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Potential Future Changes in Mangrove-Habitat in Auckland's East-Coast Estuaries

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1 Executive Summary

Mangrove-habitat expansion has been documented in many of Auckland's east-coast estuaries over the last several decades. Historical accounts also indicate that substantial loss of mangrove-habitat occurred locally during the first half of the 20th century. This was associated with reclamations for farmland, landfills, roads and ports, as well as construction of causeways that restricted tidal flows. Some of this loss would have been offset by mangrove-habitat expansion at unaffected sites. However, it is difficult to quantify the net effect of these natural and human-induced changes in mangrove habitat in Auckland's estuaries that predate the systematic aerial photographic surveys that began in NZ in the 1940s (Morrisey et al., 2007). Increases in mangrove habitat since that time have coincided with estuary infilling due to accumulation of sediments eroded from the land. Although sedimentation is a natural process, increased soil erosion due to catchment deforestation (from the mid-1800s), conversion to pasture and rapid urban development over the last 50 years or so has accelerated sedimentation in Auckland's estuaries. These eroded sediments have built intertidal flats that provide potential habitat for mangroves. In the Auckland Region, changes in mangrove distribution have been documented by several studies (section 3.3.2). However, there has been no comprehensive regional-scale assessment of historical changes in mangrove habitat.

Mangroves provide a number of ecosystem services in estuaries, which include: trapping of fine-sediments and associated stormwater contaminants; carbon sinks; primary production; habitat for juvenile fish; roosting, feeding and breeding sites for birds; and protection of low-lying shorelines from wave erosion (section 3). However, there are community concerns about mangrove-habitat expansion in Auckland's estuaries, which relate to amenity and aesthetic values and loss of other estuarine habitats. This has led to calls for more active management of mangroves in some estuaries.

In response to the potential effects of estuary sedimentation on mangrove habitat extent, the Auckland Regional Council contracted NIWA to evaluate the potential for mangrove-habitat expansion in Auckland's east-coast estuaries over the next 100 years (Figure 3.1). The present study relates specifically to likely changes in mangrove-habitat due to the deposition of catchment sediments in the study estuaries. This work does not address other potential ecological effects related to estuary sedimentation, such as changes in benthic community composition on tidal flats, which may occur irrespective of mangrove response to terrigenous sediment inputs.

The present study draws on existing information which include: historical records and projections of future sea-level rise; sediment accumulation rates (SAR); and recent mangrove research in NZ estuaries. Work undertaken in the present study includes: mapping of potential mangrove habitat from aerial photography; numerical modeling of wave-driven sediment remobilisation and tidal amplification effects on water levels. These data are used to predict the potential extent of mangrove habitat in Auckland's east coast estuaries by the 2050s and 2090s. It should be noted that this assessment does not take into account how future climate change may alter catchment sediment loads and estuary sedimentation rates.

The study objectives are to:

- map the present-day distribution of mangroves in Auckland's east coast estuaries;
- predict likely future changes in mangrove habitat extent and distribution in Auckland's east coast estuaries due to ongoing sedimentation and sea-level rise;
- provide information to demonstrate the potential long-term consequences of current landuse practices on these estuarine systems;
- provide objective information to support resource management and planning decision in Auckland's east-coast estuaries and their associated land catchments;
- present predictions of potential future changes in mangrove-habitat for Auckland's east coast estuaries in a way that is readily understood.

A glossary of technical terms used in this report is presented in section 2.

Mangroves are sensitive to changes in tidal-flat surface elevation due to their inability to be permanently submerged by the tide. The grey mangrove (Avicennia marina subsp australasica) found in North Island estuaries colonises intertidal flats down to mean tide level (MTL), where the seabed is submerged for no more than ~six hours per tidal cycle. Recruitment of mangrove seedlings on tidal flats also appears to be influenced by frequency & severity of wave exposure during the summer months when propagules are produced. In large estuaries, with wave fetches of several kilometers or more, major recruitment events may occur infrequently (i.e., years–decades apart, section 3.3 and references therein).

