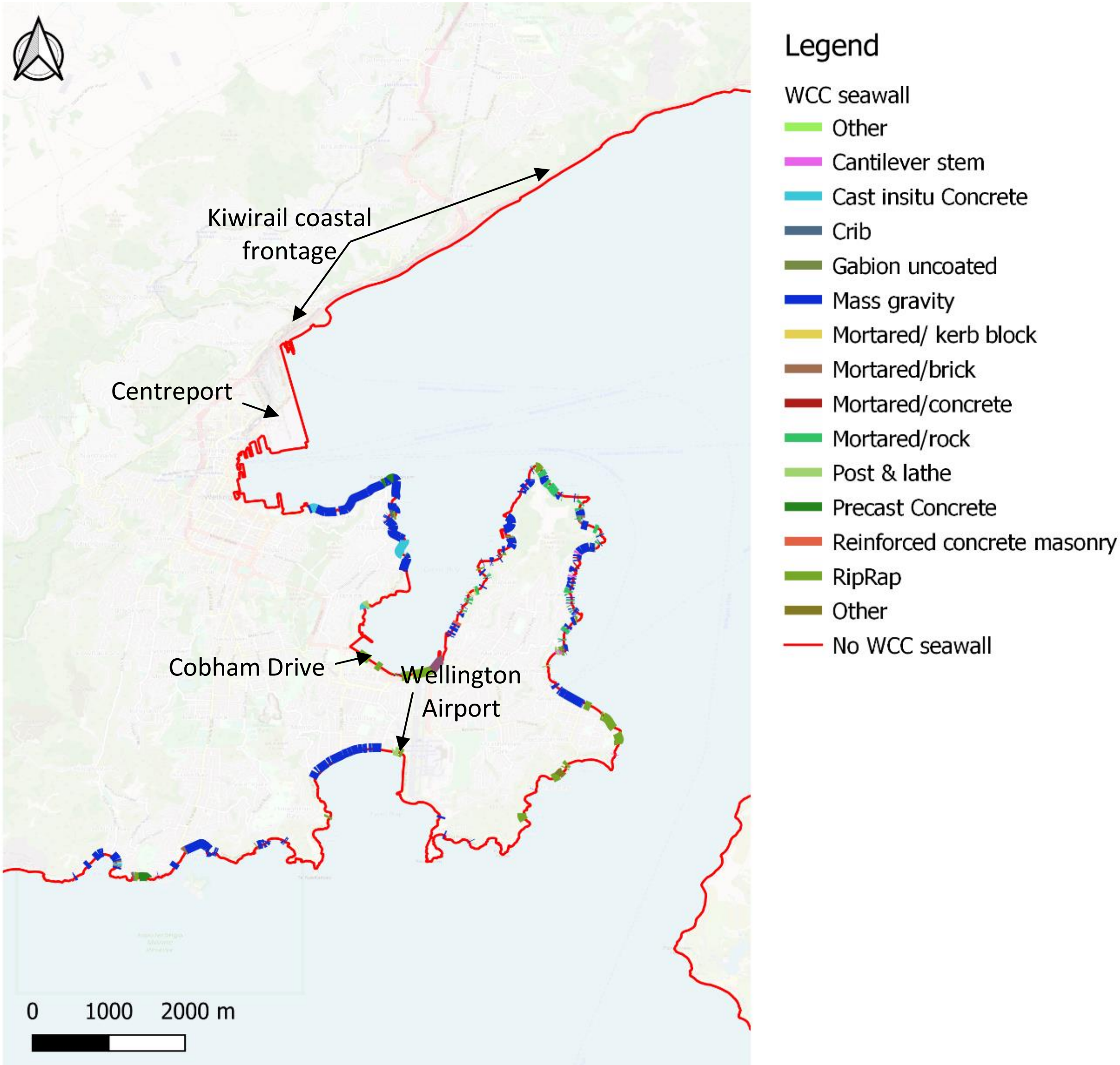


Figure 4-1: Information in "WCC seawalls" GIS layer. Note this layer is not exhaustive as it does not include "WCC_Walls" layer which has many seawalls. However, neither layer includes the known seawalls as annotated. [Source: WCC].

Where no coastal structure is shown, the shore is usually positioned above natural rocky shore platforms or offshore island or reef (Figure 4-2). These features act to dissipate wave energy thereby providing a natural protection to the coast road and coastal property and they erode at a much slower rate than unconsolidated beaches or man-made seawalls.

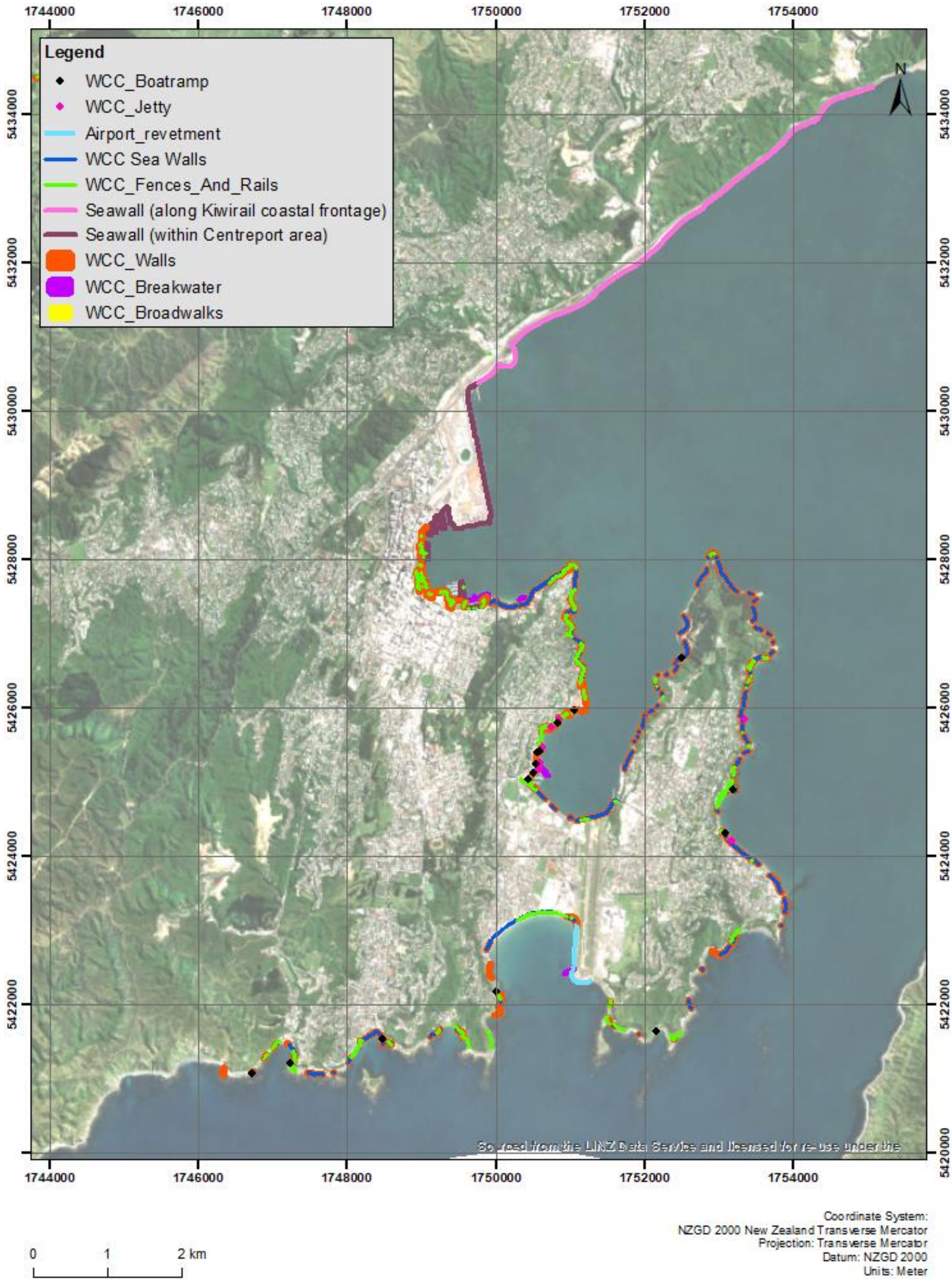


Figure 4-2: Known coastal structures around Wellington District coastlines compiled from available GIS information with manual digitisation of some large structures. Known coastal protection structures is non-exhaustive. Note the '*WCC Sea Walls'* (blue) combines all structure types from Figure 4-1. Black circles are WCC boat ramp structures, blue circles are WCC Jetty structures. [*Data sources*: WCC Assets T1 GIS Layer, WCC seawalls layer, NIWA digitisation of known large coastal structures Kaiwharawhara to Petone Kiwirail coastal structures, Thorndon/Aotea CentrePort wharves and Wellington Airport runway revetment].

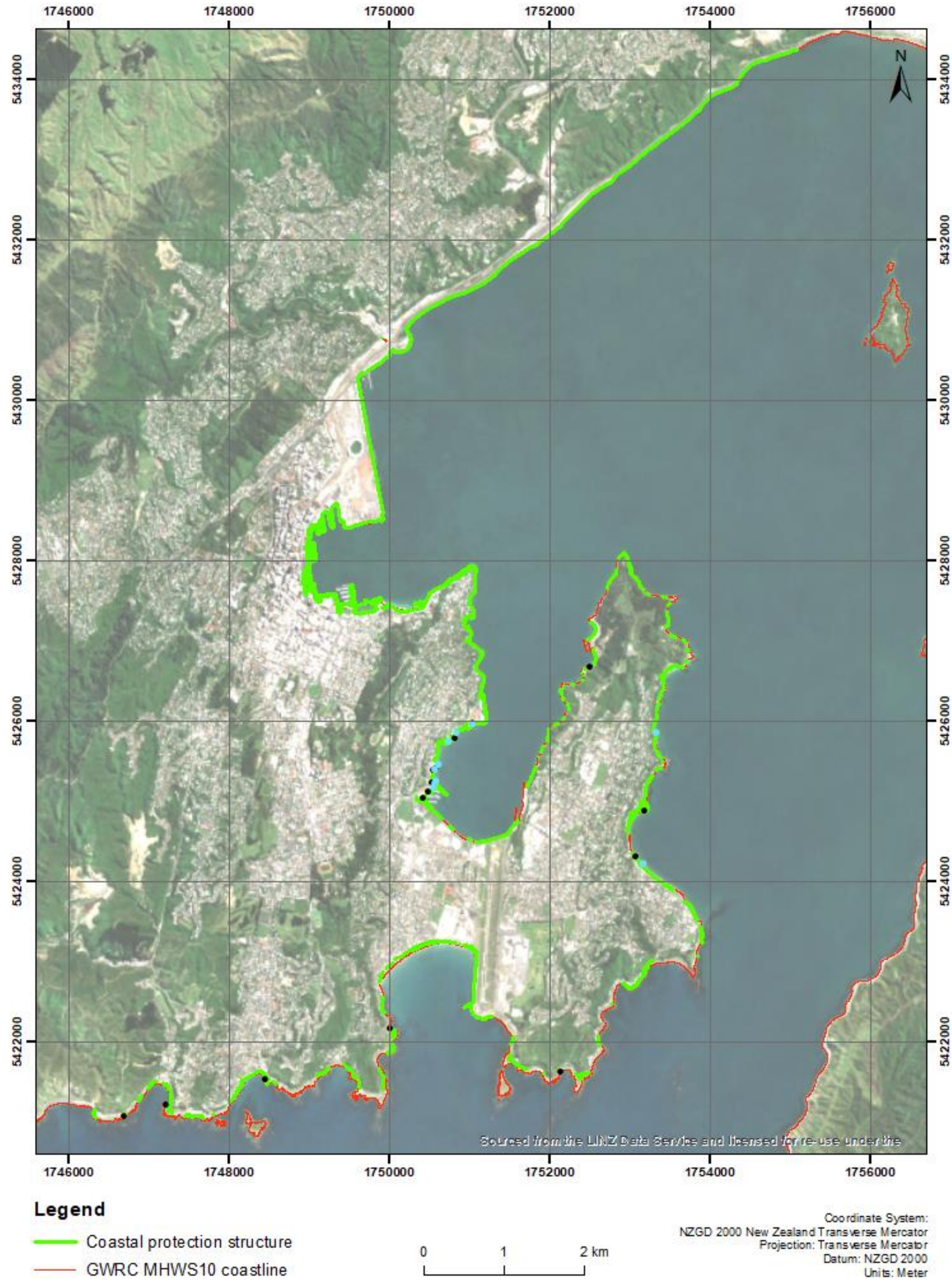


Figure 4-3: Summary of known coastal protection structures and features that may have a protective effect (green) on the underlying the Wellington City coastline (red). Known coastal protection structure are non-exhaustive and is intended to show that only small lengths of natural coast remain where potential erosion is unaffected by engineering activities. Black circles are WCC boat ramp structures, blue circles are WCC Jetty structures. Coastline is MHWS10 from GWRC. [See text for data sources].

Figure 4-3 summarises our known information on coastal structures or features which may have a protective effect around the Wellington City coasts. This shows only small lengths of coast remain where natural coastal erosion processes (see Section 2.1) could cause unmitigated erosion hazard. This highlights the few locations where empirical relationships (such as the Bruun rule for dune retreat) could forecast the future hazard for natural or unprotected coasts. Therefore, the extent of land threatened by erosion hazard is primarily governed by the presence of the structural defences or by the long-term and slow erosion of bedrock outcrops. Of these two, the coastal structures are more susceptible than bedrock to coastal processes over the 100-year timeframe, although sudden failures of bedrock are possible such as during earthquake shaking.

The potential erosion hazard for coastal areas is therefore dependant the performance of coastal structures, which, in turn depends on various parameters such as structural design (form, foundation, materials), age/condition and maintenance; the operational performance under storms; and site-specific conditions (local topographic wave focussing, long-term recession trends, underlying geology, sediment supply). Further, the future hazard extents will change with the additional effects of long-term erosion or changes due to future sea-level rise and the unknown future actions/decisions of WCC and landowners to maintain or upgrade coastal infrastructure.

To robustly assess the potential coastal erosion hazard in Wellington City, a detailed site specific engineering and hazard assessment would be required for each and every coastal protection structure (such as Island Bay, see Shand 2014), as well as bay-wide assessments of overall performance and sediment supply. It is beyond the scope of this study to conduct such a detailed engineering and erosion study for all coastlines around Wellington.

Instead, as outlined below, we have developed an alternative approach which is intentionally high-level to establish a zone which is potentially at risk due to solely to proximity to the coast.

4.2 The low-lying near-coast zone

For WCC open coast and harbour shorelines in this Project we have mapped low-lying land that is near to the sea which is the land that is most likely to be affected by coastal erosion or seawall failure; establishing a "*low-lying near-coast zone*". Creation of a low-lying near-coast zone does not constitute an assessment of coastal erosion hazard potential, rather it indicates proximity to the coast and areas more likely to be exposed to coastal erosion hazards.

The low-lying near-coast zone is defined as below 3 m above MHWS10 (which varies around the Wellington coastline) and within a horizontal offset of 30 m from the line of MHWS10. Figure 4-4 contains an overview of the GIS development of the zone. See Appendix B for full technical GIS explanation.

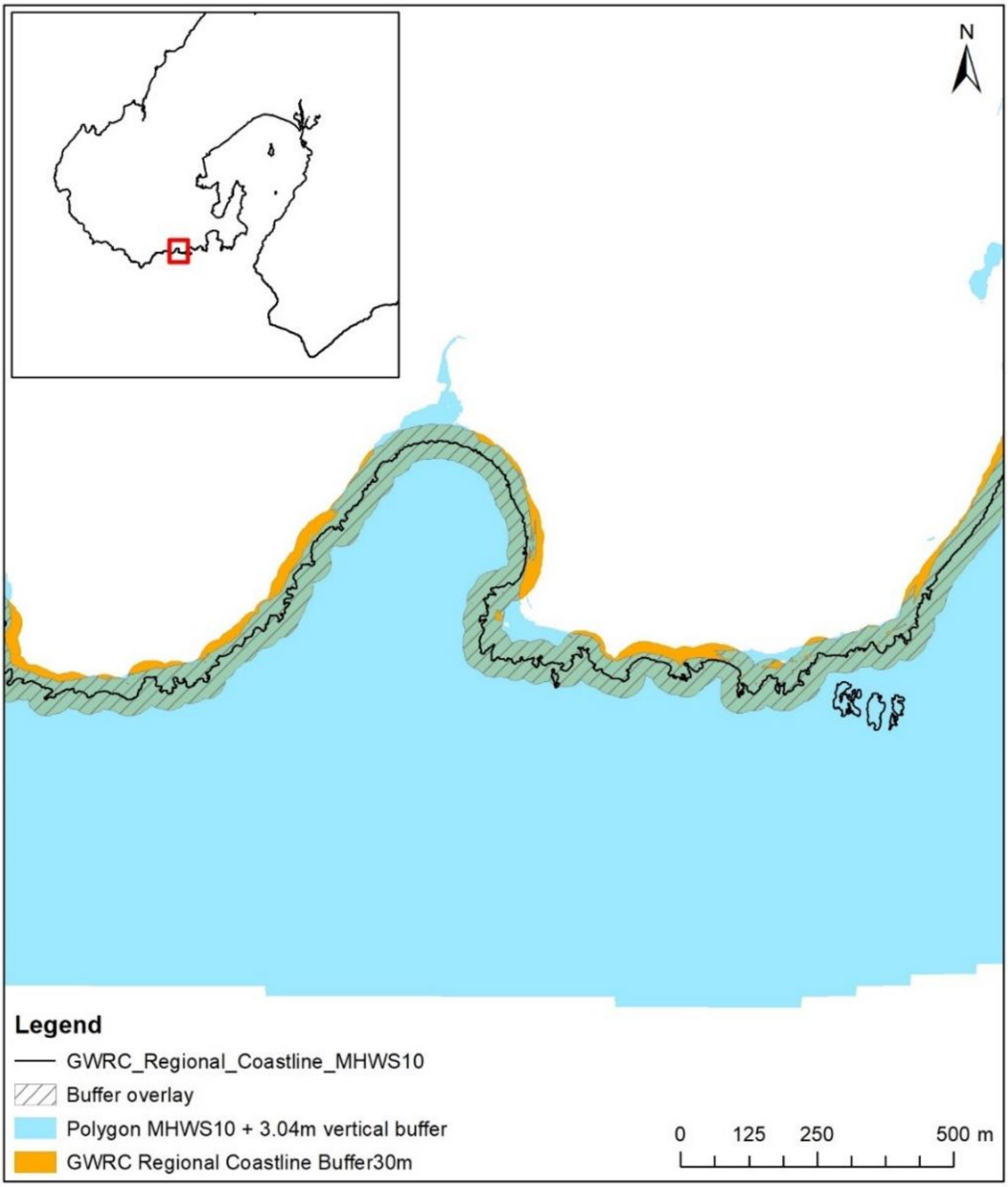


Figure 4-4: Development of low-lying near-coast zone (shown as "buffer overlay") for Ōwhiro Bay and Esplanade.

Figure 4-5 to Figure 4-11 illustrate the low-lying near-coast zone mapped for this study. GIS files of the mapped areas are provided directly to WCC.

In the development of the low-lying near-coast zone we note that:

- the +3 m vertical range above MHWS-10 was selected to encompass land that could be susceptible to coastal erosion due to proximity to the coast, excluding mass-failure of coastal escarpments.

- The selection of 30 m as horizontal offset is an arbitrary offset which would likely encompass the substantial erosion possible under a 1% AEP storm.
- The elevation and offset distances do not change with the type of coastal feature (beach, bedrock) or presence/absence of coastal structure because of the unknowns in the extent and condition of the coastal structures or bedrock, and how they will perform when tested over the 100-year timeline (refer Section 4.1).
- The MHWS10 line as mapped by GWRC[8] was based on analysis of MHWS10 elevations from PCE(2015) adjusted to include an offset to present-day MSL[9].
- The zone is mapped onto the land using the regional LiDAR (2019).
- No RSLR allowances are included.

Figure 4-5 to Figure 4-11 illustrate the low-lying near-coast zone mapped for this study. Around the Wellington district the low-lying near-coast zone generally occupies the immediate coastal fringe, coastal structures, beaches and rocky shore platforms. At Mākara Beach, the MHWS-10 shoreline used by GWRC extends approximately 2 km up Mākara Stream, with the low-lying near-coast zone accompanying it – however streambank and terrestrial flooding will dominate hazards here.

The intention of the low-lying near-coast zone is that potential development inside that zone could be managed within the District Plan by conducting detailed assessments of the potential coastal erosion hazard, incorporating, for example, site-specific information about the coastal structures, site history, vulnerability of assets and risk exposure. This detailed assessment would also include the coastal inundation study (Section 6 of this report) and the future SLR scenarios.

This approach is consistent with the approach of the recent Auckland Council Unitary Plan[10] policy that classifies "*land that may be subject to natural hazards"* as being "… c. *at an elevation less than 3 m above MHWS if the activity is within 20 m of MHWS"* (Part 2.C.5.12 –1).

We note that the mapped low-lying near-coast zone does not constitute a formal "coastal erosion hazard zone (CEHZ)", or "coastal erosion zone (CEZ)" as are often determined for district-scale erosion studies. Use of these terms implies that erosion or hazard assessments have been undertaken - when no such assessment has been completed for this study as outlined above.

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[8] https://data-gwrc.opendata.arcgis.com/datasets/782327305e22466aaa0c8ad2afc0f0d6_1

[9] GWRC mapped the MHWS-10 elevations onto the land using the 2013 LiDAR and a 0.19 m offset to WVD-53 for 1995-2013 MSL (Appendix B, PCE 2015). We adjusted the MHWS-10 elevations to a present-day (2021) MSL by applying the latest MSL measurement of 0.23 m WVD-53 (pers. comm J. Hannah for 2019, see Bell & Allis 2021).) and allowing for small 2 cm rise for the "present day" 2021 MSL. Instead of applying a MSL offset (0.235m) to the MHWS-10 elevation we used the MHWS-10 elevations directly from GWRC as the lower extent of the zone, and applied the 3 m buffer plus the 0.04 m offset to account for the rise in MSL between the datums (0.23-0.19=0.04) to define the upper extent of the zone. The effect on the zone area is negligible as the lower datum (MHWS-10 elevation as mapped on 2013 LiDAR with 0.19 m offset) is nearest to the coast and is encompassed within the low-lying near-coast zone by default. This accounts for annual MSL fluctuations (refer Bell and Allis, 2021 Figure 2-1) and the changes to land-elevation due to seismic events (Kaikoura Earthquake) with post-seismic responses alongside sea-level rise and slow regional subsidence which have altered MSL elevation (Bell and Allis, 2021).

[10] https://www.aucklandcouncil.govt.nz/plans-projects-policies-reports-bylaws/our-plans-strategies/unitary-plan/Pages/default.aspx

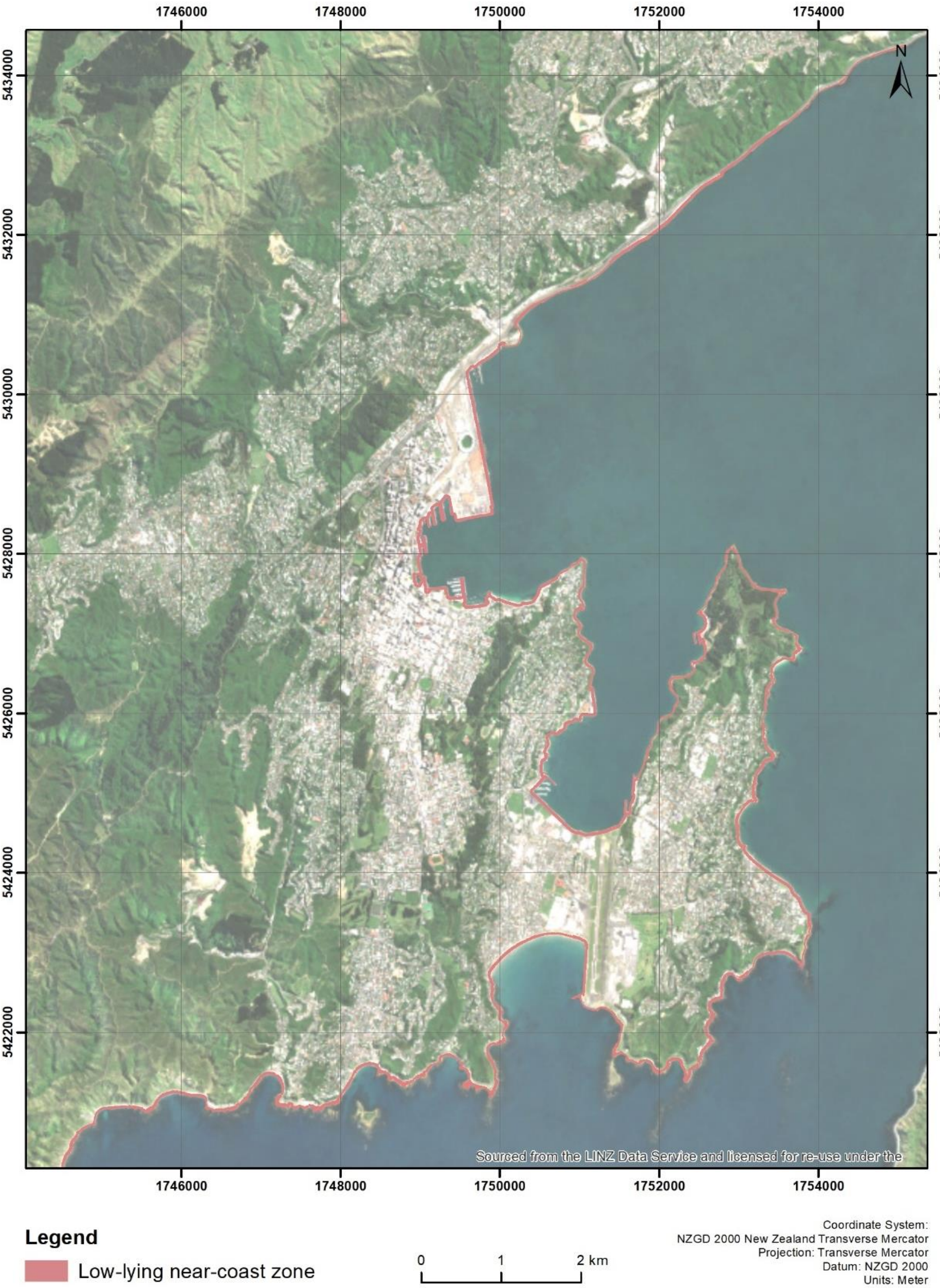

Figure 4-5: Low-lying near-coast zone for Wellington - overview.

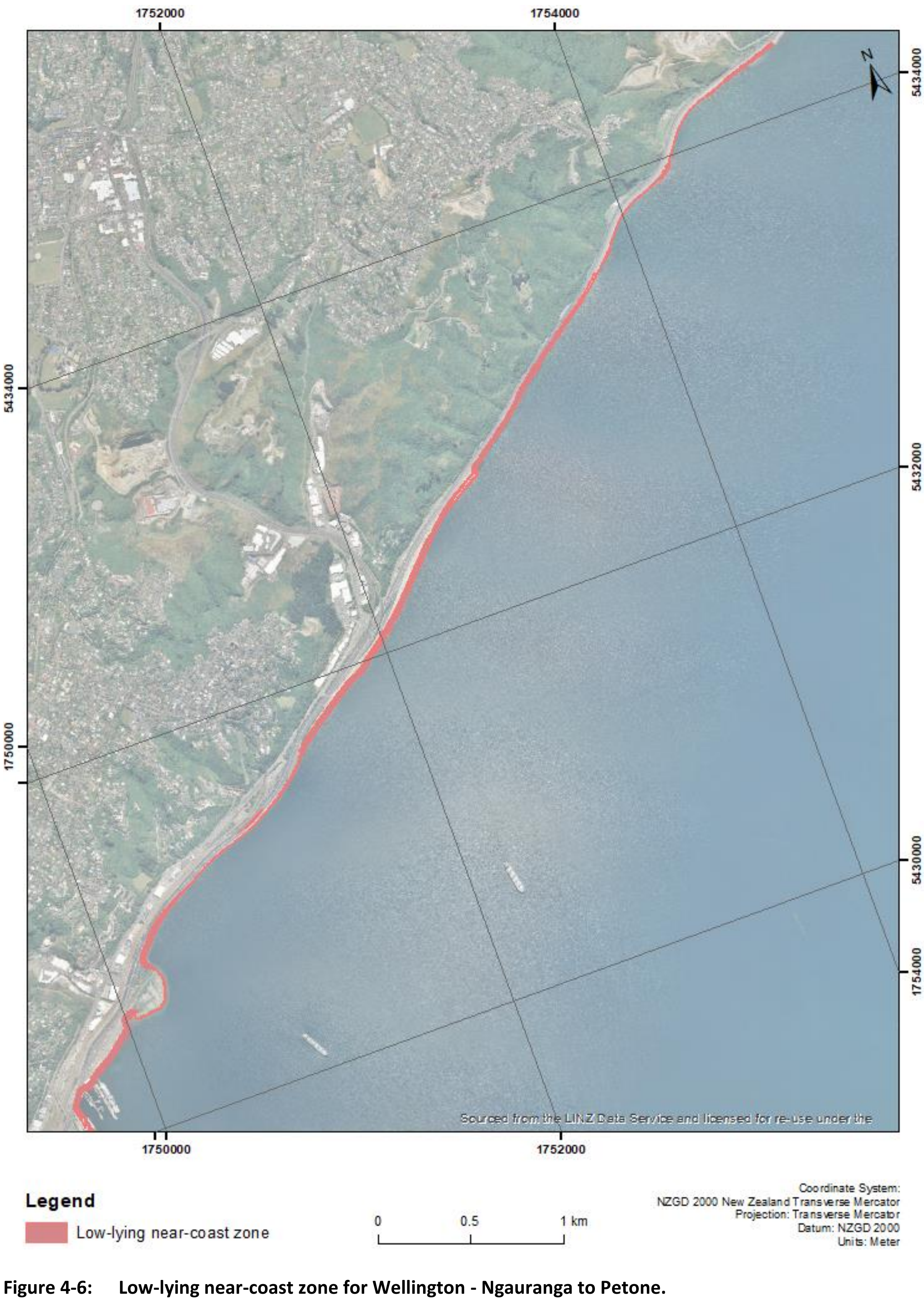

Figure 4-6: Low-lying near-coast zone for Wellington - Ngauranga to Petone.

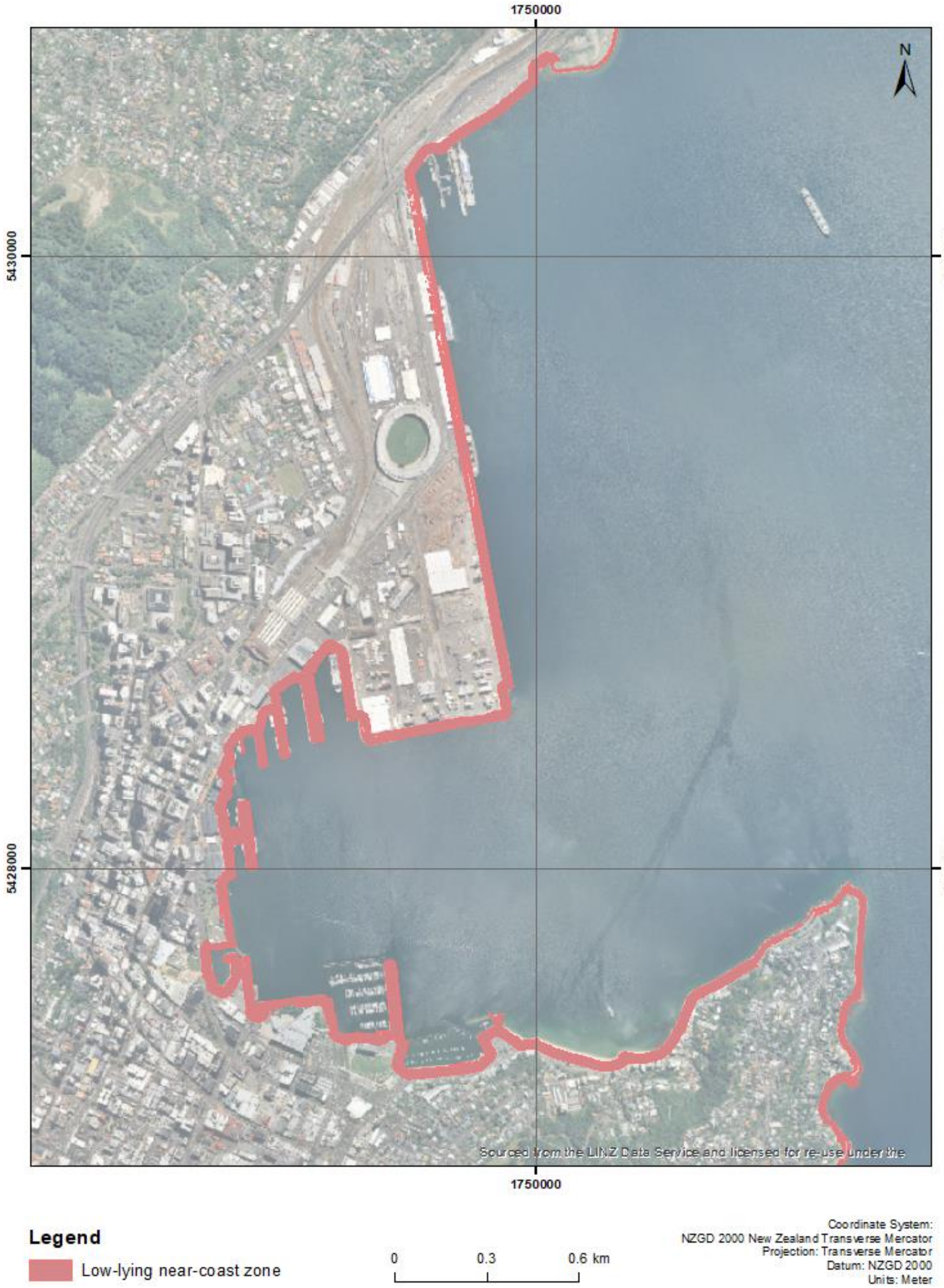

Figure 4-7: Low-lying near-coast zone for Wellington – Centra City from Point Jerningham to Ngauranga including Lambton Harbour and Aotea Quay.

