Development of an updated Coastal Marine Area boundary for the Auckland Region

Prepared for Auckland Council

July 2012

D R

Authors/Contributors:
Scott Stephens
Sanjay Wadhwa

For any information regarding this report please contact:
Scott Stephens
Coastal Scientist
Coastal and Estuarine Processes
+64-7-856 7026
s.stephens@niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
Gate 10, Silverdale Road
Hillcrest, Hamilton 3216
PO Box 11115, Hillcrest
Hamilton 3251
New Zealand

Phone +64-7-856 7026
Fax +64-7-856 0151

NIWA Client Report No:	HAM2012-111
Report date:	July 2012
NIWA Project:	ARC13233

Contents

Tables

Figures

Reviewed by

....

Approved for release by

....

Formatting checked by

Executive summary

Auckland Council commissioned NIWA to more accurately define the land/CMA boundary in the Auckland region, as delineated by a horizontal line of mean high water springs (MHWS) levels along the coast. The present Auckland Regional Plan: Coastal has a CMA landward boundary that was developed in the 1990s and is fairly coarse.

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 1. It provides a nationally-consistent estimate of MHWS that is unaffected by regional changes in individual tidal harmonic constituents, and 2. The CMA boundary line compared well with aerial photographs when generated using MHWS-10.

The MHWS-10 tide levels were then calculated at intervals along the region's coastline using available tide-gauge records and hydrodynamic numerical models.

An automated procedure was developed within GIS to produce a Coastal Marine Area (CMA) boundary line based on the intersection of the MHWS-10 levels and LiDAR[1]-generated digital elevation model of the coast.

The new CMA boundary line was validated against aerial photography. The automated procedure worked well along much of the coastline, although it was found that an additional wave setup offset was required along open coastlines to account for the background waves and swell. The automated procedure was less successful in areas with dense mangroves, and where land reclamation has occurred behind stop banks (but is still below MHWS). In these areas the automated procedure still provided an accurate guide to the location of the land–CMA boundary, but the boundary line was "patchy" and required manual editing with the aid of aerial photographs.

Confidence layers within GIS were produced that provide an informed opinion on the accuracy/confidence at different locations along the new CMA boundary, based on the quality of tidal level estimates, coverage of mangroves and the accuracy and quality of aerial photography and LiDAR datasets.

The final product was a line that faithfully reproduces the landward CMA boundary as defined by the intersection of MHWS-10 (and wave set-up on the open coast) with the coastal topography. At the time of writing this line has been included as a component of a spatial toolbox that provides a relatively accurate representation of planning boundaries, and forms an important component of the graphical representation of zones and overlays in Auckland Council's new Unitary Plan. The updated coastline better matches natural terrain boundaries and aerial imagery and more accurately represents the CMA planning boundary than Auckland Council's previous CMA boundary line.

While NIWA has made every endeavour to produce a reasonably accurate land/CMA boundary line, the confidence in the accuracy of the boundary line does vary around the Auckland region in relation to the sources of information used, as described in this report. While the supplied land/CMA boundary line overall provides a more accurate boundary for mapping and general planning purposes than that developed in the 1990s for the existing Auckland Regional Plan: Coastal, nevertheless this revised line is no substitute for accurate

[1] Light Detection And Radar aerial scanning to measure the land topography

determination of the MHWS by precise land surveying techniques in relation to individual cadastral boundaries, infrastructure, or setting out new developments or subdivisions.

1 Introduction

1.1 Background

The landward boundary of the coastal marine area or CMA (Section 2, Resource Management Act - RMA) also delineates a jurisdictional boundary under the RMA policy and planning framework and is defined by the line of mean high water springs (MHWS) except where it crosses a river. For completeness, the offshore boundary of the CMA is the outer limit of the territorial sea, defined as 12 nautical miles (22.2 km) offshore from the low-water mark.[2]

From a coastal management perspective, the inner CMA boundary is of significance as it defines the landward boundary for which various identified activities require a coastal permit and MHWS is often used as the baseline for coastal-hazard set-back zones. Conversely from a landward perspective, the CMA boundary is of significance as it defines the seaward boundary along the coastal margin for regulating the effects of land-based development through regional and district planning frameworks. Unitary authorities, such as Auckland Council, can produce a combined unitary plan that encompasses resource management across the landward CMA boundary, but the different approaches required under the RMA for managing activities and consenting in the CMA compared with land-use development still require an accurate knowledge of where the CMA boundary is located.

The mean high water springs line is dynamic in terms of its horizontal position at any particular coastal location (due to shoreline variability from coastal processes) and its definition in terms of a vertical elevation is not prescribed in the RMA or the NZ Coastal Policy Statement.

An indication of the location of the MHWS line is currently provided by the CMA boundary on the Auckland Regional Plan: Coastal (ARP:C) map series. The existing ARP:C mapped boundary consists of a single line for the entire region. This line was developed during the early 1990's prior to the proposed plan being notified in 1995. With the advancement of geographical information system (GIS) technology and the improved geo-referencing of aerial photography, this coastline now appears relatively coarse and inaccurate for some portions of the coast (e.g., Figure 1-1).

An important component of Auckland Council's new Unitary Plan will be its graphical representation of zones and overlays. These layers will be viewable along with updated aerial photography, forming a spatial toolbox that provides a relatively accurate representation of planning boundaries. To assist in this process, the coastal margin (coastline) needs to be represented in some manner as an important interface between landward environment and the coastal marine area and the different legislative frameworks that apply across this interface. The inclusion of the Coastal Plan within the Unitary Plan provides an opportunity to incorporate an updated MHWS coastline that more closely matches natural terrain boundaries and aerial imagery and more accurately represent the planning boundary.

[2] Section 3, Territorial Sea, Contiguous Zone, and Exclusive Economic Zone Act 1977

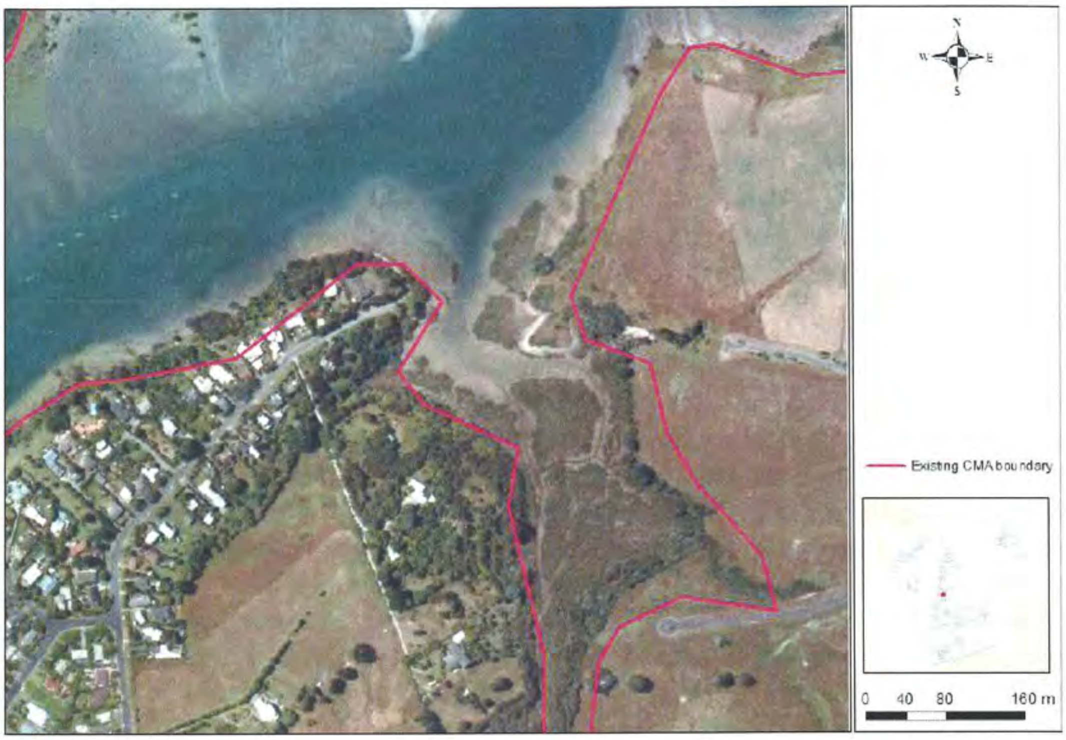

Figure 1-1: CMA boundary line for the Okura Estuary (for example) in the existing ARP:C map series.

1.2 Scope of the project

In May 2012, Auckland Council commissioned NIWA to:

- Define the land/coast CMA boundary in the Auckland region, as delineated by the horizontal line of MHWS levels along the coast.
- At project initiation, it was envisaged that the appropriate MHWS definition would be close to MHWS-10, which is the level equalled or exceeded by the largest 10% of all high tides. NIWA will check various definitions of MHWS, and provide evidence to support the use of the most appropriate MHWS definition for planning purposes in the Auckland region.
- Provide a range of tide levels at intervals along the coastline. The output sites will be chosen to allow accurate interpolation along a coastline. At each site, the tide levels will (at least) include the following MHWS level definitions (defined in Glossary): MHWSn, MHWPS, MHWSC, MHWS-10, HAT and MLWS-50.
- Develop an automated procedure within GIS to fit a MHWS CMA boundary line based on MHWS levels and LiDAR-generated digital elevation model (DEM).

- Validate the new MHWS CMA boundary line against aerial photography, and work alongside Auckland Council GIS specialists to remove fragments and 'join the dots' where data is absent (topology checks).
- The project did not include generation of a CMA boundary up river mouths and creeks, because additional rules apply in RMA interpretation, i.e., 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.
- Produce "confidence layers" within GIS that provide an informed opinion on the accuracy/confidence at different locations along the new CMA boundary, based on the quality of the LiDAR, the tidal levels, and the aerial photographs at different locations.
- The final product will be a line that faithfully reproduces the CMA boundary as defined by the intersection of MHWS with the coastal topography.

2 Methods

2.1 Sea level components – how they contribute to MHWS

There are a number of meteorological and astronomical phenomena that control sea level. The main processes involved are:

- Mean level of the sea (MLOS), which can vary up or down from months up to decades.
- Astronomical tides.
- Storm surge.
- Wave setup (and run-up).
- Climate-change affects including sea-level rise.

The mean level of the sea describes the variation of the non-tidal sea level on time scales ranging from a monthly basis up to decades due to climate variability, including the effects of El Niño–Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO) patterns on sea level, winds and sea temperatures, and seasonal warming/cooling effects. Note that MLOS describes a varying sea level on a time-scale from months upward. Thus it varies relatively slowly compared to tides, and so the tide oscillates around the mean level of the sea. Mean sea level (MSL) is calculated as the average MLOS over a known fixed period in time, usually several years. MSL is defined relative to a known vertical datum, usually Chart Datum at a Standard Port like Auckland or Onehunga.

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 of a persistent wind field, piling up against any adjacent coast (e.g., on Auckland's west coast, a NW wind will cause set-up at the coast as well as the more direct onshore SW winds).

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 at Port of Auckland. Thus, tidal harmonic analyses are used to separate the tide from other sea-level components.

Breaking swell and sea waves also temporarily raise the effective sea level at the coastline through wave set-up inside the breaker zone.

Finally, climate change is causing the mean sea level to rise. Over the last century, sea level has risen at a long-term rate of 1.5 mm/yr at Auckland relative to the land (Auckland Regional Council 2010), and it will continue to rise for many centuries due to lagged climate change effects.

For this study we are interested in defining a MHWS level that provides a reasonable representation of the vertical component of the CMA boundary line relative to recent mean sea level. Thus, there are two components of sea level that we need to define to calculate MHWS (Figure 2-1):

The mean sea level (MSL) relative to a fixed datum of interest.

The MHWS high-tide height above the mean sea level.

We ignore temporary water level variations due to storm surge and wave breaking. We average MLOS over recent years to calculate MSL. We undertake a tidal harmonic analysis to calculate high- and low-tide levels relative to MSL (which is tied to a vertical datum).

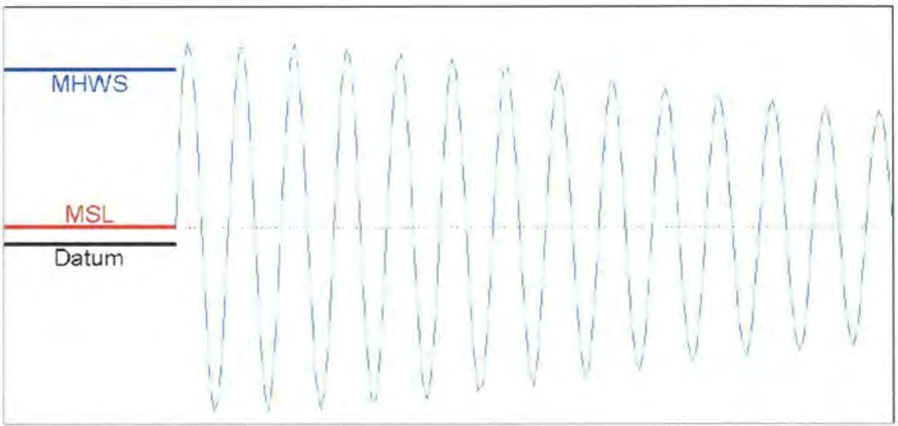

Figure 2-1: Schematic of the components contributing to MHWS: tide, MSL and vertical datum. The light blue line represents the transition of tide levels between a high spring and then neap tide. Here it is assumed that MLOS is at MSL.

2.2 Vertical datum

Before the introduction of New Zealand Vertical Datum 2009 (NZVD2009) in September 2009, land heights in New Zealand were referred to one of 13 local vertical datums, two of which are applicable to the Auckland region, being Auckland Vertical Datum–1946 and One Tree Point Datum–1964.

These local datums were established historically by determining mean sea level (MSL) at a tide-gauge and then transferring this level by precise levelling to benchmarks in the surrounding hinterland.

Sea level is known to vary around the coast of New Zealand. This means that the level of MSL determined at each datums tide-gauge will be different and that offsets will occur between adjacent datums. Also, in most cases the level of MSL for the vertical datums was determined many decades ago (apart from One Tree Point in the 1960s) and has not been officially updated since then to include the effect of sea level rise for instance.[3] Recent MSL values for these local vertical datums have been reported by Hannah and Bell (2012).

[3] http://www.linz.govt.nz/geodetic/datums-projections-heights/vertical-datums/mean-sea-level-datums

At a particular port the level of the water is expressed as a height above a local datum which is also the datum used for the depths of the sea on nautical charts, known as chart datum (CD). This datum is defined with reference to permanent benchmarks ashore and the zero of the tide gauge. The chart datum adopted usually approximates Lowest Astronomical Tide (LAT) which is the lowest level the tide can be predicted to occur under normal meteorological conditions.

Auckland Vertical Datum 1946

Auckland Vertical Datum 1946 (AVD-46) was established as the mean sea level (MSL) at Port of Auckland from 7 years of sea level measurements collected in 1909, 1917–1919 and 1921–1923 (Hannah and Bell 2012). Based on these historical measurements, the MSL for Auckland Vertical Datum-1946 (AVD-46) was set in 1946 to +1.743 m relative to the present tide gauge zero at Port of Auckland, which equals chart datum.[4]

One Tree Point Datum 1964

One Tree Point Datum-1964 (OTP-64) was established as the mean sea level (MSL) at Marsden Point from 4 years of sea level measurements collected between 1960–1963. The historic MSL set in 1964 was +1.676 m relative to local chart datum at Marsden Point.

Offset between datums

Table 2-1 is extracted from Table 2 of the Standard for the NZVD2009 (LINZ 2009) showing the official offsets of the two local vertical datums from NZVD2009. This implies that OTP-64 is 0.28 m higher than AVD-46 on average, based on several benchmarks in both local datums. Note, however, that there is some spatial variability between local benchmarks and in the geoid that results in considerable uncertainty in the calculated offset between datums. Table 2-2 shows one example of a benchmark surveyed to both local vertical datums; the offset between datums at benchmark ABHL at Wellsford is 0.206 m. Furthermore in earlier research on developing geoid models for New Zealand, Amos (2007) shows a 0.25 m offset between the two local vertical datums, although the standard deviations of the variability in the offset calculations were higher than those finally achieved for NZVD2009. Overall, OTP-64 is about 25 cm higher than AVD-46, but its exact value is unknown and could differ by about ± 4 cm. Note: a progressive move towards using NZVD2009 for land elevations will eventually eliminate these cross-boundary issues with the offsets between adjoining local vertical datums.

Table 2-1: LINZ local vertical datum offsets from New Zealand Vertical Datum 2009. The offset is positive when it is above the local datum. http://www.linz.govt.nz/geodetic/datums-projections-heights/vertical-datums/new-zealand-vertical-datum-2009/nzvd2009-datum-offsets/index.aspx

Datum	Offset to NZVD2009 (m)
One Tree Point Datum 1964	0.06
Auckland Vertical Datum 1946	0.34

[4] Note: prior to the present Chart Datum set in 1 Jan 1973, the old Auckland Harbour Board Chart Datum was 0.15 m lower

Table 2-2: LINZ geodetic mark ABHL[5] at Wellsford is surveyed to both AVD-46 and OPT-64 datums. This suggests a 0.206 m offset between AVD-46 and OTP-64.

Datum	Height (m)
Auckland Vertical Datum 1946	65.6223
One Tree Point Vertical Datum 1964	65.4164

2.3 Defining present mean sea level

The aforementioned local vertical datums were established from the mean sea level, averaged over several years during different historical periods. Sea level has risen since the AVD-46 datum was established, at a long-term rate of 1.5 mm/yr at Auckland relative to the land (Auckland Regional Council 2010). Thus, mean sea level is now higher than when the local vertical datum were established. The OTP-64 datum is somewhat of an anomaly as present MSL is still below the OTP-64 datum zero at Marsden Point (partly due to the short record used from the 1960s and the way it was defined – not known).

To define MHWS levels in the Auckland Region, we need to calculate recent MSL by averaging modern sea-level gauge records, referenced to local vertical datum, as shown in Table 2-3. For an exact comparison, the averaging periods used in Table 2-3 should be identical. We were reliant on quality-assured data that was available and so the averaging periods are a little different, but are mostly post-2001, whereas the two local vertical datums were set several decades earlier. Small (expected $O \pm 1$ cm) uncertainties introduced from using slightly different averaging periods are insignificant for the purposes of establishing the CMA boundary line.

Table 2-3: Sea-level gauges with known offsets to local vertical datum used in this study. Shown in italics is a MSL derived from Hannah and Bell (2012)* for a longer half nodal-tide period (10 years) which confirms the Auckland value. The local gauge-zero level for Pouto Point was obtained from Northland Regional Council (Dale Hansen, pers. com.) and the Anawhata gauge-zero survey was undertaken by NIWA (Pete Pattinson and Ron Ovenden, pers. com.).

Sea-level gauge location	Local vertical datum	Chart datum (or gauge zero)	Mean sea level	Averaging period
Auckland	AVD-46	-1.743 (AVD-46)	+0.15 m (AVD-46)	2006–2011
			+0.15 m (AVD–46)*	*1999–2008*
Marsden Point	OTP-64	-1.676 (OTP-64)	-0.09 m (OTP-64)	2001–2011
Onehunga	AVD-46	-2.201 (AVD-46)	+0.22 m (AVD-46)	2001–2009
Anawhata	AVD-46	-2.298 (OTP-64)	-0.20 m (OTP-64)	1999–2011
Pouto Point	OTP-64	-1.687 (OTP-64)	+0.16 m (OTP-64)	2001–2011

Figure 2-2 plots the datum offsets from Table 2-3 along with additional offsets calculated from sea-level records at Dargaville and Ruawai. The sea-level records and their associated assigned datum level indicate that mean sea level in the Kaipara Harbour at Pouto Point is about 26 cm higher than at Auckland (Waitemata), 19 cm higher than at Port Onehunga

[5] http://apps.linz.govt.nz/gdb/index.aspx?mode=text&sessionid=1926320228801307049243&code=ABHL

(Manukau), 36 cm higher than at Anawhata, and about 6 cm higher than at Ruawai. The Pouto Point level is higher than we would expect from tidal shoaling theory, and we suspect that the Pouto Point gauge level offset may need re-surveying. The Pouto Point gauge was buried by a sand wave in about September 2012, so at the time of writing it is not possible to re-survey the gauge offset. The gauge zero for the sea-level gauge that NIWA operated at Anawhata (now closed) is also likely to be inaccurate (appears to be lower than expected) due to the open-coast wave environment which makes it difficult to establish a datum without the use of a tide-board. Thus we have lower confidence in the tidal levels predicted for the Kaipara Harbour and the open west coast of the Auckland region.

