NIWA
Taihoro Nukurangi

Coastal inundation from sea-level rise in the Auckland Region

Prepared for Auckland Council

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Contents

Tables

Figures

Executive summary

Auckland Council commissioned NIWA to identify changes in the extent of coastal inundation from sea-level rise. For the purposes of this study, coastal inundation is defined as land that is or would become intertidal because of sea-level rise, assuming no change in ground level i.e., no accretion, erosion, or landslides. In the absence of adaptation it would be regularly inundated by spring tides in the future.

This is different from coastal flooding, which may cause extensive but only temporary flooding, and is addressed elsewhere (Auckland Council 2020). This study addresses coastal inundation mapping for the entire Auckland region based on mean high water spring tide (MHWS) levels relative to present-day mean sea level, plus increments of relative sea-level rise (RSLR). It does not consider the effects of storm surge or wave processes on total water levels including wave set-up and run-up nor catchment-based flooding and groundwater. The line of MHWS legally defines the land-sea boundary, so mapping of the land area exposed to inundation by MHWS + RSLR effectively shows land that could become "sea" in the future.

The MHWS elevation was defined as MHWS-10, which is the level equalled or exceeded by the largest 10% of all high tides. MHWS-10 was adopted by NIWA on the basis that it provides a nationally consistent estimate of MHWS that is unaffected by regional changes in individual tidal harmonic constituents. MHWS-10 has also been shown to provide a good match to the physical coastline boundary in the Auckland region (Stephens & Wadhwa, 2012). The MHWS-10 tide levels were calculated at intervals along the region's coastline using available tide-gauge records and numerical hydrodynamic models.

Mean sea level (MSL) estimates were updated for the 2001–2019 period for the Auckland Region, relative to Auckland Vertical Datum 1946 (AVD-46). MHWS-10 heights (relative to mean sea level) were added to the updated MSL to estimate present-day MHWS levels. Fixed increments of sea-level rise in 0.5 m increments (0.5, 1.0, 1.5, 2.0, 2.5, 3.0 m) were subsequently added to provide inundation water levels (WL) relative to AVD-46. This can be represented as WL = 2001–2019 MSL + MHWS-10 + future RSLR.

An Innovative methodology was developed within GIS to map the inundation water levels to the land area to ensure the levels were applied to a land parcel from where it is connected to the coast. Areas of future inundation were identified by intersection of the inundation water levels with the 2016–2018 LiDAR generated digital elevation model (DEM) of the coast.

Areas of future inundation were identified using a static mapping method. In this method, all land below the inundation water levels and with a physical connection to the sea is shown as flooded in its entirety. This a reasonable assumption for modelling permanent inundation caused by mean sea level change and regular tides, due to the regular nature of such inundation plus occasional additional flooding from higher tides and storm-tides and compound flooding from tidal locking of fluvial/pluvial discharge.

The identified inundation areas were checked for connectivity to the sea using the Auckland Council's stormwater linear features like channel, pipe, connection and overland flow paths.

NIWA has provided Auckland Council with maps of the region's exposure to coastal inundation. The maps were provided as GIS polygon extents of the areas of inundation and raster files of the depth of inundation.

1 Introduction

1.1 Background

Auckland has a long coastline that includes three major harbours along with the largest population density to coastline ratio in New Zealand. Auckland is exposed to coastal hazards including coastal inundation. The risk from inundation is increasing over time due to the effects of climate change induced sea level rise. Auckland Council is tasked with managing Coastal Hazards under a range of legislation including the Resource Management Act 1991 and associated NZ Coastal Policy Statement (e.g., Policies 24–27), the Local Government Act, Building Act, and the Civil Defence Emergency Management Act 2002.

Sea-level rise of 0.61–1.69 m relative to the 1995–2020 baseline mean sea level, is forecast to occur by the year 2130. These sea-level rise estimates were recently revised using IPCC AR6 projections and are based on site 1232 of NZ SeaRise, which is located at the Port of Auckland. The lower 0.61 m sea-level rise estimate is based on the medium confidence SSP1-2.6 50th percentile scenario, while the upper 1.69 m sea-level rise estimate is based on the medium confidence SSP5-8.5 83rd percentile scenario, as recommended in MfE guidance. In addition, vertical land movement (VLM) shows land generally to be sinking in the Auckland region (NZ SeaRise), which will further increase relative sea-level rise.

Auckland Council have previously commissioned various studies in understanding extreme high coastal water values across the region (Auckland Council, 2020). Extreme high coastal waters arise from the combination of very high tides and storm surges. These prior studies have helped in providing a better understanding of the potential extent of coastal flooding and the risk extreme events pose to Auckland and have been used to define the coastal storm inundation area in the Auckland Unitary Plan and create guidance for determining management provisions such as for minimum floor building levels, within zones of potential coastal inundation. Auckland Council's investment into a region wide LiDAR dataset and its continual updates have helped in the mapping of areas exposed to sea level rise.

This current study identifies areas at risk of permanent inundation from sea-level rise. The mapping of future coastal inundation during regular non-extreme sea conditions has not until now been undertaken for the whole of the Auckland Region. This study addresses coastal inundation mapping for the entire Auckland region using Mean High Water Spring (MHWS) levels, plus increments of sea-level rise. This study excludes storm surges, wave setup, wave runup and wave overtopping. The line of MHWS legally defines the land-sea boundary, so mapping of land area exposed to inundation by MHWS + sea-level rise effectively shows land that could become permanently inundated in the future (without intervention). It is envisaged this dataset would contribute to Auckland Council's public engagement on coastal hazards and climate change, and adaptive management planning, including through the Shoreline Adaptation Plan (SAP), asset management work programmes.

1.2 Scope of the project

Auckland Council commissioned NIWA to prepare maps of permanent coastal inundation, by identifying land that would be regularly inundated by the sea, both now and in the future after increments of 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 m relative sea-level rise above the 2001–2019 baseline mean sea level (Table 1-1).

The latest 2016–2018 LiDAR Digital Elevation Model (DEM) for the Auckland region was to be used for the mapping.

As this study is focused on the impacts of permanent changes to sea levels, rather than episodic extreme sea levels, static inundation mapping of the regularly attained MHWS level provides a sufficient overview of changes to the future inundation extent across the region, as opposed to more complex interactions between tides, storm surge and river flows.

GIS polygon extents of the areas of inundation were generated from the coastal inundation levels. Depth of inundation grids were generated at a 2×2 m grid size resolution and exported as GeoTIFF files.

The project did not include an update of the statutory coastal marine area boundary line as undertaken by Stephens and Wadhwa (2012).

Table 1-1: List of mapped scenarios.

Scenario Name	Sea-level rise (SLR) increments (m)
Mean High Water Springs (MHWS)	0
MHWS + SLR 0.5 m	0.5
MHWS + SLR 1 m	1
MHWS + SLR 1.5 m	1.5
MHWS + SLR 2 m	2
MHWS + SLR 2.5 m	2.5
MHWS + SLR 3 m	3

2 Methods

2.1 Calculation of sea level

To calculate present-day inundation water levels (WL) we first determined an offset for average 2001–2019 mean sea level (MSL) relative to the local vertical datum—Auckland Vertical Datum 1946 (AVD-46). We then calculated MHWS-10 elevations relative to MSL at locations around the coastline. We then added MHWS-10 to MSL. We subsequently added relative sea-level rise (RSLR) offsets of 0.5, 1, 1.5, 2, 2.5 and 3 m. This is shown by Equation 2-1 and depicted visually in Figure 1.

Equation 2-1: Equation used to calculate water level elevations for mapping. WL = (total) water level, MSL = 2001–2019 mean sea level relative to AVD-46, MHWS = mean high-water springs 10% amplitude relative to MSL, RSLR = relative sea-level rise scenario (0, 0.5, 1.0, 1.5 or 2.0 m).

WL = MSL + MHWS-10 + RSLR

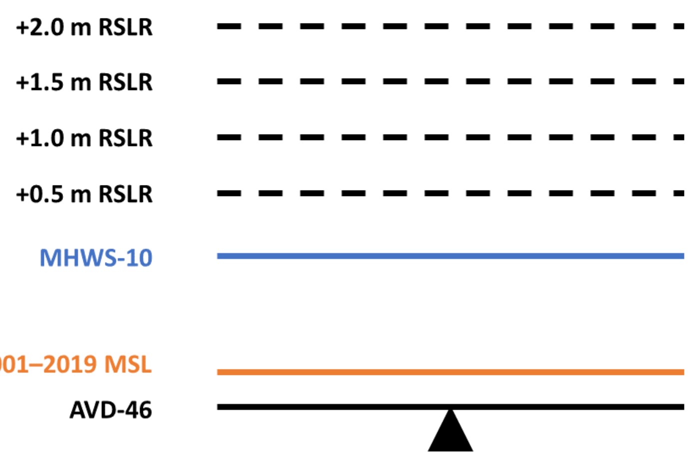

Figure 1: Schematic of inundation water level components. AVD-46 = Auckland Vertical Datum 1946, MSL = mean sea level, RSLR = relative sea-level rise.

2.1.1 Mean high water springs

The MHWS dataset used for this project is the same as that applied by Stephens and Wadhwa (2012) for the report titled Development of an updated Coastal Marine Area (CMA) boundary for the Auckland Region. That dataset is provided in the appendix of this report (Table A-1). It consists of a set of MHWS-10 elevations, these being the vertical elevation equaled or exceeded only by the highest 10% of all high tides. The tidal heights will not have substantially changed since 2012. MHWS-10 is calculated relative to MSL.

Stephens and Wadhwa (2012) did not calculate inundation levels, but instead determined the coastal marine area boundary. This required an additional vertical offset to the line of MHWS, to account for the effect of waves at the coastline and their influence on the coastal boundary. Wave runup has much smaller volume than tide and so can be ignored for the purposes of permanent inundation mapping from non-extreme (flat water) conditions. Therefore, no additional vertical elevation allowance was used for this (2022) project.

2.1.2 Mean sea level

Mean sea level has risen about 0.2 m around New Zealand over the last 100 years (Stats NZ). As time passes, the MSL offset relative to local vertical datum (e.g., Auckland Vertical Datum 1946, AVD-46) increases and needs to be updated.

In this project we have updated the sea levels (compared to the 2012 project) by revising the MSL offset to vertical datum. For the 2012 project the MSL-averaging period was approximately 1999–2011 (mid-point 2005). For this project the MSL-averaging period was 2001–2019, which updates the MSL datum offset to a mid-point of 2010 so the mapping of coastal inundation is closer to current conditions. It is possible to calculate MSL over any period, but short-duration records can be biased by short-term tidal or climate effects. It is common to calculate MSL over a full (18.6-year) tidal epoch (e.g., 2001–2019) to ensure that the nodal tides and ENSO effects are averaged out.

All of the water level elevations included in Appendix A of Stephens and Wadhwa (2012) included a built-in MSL offset from Auckland Vertical Datum 1946 (AVD-46). To update the WL elevations for this project, we subtracted the MSL used in the 2012 study and then added updated MSL estimates calculated by Reeve and Wadhwa (2021). These MSL offsets are shown in the table below and are based on the MSL offsets included in Table B-1. A MSL range is given for both Manukau and Kaipara Harbour (Table 2-1). This results from interpolation of MSL from 0.185 m outside to the higher levels inside the harbours—tidal hysteresis causes substantial increases in MSL in the upper reaches of these large harbours.

The MSL for all points are described in **Table 2-1**

Table 2-1: Updates to MSL offset values.

Region	MSL added in 2012 (AVD-46)	MSL added in 2022 (AVD-46)
Auckland East coast (Waitemata Harbour and open coast)	0.15	0.165
Manukau	0.22	0.185 to 0.23
Kaipara	0.16	0.185 to 0.27
Auckland West coast	0.16	0.185

In addition to adjusting MSL offsets, the other key difference between this study and that in 2012 has been the re-calculation of water levels in the Kaipara Harbour. When checking the present-day inundation maps we observed that the inundation areas looked sensible throughout the Auckland region but not in South Kaipara Harbour where the inundation was not contained by the stop banks. This was caused by an error in the calculation of the Kaipara water levels relative to the various datums. This has been corrected in Table A-1 of this report. After applying the updated MSL elevations the present-day mapped inundation in the South Kaipara Harbour is contained by the stop banks. Compared to the 2012 study we have much better information, including much improved LiDAR, digitised stopbanks, reliable MSL estimates and additional water level data from Helensville.

Subsequent studies (Stephens et al. 2013, Stephens and Wadhwa 2016, Allis et al. 2019) were not affected by the 2012 error in the calculation of the Kaipara water levels:

- The 2013 study did not use the 2012 MHWS elevations. Instead, a statistical modelling approach was used, which combined tides, storm surge and mean sea level anomaly measurements to predict extreme sea levels. In 2012 there was considerable uncertainty in the Kaipara Harbour MSL. This was revised in 2013, and the MSL used for the Kaipara Harbour in the 2013 study (0.23 m AVD-46) is consistent with the 2022 revision (0.185–0.27 m range). We have confirmed that the 2013 extreme sea levels were not compromised by checking the extreme sea-level analyses produced in 2013 with those by Stephens et al. 2020 (Stephens, S.A., Bell, R.G., Haigh, I.D. (2020) Spatial and temporal analysis of extreme storm-tide and skew-surge events around the coastline of New Zealand. Nat. Hazards Earth Syst. Sci., 20(3): 783-796. 10.5194/nhess-20-783-2020 https://www.nat-hazards-earth-syst-sci.net/20/783/2020/). This check shows that elevations reported in 2013 were about 0.2 m above those calculated by Stephens et al. (2020), very close to the MSL offset that was included in the 2013 table.

- The 2016 work is reliable—for this we obtained a sea-level record from Helensville that we did not previously know about, and which had been carefully quality analysed. This was used to produce a reliable extreme water level analysis, which included comparison with the exceptional 17 April 2009 storm-tide event. DHI used the 1% AEP elevation from this analysis as the downstream boundary for their modelling, which is described in the NIWA 2016 report.
- The 2019 study concerned Auckland's east coast where the MSL estimates were reliable.
- The calculation of the Coastal Marine Area (CMA) boundary (Stephens and Wadhwa 2012) is still satisfactory within the Kaipara because the 2012 study relied on digitisation of aerial photographs within the Kaipara Harbour, rather than the automated procedure used elsewhere.

To map the areas of land potentially exposed to inundation, the water levels (Equation 2-1) were intersected with the 2016–2018 LiDAR DEM to create GIS polygons for SLR scenarios of 0, 0.5, 1, 1.5, 2. 2.5 and 3 m.

The inundation polygons were then overlaid with Auckland Council's GIS layer from the stormwater network and overland flow paths. The stormwater network and overland flow paths were used to identify the hydraulically connected inundation polygons. This was used to produce a set of depth rasters and inundation polygons with only hydraulically connected inundation, as well as a set of depth rasters and inundation polygons with both hydraulically connected and disconnected inundation.

2.2 Input datasets

The water level dataset encompasses the entire Auckland Region including open coast, Kaipara Harbour, Manukau Harbour and Waitematā Harbour sites (Table 2-2, Figure 2).

The MSL offsets from local vertical datum in **Table 2-1** are based on the LINZ MSL values from Standard Ports and utilised the info for secondary ports also, for the period 2001–2019 (mid-point 2010). Thus, the MSL analysis is based on tide-gauge readings.

Most of the MHWS-10 elevations are derived from hydrodynamic models, which were calibrated against available water level measurements (Auckland Council, 2020). At the sea-level gauge locations, MHWS-10 elevations were derived directly from measurements. In the Kaipara Harbour, the MHWS-10 elevations were calculated using measurements from 7 sea-level gauges. The MHWS-10 was interpolated along the shoreline to 28 locations (Table A-1). The 28 locations include the original 7 measurement locations.

The other key input dataset used in this study is the Auckland LiDAR DEM 2016-2018. No modifications were made to the DEM to account for stopbanks, seawalls or structures.

The method identifies all land lower than the calculated water level, but not all of the land is connected to the sea. For assessing hydraulic connectivity of isolated inundation polygons the following datasets were downloaded from the Auckland Council Open Data portal. These datasets show potential flow pathways and are used to include or exclude land areas from the inundation polygon:

- Stormwater channel.
- Stormwater pipe.
- Stormwater watercourse.
- Stormwater connection.
- Overland flow paths.

Table 2-2: Number of sites.