Figure 4-8: Low-lying near-coast zone for Wellington – Evans Bay and Mirimar Peninsula.

Figure 4-9: Low-lying near-coast zone for Wellington – Seatoun to Lyall Bay.

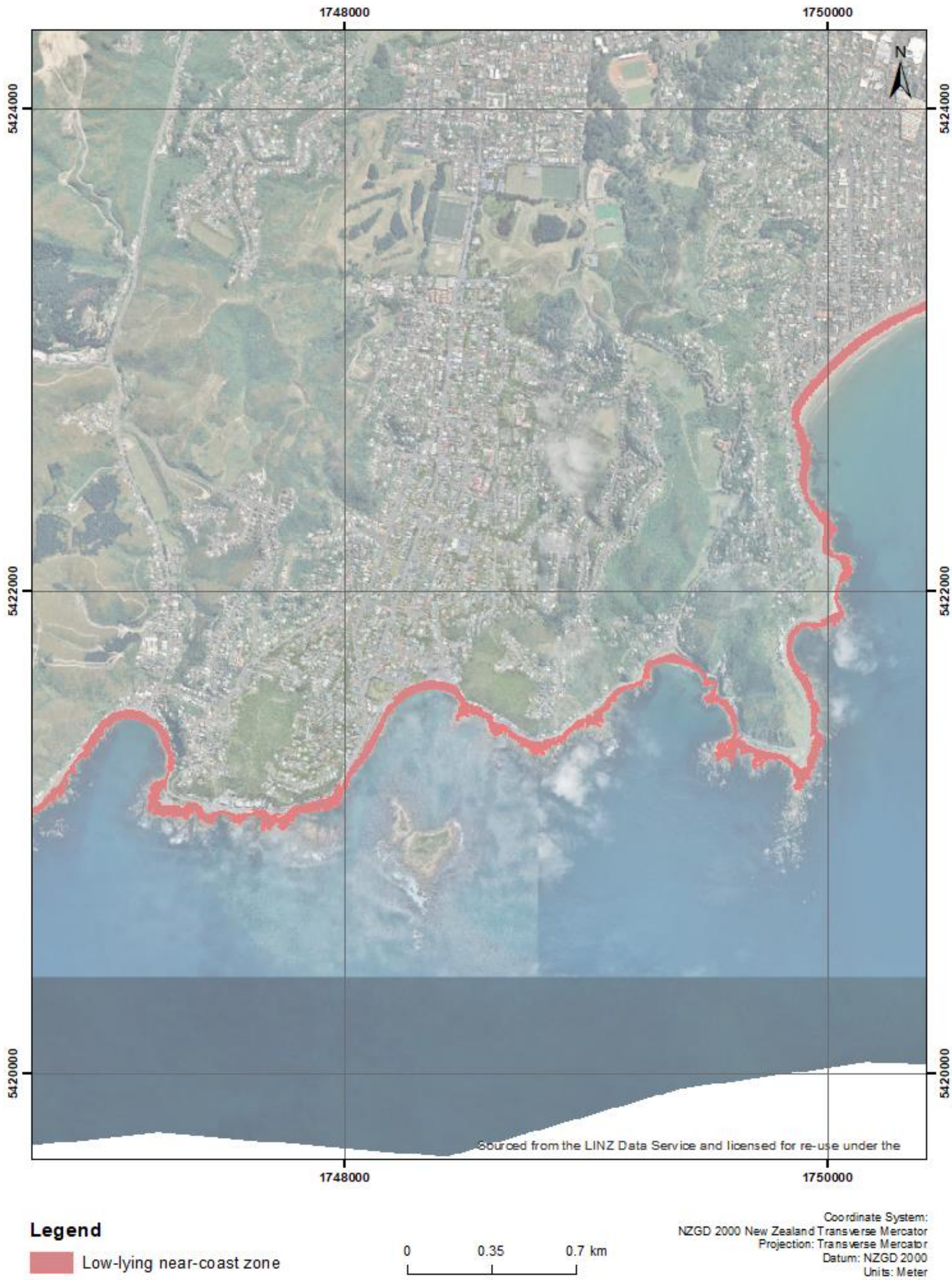

Figure 4-10: Low-lying near-coast zone for Wellington - South Coast from Lyall Bay to Ōwhiro Bay.

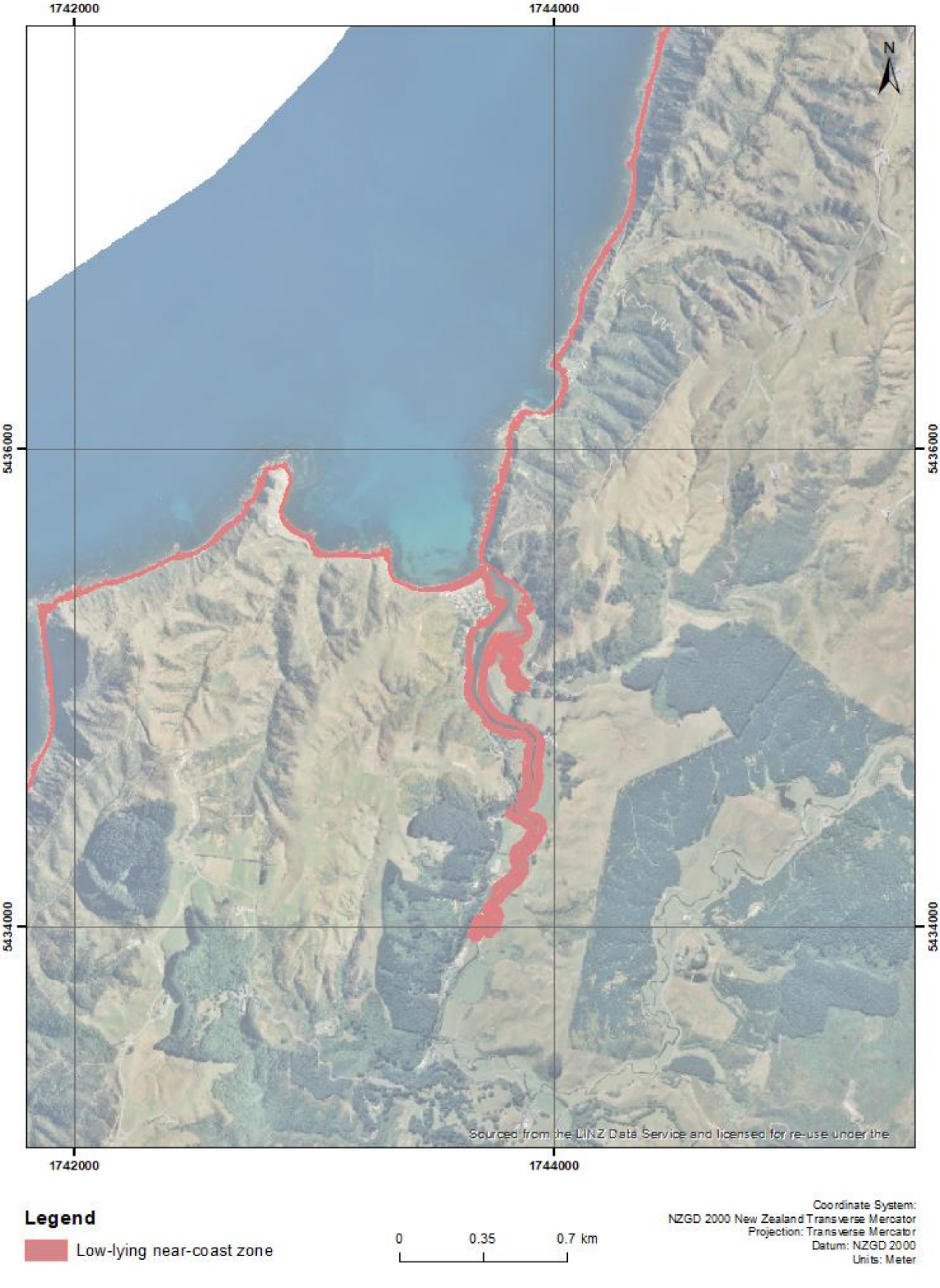

Figure 4-11: Low-lying near-coast zone for Wellington – Mākara Beach.

5 Task 3: Static inundation of Harbour shorelines

This Task relates to numerical modelling of extreme water levels within Wellington Harbour. The physical processes contributing to extreme water levels at the shoreline are described in Section 2.2 and illustrated in Figure 2-3.

5.1 Overview

The physical processes contributing to extreme water levels at the shoreline are described in 2.2 and illustrated in Figure 2-3.

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 for the Te Ara Tupua: Ngā Ūranga ki Pito-One Shared Path Project (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.

A full description of the numerical modelling process is described in the following sections.

In brief, 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 1000-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 20th highest event of a 1,000-year synthetic record represents the 2% AEP (50-year return period) value.

The number of output sites was adjusted to include additional sites around the inner Harbour and the South Coast and exclude the cluster of points from the previous study iterations (Figure 5-1). Results and extreme value statistics are provided at 25 output points spaced around the Wellington City shoreline. The extreme value statistics at sites 9-10, 150-153 are also used in comparison to the dynamic modelling undertaken for the South Coast (Section 6). The model does not include Mākara Beach.

The extreme sea level results are present day MSL are compared to storm events and other studies before being combined with the effects of climate change over the next 100 years.

Relative sea-level rise was included as described in Section 1.2.1 (Bell & Allis 2021), at values of

- NZ RCP8.5 RSLR (2120) = 1.43 m
- NZ RCP 8.5H+ RSLR (2120) = 1.73 m.

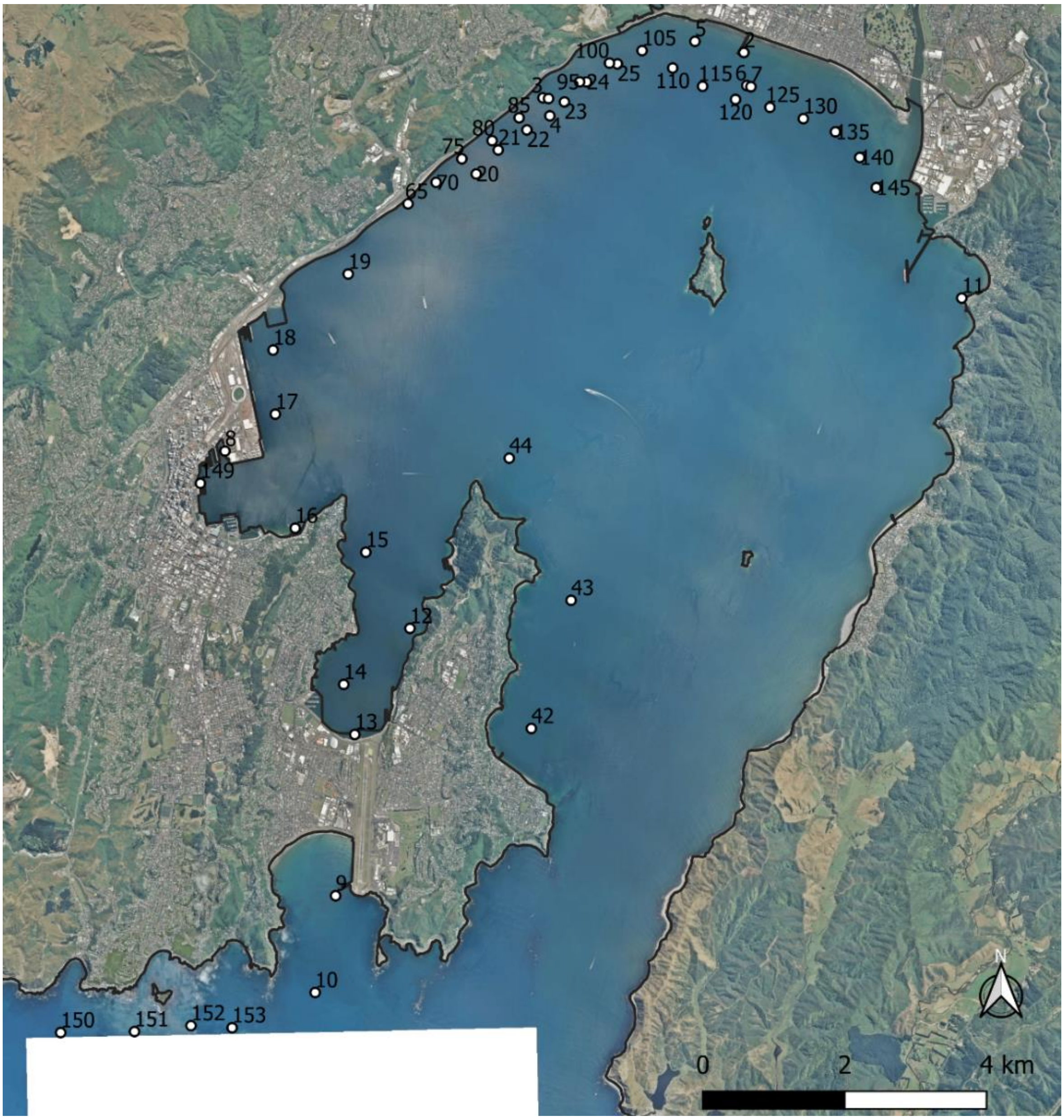

Figure 5-1: Output points for extreme sea level analysis. Not all sites to the north are included in outputs for this report as they were already included in Allis & Gorman (2020). See Table D-1 (Appendix D) for coordinates.

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" scenario which included: storm-tide + wave-setup elevations (i.e., values with Annual Exceedance Probabilities at the 1% AEP only) at about 25 output points, for the present-day and 2 future scenarios (Table 5-1).

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

And were combined with the RSLR values.

Overall, three 1% AEP storm-tide + wave setup and climate change scenarios were agreed with WCC and are mapped with results presented in Section 5.4 (Table 5-1).

Table 5-1: Summary of scenarios to be modelled and mapped within Wellington Harbour using a static inundation mapping.

ID	SLR scenario	Year	Storm-tide + wave setup AEP (%)	Climate change effects
Present day	Present day	Present day	1%	0 m SLR
1.43 m RSLR +10% storm	RCP 8.5 median (50th percentile)	2120	1%	+ 1.43 m SLR + 10% storm-tide + 10% wind speed + 10% wave height
1.73 m RSLR +10% storm	RCP 8.5 H+ (83rd percentile)	2120	1%	+ 1.73 m SLR + 10% storm-surge + 10% wind speed + 10% wave height

5.2 Numerical modelling approach

The numerical modelling approach involves collating and synthesising a long record of concurrent environmental conditions which 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 our 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.

5.2.1 Multi-variate time series simulation

We applied a joint-occurrence technique described by Heffernan and Tawn (2004). 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. On the other hand, 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. For example, the 20th highest event of a 1,000-year synthetic record represents the 2% AEP (50-year return period) value.

5.2.2 Wind

Here our aim was to derive spatially variable wind fields over Wellington Harbour from measured values of wind speed and direction at a single location, namely Wellington Airport. To this end, we extracted spatially variable wind fields (approximately 1.5 km resolution) from the New Zealand Convective Scale Model (NZSCM), which NIWA has been running for operational weather forecasting since 2014. We then perform a regression analysis between simultaneous wind records from the Wellington Airport Meteorological Station and the wind fields from NZCSM. This provided a mapping 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.

5.2.3 Tides and storm-surge

We obtained a record of 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). Water levels in this record were referenced to local Chart Datum and converted to WVD-53. A tidal decomposition allowed the sea level record to be represented as tidal and non-tidal components, i.e.,

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

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.

The variation (both spatial and temporal) of water level and depth-averaged currents throughout Wellington Harbour are required as inputs for wave modelling (discussed in the next section). To do so, 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 5-2. We note that 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 5-2: 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

5.2.4 Waves

A SWAN (Simulating WAves Nearshore) model (Booij et al. 1999, Ris et al. 1999) covering Wellington Harbour and Entrance from Cook Strait (Figure 5-3) was executed 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: 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.

- Swell incident on the domain boundary, from directional wave records outside the harbour entrance.

Data sources for the wind, water level and current forcing are described above. For wave boundary conditions, we made use of measurements made outside Wellington Harbour (1998-present) by the Wave buoy deployed off Baring Head. This buoy, however, has only provided directional records since 2015. Consequently, we used measured significant wave height and peak wave period from the buoy record but assumed 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 5-2). This shows a predominance of southerly waves, with a mean value of θ_{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°.

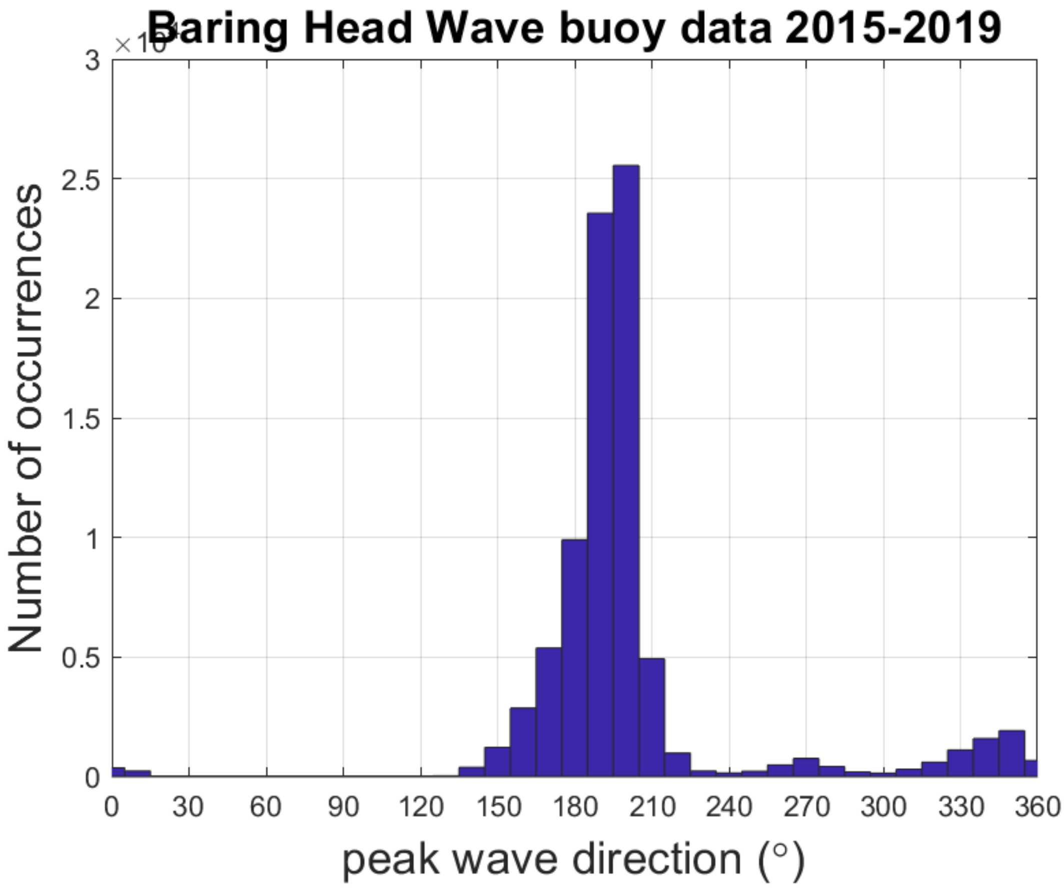

Figure 5-2: Occurrence distribution of peak wave direction from the Baring Head wave buoy record. Data is taken from the 2015-2019 period in which directional data were available. Meteorological convention (direction FROM which waves travel, in degrees clockwise from North) is used.

A factor 1.2 scaling of the measured significant wave height was applied to represent wave conditions at the boundary, based on preliminary model simulations to quantify the mean reduction in wave height between the boundary and the wave buoy site (refer Figure 5-3).

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 – see Figure 5-3) - where wave conditions may have strong spatial variability - to sufficiently represent changing wave climate along the Project foreshore inside the Harbour. 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, outside the harbour entrance) to improve computational time.

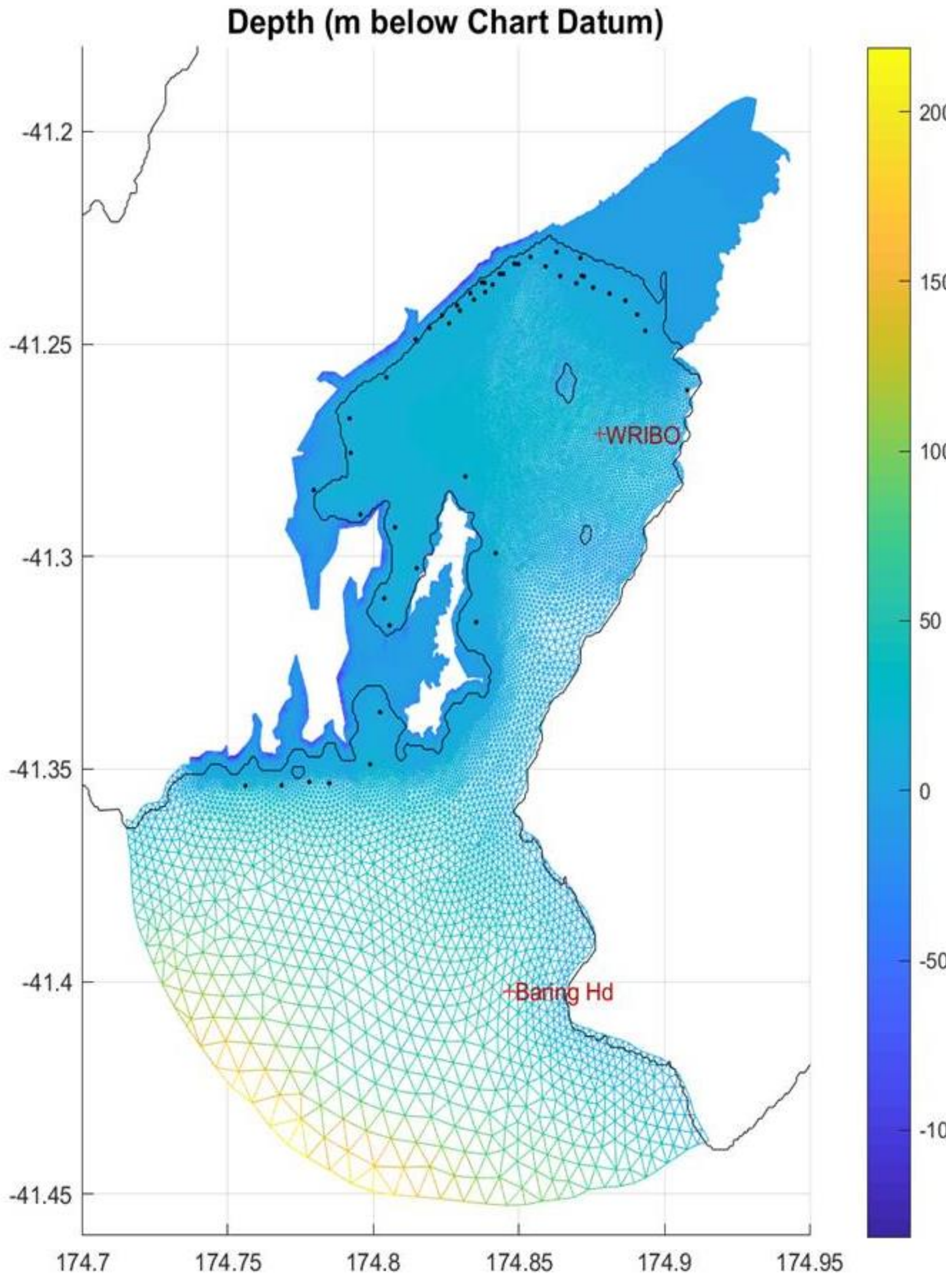

Figure 5-3: Map of Wellington Harbour showing the triangular mesh used for SWAN model simulations. The colour scale represents water depth (relative to Chart Datum). Wave measurement sites are marked (red +), as are locations (black dots) at which extreme value statistics were derived.

5.2.5 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, say, *M* input parameters. In our case, we used the following with *M*=7 parameters:

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, as described above.

Then, 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 *M*-dimensional parameter space of all possible input conditions as efficiently as possible. In our case a set of 500 samples were used. A full SWAN stationary simulation was 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 of the above 7 parameters taken from the historic records described above, to give a simulation of nearshore wave conditions at all times for which all of these inputs were available. This gives a simulation covering the years 1998-2019, less any gaps in the Baring Head, Queen's Wharf or Wellington Airport records.

In particular, this allowed the "SWAN Emulator" model to be calibrated and verified against wave measurements from the WRIBO[11] 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 is illustrated in Figure 5-4, which shows scatter plots of modelled significant wave height from measurements at three locations against corresponding values from the "historic" simulations. In these plots, each red dot shows a measured value plotted against the

[11] 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/

simulation output for the corresponding location and time. A quantile-quantile plot is overlaid on the scatter plots.

The Baring Head record (Figure 5-4a), 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 5-4b), there is a higher degree of scatter, but the quantile-quantile plot lies close to the equivalence line, particularly for the higher-energy conditions, indicates that the simulation gives a satisfactory representation of extreme-value statistics at this location.

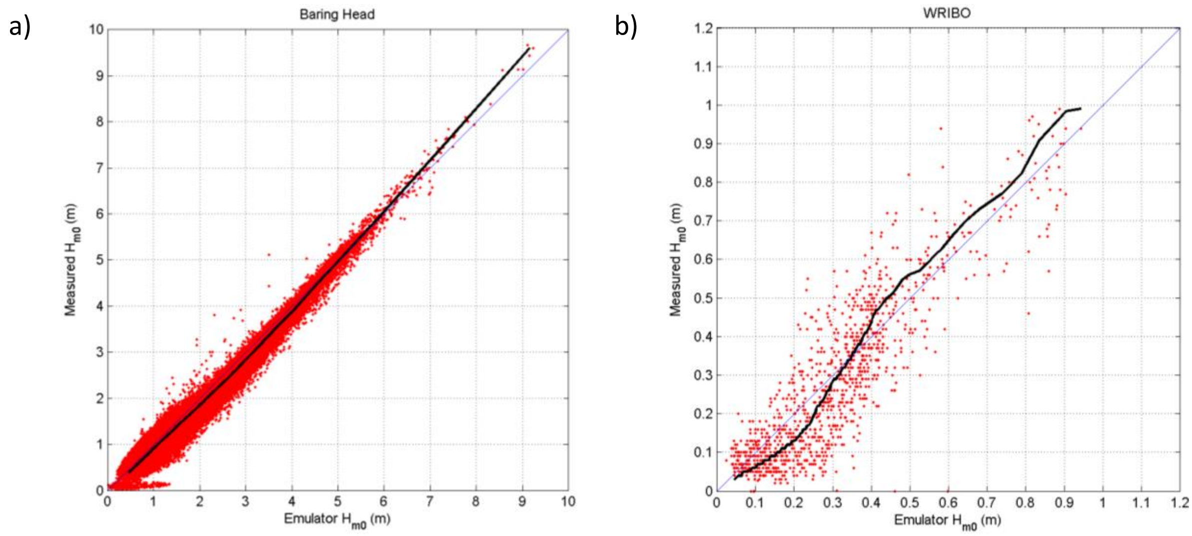

Figure 5-4: Scatter plots, overlaid with quantile-quantile plots, comparing significant wave height measurements with corresponding simulation outputs. Locations: (a) Baring Head Waverider, (b) WRIBO, SE of Matiu/Somes Island. An equivalence line (blue) for matching agreement is also shown.

5.2.6 Multi-century emulator

The simulations described above can provide a 20-year record of nearshore wave and storm tide conditions, from which extreme statistics could be derived by developing a much longer synthesised record as outlined in Section 5.2.1. 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 "SWAN Emulator" to derive multi-century synthetic time series of nearshore wave and storm tide conditions at selected sites within Wellington Harbour.

5.2.7 Climate change scenarios

In addition to applying the methodology described above 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 over the 100-year timeframe life out to 2120.

Relative sea-level rise was included as described in Section 1.2.1 (Bell & Allis 2021), at values of

- NZ RCP8.5 RSLR (2120) = 1.43 m
- NZ RCP 8.5H+ RSLR (2120) = 1.73 m.

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" scenario 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 from above (Table 5-1).

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.

5.2.8 Static coastal storm-tide elevations

The procedures outlined above provide for multi-century synthetic time series of peak high-water values of water levels and associated wind and wave statistics to be derived at locations offshore from the coast. These water levels correspond to the storm-tide line in Figure 2-3 (p. 18) and wave setup is included afterwards as it further raises the effective sea level at the coastline within the wave breaking zone from the release of wave energy against the coast.

Additionally, individual waves also runup and overtop the coastal fringe and can exacerbate coastal flooding hazards, but we do not consider this relatively small effect in this section as wave heights are limited by the confined fetch distances within the harbour and wave runup is affected by complex wave-structure interactions on shorelines around the Harbour.

Note wave runup and setup are directly modelled on the South Coast and Mākara Beach – see Section 6 below) with the results focus on how the mean sea level (averaged over multiple wave periods) is increased by wave setup.

5.2.9 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

$$\bar{\eta}_s = \bar{\eta}_b + \bar{\eta}_{sz} \qquad (5)$$

which is a combination of the setdown η_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

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

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

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

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

$$T_p = 1.1 T_{m-1,0} \quad (8)$$

is used.

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

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

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

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

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

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

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

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 slop parameter $\tan\beta$, we note that the Wellington harbour coastline is nearly all rocky armour stones, vertical seawalls or 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. This means the porosity and rugosity (macro-roughness) of coastal structures is not taking into account here. High rugosity and porosity reduce the runup while smooth structure leave the wave to runup unhindered.

5.2.10 Return values

Return values were estimated by a simple countback method from the long (1,000 year) synthetic records derived as described above.

This was completed for each of the output locations shown in Figure 5-3, for the present-day climate, and under the two climate change scenarios.

The tabulated results of the countback process are found in the following section.

5.3 Extreme sea level elevations

By way of comparison and validation for the extreme value analysis, model outputs of storm tide only (no wave processes) at the location of the long-standing tide gauge Queens Wharf were compared to the specific studies of Stephens et al (2009) and observations within Stephens et al. (2015). Figure 5-5 illustrate the comparison of extreme sea level elevation probability distributions. The present model shows a good agreement to the previous studies, with the storm-tide elevation only 2 cm higher at 1% AEP level. The results are higher than previous studies for more frequent events and provide a conservative estimate of possible extreme storm-tide elevations at these lower cases.

The tabulated results (Table 5-5) of storm-tide only illustrate that there is very little variation in storm-tide elevation around the Harbour (excluding sites on the south coast) without wave processes.