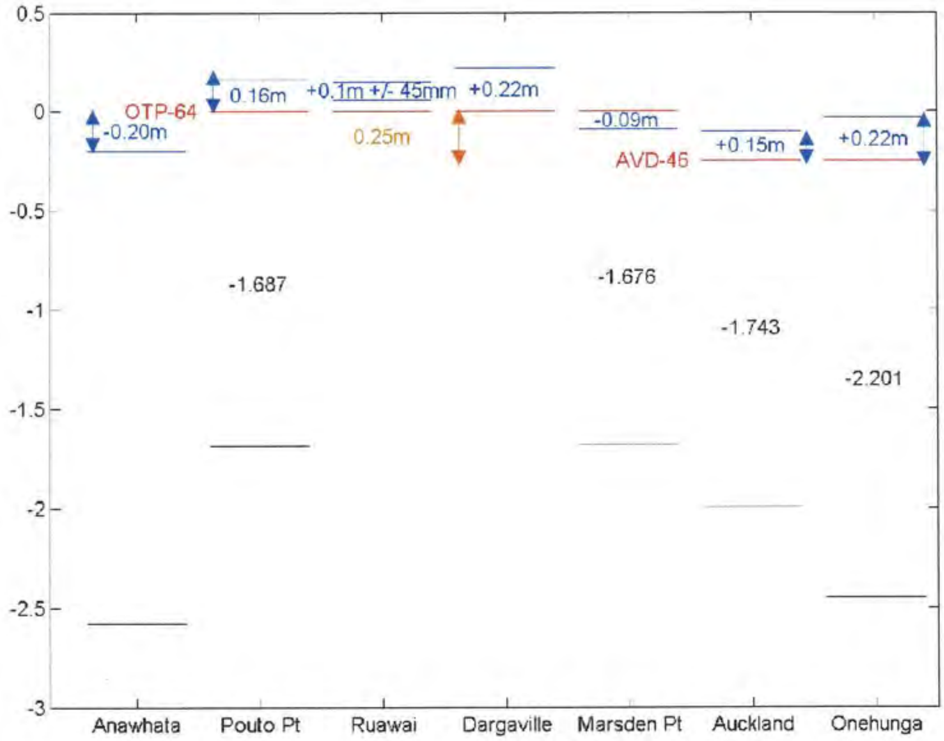

Figure 2-2: Relationship between One Tree Point 1964 datum and Auckland Vertical Datum 1946, and the derived mean level of the sea at both sites, for the period 2001-2011. An offset of 0.25 m has been assumed between OTP-64 and AVD-46. Red line indicates Local Vertical Datum, blue line indicates mean sea level, black line indicates chart datum or gauge zero.

2.4 Tides – what are they?

Ocean tides are the rise and fall of sea levels caused by the combined effects of the gravitational forces exerted by the Moon and the Sun and the rotation of the Earth.

The times and amplitude of the tides at a given location are influenced by the alignment of the Sun and Moon, by the pattern of tides in the deep ocean and by the shape of the coastline and near-shore bathymetry that substantially modifies the tidal wave.

Tidal constituents are the individual components which comprise the tides. Each constituent arises either from a specific astronomical feature or from the interaction between two or more constituents. Semi-diurnal or "twice-daily" tidal constituents dominate New Zealand tides (Walters et al. 2001) with tidal periods between 12–13 hours, e.g., the solar semi-diurnal constituent S_2 (12 hour period); the lunar semi-diurnal constituent M_2 (12.42 hour period); the elliptic semi-diurnal constituent N_2 (12.66 hour period) that covers the elliptical nature of the Moon's orbit around Earth each month.

In the Auckland Region there are two high tides most days with different heights (and two low tides also of different heights), a pattern resulting from the interaction of the M_2, S_2 and N_2 harmonic constituents, and known as a mixed semi-diurnal tide.

In New Zealand, the largest constituent is the "principal lunar semi-diurnal", also known as the M_2 tidal constituent, which results directly from the Moon's gravitational pull on the oceans (*M* stands for "Moon"). Its period is about 12 hours and 25.2 minutes, which is half the "lunar day" (24 hours 50 minutes) required for the Earth to rotate once relative to the Moon. The M_2 tidal constituent alone represents approximately an average tide range (between spring and neap). The two other most dominant harmonics are the S_2 and N_2 constituents.

S_2, the solar semi-diurnal constituent has a period of exactly 12 hours and this arises because the Sun passes over the same spot on Earth every 24 hours. Spring/neap tides occur every fortnight (14.765 days to be exact) in conjunction with Moon's phase in relation to alignment with the Sun: 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 (the solar semi-diurnal constituent). The S_2 tide is quite small on the east coast of New Zealand (Walters et al. 2001) compared to the west coast, which makes the fortnightly spring/neap cycle less pronounced on the eastern coasts (especially in the central regions).

N_2, the elliptic semi-diurnal constituent, arises from the elliptic orbit of the Moon around Earth. Each constituent has a unique tidal period. Perigean/Apogean tides occur every month (27.555 days to be exact) in conjunction with the position of the Moon in its elliptical orbit around Earth. When the Moon is closest to Earth, it is in its perigee and larger than normal Perigean tides occur. When the Moon is farthest from Earth, it is in its apogee and smaller than normal Apogean tides occurs. Another equivalent definition is that Perigean and Apogean tides are the result of M_2 (the lunar semi-diurnal constituent) beating in and out of phase with N_2 (the elliptic semi-diurnal constituent). Because the N_2 tide doesn't decrease on the east coast of New Zealand as much as the S_2 tide does, the main variation in tides on the east coast arises from a monthly Perigean/Apogean cycle superimposed on a smaller spring/neap cycle. This explains why the tides every second spring-tide period are higher than the previous set a fortnight earlier.

Perigean-spring combination tides peak about every 7 months (206.6 days to be exact) when New or Full Moon occurs at the same time as the Moon is in its perigee. Usually, these are the tides with the largest tidal range often referred to as "king tides". NIWA publishes annually a red-alert tide calendar[6] which covers the dates in New Zealand when higher Perigean-spring tides will occur and if they combine with storms, can have the potential to cause coastal inundation of low-lying areas.

While M_2, S_2 and N_2 are the major harmonic constituents in the Auckland Region, there are 62 tidal constituents (albeit mostly small) resolved in most harmonic analysis techniques, depending on the sea-level record length and quality.

2.5 High and low tide definition

The definition of MHWS continues to be subjective and various definitions have been applied for planning, nautical and legal purposes. For example, the nautical definition of mean high water spring tide has been traditionally defined as $MHWSn = M_2 + S_2$ amplitudes (half-range) above the mean sea level with the combination representing the higher high tide every fortnight on average. Another MHWS definition is the mean high water Perigean-spring tide, calculated from the combination of the three major tidal harmonic constituents as $MHWPS = M_2 + S_2 + N_2$, representing approximately the highest high tides in the months when the Moon's perigee approximately coincides with spring tides.

A numerical tidal model of the Exclusive Economic Zone around New Zealand has been developed (Walters et al. 2001), which was verified using tide data from a purpose-built network of open-coast sea-level gauges and satellite sea-surface height measurements in the ocean (Foreman et al.). Despite New Zealand's tidal regime being semi-diurnal, this study highlighted the contrast between the east and west coasts of New Zealand, as mentioned previously. On the west coast, the tidal regime is dominated by the more well-known spring and neap tides, so *MHWSn* is a more reasonable estimate of MHWS (excluding background wave/swell set-up). However, on the east coast of New Zealand the tidal regime is dominated by the 27.5-day cycle of Perigean and Apogean tides because the solar tide S_2 degenerates to quite low amplitudes (half-range). This means that in mid-eastern New Zealand locations, up to 50% of all high tides can exceed *MHWSn*. So simply on the grounds of substantial differences in tidal regime around New Zealand, the nautical definition of MHWS is not a nationally consistent measure of upper foreshore tide levels and should not be used for cadastral and administrative uses (Bell 2010).

Land Information NZ (LINZ) changed their method of calculating MHWS levels at Standard Ports in New Zealand to take into account the geographical variation in the semi-diurnal tide regime. LINZ produces two separate tables[7] for navigation and engineering/cadastral purposes, using a "search and average" algorithm. The MHWS values for engineering/cadastral purposes (*MHWS-C*) are based on tide prediction for the coming 19 years (approximately a nodal tide epoch) while those for navigation are only based on the year ahead. The algorithm for *MHWS-C* searches for two lots of successive pairs of highest tides per month, which are then averaged over the prediction period. This allows mixed Perigean and spring tides to be implicitly included (Bell 2010). However, the *MHWS-C* defined tide heights only apply to the areas in the vicinity of the 16 Standard Ports (and a former Standard Port at Whangarei).

[6] http://www.niwa.co.nz/natural-hazards/physical-hazards-affecting-coastal-margins-and-the-continental-shelf/storm-tide-red-alert-days-2013

[7] http://www.linz.govt.nz/hydro/tidal-info/tide-tables/tidal-levels/index.aspx and http://www.linz.govt.nz/geodetic/datums-projections-heights/vertical-datums/tidal-level-information-for-surveyors/index.aspx

Recent advancements arising from sea level modelling work in New Zealand have led to the development of high-tide exceedance curves calculated from all the tidal constituents that can be extracted from either tidal model results or measurements. These exceedance curves are typically based on predicting high tides over a 100-year period to encapsulate all possible tide combinations relative to a zero MSL initially, then adding on an offset for the present-day MSL relative to the required vertical datum (e.g. AVD-46). Similarly, an exceedance curve can also be produced for all low tides.

Annotating these Exceedance curves with various MHWS definitions (and even levels for other physical features such as edge of vegetation or toe of dune) provides a consistent framework for making long term pragmatic decisions on the appropriate vertical definition for MHWS and therefore the horizontal placement of the land/CMA boundary (Figure 2-3). Tide exceedance curves can also incorporate sea-level rise in a consistent, readily interpretable manner (Bell 2010) and are easily updated every 5-10 years as MSL changes by changing the MSL offset.

Tide exceedance curves for both high and low tide levels are plotted in Figure 2-3, for a location offshore of Mangawhai Harbour. In Figure 2-3, the tide exceedance curves were generated using 13 harmonic constituents from NIWA's EEZ tide model (Walters et al. 2001), but this study also uses harmonic analyses of tide gauge data. From the curves, a defining high- or low-tide level can be determined for any desired exceedance level, in this example the *MHWS-10* (high-tide level equalled or exceeded by only the highest 10% of all high tides) and *MLW-50* (low-tide level equalled or exceeded by 50% of all low tides) are marked. Tidal definitions marked on Figure 2-3 are:

- Highest astronomical tide – *HAT* (in this analysis the maximum in a 100-year prediction excluding any change in MSL including sea-level rise)
- Mean high water Perigean springs – *MHWPS* = $M_2 + S_2 + N_2$ amplitudes[8]
- Mean high water springs 10% – *MHWS-10* = the level equalled or exceeded by the highest 10% of all high tides.
- LINZ mean high water springs levels for Cadastral and Engineering purposes – *MHWS-C* = the averages of the levels of all monthly higher "spring" tides predicted to occur under average meteorological conditions during the next 18.6-year tidal epoch.
- Mean high water springs nautical – *MHWSn* = $M_2 + S_2$ amplitudes.
- Mean high water neaps nautical – *MHWNn* = $M_2 - S_2$ amplitudes
- Mean high water Apogean neaps – *MHWAN* = $M_2 - S_2 - N_2$ amplitudes
- Mean low water 50% – *MLW-50* = the level equalled or exceeded by 50% of all low tides.
- Lowest astronomical tide – *LAT* (minimum for a 100-year period).

[8] Amplitude is the tidal half-range for that particular tidal constituent – twice the amplitude gives the constituent tidal range

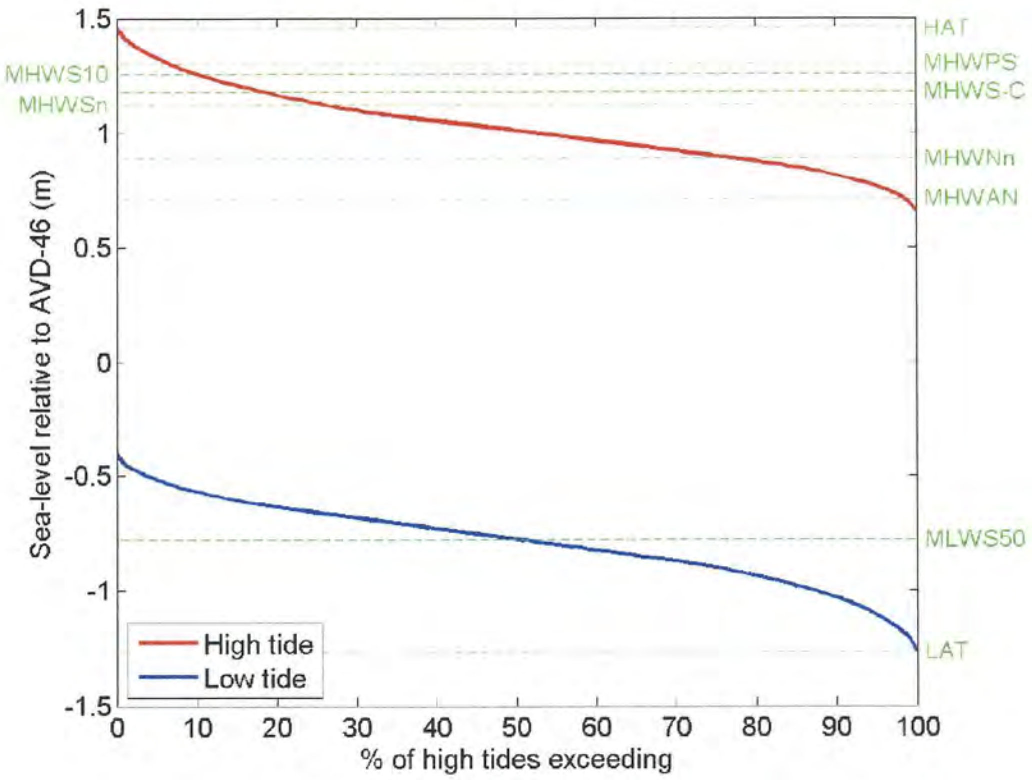

Figure 2-3: High-tide exceedance curves with various MHWS and low-water definitions marked, based on NIWA's EEZ tide model at Te Arai Point. Abbreviations are explained in the text.

2.6 Calculation of mean high water spring tide level

MHWS varies around the Auckland Region because the amplitude and phase of the various tidal constituents are modified differently by their interaction with the local coastal bathymetry including up estuaries and tidal creeks. Thus, MHWS must be calculated separately at different locations, rather than rely solely on the level at the nearest Standard Port. Our approach was to:

A. Use NIWA's numerical tidal model of the Exclusive Economic Zone around New Zealand (Walters et al. 2001) to extract tidal constituents and produce exceedance curves for sites along the open coast of the Auckland Region.

B. Use existing long-term sea-level gauge records to calculate tidal constituents and exceedance curves inside the Waitemata, Kaipara and Manukau Harbours. Use temporary sea-level gauges to calculate tidal amplification[9] factors for other locations within the harbours, relative to the permanent gauges. Apply the amplification factors to estimate tide levels at other sites.

[9] The tidal range generally increases (amplifies) as one goes up an estuary, harbour or tidal creek until it reaches an "upstream," peak before decreasing rapidly as the incoming tide enters rivers and streams.

The best source of information is sea-level gauge records of sufficient length and quality to undertake quality tidal harmonic analyses. Ideally, a minimum duration of 206-days is required for a tide-gauge to resolve sufficient tidal components to generate tide exceedance curves for use in defining the land/CMA boundary, and support predictions of extreme storm-tide levels. A 1-month duration is required for a basic harmonic analysis, but some constituents of relevance will not be resolved. A 366-day duration is required to separate out seasonal influences, but these tend to be similar across a harbour and so are usually captured by permanent gauges. Fortunately there are some good-quality sea-level records within the 3 major harbours in the Auckland Region at Port of Auckland (Waitemata), Port of Onehunga (Manukau), and Pouto Point (Kaipara).

MHWS on the open coast

The NIWA EEZ tidal model was used to calculate tidal harmonic constituents at sites offshore from the open coast of the Auckland Region (Figure 2-4). The EEZ tidal model includes the 13 most important harmonic constituents for the New Zealand EEZ (M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1, $2N_2$, MU_2, NU_2, L_2 and T_2)[10].

The principal M_2, S_2 and N_2 constituents were used to define high- and low-tide "nautical" spring and neap levels, along with Perigean spring and Apogean neap levels. From the constituents, a 100-year timeseries of tides was predicted, from which *HAT* was calculated plus the highest 25% of high-tide exceedance levels, in 1% increments, e.g., *MHWS-1* (%) through to *MHWS–25* (25%). Likewise, *LAT* and the lowest 25% of low-tide exceedance levels were predicted, in 1%-exceedance increments.

The EEZ tidal model predicts the astronomical tidal component of water level variation, relative to the mean level of the sea (effectively a MSL = 0). To predict the absolute level of MHWS relative to a known vertical datum, the mean sea level offset must be added to the predicted tide. The mean sea level offset was calculated from the Port of Auckland tide gauge record relative to AVD-46 (+0.15 m, Table 2-3); the AVD-46 datum being originally established from historical sea level measurements at this location, and the Port of Auckland being located close to the entrance of Waitemata Harbour and Auckland's open east coast. Spatial changes in the mean level of the sea are gradual along the open coast, therefore the 0.15 m mean sea level offset will be a close approximation for locations on the east coast of the Auckland Region. On the west coast of the Auckland Region, the Anawhata gauge measured a mean sea level of +0.08 m (AVD-46) from 1999–2011. This seems too low. The more reliable Onehunga gauge shows MSL is +0.22 m (AVD-46). At Paratutae Island at the Manukau Harbour entrance MSL is about 4.5–6 cm lower than at Onehunga (Bell et al. 1998), or 0.16–0.175 m (AVD-46). It seems a much needed task for both Auckland and Northland Regional Councils to invest in a precise survey and temporary small tide sensors to get more definitive Kaipara harbour and west coast sea levels in AVD-46 and at same time in NZVD2009 (which will be a more consistent (not level) datum across the region).