Sites	Number of data points
Open coast and small estuaries	130
Kaipara Harbour	28
Manukau Harbour	72
Waitemata Harbour	61

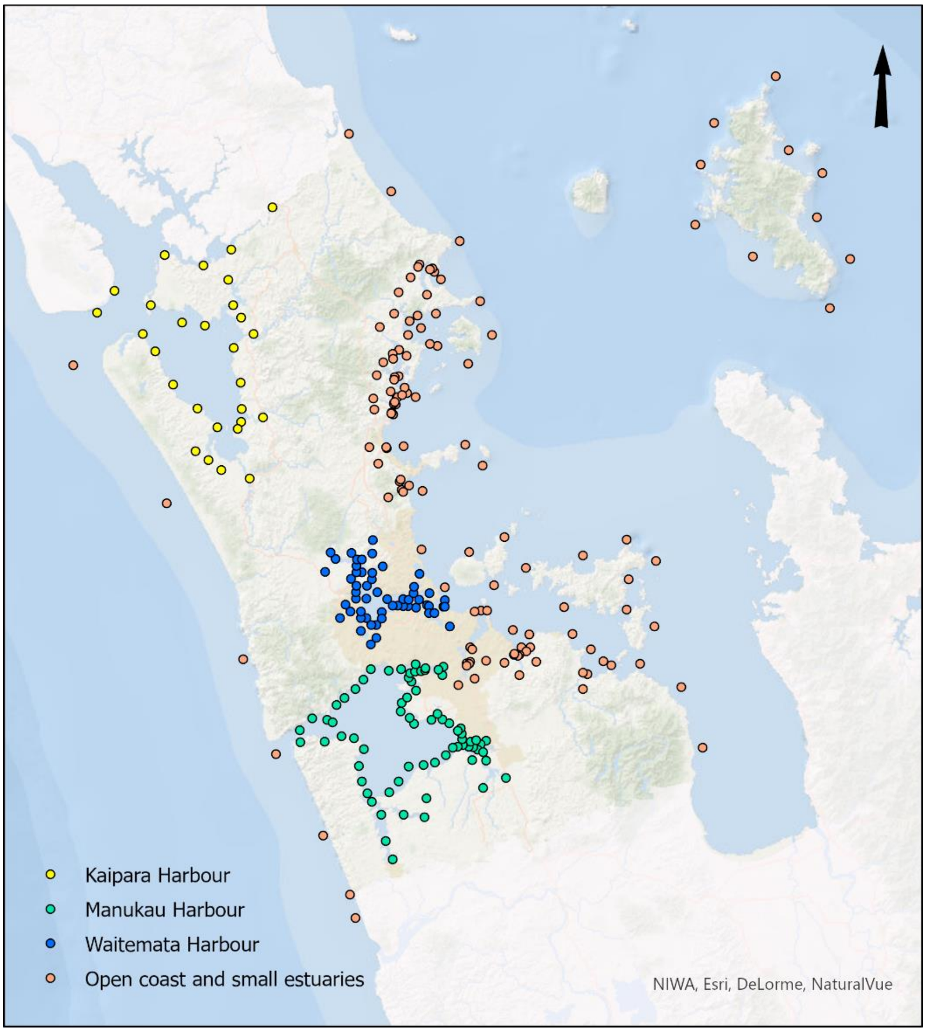

Figure 2: MHWS-10 site locations.

2.3 Method for mapping inundation

Areas of land inundated by the sea were mapped by first creating a water surface that varies in elevation by interpolating between the water levels around the coastline of the Auckland region (Figure 2, Table A-1). The water surface was then intersected with the LiDAR DEM to the same AVD-46 datum.

2.3.1 Creation of a varying level water surface around the region from water levels

The process to transfer water levels to the land mass is described in the following steps (Figure 3):

1. The source input point locations are interpolated to ensure a smooth transition between the available WL elevations by inserting points at an interval of 10 m.
2. The land area is split into several polygon areas connecting to the sea, based on topography (catchment boundaries and ridgelines.
3. A connecting point is created close to the coastline for each of the polygon areas (created in step 2).

4. The connecting points are assigned WL values from the interpolated offshore input site locations (created in step 1).

5. The assigned values from the connecting points (created in step 3) are then transferred to their corresponding polygon boundaries (created in step 2).

6. The polygon boundary layer now having the WL elevations, is converted into a grid surface. Updated MSL offset is added to create a total WL surface.

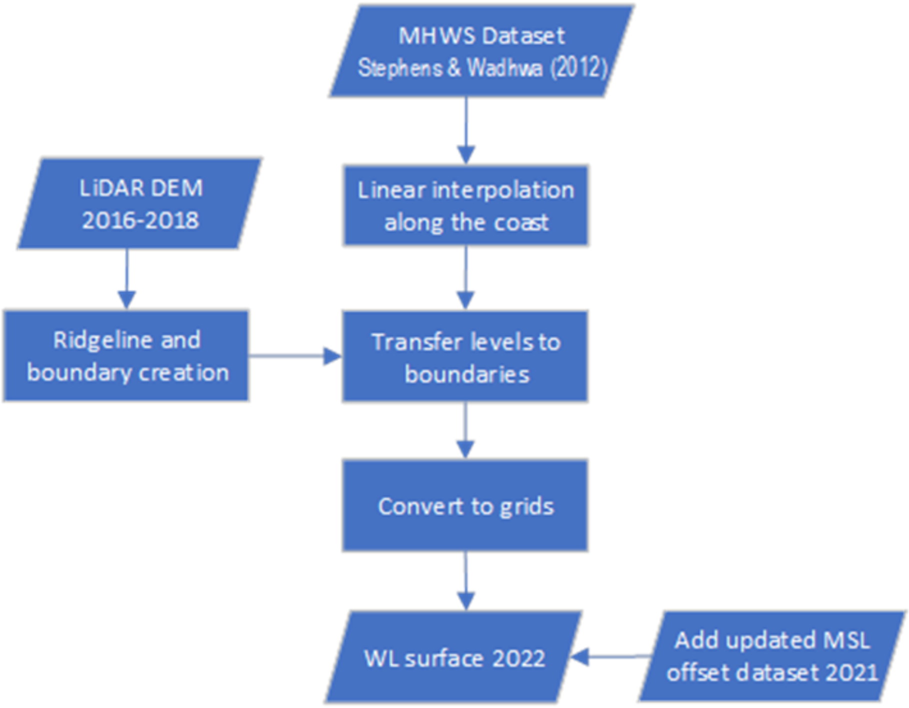

Figure 3: Water level surface preparation.

The sparse water level points at label locations shown in Figure 2 are interpolated to smooth the transition in MHWS levels along the length of coastline. The model points are connected by straight line segments close to the coastline. Points are then produced on the line segments at 10 m intervals as shown in Figure 4.

A water surface is needed next for intersecting with LiDAR DEM. This surface uses levels from the interpolated point dataset along the coastline shown in Figure 4. While applying the levels to the land mass, consideration of coastal geography and topography is made to ensure the levels are applied to correct part of land extent. The topographic information from the DEM is used to create polygon boundaries to assist delineation (Figure 5).

The DEM is resampled from 1 m to 4×4 m cell size. A series of tools available in ArcGIS Spatial Analyst toolbox, Hydrology toolset were used to derive polygon boundaries and their connecting points near the coast. The connecting points to these polygon boundaries assist in identifying which side of the coast a land parcel is connected to. Note that a 4×4m cell size was used only for the purposes of establishing the polygon catchment boundaries to save computing time—the inundation maps have 2×2 m resolution.

A grid interpolation would not be feasible with this complex set of boundaries when used as barriers in the interpolation tool. Hence a direct transfer of levels to land mass is undertaken (Figure 5).

The interpolated water levels from source points (Figure 2) are transferred to the destination points (connecting points) shown in Figure 4. The 2012 CMA boundary coastline is used as a barrier to ensure the levels are applied to a connecting point on the same side of the coast.

A map with the polygon boundaries used is shown in Figure 6 with major ridge lines in black.

A map with levels assigned to the connecting points is shown in Figure 7.

A map of coast points with levels assigned for the Auckland region is shown in Figure 8.

From the connecting points the interpolated level information is transferred to their associated polygon boundaries using a table join on the ‘id’ field within ArcGIS. A map of the boundaries with water level values is shown in Figure 9.

The boundaries are then converted to a region wide grid at 2×2 m cell size. Following the addition of MSL offset it is now ready for intersecting with LiDAR DEM to identify areas of inundated land.

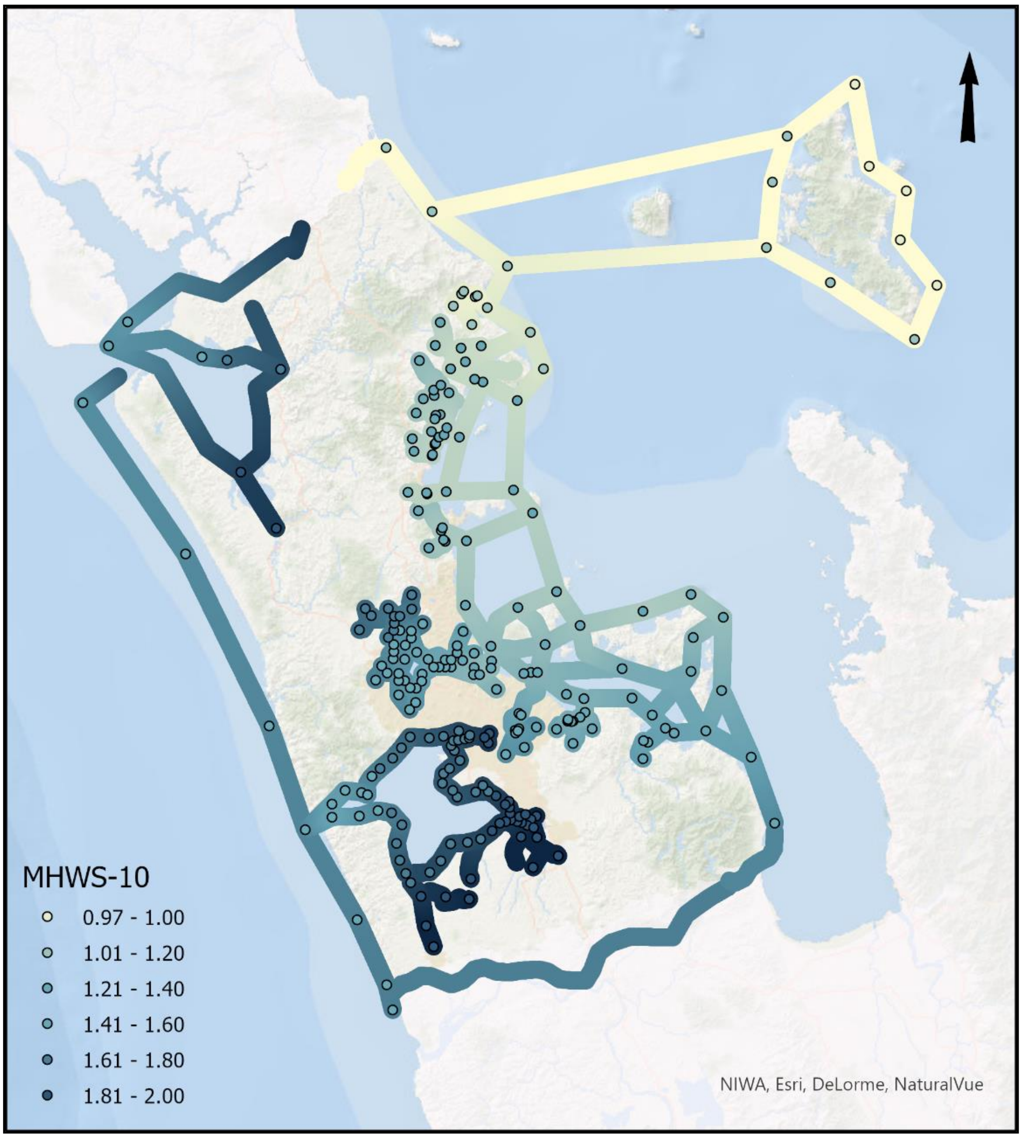

Figure 4: Connecting the model points and linear interpolation. Figures 4, 7 & 8 show MHWS-10 levels relative to mean sea level and don't include mean sea level offset from a fixed datum.

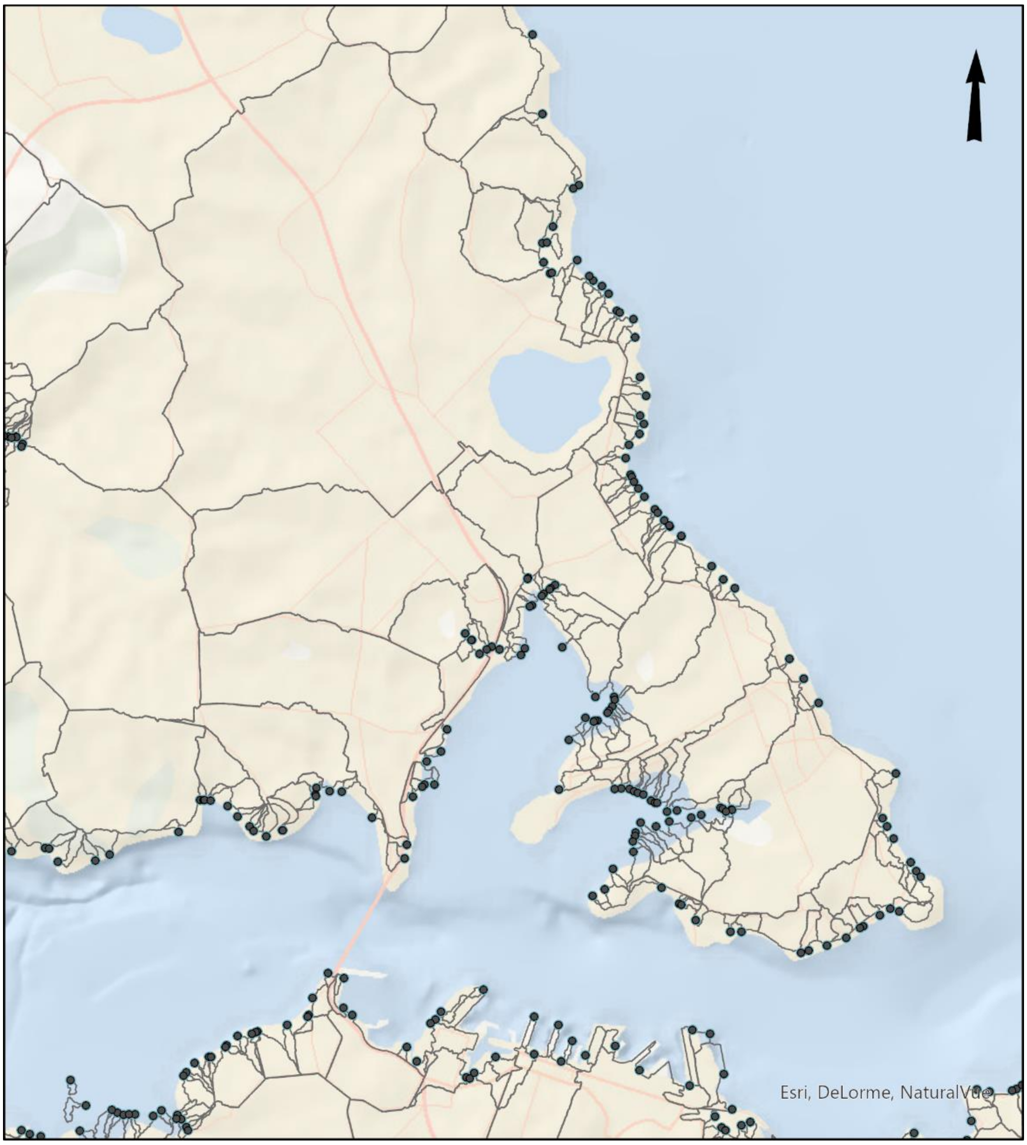

Figure 5: Polygon boundaries with connecting points. The grey lines mark the catchment boundaries—NIWA created these from the digital elevation model.

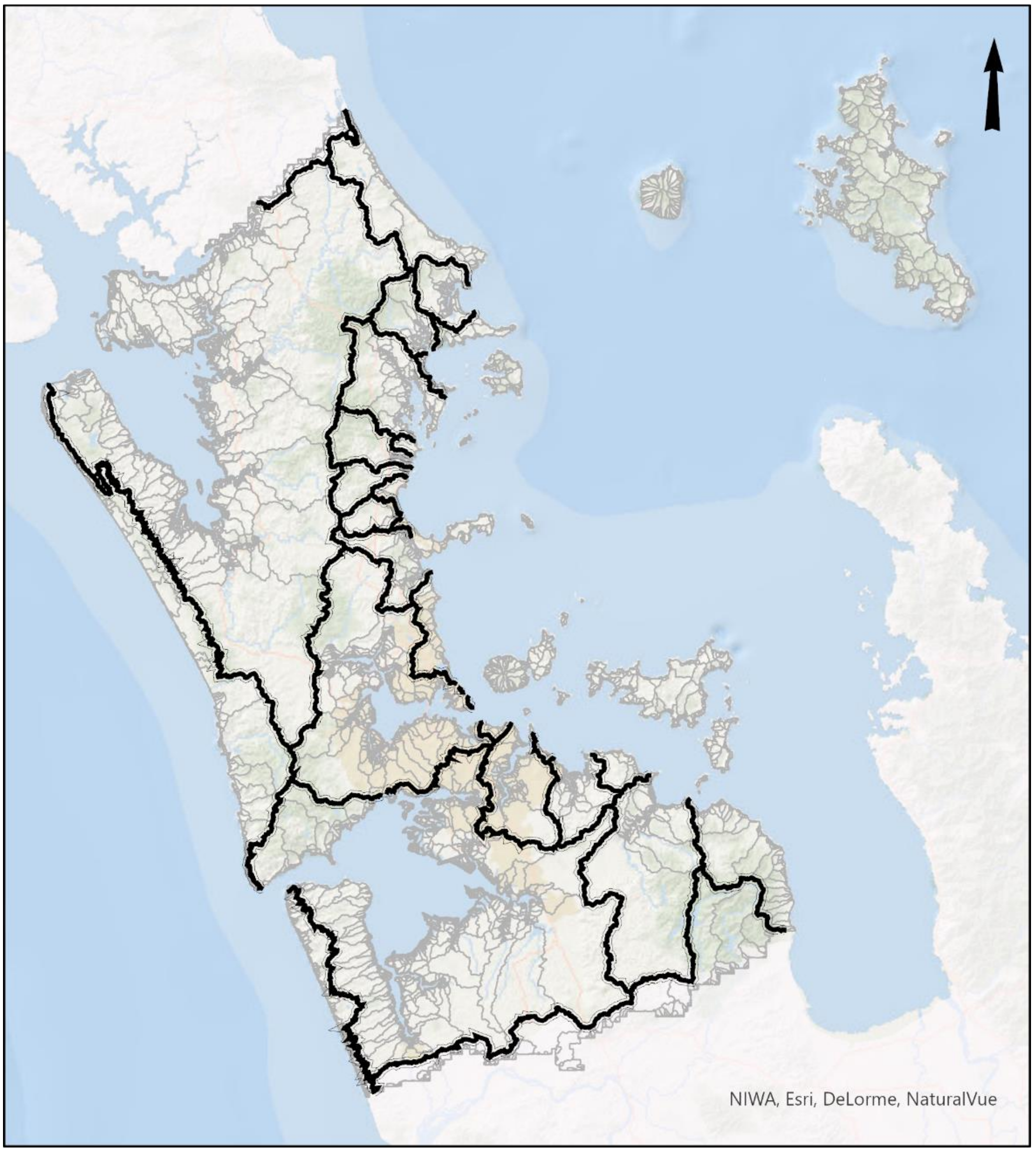

Figure 6: Polygon boundaries connected to the coast for Auckland Council area with major ridge lines shown in black. The ridge lines were not used in processing but help to visualise the larger catchments.