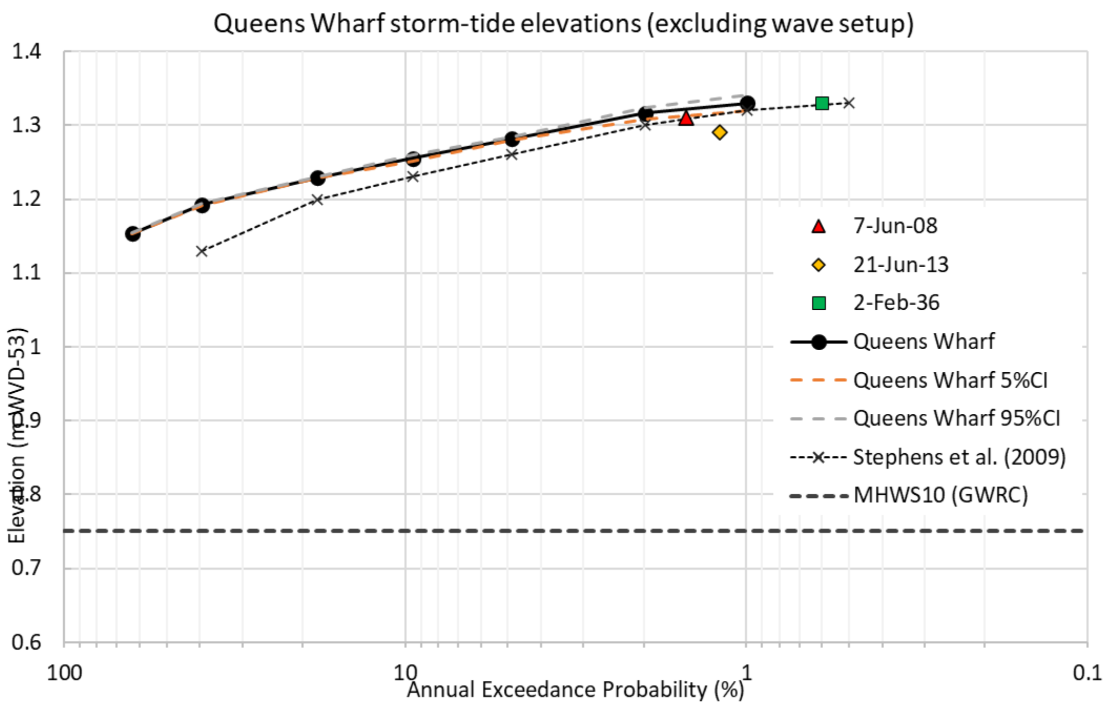

Figure 5-5: Comparison of extreme storm tide elevations at Queens Wharf with notable storms and previous studies.

Table 5-3: Storm-tide elevations at present day excluding wave setup (m WVD-53). * indicates site outside the Harbour.

	ARI (years)	1	2	5	10	20	50	100
Site	**AEP (%)**	**63**	**39**	**18**	**10**	**5**	**2**	**1**
3	Rocky Point	1.15	1.19	1.23	1.26	1.28	1.31	1.33
9	Lyall Bay inner*	1.15	1.19	1.23	1.26	1.28	1.31	1.32
10	Lyall Bay outer*	1.15	1.19	1.23	1.26	1.28	1.31	1.33
11	Lowry Bay	1.15	1.19	1.23	1.26	1.28	1.31	1.33
12	Shark Bay	1.15	1.19	1.23	1.26	1.28	1.31	1.33
13	Mirimar Wharf	1.15	1.19	1.23	1.26	1.28	1.31	1.33
14	Evans Bay	1.15	1.19	1.23	1.26	1.28	1.31	1.33
15	Balaena Bay	1.15	1.19	1.23	1.26	1.28	1.31	1.33
16	Oriental Bay	1.15	1.19	1.23	1.26	1.28	1.31	1.33
17	Aotea Quay	1.15	1.19	1.23	1.26	1.28	1.31	1.33
18	Ferry Terminal	1.15	1.19	1.23	1.25	1.28	1.31	1.33
19	Kaiwharawhara	1.15	1.19	1.23	1.26	1.28	1.31	1.33
25	Horokiwi	1.15	1.19	1.23	1.26	1.28	1.31	1.33
42	Seatoun	1.15	1.19	1.23	1.26	1.28	1.31	1.33
43	Scortching Bay	1.15	1.19	1.23	1.26	1.28	1.31	1.33
44	Point Halswell	1.15	1.19	1.23	1.26	1.28	1.31	1.33
65	Ngauranga Gorge	1.15	1.19	1.23	1.26	1.28	1.31	1.34
149	Queens Wharf	1.15	1.19	1.23	1.26	1.28	1.32	1.33
150	Ōwhiro Bay*	1.15	1.19	1.23	1.26	1.28	1.31	1.33
151	The Sirens Rocks*	1.15	1.19	1.23	1.26	1.28	1.31	1.33
152	Island Bay*	1.15	1.19	1.23	1.26	1.28	1.31	1.33
153	Houghton Bay*	1.15	1.19	1.23	1.26	1.28	1.31	1.34

The inclusion of wave setup to the extreme value analysis at all sites (Table 5-4) results in more variability to extreme sea levels within the harbour as the exposure to wave processes alters the wave setup contribution, particularly on the South Coast and Seatoun.

Table 5-4: Storm-tide plus wave setup elevations at present day (m WVD-53). * indicates site outside the Harbour. The 1% AEP values are plotted in Figure 5-6.

	ARI (years)	1	2	5	10	20	50	100
Site	AEP (%)	63	39	18	10	5	2	1
3	Rocky Point	1.20	1.24	1.28	1.31	1.34	1.38	1.41
9	Lyall Bay inner*	1.49	1.57	1.67	1.73	1.78	1.87	1.91
10	Lyall Bay outer*	1.72	1.85	2.00	2.10	2.17	2.30	2.37
11	Lowry Bay	1.22	1.26	1.30	1.34	1.37	1.41	1.43
12	Shark Bay	1.18	1.23	1.26	1.29	1.32	1.35	1.38
13	Mirimar Wharf	1.18	1.22	1.26	1.29	1.32	1.35	1.37
14	Evans Bay	1.18	1.22	1.26	1.29	1.32	1.35	1.37
15	Balaena Bay	1.18	1.22	1.26	1.29	1.32	1.35	1.37
16	Oriental Bay	1.18	1.22	1.26	1.29	1.32	1.34	1.37
17	Aotea Quay	1.17	1.21	1.25	1.28	1.31	1.34	1.36
18	Ferry Terminal	1.18	1.22	1.25	1.28	1.31	1.35	1.36
19	Kaiwharawhara	1.18	1.22	1.26	1.28	1.31	1.34	1.37
25	Horokiwi	1.19	1.23	1.27	1.30	1.33	1.38	1.38
42	Seatoun	1.32	1.37	1.42	1.47	1.51	1.56	1.60
43	Scortching Bay	1.27	1.32	1.37	1.41	1.45	1.49	1.52
44	Point Halswell	1.21	1.25	1.29	1.32	1.35	1.38	1.41
65	Ngauranga Gorge	1.17	1.21	1.25	1.28	1.31	1.34	1.38
149	Queens Wharf	1.16	1.20	1.24	1.27	1.30	1.33	1.35
150	Ōwhiro Bay*	1.78	1.91	2.07	2.17	2.25	2.38	2.48
151	The Sirens Rocks*	1.78	1.91	2.07	2.17	2.25	2.39	2.48
152	Island Bay*	1.76	1.88	2.04	2.14	2.22	2.36	2.42
153	Houghton Bay*	1.80	1.94	2.10	2.21	2.30	2.43	2.52

Table 5-5 shows the elevation of the extreme storm-tide plus wave setup elevations at the present day and with the two future climate change scenarios. Figure 5-6, Figure 5-7 in Figure 5-8 and plot these elevations around.

Table 5-5: Storm-tide plus wave setup elevations (m WVD-53) at 1% AEP for present-day and climate change scenarios. * indicates site outside the Harbour where results are indicative and the dynamic modelling from Section 6 should be used. Full results for other AEP/ARI conditions are in Appendix D.

Site ID	Site name	Present day	1.43 m RSLR + 10% storms	1.73 m RSLR + 10% storms
3	Rocky Point	1.41	2.91	3.20
9	Lyall Bay inner*	1.91	3.47	3.78
10	Lyall Bay outer*	2.37	3.93	4.23
11	Lowry Bay	1.43	2.95	3.26
12	Shark Bay	1.38	2.86	3.16
13	Mirimar Wharf	1.37	2.86	3.16
14	Evans Bay	1.37	2.86	3.16
15	Balaena Bay	1.37	2.85	3.16
16	Oriental Bay	1.37	2.85	3.16
17	Aotea Quay	1.36	2.85	3.15
18	Ferry Terminal	1.36	2.85	3.16
19	Kaiwharawhara	1.37	2.86	3.16
25	Horokiwi	1.38	2.91	3.21
42	Seatoun	1.60	3.11	3.41
43	Scortching Bay	1.52	3.05	3.36
44	Point Halswell	1.41	2.91	3.21
65	Ngauranga Gorge	1.38	2.86	3.16
149	Queens Wharf	1.35	2.84	3.14
150	Ōwhiro Bay*	2.48	4.02	4.33
151	The Sirens Rocks*	2.48	4.05	4.35
152	Island Bay*	2.42	4.00	4.27
153	Houghton Bay*	2.52	4.07	4.37

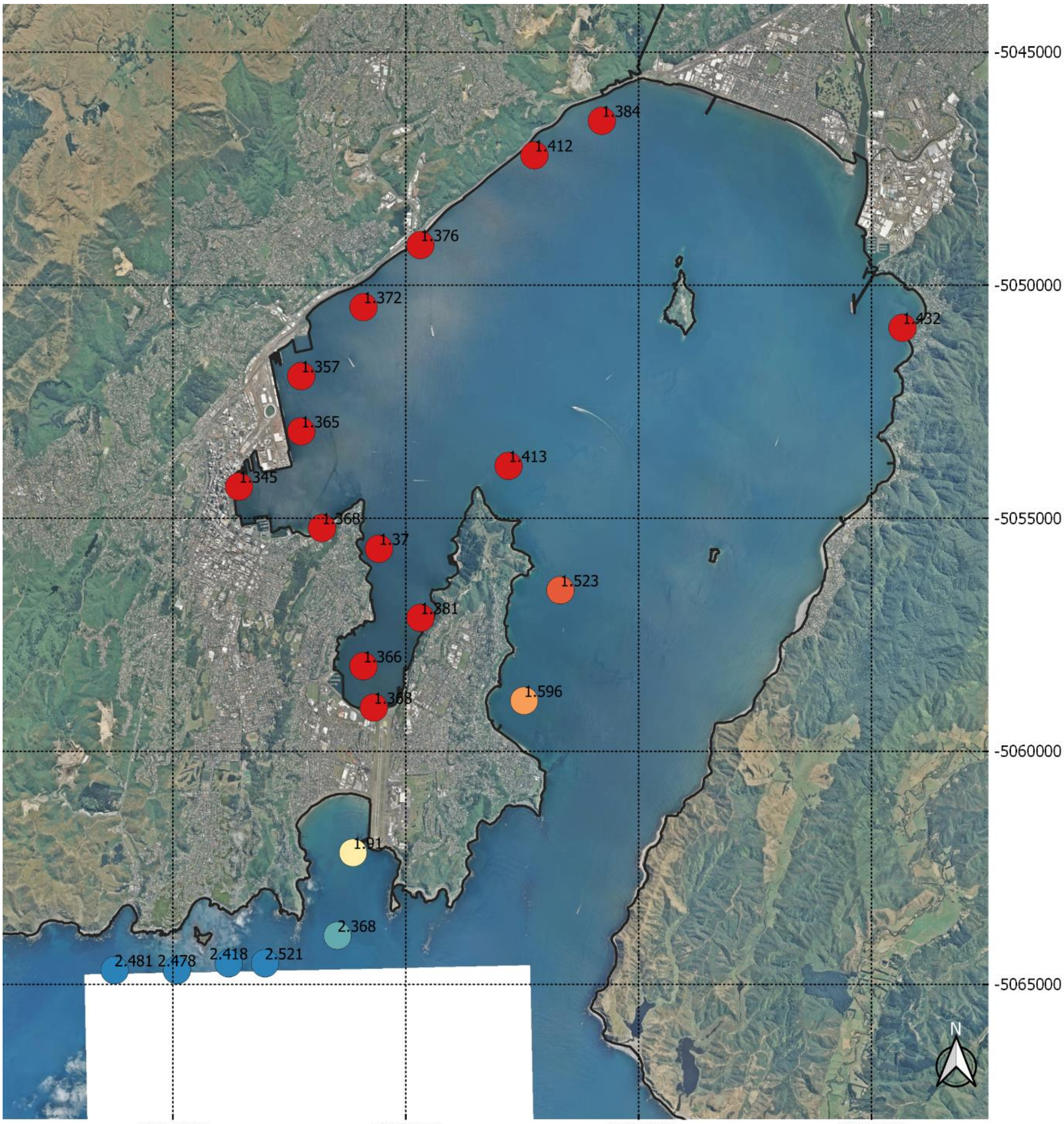

Figure 5-6: Extreme 1% AEP storm-tide plus wave setup elevations at present day sea levels.

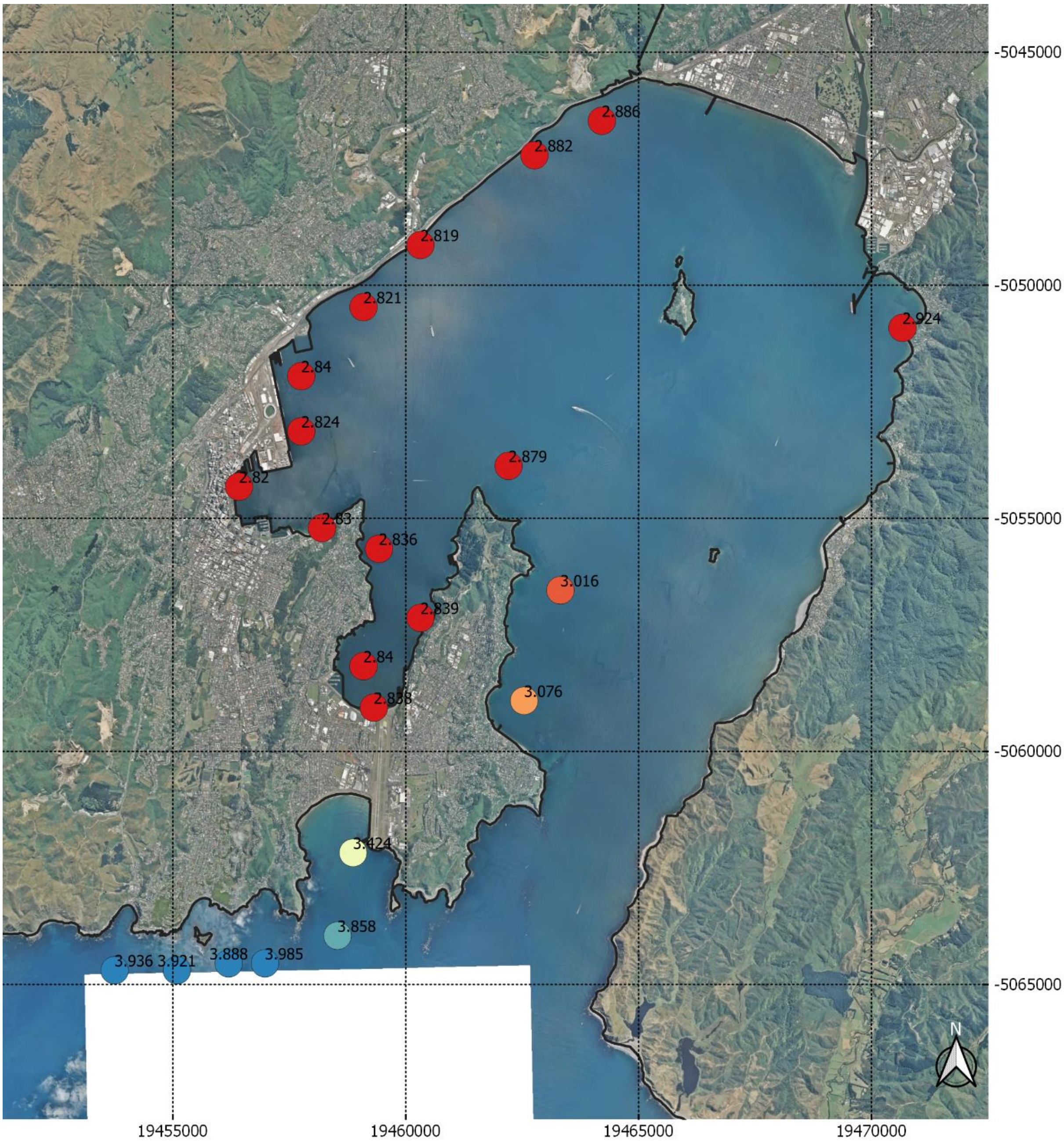

Figure 5-7: Extreme 1% AEP storm-tide plus wave setup elevations with 1.43m RSLR + 10% storm.

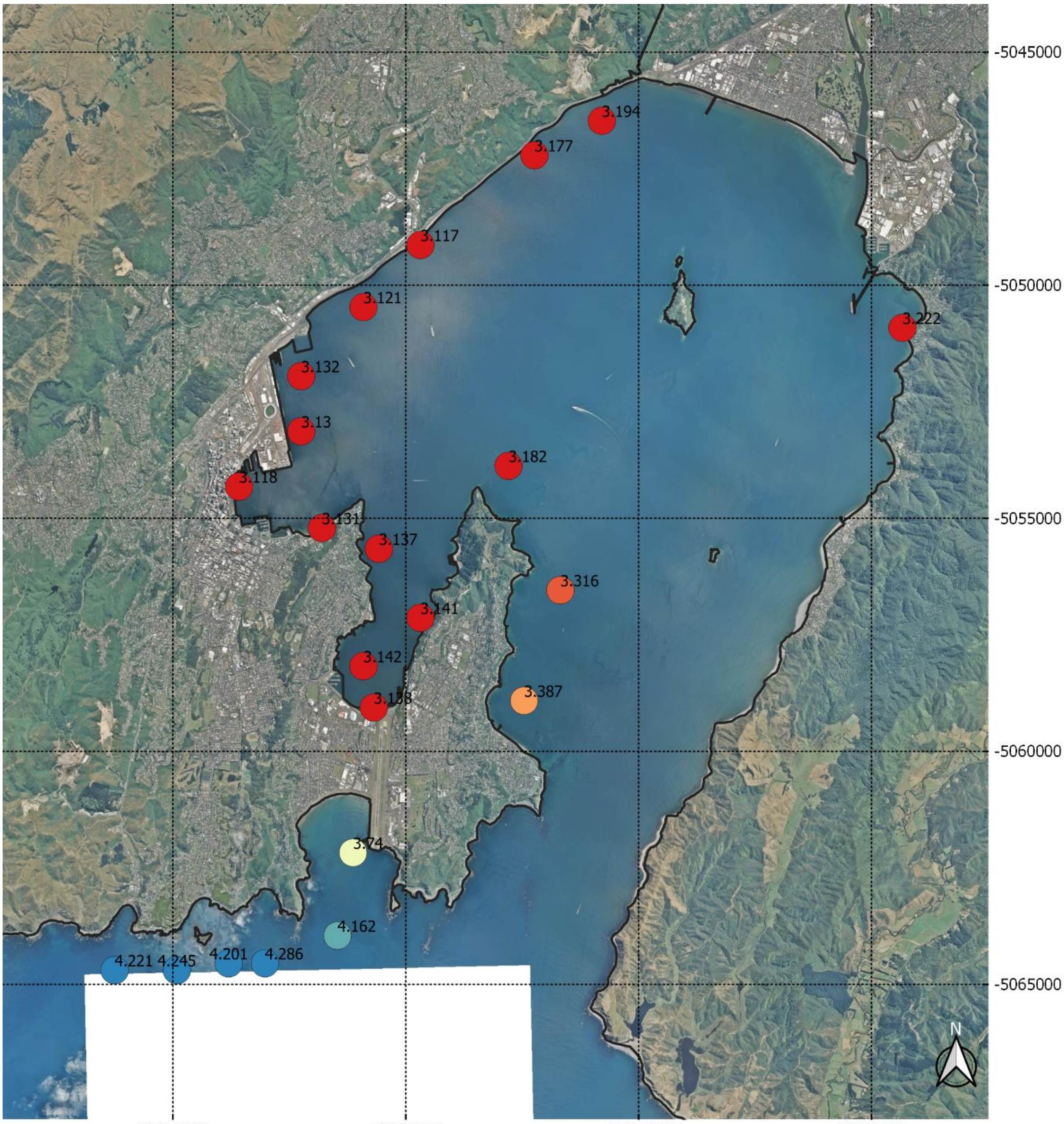

Figure 5-8: Extreme 1% AEP storm-tide plus wave setup elevations with 1.73m RSLR + 10% storm.

5.4 GIS mapping – static inundation of Harbour shorelines

Inside the harbour the calculated total water level elevations from above (from storm-tide + wave-setup) were interpolated from the coastal locations onto the LiDAR and mapped within GIS.

The static inundation mapping technique assumes that all land areas lower than the water levels at the shoreline are flooded to the same height as the shoreline water level. With the following notes

- Only areas that have a direct hydraulic connection to the sea are mapped, including areas connected via culverts. Note that we have not undertaken any checks on completeness of the infrastructure databases or functioning of the culverts. For the avoidance of doubt, if a culvert is shown to link seawater with an inland area, then it is assumed to have a viable hydraulic connection. We do not assess the capacity of the culvert, or presence of floodgates/valves which would limit the inland extend of sea-water inundation.
- Note that this excludes the potential for additional flooding effects from streams or drains 'backing-up' behind high coastal floodwaters, higher groundwater levels caused by rise of sea level and/or storm tides, and any terrestrial flooding from rainfall.
- The static inundation maps exclude the building footprints. The exclusion does not affect the mapped inundation depths as the static inundation does not account for volume continuity or presence/absence of buildings.

The calculated static inundation maps of storm-tide plus wave setup for the harbour shorelines are shown in Figure 5-9 for the present day, and Figure 5-10 to Figure 5-11 for the two climate change scenarios.

A technical description of the GIS processing steps to produce the inundation maps is included in Appendix C. The static inundation layers are provided directly to WCC as digital layers of depth of water above land and polygons of the inundation extent with each layer (shapefile).

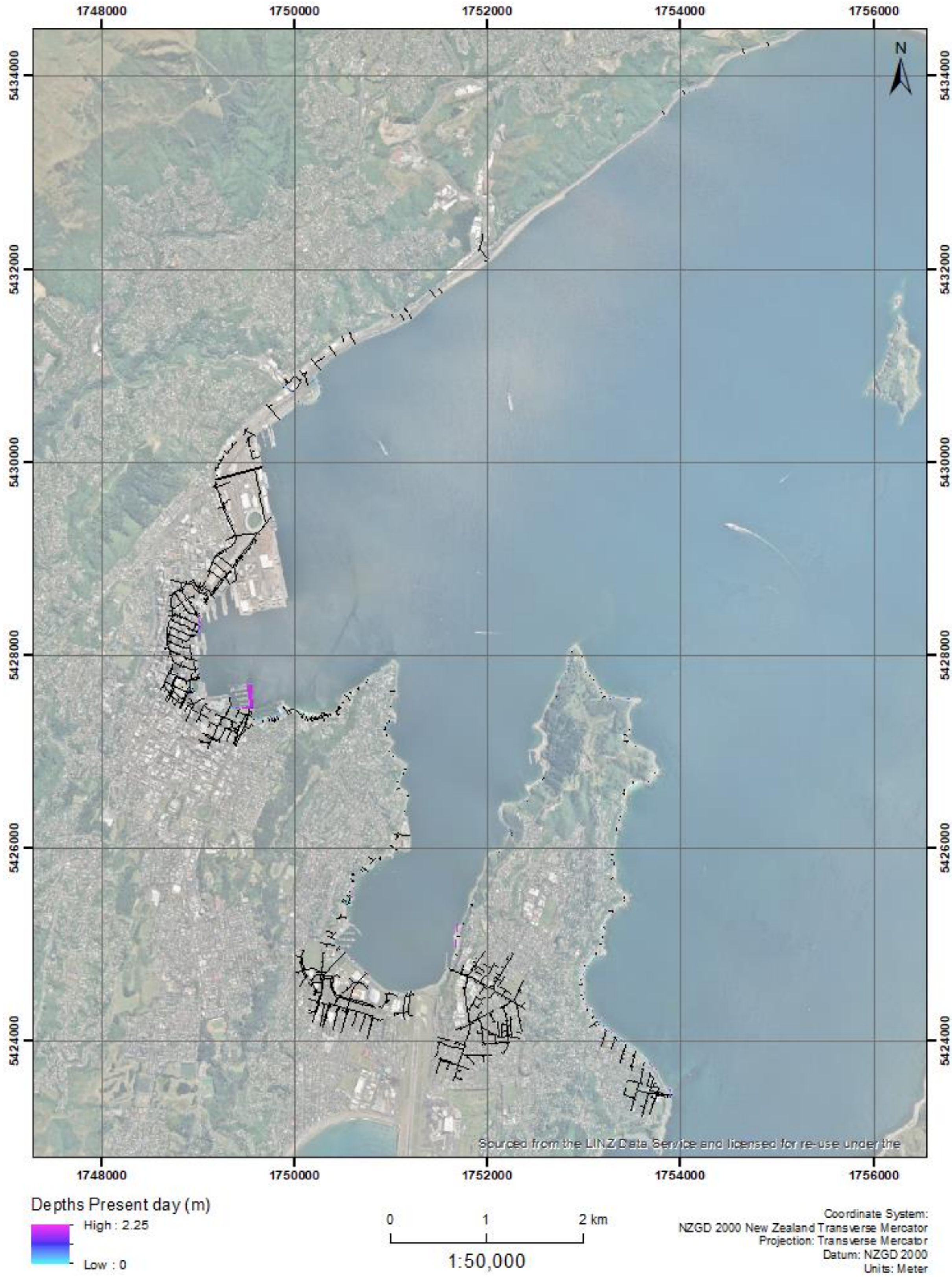

Figure 5-9: Inundation extent (water depth above land) for 1% AEP storm-tide plus wave setup at present day.

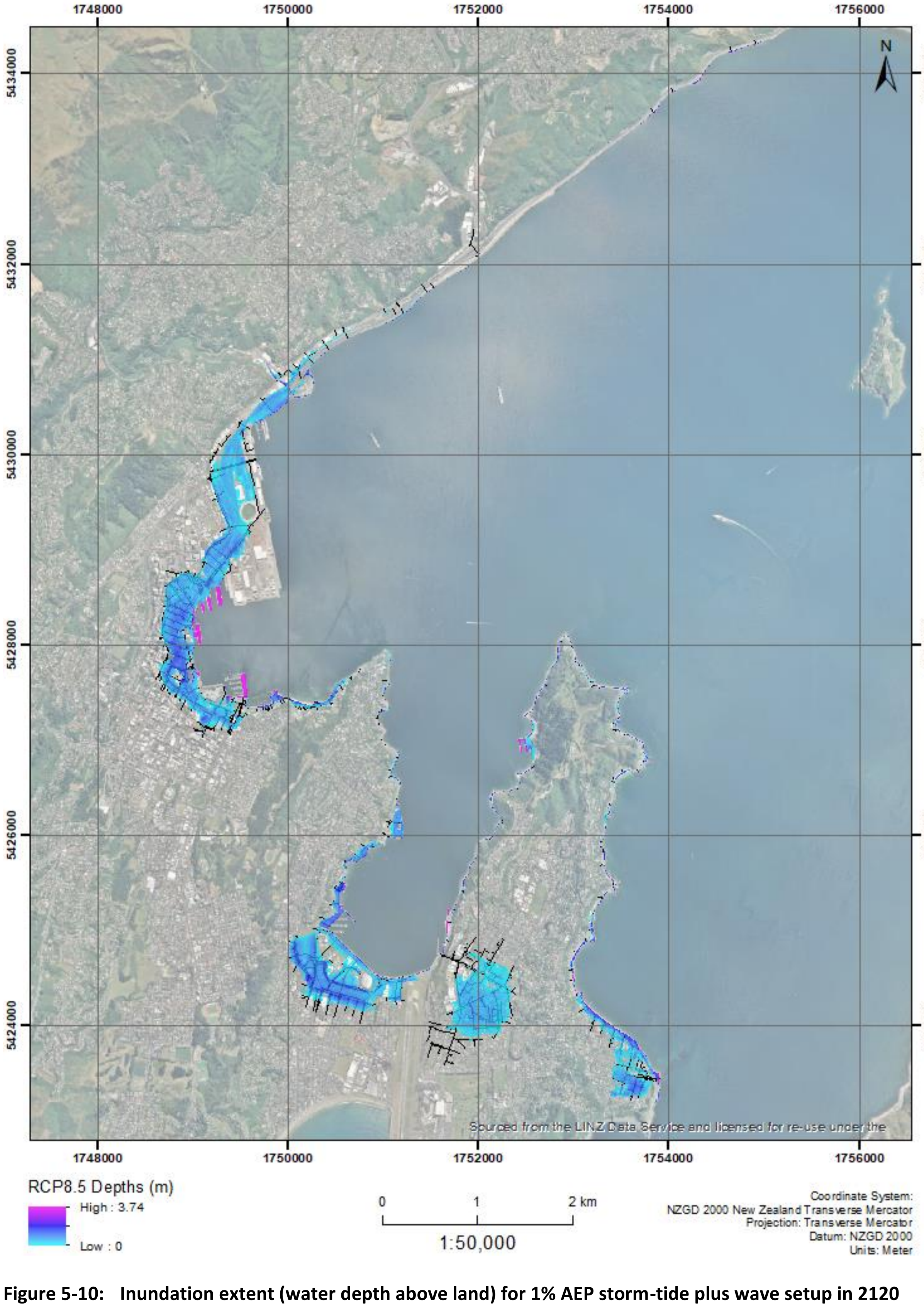

Figure 5-10: Inundation extent (water depth above land) for 1% AEP storm-tide plus wave setup in 2120 under climate change scenario RCP8.5 including +10% storm increases.

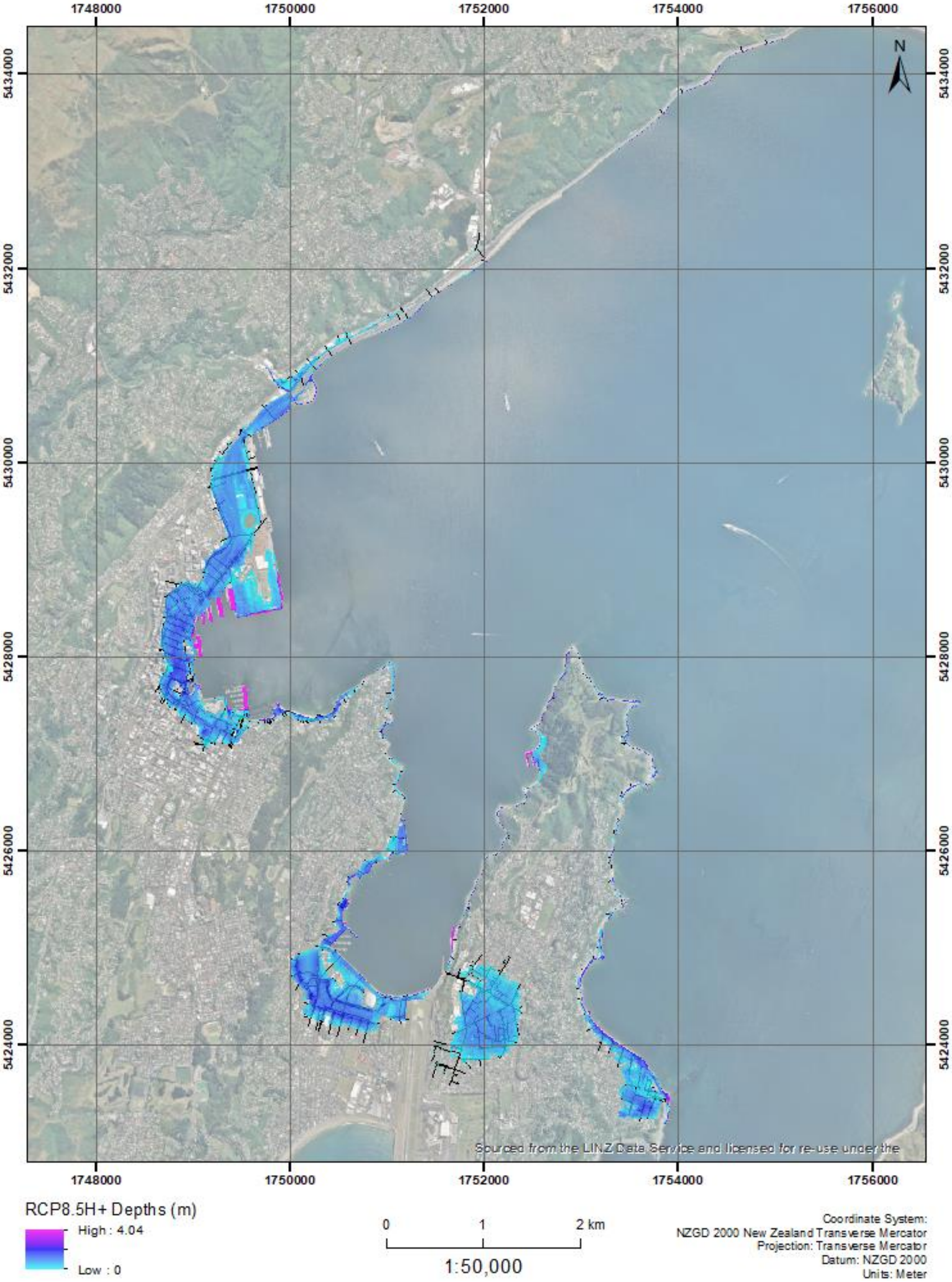

Figure 5-11: Inundation extent and depth for 1% AEP storm-tide plus wave setup in 2120 under climate change scenario RCP8.5H+ including +10% storm increases. Colours indicate depth of inundation above land surface. Thin black lines show WCC culvert network.