The development of intertidal flats occurs over time as catchment sediments are delivered to estuaries and deposited. Tidal-flat surface elevation continues to increase due to ongoing sedimentation. As a consequence of this sedimentation the area of intertidal flat that is potentially suitable as mangrove habitat progressively increases. However, estuary infilling and increases in tidal-flat surface elevation are also offset by sea-level rise (SLR). In Auckland's east-coast estuaries, average SAR on intertidal flats of 3.8 mm yr-1 (section 4.3) has been offset by SLR of 1.6 mm yr-1 since 1950 (section 4.3.3). We assume that SAR is a reasonable proxy for surface elevation changes on the intertidal-flat sediments (section 4.3). Thus, in this assessment, the primary processes that control tidal-flat development, are estuary sedimentation and sea-level rise. The magnitude of changes in the horizontal position of the MTL isobath is controlled by the local tidal-flat slope.

Scenarios of future changes in sea level to the 2050s and 2090s are based on the historical trend observed at the Port of Auckland and recommendations of the MfE (2008) Guidance Manual (section 3.3.4). The three SLR scenarios considered in the present study are:

- **Scenario One:** based on the historical trend in sea level observed at the Port of Auckland since 1950. Average SLR of 1.6 mm yr^{-1} resulting in an increase in sea-level of 0.08 m by the 2050s ($SLR_{0.08m}$) and 0.14 m by the 2090s ($SLR_{0.14m}$).

- **Scenario Two:** based on MfE (2008) guidance incorporating most recent IPCC (2007) projections. Average SLR of 4.6 mm yr^{-1} and increase in sea level of 0.22 m by the 2050s ($SLR_{0.22m}$) and 5.4 mm yr^{-1} (0.47 m) by the 2090s ($SLR_{0.47m}$). Scenario Two represents a mid-range SLR projection.

- **Scenario Three:** based on MfE (2008) guidance incorporating most recent IPCC (2007) projections. Average SLR of 6.9 mm yr^{-1} and increase in sea level of 0.33 m by the 2050s ($SLR_{0.33m}$) and 8.8 mm yr^{-1} (0.77 m) by the 2090s ($SLR_{0.77m}$). Scenario Three represents a possible upper-range SLR projection.

The prediction of future changes in potential mangrove habitat in Auckland's east-coast estuaries is based on field observations and numerical modeling. The methods employed in the study are presented in sections 4.1–4.9 and briefly described here (sections 4.1–4.9). The area of potential mangrove habitat above mean tide level (MTL-2007) isobath was mapped from 1:50,000 scale aerial orthophotos using the waterline method (section 4.2.1). The present distribution of mangroves in the estuaries were also mapped. Tidal-flat elevation profiles were measured using an RTK GPS system to determine tidal-flat slope and fix the lower-elevation limit (LEL) for mangrove trees and seedlings in terms of MTL-2007 (sections 3.3.3 & 4.2.2) and the Auckland Vertical Datum 1946 (AVD-46). A regional average SAR of 3.8 mm yr^{-1} was adopted for intertidal flats, based on previous sediment core studies undertaken in Auckland's east-coast estuaries. This SAR value was validated using an independent dating technique (section 4.3). The magnitude of tidal-amplification due to water depth and estuary shape was quantified for past, present and future bathymetry using calibrated hydrodynamic models (section 4.5). The influence of long-term wave climate on bed-sediment mobilisation, which in turn influences seedling establishment, was assessed using an empirical wave model of each estuary (section 5.6). The results of the model simulations are presented in a companion report (Gorman and Swales, 2009). Changes in potential mangrove habitat above MTL were mapped for 1950, 2050s and 2090s using GIS methods to adjust the position of the MTL-2007 isobath due to net changes in sea level (i.e., sea-level change offset by sedimentation). This involved development of digital elevation models (DEM) of the intertidal flats in each estuary using LiDAR and RTK-GPS elevation data (sections 4.7–4.8). Catchment sediment loads derived from empirical models and the tidal prism volumes were used to estimate the sediment infill time for each estuary (section 4.9) and provide an index of the relative vulnerability of each estuary to sedimentation.

The potential for future mangrove habitat expansion out to the 2090s is assessed in each estuary based on: (1) the relative likelihood of seedling establishment. This assessment is based on the probability of bed disturbance by waves (sections 4.6.3 & 5.8); and (2) changes in the position of the MTL isobath due to the net effect of estuary sedimentation and projected increases in sea level under Scenarios 1–3.