[10] The original paper on the EEZ tide model (Walters et al. 2001) only included 8 tidal constituents

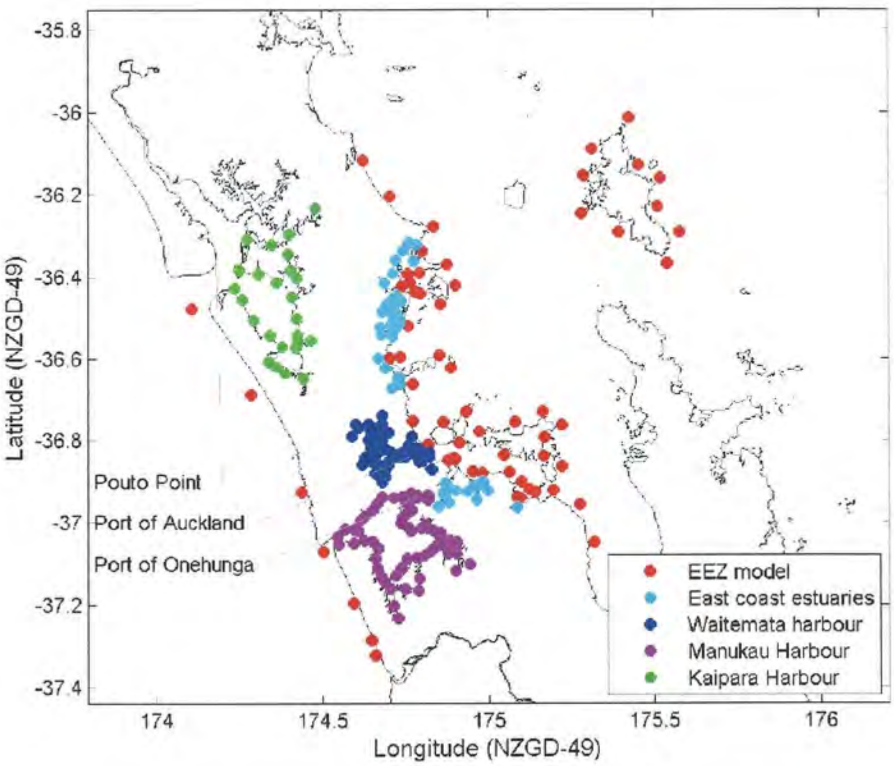

Figure 2-4: Location of tide level output sites in the Auckland Region. Red dots mark locations where tide levels were calculated using the the NIWA EEZ tide model, blue are Waitemata Harbour sites, green are Kaipara Harbour sites and purple are Manukau Harbour sites, light blue are Auckland east-coast estuaries. Locations of long-term sea-level gauges at Pouto Point, Port of Auckland and Onehunga are marked.

MHWS in the Waitemata, Manukau and Kaipara Harbours

We used available sea-level gauge records to calculate tidal exceedance levels in the Waitemata, Manukau and Kaipara Harbours. At present, accurate numerical tidal models are not presently available for most of the upper reaches of Auckland harbours and estuaries (e.g. Tamaki Inlet, Upper Waitemata harbour, Waiuku Inlet etc), mainly due to a paucity of seabed bathymetry (which critically controls the tide range in shallower waters). Hence the reason at this stage to use available historic measurements and interpolate between gauge locations rather than rely on coarse-resolution numerical models, whose performance can be uncertain in upper-harbour locations where the bathymetry is not well known. Furthermore, NIWA's high-resolution hydrodynamic model of the Kaipara Harbour for Auckland Council is still under development.

All three harbours have some high-quality long-term digital sea-level gauge records that allow robust tidal harmonic analyses. Like the EEZ tidal model, the harmonic analyses of the sea-level gauges were used to calculate MHWS and MLWS levels at the gauge sites. The long-term sea-level gauges are surveyed to local vertical datum, and so the local mean sea level offset was calculated for each gauge (Table 2-3). The high tide height tends to be amplified as the tidal wave propagates further up toward the upper arms of the harbours, caused by the shoaling of the tidal wave over the shallowing seabed, and it being squeezed into narrow upper-harbour arms.

Numerous short-term sea-level gauge records are available in all three harbours, accumulated from environmental studies conducted by NIWA and Auckland Council's predecessor organisations. These short-term records were not surveyed to local vertical datum, but at many locations were of 1-month duration, enabling the M_2, S_2 and N_2 constituents to be resolved from tidal harmonic analyses, using inference from the permanent sea-level gauges to infer some of the other key tidal constituents. Tidal amplification factors were then calculated based on the relative amplitude of the *MHWPS* (M_2 + S_2 + N_2) [or from the M_2 (average-tide) component where only that was available], and the distance between the short-term and permanent sea-level gauges (e.g., Table 2-4; Table 2-5, Table 2-6 and Figure 2-5 for the Kaipara Harbour). A tidal amplification factor was then calculated for output sites within the harbour, based on their along-channel distance from the permanent sea-level gauge. These tidal amplification factors were then applied to extend and adjust tidal levels from the permanent gauge site to the local output location. The local amplification factor was applied to all of the MHWS levels calculated from the permanent sea-level gauge.

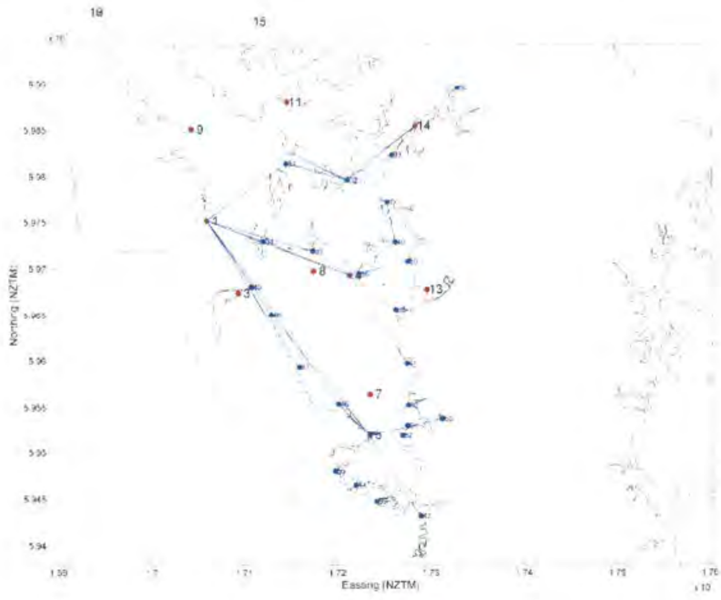

Figure 2-5: Kaipara Harbour showing tidal amplification track lines. Blue dots locations where tide levels were predicted, blue lines are distance tracks from the Pouto Point sea-level gauge, and red dots are short-term sea-level measurement locations.

Table 2-4: Waitemata Harbour sea-level gauge locations and M_2, S_2 and N_2 harmonic constituents. Amplitude (half-range) in cm and phase in °(NZST). Amplification (amp) factors calculated relative to Port of Auckland.

Site	Lon. (E) (WGS84)	Lat (N) (WGS84)	M_2 observed		S_2 observed		N_2 observed		*MHWPS*	M_2 amp. factor	*MHWSP* amp. factor
			Amp. (cm)	Phase (°)	Amp. (cm)	Phase (°)	Amp. (cm)	Phase (°)			
Port of Auckland	174.7649	-36.8423	1.14	204	0.18	276	0.22	171	1.54	1.00	1.00
Lucas Creek, Salthouse Jetty	174.6600	-36.7700	1.22	213	0.20	296	0.30	184	1.71	1.06	1.11
Beach Haven	174.6792	-36.7989	1.20	208	0.18	283	0.24	173	1.62	1.04	1.09
Lower Henderson Creek	174.6519	-36.8110	1.20	207	0.20	279	0.25	172	1.65	1.05	1.08
Upper Henderson Creek	174.6322	-36.8398	0.98	238						1.05	1.09
Down channel from Whau River	174.6733	-36.8497	1.10	235	0.33	300	0.18	297	1.62	1.04	1.05
Upper Whau River	174.6631	-36.8800	1.16	212	0.18	282	0.27	171	1.61	1.05	1.07
Lower Whau River	174.6616	-36.8521	1.20	208	0.19	279	0.25	172	1.64	1.05	1.06
Mid Harbour	174.6817	-36.8337	1.18	205	0.19	280	0.25	170	1.61	1.03	1.06
Shoal Bay	174.7603	-36.8107	1.17	206	0.18	281	0.25	166	1.59	1.02	1.02
Henderson c Creek outer channel	174.6653	-36.8161	1.20	207	0.18	278	0.25	170	1.63	1.05	1.07
Watchman Island	174.7382	-36.8324	1.16	205	0.19	278	0.25	169	1.59	1.01	1.02

Table 2-5: Manukau Harbour sea-level gauge locations and M_2, S_2 and N_2 harmonic constituents. Amplitude in cm and phase in °(NZST). Amplification (amp) factors calculated relative to Port of Onehunga.

Site	Lon. (E) (WGS84)	Lat (N) (WGS84)	M_2 observed Amp. (cm)	M_2 observed Phase (°)	S_2 observed Amp. (cm)	S_2 observed Phase (°)	N_2 observed Amp. (cm)	N_2 observed Phase (°)	*MHWPS*	M_2 amp. factor	*MHWS P* amp. factor
Onehunga			135.90	303	34.70	357	25.00	288	195.60	1.00	1.00
d05A	174.865	-37.054	138.82		33.29		28.72		200.83		1.03
d06A	174.858	-37.054	134.75		49.76		28.74		213.25		1.09
d07A	174.877	-37.073	140.12		33.78		28.75		202.65		1.04
d08A	174.885	-37.063	136.33		50.59		28.96		215.88		1.10
d10A	174.902	-37.087	134.45		30.68		26.36		191.49		0.98
d11A	174.917	-37.06	136.90		32.60		27.36		196.86		1.01
Waiau Pa 1977-78			126.80	299	32.90	350	19.30	279	179.00		0.92
Paratutae Island	174.511	-37.047	109.50	281						0.83	
Waiuku Channel	174.673	-37.12	131.30	300						0.99	
Papakura Channel	174.665	-37.027	122.10	294						0.92	
Papakura Channel	174.6969444	-37.03777778	125.40	294						0.95	
Papakura Channel	174.7991667	-37.03333333	132.50	299						1.00	
Purakau Channel	174.7080556	-37.97722222	126.00	296						0.95	
Wairopa Channel	174.7433333	-37.93833333	129.90	300						0.98	

Table 2-6: Kaipara Harbour sea-level gauge locations and M_2, S_2 and N_2 harmonic constituents. Amplitude in cm and phase in °(NZST). Amplification (amp) factors calculated relative to Pouto Point.

			M_2 observed		*S_2* observed		*N_2* observed				
Site	Lon. (E) (WGS84)	Lat. (N)(WGS84)	Amp. (cm)	Phase (°)	Amp. (cm)	Phase (°)	Amp. (cm)	Phase (°)	*MHWPS*	*M_2* amp. factor	*MHWSP* amp. factor
Pouto Point	174.1816	-36.3626	1.15	296	0.29	345	0.21	278	1.65	1.00	1.00
Harbour Entrance	174.1486	-36.3962	1.14	297	0.28	349	0.20	281	1.62	0.99	0.98
Orongo Point	174.3536	-36.4139	1.23	300	0.31	353	0.22	285	1.76	1.07	1.07
Shelly Beach Wharf	174.3802	-36.5705	1.35	305	0.33	360	0.24	290	1.91	1.17	1.16
Tauhoa Channel	174.3105	-36.4100	1.15	299	0.30	352	0.22	284	1.67	1.00	1.01
Ru Point	174.1616	-36.2735	1.23	305	0.29	360	0.22	287	1.74	1.07	1.05
Tinopai	174.2757	-36.2457	1.26	307	0.31	4	0.22	292	1.80	1.10	1.09
Ruawai (1)	174.0354	-36.1605	1.26	314	0.30	11	0.22	297	1.78	1.09	1.08
Ruawai (2)	174.0354	-36.1605	1.31	316	0.30	17	0.22	302	1.84	1.14	1.11
Hoteo	174.4467	-36.4261	1.30	307	0.32	2	0.22	289	1.83	1.12	1.11

MHWS in estuaries on Auckland's east coast

There are a number of estuaries on the east coast of the Auckland region for which there are no measured or modelled sea-level data. These estuaries include Whangateau, Matakana, Orewa and Silverdale, for example (light blue points in Figure 2-4). For these locations, we used a similar approach to that taken for the Waitemata, Manukau and Kaipara Harbours. We generated tide levels close to the entrance of these estuaries using the EEZ tide model, and applied an amplification factor that increased with distance from the entrance of each estuary. The applied tidal amplification rate was equivalent to the amplification between the Port of Auckland and Salthouse Jetty gauges in the Waitemata Harbour. We also calculated tidal harmonic constituents (and tidal amplification rates) using existing sea-level records at Pakuranga Bridge (Tamaki Estuary, Bell et al. 1996) and Dawsons Landing (Mahurangi Estuary, Oldman and Black 1997). The Tamaki estuary had a similar tidal amplification rate to the Waitemata Harbour, whereas the Mahurangi Harbour rate was approximately double. Thus there is uncertainty in the tidal amplification rates used for the smaller estuaries that have no sea-level records. This causes an uncertainty of about 2 cm elevation, which is of minor significance to the calculation of the CMA boundary line as confirmed by comparison of the CMA line with aerial photography.

2.7 Calculation of mean low water

Tidal exceedance curves also provide the opportunity to develop an indicative low tide contour for the Auckland region at the same time. Having an indication of the low tide line would be of value to assist with quantifying and mapping the spatial extent of intertidal resources in the Auckland region, assist with ecological value assessments and improve the understanding of coastal ecosystems. These areas are recognised for their complexity and high diversity, with the majority of Coastal Protection Areas in the present ARP:C including intertidal environments and associated ecosystem resources. Indicative extents of intertidal areas would also have value for coastal planning, with the locations of activities like Mooring Management Areas potentially influenced by intertidal ranges.

Expert advice has suggested that the median low water level (MLW-50) is a pragmatic low tide definition to delineate the low water extent of the intertidal zone from a biological perspective (Judy Hewitt, NIWA, *pers. comm.*). The MLW-50 definition is the low tide level that likely best coincides with intertidal community gradients and therefore provides the best representative contour line of intertidal extents.

Tide levels to estimate MLW-50 were calculated as for MHWS levels, described in the previous section.

2.8 CMA boundary line development

Auckland Council now has LiDAR data available for the entire region. This provides the council with detailed topographic information and digital elevation models which includes the coastal margins across the region. LiDAR data utilises the Auckland Vertical Datum–1946 for its elevation baseline, bearing in mind that present-day MSL is now about 0.15 m above this datum. The zero LiDAR contour therefore provides a historic MSL that is slightly lower than present-day MSL for the entire region, but is nevertheless tied into the widely-used AVD-46 vertical datum. Contouring above this line typically has a resolution of 0.125 m ground sampling distance (GSD) for urban areas and 0.5 m GSD for rural areas.

The high resolution and region wide accuracy of the dataset can potentially allow for the development of a coastline that more consistently matches aerial imagery. A landward offset to the MSL to take into account the high tide range can be developed which would bring the MSL LiDAR line to a closer approximation of MHWS tidal extents. Note that in rural areas, accuracy of aerial photography is ±3 m in the horizontal (Jovanna Leonardo, Auckland Council pers comm.), but is much better in urban areas.

Following the development and collation of point data associated with MHWS-10 around the region, it was proposed by NIWA that this MHWS-10 tidal height be used as the offset for development of a new indicative coastline that will become the new CMA landward boundary for the Unitary Plan (e.g., Figure 2-1). MHWS-10 was adopted by NIWA on the basis that 1. It provides a nationally-consistent estimate of MHWS that is unaffected by regional changes in individual tidal harmonic constituents, and 2. The CMA boundary line compared well with aerial photographs when generated using MHWS-10. The MHWS-10 point data was overlaid with the LiDAR digital elevation model (DEM) and a line approximating the coastline was then interpolated between the points, using aerial photographs as a reference. Ideally, a similar process would then be undertaken to develop a line approximating the MLW-50 contour to provide an indication of intertidal extents. However, the low-tide coverage of the LiDAR is insufficient to generate a MLW-50 line, since LiDAR does not easily penetrate the water surface at high tide.

2.8.1 Algorithm for CMA boundary line development

The CMA boundary line was developed by first creating a water surface that varied in elevation closely matching the MHWS-10 tide elevations around the coastline of the Auckland Region. This water surface was then intersected with the LiDAR digital elevation model (DEM) to the same AVD–46 datum. The line of intersection was captured which formed the raw CMA landward boundary. This line was then manually checked and adjusted by removing anomalies (such as in mangrove areas), and in some special cases a seawall line was added where needed (that wasn't captured in the LiDAR data).

The process used to develop the CMA boundary line in GIS is now described:

Creation of a varying level water surface around the region using MHWS-10 tidal height levels

1. Obtain the existing Auckland region CMA boundary line to use as a "coastline guide".
2. "Densify" the coastline guide by inserting a vertex every 10 m along the guiding coastline using the ArcGIS "Densify" tool.
3. Convert the guiding coastline to coast points using the "Feature vertices to points" tool. This created a new point shapefile for all the vertices in the guiding coastline shapefile.
4. Insert the MHWS-10 tide level data (included in Appendix) into a new shapefile (Figure 2-6).
5. Spatial join of tide level points to coast vertices. For all tide level output locations, a single coast vertex nearest to each of the tide level output locations was assigned the elevation of that nearest tide level. All other coast vertices in between remain empty.
6. Linear interpolation was used to interpolate tide levels to all vertices along the guiding coastline using the known levels for points that were nearest to tide output locations (Figure 2-7).
7. A buffer was created around the guiding coastline. The buffer can be described as a "window" within which the GIS will look for the intersection of the MHWS-10 elevation with the LiDAR DEM. The purpose of the buffer is to restrict the interpolation process to areas adjacent to the guiding coastline; otherwise the interpolation would be applied to the entire Auckland Region, causing slow computer performance, likely computer memory deficiency and spurious coastline generation. Before creating the buffer boundary, small islands like Pollen Island (Motu Manawa) and Herald Island that are close to the coast were added to the coastline file.
8. Random points were created in the coastal buffer. These random points along with coast points were subsequently used to create the water surface.
9. Spatial join of random points and the guiding coastline vertices. The random points within the buffers were assigned the elevations from the nearest guiding coastline vertices (created in step 6).

10. A terrain dataset was created using the random points with assigned tide levels.
11. The terrain data was converted to a raster of 1 m cell size. This raster is now a spatially-varying water level surface (Figure 2-8).

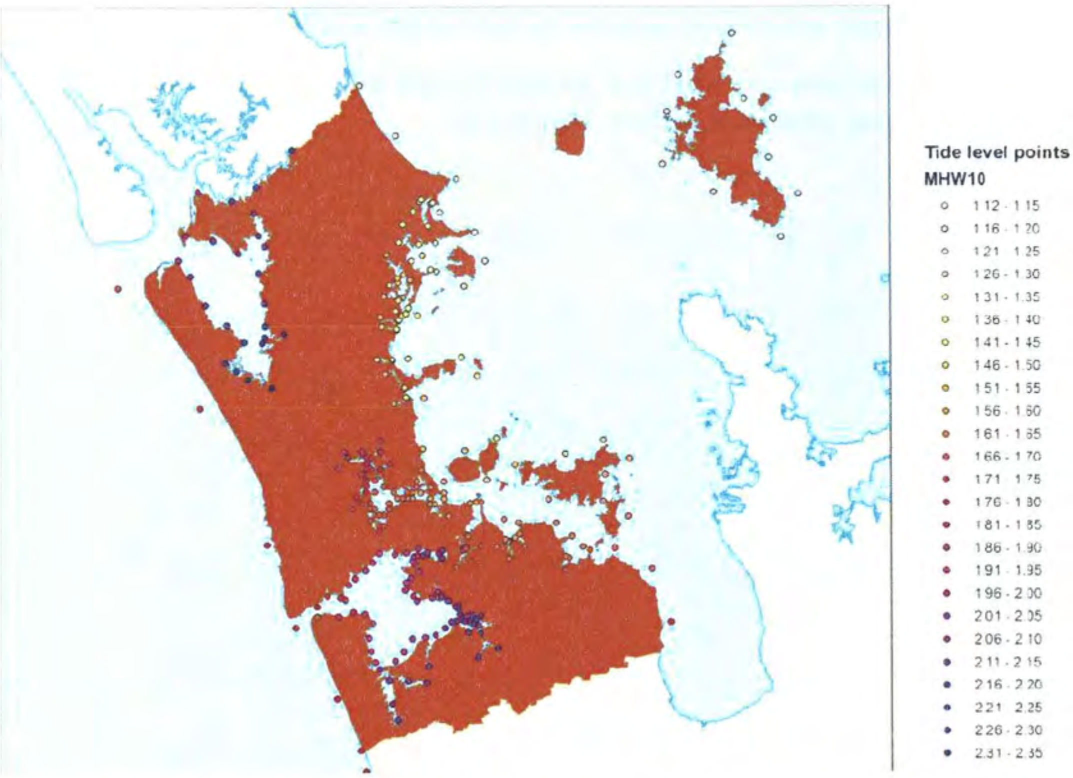

Figure 2-6: Map of the Auckland Region with MHWS-10 tide elevations marked at tide output locations.