5.4.1 Coastal flood inundation mapping limitations for extreme sea-levels

The major assumption in the GIS mapping procedure was the "bathtub" method use to map and assign the land area below extreme sea-levels as inundated. Storm-tide peaks may however, last for 1–3 hours close to high tide (Stephens et al. 2016). This duration may not be sufficient to temporally inundate large land areas, particularly if storm-tide flow rates are restricted by a narrow connection to the sea e.g. drainage channels, culverts. The extreme sea-level inundation area maps therefore do not fully capture the dynamic and time-variant processes that occur during a coastal-storm event, but rather are indicative of areas coastal inundation from static sea-levels, or residual risk behind coastal defences such as stop banks.

Bathtub inundation mapping usually results in an over estimation of coastal inundation extents from storm-tide levels where wave processes are less significant. This is demonstrated by the comparative inundation extents from 'bathtub' and 'dynamic' models in Figure 5-12 and Figure 5-13 for other recent studies (Stephens 2015).

The bathtub models show that more inundation (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 5-13 where the bathtub model overestimates inundation north of the main river feature where the topography is relatively lower with distance from the coast. Little difference in inundation occurs south of the river where topography is steeper.

Despite its limitations, a bathtub method provides an approximation of coastal inundation extents for identifying key elements at risk e.g. populations, buildings, roads etc. More detailed dynamic modelling will produce more accurate inundation scenario maps which may be required in areas with potentially high population and/or asset exposure (e.g. 'hotspots'), or where wave processes are a major contributor to inundation as for the Wellington South Coast.

Figure 5-12: Comparison of dynamic model of inundation (blue) with bathtub model (red). The scenario modelled was a 1% AEP storm-tide + 1.25 m SLR in Tauranga (Reeve et al. 2019)

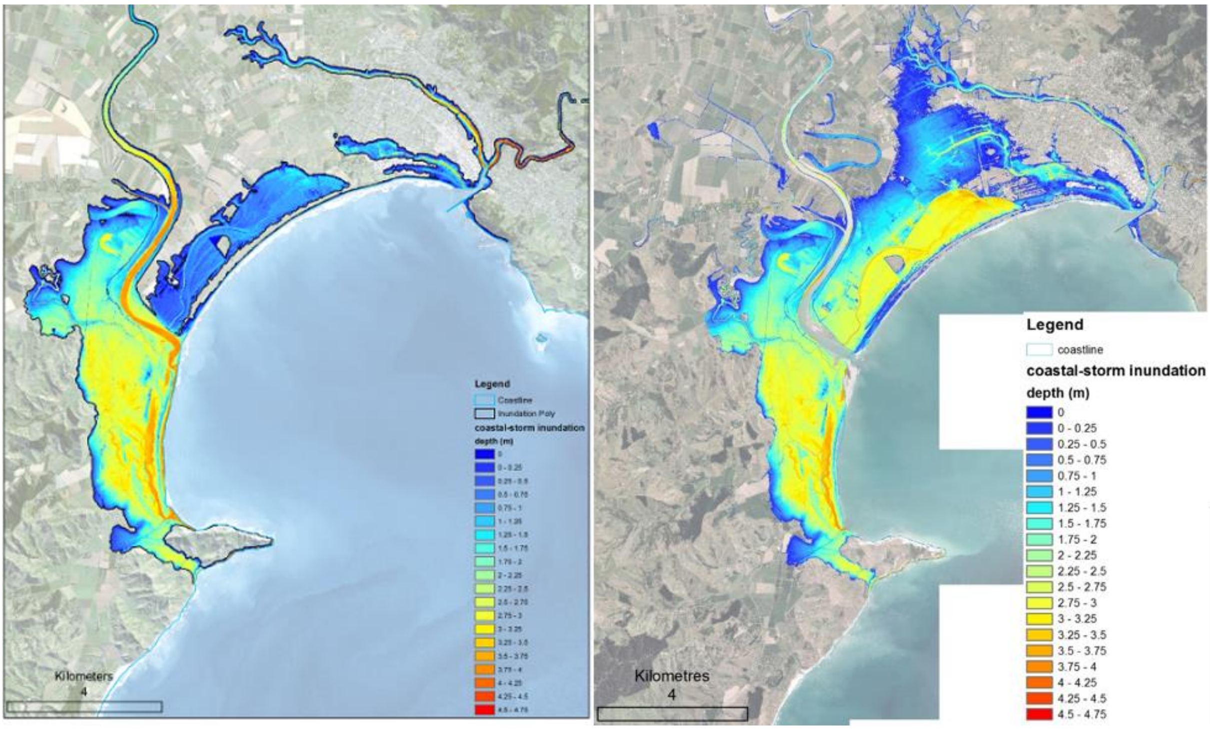

Figure 5-13: Comparison of dynamic model of coastal inundation (left) with bathtub model (right). Note the larger coastal inundation extent created by the bathtub model. Source: Stephens et al. 2015, Paulik et al. 2019).

6 Task 4: Coastal Inundation on the Open Coast

As outlined in Section 2.2 and illustrated in Figure 2-3, wave setup is a key driver of coastal storm inundation at the coast. Static inundation models (as undertaken for the Harbour shorelines) do not resolve all the processes required to establish the extreme sea-levels on wave exposed coasts.

In this section, wave runup and setup are modelled on the Wellington South Coast and Mākara Beach using a 'dynamic' model. The modelling focusses on how the mean sea level (averaged over multiple wave periods) is increased by wave setup in addition to extreme storm-tides.

Full details of the model specifications, assumption and calibration are presented in the following section. In brief, a modified version of XBeach was employed, the model is compiled to be executed on high performance Graphics Processing Units (GPU). Calibration was performed against the runup evidence of two recent storms (one in 2020 and one in 2013). Some initial benchmarking of the model is presented by Rautenbach et al. (2021).

6.1 Model Details

6.1.1 Model description

The process-based model XBeach_GPU[12] (Bosserelle, 2014) is a variant of XBeach (Roelvink, Reniers et al. 2009) and is used in the present study for inundation simulations. XBeach_GPU uses the same wave-group resolving wave model and coupled hydrodynamics model as XBeach ('Surf beat mode'), but the models are optimised to run on Graphics Processing Units (GPU or graphics cards) for improved computational speeds.

XBeach_GPU has been validated against XBeach for identical model domains and inputs (Rautenbach et al. (2021)). The model explicitly includes waves, simulated as group-varying wave energy, and storm-tide simulated in a shock-capturing hydrodynamics model tightly coupled to the wave model. The coupled model allows the simulation to explicitly account for wave transformations in the nearshore, and the interaction between waves, currents, and water levels in the surf zone. As an example of this interaction is provided in Figure 6-1. Here the RMS wave height at a particular output time step is given. This image is an illustration of the group resolving nature of the wave computations incorporated into XBeach_GPU. The wave groups are generated on the model boundary based on a JONSWAP (Hasselmann, 1980) wave spectrum, used to generate a statistical representative short-wave time series. The averaged behaviour may be seen in Figure 6-2, where the average RMS wave height over a three-hour simulation is given. Here it is especially clear how the waves loose energy as they propagate over the reefs and into the nearshore (an image more like the typical phase averaged wave model outputs of SWAN or WaveWatch III).

[12] See https://github.com/CyprienBosserelle/xbeach_gpu/wiki/Validation

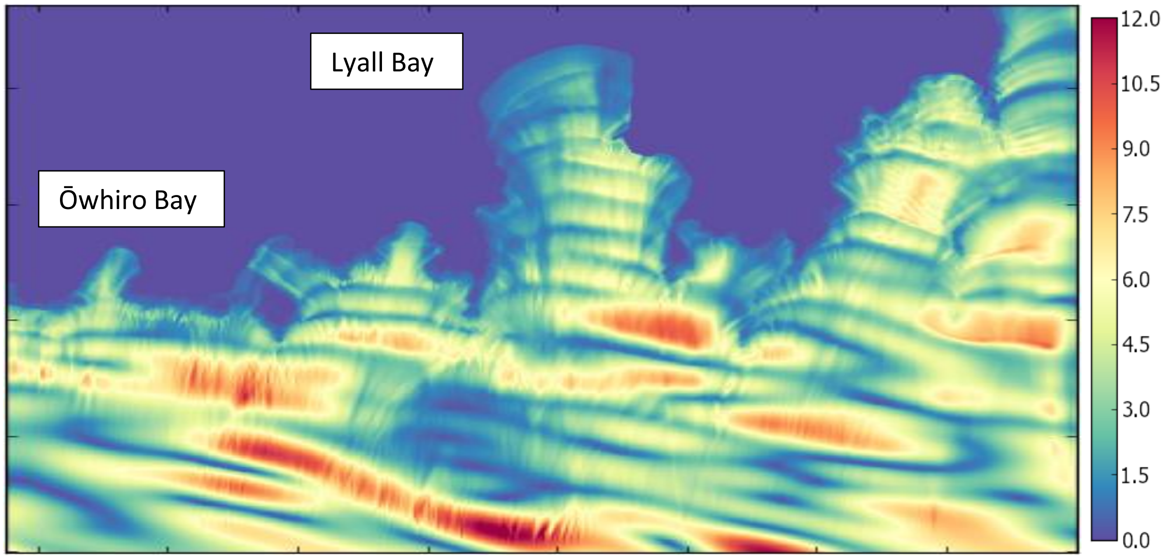

Figure 6-1: RMS wave height [m] example, 6 hours into an example simulation.

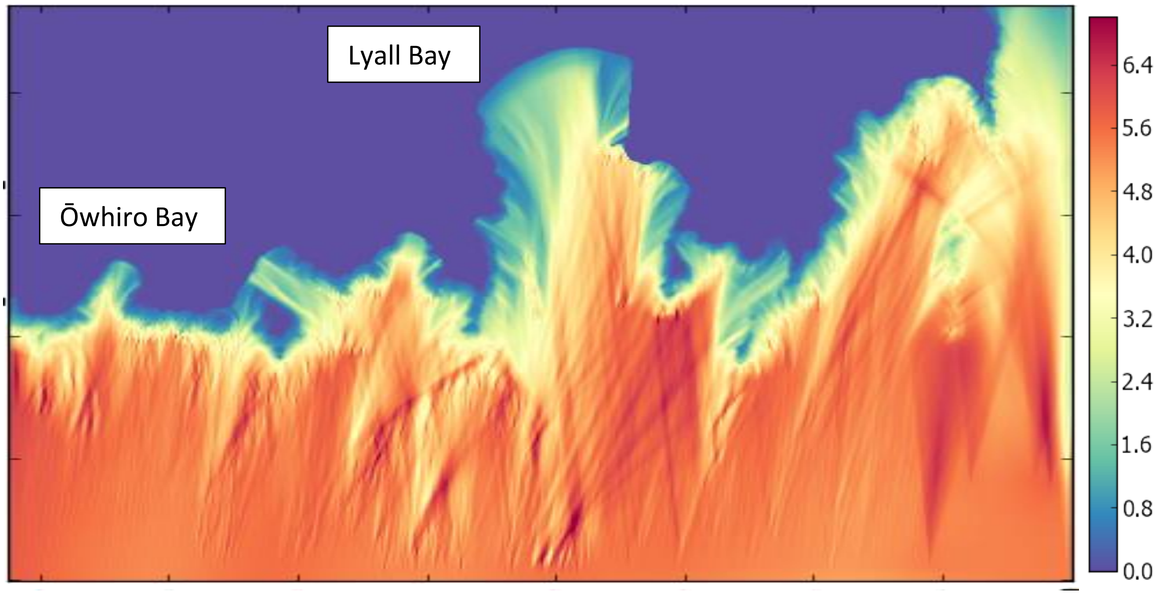

Figure 6-2: An example of the mean RMS wave heights [m] over a three hour period.

In Figure 6-3 an example of the water level above the vertical refence datum is provided. These water level changes are due to infra-gravity (IG) waves (long waves) that propagate into the nearshore. These IG waves are initially bound to wave group (also referred to as sets) and grow. They are released when the wave group dissipate (via wave breaking) in the nearshore.

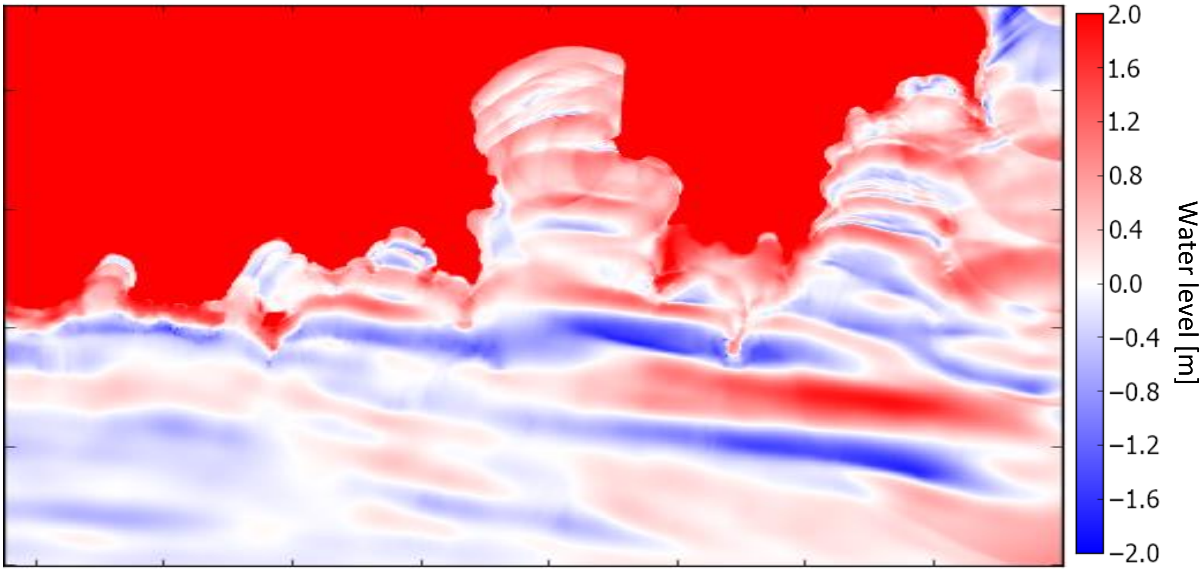

Figure 6-3: Long waves (or infragravity waves) propagating into the numerical model as water levels [m].

The simulation of surf-zone dynamics is important for inundation simulations because it considers infragravity wave generation, propagation, and dissipation. Maximum inundation is calculated on the two-dimensional grids as the maximum water level and maximum flow depth over the duration of the simulation (9 hours). The model is setup on a topographic grid at 5m resolution, accounting for variation in beach slope, cross-shore and alongshore.

6.1.2 Bathymetry

The bathymetry utilised in the present study has been noteworthy. Most, high resolution, numerical studies do not have accurate bathymetry information in the intertidal and surfer breaker zones. The present study overcame this limitation by making use of state-of-the-art remotely sensed techniques to infer the bathymetry in these zones. In Figure A-1(Appendix A) the gaps, together with the existing LiDAR and bathymetry data are given. Satellite Derived Bathymetry (SBD) was sub-contracted to a commercial provider, EOMAP, and incorporated into the underpinning topography/bathymetry employed during the numerical runup simulations. Details of the SDB work are found in Appendix A.

The SDB data were then interpolated to a constant 5 m grid resolution. In Figure 6-4 the combined topography and bathymetry are given up to the 5 m land contour for the Wellington South coast. In Figure 6-5 the combined topography and bathymetry used for the Mākara beach model is given. The numerical model domain is indicated via the blue-hashed area.

All the elevation data used in the dynamic model and results are relative to the New Zealand Vertical Datum 2016 (hereafter NZVD).

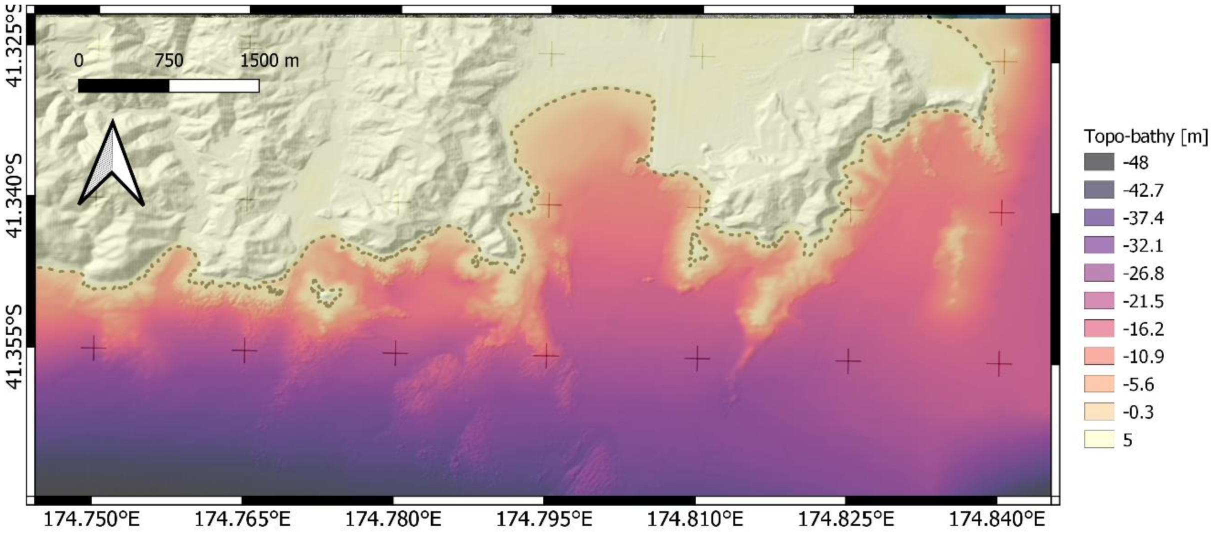

Figure 6-4: Topography and bathymetry employed for the Wellington South coast relative to NZVD. All underlying data have been interpolated to a 5 m resolution, regular numerical grid. The dotted contour indicates the MHWS10 coastline.

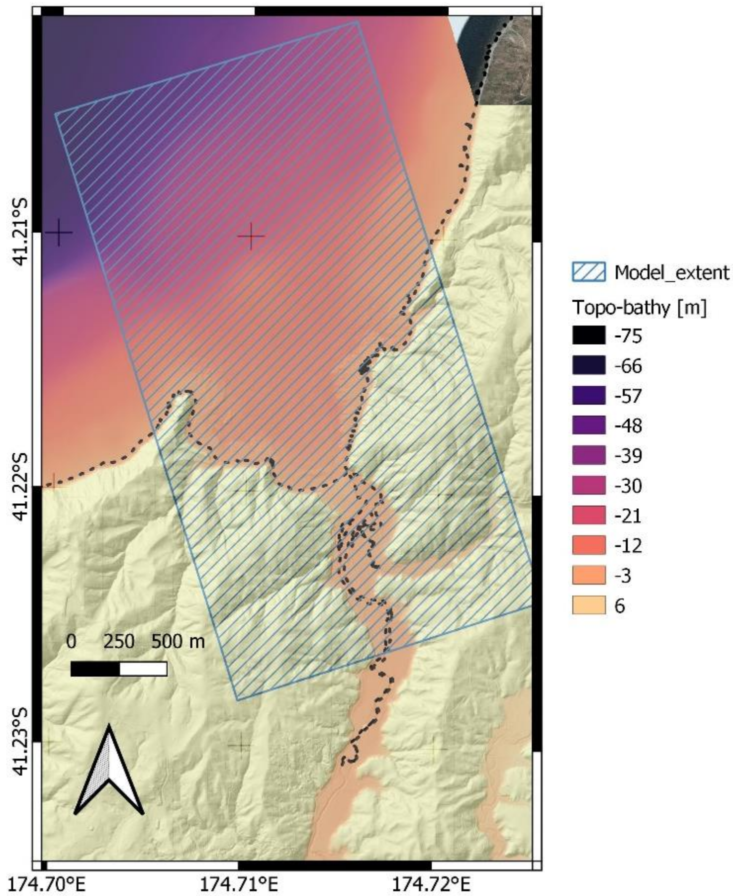

Figure 6-5: Topography and bathymetry employed at Mākara beach. All underlying data have been interpolated to a 5m resolution, regular numerical grid. The dotted contour indicates the MHWS10 coastline. All these are relative to NZVD.Data sources

The LiDAR topography data was provided by Land Information New Zealand (LINZ). The reference data set is the 1m DEM (2013-2014) for Wellington[13]. The SDB were created for the current project and the multibeam bathymetry data were obtained from the NIWA collection.

6.1.4 Grid

Both the Wellington south coast and Mākara models were created with a 5 m horizontal resolution. This represents an exceptional high resolution compared with most models typically employed for coastal inundation studies (Lashley et al. 2020).

6.1.5 Calibration

The models developed in the present study consisted of various sensitivity analysis. These were performed on the major model parameter settings. As an example, the reef areas are rougher than the sandy areas. Thus, these will present more friction to water and wave movement. For accurate wave runup modelling these must be considered. Through a series of simulations, the most stable and accurate simulations were achieved with a space varying roughness. The distinction was between reef versus sandy areas. All the setting employed were well within international, widely accepted, parameters settings for these two substrate descriptions. The main parameters are presented in Table 6-1. The Roelvink et al. (2009) wave dissipation model was employed together with the Smagorinsky formulation for calculating viscosity (with a Smagorinsky coefficient equal to 0.3).

The parameter settings for the Wellington South coast and Mākara beach were different. The sensitivity analysis revealed that the best validation was obtained with a broader wave directional spreading at the Wellington South coast boundary compared to that at Mākara beach. This also agreed with spectral wave model hindcast details in the areas of interest. The reef friction was also set to be slightly smoother at Mākara beach as the calibration process found smoother substrate conditions resulted in more accurate simulations. All building footprints and significant vegetation were also added through increased local friction, basically approach as local reef friction.

Table 6-1: Main parameter setting employed at the Wellington south coast, Xbeach_GPU model.

	South coast		Mākara	
Parameter	Sandy	Reef	Sandy	Reef
Flow bottom friction (c_f)	0.010	0.025	0.001	0.020
Wave bottom dissipation (w_f)	0.010	0.330	0.001	0.020
Wave breaking (γ)	0.650	0.650	0.750	0.750
Roller slope dissipation (β)	0.157	0.157	0.157	0.157
n (exponential in Roelvink model)	9.000	9.000	9.000	9.000

In all the models a Courant number (CFL) (Vousdoukas et al. 2012) was employed that ensured model stability together with reasonable computational times. In the present study a value of 0.3 was chosen as the maximum CFL number. All simulations were executed for a real-world simulation period of 9 hours. This allowed for the realistic determinations of wave runup related inundation

[13] See LINZ data service: https://data.linz.govt.nz/layer/53621-wellington-lidar-1m-dem-2013-2014/

extents. Water levels were ramped up to the maximum water level and then back down again to simulate the passing of a storm and the flooding and draining associated with them.

6.1.6 Waves and water level

A selection of 7 storms were used in the present study to capture the full range of inundation patterns; six for the Wellington South coast and one for Mākara[14]. These storms, together with their wave and storm-tide values are presented in Table 6-2.

Following a similar method to Lane et al. (2012) the storms were adjusted by modifying the storm-tide level to match the 1% AEP of joint-probability of storm-tide and wave height, where the 1% AEP is established in the joint probability study of Stephens et al. (2011). Wave conditions will remain unchanged. Sea-level rise was added by increasing the base mean sea level to the elevation identified in Task 1. Only the June 2013 storm (at Wellington South coasts) and the February 2018 storm (Mākara Beach) were not adjusted as they represented a storm larger than the joint 1% AEP. Here the actual values were kept unchanged as a conservative approach (as measured at the Baring Head wave buoy, just offshore of the Wellington south coast for June 2013). The 2013 storm represented the 83-year ARI event when considering storm-tide alone but was rarer than a 1% *joint* AEP when including the 9.57 m wave magnitude (Stephens et al. 2015).

Based on the examination of extreme wave event approach directions at the Baring Head wave buoy, the wave peak direction was chosen as 190^{o}TN for the Wellington south coast. At Mākara beach a spectral wave model hindcast were examined and the approach direction of the storm were chosen as 285^{o}TN. The typical wave directional spreading is at the Wellington South coast is 30^{o} and at Mākara was 14^{o} (refer to Section 5.2.4). The wave energy dispersion within XBeach is generally over exaggerated, as described by Roelvink (2018). One solution to this is to decrease the wave directional spreading of the JONSWAP (Hasselmann 1980) spectrum generated on the model boundary. For the Wellington South coast the accurate inundation levels (presented in Section 6.1.7) were obtained by generating a JONSWAP wave spectrum with cosine power distribution equal to 40. For Mākara a much narrower spectrum was used and equal to 800. These decreases in the directional spreading compensate for the inflated wave energy spread within the model. The Peak Enhancement Factor (PEF) were fixed at a value of 3.3 for both models. The South coast model employed a constant extreme peak wave period of 15.5s while the Mākara model employed 11.5s.

It should be noted that a typical storm passing the Wellington region will actually generate a range of wave conditions over time (directions, wave heights and peak wave periods) as the peak of the storm moves across the region. In the present study these parameters are fixed to the values observed close to the *peak* of the storm. This could result in the under/ over estimation of the peak storm inundation extents.

[14] Five storms were initially selected for Mākara beach, but unfortunately very limited validation data were available for the other proposed storms (i.e. no records of inundation from the other Lane et al 2012 storms). The offshore forcing conditions were also not readily available and different from the storm simulated by Bosserelle and Lane (2019).

Table 6-2 Dates and conditions of modelled storms for the South Coast and Mākara. Here the significant wave heights (Hs) were as they were observed close to the 50 m contour and either the Storm-Tide (ST) observed in Queen's Wharf or the Adjusted Storm Tide (AST) to ensure the 1% AEP of the joint-probability of storm-tide and wave height. Both units are in meters.

Scenario ID	Storm date	Forcing conditions		
		Wave height (m)	Adjusted storm-tide (relative to WVD-53 including MSL offset 2005-2011 =0.196 m)	Adjusted storm-tide (relative to NZVD including 01-19 MSL offset (0.215m) by using Tide gauge datum offset from LINZ (Bell and Allis, 2021)
Wellington south coast				
1	15 Jun 1975*	Hs = 6	AST = 1	AST = 0.669
2	15 May 1985*	Hs = 8.7	AST = 0.55	AST = 0.219
3	17 Aug 1990*	Hs = 2.5	AST = 1.25	AST = 0.919
4	9 May 1992*	Hs = 7	AST = 0.85	AST = 0.519
5	21 Jun 2013[15]	Hs = 9.57	ST = 1.03	ST = 0.699
6	15 Apr 2020[16]	Hs = 6.0	ST = 0.61	ST = 0.279
Mākara				
7	21 Feb 2018 [17] (ex-TC *Gita*)	Hs = 5	ST = 1.31	ST = 1.01

*Modelled by Lane et al. (2012)

AST is the elevation above MSL, for the calibration events a MSL offset of -0.135 m NZVD-2016 (refer Section 3) for the South Coast, an additional +3cm offset was applied for the Mākara model , i.e. MSL=-0.132 m NZVD-2016.

6.1.7 Validation

Validation is presented for both the Wellington south coast and Mākara. Recent storms with photographic and video evidence of coastal impact were employed for this purpose. The particular image illustrating the impact was digitised via geographically referenced maps and correlated with the runup/ flow depth extent predicted by each 9-hour storm simulations. The parameters mentioned in Section 6.1.5 were then altered until the most realistic inundation extents were achieved. The parameters values were only varied within physical range of that parameter (e.g. to ensure one parametrisation does not overcompensate for other physical phenomena).

South coast

Model validation was performed against two recent events: 21 June 2013 (storm 5) and 15 April 2020 (storm 6) in Table 6-2.

21 June 2013 (storm 5)

The storms used in the present modelling investigation have been numbered in Table 6-2, storm 1 to 7. These storms were chosen due to their recorded coastal impacts and the fact that they occurred recently. Storm 5 resulted in an estimated NZ$ 39.3 million in claims from both the North and South Island and represents one of the most extreme storms recorded on the Wellington south coast.

[15] https://hwe.niwa.co.nz/event/June_2013_New_Zealand_Storm , https://www.youtube.com/watch?v=e7lUYUkSF6I
[16] https://wellington.govt.nz/your-council/news/2020/04/big-waves-hit-wellington-coast
[17] https://www.stuff.co.nz/national/101635786/gita-smashes-wellington-seaside-village-flooding-houses-and-destroying-property

Figure 6-6 presents the validation locations collected from readily available sources. Three zoomed extents are also provided where each specific location is labelled. The photographic evidence then follows each zoomed map extent.

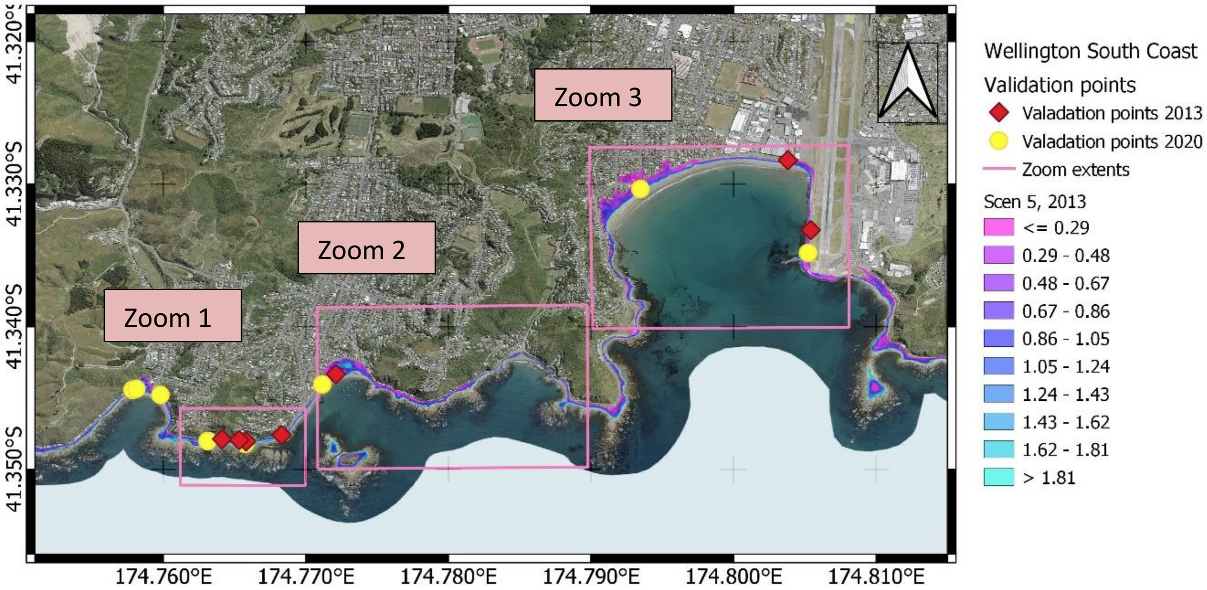

Figure 6-6: Wellington south coast illustrating the geographical locations of where runup evidence were collected during the June 2013 storm. The zoom extents are given in Figure 6-7, Figure 6-12, and Figure 6-14.