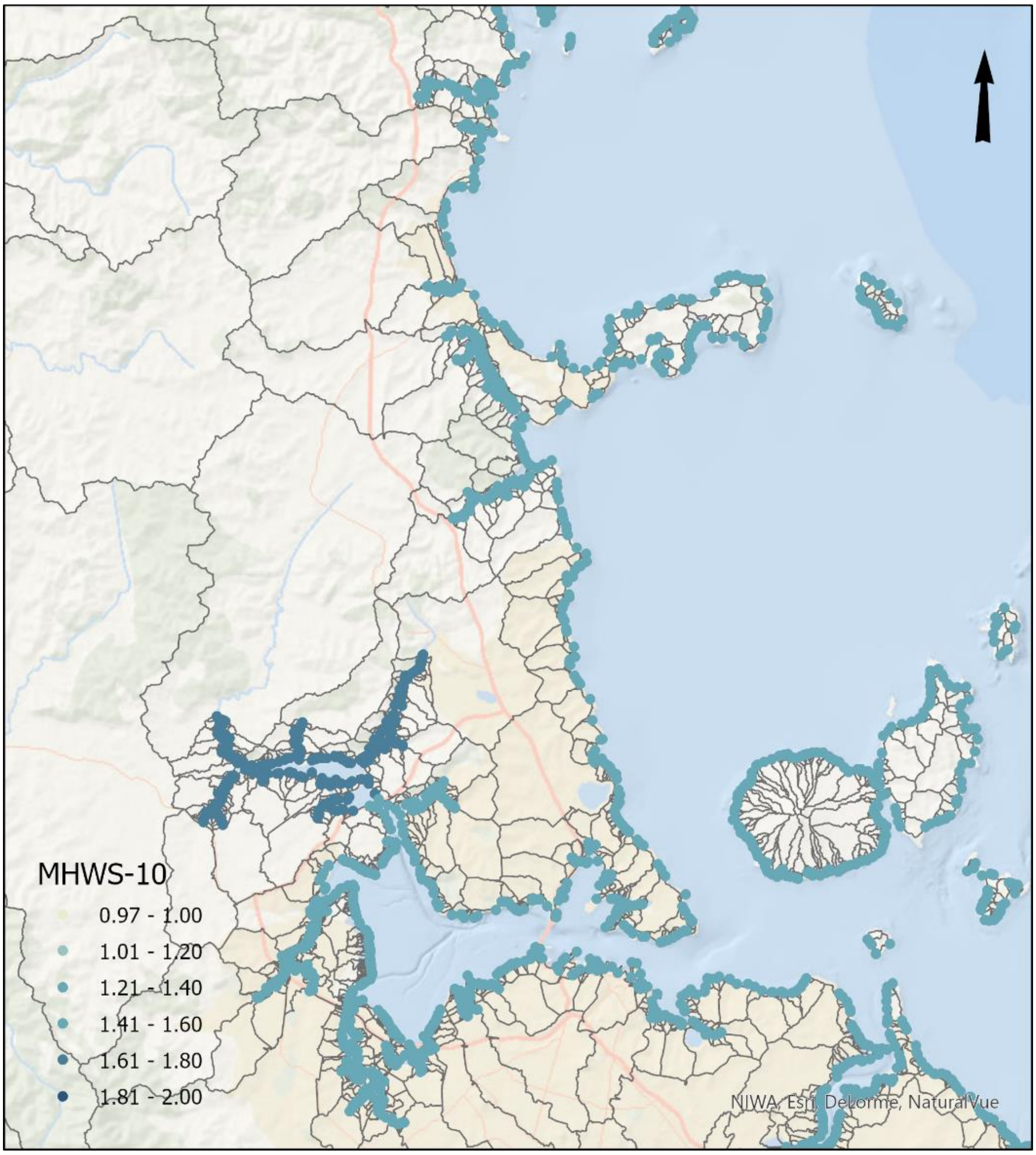

Figure 7: MHWS levels assigned to connecting points along the coast from offshore points.

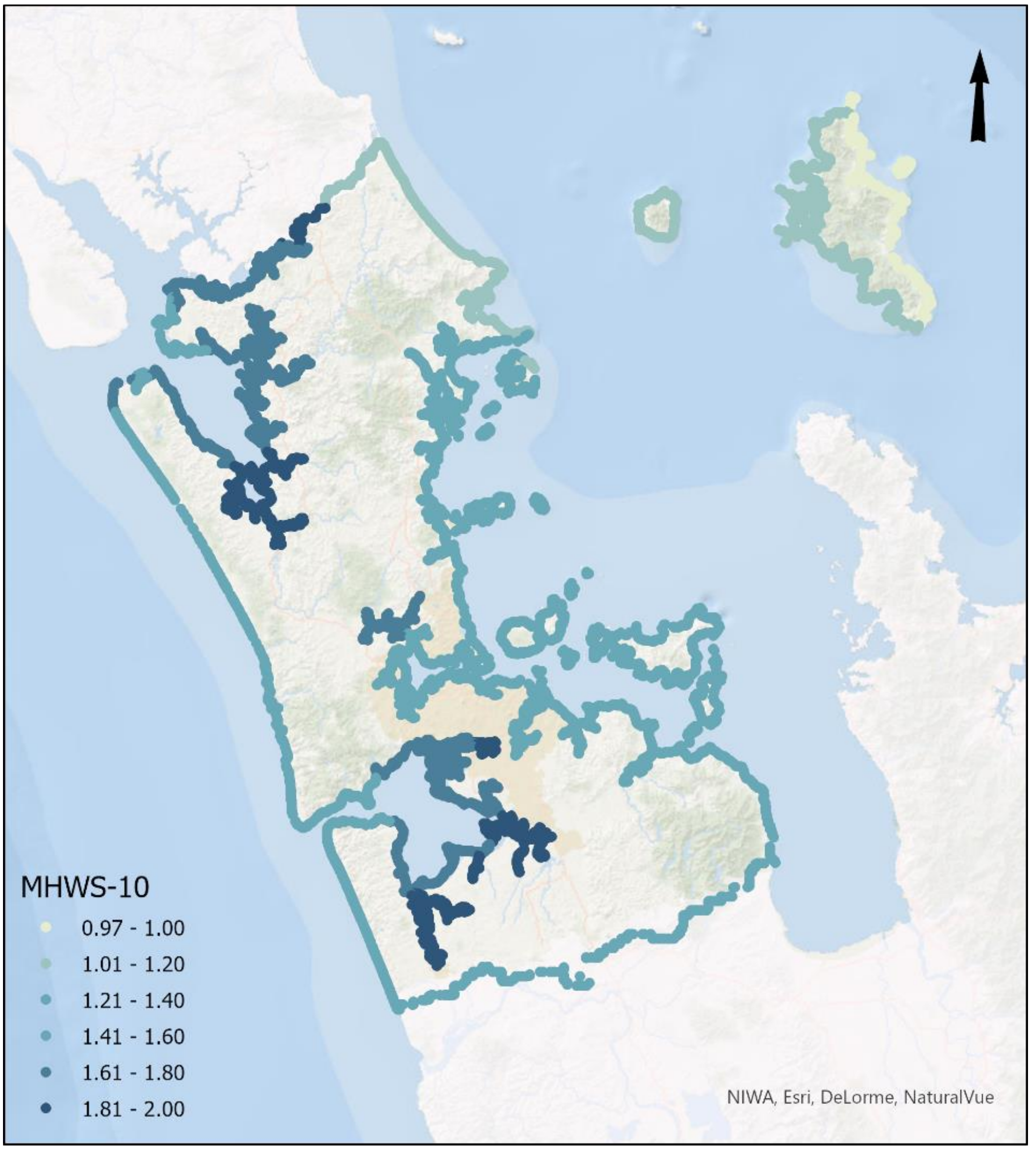

Figure 8: Points with levels closely following the coastline. Figures 4, 7 & 8 show MHWS-10 levels relative to mean sea level and don't include mean sea level offset from a fixed datum.

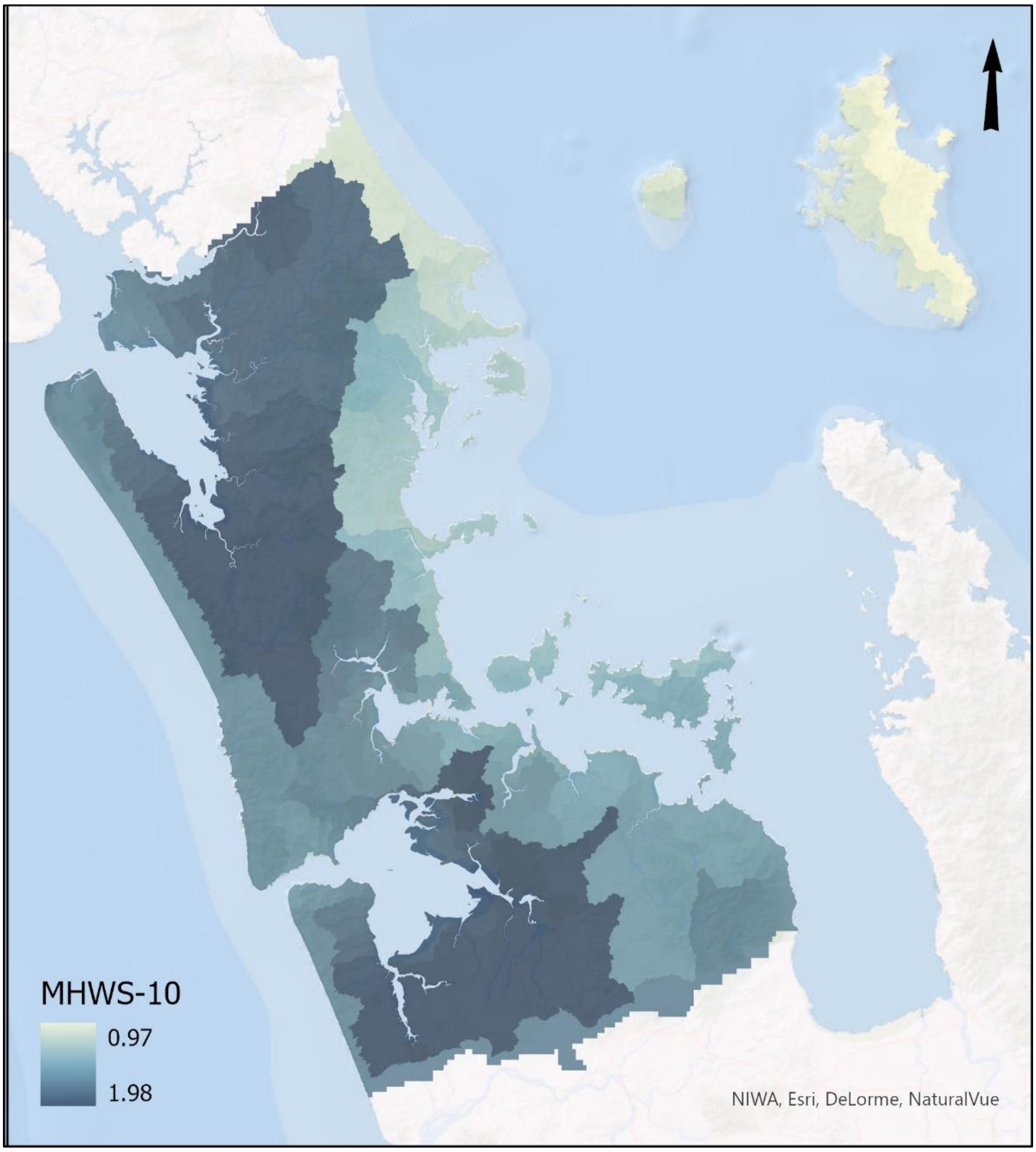

Figure 9: **Water surface polygons.** Shading indicates MHWS-10 water level (MSL not included). These polygons do not indicate the area of inundated land, they show the interpolated water surfaces only.

2.3.2 Inundation polygon processing

The water surface for MHWS-10 levels relative to MSL (MSL not included) were converted to a region wide grid at 2×2 m cell size—these water surfaces are illustrated in Figure 9. The updated MSL (2001–2019) offset from AVD-46 was subsequently added to create a total water level (WL) grid. The WL grid was then intersected with Auckland LiDAR DEM 2016–2018 to identify areas of inundated land. This was repeated for relative sea-level rise offsets of +0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 m, which were added to the water surface grid and intersected with LiDAR DEM to identify future areas of inundation (Figure 10).

The grids were then converted to polygons and checked with stormwater channel, pipe and overland flow dataset from Auckland Council to determine hydraulic connectivity to the sea. The overland flow dataset is based on fluvial/pluvial flooding but we have assumed it could act as a reverse flow path during high tides.

The disconnected inundation polygons were checked against Auckland Council's stormwater network and overland flow paths GIS layer. It was observed that almost all the disconnected polygons overlap with stormwater network or overland flow paths. A few polygons that seem to be generated due to artefacts in the DEM were removed. These are indicated by a red dot in Figure 11. Only polygons that were generated from artefacts in the DEM were removed. The dataset provided to AC includes both connected and disconnected polygons, for example all polygons as shown in Figure 11.

Another example of a disconnected polygon is for a part of natural water course not represented in the LiDAR DEM due to a bridge. This is shown connected by the overland flow path layer in Figure 12.

Following polygon connectivity assessment, depth grids were generated based on the DEM and inundation grids for each scenario.

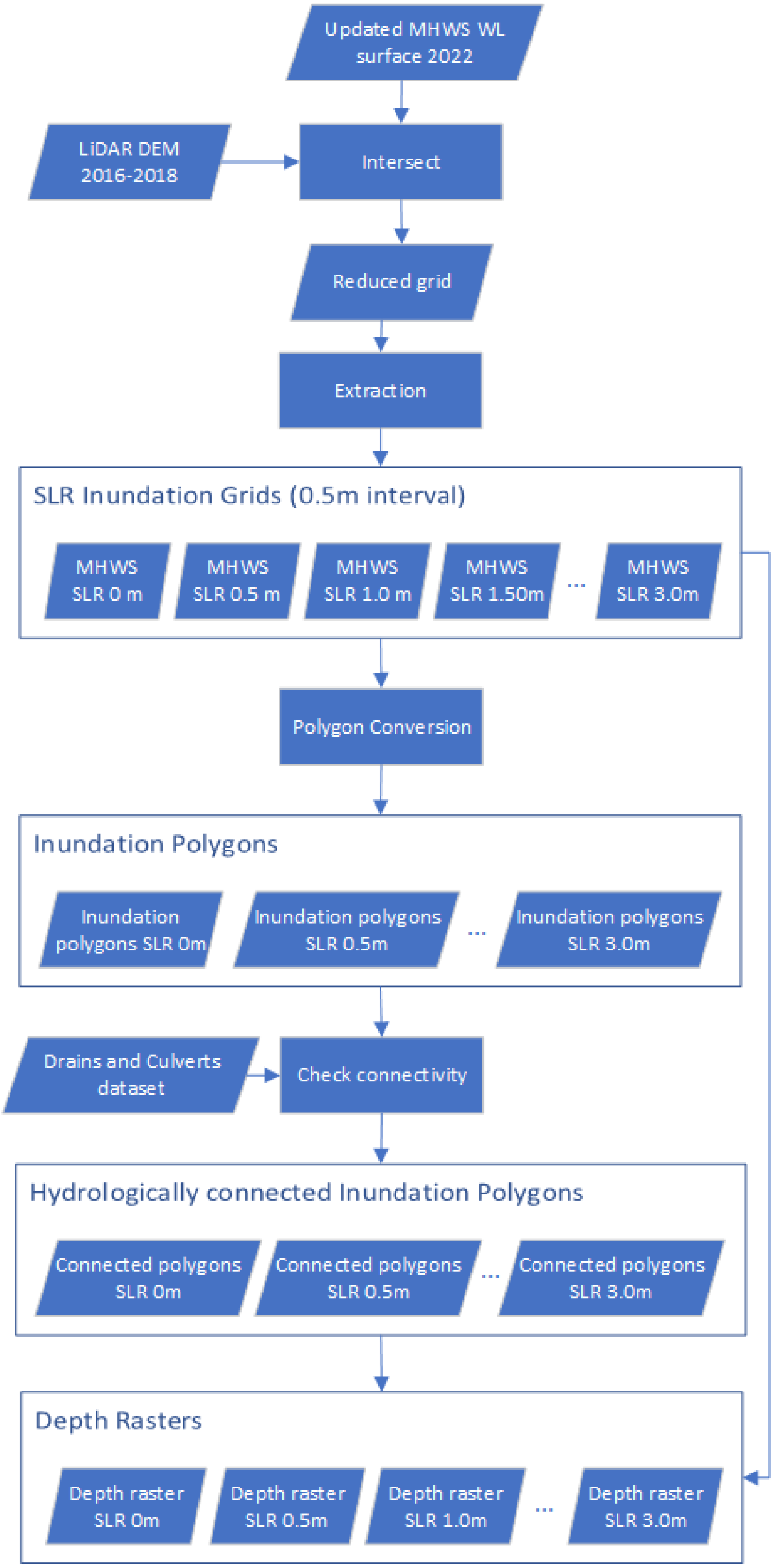

Figure 10: MHWS inundation polygons and depth grids processing.