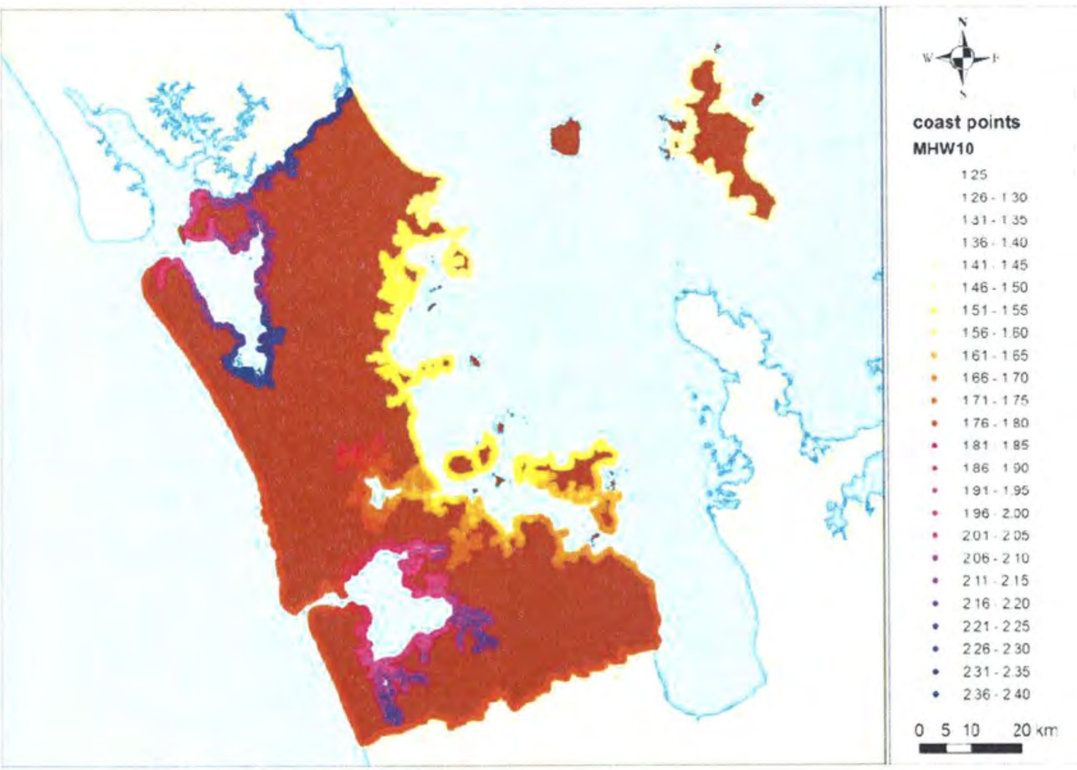

Figure 2-7: MHWS-10 tide elevations interpolated onto vertices along the guiding coastline.

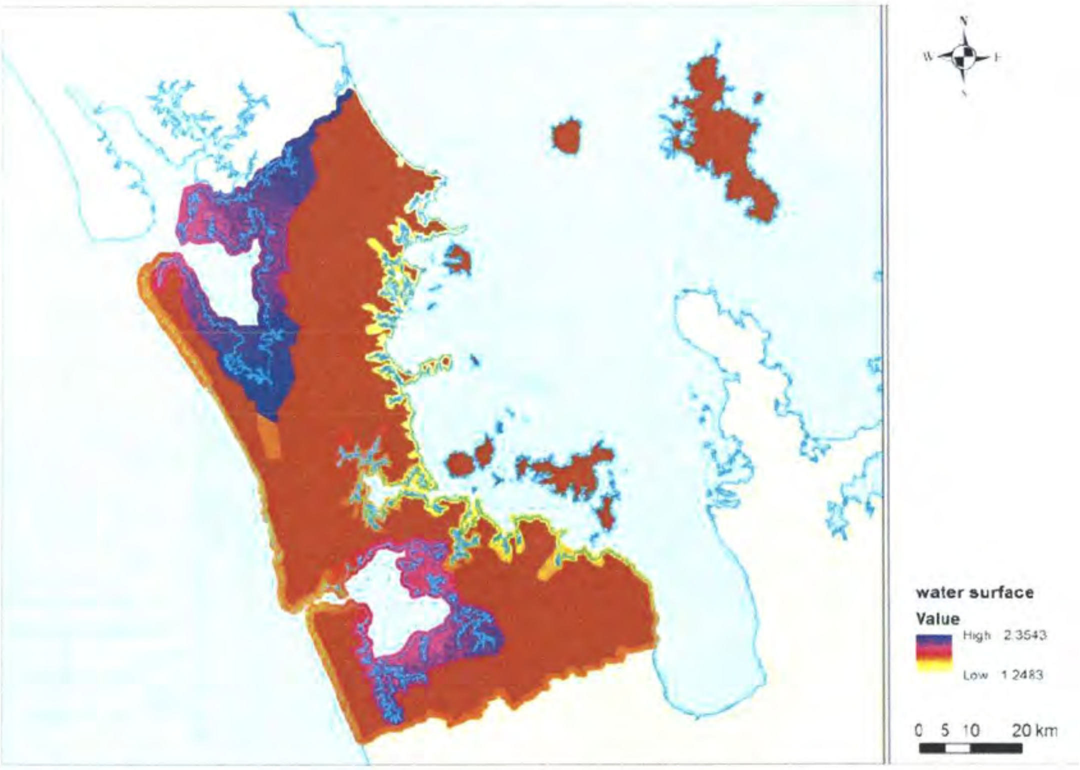

Figure 2-8: Spatially-varying water level surface raster built on a buffer around the existing CMA landward boundary.

Intersection of water level surface generated in with the LiDAR DEM and generation of coastline.

1. The "Minus" tool in Spatial Analyst toolbox in ArcGIS was used to subtract the water level surface from the LiDAR DEM. This created a difference raster.
2. Generation of line of intersection between the two surfaces. The "Contour" tool was used to create a contour of zero elevation on the difference raster. This provided the raw CMA boundary line for subsequent validation (Figure 2-9).

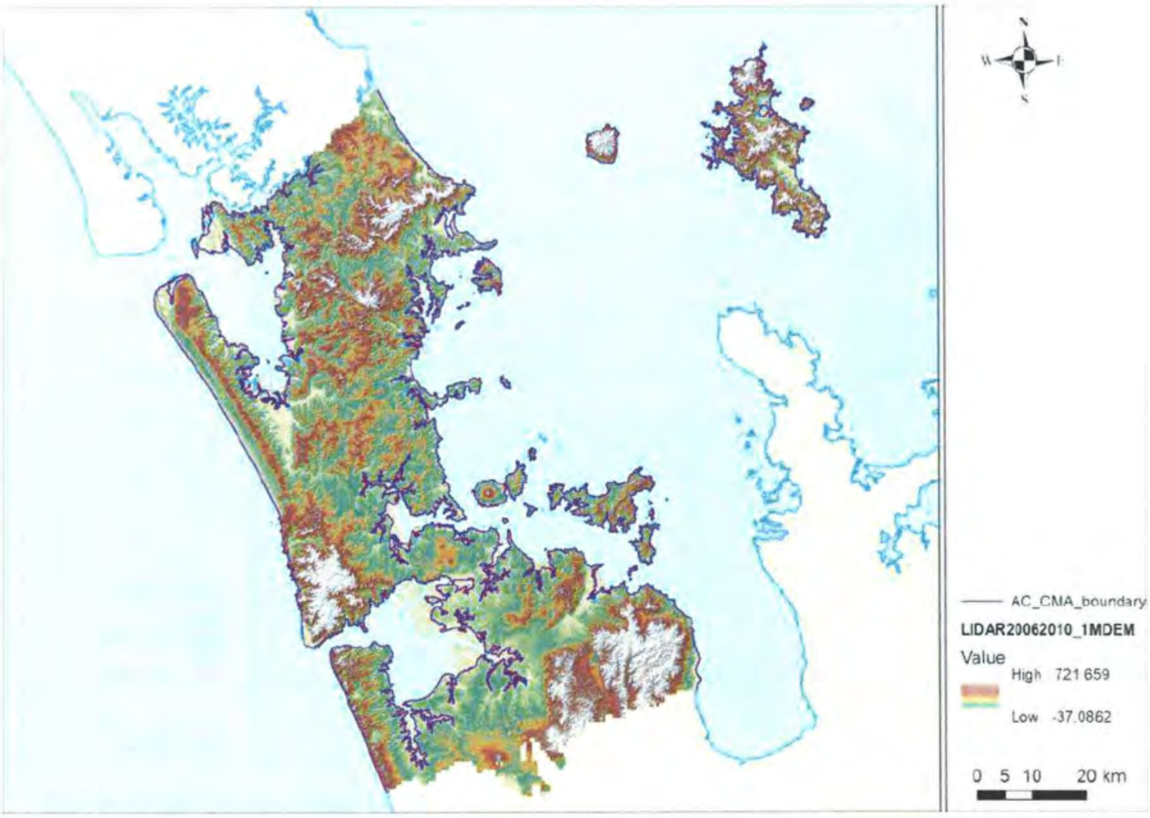

Figure 2-9: The newly-interpolated raw CMA boundary line, overlaid on a digital elevation model of the Auckland Region.

Validation of raw CMA boundary line

The CMA boundary line was validated by visually comparing it with recent orthorectified aerial photos, along with the existing coastline.

Uncertainty due to dense mangroves

In regions where dense mangroves were present, the LiDAR data often did not represent true ground level because the LiDAR did not penetrate the mangrove leaf canopy. In these regions the mangrove canopies created many "crossings" of the MHWS level, causing the automated GIS algorithm to return a "patchy" shoreline (Figure 2-10). This was corrected by manually editing the shoreline. The raw lines were overlaid on orthorectified aerial photos (Figure 2-10). Lines that followed the land boundary were kept and the remaining were erased using editing tools in ArcMap. The gaps were then filled in by digitising on screen using the aerial photo as a guide.

Wave setup in open-coast regions

The "open coast" is defined as regions that are exposed to ocean-generated swell waves. When waves break they release energy, causing the average sea level at the coast to be raised, or "set up" relative to sea level offshore from the surf zone. On sheltered coasts the intersection of the land with MHWS elevation is a good indication of the "average" land-sea boundary, but a wave setup factor needs to be added to MHWS for the open coast to incorporate average or background wave conditions. Wave setup was approximately calculated based on the average expected wave conditions. An average wave setup of 1–2 m was expected on the energetic west coast and 0.5–1 m on the east coast.

Several wave setup factors were trialled for both the east and west open-coast beaches, and values were chosen that best matched the leading edge of the most seaward sand dune vegetation line. For the west coast a wave setup value of 1.7 m was used. Figure 2-11 compares the MHWS line (top plot) and MHWS + 1.7 m wave setup line (lower plot). For the east coast a wave setup value of 0.7 m was used. Figure 2-12 compares the MHWS line (top plot) and MHWS + 0.7 m wave setup line (lower plot).

Stop banks

In parts of the Auckland region reclamation of intertidal flats has occurred in recent years. The reclamations involve the building of stop banks to hold the tide back from the original tidal flats, and the conversion of those tidal flats to pasture for grazing. The reclaimed land may still lie below MHWS, but is no longer flooded by the tide owing to the stop banks. Thus the automated GIS algorithm identifies the reclaimed land as seaward of the land-CMA boundary, when it is presently dry land. Furthermore, in the Kaipara Harbour the LiDAR was flown in 2006, before some stop banks were constructed, whereas the aerial photographs were flown in 2010–11, leading to a mis-match in information. In some cases the LiDAR picked up the stop bank, but not in sufficient detail to accurately resolve the shoreline, since the reclamations are mostly in rural areas where the LiDAR coverage is of lower resolution compared to urban areas. The top plot in Figure 2-13 gives an example of the raw land–CMA boundary line fitted to a reclaimed area. Like the mangrove areas, the land–sea boundary for reclamations was manually adjusted. Lines that followed the stop bank were kept and the remaining spurious boundary lines were erased using editing tools in ArcMap. The gaps were then filled in by digitising on screen using the aerial photo as a guide.

Confidence layers

Confidence layers were generated in ArcMap according to:

1. The quality of the LiDAR.
2. Our confidence in the tidal elevations.
3. Our judgement on the quality of aerial photographs.
4. Ability of the GIS procedure to automatically extract the CMA boundary.

Note that we have lower confidence in the automatically-generated CMA boundary line at beaches, than we do on "firmer" coastlines. Although the tides, LiDAR and photographs might all be high quality at beach areas, the sand can move on, off, or along the beach at short timescales in response to weather and wave events plus the photography and LiDAR were flown at different times. The automated procedure will fit to the position of the beach as recorded at the time the LiDAR was flown, and so the generated CMA boundary line might not match present beach position.

Figure 2-14 shows an example of the confidence layer produce for tidal levels. We have "high" confidence where we have tide gauge deployments, and on the open coast where the nearshore bathymetry is well resolved in the EEZ tide model. We have relatively "low" confidence in upper-harbour regions where there are no tide gauge records, and where there is uncertainty in the accuracy of the bathymetry in the numerical models used to predict the tides. We have "medium" confidence between these zones. Relatively "low" confidence in the Kaipara Harbour and on the open west coast occurs because we are not confident in the levelling offset for the Pouto Point or Anawhata tide gauges. Furthermore, our confidence is reduced in open-coast areas due to uncertainty in wave setup, which elevates the natural land-sea boundary above the MHWS level.

The confidence level for the DEM grids (Figure 2-15) was assigned based on LiDAR acquisition date:

- High – North Shore 1 point per square metres, ± 0.1 m accuracy at the 68% confidence interval.
- Medium – Urban 1 point per every 2 square metres, ± 0.25 m accuracy at the 95% confidence interval.
- Low – Rural 1 point per 25 square metres, ± 0.5 m accuracy at the 95% confidence interval.

The confidence level for aerial photography (Figure 2-16) was based on imagery acquisition date; high 2010–2011 ±0.3 m horizontal accuracy, low 2006–2008 ± 3 m horizontal accuracy. Aerial images were used to check the automated CMA boundary line fit. Aerial photographs were also used to adjust anomalies that occurred where mangroves and stop-banks disrupted the automated CMA line fitting procedure. Along with superior horizontal accuracy, modern imagery provides a more recent representation of the coastline.

Figure 2-17 indicates the author's opinion of the overall confidence in the CMA boundary line. This is guided mainly by our confidence in the DEM grids and the MHWS-10 tidal elevations. A sensitivity test indicated that the horizontal accuracy of the 1 m^2 DEM has more influence on the position of the CMA boundary line than uncertainty in tidal elevations in most east-coast locations and in the Waitemata and Manukau Harbours. The exceptions are in the upper reaches of estuaries where tidal shoaling is uncertain, and in the Kaipara Harbour and on the west coast, where tidal levelling is uncertain. Our confidence is further reduced in open-coast areas due to wave setup and temporal variability in the volume of sand on open-coast beaches.

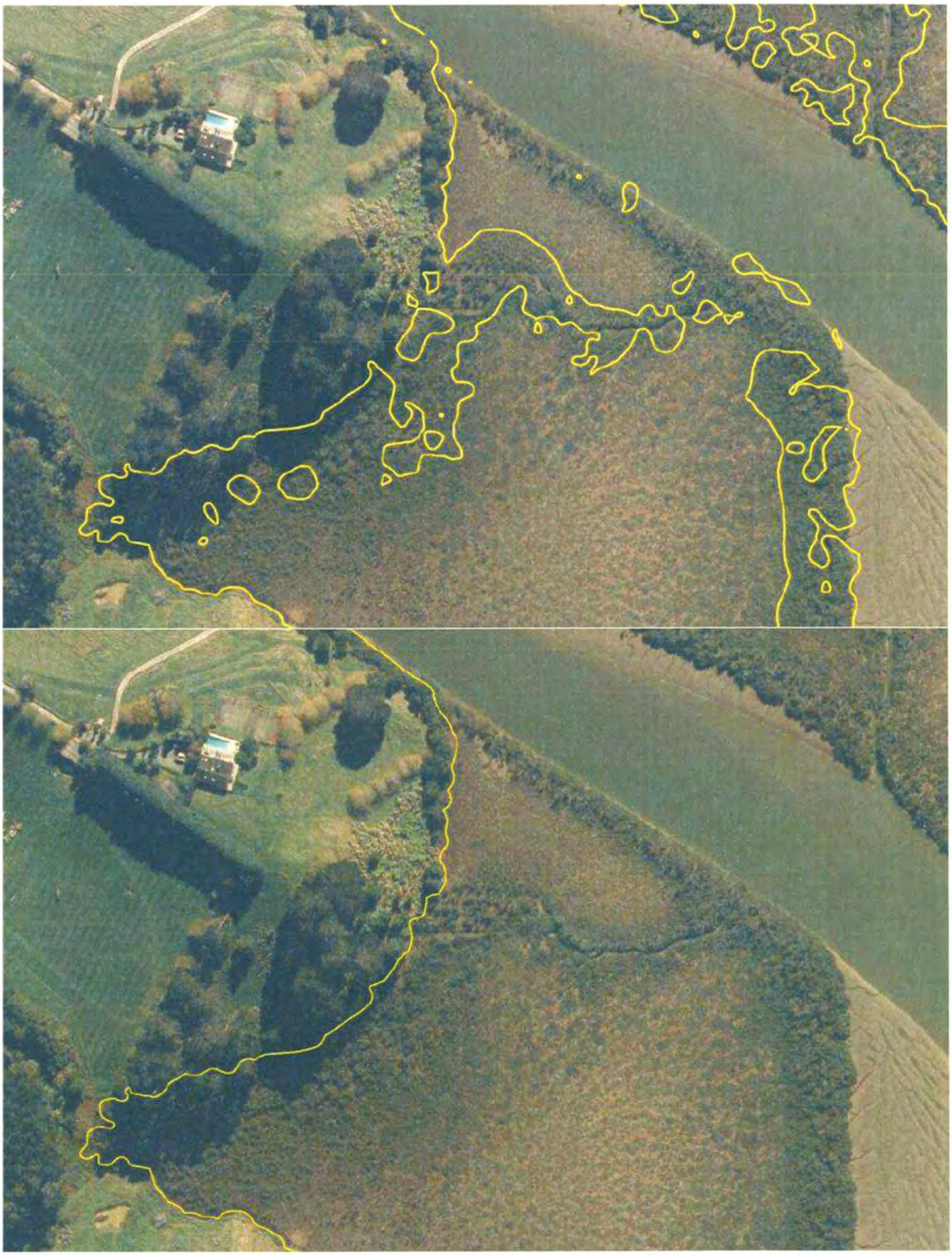

Figure 2-10: Example of the effect of dense mangroves on the automated CMA boundary contouring. The top plot represents the raw line fitted by the automated method. The bottom plot shows the manually adjusted CMA boundary.