Summary statistics of historical changes in mangrove habitat as well as predicted future changes in potential habitat (i.e., interidal-flat areas above MTL) focus on regional and estuary-scale patterns rather than local effects. However, maps of each study estuary do provide spatial information on past and future predicted changes in mangrove habitat (sections 5.7 & 5.8). The overall findings, implications as well as the uncertainties inherent in this study are presented in section 6.

Regional and local patterns in historical changes and present-day distribution of mangroves in Auckland's east-coast estuaries are summarised below:

- Mangroves presently occupy 58% (27.1 km^2) of the 46.5 km^2 of potential mangrove habitat above MTL-2007 in Auckland's east-coast estuaries (range = 22–75%, section 5.4). The Waitemata Harbour accounts for 32% (8.8 km^2) of the present-day mangrove habitat. Mangroves have not substantially increased their distribution in the Central Waitemata Harbour since the late 1950s.

- The area of mangrove stands in the study estuaries has increased by between 28–400% (0.8–8.4% per annum) since the 1940s–1960s. The largest increases have occurred in the smallest estuaries with high-tide areas less than 1.5 km^2: Okura, Orewa, Waiwera (section 5.7). During this time period, the area of intertidal flat above MTL is estimated to have increased by only 3–19%.

- The disproportionately larger increase in mangrove distribution over the last 50 years indicates that large areas of intertidal flat have been colonised since the 1950s, with a substantial time lag, in the order of decades, between tidal-flat development (i.e., above MTL elevation) and mangrove colonisation (section 6.3).

- Total area of potential mangrove habitat (i.e., tidal-flat area above MTL-2007) is well predicted by the estuary to catchment area (ECA) ratio (section 5.3). Estuaries with large catchments have a larger proportion of intertidal flat above MTL-2007 and can be estimated as HEA = -0.21(LN(ECA) -0.1 ($r^2 = 0.77$, $P < 0.001$), where HEA is the habitat to estuary area ratio and LN denotes a natural log transformation. The relationship between HEA and T_A was also significant but did not explain any more of the data variability ($r^2 = 0.75$, $P < 0.001$). The T_A is also more difficult to calculate than the ECA.

- Estuaries with presently less than 50% mangrove occupation of intertidal flats above MTL-2007 (i.e., their potential habitat) include small estuaries with slow sediment infilling rates (T_A, e.g., Bon Accord and North Cove) and larger estuaries with relatively high infill rates (e.g., Whitford). Likewise, estuaries with mangrove occupation greater than 50% of their potential habitat include small and large estuaries with variable infill rates. These patterns suggest that local factors, such as tidal-flat wave exposure are also influential (section 3.3).

- The lower elevation limit (LEL) for mangrove trees and seedlings averaged 0.35 m MTL-2007 (0.48 m AVD-46) and -0.15 m MTL-2007 (-0.02 m AVD-46) respectively (section 5.4). There are large between-estuary variations in LEL. Mangrove trees occupy most of their potential habitat down to MTL-2007 in sheltered environments, such as tidal creeks and on tidal flats in the smaller fetch-limited estuaries. Based on our present understanding, we have a limited ability to predict the local distribution of mangrove stands on intertidal flats above MTL-2007.

- Tidal amplification of water levels in the estuaries will have a minor effect on the horizontal position of the MTL isobath, and thus the potential extent of mangrove habitat, in comparison to future sea-level rise (section 5.5).

- The rate of sea-level rise relative to sedimentation rates will ultimately determine the long-term fate of mangrove stands in Auckland's east-coast estuaries.

- Estuaries most at risk of infilling with catchment sediment are the Matakana, Puhoi, Waiwera and Wairoa estuaries, with estuary infill times (T_A) of less than 500 years (section 5.1). These systems have catchments 10–100 times larger than their estuaries. The annual rate of sediment delivery to these estuaries is relatively large in comparison to the available estuary storage volume so that tidal flats suitable for mangrove habitat develop rapidly. This estuary infilling is offset by a reduction in the proportion of catchment sediment that is trapped (i.e., sediment trapping efficiency) due to the progressive reduction in sediment accommodation space. Thus, the T_A parameter should be considered as an index of the relative vulnerability of an estuary to sediment infilling.