In general, the model performed well, predicting the extent and flow depth of the maximum wave run-up accurately. Here, wave runup depth was defined as the depth above the vertical reference datum and flow depth the actual depth of the water. Throughout Section 6 these will be given by the colour bars. In some photographs the actual wave breaking and runup can be seen. An example of this is illustrated in Figure 6-24. This particular wave does not necessarily represent the furthest extent of the storm waves. In other validation photographs the debris line is useful in providing confidence regarding the runup extent (e.g Figure 6-8). The size of the debris can also attest to the amount of water contributing to the runup extent (e.g. Figure 6-10). Site 5 in Figure 6-12 and Figure 6-13 does not provide direct evidence of the runup extent. This only illustrates that there were extreme runup in the nearshore. No photographic evidence of more inland inundation was readily found. Given the accuracy of the model at the other validations sites it is assumed the model was accurate in Island Bay as well. It should however be noted that the topography does not include houses and thus the inundation extents presented here might be excessive in the built environment. The frictional effect of houses and vegetation is approximated in the models via an increased wave and flow friction.

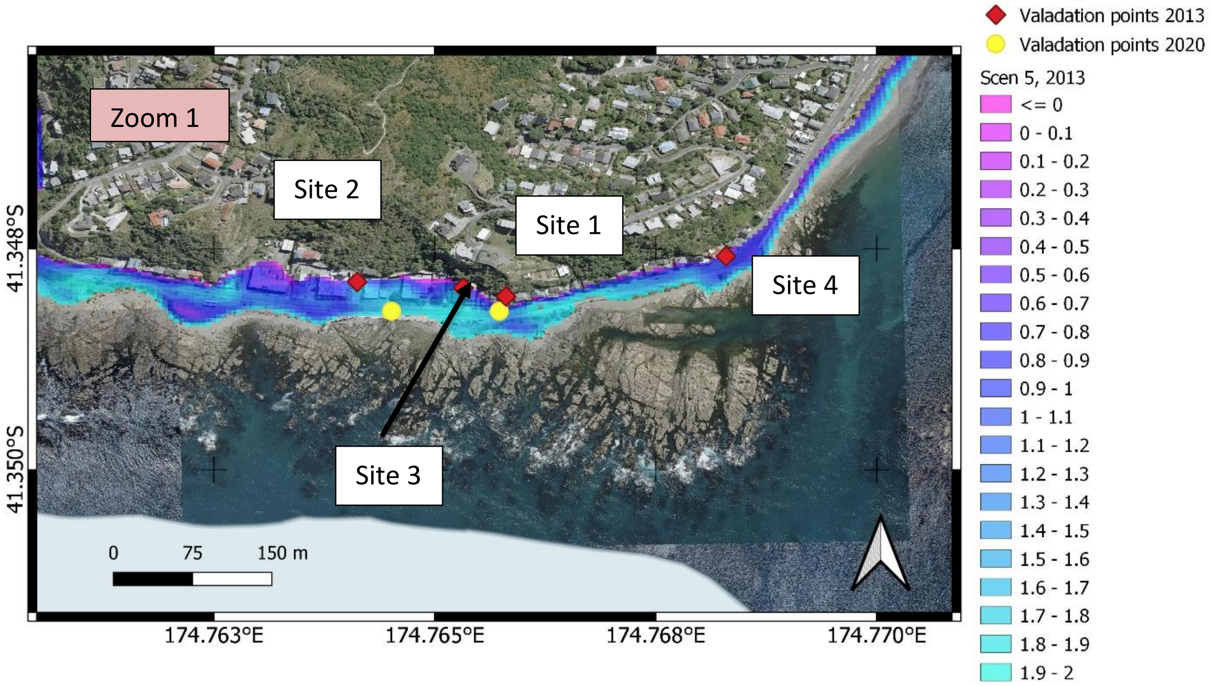

Figure 6-7: Zoom extent 1 indicating the first four validation locations together with the flow depth [m]. Both the 2013 and 2020 storm validation locations are indicated for ease of reference.

Figure 6-8: Coastal inundation evidence and debris line at site 1 in Figure 6-7. [Source: http://www.niwa.co.nz/news-publications/photo-galleryhttp://www.niwa.co.nz/news-publications/photo-gallery].

Figure 6-9: Coastal inundation evidence and debris line at site 2 in Figure 6-7 (Esplanade, Ōwhiro Bay). [Source: https://niwa.co.nz/file/33798].

Figure 6-10: Coastal inundation evidence and debris line at site 3 in Figure 6-7. [Source: Wellington City Council].

Figure 6-11: Coastal inundation evidence and debris line at site 4 in Figure 6-7. [Source: Wellington City Council].

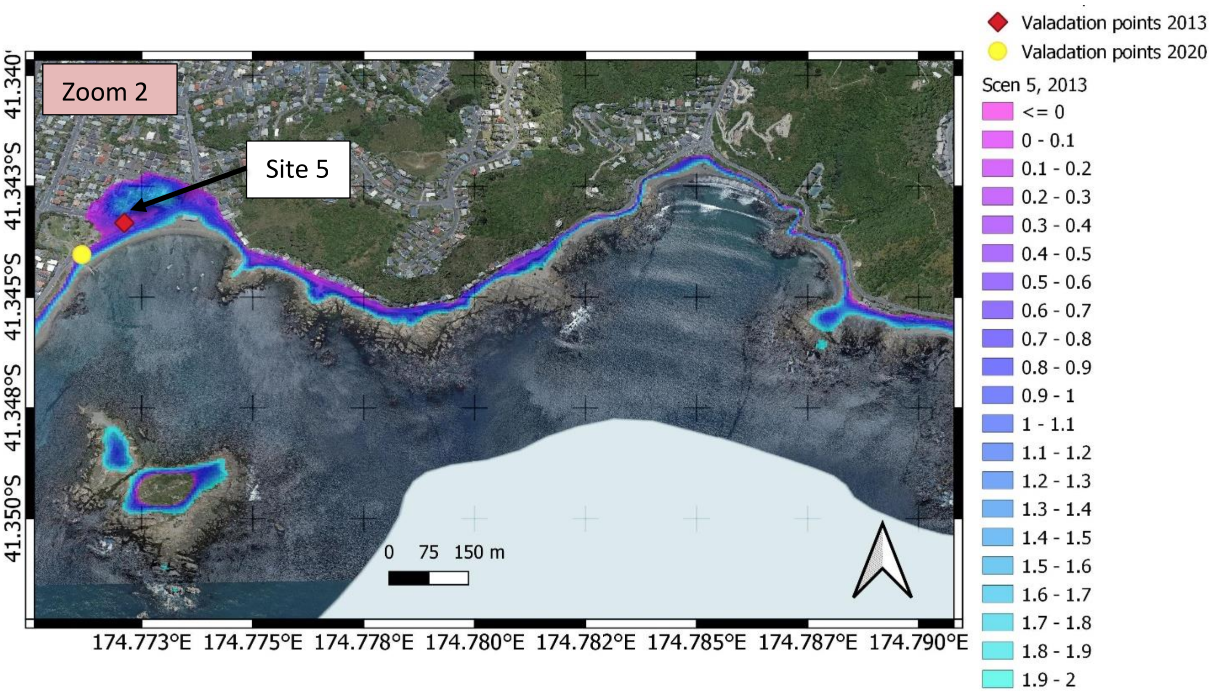

Figure 6-12: Zoom extent 2 indicating the fifth validation locations together with the flow depth [m].

Figure 6-13: Coastal inundation evidence and debris line at site 5 in Figure 6-12. [Source: *NIWA New Zealand*].

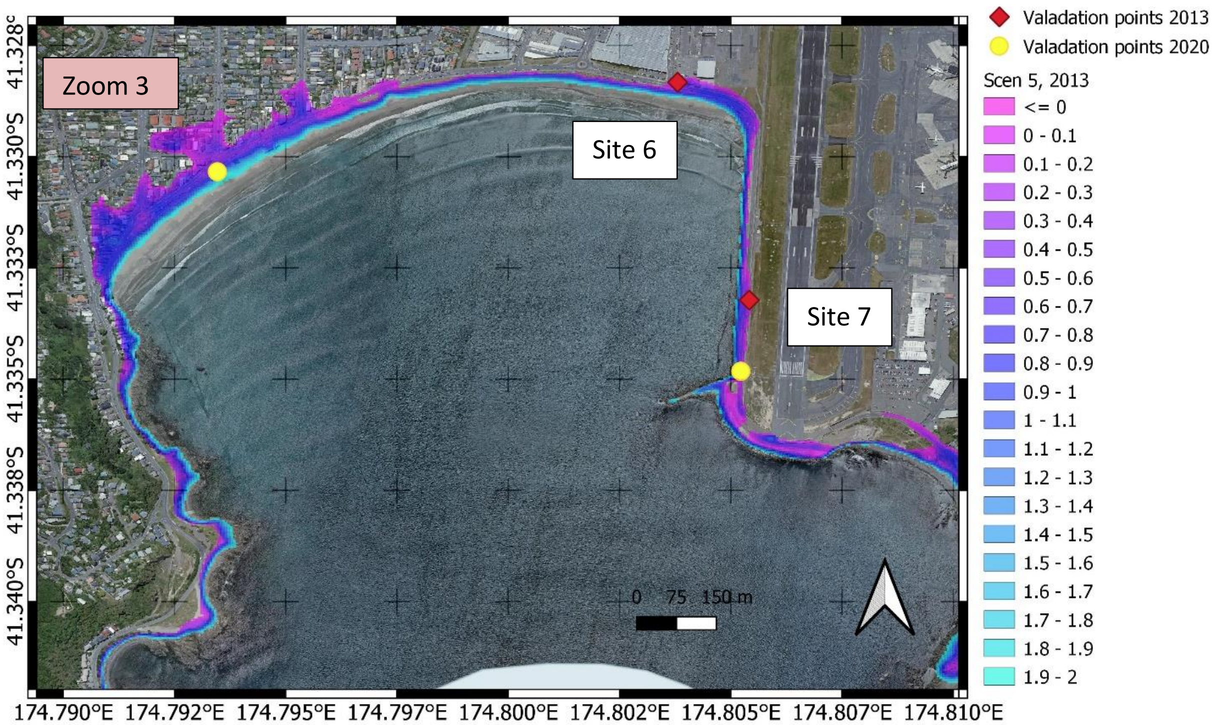

Figure 6-14: Zoom extent 3 indicating the sixth and seventh validation locations together with the flow depth [m].

Figure 6-15: Coastal inundation evidence and debris line at site 6 in Figure 6-14. [Source: *Wellington City Council*].

Figure 6-16: Coastal inundation evidence and debris line at site 7 in Figure 6-14. [Source: *Wellington City Council*].

Figure 6-17: Coastal inundation evidence and debris line at site 7 in Figure 6-14. [Source: *Wellington City Council*].

15 April 2020 (storm 6) *[Source: https://www.youtube.com/watch?v=JXG5b9UgiqU]*

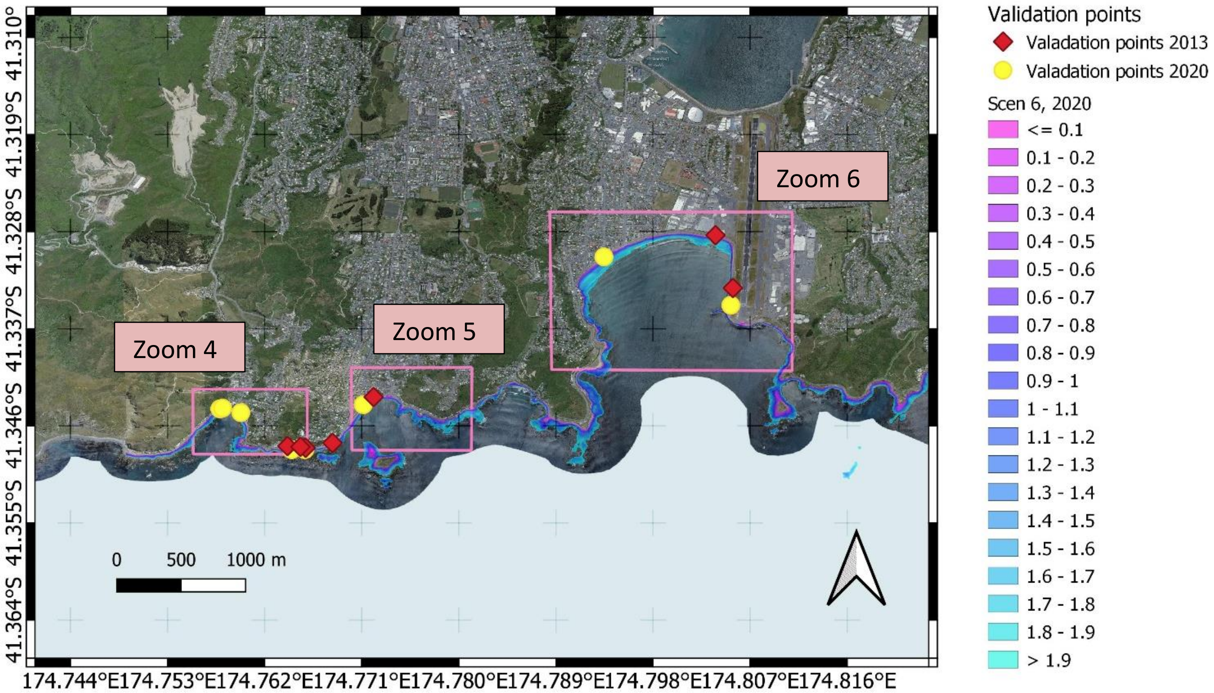

Figure 6-18: Wellington south coast illustrating the geographical locations of where runup evidence were collected during the April 2020 storm. The zoom extents are given in Figure 6-7, Figure 6-12, and Figure 6-14. Both the 2013 and 2020 storm validation locations are indicated for ease of reference.

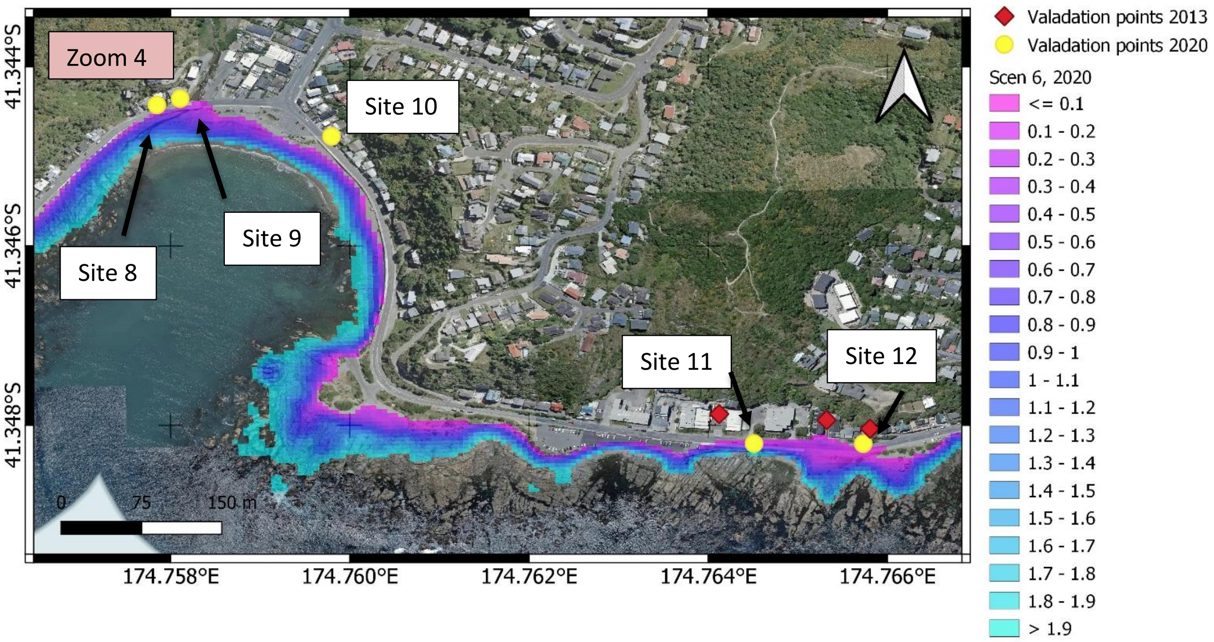

Figure 6-19: Zoom extent 4 indicating the eight, nineth, tenth, eleventh, and twelfth validation locations together with the flow depth [m].

Figure 6-20: Coastal inundation evidence and debris line at site 8 in Figure 6-19. [Sources: https://www.stuff.co.nz/dominion-post/news/121145008/two-days-warning-for-massive-wellington-waves-but-nobody-raised-alarm].

Figure 6-21: Coastal inundation evidence and debris line at site 9 in Figure 6-19. [Source: https://www.rnz.co.nz/news/national/414272/huge-waves-hit-wellington-s-south-coast-person-swept-out-to-sea-rescued].

Figure 6-22: Coastal inundation evidence and debris line at site 10 in Figure 6-19. [Source: https://www.stuff.co.nz/dominion-post/news/121145008/two-days-warning-for-massive-wellington-waves-but-nobody-raised-alarm].

Figure 6-23: Coastal inundation evidence and debris line at site 10 in Figure 6-19. [Source: https://www.stuff.co.nz/dominion-post/news/121145008/two-days-warning-for-massive-wellington-waves-but-nobody-raised-alarm].

Figure 6-24: Coastal inundation evidence and debris line at site 11 in Figure 6-19. [Source: https://www.stuff.co.nz/dominion-post/news/121145008/two-days-warning-for-massive-wellington-waves-but-nobody-raised-alarm].

Figure 6-25: Coastal inundation evidence and debris line at site 12 in Figure 6-19. [Source: https://wellington.govt.nz/news-and-events/news-and-information/our-wellington/2020/04/big-waves-hit-wellington-coast].

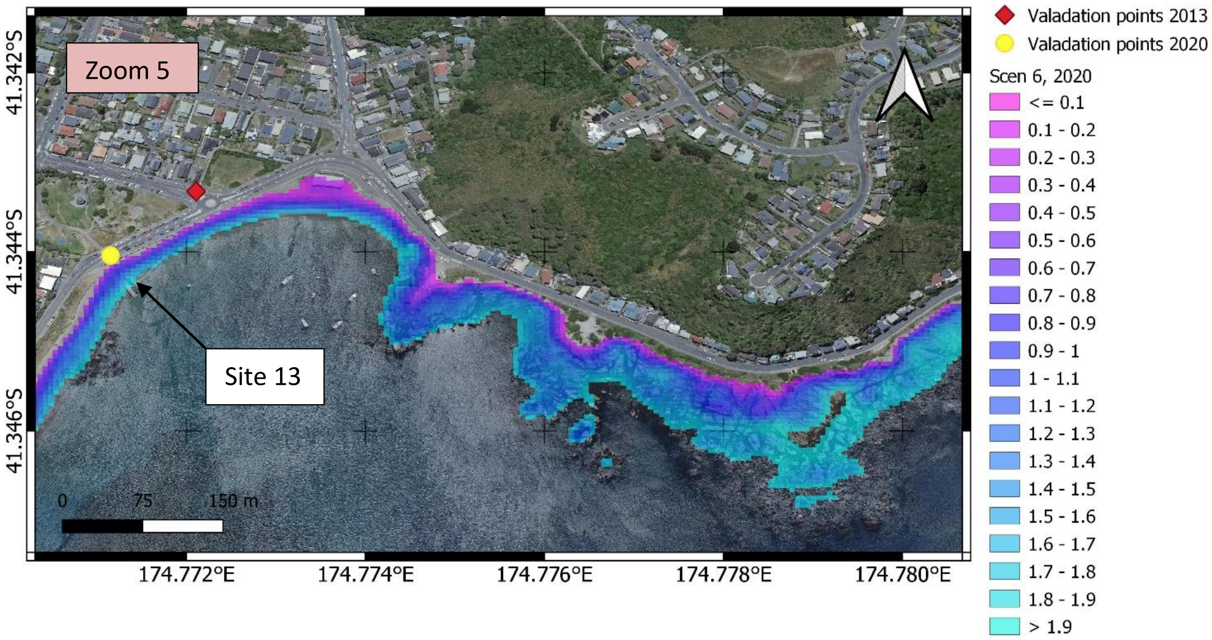

Figure 6-26: Zoom extent 5 indicating the thirteenth validation locations together with the flow depth [m].

Figure 6-27: Coastal inundation evidence and debris line at site 13 in Figure 6-26. [Source: https://www.rnz.co.nz/news/national/414272/huge-waves-hit-wellington-s-south-coast-person-swept-out-to-sea-rescued].

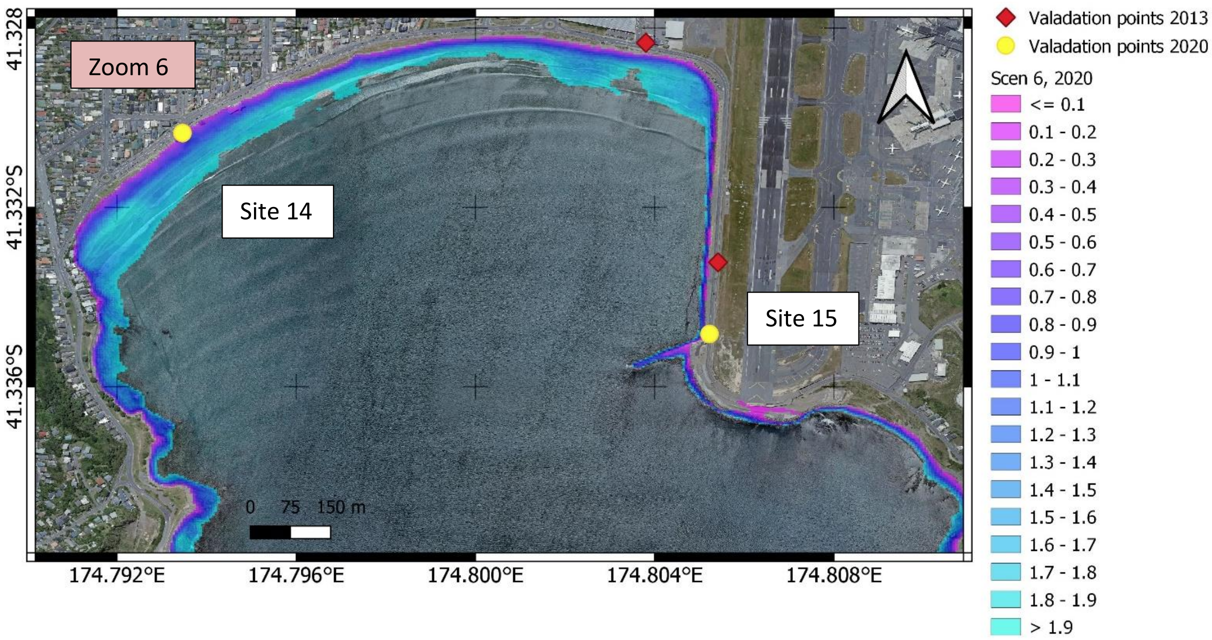

Figure 6-28: Zoom extent 6 indicating the fourteenth and fifteenth validation locations together with the flow depth [m].

Figure 6-29: Coastal wave runup evidence at site 14 in Figure 6-28. [Source: https://www.stuff.co.nz/dominion-post/news/74187528/rising-seas-a-slowly-unfolding-red-zone].

Figure 6-30: Coastal inundation evidence and debris line at site 15 in Figure 6-28. [Source: https://wellington.govt.nz/news-and-events/news-and-information/our-wellington/2020/04/big-waves-hit-wellington-coast].

The model performance presented here agrees well will eyewitness accounts as well as video and photographic evidence. During the course of the present study a field visit was made to the residents of Breaker Bay. The evidence and guidance of the residents were used to recalibrate the numerical model for the Wellington South coast. The results presented here faithfully represent their experiences. An in-depth analysis and documentation of their accounts and experiences fall outside the scope of the present study.

In Figure 6-22 and Figure 6-23 the inundation experienced during the 2020 storm is given for Ōwhiro Bay. The numerical model is underpredicting the overtopping on the eastern periphery of this bay. The main reason for this might be related to either local long wave dynamics (local resonance and directional spreading sensitivities) or might be due to the offshore boundary assumptions. The latter is because the actual progression of a storm does don't occur with a stationary approach direction but rather with a sequence of changing directions and wave periods. The rest of the sensitivity analysis and consequent validation for the Wellington South coast were well represented by these assumptions. A more focused and in-depth study of the long wave dynamics at Ōwhiro Bay is thus required beyond the scope of the present investigation.

Mākara

Model validation was performed against one recent event**: 21 February 2018 (Storm 11)** in Table 6-2.

21 February 2018 (storm 6) associated with extra-tropical cyclone *Gita*

In Figure 6-31 the validation results for Mākara beach is provided.

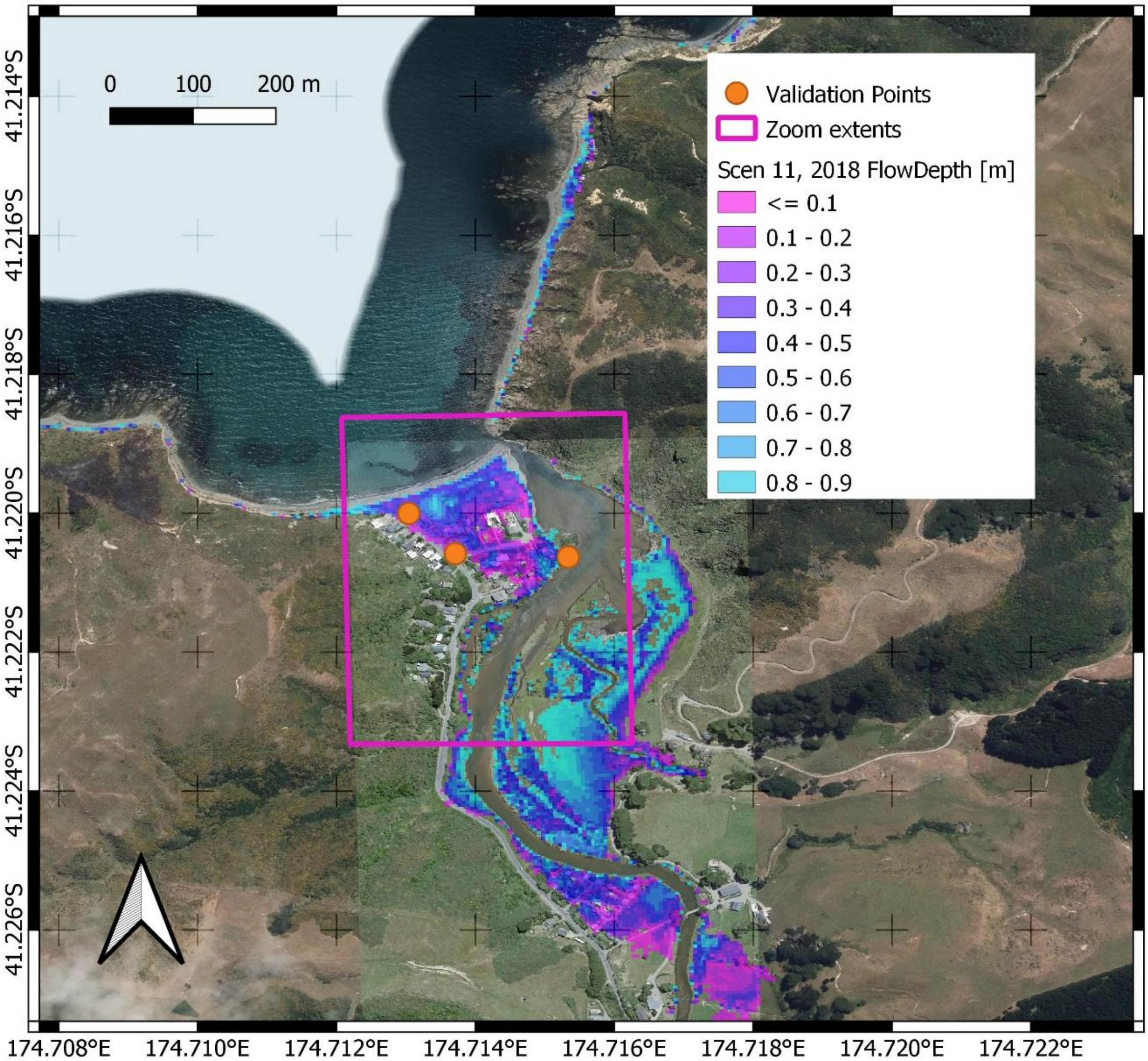

Figure 6-31: Mākara beach illustrating the geographical locations of where runup evidence were collected during the February 2018 storm. The zoom extent is given in Figure 6-32.

Several simulations were completed in the calibration process. These simulations were aimed at understanding some of the impacts of the most crucial model parameters described in Table 6-1. Here the physical dynamics were different compared to the Wellington south coast. Validation was achieved with much smoother settings for the bathymetry compared to the Wellington south coast and a narrower wave directional spreading. The flow depth indicated in Figure 6-32 appears to be too extreme but this model was executed with no buildings, boundary fences or walls, storm drains or vegetation. The house footprints, vegetation and reefs have however been included through increase wave and flow friction. Based on the compelling eyewitness account of Peter Shearer

(Mākara resident for 30 years[18]) there were waves coming down Mākara road along with large pieces of driftwood being washed down the same road. He also recollects the waves going down Estuary street. Mākara beach café was also inundated. Numerous houses were flooded. Fences were also knocked down although the wind was apparently not as extreme as it has been in the past.

In Figure 6-32, the results of the model are provided as zoomed in details. At validation site 2 approximately 40 cm maximum water depth was achieved during the 9 hours simulation period. This seems to corroborate the eyewitness reports. This amount of water will be enough to be perceived as waves propagating down the road.

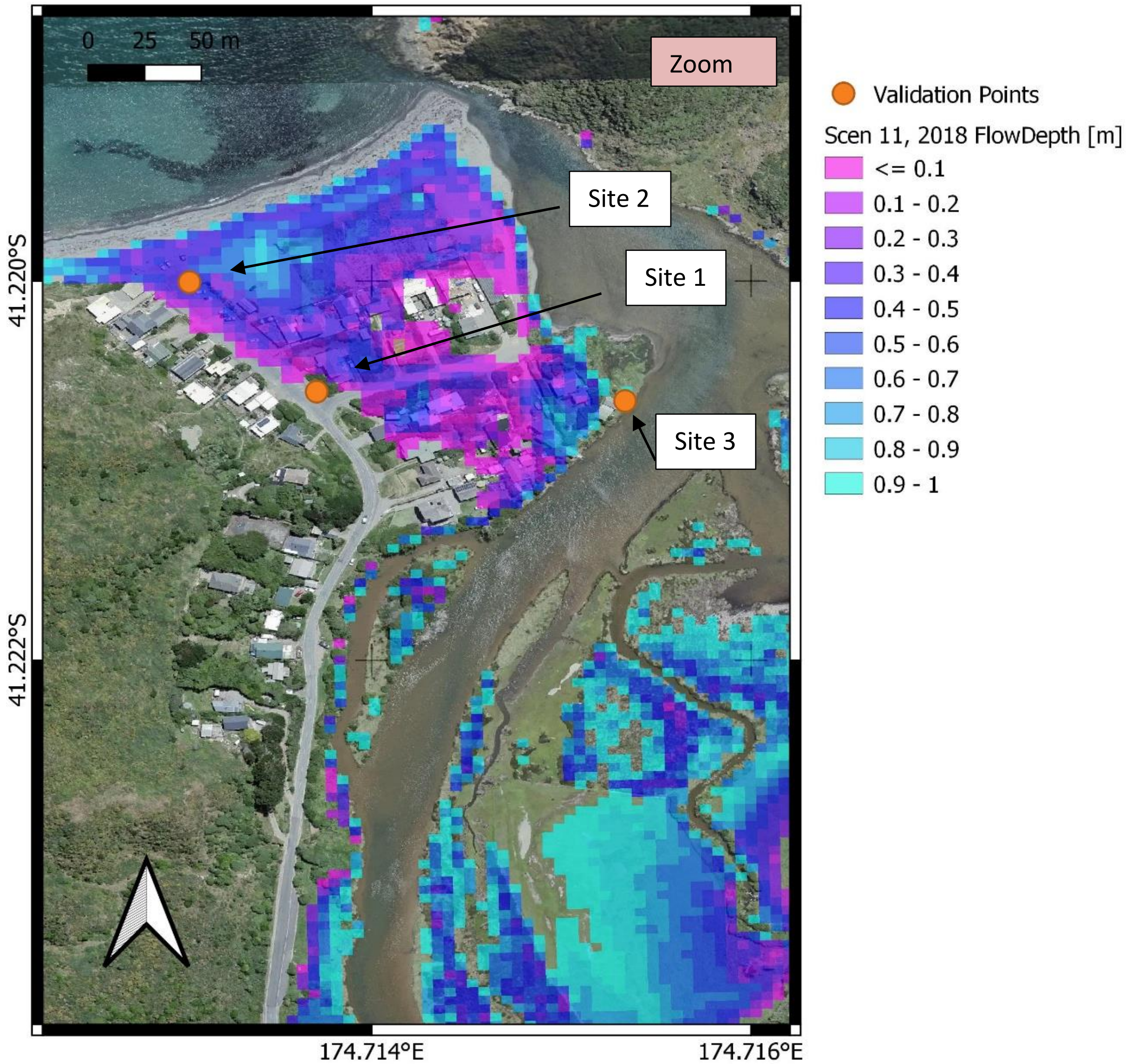

Figure 6-32: Zoom extent of Mākara beach, indicating the three validation locations together with flow depth [m].