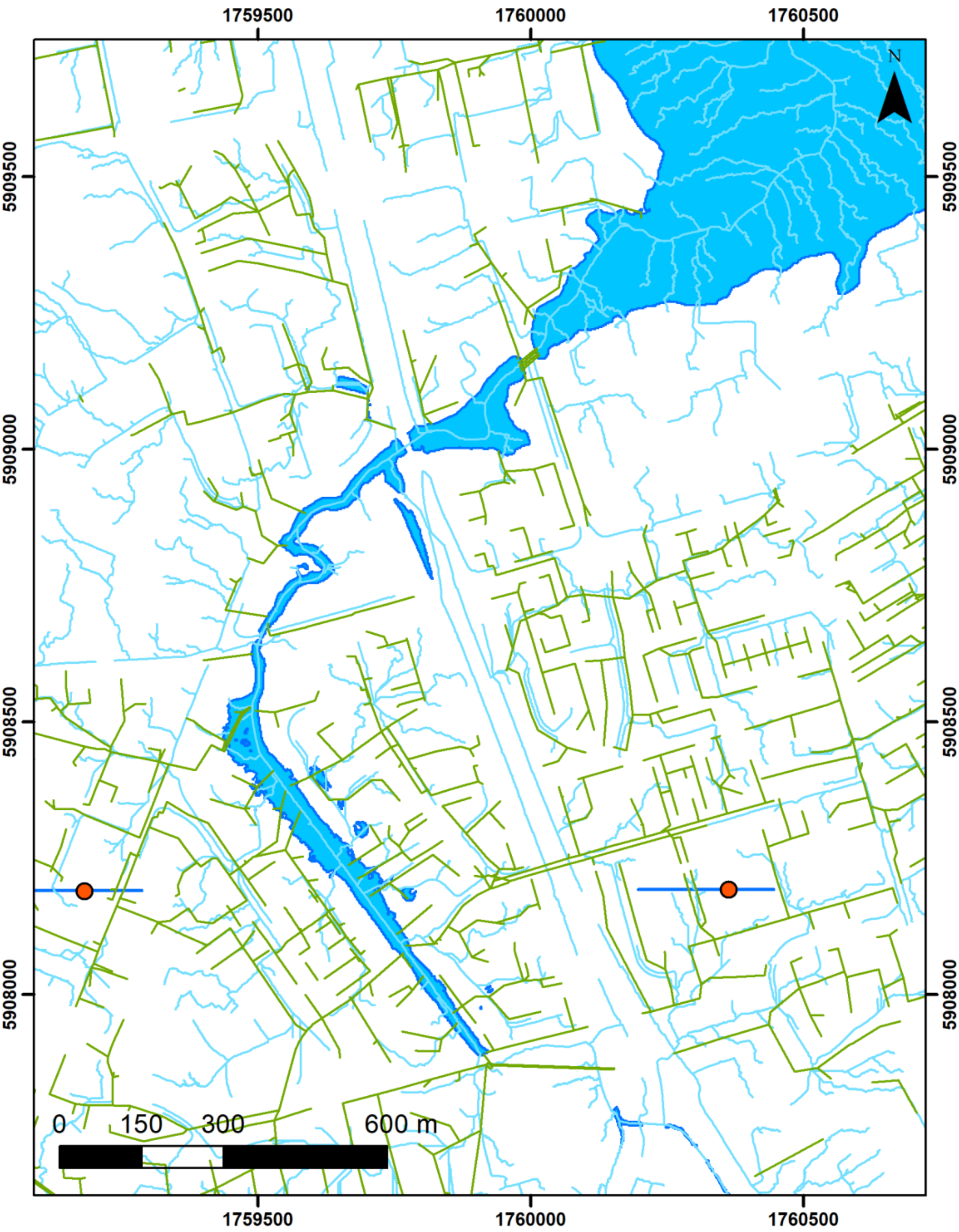

Figure 11: Stormwater network (green) and overland flow path (blue) line features from Auckland Council with inundation polygons for WL + 2m SLR. Red dots indicate DEM artefacts that were removed. Overland flow path = light blue, Inundation polygons = darker blue.

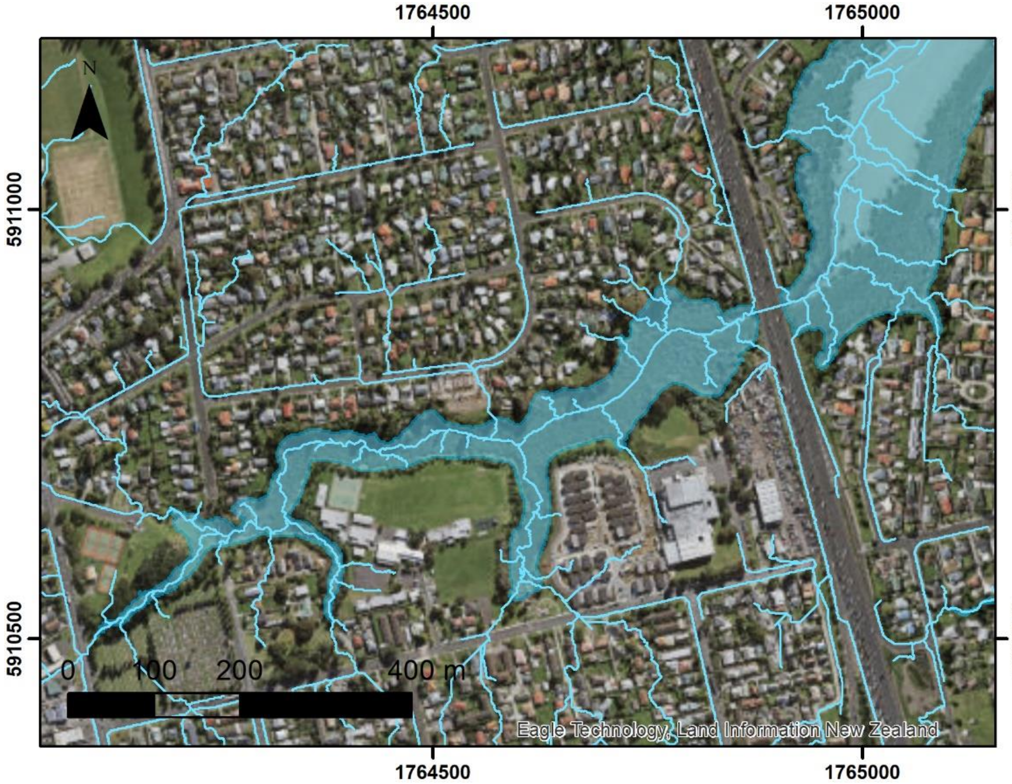

Figure 12: Example of a disconnected polygon showing connected by overland flow path lines (light blue).

2.3.3 Assumptions and Limitations

The major assumption in the GIS mapping procedure is the use of a static inundation flooding approach. In this approach, all land below the mapped levels and with a physical connection to the sea is shown as flooded in its entirety. This a reasonable assumption for modelling permanent inundation caused by mean sea level change and regular tides, because MHWS levels are reached regularly and will therefore have permanent impacts on the land surface. Detailed hydrodynamic models could be used to simulate inundation more accurately, but are likely to provide minor benefits for modelling permanent inundation caused by mean sea level change and regular tides.

Higher sea levels are experienced during very high tides or storm-tides when storm surges and waves combine to cause flooding. The water levels in this study include only mean sea level, mean high water spring tides and relative sea-level rise, and not storm surges or waves which would increase flood extent and depth. Wave setup and runup from background wave conditions is not included so this mapping will underestimate inundation during typical conditions at MHWS in high wave energy areas in particular e.g., by ~1.5 m for open west coast and ~0.7 m for open east coast, based on the vertical adjustment needed for CMA boundary (Stephens and Wadhwa 2012). Assessment of extreme coastal flood events including storm surges and wave setup is covered by other studies (Auckland Council, 2020) and already available through Council's Geomaps Coastal Flooding.

Another assumption is that the tidal amplification or attenuation remain the same as for the present day coastline and sea level, i.e. the MHWS-10 component relative to mean sea level doesn't change as mean sea level rises. International studies have shown that changes in geometry and depth of the harbours could impact the magnitude of tidal components, although these changes are small in comparison to the sea-level rise.

Sea level rise increments were applied consistently across the Auckland region. There is no differentiation to account for local variations in relative sea level rise due to subsidence or uplift across Auckland. Therefore, for different sites it may be appropriate to consider different timing of the various sea level increment scenarios.

The coastal inundation modelling has assumed that the topography remains as per the provided surveyed LiDAR grid.

The LiDAR data does not include post LiDAR earthworks, e.g., in greenfields (and brownfields) for subdivision and development projects and doesn't include structures. Nor does it include post-LiDAR natural changes in elevation, like landslides, erosion, or accretion.

The process of creating a DEM from LiDAR often does not accurately capture the presence or height of stop banks or other coastal defence structures. No coastal defences are included except where stop banks are resolved in the DEM. Accordingly, in areas where there are stop banks there is potential that the mapped inundation is greater than what would naturally occur. Nevertheless, most existing stop banks would be overtopped by large sea-level rise.

3 Results

Examples of the inundation polygon outlines, overlaid on aerial photographs, are shown in Figure 13–Figure 14. These figures show that polygons with 0 m SLR accurately map the areas presently flooded by high tide.

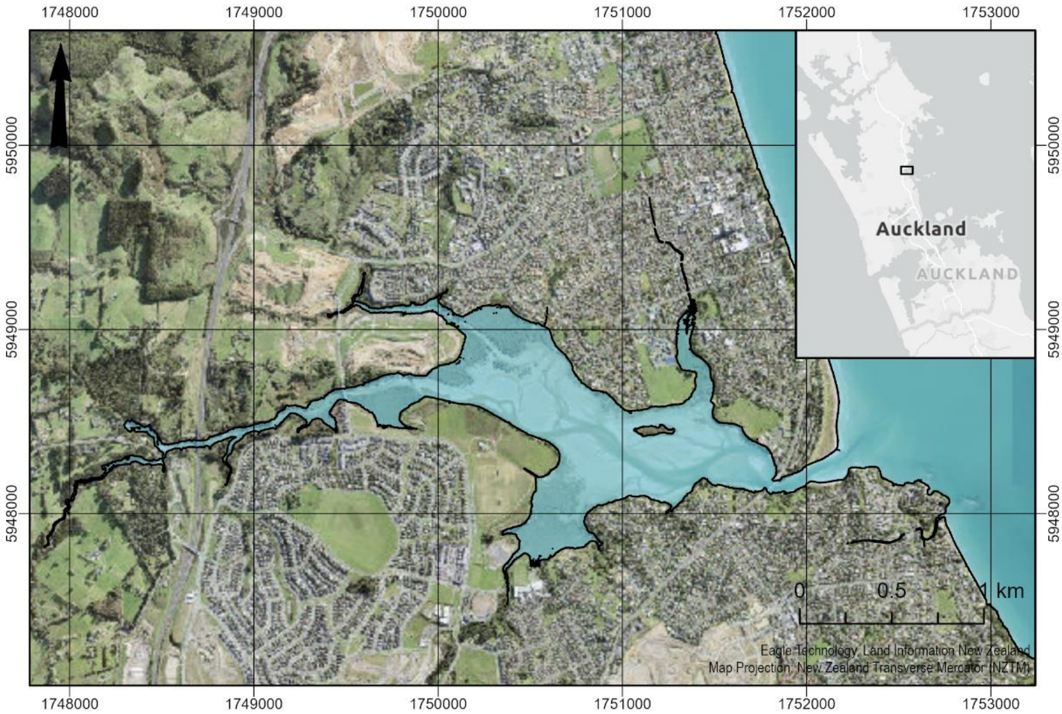

Figure 13: Map of Orewa area with polygon outline for WL + 0m SLR.

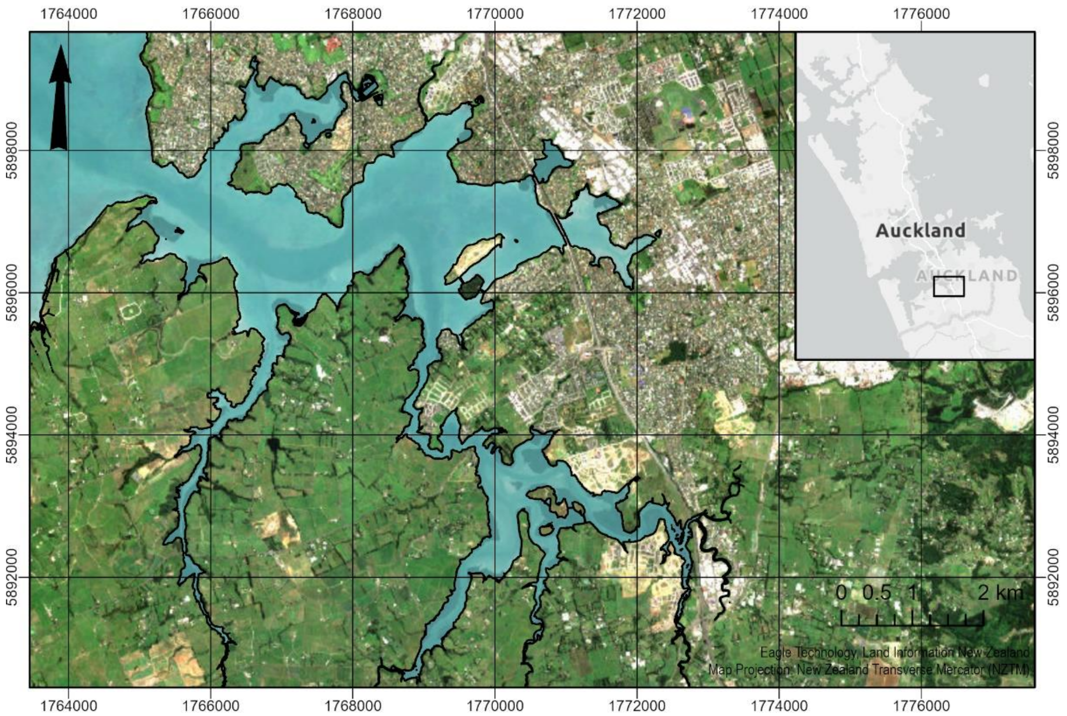

Figure 14: Map of Pahurehure inlet with polygon outline for WL + 0m SLR.

The Kaipara River includes a range of stop bank structures. In applying the static inundation modelling approach to the Helensville–Parakai area, the polygons for WL + 0 m SLR are shown to be a close fit in some areas. Within the DEM, the level of some of these features is well defined. However, as shown in Figure 15, there are some disconnects in the DEM that result in large landward areas being identified as inundated in the present day. In Figure 15 this is shown by the blue shading in the top plot. These areas were clipped out using the coastline boundary for the southern Kaipara Harbour—for example, after clipping the inundation polygon boundary is shown by the yellow line in the lower plot of Figure 15. The clipped areas are displayed in magenta colour in Figure 16. For all other scenarios where SLR is greater than 0 m, no manual clipping was undertaken because stop bank breaches are expected under rising sea level scenarios.