Predictions of potential future changes in mangrove habitat by the 2050s and 2090s in Auckland's east-coast estuaries are summarised below:

- Predictions of potential future changes in mangrove habitat by the 2050s and 2090s indicate increases in potential mangrove habitat under SLR Scenario One and reductions in potential mangrove habitat under SLR Scenarios Two and Three. The primary reason for these different predicted outcomes is that under Scenarios Two and Three the rate of sea-level rise in the next century will exceed sedimentation rates in Auckland's east-coast estuaries (section 4.8). The main exception to this pattern is that higher sedimentation rates in tidal creeks (close to catchment outlets) are likely to more than likely compensate for any future increases in SLR rates.

- Scenario One: increases in potential mangrove habitat (i.e., tidal flat area above MTL) will average 8% by the 2050s and 14% by the 2090s (section 5.8). Thus, future estuary sedimentation will potentially add a further 3 km^2 of potential mangrove habitat by the 2050s and 5.8 km^2 by the 2090s. These rates are in line with values over the last 50 years.

- Scenarios Two and Three: the area of potential mangrove habitat is predicted to reduce by 4.5 km^2 (Scenario Two) and 11 km^2 (Scenario Three) by the 2090s.

- Mangroves may respond to rising sea-level by retreating landward or by increasing tidal-flat surface elevations at a rate equal to or exceeding SLR. In many of Auckland's estuaries engineering structures, such as stopbanks, motorway reclamations and seawalls will prevent landward retreat of mangrove stands. The effect of this relative increase in sea level will be increased water depths, landward retreat of the MTL isobath and increasing exposure of existing mangrove stands and forests to direct wave attack. The effects of this accelerated SLR will be most severe in the largest and therefore least fetch-limited estuaries (i.e., CWH, Shoal Bay and Mahurangi) and estuaries directly exposed to the open coast (e.g., Okura, Whitford, Wairoa, Waiheke and Kawau Island estuaries).

- It is unlikely that tidal-flat surface elevations will keep pace with accelerated SLR envisaged under Scenarios Two and Three. This would require substantial increases in catchment sediment loads and/or sediment redistribution within estuaries (e.g., tidal flat erosion). For example, long-term average intertidal SAR of 3.8 mm yr^{-1} (1950 – present) would have to more than double to keep pace with the average 8.8 mm yr^{-1} SLR predicted under Scenario Three (section 3.3.4). The doubling of sediment loads implied by this scenario is unlikely to occur unless there is a major shift in rainfall patterns and/or landuse that substantially enhance soil erosion. Sedimentation is enhanced in mangrove stands fringing tidal creeks (Craggs et al. 2001; Swales et al. 2002b) and tidal flats (Swales et al. 2007a) so that locally mangrove forests may keep pace with future sea-level rise. However, this is not the case for the mature mangrove stands on the upper intertidal flat where SAR are likely to track closely with historical SLR (Swales et al. 2008). In these mature forest stands sediment delivery is limited by the low frequency and duration of tidal inundation. Future accelerated SLR would increase tidal inundation and potential for sediment delivery to these mature mangrove forests, but this will also depend on the rate of sediment supply from catchments.

- Mapping the future landward retreat of the MTL isobath under SLR Scenarios Two and Three indicates that loss of existing mangrove stands is unlikely to occur until after the 2090s in most estuaries. Tidal creeks will provide refuge for mangroves, assuming that the rapid sedimentation (~20 mm yr^{-1}) observed in these environments over the last 50 years occurs in the future. Thus, over time mangroves would be displaced from intertidal flats in the main body of estuaries but remain in tidal creeks where they are likely to have first colonised these systems.

- Rapid increases in mangrove habitat over the next 50 years are most likely to occur in relatively small estuaries (i.e., high-tide area < 5 km^2) with limited wave fetch and large catchment sediment input. These estuaries are identified below.

- The analysis indicates that there is a low likelihood of large-scale mangrove habitat expansion in most of Auckland's east-coast estuaries during the next century. The likelihood of mangrove habitat expansion in each of the study estuaries is assessed as follows: high likelihood (Waiwera); medium – low likelihood (Whangateau, Matakana, Orewa, Okura, Hobson Bay); low likelihood (North Cove, Bon Accord, Mahurangi, Puhoi, Weiti, UWH, CWH, Shoal Bay, Tamaki, Whitford, Wairoa, Putiki, Awaawaroa, Te Matuku).