Figure 2-11:Adding a 1.7 m wave setup elevation (bottom) to the MHWS-10 elevation (top) on the west coast.

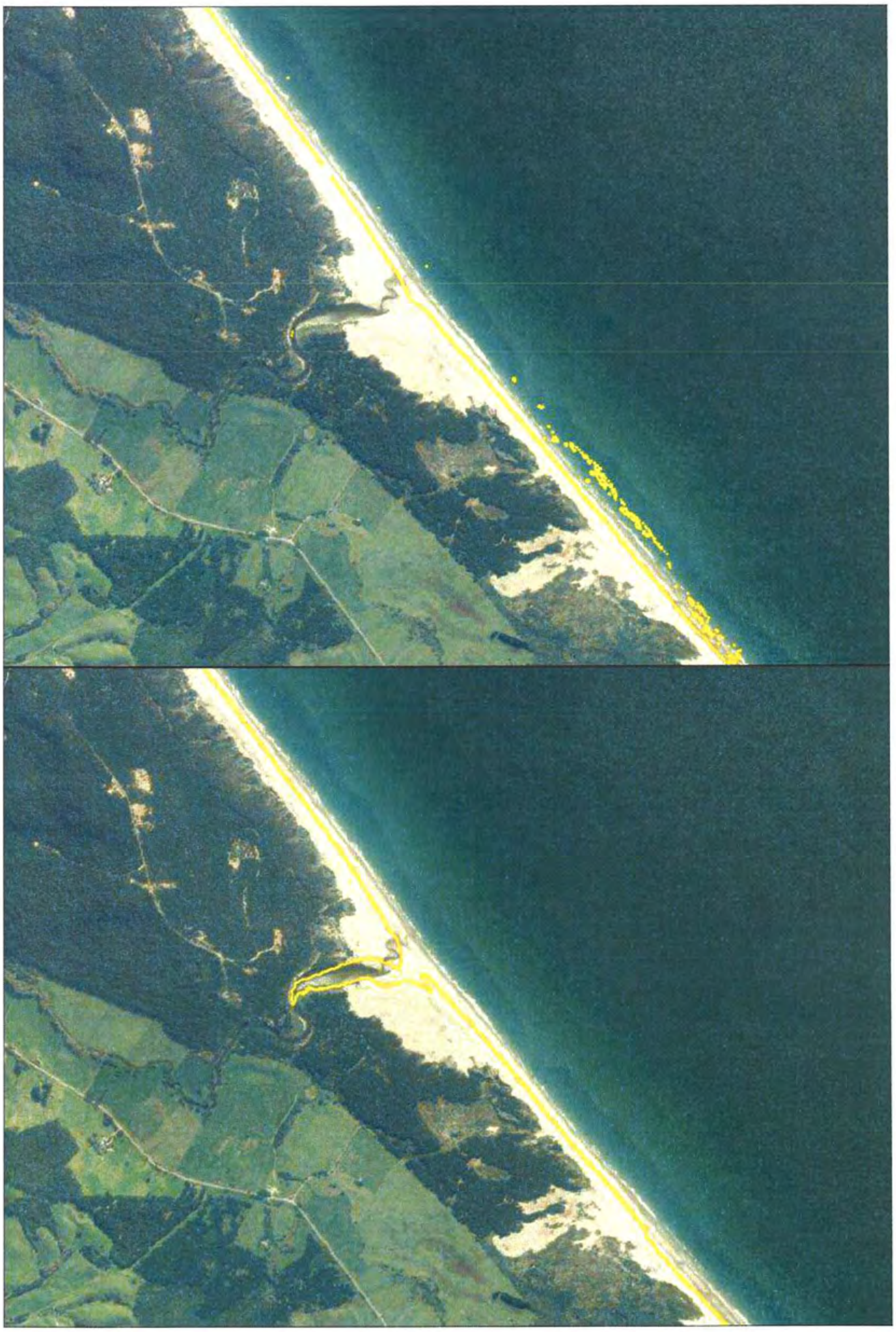

Figure 2-12:Adding a 0.7 m wave setup elevation (bottom) to the MHWS-10 elevation (top) on the east coast.

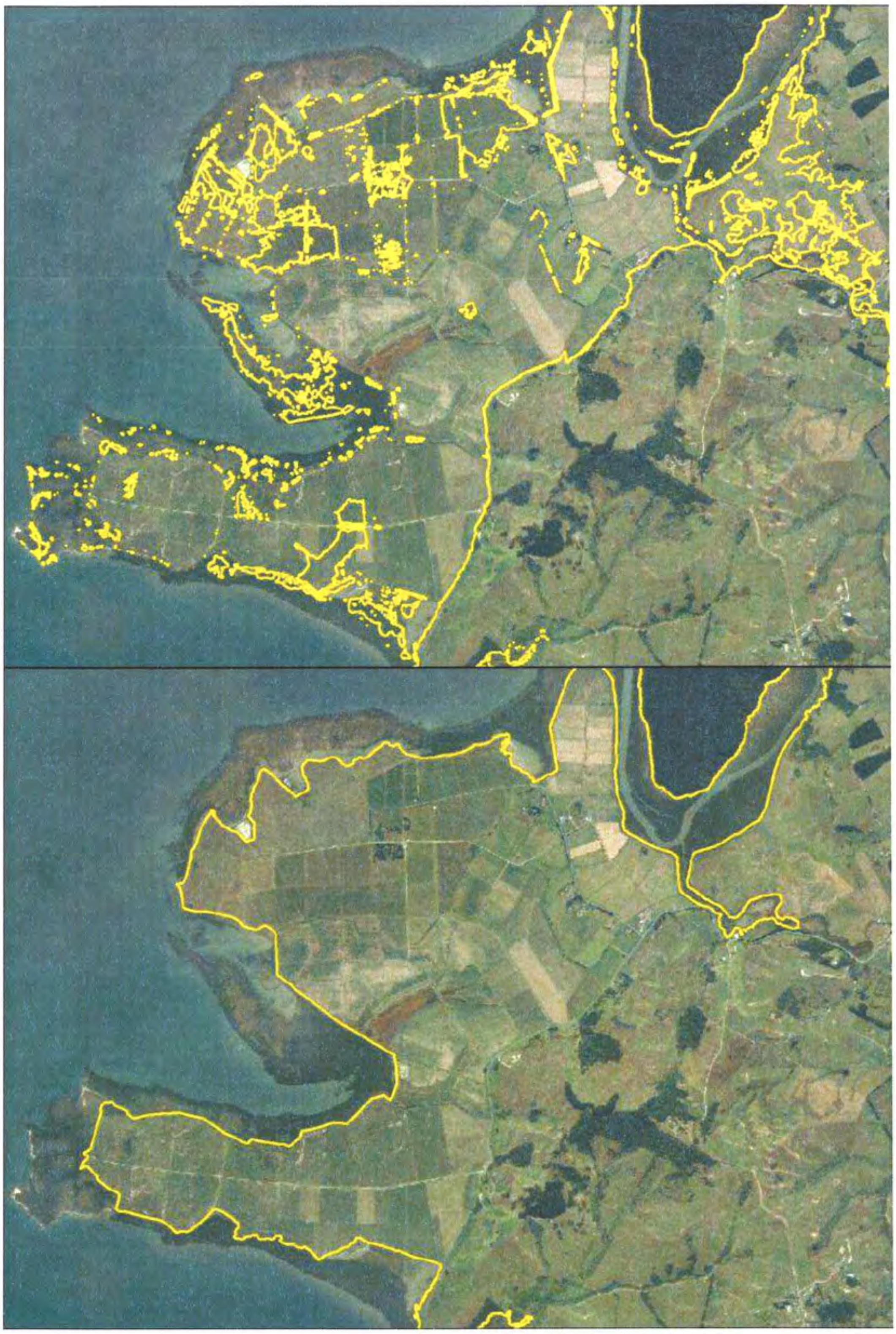

Figure 2-13:Example of the effect of reclamation behind stop banks on the automated CMA boundary contouring. The top plot represents the raw boundary line fitted by the automated method. The bottom plot shows the manually adjusted CMA boundary.

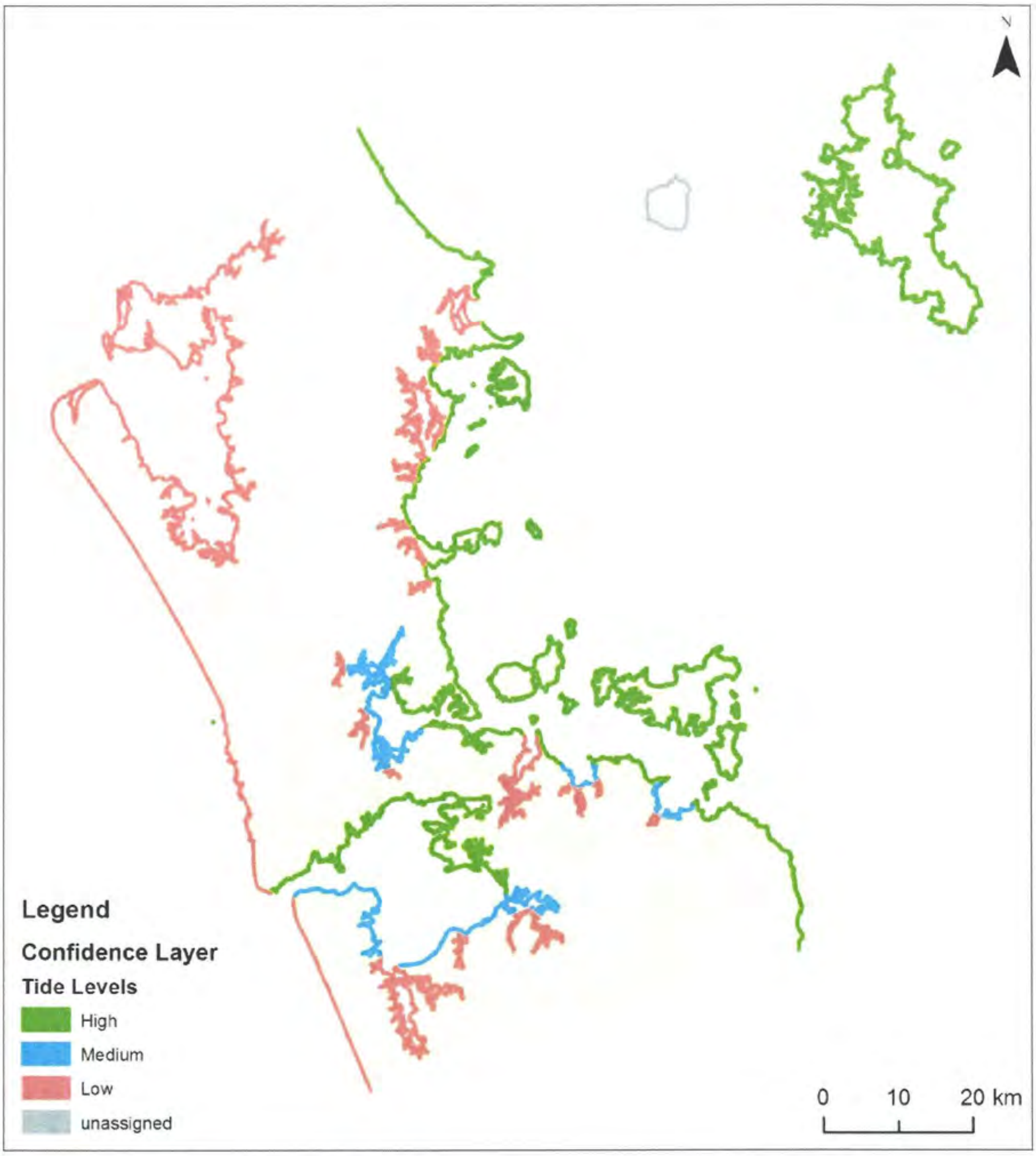

Figure 2-14:Confidence in the MHWS-10 tide elevation used to produce the CMA boundary line.

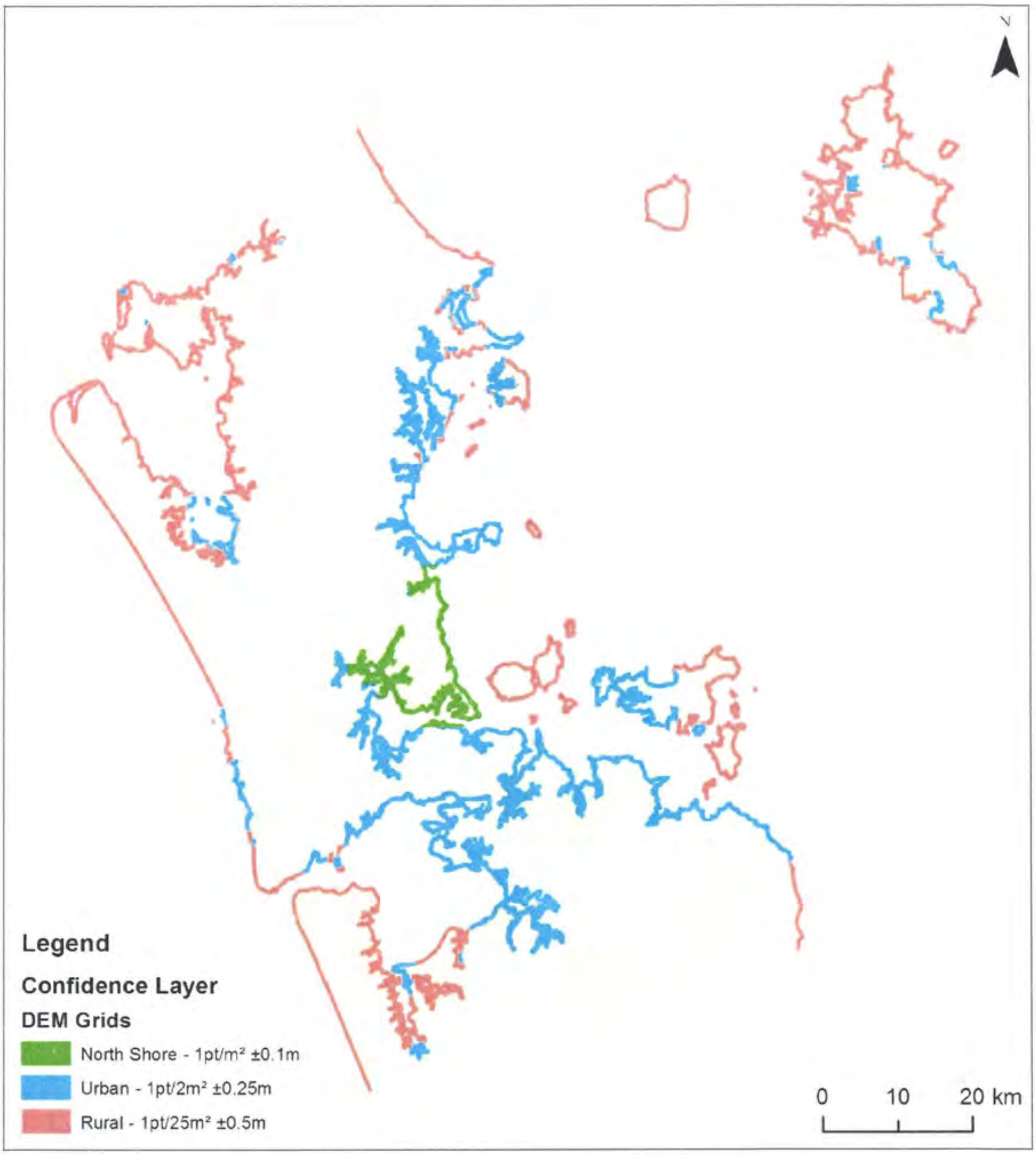

Figure 2-15:Confidence in the DEM grids used to produce the CMA boundary line. The confidence level was assigned on the vertical accuracy of the LIDAR.

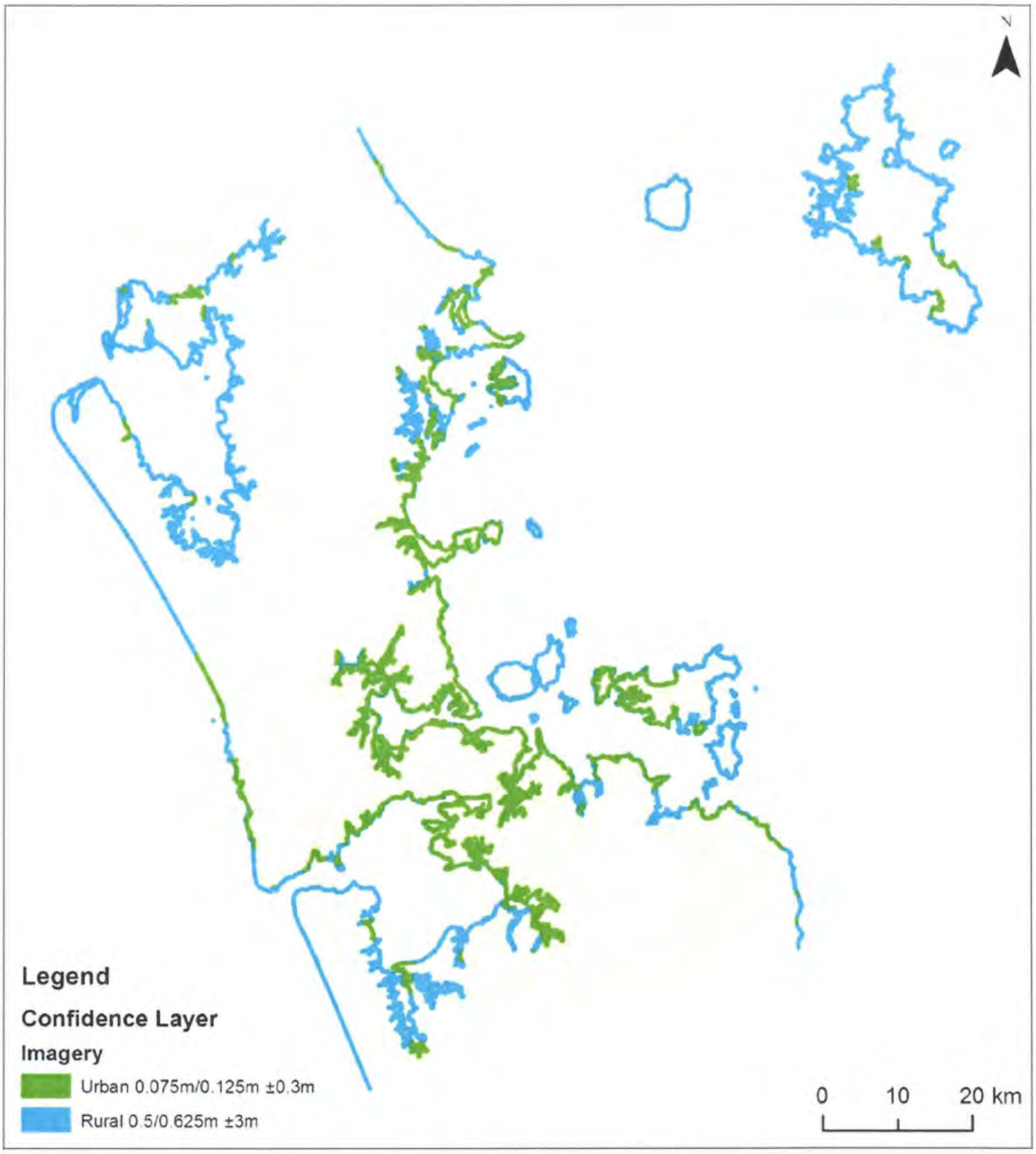

Figure 2-16:Confidence in the aerial photography images used to produce the CMA boundary line. The confidence level was based on imagery acquisition date and associated horizontal accuracy.