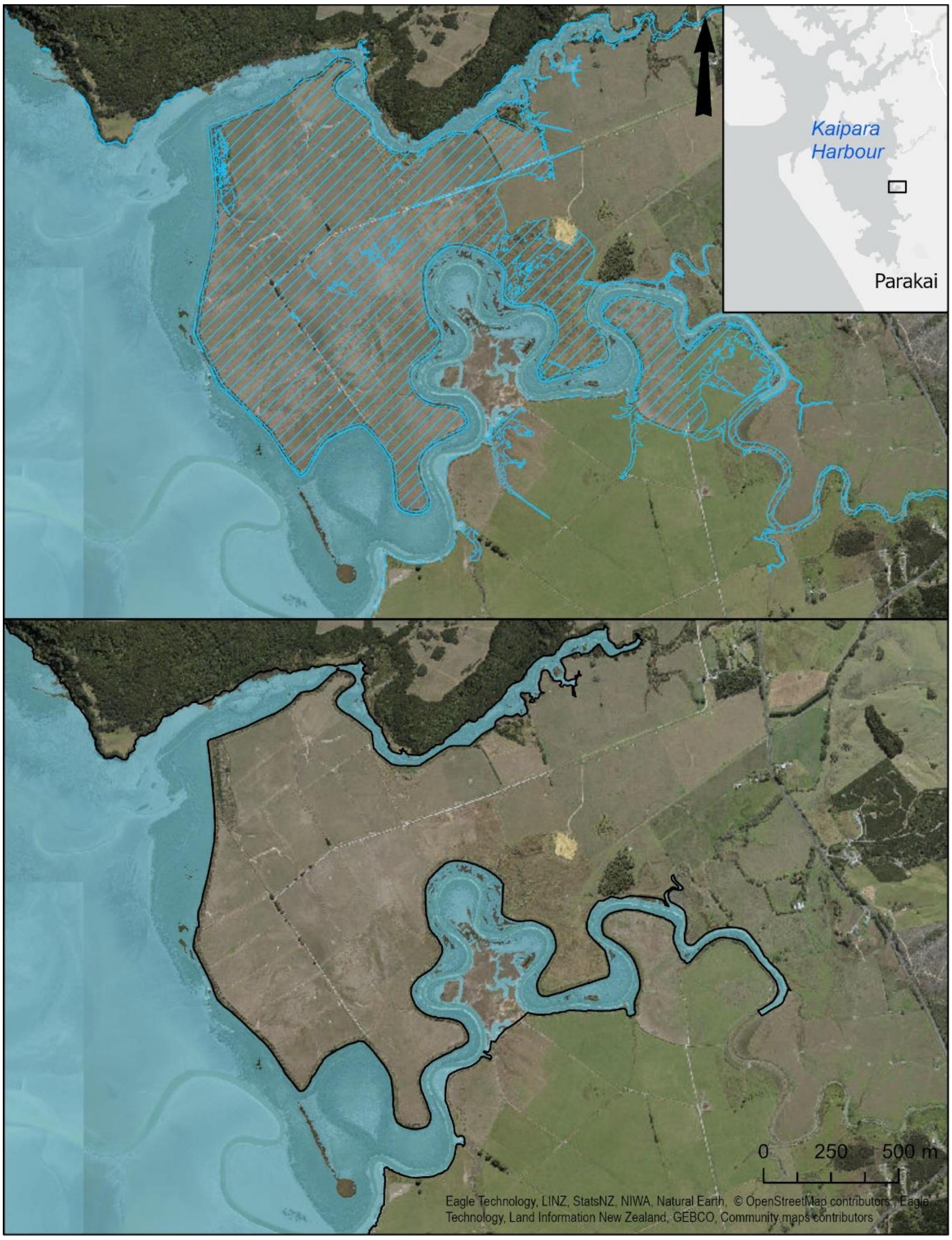

Figure 15: Example of manual clipping in inundated areas in the Parakai-Helensville region. The top image shows all land lower than WL shaded as inundated, and the hatched area that was clipped out because is presently protected by stopbanks. The bottom image shows the boundary of inundation area following manual removal of the part of the polygon that is protected by stopbanks.

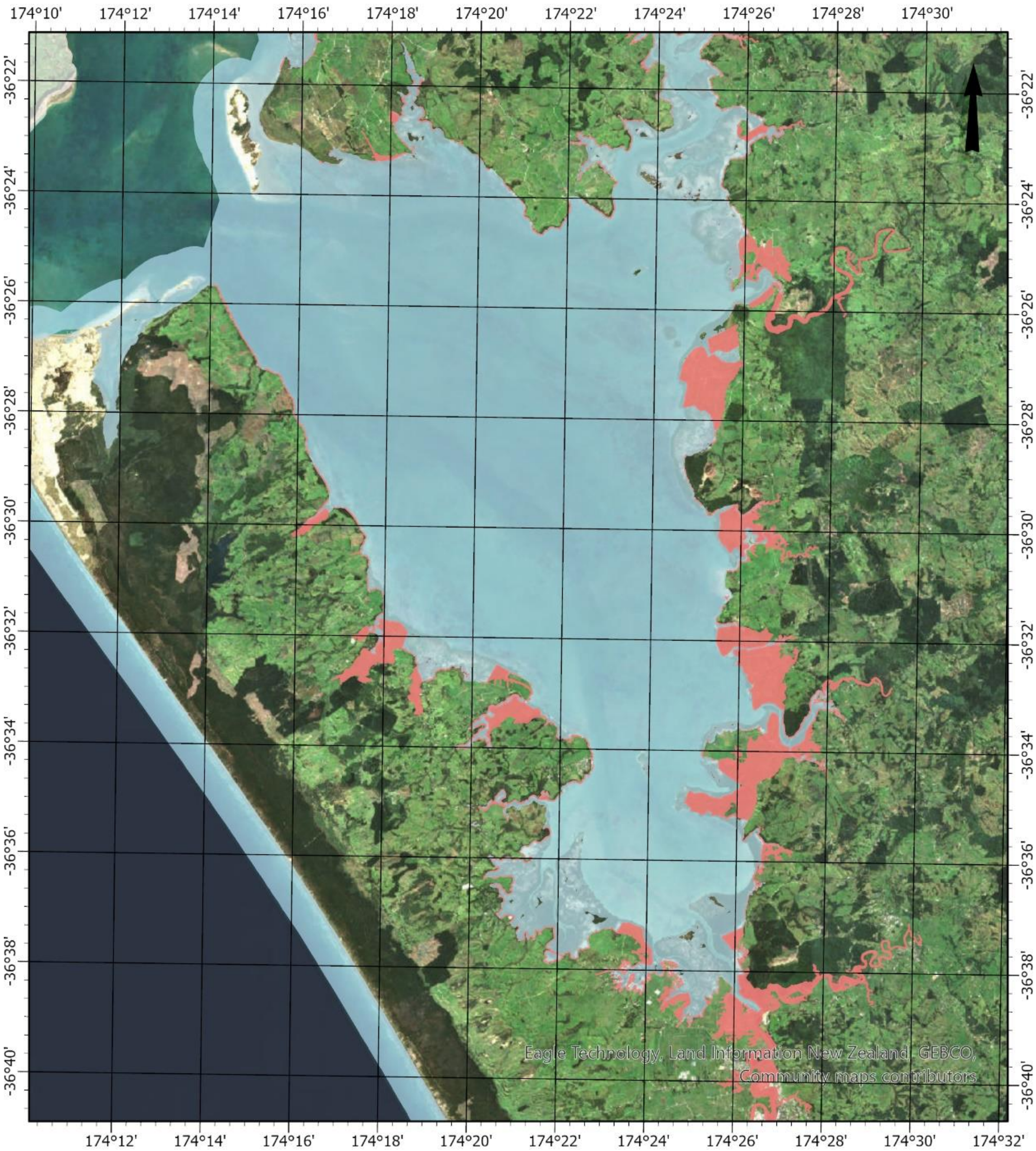

Figure 16: Map of Kaipara South area with inundation polygon for MHWS-10 + 0m SLR. The image shows areas in pink colour where land protected by stopbanks was manually assigned as not inundated.

Figure 17 shows an example of the impacts of relative sea-level rise at Mission Bay. There is little inundation at present-day MSL (0 m SLR scenario). As 0.5 m increments of SLR are added the inundated area increases. Some isolated polygons are shown for SLR scenarios ≤ 1.5 m. These polygons have a connection to the sea via stormwater connections or overland flow paths. A broad area of Mission Bay is predicted to be permanently inundated after 2 m of RSLR.

Figure 17. **Mission Bay area in Auckland showing mapped WL + 0.5 m SLR increments up to 2.0 m.**

4 Outputs

The following outputs were supplied to Auckland Council:

1. This report, which describes the project background, methods and results.
2. Digital datasets of:
   A. Shapefiles of model output points including coastal water level elevation (Table A-1).

   B. Polygons of area inundated for each RSLR scenario including both (1) areas connected to the sea and separately (2) areas lower than WL but disconnected from the sea.

   C. Rasters of inundation depth for each RSLR scenario including both (1) areas connected to the sea and separately (2) areas lower than WL but disconnected from the sea.

   D. Intermediate outputs from the analyses including catchment polygon boundaries and connecting points with assigned water levels.

5 Conclusions

Revised MHWS inundation extents referenced to the 2016–2018 LiDAR generated DEM and relative to the 2001-2019 MSL have been defined for the Auckland Region. Future impacts of relative sea level rise have been simulated by assessing future inundation resulting from sea level rise increments of 0.5m (0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 m).

An innovative methodology was developed within GIS to map static inundation levels to the land area to ensure the levels were applied to a land parcel that is directly connected to the coast.

The output of the mapping includes GIS polygon extents of the areas of inundation and raster files of the depth of inundation. These outputs were supplied to Auckland Council.

6 Glossary of abbreviations and terms

AVD-46	**Auckland Vertical Datum 1946** was established as the mean sea level at Port of Auckland from 7 years of sea level measurements collected in 1909, 1917–1919 and 1921–1923.
CMA	The **coastal marine area** is defined in s2 of the RMA as meaning: *"The foreshore, seabed, and coastal water, and the air space above the water -* *(a) Of which the seaward boundary is the outer limits of the territorial sea.* *(b) Of which the landward boundary is the line of mean high water springs, except that where that line crosses a river, the landward boundary at that point shall be whichever is the lesser of -* *(i) One kilometre upstream from the mouth of the river; or* *(ii) The point upstream that is calculated by multiplying the width of the river mouth by five".*
DEM	**Digital Elevation Model** - a digital model or 3D representation of a terrain's surface topography.
ENSO	**El Niño-Southern Oscillation** – The El Niño-Southern Oscillation (ENSO) is a recurring climate pattern involving changes in the temperature of waters in the central and eastern tropical Pacific Ocean. On periods ranging from about three to seven years, the surface waters across a large swath of the tropical Pacific Ocean warm or cool by anywhere from 1°C to 3°C, compared to normal. This oscillating warming and cooling pattern, referred to as the ENSO cycle, directly affects rainfall distribution in the tropics and can have a strong influence on weather across the world.
GIS	**Geographical Information Systems** – a system of hardware and software used for storage, retrieval, mapping, and analysis of geographic data. Practitioners also regard the total GIS as including the operating personnel and the data that go into the system.
LiDAR	**Li**ght **D**etection **A**nd **R**anging – 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 beat 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. This work has used the MHWS-10 definition.

MHWS-10	**Mean high water springs 10%** – high-tide level equalled or exceeded by only the highest 10% of all high tides, at a specified location. In this study MHWS-10 levels are generally provided relative to mean sea level rather than a conventional datum e.g., NZVD2016.
MSL	**Mean sea level** – calculated by averaging sea level measurements relative to a known datum over a known fixed period in time, usually several years. It is possible to calculate MSL over any period, but short-duration records can be biased by short-term tidal or climate effects. It is common to calculate MSL over a full (18.6-year) tidal epoch (e.g., 2001–2019) to ensure that the nodal tides and El Niño-Southern Oscillation effects are averaged out.
NZVD2016	The New Zealand Vertical Datum 2016 (NZVD2016) is the official vertical datum for New Zealand and its offshore islands (see web site: NZVD2016).
Polygon	Within GIS a Polygon object is a closed shape defined by a connected sequence of x,y coordinate pairs.
RMA	Resource Management Act – Act of parliament, passed in 1991 (with subsequent amendments), promotes the sustainable management of natural and physical resources such as land, air and water. New Zealand's Ministry for the Environment describes the RMA as New Zealand's principal legislation for environmental management. The adoption of the RMA was significant for three reasons: 1. The RMA established one integrated framework that replaced the many previous resource-use regimes, which had been fragmented between agencies and sectors, such as land use, forestry, pollution, traffic, zoning, water and air. 2. The RMA was the first statutory planning regime to incorporate the principle of sustainability. 3. The RMA incorporated 'sustainable management', as an explicitly stated purpose placed at the heart of the regulatory framework and this purpose is to direct all other policies, standards, plans and decision-making under the RMA. Having the purpose of the RMA at the apex of an unambiguous legislative hierarchy was a unique concept worldwide at the time of the law's inception.
RSLR	**Relative sea-level rise**—is defined as the sea level that is observed with respect to a land-based reference frame. It is often contrasted with eustatic sea-level rise, which is a measure of the increase in total mass or volume of the oceans. Relative sea level can change by the processes changing eustatic sea level (e.g., ice melt and thermal expansion), but also by changes on land such as subsidence and isostatic rebound.

SLR	**Sea-level rise**—Eustatic sea-level rise is the global or regional sea level rise related to changes in the volume of water in the ocean. These can be due to thermal expansion of the water, changes in the volume of glacial ice on land, or to changes in the shape of the seafloor caused by plate tectonic processes.
Sea-level gauge	Sea-level gauge. An instrument that automatically registers the rise and fall of the tide and other non-tidal sea-level variations relative to the landmass it sits on. The registration is accomplished by recording the sea-level heights at regular time intervals (e.g., 1-60 minutes) in digital or analogue (chart) format. A variety of sensors used for measuring the sea surface height, the main ones being a pressure gauge, ultrasonic sender/receiver (or a mechanical float), and counter-weight system on a pulley. Long-term gauges, particularly at Standard Ports, are regularly checked against nearby benchmarks to provide levels relative to a vertical datum.
Spring/neap tides	Spring/neap tides occur every fortnight (14.765 days to be exact) in conjunction with Moon's phase: spring tides occur just after New and Full Moon; neap tides occur just after First and Last Quarter. Spring tides have a much larger tidal range than neap tides because at New and Full Moon, the Moon and Sun are lined up and they pull together upon Earth's waters; whereas at First and Last Quarter the Moon and Sun are opposed and the pull is less. Another equivalent definition is that spring and neap tides are the result of M_2 (the lunar semi-diurnal constituent) beating in and out of phase with the S_2 tide (the solar semi-diurnal constituent).

7 References

Allis, M., R. Gorman, S. Stephens, R. Ovenden, and C. Eager. 2019. Coastal Inundation levels by storm-tides and waves at Great Barrier Island. NIWA Client Report 2019336HN to Auckland Council, November 2019, 84p.

Auckland Council. 2020. Auckland's exposure to coastal inundation by storm-tides and waves. Auckland Council Technical Report TR2020/024. . TR2016/017.

Foreman, M. G. G., J. Y. Cherniawsky, and V. A. Ballantyne. 2009. Versatile Harmonic Tidal Analysis: Improvements and Applications. Journal of Atmospheric and Oceanic Technology **26**:806-817.

Reeve, G., and S. Wadhwa. 2021. New Zealand tidal model calibration. NIWA Client Report 2021215HN to Land Information New Zealand, July 2021. . 2021215HN.

Stephens, S., and S. Wadhwa. 2012. Development of an updated Coastal Marine Area boundary for the Auckland Region. NIWA Client Report HAM2012-111 to Auckland Council, July 2012. HAM2012-111.

Stephens, S. A., D. Bremner, R. Budd, S. Edhouse, N. Goodhue, C. Hart, G. Reeve, and S. Wadhwa. 2011. Kaipara Harbour hydrodynamic data collection. Client Report to Auckland Council HAM2011-131, NIWA, Hamilton.

Stephens, S. A., and S. Wadhwa. 2016. Technical report: coastal-storm inundation in the Auckland Region - supplementary information: Updated coastal-storm exposure at Parakai and remapping of east-coast estuaries. NIWA Client Report prepared for Auckland Council HAM2016-015.

Stephens, S. A., S. Wadhwa, R. Gorman, N. Goodhue, M. Pritchard, R. Ovenden, and G. Reeve. 2013. Coastal inundation by storm-tides and waves in the Auckland Region. NIWA Client Report to Auckland Council, HAM2013-059, 138p. https://www.aucklandcouncil.govt.nz/environment/what-we-do-to-help-environment/Documents/coastal-inundation-in-auckland.pdf.

Appendix A Water levels used in the study

Table A-1: Water levels (WL) used in this study. MHWS-10 = elevation exceeded only by the highest 10% of all high tides. MSL = Mean sea level offset from Auckland Vertical Datum (1946), calculated over 2001–2019 epoch. WL = MSL + MHWS-10. Site labels: K = Kaipara Harbour locations used by Stephens & Wadhwa (2012), KG = Kaipara Harbour gauged locations, M = Manukau Harbour, O = open east coast and small east-coast estuaries, W = Waitemata Harbour.