Mitigating future rates of mangrove-habitat expansion in "at risk" estuaries, will require reductions in catchment sediment yields that in turn reduce estuary sedimentation rates and the creation of intertidal flats. Mean annual sediment yields from Auckland's catchments increase with catchment size (section 5.1) as well as land use, mean slope and rainfall (Hicks et al., 2009). Thus, land-management practices that reduce sediment delivery to estuaries are likely to be the only effective options.

However, in some estuaries, a large proportion of the annual sedimentation budget can be supplied from other nearby catchments by tidal currents so that sedimentation rates can be high even in estuaries with relatively small catchments due to sediment delivery from “far-field” sources. Shoal Bay, in the Central Waitemata Harbour, is a good example of this process where a large fraction of the sediment deposited in the Bay originates from the Henderson Creek catchment (Green 2007; Swales et al., 2007b). Thus to be effective, management plans aimed at reducing sediment delivery to target estuaries should be informed by site-specific information on sediment-sources, which would include contributions from different land uses, sub-catchments as well as the potential sediment delivery from “far-field” sources.

In interpreting the results of this study, the uncertainties inherent in any assessment of future environmental changes should be borne in mind (section 6.5). The area of intertidal flat above mean tide level (MTL) represents the maximum possible extent of mangrove habitat in Auckland’s east-coast estuaries. This lower elevation limit, which reflects a physiological constraint, is well documented in the scientific literature (section 3.3 and Morrisey et al., 2007). The validation of the hindcast MTL-1950 isobath using historical orthophotos (section 5.7.3) indicates that we can have confidence in the methodology employed to make predictions of the MTL position under the future SLR Scenarios 1–3.

The present study also shows that, particularly in large estuaries, there are large areas of interidal flat above MTL -2007 that have not been colonised by mangroves. This is attributed to wave-driven sediment mobilisation, which limits seedling establishment (section 3.3). We were unable to demonstrate a strong relationship between wave exposure and observed LEL for mangrove trees in the present study. This mainly reflects the limitations of the wave modeling and the data rather the absence of such a relationship. However, this presently limits our ability to quantitatively predict, at a local scale, areas of bare intertidal flat above MTL that will be colonised by mangroves.

Future changes in the MTL isobath also depend on SLR projections and estuary sedimentation rates and therefore less certain than the mapping of the present MTL-2007 isobath. While an acceleration in SLR is widely accepted (and already showing up in NZ tide records), there remains considerable uncertainty in the projections of possible upper limits of SLR by the end of this century, with a number of estimates now above 1 m. This uncertainty in the upper limits arises from a range of plausible responses of the ice sheets to accelerated warming. Estimates of future estuary sedimentation are also based on recent-historical rates (i.e., last ~50 years), so that the forward assessment assumes no change in sediment delivery rates from catchments.

Predictions of future changes in mangrove habitat in Auckland’s east-coast estuaries under accelerated SLR scenarios indicate that large-scale loss of mangroves is unlikely to occur over the next century. Recent studies indicate that rates of sea-level rise over the next century are likely to equal or exceed SLR Scenario Three (section 3.3.4). On this basis, the historical trend in sea level observed at the Port of Auckland (i.e., Scenario One) is unlikely to be sustained in the future.

2 Glossary of terms

AVD-46: Auckland Vertical Datum-1946 is a fixed reduced level based on measurements of the Mean Level of the Sea (MLOS, see definition below) at the Port of Auckland during the 1920s–1940s.

Bathymetry: The topography of the sea bed relative to a particular vertical datum.

^{137}Cs: caesium 137 is an artificially produced radioisotope (see definition) that was introduced to the environment by atmospheric nuclear weapons tests from the 1940s onwards. Major peaks in ^{137}Cs input occurred in the 1950s and 1960s. The half life of ^{137}Cs is 30 years and this radioisotope has been used in NZ estuaries & lakes to identify sediments deposited since the early 1950s.

DEM: Digital Elevation Model is a three-dimensional representation of the earth's surface.

ECA Ratio: Estuary to Catchment Area Ratio. The ECA Ratio is used in the present study to provide a standard (normalised) measure of the estuary areal size relative to the catchment area.