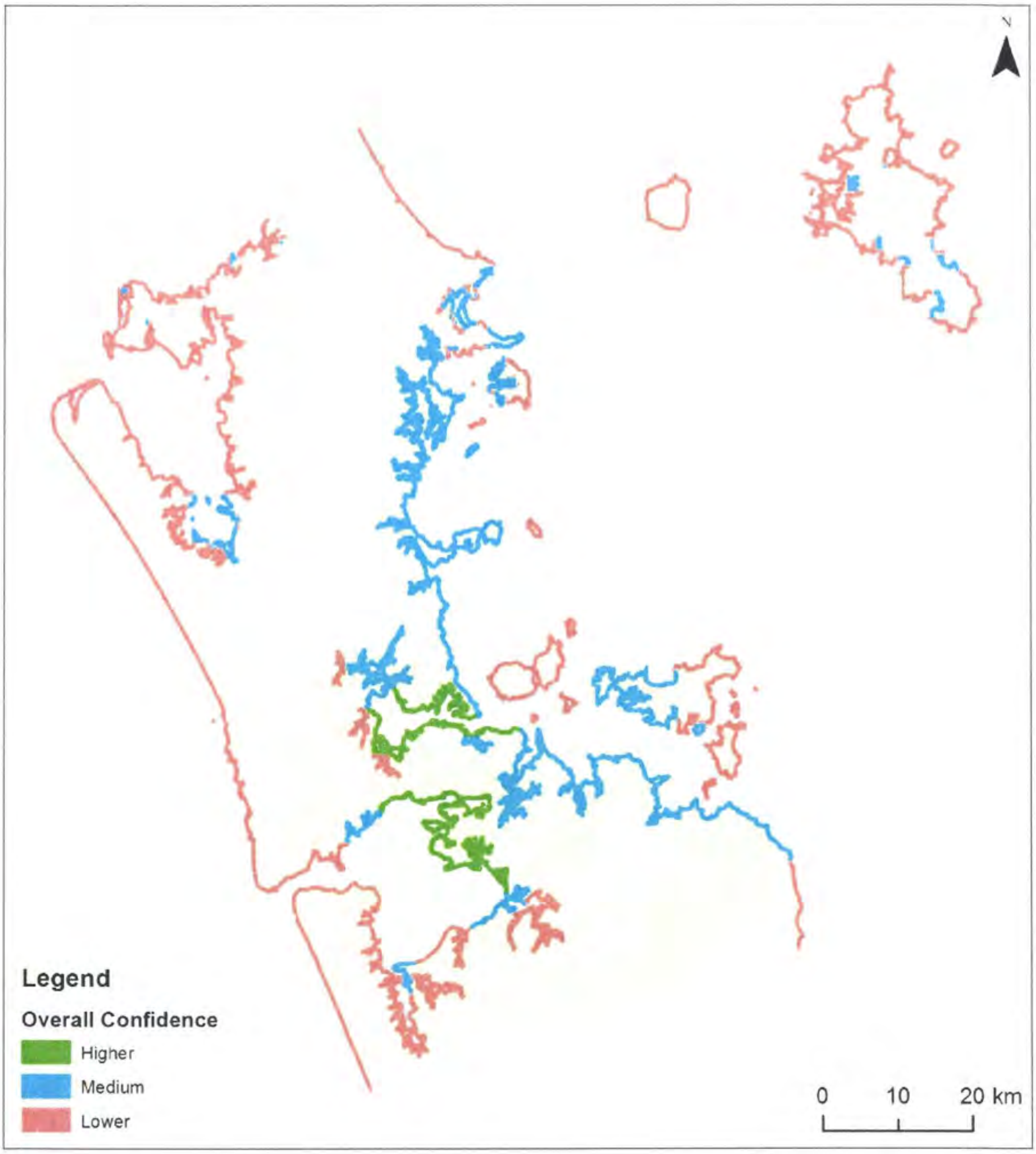

Figure 2-17: Overall confidence in the quality of the CMA boundary line. The overall confidence represents the opinion of the authors based primarily on the accuracy of the DEM and of tide elevations.

3 Results

Examples of the existing and new CMA "mean high water springs" boundary lines, overlaid on aerial photographs, are shown in Figure 3-1 to Figure 3-6. Figure 3-1 and Figure 3-2 show locations in the Okura Estuary. These figures show that for the regions shown, the existing CMA boundary provides a relatively coarse representation of the land–CMA interface when compared to aerial photography, encroaching on intertidal flats and cutting across property boundaries in some instances. In comparison, the new CMA boundary faithfully represents the land–CMA interface with sufficient accuracy that residential property boundaries accurately match aerial photographs.

Figure 3-1 to Figure 3-6 show areas where the existing CMA boundary provides a relatively poor fit. In highly urbanised areas such as the Waitemata Harbour the existing CMA boundary still provides a close match to aerial photographs and the new CMA boundary line.

MHWS tide levels and MLWS-50 levels are provided in the Appendix Table A-1 – Table A-4.

Auckland Council has been provided with the new CMA boundary line in GIS format.

While NIWA has made every endeavour to produce a reasonably accurate land/CMA boundary line, the confidence in the accuracy of the boundary line does vary around the Auckland region in relation to the sources of information used, as described in this report. While the supplied land/CMA boundary line overall provides a more accurate boundary for mapping and general planning purposes than that developed in the 1990s for the existing Auckland Regional Plan: Coastal, nevertheless this revised line is no substitute for accurate determination of the MHWS by precise land surveying techniques in relation to individual cadastral boundaries, infrastructure, or setting out new developments or subdivisions.

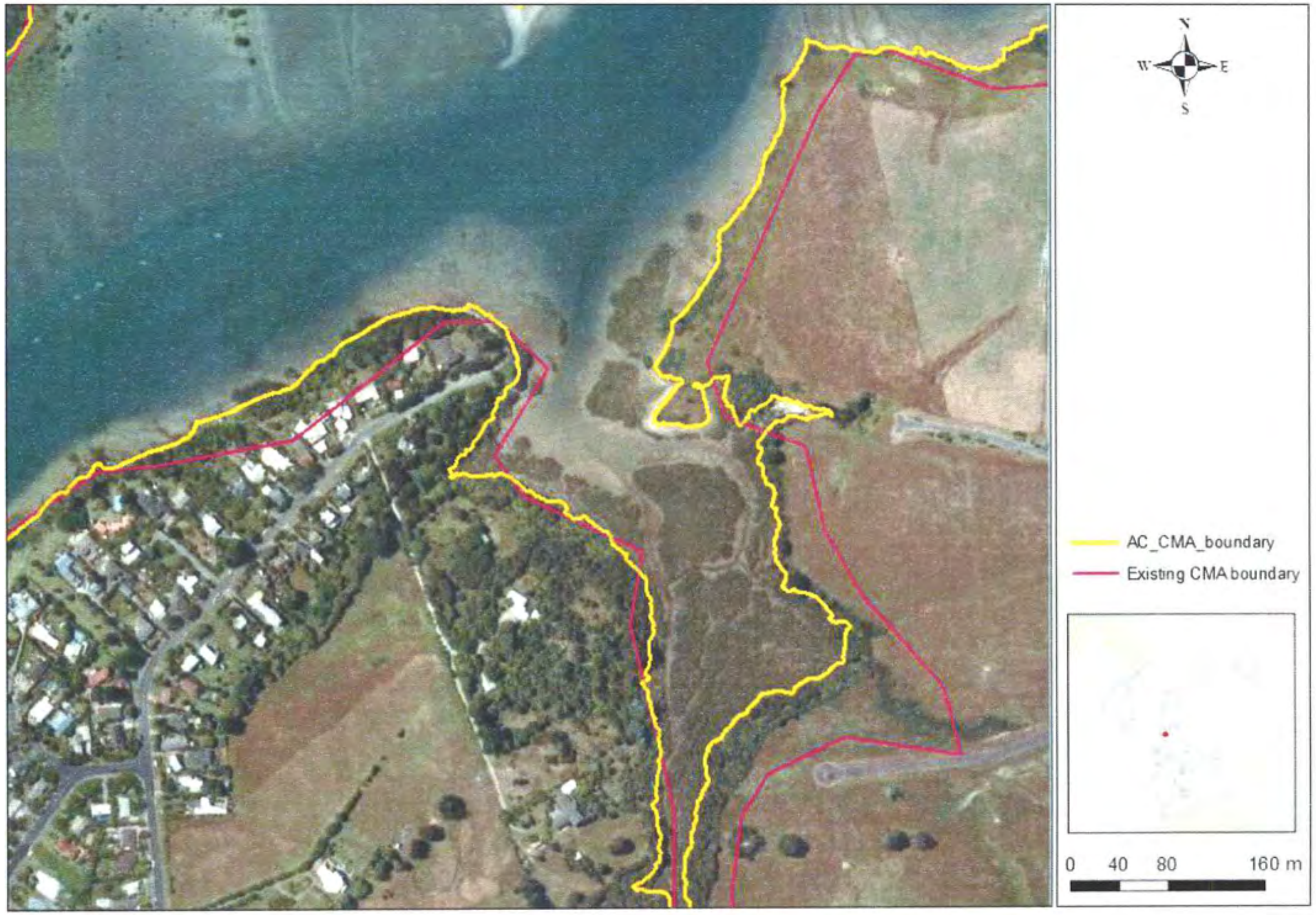

Figure 3-1: Orthorectified aerial photograph of Okura Estuary with existing (pink) CMA boundary line and proposed new CMA boundary line (yellow) superimposed.

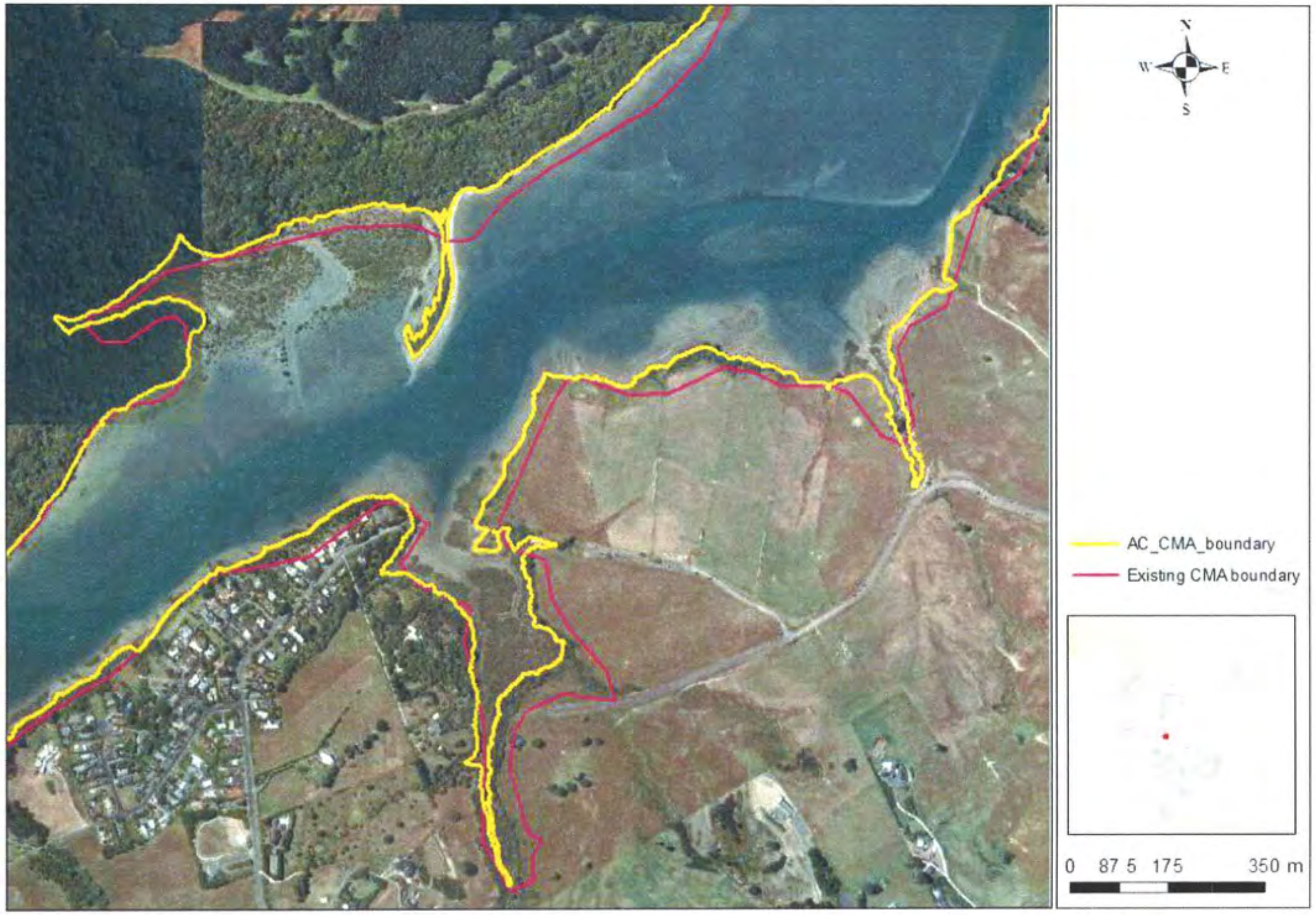

Figure 3-2: Orthorectified aerial photograph of Okura Estuary with existing (pink) CMA boundary line and proposed new CMA boundary line (yellow) superimposed.

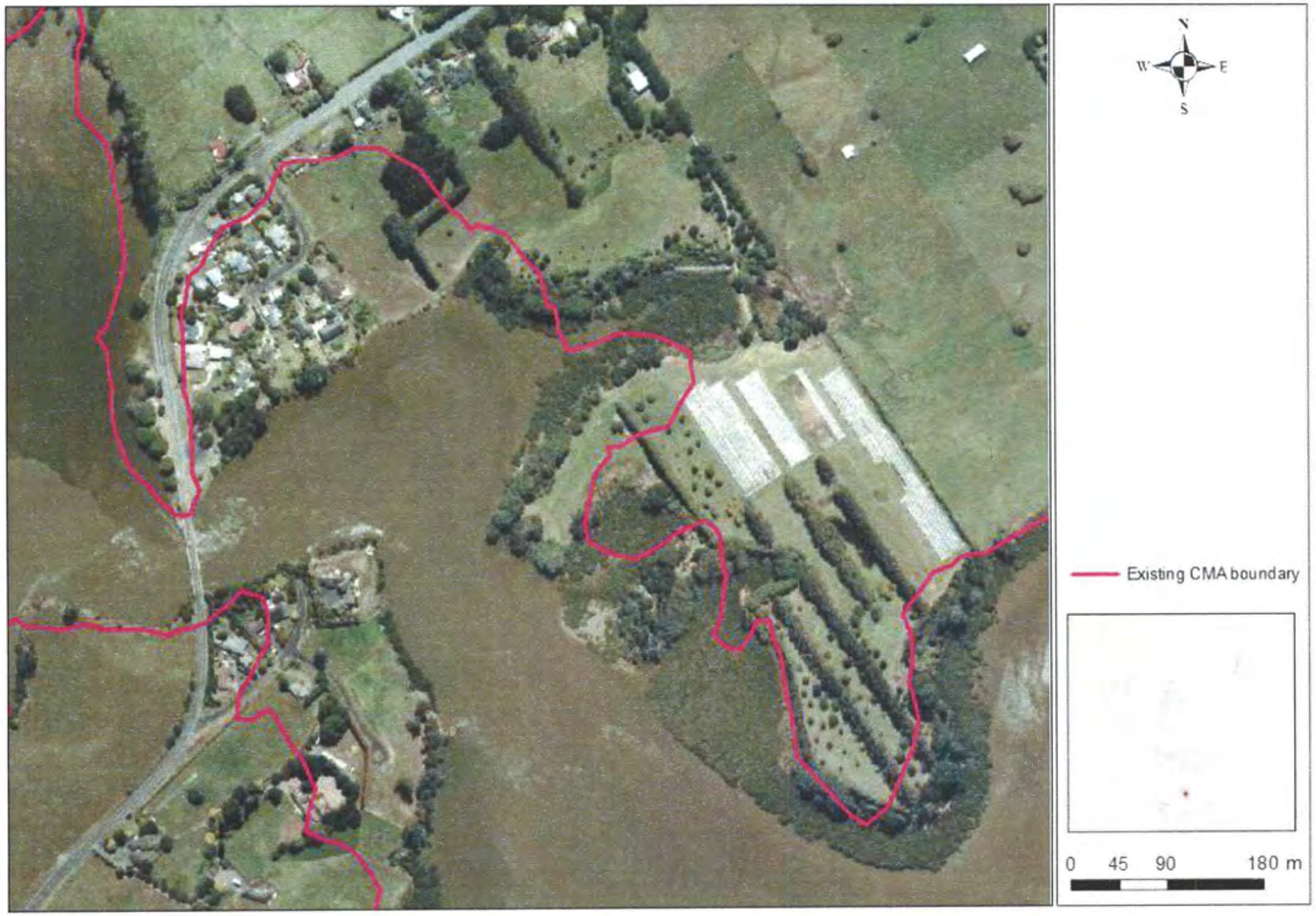

Figure 3-3: Orthorectified aerial photograph of Pahurehure Estuary (location 1) with existing CMA boundary line superimposed.

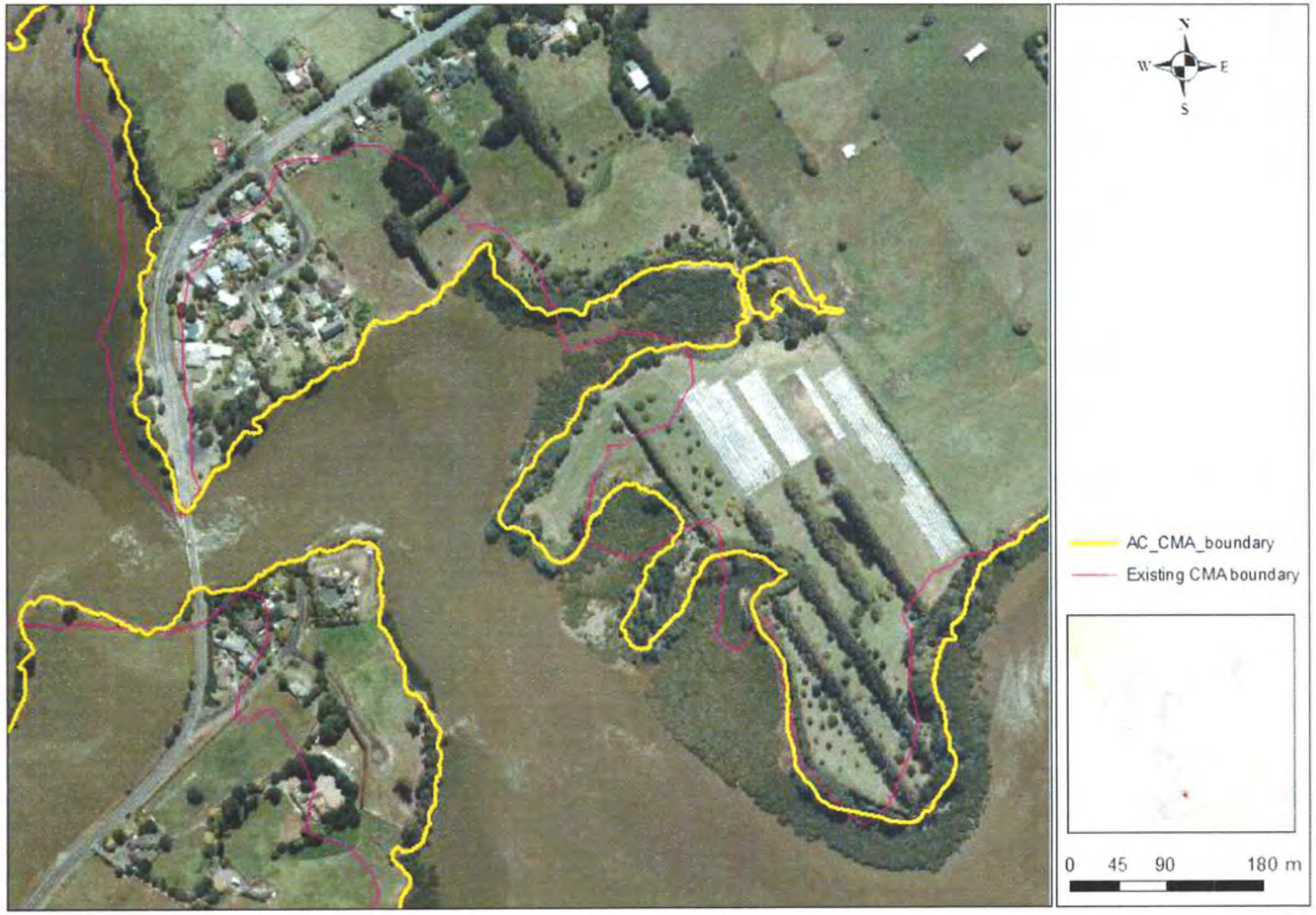

Figure 3-4: Orthorectified aerial photograph of Pahurehure Estuary (location 1) with existing (pink) CMA boundary line and proposed new CMA boundary line (yellow) superimposed.