If the model did include houses and walls most of the water would flow down Mākara road and into Estuary street. Thus, it must be kept in mind that the actual flow pattern on this scale will be slightly different in reality. Nevertheless, the amount of water overtopping into Mākara beach appears

[18] https://www.stuff.co.nz/environment/110423337/wellington-seaside-village-hatches-climate-change-plan-after-cyclone-gita-mayhem

reliable and a good indication of the inundation extent. In general, the bright magenta areas in Figure 6-32 represent water depths of less than 10 cm and therefor at the lower end of what would be considered inundation. Or alternatively, these flow depths can easily be mitigated via the use of sandbags and other ad hoc interventions. A community perception and engagement study has been completed with the Mākara Beach residents and presented by WCC[19] . According to these eyewitnesses account the flooding was not associated with an "horrendous amount of water" but the community was just not prepared for it. Residents reported jelly fish in their gardens and under their houses – also corresponding with the results of Figure 6-32.

In Figure 6-33 the photographic evidence of large pieces of driftwood in Mākara road is shown. This particular log was carried all the way down to the Estuary street intersection and thus represents a significant amount of water. In Figure 6-34 the pebbles from the beach protection scheme can be seen in Mākara road.

Figure 6-33: Big pieces of drift wood accompanied waves down the two main streets of Mākara. [Source: https://www.stuff.co.nz/environment/110423337/wellington-seaside-village-hatches-climate-change-plan-after-cyclone-gita-mayhem].

[19] Mākara Beach Project (arcgis.com)

Figure 6-34: Debris and drift wood being washed down Makara road on its way to Estuary street. [Source: https://www.stuff.co.nz/environment/110423337/wellington-seaside-village-hatches-climate-change-plan-after-cyclone-gita-mayhem].

Figure 6-35: Debris in Mākara road. [Sources: https://Mākara-wcc.opendata.arcgis.com/].

The link to some useful interviews are provided in the caption of Figure 6-33 and Figure 6-34. In Figure 6-36 and Figure 6-37 the inundation damage at validation site 3 is given.

Figure 6-36: Validation site 3. Here the water levels were significantly higher as can bee seen from the damage to the boat shed. https://www.stuff.co.nz/environment/110423337/wellington-seaside-village-hatches-climate-change-plan-after-cyclone-gita-mayhem.

Figure 6-37: Damage presented in Figure 6-36 from the inside of the shed. https://www.stuff.co.nz/environment/110423337/wellington-seaside-village-hatches-climate-change-plan-after-cyclone-gita-mayhem.

It should be noted that the stream flow was not included in the present study. With a large rainfall event the terrestrial contribution of water down the stream would potentially exacerbate the flooding as this water will not be able to drain to the ocean (depending on the storm tidal levels).

6.2 Model results

As an overview of the runup extents only the maximum reach of the runup, per storm, is presented here. This envelope represents the maximum extent of inundation across the modelled scenarios. These shapefiles will also be provided together with the final report. All the validation locations are also plotted together with the results as well as the extreme extent envelope (thick black line in Section 6.2.1 and 6.2.3.

6.2.1 Historical runup – Wellington south coast

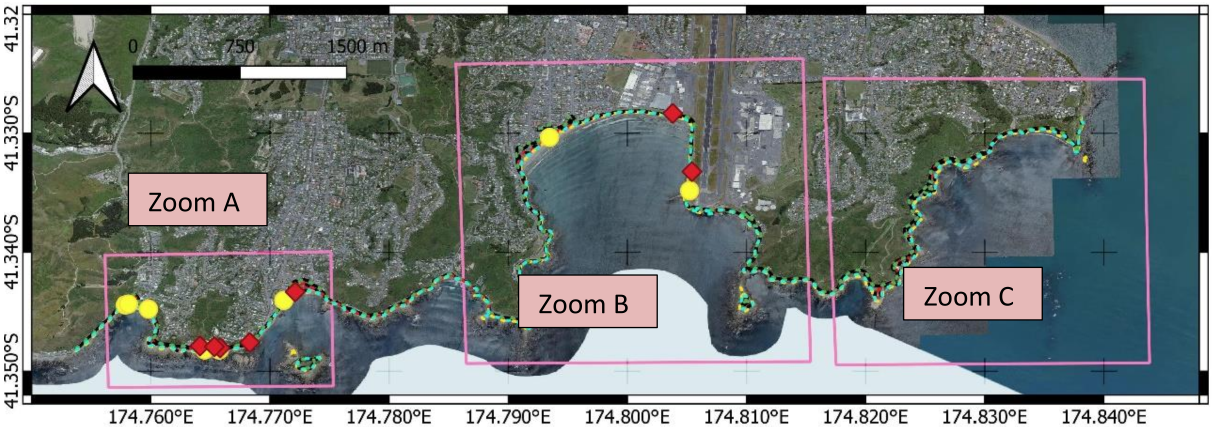

Figure 6-38: Map view of approximate zoom extents provided as an overview of maximum storm runup results.

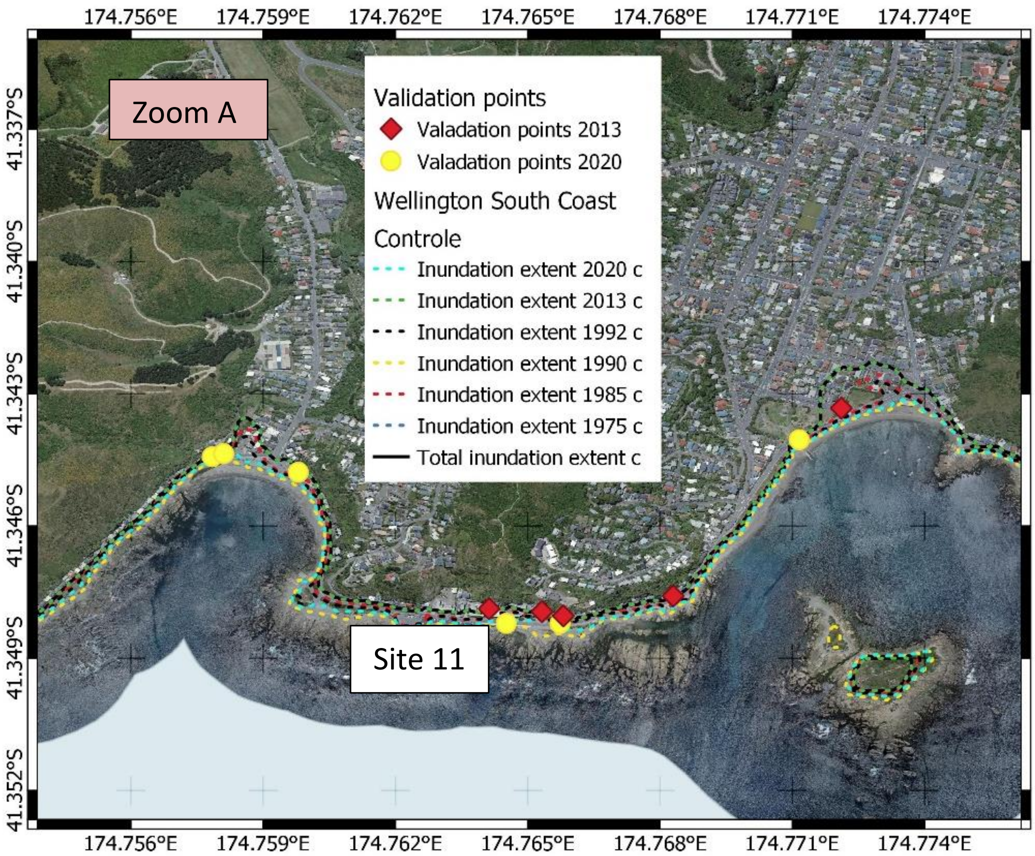

Figure 6-39: All the storm inundation extents presented in Table 6-2 for the Wellington south coast and zoom extent A.

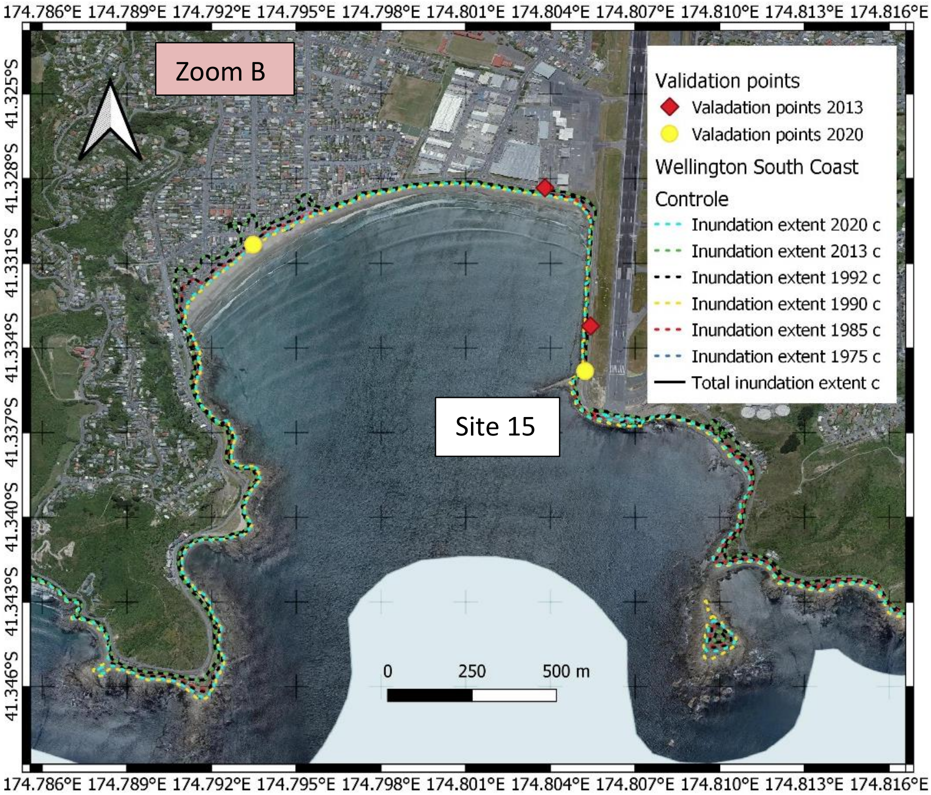

Figure 6-40: All the storm inundation extents presented in Table 6-2 for the Wellington south coast and zoom extent B.

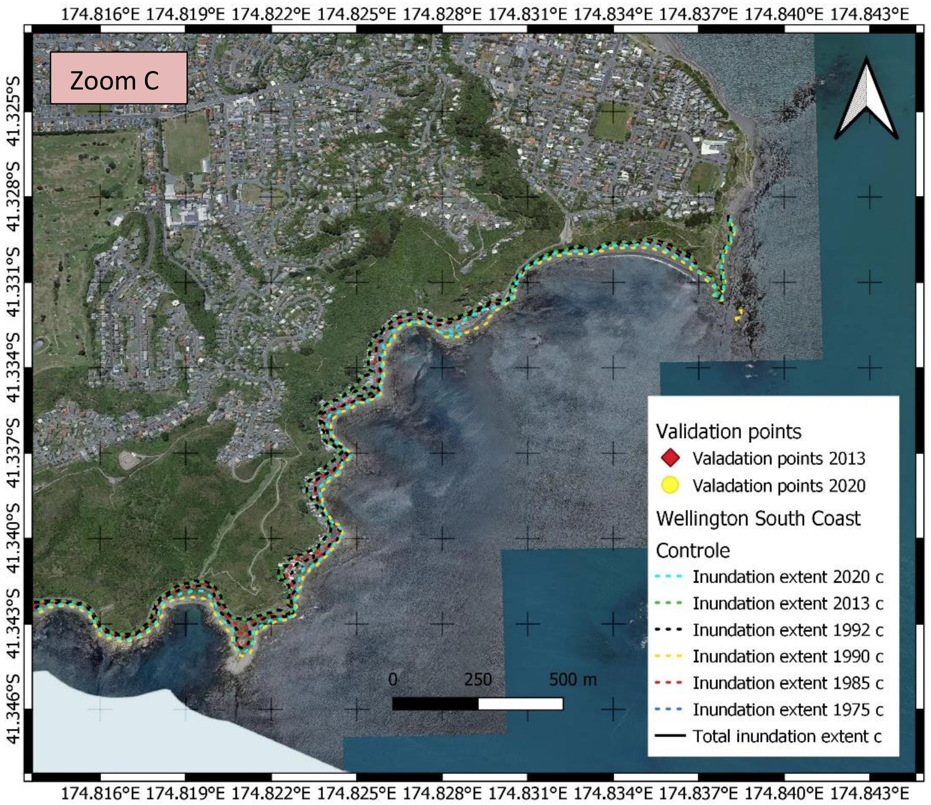

Figure 6-41: All the storm inundation extents presented in Table 6-2 for the Wellington south coast and zoom extent C.

For most of these events, the 2013 storm dominated the maximum runup. The maximum wave inundation extents are limited to a narrow strip along the coast by the rising steep topography behind many of the bays (e.g. Breaker Bay, Figure 6-41 or The Sirens Rocks, Figure 6-39). Inundation extents are broadest within the lower elevation areas of the embayments (e.g. Ōwhiro Bay, Island Bay and Lyall Bay) where runup is seen to flow a hundred metres or more inland by flowing into the streambeds, former backshore depressions and along roadways.

6.2.2 Historical runup – Mākara

The run-up extent of the February 2018 storm is presented in Figure 6-32. Here the entire flow depth is given as a contour is not as clear as it was for the Wellington south coast. Most of Mākara beach is low lying and thus when the wave does overtop the inundation extents are far reaching. Due to boundary walls, storm drains, and houses the majority of the witnessed flow would have been restricted to Mākara road and Estuary street. Although inundation was reported throughout Mākara Beach.

6.2.3 Future scenarios

The climate change scenarios were based on a 10% increase of the H_s and AST levels together with two RSLR scenarios (refer Section 3). Table 6-3 contains the adjusted storm scenarios are provided for the reference storms for the 2120 simulations. Figure 6-42 to Figure 6-47 shows the results of the inundation mapping for future scenarios. Similar to the historical runup simulations (Section 6.2.1) only the maximum extent of the runup is shown in the results.

Table 6-3: Future storm scenarios. Units of Hs and AST are metres. AST relative to NZVD including 01-19 MSL offset (0.215m) by using Tide gauge datum offset from LINZ.

Scenario ID	Storm date	Forcing conditions: RSLR = 1.24m + 10% Hs and AST	Forcing conditions: RSLR = 1.54m + 10% Hs and AST
		Wellington south coast	
1	15 Jun 1975	Hs = 6.6, AST = 1.976	Hs = 6.6, AST = 2.276
2	15 May 1985	Hs = 9.57, AST = 1.481	Hs = 9.57, AST = 1.781
3	17 Aug 1990	Hs = 2.75, AST = 2.251	Hs = 2.75, AST = 2.551
4	9 May 1992	Hs = 7.7, AST = 1.811	Hs = 7.7, AST = 2.111
5	21 Jun 2013	Hs = 10.53, ST = 2.009	Hs = 10.53, ST = 2.309
6	15 Apr 2020	Hs = 6.6, ST = 1.547	Hs = 6.6, ST = 1.847
		Mākara Beach	
11	21 Feb 2018 (ex-TC *Gita*)	Hs = 5.5, ST = 2.35	Hs = 5.5, ST = 2.65

The inundation assessments including climate change effects show an escalation of coastal hazards around the entire South Coast from Breaker Bay to Ōwhiro Bay. The inland extent of inundation increases considerably as the current roadways and landforms (with both engineered and natural defences) are overwhelmed by the wave processes on top of a higher sea level. Inundation reaches several hundred metres inland at Ōwhiro Bay, Island Bay and western Lyall Bay as the overland wave flow follows the alignment of the stream bed channels, the roadways and low-lying former backshore areas.

Areas where houses are situated between the coast road and the steep hillside (e.g. Breaker Bay, The Sirens, eastern/western flank of Ōwhiro Bay) are shown to be overwhelmed during storms under climate change scenarios with waves reaching behind houses and only being held back by the rising hillside.

Wellington south coast

2120: RSLR = 1.24 + 10% storm increase

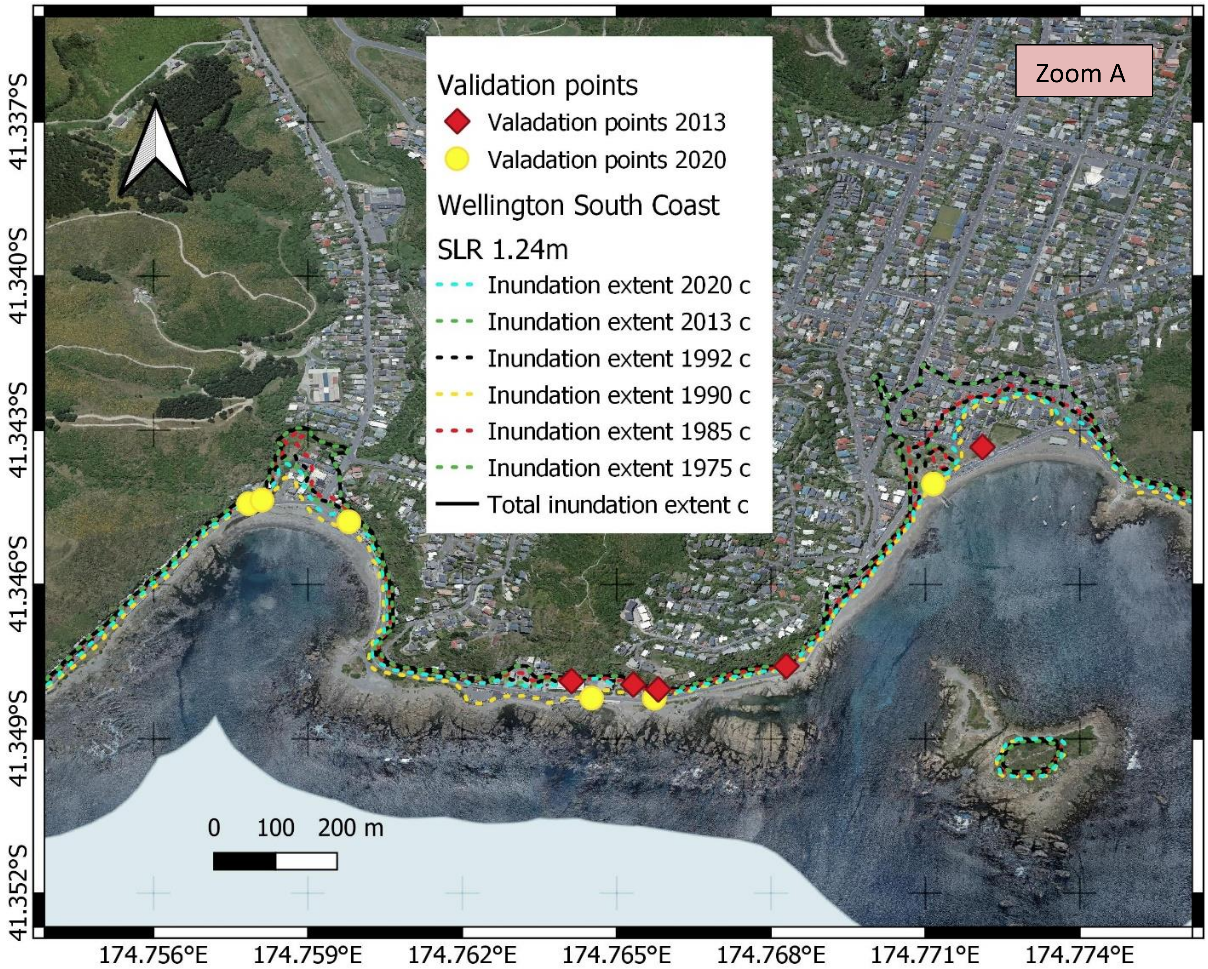

Figure 6-42: All storm inundation extents presented in Table 6-2 for the Wellington south coast, RSLR = 1.24 + 10% storm increase and zoom extent A.

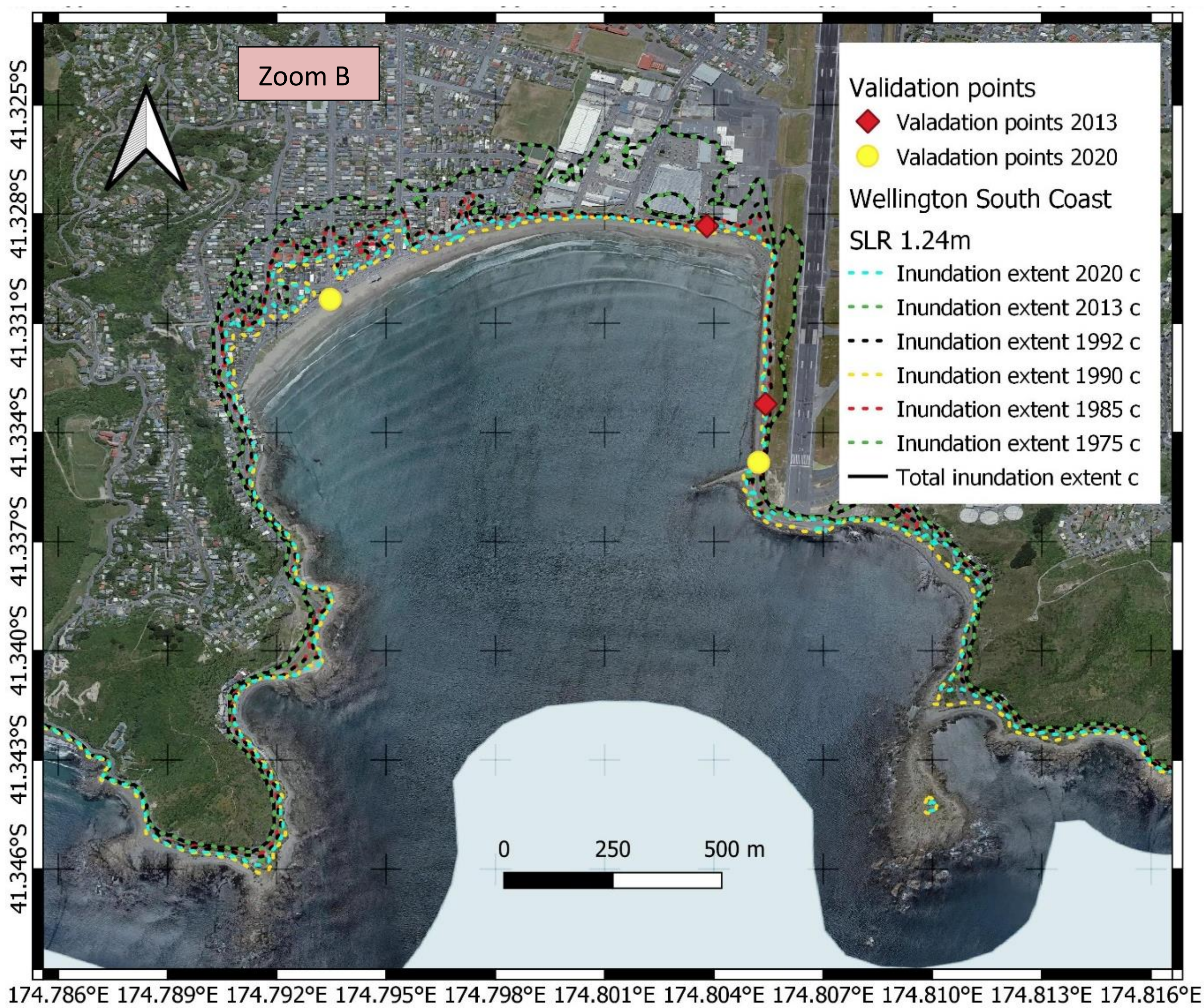

Figure 6-43: All storm inundation extents presented in Table 6-2 for the Wellington south coast, RSLR = 1.24 + 10% storm increase and zoom extent B.

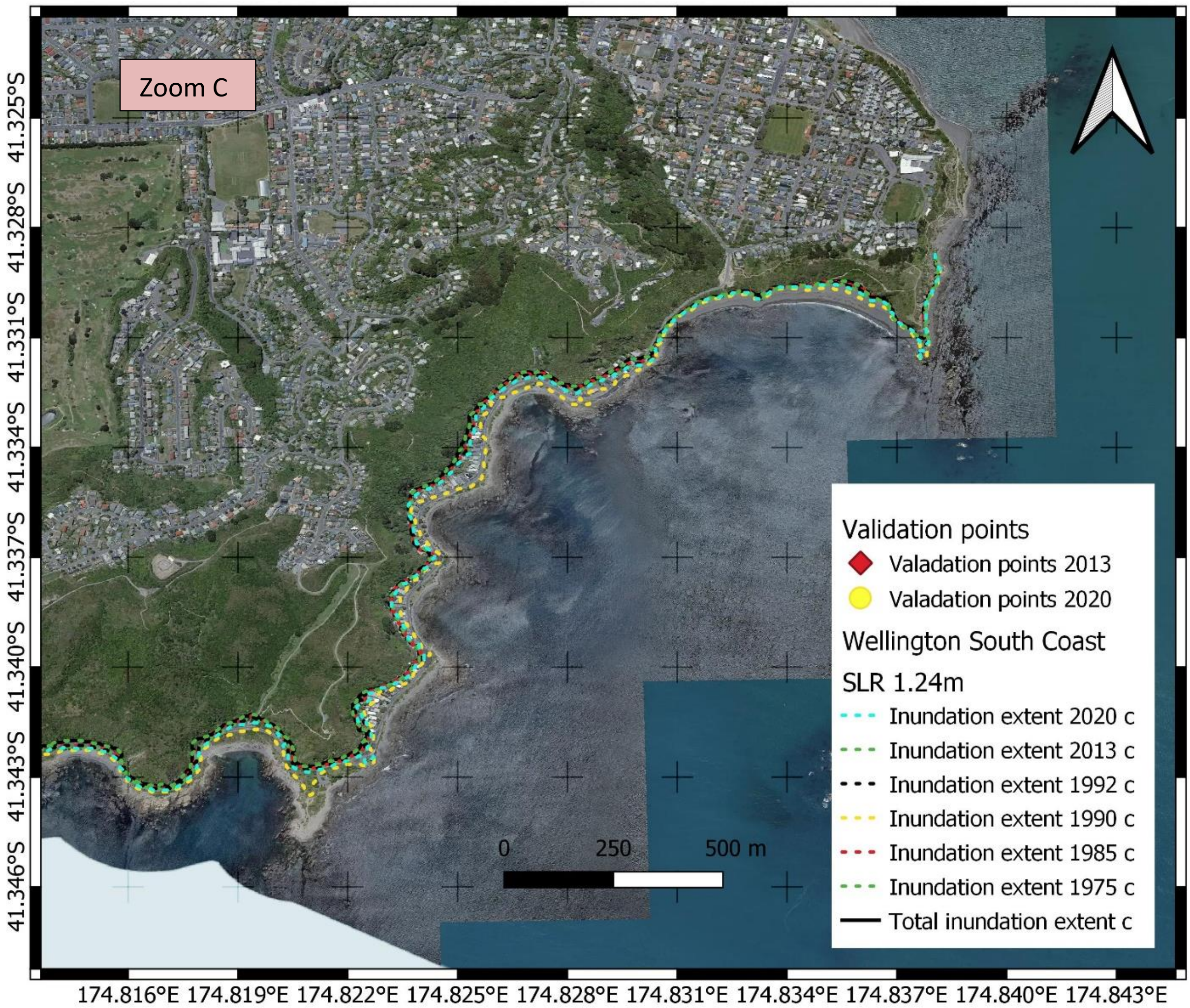

Figure 6-44: All storm inundation extents presented in Table 6-2 for the Wellington south coast, RSLR = 1.24 + 10% storm increase and zoom extent C.

Future scenario 2120: RSLR = 1.54 + 10% storm increases

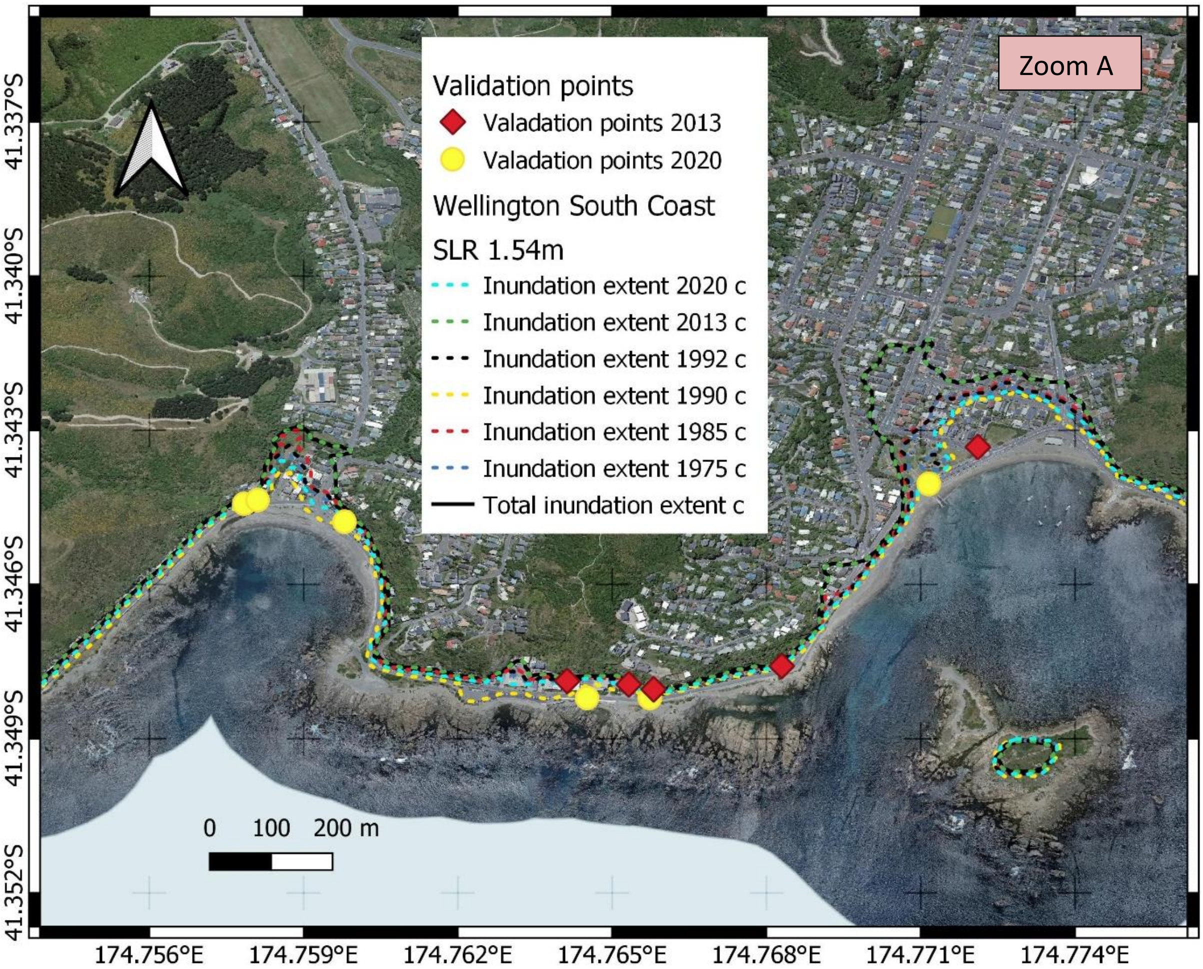

Figure 6-45: All storm inundation extents presented in Table 6-2 for the Wellington south coast, RSLR = 1.54 + 10% storm increase and zoom extent A.