Site	Longitude	Latitude	MHWS-10 relative to MSL (MSL removed)	Updated MSL (2001-2019) offset from AVD-46	WL = MSL + MHWS–10
K1	174.479	-36.231	1.82	0.27	2.09
K2	174.276	-36.307	1.63	0.20	1.82
K3	174.349	-36.322	1.67	0.21	1.88
K4	174.401	-36.297	1.72	0.23	1.96
K5	174.250	-36.384	1.57	0.19	1.76
KG5	174.310	-36.410	1.59	0.20	1.78
KG3	174.354	-36.414	1.67	0.21	1.88
K8	174.397	-36.344	1.74	0.23	1.96
K9	174.409	-36.448	1.76	0.23	1.99
K10	174.423	-36.401	1.74	0.23	1.97
K11	174.407	-36.383	1.74	0.23	1.96
K12	174.423	-36.501	1.78	0.24	2.01
KG6	174.447	-36.426	1.74	0.25	1.98
K13	174.426	-36.541	1.80	0.24	2.05
KG7	174.443	-36.648	1.83	0.27	2.09
K15	174.364	-36.621	1.81	0.24	2.05
KG4	174.380	-36.571	1.81	0.23	2.04
K17	174.342	-36.541	1.74	0.22	1.95
K18	174.295	-36.506	1.71	0.20	1.90
K19	174.260	-36.455	1.65	0.19	1.84
K20	174.236	-36.428	1.61	0.19	1.80
K21	174.467	-36.554	1.81	0.26	2.07
K22	174.425	-36.561	1.81	0.25	2.05
K23	174.419	-36.572	1.81	0.25	2.05
K24	174.389	-36.636	1.82	0.25	2.07
K25	174.339	-36.607	1.81	0.23	2.04
KG1	174.182	-36.363	1.52	0.19	1.71
KG2	174.149	-36.396	1.54	0.19	1.72
M1	174.904	-37.045	1.91	0.23	2.14
M2	174.894	-37.05	1.9	0.23	2.13
M3	174.888	-37.059	1.89	0.23	2.12

Site	Longitude	Latitude	MHWS-10 relative to MSL (MSL removed)	Updated MSL (2001-2019) offset from AVD-46	WL = MSL + MHWS–10
M4	174.879	-37.055	1.88	0.23	2.11
M5	174.871	-37.054	1.87	0.23	2.10
M6	174.874	-37.047	1.87	0.23	2.10
M7	174.885	-37.044	1.89	0.23	2.12
M8	174.859	-37.052	1.85	0.23	2.08
M9	174.858	-37.043	1.85	0.23	2.08
M10	174.857	-37.035	1.84	0.23	2.07
M11	174.855	-37.026	1.84	0.23	2.07
M12	174.849	-37.03	1.83	0.23	2.06
M13	174.833	-37.019	1.81	0.23	2.04
M14	174.819	-37.013	1.79	0.23	2.02
M15	174.81	-37.005	1.78	0.23	2.01
M16	174.798	-37.014	1.76	0.23	1.99
M17	174.765	-37.021	1.74	0.23	1.97
M18	174.757	-37.012	1.73	0.23	1.96
M19	174.739	-37.002	1.72	0.23	1.95
M20	174.741	-36.989	1.72	0.23	1.95
M21	174.751	-36.981	1.74	0.23	1.97
M22	174.768	-36.97	1.76	0.23	1.99
M23	174.759	-36.956	1.76	0.23	1.99
M24	174.753	-36.95	1.76	0.23	1.99
M25	174.756	-36.943	1.77	0.23	2.00
M26	174.765	-36.941	1.78	0.23	2.01
M27	174.777	-36.94	1.79	0.23	2.02
M28	174.784	-36.938	1.8	0.23	2.03
M29	174.785	-36.935	1.8	0.23	2.03
M30	174.905	-37.075	1.92	0.23	2.15
M31	174.899	-37.062	1.91	0.23	2.14
M32	174.943	-37.101	1.99	0.23	2.22
M33	174.9	-37.117	1.94	0.23	2.17
M34	174.878	-37.075	1.89	0.23	2.12
M35	174.85	-37.055	1.84	0.23	2.07
M36	174.84	-37.056	1.83	0.23	2.06
M37	174.827	-37.068	1.81	0.23	2.04
M38	174.807	-37.08	1.79	0.23	2.02
M39	174.785	-37.084	1.77	0.23	2.00
M40	174.792	-37.135	1.86	0.23	2.09

Site	Longitude	Latitude	MHWS-10 relative to MSL (MSL removed)	Updated MSL (2001-2019) offset from AVD-46	WL = MSL + MHWS−10
M41	174.756	-37.087	1.75	0.23	1.98
M42	174.738	-37.11	1.77	0.23	2.00
M43	174.72	-37.127	1.78	0.23	2.01
M44	174.687	-37.142	1.8	0.23	2.03
M45	174.706	-37.161	1.84	0.23	2.07
M46	174.749	-37.161	1.86	0.23	2.09
M47	174.789	-37.164	1.9	0.23	2.13
M48	174.715	-37.202	1.92	0.23	2.15
M49	174.729	-37.23	1.98	0.23	2.21
M50	174.678	-37.129	1.77	0.22	1.99
M51	174.667	-37.111	1.73	0.22	1.95
M52	174.661	-37.087	1.69	0.22	1.91
M53	174.67	-37.061	1.64	0.22	1.86
M54	174.651	-37.045	1.61	0.21	1.82
M55	174.627	-37.042	1.58	0.21	1.79
M56	174.595	-37.051	1.54	0.20	1.74
M57	174.599	-37.017	1.55	0.20	1.75
M58	174.616	-36.994	1.59	0.20	1.79
M59	174.631	-36.983	1.61	0.21	1.82
M60	174.652	-36.969	1.64	0.21	1.85
M61	174.681	-36.938	1.7	0.22	1.92
M62	174.715	-36.94	1.73	0.22	1.95
M63	174.739	-36.937	1.75	0.23	1.98
M64	174.766	-36.929	1.79	0.23	2.02
M65	174.819	-36.932	1.84	0.23	2.07
M66	174.609	-37.021	1.56	0.20	1.76
M67	174.818	-36.945	1.83	0.23	2.06
M68	174.667	-36.954	1.67	0.21	1.88
M69	174.57	-37.015	1.52	0.19	1.71
M70	174.548	-37.052	1.48	0.18	1.66
M71	174.547	-37.034	1.49	0.19	1.68
M72	174.81	-36.937	1.83	0.23	2.06
O1	174.622	-36.116	1.1	0.165	1.265
O2	174.703	-36.204	1.12	0.165	1.285
O3	174.835	-36.278	1.16	0.165	1.325
O4	174.801	-36.337	1.18	0.165	1.345
O5	174.876	-36.37	1.2	0.165	1.365

Site	Longitude	Latitude	MHWS-10 relative to MSL (MSL removed)	Updated MSL (2001-2019) offset from AVD-46	WL = MSL + MHWS–10
O6	174.765	-36.413	1.25	0.165	1.415
O7	174.796	-36.44	1.25	0.165	1.415
O8	174.757	-36.519	1.27	0.165	1.435
O9	174.736	-36.595	1.27	0.165	1.435
O10	174.853	-36.591	1.28	0.165	1.445
O11	174.887	-36.622	1.29	0.165	1.455
O12	174.773	-36.663	1.31	0.165	1.475
O13	174.773	-36.753	1.34	0.165	1.505
O14	174.819	-36.81	1.38	0.165	1.545
O15	174.889	-36.845	1.41	0.165	1.575
O16	174.951	-36.874	1.42	0.165	1.585
O17	175.065	-36.878	1.46	0.165	1.625
O18	175.125	-36.919	1.48	0.165	1.645
O19	175.195	-36.921	1.47	0.165	1.635
O20	175.275	-36.956	1.49	0.165	1.655
O21	175.319	-37.048	1.57	0.165	1.735
O22	175.221	-36.864	1.44	0.165	1.605
O23	175.221	-36.763	1.37	0.165	1.535
O24	175.164	-36.731	1.33	0.165	1.495
O25	175.082	-36.757	1.31	0.165	1.475
O26	174.973	-36.778	1.35	0.165	1.515
O27	175.048	-36.837	1.44	0.165	1.605
O28	175.167	-36.839	1.45	0.165	1.615
O29	175.17	-36.792	1.4	0.165	1.565
O30	174.913	-36.806	1.39	0.165	1.555
O31	174.931	-36.731	1.32	0.165	1.485
O32	174.864	-36.755	1.33	0.165	1.495
O33	174.856	-36.466	1.24	0.165	1.405
O34	174.9	-36.421	1.2	0.165	1.365
O35	175.289	-36.153	1.06	0.165	1.225
O36	175.281	-36.245	1.11	0.165	1.275
O37	175.392	-36.292	1.1	0.165	1.265
O38	175.54	-36.368	1.01	0.165	1.175
O39	175.576	-36.292	0.97	0.165	1.135
O40	175.511	-36.229	0.97	0.165	1.135
O41	175.519	-36.161	0.97	0.165	1.135
O42	175.454	-36.127	0.97	0.165	1.135

Site	Longitude	Latitude	MHWS-10 relative to MSL (MSL removed)	Updated MSL (2001-2019) offset from AVD-46	WL = MSL + MHWS–10
O43	175.426	-36.014	0.98	0.165	1.145
O44	175.312	-36.088	1.04	0.165	1.205
O45	174.105	-36.478	1.55	0.185	1.735
O46	174.286	-36.688	1.56	0.185	1.745
O47	174.436	-36.926	1.57	0.185	1.755
O48	174.502	-37.071	1.58	0.185	1.765
O49	174.66	-37.321	1.6	0.185	1.785
O50	174.817	-36.84	1.41	0.165	1.575
O51	174.765	-36.842	1.45	0.165	1.615
O52	174.786	-36.838	1.43	0.165	1.595
O53	174.817	-36.84	1.41	0.165	1.575
O54	175.14	-36.925	1.48	0.165	1.645
O55	175.101	-36.901	1.47	0.165	1.635
O56	174.782	-36.437	1.25	0.165	1.415
O57	174.792	-36.39	1.24	0.165	1.405
O58	174.595	-37.195	1.59	0.185	1.775
O59	174.648	-37.285	1.6	0.185	1.785
O60	174.74	-36.424	1.25	0.165	1.415
O61	174.758	-36.394	1.25	0.165	1.415
O62	175.095	-36.939	1.48	0.165	1.645
O63	174.968	-36.9	1.43	0.165	1.595
O64	174.747	-36.655	1.32	0.165	1.485
O65	174.715	-36.546	1.27	0.165	1.435
O66	174.719	-36.531	1.27	0.165	1.435
O67	174.74	-36.513	1.27	0.165	1.435
O68	174.743	-36.402	1.25	0.165	1.415
O69	174.788	-36.326	1.15	0.165	1.315
O70	174.743	-36.335	1.18	0.165	1.345
O71	174.721	-36.358	1.3	0.165	1.465
O72	174.775	-36.361	1.18	0.165	1.345
O73	174.713	-36.391	1.28	0.165	1.445
O74	174.686	-36.412	1.39	0.165	1.555
O75	174.694	-36.466	1.34	0.165	1.505
O76	174.682	-36.486	1.33	0.165	1.495
O77	174.676	-36.522	1.31	0.165	1.475
O78	174.679	-36.539	1.31	0.165	1.475
O79	174.67	-36.597	1.28	0.165	1.445

Site	Longitude	Latitude	MHWS-10 relative to MSL (MSL removed)	Updated MSL (2001-2019) offset from AVD-46	WL = MSL + MHWS–10
O80	174.688	-36.622	1.38	0.165	1.545
O81	174.708	-36.674	1.36	0.165	1.525
O82	174.997	-36.922	1.47	0.165	1.635
O83	174.936	-36.924	1.47	0.165	1.635
O84	174.965	-36.943	1.48	0.165	1.645
O85	174.88	-36.95	1.54	0.165	1.705
O86	174.849	-36.96	1.55	0.165	1.715
O87	175.087	-36.962	1.51	0.165	1.675
O88	174.738	-36.456	1.33	0.165	1.495
O89	174.709	-36.511	1.29	0.165	1.455
O90	174.901	-36.922	1.55	0.165	1.715
O91	174.76	-36.315	1.17	0.165	1.335
O92	174.784	-36.321	1.15	0.165	1.315
O93	174.757	-36.319	1.17	0.165	1.335
O94	174.78	-36.322	1.15	0.165	1.315
O95	174.724	-36.447	1.35	0.165	1.515
O96	174.712	-36.453	1.34	0.165	1.505
O97	174.713	-36.461	1.33	0.165	1.495
O98	174.724	-36.487	1.3	0.165	1.465
O99	174.716	-36.489	1.31	0.165	1.475
O100	174.715	-36.493	1.3	0.165	1.465
O101	174.736	-36.505	1.28	0.165	1.445
O102	174.721	-36.519	1.27	0.165	1.435
O103	174.723	-36.519	1.27	0.165	1.435
O104	174.731	-36.516	1.28	0.165	1.445
O105	174.715	-36.529	1.28	0.165	1.445
O106	174.717	-36.527	1.28	0.165	1.445
O107	174.712	-36.543	1.28	0.165	1.445
O108	174.711	-36.545	1.28	0.165	1.445
O109	174.704	-36.598	1.27	0.165	1.435
O110	174.703	-36.597	1.25	0.165	1.415
O111	174.729	-36.649	1.33	0.165	1.495
O112	174.731	-36.646	1.33	0.165	1.495
O113	174.733	-36.662	1.33	0.165	1.495
O114	174.736	-36.665	1.33	0.165	1.495
O115	174.901	-36.845	1.41	0.165	1.575
O116	174.877	-36.847	1.41	0.165	1.575

Site	Longitude	Latitude	MHWS-10 relative to MSL (MSL removed)	Updated MSL (2001-2019) offset from AVD-46	WL = MSL + MHWS–10
O117	174.982	-36.88	1.42	0.165	1.585
O118	174.985	-36.9	1.43	0.165	1.595
O119	174.87	-36.902	1.48	0.165	1.645
O120	174.874	-36.905	1.48	0.165	1.645
O121	174.977	-36.906	1.43	0.165	1.595
O122	174.964	-36.912	1.44	0.165	1.605
O123	174.961	-36.913	1.44	0.165	1.605
O124	174.954	-36.912	1.45	0.165	1.615
O125	174.955	-36.91	1.44	0.165	1.605
O126	174.864	-36.926	1.51	0.165	1.675
O127	174.87	-36.924	1.51	0.165	1.675
O128	174.869	-36.927	1.51	0.165	1.675
O129	174.864	-36.93	1.52	0.165	1.685
O130	175.087	-36.937	1.48	0.165	1.645
W1	174.75	-36.84	1.44	0.165	1.605
W2	174.74	-36.83	1.46	0.165	1.625
W3	174.74	-36.84	1.46	0.165	1.625
W4	174.73	-36.84	1.47	0.165	1.635
W5	174.72	-36.84	1.48	0.165	1.645
W6	174.7	-36.85	1.5	0.165	1.665
W7	174.7	-36.86	1.51	0.165	1.675
W8	174.69	-36.89	1.53	0.165	1.695
W9	174.69	-36.87	1.52	0.165	1.685
W10	174.68	-36.87	1.53	0.165	1.695
W11	174.67	-36.86	1.53	0.165	1.695
W12	174.66	-36.88	1.55	0.165	1.715
W13	174.68	-36.9	1.59	0.165	1.755
W14	174.66	-36.88	1.55	0.165	1.715
W15	174.66	-36.86	1.55	0.165	1.715
W16	174.66	-36.86	1.55	0.165	1.715
W17	174.66	-36.85	1.54	0.165	1.705
W18	174.67	-36.83	1.54	0.165	1.705
W19	174.65	-36.82	1.56	0.165	1.725
W20	174.65	-36.83	1.56	0.165	1.725
W21	174.65	-36.82	1.56	0.165	1.725
W22	174.63	-36.84	1.58	0.165	1.745
W23	174.64	-36.85	1.59	0.165	1.755

Site	Longitude	Latitude	MHWS-10 relative to MSL (MSL removed)	Updated MSL (2001-2019) offset from AVD-46	WL = MSL + MHWS–10
W24	174.62	-36.86	1.59	0.165	1.755
W25	174.65	-36.81	1.56	0.165	1.725
W26	174.67	-36.81	1.54	0.165	1.705
W27	174.68	-36.8	1.54	0.165	1.705
W28	174.68	-36.8	1.55	0.165	1.715
W29	174.66	-36.79	1.6	0.165	1.765
W30	174.64	-36.8	1.61	0.165	1.775
W31	174.65	-36.79	1.61	0.165	1.775
W32	174.65	-36.78	1.62	0.165	1.785
W33	174.65	-36.77	1.63	0.165	1.795
W34	174.61	-36.77	1.66	0.165	1.825
W35	174.59	-36.79	1.66	0.165	1.825
W36	174.6	-36.76	1.68	0.165	1.845
W37	174.64	-36.76	1.66	0.165	1.825
W38	174.66	-36.77	1.62	0.165	1.785
W39	174.66	-36.77	1.62	0.165	1.785
W40	174.66	-36.77	1.62	0.165	1.785
W41	174.68	-36.76	1.64	0.165	1.805
W42	174.68	-36.74	1.66	0.165	1.825
W43	174.68	-36.79	1.59	0.165	1.755
W44	174.68	-36.79	1.59	0.165	1.755
W45	174.7	-36.78	1.6	0.165	1.765
W46	174.69	-36.82	1.52	0.165	1.685
W47	174.71	-36.83	1.49	0.165	1.655
W48	174.74	-36.83	1.47	0.165	1.635
W49	174.75	-36.83	1.46	0.165	1.625
W50	174.76	-36.82	1.46	0.165	1.625
W51	174.77	-36.83	1.46	0.165	1.625
W52	174.77	-36.83	1.45	0.165	1.615
W53	174.76	-36.81	1.47	0.165	1.635
W54	174.77	-36.79	1.5	0.165	1.665
W55	174.79	-36.82	1.47	0.165	1.635
W56	174.79	-36.84	1.41	0.165	1.575
W57	174.79	-36.85	1.4	0.165	1.565
W58	174.8	-36.85	1.39	0.165	1.555
W59	174.83	-36.87	1.43	0.165	1.595
W60	174.82	-36.83	1.38	0.165	1.545