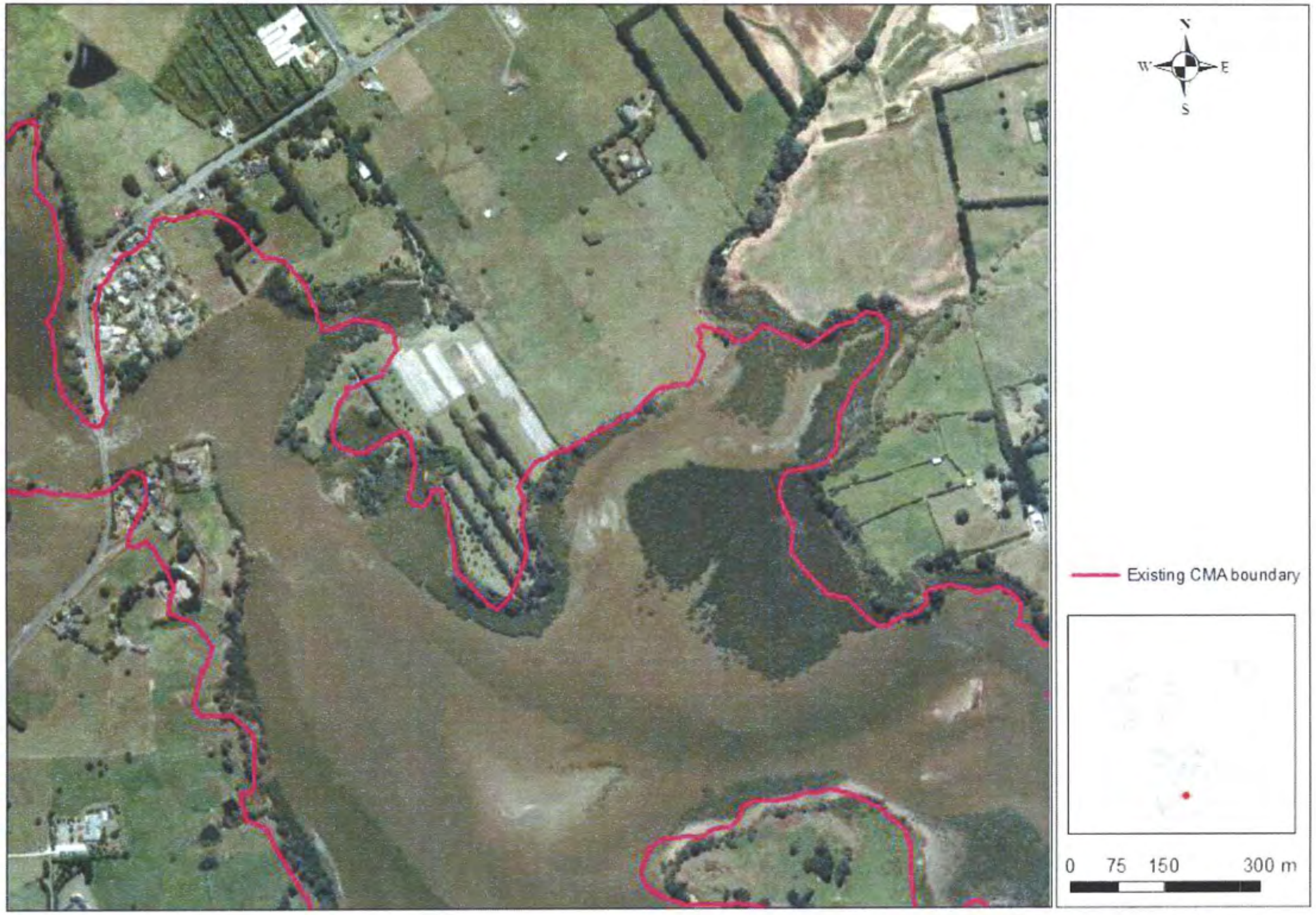
N
W
E
S
Existing CMA boundary
0
75
150
300 m

Figure 3-5: Orthorectified aerial photograph of Pahurehure Estuary (zoomed out at location 1) with pre-existing CMA boundary line superimposed.

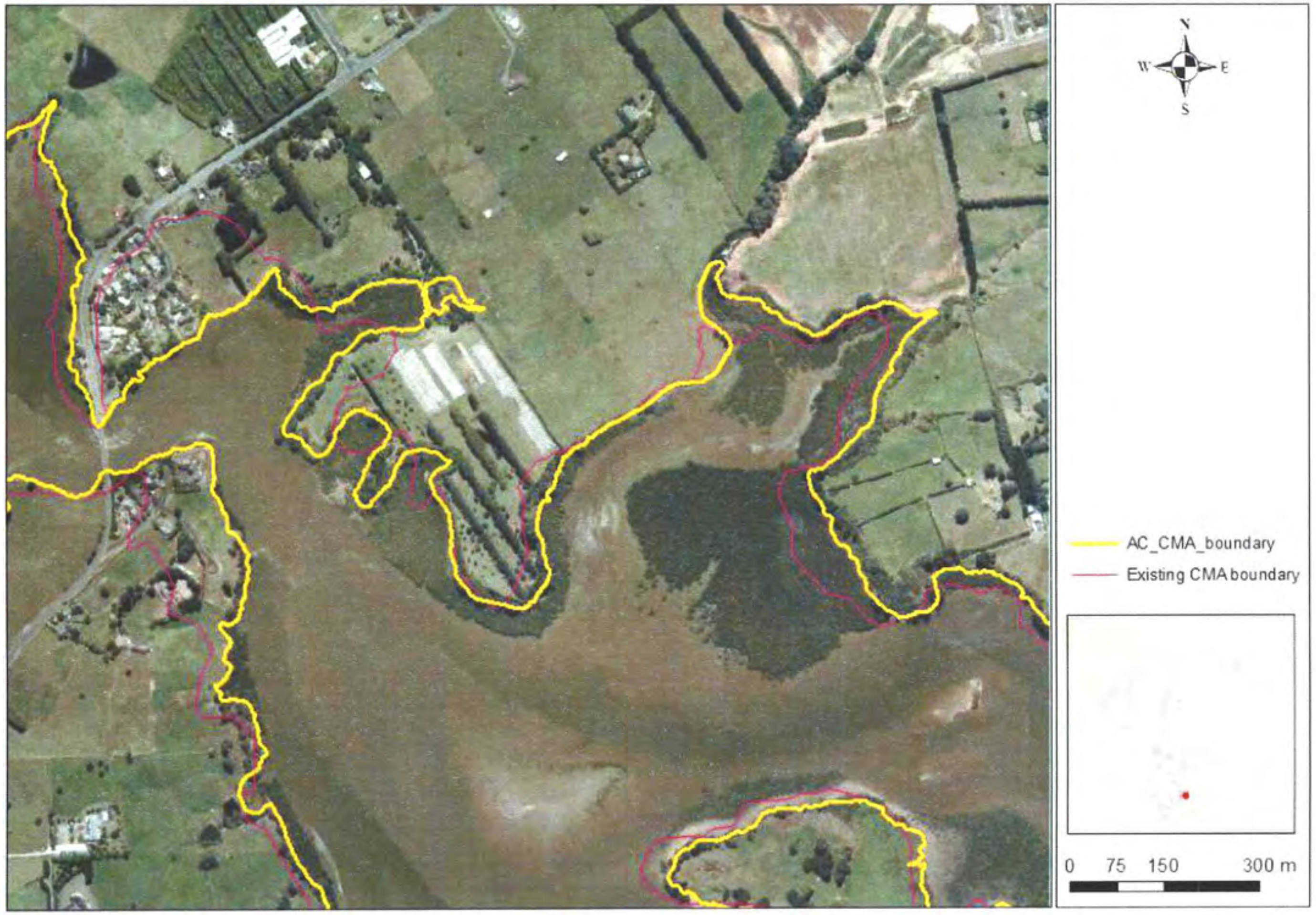

Figure 3-6: Orthorectified aerial photograph of Pahurehure Estuary (zoomed out at location 1) with pre-existing (pink) CMA boundary line and proposed new CMA boundary line (yellow) superimposed.

4 Acknowledgements

Auckland Council supplied the LiDAR and aerial photography. Scott Speed (Auckland Council) had been trialling the promising use of a single fixed level (1.5 m AVD-46) to represent the CMA boundary on the Auckland east coast. The idea to use varying tide levels to cover the entire Auckland Region arose from discussions between Scott Speed, and Scott Stephens (NIWA). The GIS code was developed by Sanjay Wadhwa of NIWA.

The use of historic tide-gauge records from several past NIWA research projects and joint Auckland Council studies is acknowledged.

5 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.

EEZ — An exclusive economic zone (EEZ) is a seazone prescribed by the United Nations Convention on the Law of the Sea over which a state has special rights over the exploration and use of marine resources, including energy production from water and wind. New Zealand's EEZ stretches from the seaward edge of the state's territorial sea out to 200 nautical miles from its coast.

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.

HAT — **Highest astronomical tide** – the highest level the tide can be predicted to occur under normal meteorological conditions.

LAT — **Lowest astronomical tide** – the lowest level the tide can be predicted to occur under normal meteorological conditions.

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.

M_2	In New Zealand, the largest tidal harmonic constituent is the "**principal lunar semi-diurnal**" tide, which results directly from the Moon's gravitational pull on the oceans (*M* stands for "Moon") but is modified as the wave propagates into and around the continental shelf. Its period is about 12 hours and 25.2 minutes, which is half the time required for the Earth to rotate once relative to the Moon.
MHWPS	**Mean high water Perigean spring tide**, calculated from the amplitudes (half-range) of the three major tidal harmonic constituents as $MHWPS = M_2 + S_2 + N_2$, the combination of which contributes to greater high tides in some months where the Moon's Perigee coincides around the time of spring tides.
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 has led to subjectivity when defining the CMA for RMA purposes but this report provides a pragmatic solution that builds in variability in tide range and the effect of wave setup on open coasts.
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.
MHWS-C	**Mean high water springs cadastral** – LINZ definition of mean high water springs for engineering and cadastral purposes at Standard Ports: http://www.linz.govt.nz/geodetic/datums-projections-heights/vertical-datums/tidal-level-information-for-surveyors
MHWSn	**Mean high water springs "nautical"**, calculated from the sum of amplitudes of $M_2 + S_2$ tidal harmonic constituents, the beat of which, in isolation from other constituents, contributes to a higher high tide approximately every 2 weeks.
MLOS	**Mean level of the sea** – the variation of the non-tidal sea level on time scales ranging from a monthly basis up to decades due to climate variability, including the effects of El Niño–Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO) patterns on sea level, winds and sea temperatures, and seasonal effects.
MLW-50	**Mean low water 50%** – low-tide level equalled or exceeded by 50% of all low tides.
MSL	**Mean sea level** – calculated as the average MLOS over a known fixed period in time, usually several years.
N_2	**Elliptic semi-diurnal** tidal harmonic constituent – arises from the elliptic orbit of the Moon around Earth on a cycle of 27.555 days.

NZVD2009 The New Zealand Vertical Datum–2009 is a consistent national vertical datum based on a geoid model and GPS ellipsoid height measurements (see web site: http://www.linz.govt.nz/survey-titles/cadastral-surveying/cadastral-standards/DocumentSummary.aspx%3Fdocument%3D253)

OTP-64 One Tree Point Datum-1964 (OTP-64) was established as the mean sea level (MSL) at Marsden Point from 4 years of sea level measurements collected between 1960–1963. The historic MSL set in 1964 was +1.676 m relative to local chart datum at Marsden Point.

Perigean spring tides Larger tide ranges that occur in waxing and waning clusters peaking about every 7 months (206.6 days to be exact) when New or Full Moon occurs at around the same time as the Moon is in its Perigee. Usually, these are the tides with the largest tidal range.

Perigean/Apogean tides The cycle that occurs every month (27.555 days to be exact) that increases and decreases in conjunction with the position of the Moon in its elliptical orbit around Earth. When the Moon is closest to Earth, it is in its perigee and larger than normal Perigean tides occur. When the Moon is farthest from Earth, it is in its apogee and smaller than normal Apogean tides occurs. Another equivalent definition is that Perigean and Apogean tides are the result of M_2 (the lunar semi-diurnal constituent) beating in and out of phase with the N_2 tide (the elliptic semi-diurnal constituent).

RMA Resource Management Act – Act of parliament, passed in 1991 (with subsequent ammendements), 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.

S_2	**Solar semi-diurnal** tidal harmonic constituent – has a period of exactly 12 hours and this arises because the Sun passes over the same spot on Earth every 24 hours. '*S*' stands for Solar.
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., 5-10 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.
Semi-diurnal tides	Semi-diurnal tides are tidal constituents which occur approximately twice daily, i.e., they have a tidal period of approximately 12–13 hours, e.g., the solar semi-diurnal constituent S_2 (12 hour period); the lunar semi-diurnal constituent M_2 (12.42 hour period); the elliptic semi-diurnal constituent N_2 (12.66 hour period).
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).
Tidal constituents	Individual components which are used to represent various repeating cycles that comprise the overall tide that is observed at any location. Each constituent arises either from a specific astronomical feature or from the interaction between two or more constituents. For example, M_2, S_2, N_2.
Tidal period	Interval of time over which a tidal constituent completes a single but repeating cycle. Each constituent has a unique period, governed by a particular astronomical effect. For example, the solar semi-diurnal constituent S_2 has a period of exactly 12 hours and this arises because the Sun passes over the same spot on Earth every 24 hours. Similarly, the lunar semi-diurnal constituent M_2 has a period of 12.42 hours and this arises because the Moon passes over the same spot on Earth every 24.84 hours.

6 References

Amos, M.J. (2007). Quasigeoid modelling in New Zealand to unify multiple local vertical datums. Unpublished PhD thesis, Curtin University of Technology, Perth, Australia.

Auckland Regional Council (2010). Sea level change in the Auckland Region. Report prepared for the Auckland Regional Council by the University of Otago and the National institute of Water and Atmospheric Research. *ARC Technical Report TR065* No. 36 p.

Bell, R.G.; Dumnov, S.V.; Williams, B.L.; Greig, M.J.N. (1998). Hydrodynamics of Manukau Harbour, New Zealand. New Zealand Journal of Marine and Freshwater Research 32(1): 81-100.

Bell, R.G.; Swales, A.; Hill, A.F. (1996). Field studies in Upper Tamaki Estuary for the environmental assessment of the Otahuhu power station heated cooling-water discharge. Prepared for Kingett Mitchell and Associates, Takapuna. Client Report KIM60203/1, 15p.

Bell, R.G. (2010). Tidal exceedances, storm tides and the effect of sea-level rise. Presented at the Proceedings of the 17th Congress of the Asia and Pacific Division of the IAHR, Auckland, New Zealand, 21–24 February 2010. 10.

Foreman, M.G.G.; R.G. Bell; J.Y. Cherniawsky; B. Beckley (2004). Tides and sea-level variability in the south-west Pacific from TOPEX/Poseidon. *NZ Journal of Marine & Freshwater Research 38(4)*: 649–669.

Hannah, J. and R.G. Bell (2012). Regional sea level trends in New Zealand. *Journal of Geophysical Research–C 117*: C01004.

LINZ (2009). Standard for New Zealand Vertical Datum 2009. Land Information NZ Standard LINZS25004. http://www.linz.govt.nz/survey-titles/cadastral-surveying/cadastral-standards/DocumentSummary.aspx%3Fdocument%3D253

Oldman, J.W.; Black, K.P. (1997). Mahurangi Estuary numerical modelling. NIWA Client Report for Auckland Regional Council ARC60208/1; TR 2009/041.

Walters, R.A.; Goring, D.G.; Bell, R.G. (2001). Ocean tides around New Zealand. *New Zealand Journal of Marine and Freshwater Research 35*: 567–579.

Appendix A MHWS levels

Table A-1: MHWS elevations in the Waitemata Harbour, at mean sea level (2006–11) relative to Auckland vertical datum 1946. Positions are specified in NZGD-49. HAT = highest astronomical tide; MHWPS = mean high water Perigean springs; MHWSC = LINZ cadastral MHWS definition; MHWS-10 = elevation exceeded only by the highest 10% of all high tides.