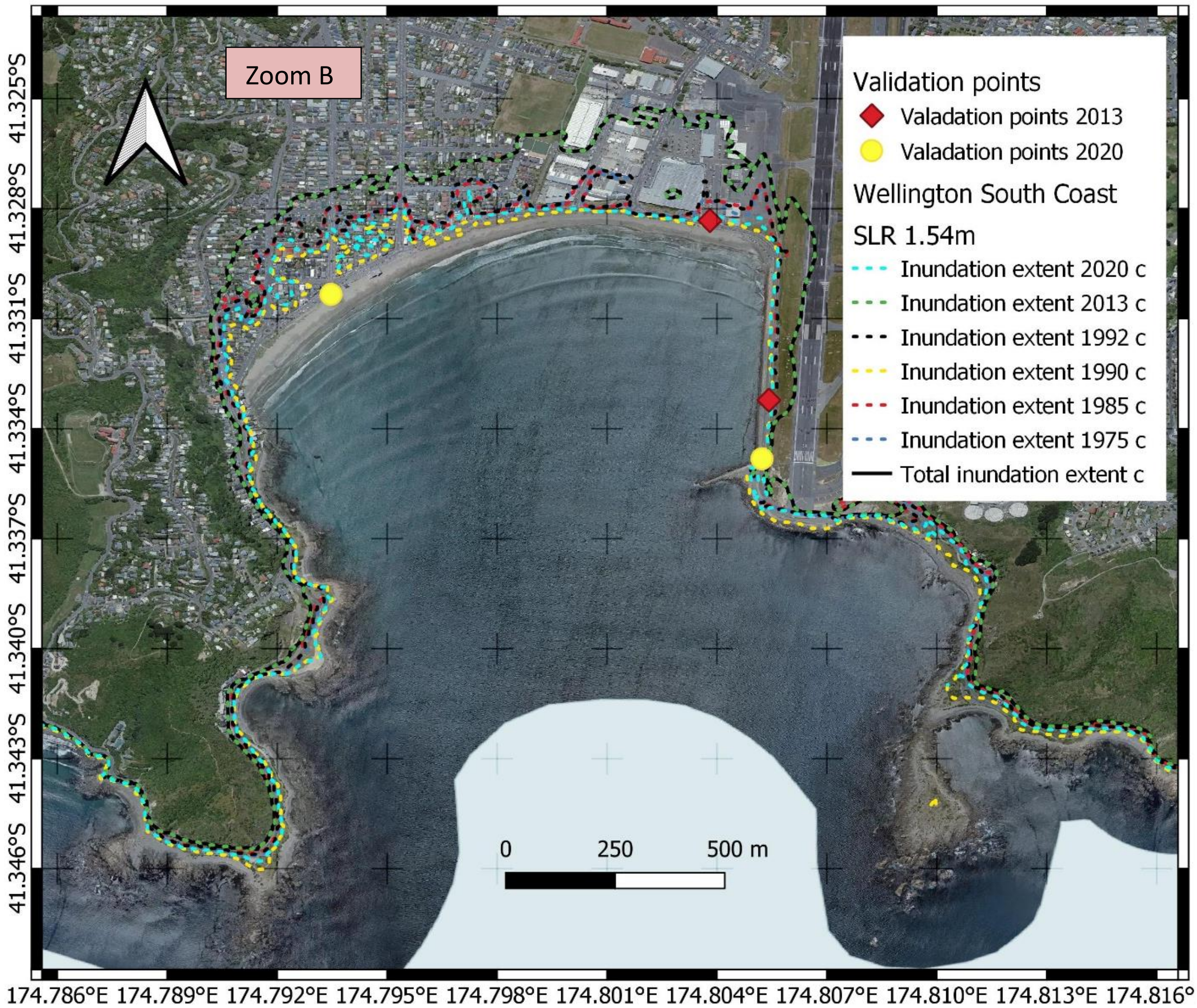

Figure 6-46: All storm inundation extents presented in Table 6-2 for the Wellington south coast, RSLR = 1.54 + 10% storm increase and zoom extent B.

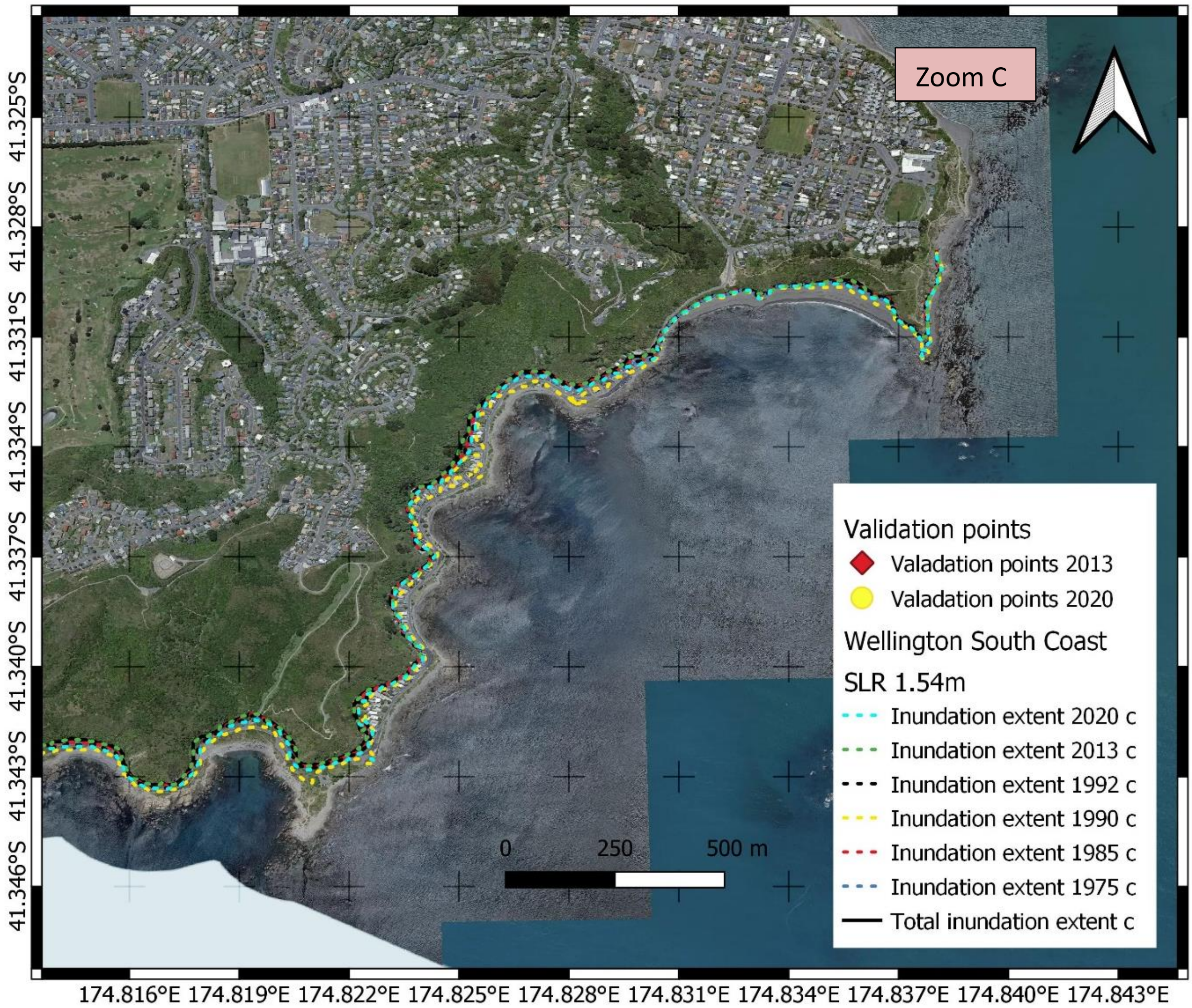

Figure 6-47: All storm inundation extents presented in Table 6-2 for the Wellington south coast, RSLR = 1.54 + 10% storm increase and zoom extent C.

Mākara beach

The climate change and Sea Level Rise scenarios for Mākara beach are presented in Figure 6-48 and Figure 6-49. Here the total flow depths are presented as there are only one case and because the inundation is more complex than the Wellington south coast. E.g. drawing a contour is less effective in elucidating the inundation extent. With these scenarios most of Mākara will be inundated. Keeping in mind that storm drains, boundary walls and houses are not included in the model albeit an increased friction of houses, vegetation and reefs are included. The joint probability of extreme river flow in also not included as this terrestrial contribution of water could potentially exacerbate the flooding scenarios. Mākara is basically surrounded by water and thus makes preparing of adaptation to flood risks complex and difficult to plan for.

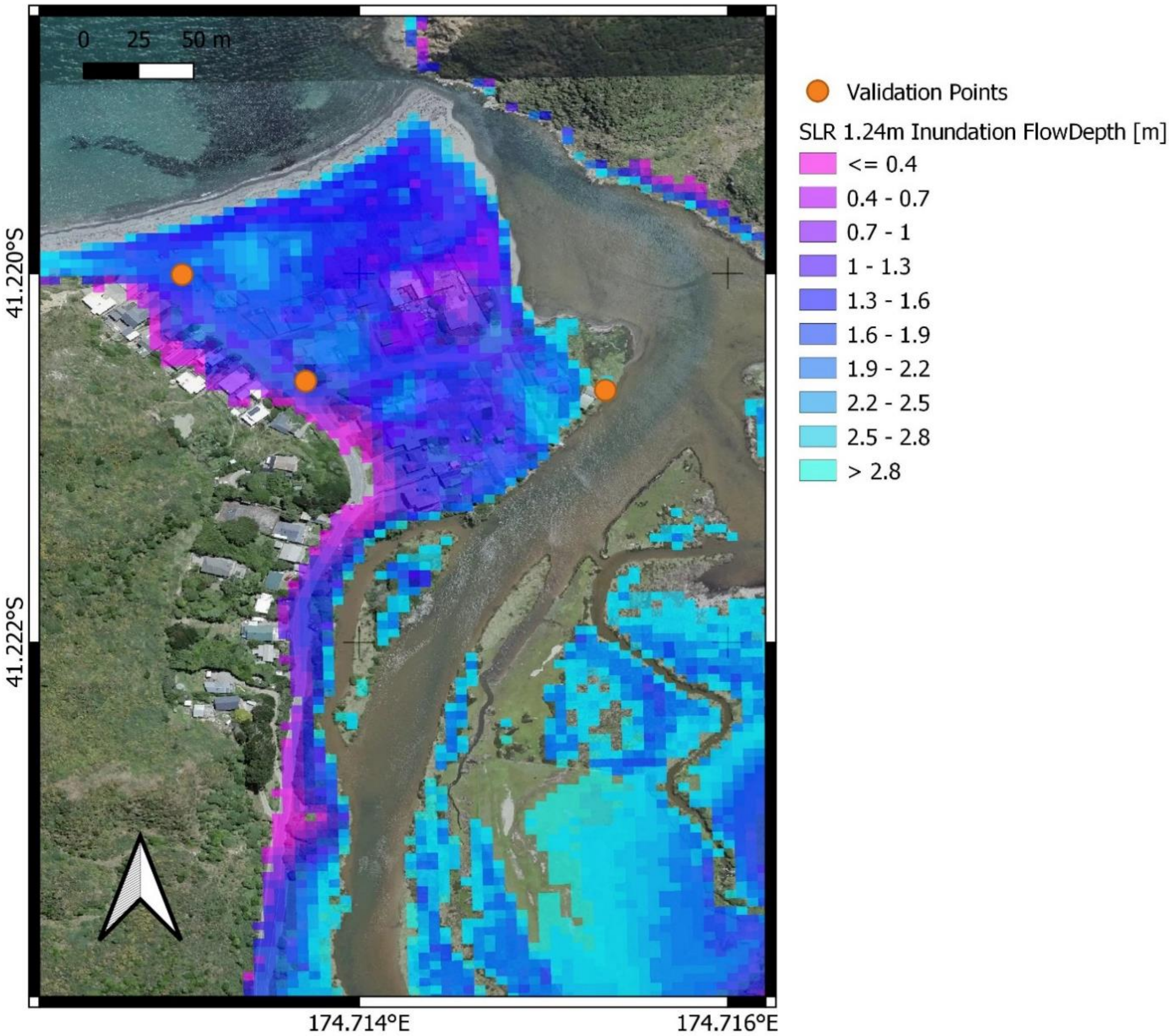

Figure 6-48: Storm inundation extents presented in Table 6-2 for the Wellington south coast, RSLR = 1.24 + 10% storm increase.

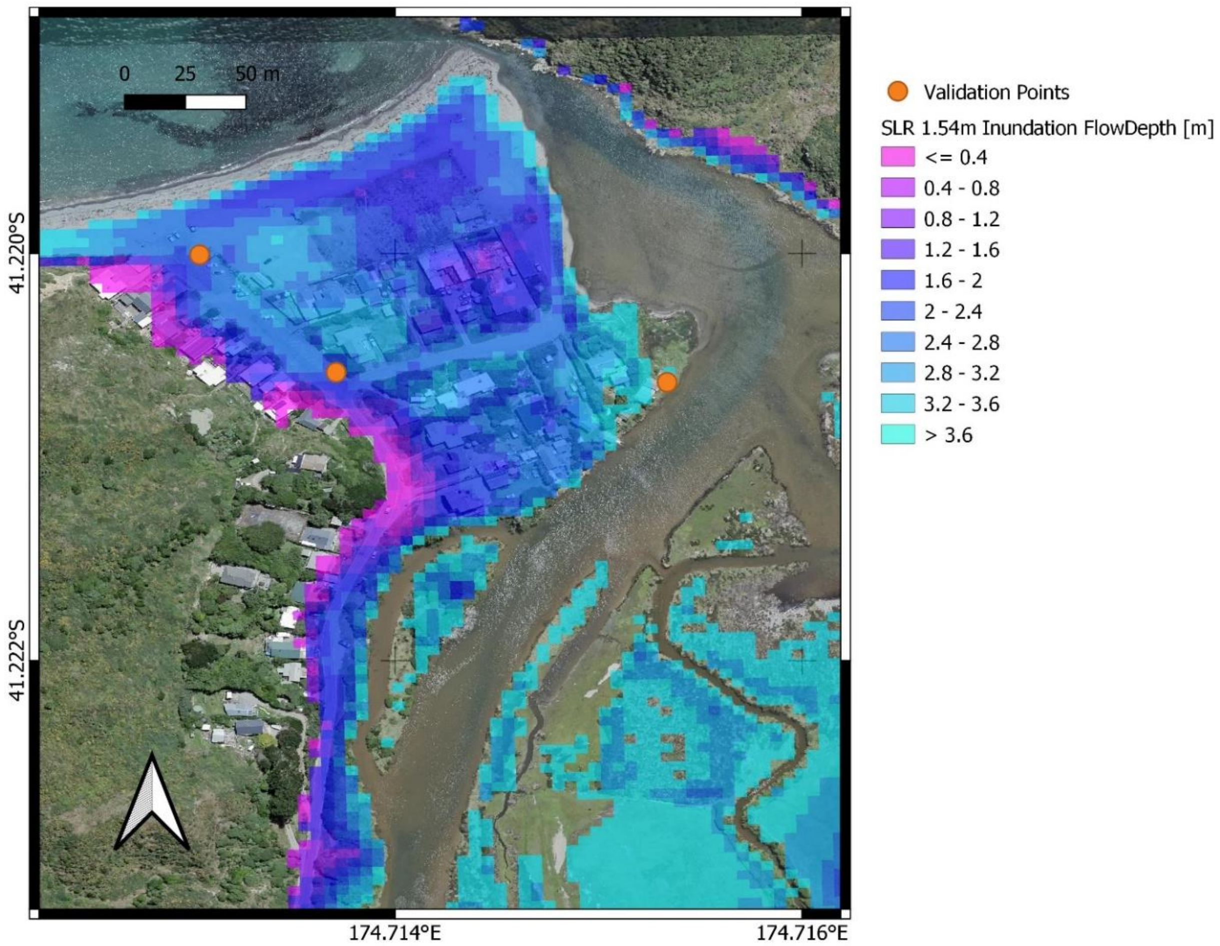

Figure 6-49: All storm inundation extents presented in Table 6-2 for the Wellington south coast, RSLR = 1.54 + 10% storm increase.

7 Summary and recommendations

This study has evaluated coastal hazards (excluding tsunami) around the Wellington City district shorelines, including the effects of climate change, to inform and support the current revision cycle of the District Plan.

This scope of this study included assessment of sea-level rise projections for the 100-year timeframe (2120), assessment of coastal erosion hazards and assessment of coastal inundation hazards at the end of this timeframe.

Maps and data from the coastal hazard assessments have been provided directly WCC as digital files.

7.1 Next steps

The hazard information in this investigation could be used to provide information that enables Wellington City Council and residents to manage and adapt to SLR. Refining the model work to include smaller increments of sea-level rise (such as increments of 0.2 m) would show the emergence of coastal hazards, and allow incremental stress-testing and advance warning of when a hazard may become intolerable, and thus when adaptive decisions are needed. This would also eliminate the need to re-work the model results each time SLR projections are updated e.g. the latest IPCC AR6 report (released August 2021) projects SLR in 2100-2120 may be 0.04 to 0.09 m *higher* than the MfE (2017) projections.

Adaptive decisions could include steps such as pumped stormwater networks for inland low-lying areas, upgrade of coastal defences, enabling managing retreat from less-densely populated and at risk coastal areas. Further work is needed to capture the relative cost and risk of various adaptation option and engagement of the affected communities.

7.2 Recommendations

We recommend WCC further collate information about all known WCC and private coastal defences assets in the district. This information would enable WCC to create a vulnerability index where developments are protected by private assets but have an unknown level of protection. This would, for example, highlight potential vulnerability due to unknown age/condition/design of the seawall/revetment, the characteristics of the property itself, and complexity of rebuilding/maintaining.

We also recommend WCC collect and maintain records of coastal flood inundation and overtopping around the district. This should include photographs and GPS surveys of debris lines and runup extents, damaged property etc. This additional information serves as an excellent resource for any future coastal hazard mapping studies.

8 Glossary of abbreviations and terms

AEP	Annual Exceedance Probability. The probability of a given (usually high) sea level or wave height being equalled or exceeded in elevation in any given calendar year. AEP can be specified as a fraction (e.g., 0.01) or a percentage (e.g., 1%).
ARI	Average Recurrence Interval. The average time interval (averaged over a very long time period and many “events”) that is expected to elapse between recurrences of an infrequent event of a given large magnitude (or larger). A large infrequent event would be expected to be equalled or exceeded in elevation, once, on average, every “ARI” years, but with considerable variability.
Joint-Probability	The probability of two separate processes occurring together (e.g., large waves and high storm-tide).
LiDAR	Light Detection And Ranging – an airborne laser scanning system that determines ground levels at a very high density (often as little as 1 m spacing between measurements) along a swathe of land underneath the track of the airplane. Most systems used in New Zealand collect data only on land above water levels, but systems are available that can also determine shallow water bathymetry levels in clear water. Vertical accuracy is typically better than ±0.15 m.
MHWS	Mean high water springs – The high tide height associated with higher than normal high tides that result from the superposition of various tidal harmonic constituents. Mean high water springs occur every 2 weeks approximately. MHWS can be defined in various ways, and the MHWS elevation varies according to definition.
MHWS10	The mean high-water spring elevation defined by exceedance curves where the elevation is exceeded by 10 percent of high tides. MHWS10 it is often used as a practical high tide level for infrastructure design works, and also for the base elevation for estimating extreme high storm tides (e.g. the 100-year Average Recurrence Interval),
MSL	Mean Sea Level. The mean non-tidal component of sea level, averaged over a defined time period, usually several years. New Zealand’s local vertical datums were obtained in this way, with AVD-46 being the MSL from sea-level measurements made between 1909 and 1923. Mean sea level changes with the averaging period used, due to climate variability and long-term sea-level rise.
Significant wave height	The average height of the highest one-third of waves in the wave record; experiments have shown that the value of this wave height is close to the value of visually estimated wave height.

Storm surge	The rise in sea level due to storm meteorological effects. Low-atmospheric pressure relaxes the pressure on the ocean surface causing the sea-level to rise, and wind stress on the ocean surface pushes water down-wind (onshore winds) and to the left up against any adjacent coast (alongshore winds). Storm surge has timescales of sea-level response that coincide with typical synoptic weather motions; typically 1–3 days.
Storm-tide	Storm-tide is defined as the sea-level peak around high tide reached during a storm event, resulting from a combination of sea-level + tide + storm surge.
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 Bathymetry data

AdditionalThe Wellington South Coast and Mākara Beach areas required additional high-resolution bathymetry was required to infill gaps between NIWA's multibeam (MBES) dataset and terrestrial LiDAR (e.g. Figure A-1) along the Wellington South Coast and Mākara Beach areas. We). Although NIWA are experienced hydrographic surveyors and would prefer to use multibeam soundings to underpin numerical wave models (as for the rest of the Project area), however the gaps in MBES data remaining gaps weare very small nearshore rocky areas. These areas that could not be safely surveyed from a vessel except in , and any attempts surveying would require a costly wait for near-perfect conditions, and gaps may remain. Common approaches to infill gaps are interpolation and smoothing, however, smoothing and interpolation were inadequate for this project given the critical role this nearshore area plays in wave transformation and runup processes.weather.

We subcontracted a satellite derived bathymetry (SDB) product from commercial provider EOMAP[20] to fill the gaps. SDB is a method of surveying shallow waters which requires no mobilisation of persons or surveying equipment. SDB algorithms follow physics-based, quantitative solutions to convert the information collected by the satellite sensors (e.g. cameras: infrared and visual spectrum) into bathymetric data.

We provided terrestrial LiDAR (GWRC/LINZ) and offshore MBES data (NIWA) for EOMAP to merge with SDB and create a seamless high resolution bathymetry dataset.

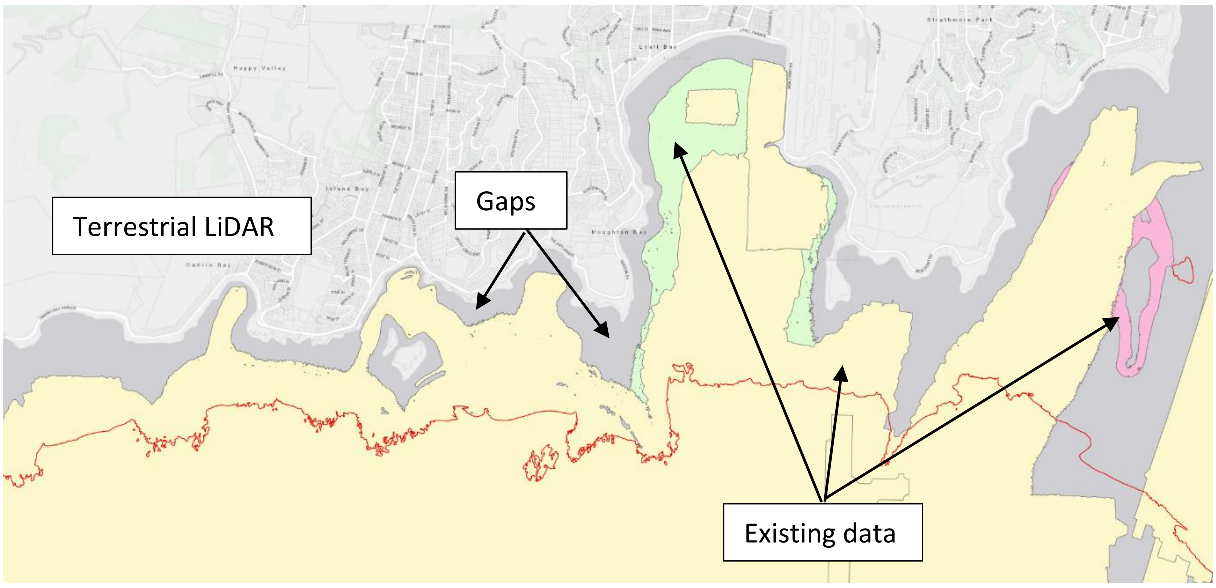

Figure A-1: Existing bathymetric data and gaps between bathymetry and LiDAR along Wellington South Coast. Red line = 20m contour, yellow/green/pink shading = existing multibeam soundings from previous survey voyages, light grey shading = approximate LiDAR extents on land, dark grey shading = gap.

The resulting SDB outputs (Figure A-2 and Figure A-3 below) were incorporated into the model grid for the South Coast.

[20] https://www.eomap.com/services/bathymetry/

Figure A-2: Satellite derived bathymetry for Wellington south coast as commissioned for this project. [*source*: EOMAP, Google Earth].

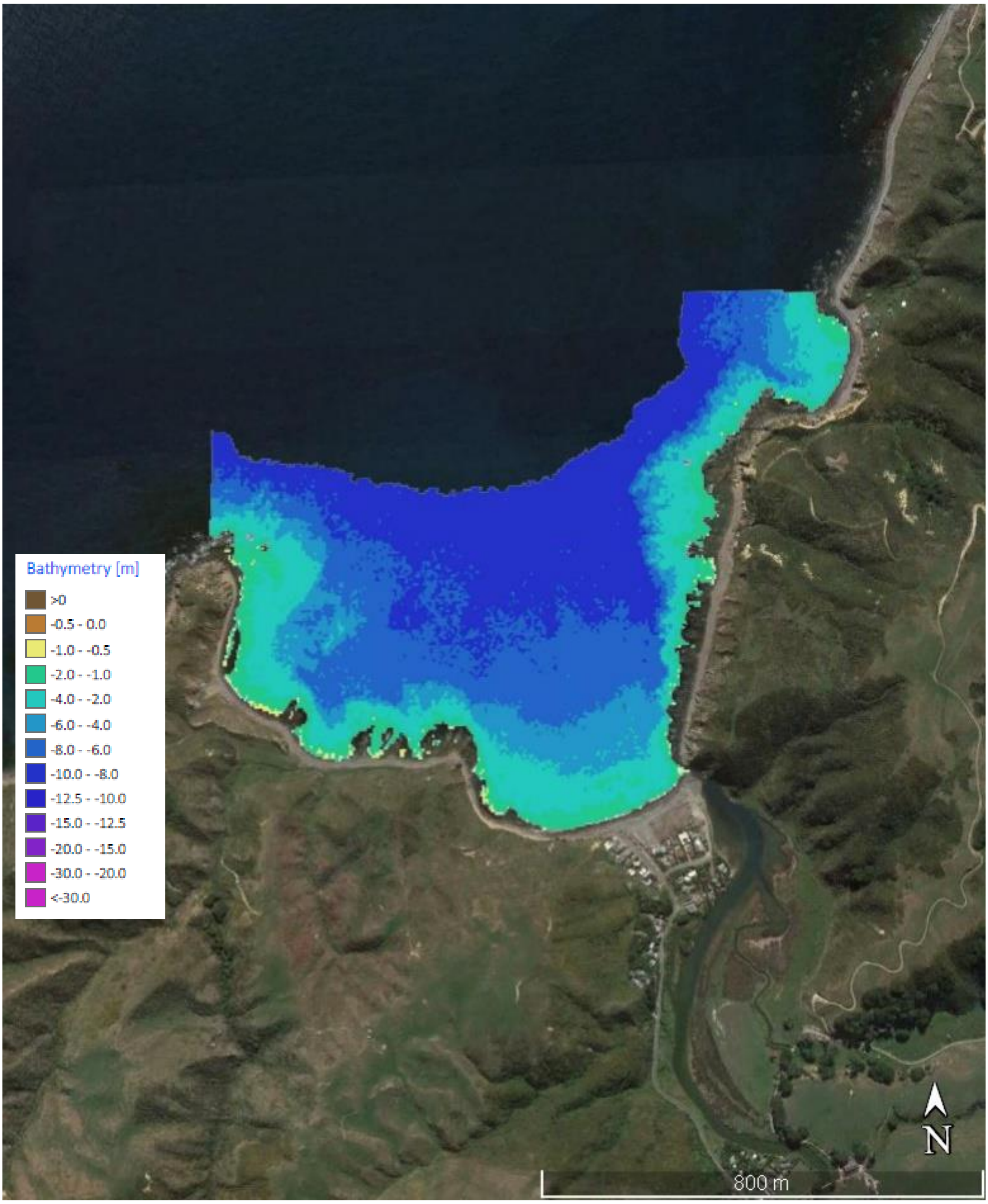

Figure A-3: Satellite derived bathymetry for Mākara as commissioned for this project. [*source*: EOMAP, Google Earth].

Appendix B GIS methodology: Low-lying near-coast zone

A description the GIS methodology to develop the low-lying near-coast zone.

GWRC Regional MHWS10 line was downloaded https://data-gwrc.opendata.arcgis.com. This dataset has an attribute 'contour' having MHWS10 levels. Random points were created in the analysis area. These points were spatially joined to the nearest GWRC MHWS10 line section to transfer the MHWS10 values (Figure B-1).

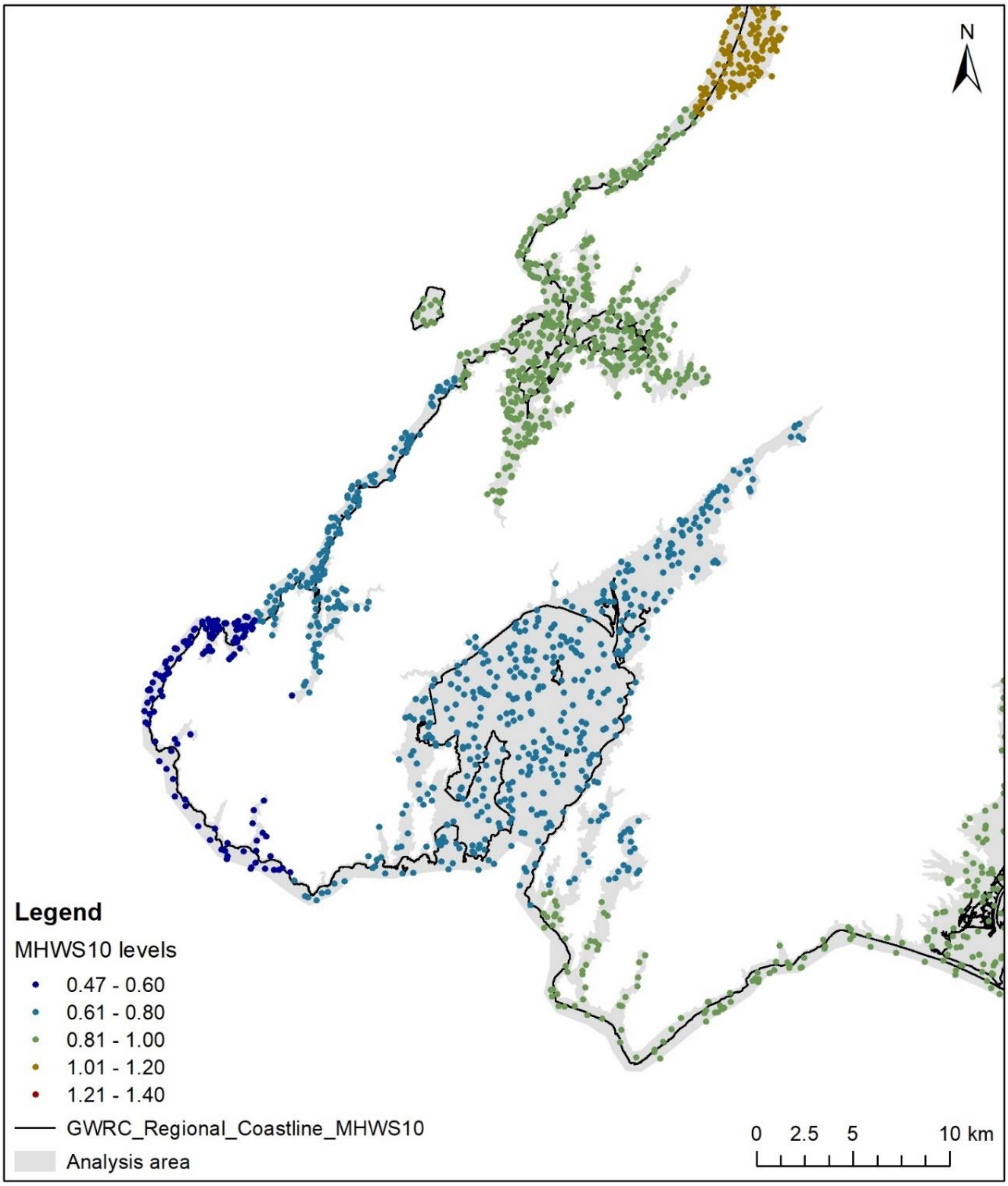

Figure B-1: Step 1 - GIS methodology: Low-lying near-coast zone.