Site	Longitude	Latitude	MHWS-10 relative to MSL (MSL removed)	Updated MSL (2001-2019) offset from AVD-46	WL = MSL + MHWS−10
W61	174.82	-36.84	1.38	0.165	1.545

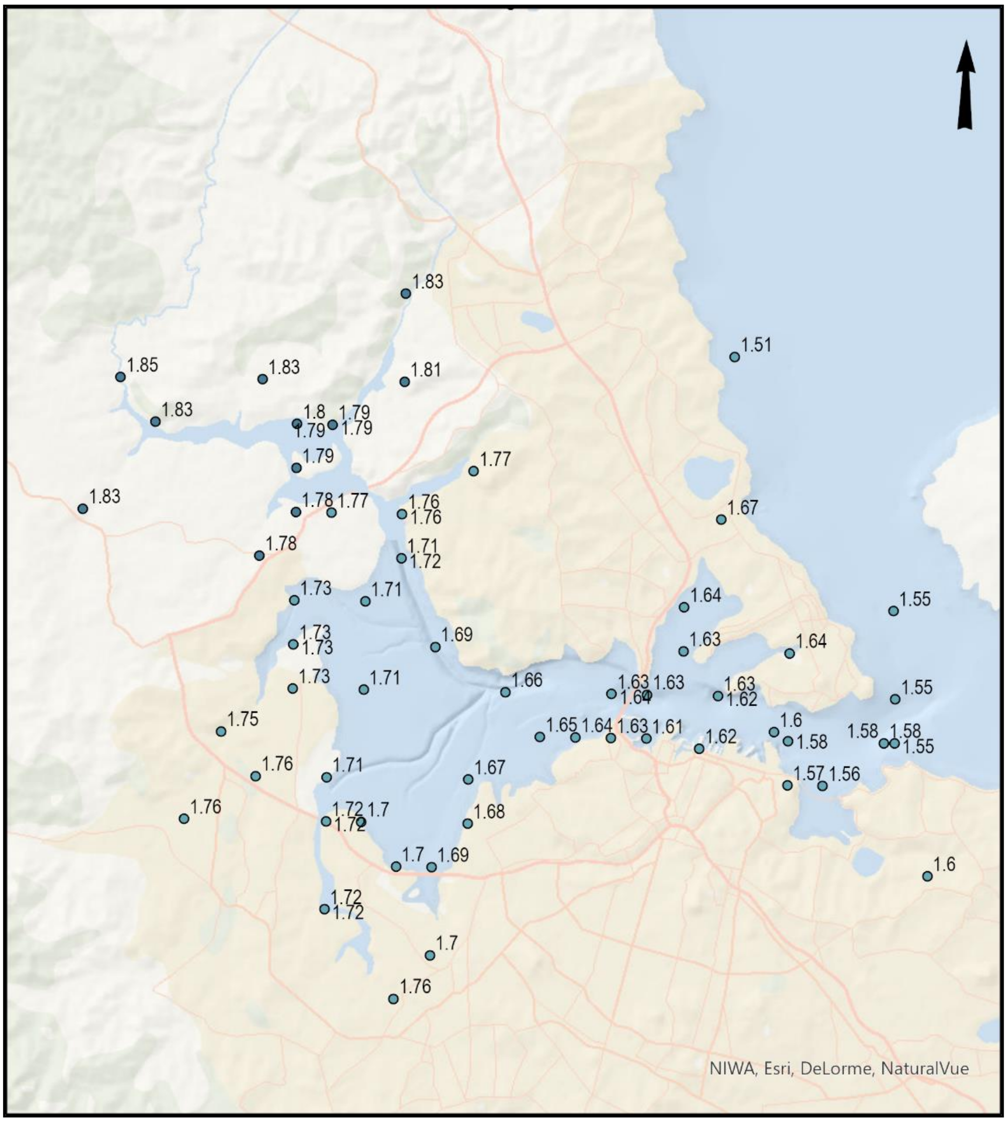

Figure A-1: Water level elevations including present-day MSL values relative to AVD-46 in the Waitemata Harbour.

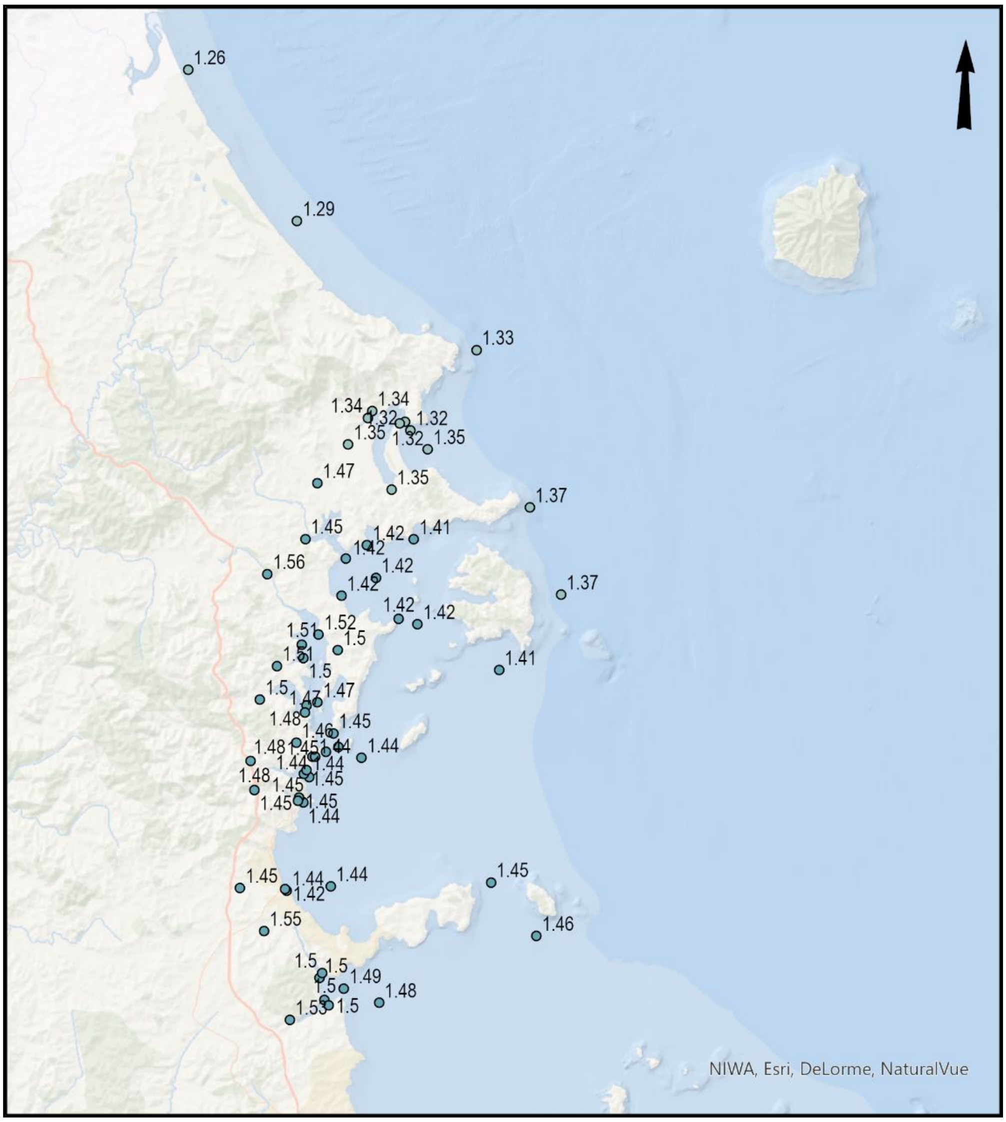

Figure A-2: Water level elevations including present-day MSL values relative to AVD-46 on Auckland's East coast.

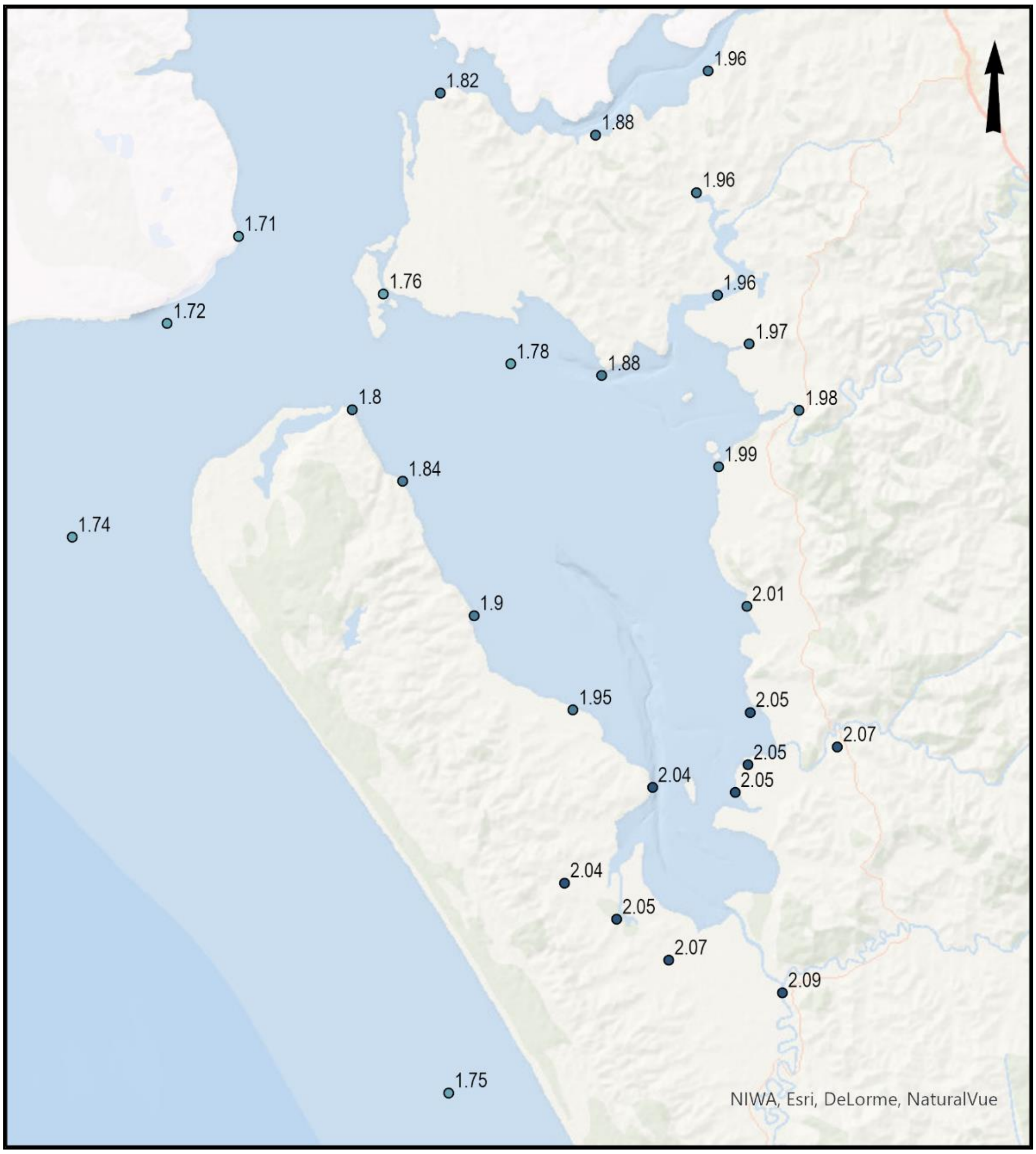

Figure A-3: Water level elevations including present-day MSL values relative to AVD-46 in the Kaipara Harbour and on the West Coast.

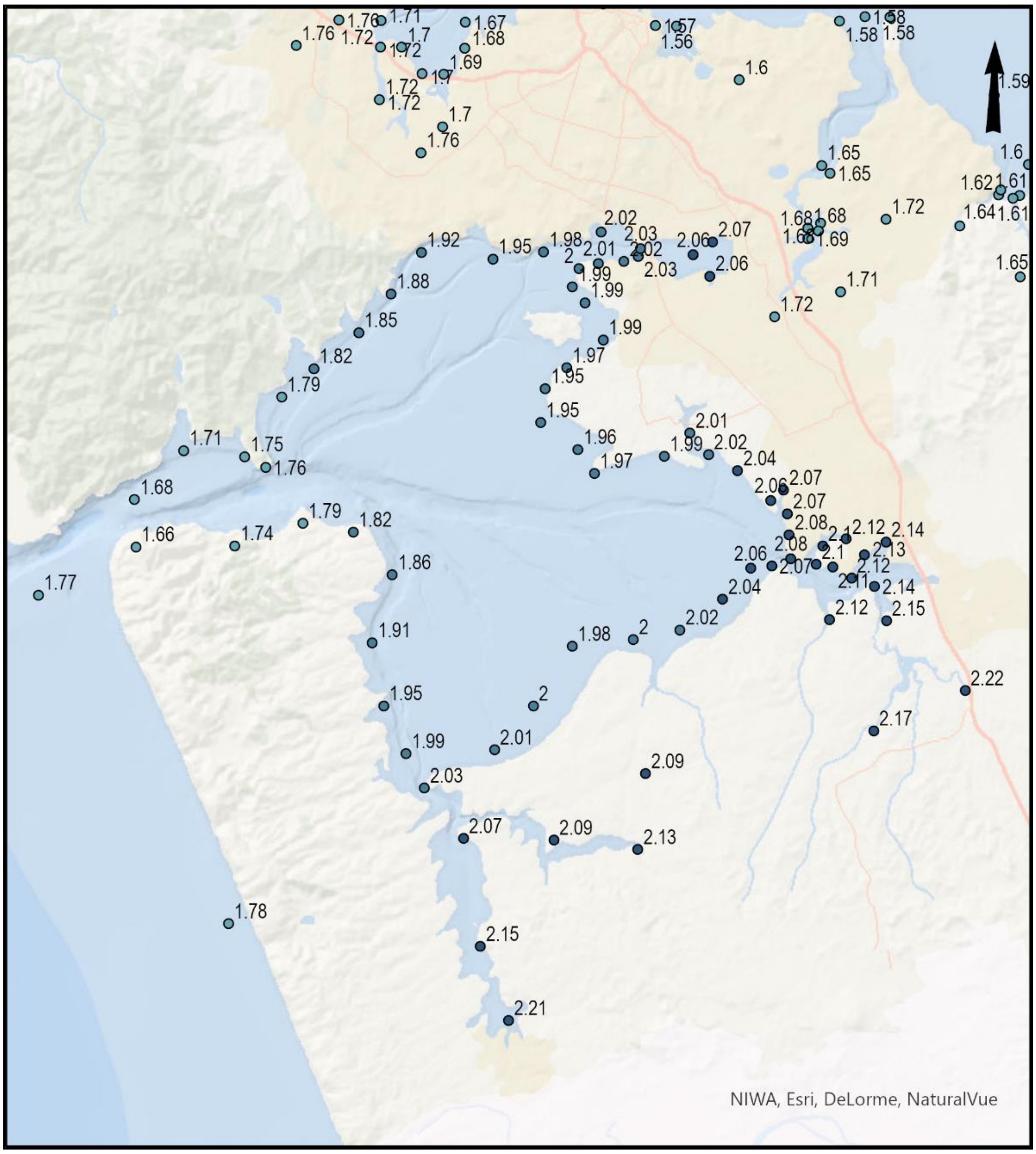

Figure A-4: Water level elevations including present-day MSL values relative to AVD-46 in the Manukau Harbour and on the West Coast.

Appendix B Mean sea level offsets

Table B-1: MSL offsets used in this study. The source project was reported by Reeve, G & Wadhwa, S. (2021) New Zealand tidal model calibration. NIWA Client Report 2021215HN to Land Information New Zealand, July 2021, 54 p., although the elevations in this table were not included in that report but are presented here instead.