Site	Longitude	Latitude	HAT	MHWPS	MHWSC	MHWSn	MHWS-10	MLWS-50
1	174.75	-36.84	1.88	1.7	1.48	1.46	1.59	-0.97
2	174.74	-36.83	1.89	1.71	1.49	1.47	1.61	-0.98
3	174.74	-36.84	1.89	1.72	1.49	1.47	1.61	-0.98
4	174.73	-36.84	1.91	1.73	1.51	1.48	1.62	-0.98
5	174.72	-36.84	1.91	1.73	1.51	1.49	1.63	-0.98
6	174.7	-36.85	1.94	1.76	1.53	1.51	1.65	-0.99
7	174.7	-36.86	1.95	1.77	1.54	1.52	1.66	-1
8	174.69	-36.89	1.97	1.79	1.56	1.54	1.68	-1
9	174.69	-36.87	1.96	1.78	1.55	1.53	1.67	-1
10	174.68	-36.87	1.98	1.79	1.56	1.54	1.68	-1
11	174.67	-36.86	1.98	1.8	1.57	1.54	1.68	-1.01
12	174.66	-36.88	2	1.81	1.58	1.56	1.7	-1.01
13	174.68	-36.9	2.04	1.85	1.61	1.59	1.74	-1.04
14	174.66	-36.88	2	1.82	1.58	1.56	1.7	-1.01
15	174.66	-36.86	2	1.81	1.58	1.55	1.7	-1.01
16	174.66	-36.86	2	1.81	1.58	1.56	1.7	-1.01
17	174.66	-36.85	1.99	1.81	1.57	1.55	1.69	-1.01
18	174.67	-36.83	1.99	1.8	1.57	1.55	1.69	-1.01
19	174.65	-36.82	2.01	1.82	1.59	1.57	1.71	-1.02
20	174.65	-36.83	2.01	1.82	1.59	1.56	1.71	-1.01
21	174.65	-36.82	2.02	1.83	1.59	1.57	1.71	-1.02
22	174.63	-36.84	2.03	1.84	1.6	1.58	1.73	-1.02
23	174.64	-36.85	2.05	1.85	1.62	1.59	1.74	-1.03
24	174.62	-36.86	2.05	1.86	1.62	1.6	1.74	-1.03
25	174.65	-36.81	2.01	1.82	1.59	1.57	1.71	-1.02
26	174.67	-36.81	1.99	1.81	1.58	1.55	1.69	-1.01
27	174.68	-36.8	1.99	1.8	1.57	1.55	1.69	-1.01
28	174.68	-36.8	2	1.81	1.58	1.55	1.7	-1.01
29	174.66	-36.79	2.06	1.87	1.63	1.6	1.75	-1.05
30	174.64	-36.8	2.07	1.87	1.63	1.61	1.76	-1.04
31	174.65	-36.79	2.07	1.88	1.64	1.61	1.76	-1.04
32	174.65	-36.78	2.08	1.89	1.65	1.62	1.77	-1.05
33	174.65	-36.77	2.09	1.9	1.65	1.63	1.78	-1.05
34	174.61	-36.77	2.12	1.93	1.68	1.65	1.81	-1.06
35	174.59	-36.79	2.12	1.93	1.68	1.65	1.81	-1.06

Site	Longitude	Latitude	HAT	MHWPS	MHWSC	MHWSn	MHWS-10	MLWS-50
36	174.6	-36.76	2.15	1.95	1.7	1.68	1.83	-1.07
37	174.64	-36.76	2.13	1.93	1.68	1.66	1.81	-1.07
38	174.66	-36.77	2.09	1.89	1.65	1.62	1.77	-1.05
39	174.66	-36.77	2.08	1.89	1.65	1.62	1.77	-1.05
40	174.66	-36.77	2.09	1.89	1.65	1.62	1.77	-1.05
41	174.68	-36.76	2.11	1.91	1.67	1.64	1.79	-1.07
42	174.68	-36.74	2.13	1.93	1.69	1.66	1.81	-1.08
43	174.68	-36.79	2.05	1.86	1.62	1.6	1.74	-1.04
44	174.68	-36.79	2.05	1.86	1.62	1.59	1.74	-1.04
45	174.7	-36.78	2.06	1.87	1.63	1.6	1.75	-1.05
46	174.69	-36.82	1.96	1.78	1.55	1.53	1.67	-1
47	174.71	-36.83	1.93	1.75	1.53	1.5	1.64	-0.99
48	174.74	-36.83	1.91	1.73	1.51	1.48	1.62	-0.98
49	174.75	-36.83	1.89	1.71	1.49	1.47	1.61	-0.98
50	174.76	-36.82	1.9	1.72	1.5	1.47	1.61	-0.98
51	174.77	-36.83	1.89	1.71	1.49	1.47	1.61	-0.98
52	174.77	-36.83	1.88	1.7	1.48	1.46	1.6	-0.97
53	174.76	-36.81	1.91	1.73	1.51	1.49	1.62	-0.98
54	174.77	-36.79	1.94	1.76	1.53	1.51	1.65	-0.99
55	174.79	-36.82	1.91	1.73	1.51	1.49	1.62	-0.98
56	174.79	-36.84	1.84	1.66	1.45	1.43	1.56	-0.95
57	174.79	-36.85	1.83	1.66	1.44	1.42	1.55	-0.95
58	174.8	-36.85	1.82	1.64	1.43	1.41	1.54	-0.94
59	174.83	-36.87	1.86	1.68	1.47	1.44	1.58	-0.97
60	174.82	-36.83	1.8	1.63	1.42	1.4	1.53	-0.93
61	174.82	-36.84	1.8	1.63	1.42	1.4	1.53	-0.93

Table A-2: MHWS elevations on the open coast of the Auckland Region, at mean sea level relative to Auckland vertical datum 1946. Positions are specified in NZGD-49. HAT = highest astronomical tide; MHWPS = mean high water Perigean springs; MHWSC = LINZ cadastral MHWS definition; MHWS-10 = elevation exceeded only by the highest 10% of all high tides.

Site	Longitude	Latitude	HAT	MHWPS	MHWSC	MHWSn	MHWS-10	MLWS-50
1	174.623	-36.116	1.45	1.30	1.17	1.13	1.25	-0.77
2	174.703	-36.204	1.47	1.32	1.19	1.14	1.27	-0.78
3	174.835	-36.278	1.52	1.36	1.22	1.18	1.31	-0.81
4	174.801	-36.337	1.54	1.38	1.24	1.20	1.33	-0.83
5	174.876	-36.370	1.57	1.41	1.26	1.22	1.35	-0.85
6	174.765	-36.413	1.63	1.46	1.31	1.26	1.40	-0.88
7	174.796	-36.440	1.63	1.46	1.31	1.26	1.40	-0.88
8	174.757	-36.519	1.65	1.48	1.32	1.28	1.42	-0.90
9	174.737	-36.595	1.65	1.49	1.33	1.28	1.42	-0.90
10	174.853	-36.591	1.66	1.49	1.33	1.28	1.43	-0.90
11	174.887	-36.622	1.67	1.50	1.34	1.29	1.44	-0.91
12	174.773	-36.663	1.70	1.53	1.37	1.32	1.46	-0.93
13	174.773	-36.753	1.72	1.55	1.39	1.34	1.49	-0.95
14	174.819	-36.810	1.78	1.60	1.43	1.38	1.53	-0.99
15	174.889	-36.845	1.80	1.63	1.46	1.40	1.56	-1.01
16	174.951	-36.874	1.82	1.64	1.47	1.42	1.57	-1.02
17	175.065	-36.878	1.87	1.69	1.51	1.45	1.61	-1.05
18	175.125	-36.919	1.89	1.71	1.52	1.47	1.63	-1.06
19	175.195	-36.921	1.88	1.70	1.52	1.46	1.62	-1.06
20	175.275	-36.956	1.90	1.72	1.53	1.48	1.64	-1.07
21	175.319	-37.048	1.98	1.80	1.60	1.55	1.72	-1.13
22	175.221	-36.864	1.85	1.67	1.49	1.43	1.59	-1.03
23	175.221	-36.763	1.76	1.59	1.42	1.37	1.52	-0.98
24	175.164	-36.731	1.71	1.54	1.38	1.33	1.48	-0.94
25	175.082	-36.757	1.70	1.53	1.37	1.32	1.46	-0.93
26	174.973	-36.778	1.74	1.57	1.40	1.35	1.50	-0.96
27	175.048	-36.837	1.84	1.66	1.49	1.43	1.59	-1.03
28	175.167	-36.839	1.85	1.67	1.50	1.44	1.60	-1.04
29	175.170	-36.792	1.80	1.63	1.45	1.40	1.55	-1.00
30	174.913	-36.806	1.79	1.62	1.44	1.39	1.54	-1.00
31	174.931	-36.731	1.71	1.54	1.37	1.32	1.47	-0.94
32	174.864	-36.755	1.71	1.54	1.38	1.33	1.48	-0.94
33	174.856	-36.466	1.62	1.46	1.30	1.25	1.39	-0.88
34	174.900	-36.421	1.57	1.41	1.26	1.21	1.35	-0.84
35	175.289	-36.153	1.42	1.27	1.14	1.09	1.21	-0.74
36	175.281	-36.245	1.47	1.31	1.17	1.13	1.26	-0.77
37	175.392	-36.292	1.46	1.31	1.17	1.13	1.25	-0.77

Site	Longitude	Latitude	HAT	MHWPS	MHWSC	MHWSn	MHWS-10	MLWS-50
38	175.540	-36.368	1.36	1.21	1.08	1.04	1.16	-0.69
39	175.576	-36.292	1.31	1.17	1.05	1.01	1.12	-0.67
40	175.511	-36.229	1.31	1.16	1.04	1.00	1.12	-0.66
41	175.519	-36.161	1.31	1.16	1.04	1.00	1.12	-0.66
42	175.454	-36.127	1.32	1.17	1.05	1.01	1.12	-0.67
43	175.426	-36.014	1.33	1.18	1.06	1.02	1.13	-0.67
44	175.312	-36.088	1.39	1.24	1.11	1.07	1.19	-0.71
45	174.105	-36.478	2.00	1.81	1.64	1.60	1.70	-0.89
46	174.287	-36.688	2.02	1.82	1.65	1.61	1.71	-0.90
47	174.436	-36.926	2.03	1.83	1.66	1.62	1.72	-0.91
48	174.502	-37.071	2.04	1.85	1.67	1.63	1.73	-0.92
49	174.660	-37.321	2.06	1.87	1.69	1.65	1.75	-0.93
50	174.817	-36.840	1.81	1.63	1.46	1.41	1.56	-1.01
51	174.765	-36.842	1.85	1.67	1.49	1.44	1.60	-1.04
52	174.786	-36.838	1.84	1.66	1.48	1.43	1.58	-1.03
53	174.817	-36.840	1.81	1.63	1.46	1.41	1.56	-1.01
54	175.141	-36.925	1.89	1.71	1.52	1.47	1.63	-1.06
55	175.101	-36.901	1.88	1.70	1.52	1.46	1.62	-1.06
56	174.782	-36.437	1.63	1.46	1.31	1.26	1.40	-0.88
57	174.793	-36.391	1.61	1.45	1.30	1.25	1.39	-0.87
58	174.595	-37.195	2.05	1.86	1.68	1.64	1.74	-0.92
59	174.648	-37.285	2.06	1.86	1.68	1.65	1.75	-0.93
60	174.740	-36.423	1.63	1.47	1.31	1.26	1.40	-0.89
61	174.758	-36.394	1.63	1.46	1.31	1.26	1.40	-0.88
62	175.095	-36.939	1.89	1.71	1.53	1.47	1.63	-1.07
63	174.968	-36.900	1.83	1.65	1.47	1.42	1.58	-1.02
64	174.747	-36.655	1.70	1.53	1.37	1.32	1.47	-0.93
65	174.715	-36.546	1.65	1.49	1.33	1.28	1.42	-0.90
66	174.719	-36.531	1.65	1.49	1.33	1.28	1.42	-0.90
67	174.740	-36.513	1.65	1.49	1.33	1.28	1.42	-0.90
68	174.743	-36.402	1.63	1.46	1.31	1.26	1.40	-0.88
69	174.788	-36.326	1.51	1.35	1.21	1.17	1.30	-0.80

Table A-3: MHWS elevations in the Manukau Harbour, at mean sea level relative to Auckland vertical datum 1946. Positions are specified in NZGD-49. HAT = highest astronomical tide; MHWPS = mean high water Perigean springs; MHWSC = LINZ cadastral MHWS definition; MHWS-10 = elevation exceeded only by the highest 10% of all high tides.

Site	Longitude	Latitude	HAT	MHWPS	MHWSC	MHWSn	MHWS-10	MLWS-50
1	174.904	-37.045	2.54	2.33	2.07	2.07	2.13	-1.20
2	174.894	-37.050	2.53	2.32	2.06	2.06	2.12	-1.19
3	174.888	-37.059	2.52	2.31	2.05	2.05	2.11	-1.19
4	174.879	-37.055	2.50	2.30	2.04	2.04	2.10	-1.18
5	174.871	-37.054	2.49	2.28	2.02	2.03	2.09	-1.17
6	174.874	-37.047	2.49	2.29	2.03	2.03	2.09	-1.18
7	174.885	-37.044	2.51	2.30	2.04	2.05	2.11	-1.18
8	174.859	-37.052	2.47	2.27	2.01	2.01	2.07	-1.17
9	174.858	-37.043	2.47	2.26	2.00	2.01	2.07	-1.17
10	174.857	-37.035	2.46	2.26	2.00	2.01	2.06	-1.16
11	174.855	-37.026	2.46	2.26	2.00	2.00	2.06	-1.16
12	174.849	-37.030	2.45	2.25	1.99	1.99	2.05	-1.16
13	174.833	-37.019	2.42	2.22	1.97	1.97	2.03	-1.15
14	174.819	-37.013	2.40	2.20	1.95	1.95	2.01	-1.14
15	174.810	-37.005	2.39	2.19	1.94	1.94	2.00	-1.14
16	174.798	-37.014	2.36	2.17	1.92	1.92	1.98	-1.13
17	174.765	-37.021	2.34	2.15	1.90	1.91	1.96	-1.09
18	174.757	-37.012	2.33	2.14	1.90	1.90	1.95	-1.09
19	174.739	-37.002	2.31	2.12	1.88	1.88	1.94	-1.08
20	174.741	-36.989	2.32	2.13	1.89	1.89	1.94	-1.08
21	174.751	-36.981	2.33	2.14	1.90	1.90	1.96	-1.09
22	174.768	-36.970	2.36	2.17	1.92	1.93	1.98	-1.10
23	174.759	-36.956	2.36	2.17	1.92	1.93	1.98	-1.10
24	174.753	-36.950	2.36	2.16	1.92	1.92	1.98	-1.10
25	174.756	-36.943	2.37	2.17	1.93	1.93	1.99	-1.10
26	174.765	-36.941	2.38	2.18	1.94	1.94	2.00	-1.11
27	174.777	-36.940	2.40	2.20	1.95	1.95	2.01	-1.11
28	174.784	-36.938	2.41	2.21	1.96	1.96	2.02	-1.12
29	174.785	-36.935	2.41	2.21	1.96	1.97	2.02	-1.12
30	174.905	-37.075	2.56	2.34	2.08	2.08	2.14	-1.20
31	174.899	-37.062	2.54	2.33	2.07	2.07	2.13	-1.19
32	174.943	-37.101	2.63	2.41	2.14	2.15	2.21	-1.23
33	174.900	-37.117	2.58	2.37	2.10	2.10	2.16	-1.21
34	174.878	-37.075	2.51	2.30	2.04	2.05	2.11	-1.18
35	174.850	-37.055	2.46	2.25	2.00	2.00	2.06	-1.16
36	174.840	-37.056	2.44	2.24	1.98	1.99	2.05	-1.16

Site	Longitude	Latitude	HAT	MHWPS	MHWSC	MHWSn	MHWS-10	MLWS-50
37	174.827	-37.068	2.42	2.22	1.97	1.97	2.03	-1.15
38	174.807	-37.080	2.40	2.20	1.95	1.96	2.01	-1.14
39	174.785	-37.084	2.37	2.18	1.93	1.93	1.99	-1.13
40	174.792	-37.135	2.47	2.27	2.02	2.02	2.08	-1.10
41	174.756	-37.087	2.35	2.16	1.91	1.92	1.97	-1.08
42	174.738	-37.110	2.37	2.17	1.93	1.93	1.99	-1.08
43	174.720	-37.127	2.38	2.19	1.94	1.95	2.00	-1.09
44	174.687	-37.142	2.40	2.20	1.96	1.96	2.02	-1.09
45	174.706	-37.161	2.45	2.25	2.00	2.00	2.06	-1.10
46	174.749	-37.161	2.47	2.27	2.02	2.02	2.08	-1.10
47	174.789	-37.164	2.52	2.31	2.06	2.06	2.12	-1.11
48	174.715	-37.202	2.54	2.33	2.07	2.08	2.14	-1.11
49	174.729	-37.230	2.61	2.40	2.13	2.14	2.20	-1.13
50	174.678	-37.129	2.37	2.17	1.93	1.93	1.99	-1.08
51	174.667	-37.111	2.33	2.13	1.89	1.90	1.95	-1.07
52	174.661	-37.087	2.27	2.09	1.85	1.85	1.91	-1.07
53	174.670	-37.061	2.21	2.03	1.80	1.80	1.86	-1.05
54	174.651	-37.045	2.18	2.00	1.77	1.77	1.83	-1.02
55	174.627	-37.042	2.14	1.97	1.74	1.75	1.80	-1.01
56	174.595	-37.051	2.10	1.92	1.71	1.71	1.76	-0.99
57	174.599	-37.017	2.11	1.94	1.72	1.72	1.77	-0.99
58	174.616	-36.994	2.15	1.98	1.75	1.76	1.81	-1.01
59	174.631	-36.983	2.18	2.00	1.77	1.78	1.83	-1.02
60	174.652	-36.969	2.22	2.04	1.81	1.81	1.86	-1.04
61	174.681	-36.938	2.28	2.10	1.86	1.86	1.92	-1.07
62	174.715	-36.940	2.32	2.13	1.89	1.89	1.95	-1.08
63	174.739	-36.937	2.35	2.16	1.91	1.92	1.97	-1.10
64	174.766	-36.929	2.39	2.19	1.95	1.95	2.01	-1.11
65	174.819	-36.932	2.46	2.25	2.00	2.00	2.06	-1.14
66	174.609	-37.021	2.13	1.95	1.73	1.73	1.78	-1.00
67	174.818	-36.945	2.44	2.24	1.99	1.99	2.05	-1.14
68	174.667	-36.954	2.25	2.07	1.83	1.84	1.89	-1.05
69	174.570	-37.015	2.08	1.91	1.69	1.70	1.74	-0.98
70	174.548	-37.052	2.03	1.86	1.65	1.66	1.70	-0.96
71	174.547	-37.034	2.04	1.87	1.66	1.66	1.71	-0.96
72	174.810	-36.937	2.44	2.24	1.99	1.99	2.05	-1.13

Table A-4: MHWS elevations in the Kaipara Harbour, at mean sea level relative to Auckland vertical datum 1946. Positions are specified in NZGD-49. HAT = highest astronomical tide; MHWPS = mean high water Perigean springs; MHWSC = LINZ cadastral MHWS definition; MHWS-10 = elevation exceeded only by the highest 10% of all high tides.

Site	Longitude	Latitude	HAT	MHWPS	MHWSC	MHWSn	MHWS-10	MLWS-50
1	174.479	-36.231	2.73	2.45	2.22	2.20	2.30	-0.87
2	174.276	-36.307	2.43	2.18	1.98	1.96	2.05	-0.77
3	174.349	-36.322	2.52	2.27	2.06	2.04	2.13	-0.80
4	174.402	-36.297	2.59	2.33	2.11	2.09	2.18	-0.82
5	174.250	-36.384	2.37	2.13	1.93	1.91	2.00	-0.74
6	174.309	-36.392	2.42	2.17	1.97	1.95	2.04	-0.75
7	174.364	-36.414	2.46	2.21	2.01	1.99	2.08	-0.76
8	174.397	-36.344	2.56	2.30	2.09	2.07	2.16	-0.79
9	174.409	-36.448	2.51	2.26	2.05	2.03	2.12	-0.78
10	174.423	-36.401	2.51	2.26	2.05	2.03	2.12	-0.78
11	174.407	-36.383	2.51	2.26	2.05	2.03	2.12	-0.78
12	174.423	-36.501	2.56	2.30	2.09	2.07	2.16	-0.79
13	174.426	-36.541	2.73	2.45	2.22	2.20	2.30	-0.87
14	174.443	-36.650	2.77	2.49	2.26	2.24	2.34	-0.88
15	174.364	-36.621	2.73	2.45	2.22	2.20	2.30	-0.86
16	174.381	-36.571	2.66	2.39	2.17	2.14	2.24	-0.84
17	174.342	-36.541	2.59	2.33	2.11	2.09	2.19	-0.82
18	174.295	-36.506	2.52	2.27	2.06	2.04	2.13	-0.80
19	174.260	-36.455	2.45	2.20	2.00	1.98	2.07	-0.78
20	174.236	-36.428	2.41	2.16	1.96	1.94	2.03	-0.76
21	174.467	-36.554	2.75	2.47	2.24	2.22	2.32	-0.87
22	174.425	-36.561	2.66	2.39	2.17	2.15	2.25	-0.84
23	174.419	-36.572	2.66	2.39	2.17	2.15	2.25	-0.84
24	174.389	-36.636	2.77	2.49	2.26	2.23	2.34	-0.88
25	174.339	-36.607	2.73	2.45	2.22	2.20	2.30	-0.87