The points were then interpolated to create a MHWS10 grid surface (Figure B-2).

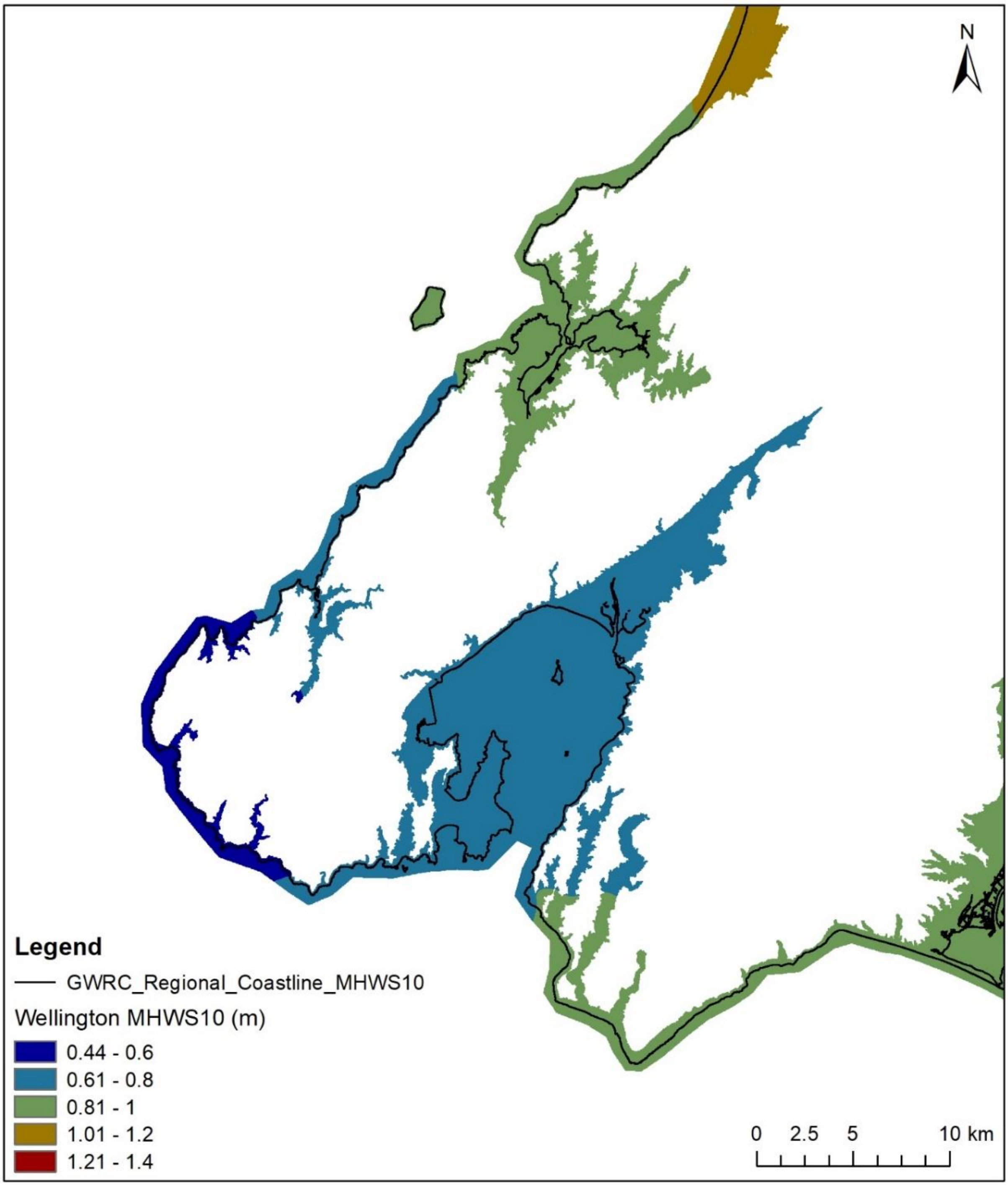

Figure B-2: Step 2 - GIS methodology: Low-lying near-coast zone.

The vertical coordinate system was changed for Wellington 1m LiDAR DEM from NZVD2016 to WVD-53 using the offset grids. LiDAR DEM and the conversion grids were downloaded from data.linz.govt.nz.

A grid overlay was carried out using the equation MHWS10 Reduced grid = LiDAR DEM – MHWS10 grid.

The reduced grid was reclassified into cell values above 3.04m and below 3.04m. Area below 3.04m was extracted and converted to a vertical buffer polygon layer (Figure B-3).

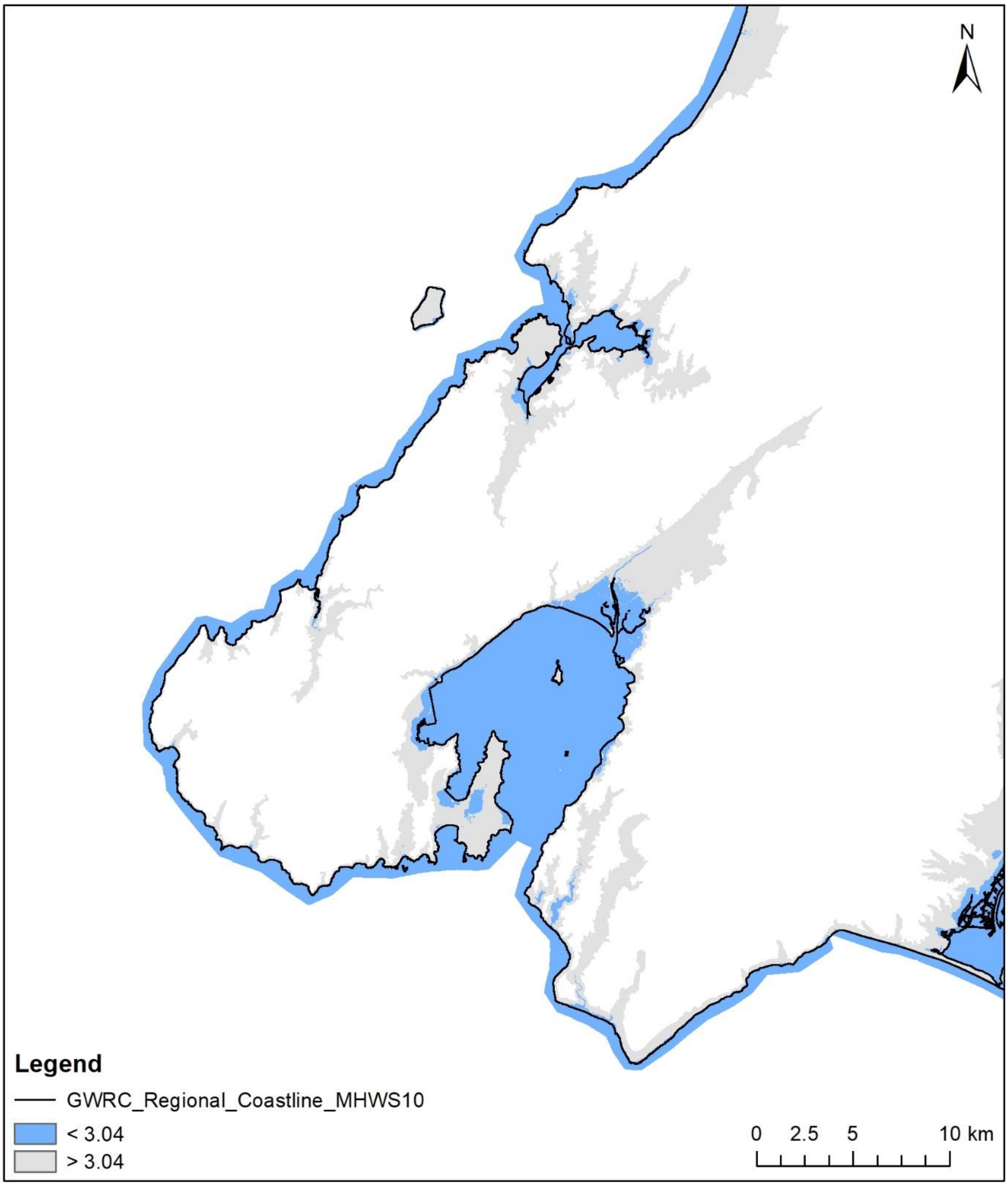

Figure B-3: Step 3 - GIS methodology: Low-lying near-coast zone.

A 30 m horizontal buffer polygon was created from the GWRC Regional Coastline MHWS10 (Figure B-4).

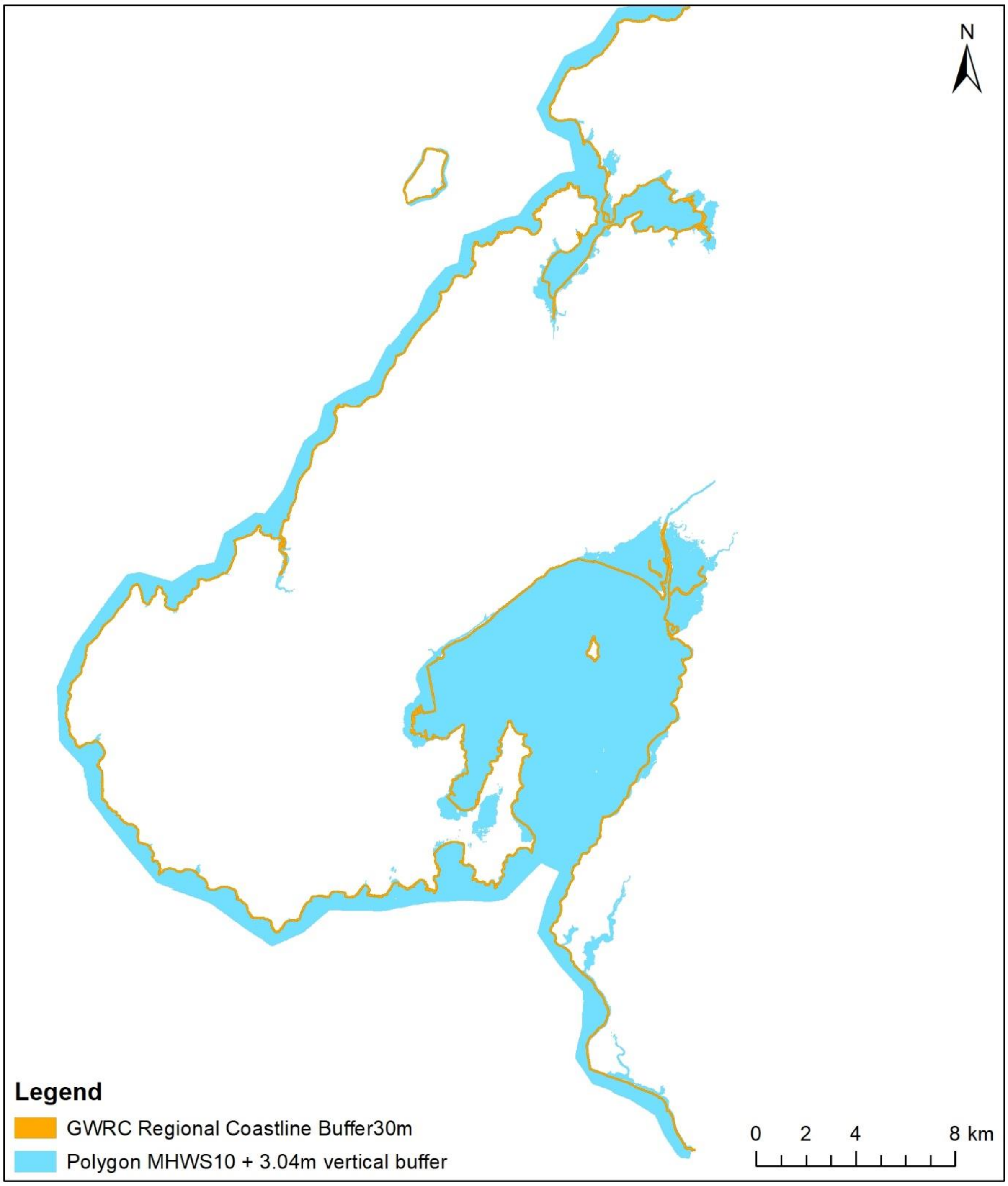

Figure B-4: Step 4 - GIS methodology: Low-lying near-coast zone.

An overlay operation was carried out with the horizontal buffer of 30m and the vertical buffer (3.04m) to work out common (overlapping) areas (Figure B-5).

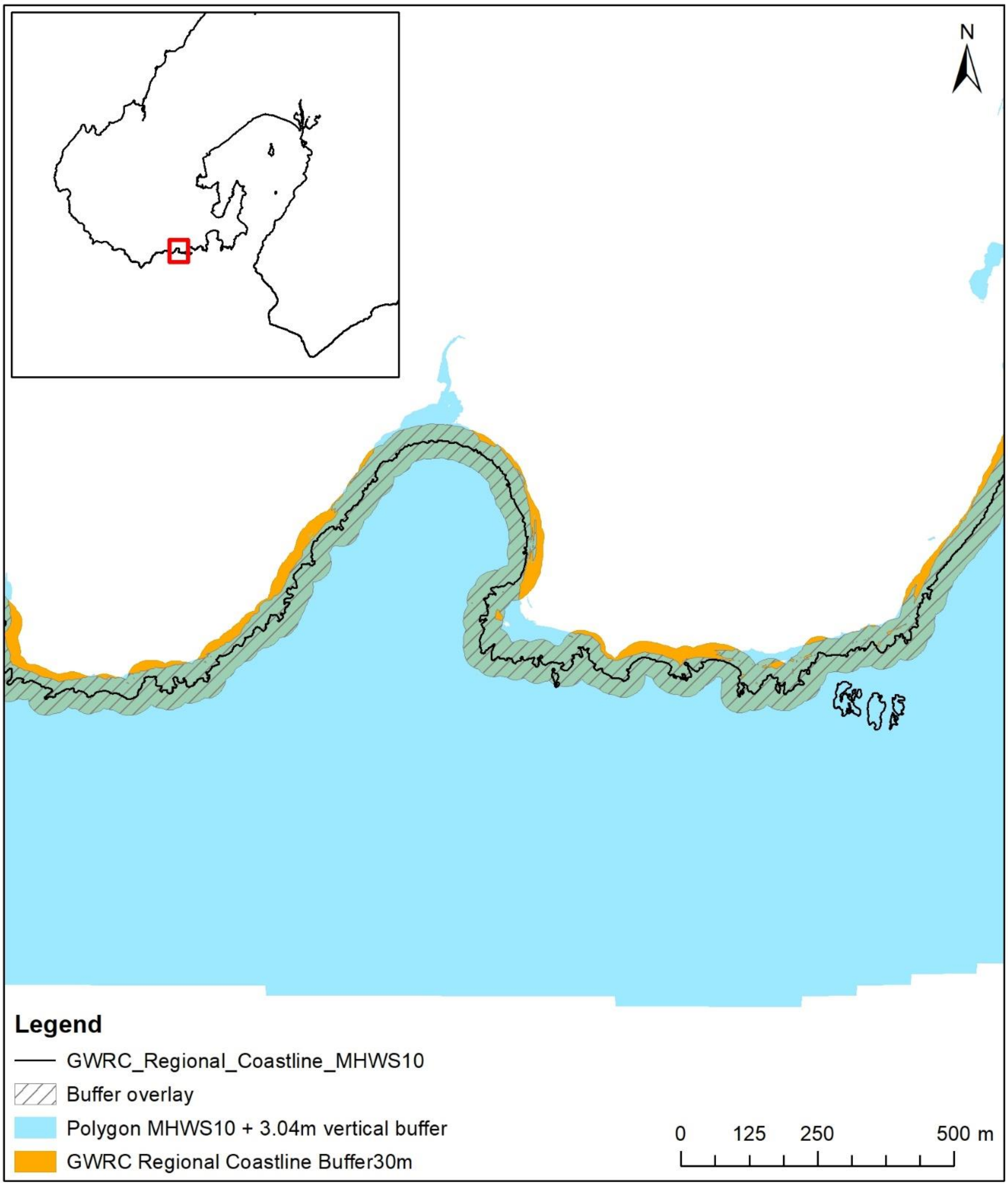

Figure B-5: GIS methodology: summary of process.

Appendix C GIS methodology: Static inundation (Harbour shorelines)

Description of GIS processing methodology for static inundation of storm-tide plus wave setup for Harbour shorelines only, including culvert connection.

Points at the extreme value analysis output coordinates (Figure C-1) were plotted having levels data for ARI100 year Present Day, RCP8.5 Median and RCP8.5H+ in attribute columns.

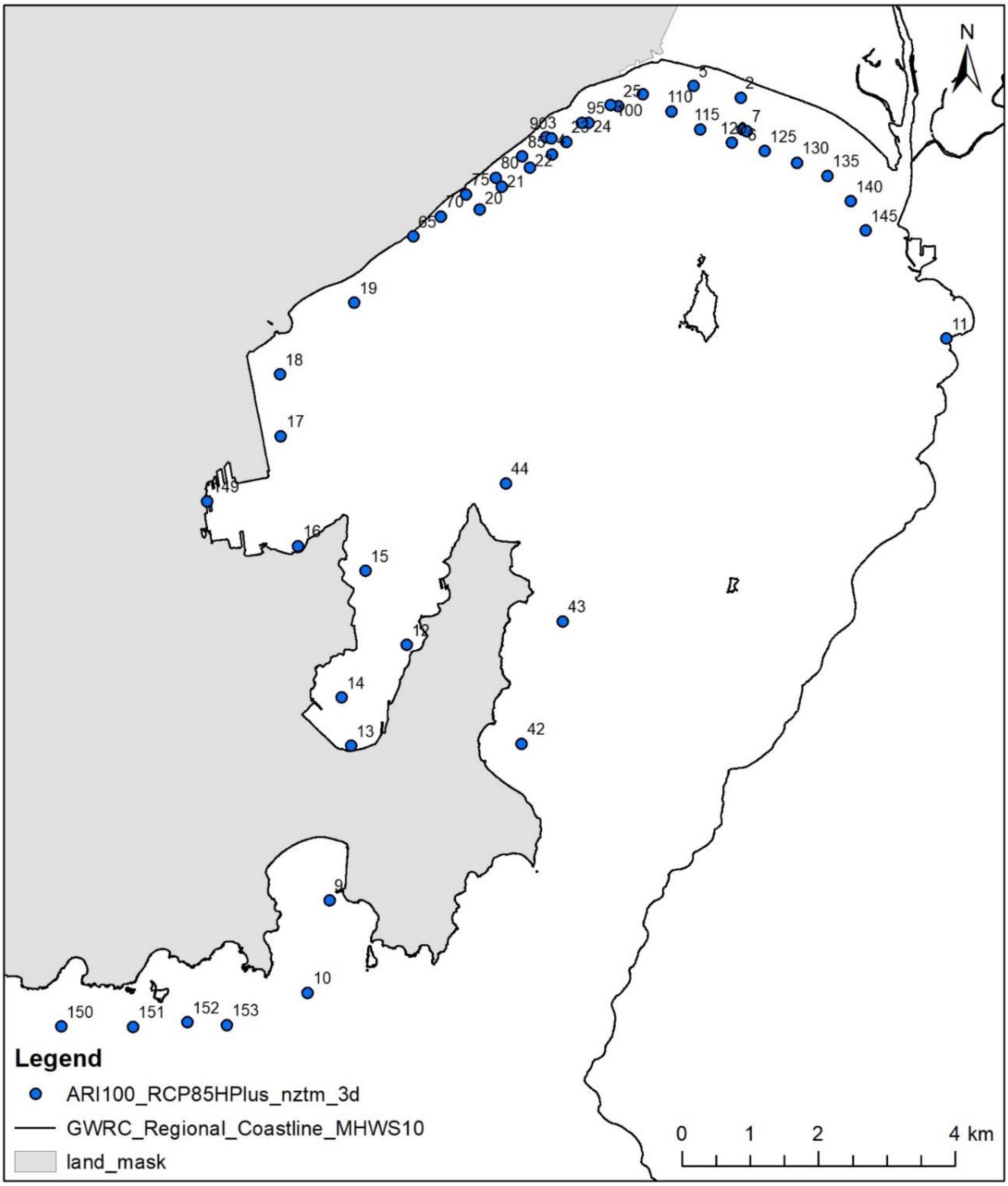

Figure C-1: Step 1 - GIS methodology: static inundation (Harbour shorelines).

The points were interpolated into separate grids for each of the sea-level scenarios. The grids were then overlayed with LiDAR DEM to establish inundation polygons.

The polygons were overlayed with WCC stormwater pipes and channels to determine connectivity to coastal inundation polygons (Figure C-2).

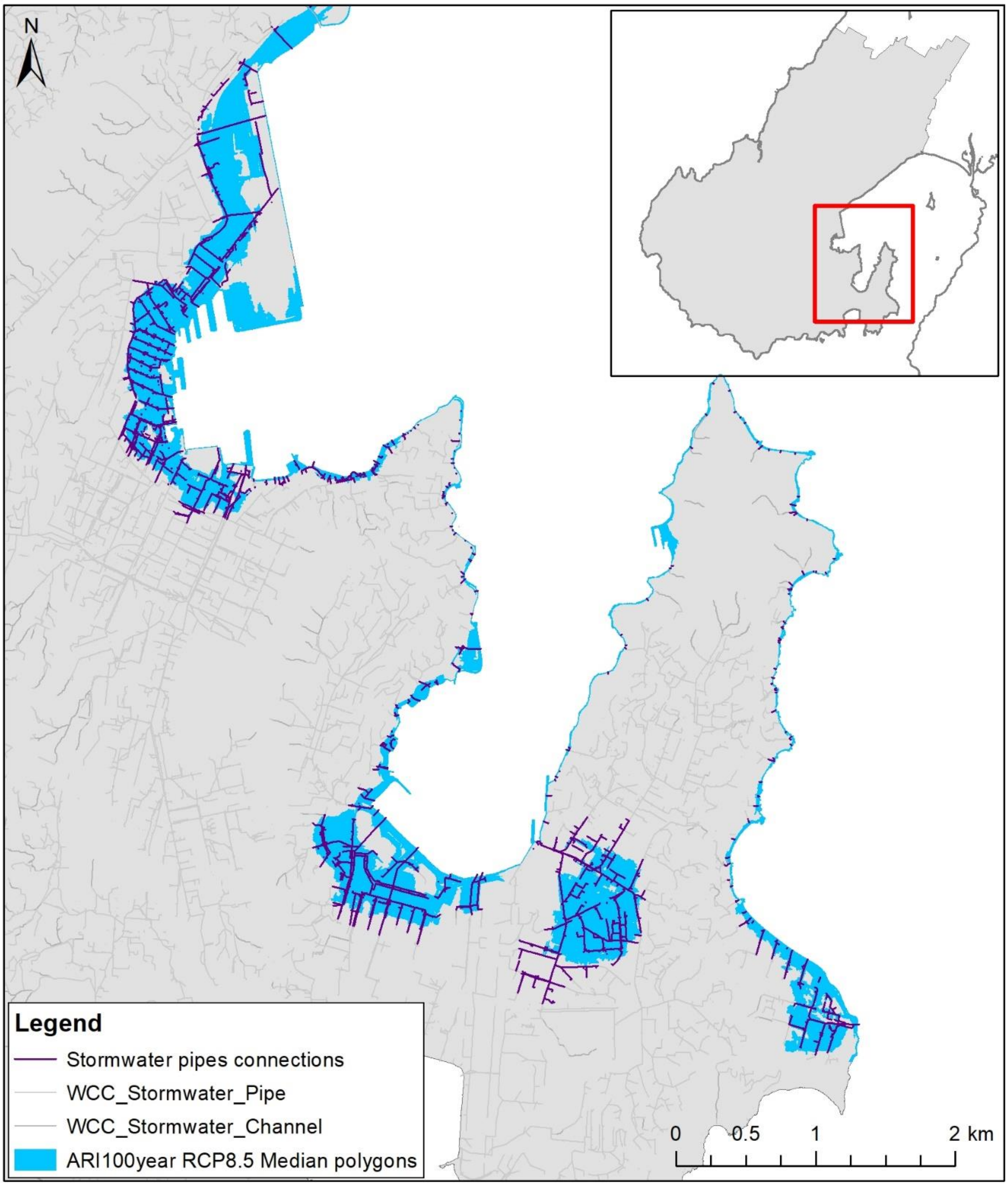

Figure C-2: Step 1 - GIS methodology: static inundation (Harbour shorelines).

Appendix D Extreme value analysis (Harbour shorelines)

Table D-1: Extreme value analysis output coordinates. .

Site	Site No	Latitude	Longitude
Rocky Point	3	174.8373	-41.2355
Lyall Bay inner	9	174.8023	-41.3366
Lyall Bay outer	10	174.7989	-41.3489
Lowry Bay	11	174.9078	-41.2609
Shark Bay	12	174.8149	-41.3028
Mirimar Wharf	13	174.8056	-41.3162
Evans Bay	14	174.8037	-41.3099
Balaena Bay	15	174.8074	-41.2931
Oriental Bay	16	174.7955	-41.2901
Aotea Quay	17	174.7922	-41.2756
Ferry Terminal	18	174.7918	-41.2675
Kaiwharawhara	19	174.8045	-41.2579
Horokiwi	25	174.8498	-41.2312
Seatoun	42	174.8353	-41.3154
Scortching Bay	43	174.842	-41.2992
Point Halswell	44	174.8316	-41.2812
Ngauranga Gorge	65	174.8145	-41.249
Queens Wharf	149	174.7795	-41.2844
Ōwhiro Bay	150	174.756	-41.3539
The Sirens Rocks	151	174.7685	-41.3538
Island Bay	152	174.778	-41.3531
Houghton Bay	153	174.7849	-41.3533

Table D-2: Return values for storm-tide level plus wave setup (m above WVD-53) at 2120 with 1.43 m RSLR and including +10% storm increases for Wellington City sites.

	ARI	1	2	5	10	20	50	100
Site No	AEP	63	39	18	10	5	2	1
3	Rocky Point	1.15	1.19	1.23	1.26	1.28	1.31	1.33
9	Lyall Bay inner	1.15	1.19	1.23	1.26	1.28	1.31	1.32
10	Lyall Bay outer	1.15	1.19	1.23	1.26	1.28	1.31	1.33
11	Lowry Bay	1.15	1.19	1.23	1.26	1.28	1.31	1.33
12	Shark Bay	1.15	1.19	1.23	1.26	1.28	1.31	1.33
13	Mirimar Wharf	1.15	1.19	1.23	1.26	1.28	1.31	1.33
14	Evans Bay	1.15	1.19	1.23	1.26	1.28	1.31	1.33
15	Balaena Bay	1.15	1.19	1.23	1.26	1.28	1.31	1.33
16	Oriental Bay	1.15	1.19	1.23	1.26	1.28	1.31	1.33
17	Aotea Quay	1.15	1.19	1.23	1.26	1.28	1.31	1.33
18	Ferry Terminal	1.15	1.19	1.23	1.25	1.28	1.31	1.33
19	Kaiwharawhara	1.15	1.19	1.23	1.26	1.28	1.31	1.33
25	Horokiwi	1.15	1.19	1.23	1.26	1.28	1.31	1.33
42	Seatoun	1.15	1.19	1.23	1.26	1.28	1.31	1.33
43	Scortching Bay	1.15	1.19	1.23	1.26	1.28	1.31	1.33
44	Point Halswell	1.15	1.19	1.23	1.26	1.28	1.31	1.33
65	Ngauranga Gorge	1.15	1.19	1.23	1.26	1.28	1.31	1.34
149	Queens Wharf	1.15	1.19	1.23	1.26	1.28	1.32	1.33
150	Ōwhiro Bay	1.15	1.19	1.23	1.26	1.28	1.31	1.33
151	The Sirens Rocks	1.15	1.19	1.23	1.26	1.28	1.31	1.33
152	Island Bay	1.15	1.19	1.23	1.26	1.28	1.31	1.33
153	Houghton Bay	1.15	1.19	1.23	1.26	1.28	1.31	1.34

Table D-3: Return values for storm-tide level plus wave setup (m above WVD-53) at 2120 with 1.43 m RSLR and including +10% storm increases for Wellington City sites.

	ARI	1	2	5	10	20	50	100
Site No	AEP	63	39	18	10	5	2	1
3	Rocky Point	2.67	2.72	2.77	2.80	2.83	2.88	2.91
9	Lyall Bay inner	2.99	3.08	3.21	3.28	3.34	3.42	3.47
10	Lyall Bay outer	3.22	3.37	3.53	3.63	3.73	3.86	3.93
11	Lowry Bay	2.70	2.75	2.80	2.84	2.87	2.92	2.95
12	Shark Bay	2.66	2.70	2.74	2.77	2.80	2.84	2.86
13	Mirimar Wharf	2.65	2.70	2.74	2.77	2.80	2.84	2.86
14	Evans Bay	2.66	2.70	2.75	2.78	2.81	2.84	2.86
15	Balaena Bay	2.65	2.69	2.74	2.77	2.79	2.84	2.85
16	Oriental Bay	2.65	2.69	2.74	2.77	2.80	2.83	2.85
17	Aotea Quay	2.65	2.69	2.73	2.76	2.79	2.82	2.85
18	Ferry Terminal	2.65	2.69	2.73	2.76	2.79	2.84	2.85
19	Kaiwharawhara	2.65	2.69	2.73	2.76	2.80	2.82	2.86
25	Horokiwi	2.68	2.72	2.77	2.80	2.84	2.89	2.91
42	Seatoun	2.80	2.85	2.92	2.97	3.02	3.08	3.11
43	Scortching Bay	2.76	2.81	2.87	2.91	2.96	3.02	3.05
44	Point Halswell	2.68	2.72	2.77	2.80	2.83	2.88	2.91
65	Ngauranga Gorge	2.64	2.69	2.73	2.76	2.79	2.82	2.86
149	Queens Wharf	2.64	2.69	2.73	2.76	2.79	2.82	2.84
150	Ōwhiro Bay	3.29	3.44	3.61	3.71	3.81	3.94	4.02
151	The Sirens Rocks	3.29	3.43	3.60	3.71	3.81	3.92	4.05
152	Island Bay	3.28	3.42	3.58	3.69	3.77	3.89	4.00
153	Houghton Bay	3.31	3.46	3.64	3.75	3.85	3.98	4.07

Table D-4: Return values for storm-tide level plus wave setup (m above WVD-53) at 2120 with 1.73 m RSLR and including +10% storm increases for Wellington City sites.

	ARI	1	2	5	10	20	50	100
Site No	AEP	63	39	18	10	5	2	1
3	Rocky Point	2.98	3.02	3.07	3.10	3.14	3.18	3.20
9	Lyall Bay inner	3.30	3.39	3.52	3.59	3.66	3.74	3.78
10	Lyall Bay outer	3.53	3.66	3.83	3.93	4.02	4.16	4.23
11	Lowry Bay	3.01	3.05	3.10	3.14	3.17	3.22	3.26
12	Shark Bay	2.96	3.00	3.04	3.07	3.10	3.14	3.16
13	Mirimar Wharf	2.96	3.00	3.04	3.07	3.10	3.14	3.16
14	Evans Bay	2.96	3.01	3.05	3.08	3.11	3.14	3.16
15	Balaena Bay	2.95	3.00	3.04	3.07	3.10	3.14	3.16
16	Oriental Bay	2.95	2.99	3.04	3.07	3.10	3.13	3.16
17	Aotea Quay	2.95	2.99	3.03	3.06	3.09	3.13	3.15
18	Ferry Terminal	2.95	2.99	3.03	3.06	3.09	3.13	3.16
19	Kaiwharawhara	2.95	2.99	3.03	3.06	3.09	3.12	3.16
25	Horokiwi	2.98	3.02	3.08	3.11	3.14	3.19	3.21
42	Seatoun	3.11	3.16	3.22	3.27	3.33	3.39	3.41
43	Scortching Bay	3.07	3.11	3.17	3.22	3.26	3.32	3.36
44	Point Halswell	2.98	3.03	3.07	3.10	3.14	3.18	3.21
65	Ngauranga Gorge	2.94	2.99	3.03	3.06	3.09	3.12	3.16
149	Queens Wharf	2.94	2.99	3.03	3.05	3.09	3.12	3.14
150	Ōwhiro Bay	3.60	3.74	3.91	4.01	4.13	4.22	4.33
151	The Sirens Rocks	3.59	3.73	3.90	4.01	4.10	4.25	4.35
152	Island Bay	3.58	3.72	3.88	3.98	4.08	4.20	4.27
153	Houghton Bay	3.60	3.76	3.93	4.05	4.13	4.29	4.37