Tide gauge site	Longitude E (WGS-84)	Latitude N (WGS-84)	MSL (CD or TG0) [m]	MSL epoch	No. of yrs	LVD name	Ref BM	BM above TG0 [m]	BM (LVD) [m]	BM (NZVD16) [m]	Offset: TG0 to LVD	Offset: TG0 to NZVD-2016	MSL (LVD) [m]	MSL (NZVD-16) [m]	Notes:
Opua - Bay of Islands	174.1211	-35.3122	1.50	2001-2019 (est)	19	OTP-64	A1DG (9)	4.681	3.1231	3.0494	1.558	1.632	-0.058	-0.132	Using 1993-94 Opua data (1.389 m), for same period Marsden Pt was 1.485 m and 1.60 m for 2001-2019 - so factor increase is 1.0774 - so for Opua factor * 1.389 m = 1.50 m. TGzero (CD) is rel to A1DG (9) BM - and used adjacent BM A1E6 for NZVD2016 offset
Whangarei Port	174.35	-35.767	1.85	2001-2019 (est)	19	OTP-64	A2Q9	5.182	3.27	3.1400	1.912	2.042	-0.062	-0.192	MSL for Sept 1999 to Jun 2007 from Hannah & Bell (2012) - pro-rat'd with same period at Marsden Pt (1.598 m) to estimate 2001-2019 MSL (needed a x factor of 1.01 or a 15 mm increase
Marsden Point	174.5	-35.842	1.610	2001 – 2019	19	OTP-64	DJM9	4.8160	3.1378	3.0700	1.678	1.746	-0.068	-0.136	
Port Auckland	174.76938	-36.8436	1.910	2001 – 2019	19	AVD-46	DD1N	5.2330	3.4878	3.1370	1.745	2.096	0.165	-0.186	
Manukau Entr	174.5117	-37.0466	3.650	2010 - 2020	10	AVD-46	EW4T			3.5500			0.187	-0.100	Older TG0 used BM EFYL: - 5.209 m below EFYL in LINZ get data page. Calculated AVD-46 from LINZ Conv site
Onehunga	174.7841	-36.933	2.430	2001 – 2019	17	AVD-46	ADLT	5.5930	3.3890	3.1000	2.204	2.493	0.226	-0.063	

Tide gauge site	Longitude E (WGS-84)	Latitude N (WGS-84)	MSL (CD or TG0) [m]	MSL epoch	No. of yrs	LVD name	Ref BM	BM above TG0 [m]	BM (LVD) [m]	BM (NZVD16) [m]	Offset: TG0 to LVD	Offset: TG0 to NZVD-2016	MSL (LVD) [m]	MSL (NZVD-16) [m]	Notes:
Clarks Beach - Manukau	174.69255	-37.14745													
Anawhata															
Port Albert - mid Kaipara Hbr						AVD-46	F4C1		3.0630	2.7500			0.270	-0.040	Used recent JLAS leveling - no AVD-46 level directly available. Estimate using LINZ Coord Transform for same BM gives 3.063 m AVD-46 (so offset between datums is 0.313 m
Pouto Point - Kaipara	174.1816	-36.3626	2.301	2004-2019	15	OTP-64	B5R9	5.3270	3.1700	2.8800	2.157	2.447	0.144	-0.146	From Tideda file held by NIWA for NRC data from Pouto
Helensville	174.4430	-36.6480		2006 – 2013									0.28		From analysis of Helensville sea-level gauge in report: Technical report: coastal-storm inundation in the Auckland Region - supplementary information, Updated coastal-storm exposure at Parakai and re-mapping of east-coast estuaries, Prepared for Auckland Council, March 2016

Appendix C Miscellaneous tidal information

Table C-1: Tidal harmonic analyses undertaken January 2023. Epoch-averaged tidal harmonic analysis, undertaken using UniTide (Foreman et al. 2009) applied with full statistics and signal-to-noise-ratio = 10. Elevations in metres above MSL (do not include any MSL offset from LVD).

Site	Analysis timeseries start	Analysis timeseries finish	HAT	MHWPS	MHWSC	MHWSn	MHWS-10	MLWS-50	M2	S2	N2
Ports of Auckland tide gauge	1/10/1998 06:00	30/09/2017 23:00	1.79	1.55	1.39	1.32	1.49	-1.14	1.14	0.18	0.23
Onehunga	1/01/2001 15:40	31/05/2011 23:55	2.14	1.93	1.72	1.58	1.77	-1.47	1.34	0.35	0.25
Pouto Point	18-Apr-01	1-Sep-12	1.84	1.64	1.46	1.36	1.51	-1.17	1.15	0.21	0.29
Helensville	31/05/2005 15:00	3/09/2014 10:00	2.22	1.93	1.77	1.60	1.83	-1.49	1.37	0.33	0.23
Anawhata	6-Jan-99	31/12/2011 23:00	1.74	1.54		1.25	1.40	-1.06	1.05	0.29	0.20
Dargaville	8/01/1995 18:00	8/01/2014 12:00	2.33	1.88	1.84	1.58	1.91	-1.43	1.36	0.30	0.22

Table C-2: Tidal harmonic analyses of water-level records collected in the Kaipara Harbour. Source: Stephens et al. (2011). Elevations in metres above MSL (do not include a MSL offset from LVD). MHWSP were calculated at all locations: MHWPS = M2 + S2 + N2. MHWS-10 elevations were calculated at Pouto Point and Helensville only—they were estimated at other locations using the average ratio of MHWS-10 to MHWPS at Pouto Point and Helensville.

Site	Longitude (WGS84)	Latitude (WGS84)	*MHWSP*	*MHWS10 (scaled)*	*M2*	*S2*	*N2*
Pouto Point	174.1816	-36.3626	1.65	1.52	1.15	0.21	0.29
Harbour Entrance	174.1486	-36.3962	1.62	*1.52*	1.14	0.28	0.20
Orongo Point	174.3536	-36.4139	1.76	*1.65*	1.23	0.31	0.22
Shelly Beach Wharf	174.3802	-36.5705	1.91	*1.79*	1.35	0.33	0.24
Tauhoa Channel	174.3105	-36.4100	1.67	*1.57*	1.15	0.30	0.22
Ru Point	174.1616	-36.2735	1.74	*1.62*	1.23	0.29	0.22
Tinopai	174.2757	-36.2457	1.80	*1.68*	1.26	0.31	0.22
Ruawai (ADCP)	174.0354	-36.1605	1.78	*1.66*	1.26	0.30	0.22
Ruawai (Dobie)	174.0354	-36.1605	1.84	*1.71*	1.31	0.30	0.22
Hoteo	174.4467	-36.4261	1.83	*1.72*	1.30	0.32	0.22
Port Albert	174.4297	-36.2671	1.90	*1.77*	1.35	0.33	0.23
Helensville	174.4430	-36.6480	1.93	1.83	1.37	0.33	0.23

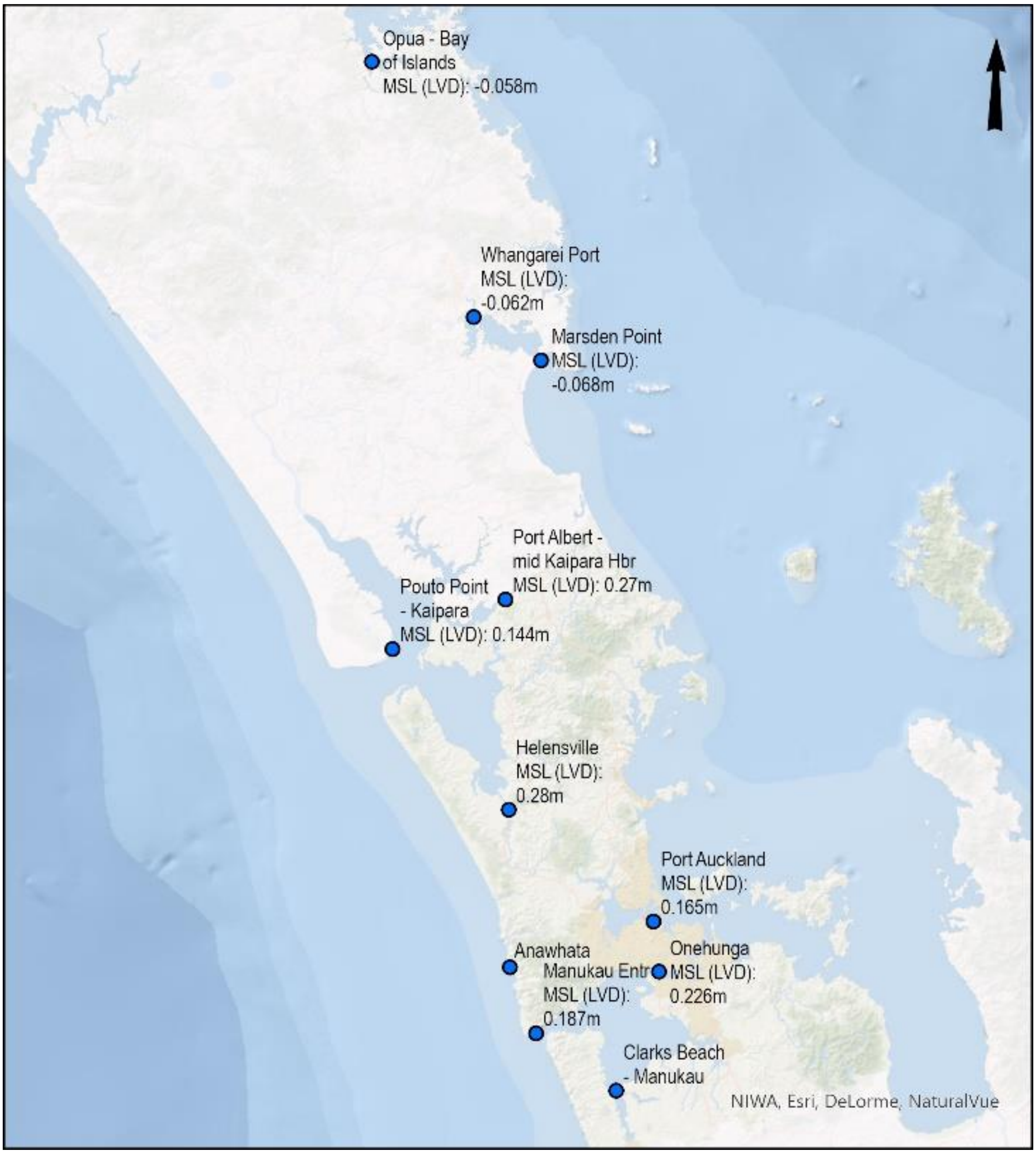

Figure C-1: MSL offsets used in this study (Table A-1).

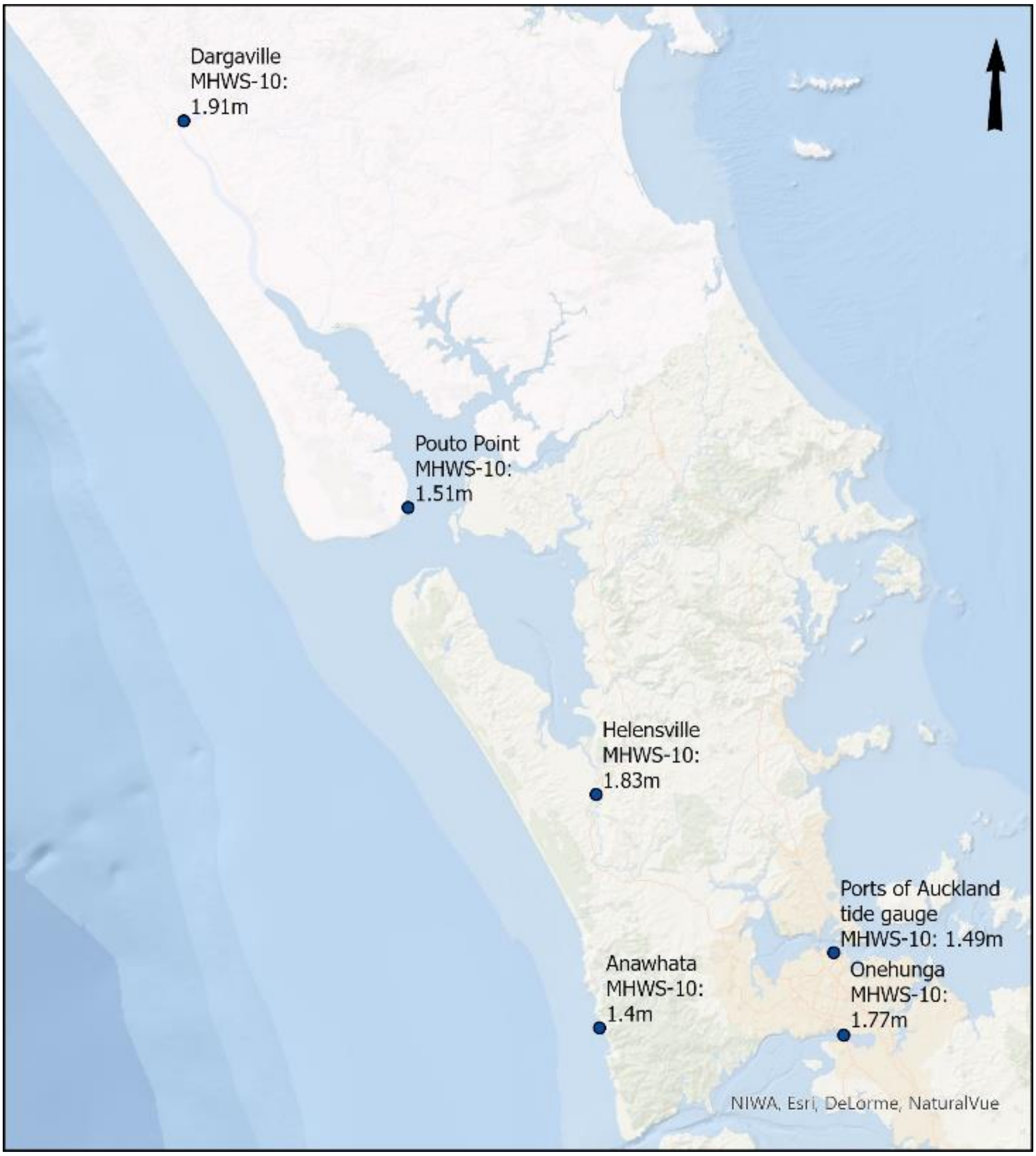

Figure C-2: MHWS-10 elevations from tidal Harmonic analyses from (Table C-1).

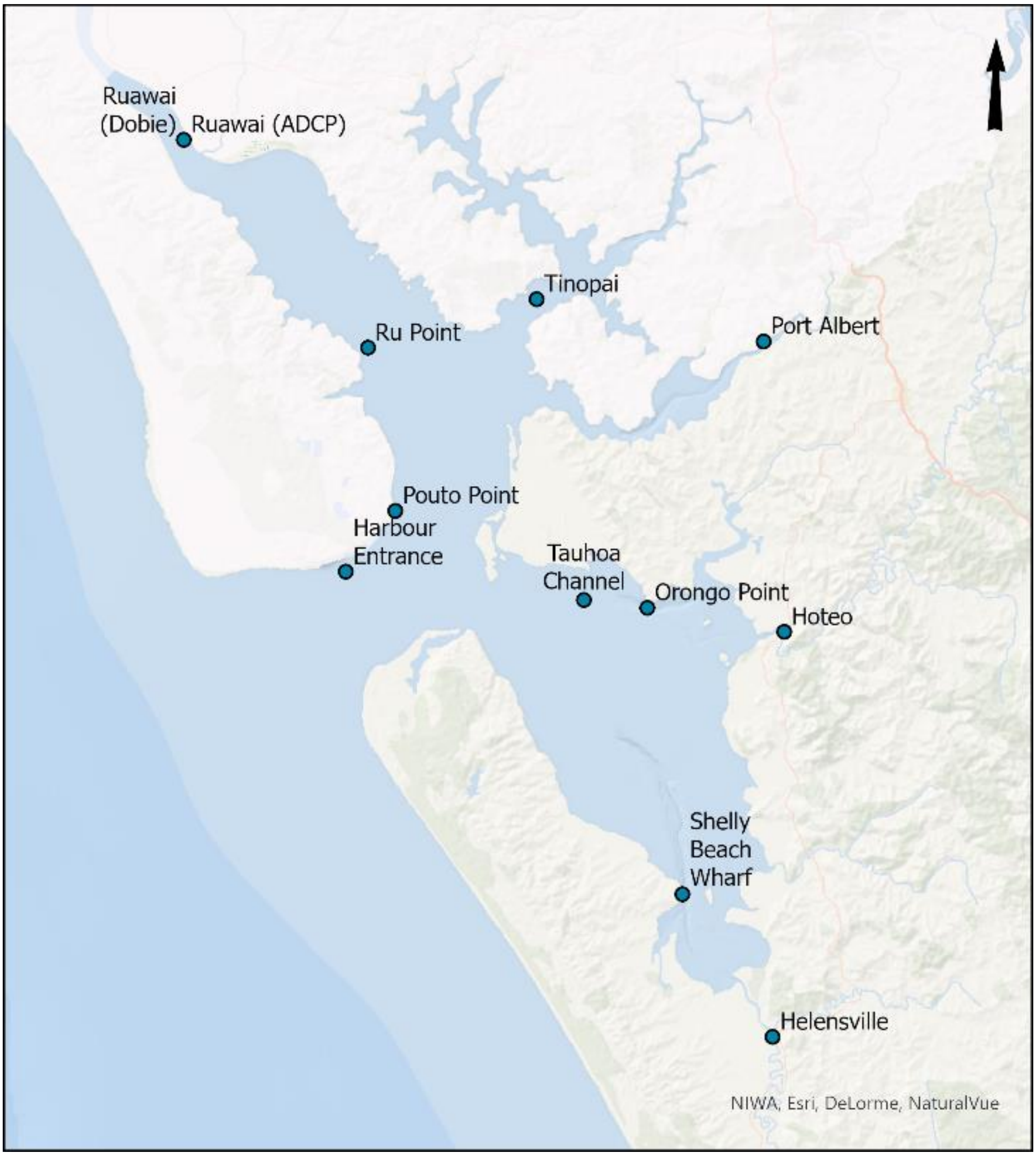

Figure C-3: Location of water level records used for tidal harmonic analyses within the Kaipara Harbour (Table C-2).