Entrainment: in the earth sciences, entrainment refers to the picking up and setting into motion of sediment particles by water, wind or ice. In estuaries, sediments are mainly entrained by tide and wave-driven currents, with waves being the main mechanism on intertidal flats.

ENSO: El Niño Southern Oscillation. A large-scale oscillation of the ocean-atmosphere system which alters the atmospheric heat balance and changes wind patterns mainly over the Pacific Ocean. A key feature is alternation between El Niño and La Niña states over 2-5 years cycles. The strength of ENSO is measured by the Southern Oscillation Index (SOI), which is calculated from the monthly or seasonal fluctuations in the air pressure difference between Tahiti and Darwin. SOI is negative during El Niño and positive during La Niña episodes.

Estuaries: can be defined in a number of ways. Ocean scientists define estuaries as water bodies that are connected to the open sea where sea water mixes with and is measurably diluted by freshwater runoff from the land. Marine geologists view estuaries as sediment traps. The estuaries that we see today occupy ancient river valleys that were flooded by the sea at the end of the last ice age, between 12,000 and 7,000 years ago. Estuaries receive and trap sediment from the land as well as from the sea. This sediment has built up over time to form the tidal flats that we see today. Because of this sediment infilling many NZ estuaries are classified as mature. A biological definition of estuaries is that they are coastal habitats which sustain plants and animals that are able to tolerate a wide range of water salinity for part of, or all of their lives.

Fetch: The effective length of continuous water surface over which waves are generated by a wind having a constant direction and speed.

GCM: A model of the global ocean-atmosphere system used to predict future climate scenarios, correctly called a General Circulation Model (GCM). The most recent GCMs include global representations of the atmosphere, oceans, and land surface.

GCP: Ground Control Points are points on the earth surface of known location (i.e., fixed within a particular co-ordinate system) which are commonly used to geo-reference images collected by aircraft or orbiting satellites. Geo-referenced images are used in the present study to determine historical changes in mangrove-habitat extent and to locate the position of the MTL isobath under present-day and future sea-level scenarios.

GPS: the Global Positioning System is a network of satellites that orbit the earth and make it possible to pinpoint geographic locations within a few metres of their actual position on the earth's surface.

Greenhouse gas: Any gas that absorbs infrared radiation in the earth's atmosphere. Greenhouse gases include, but are not limited to, water vapour, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3), a range of fluorocarbons and sulfur hexafluoride (SF_6).

HEA Ratio: Habitat to Estuary Area Ratio. The HEA Ratio is used in the present study to provide a standard (normalised) measure of the area of potential mangrove habitat relative to the high-tide surface area of an estuary. The potential mangrove habitat is the area of intertidal flat at or above MTL elevation.

Hindcast: a retrospective analysis or re-analysis of the past state of a dynamic system with the aid of a numerical model. Unlike forecasts where observations (i.e., measurements) are available only for the initialisation of the forecast, observations are generally available for the entire hindcast period and can therefore be incorporated into the model simulations and/or used to validate the hindcast. Hindcasts are sometimes also referred to as reconstructions.

Hydrodynamic Model: a numerical computer model that simulates the dynamic flow of water and its level throughout a time period over a schematized or simplified representation of the sea-bed. Hydrodynamic models are forced on the open "wet" boundaries by a series of tidal heights or flows into and out of the model domain and can include wind stress over the model surface.

Intertidal: the area of an estuary or harbour alternately exposed and covered by water at any time between the lowest low tide and highest high tide.

IPCC: Intergovernmental Panel on Climate Change. The IPCC was established jointly by the United Nations Environment Programme and the World Meteorological Organization in 1988. The purpose of the IPCC is to assess information in the scientific and technical literature related to all significant components of the issue of climate change. The IPCC draws upon many of the world's expert scientists as authors and expert reviewers. IPCC prepares periodic assessments of the scientific underpinnings for understanding global climate change and its consequences, producing its 4th Assessment Report in 2007.

IPO: Interdecadal Pacific Oscillation. A long timescale oscillation in the ocean–atmosphere system that shifts climate and ocean response in the Pacific region every one to three decades. The IPO shifted to its negative phase around 1999.

Isobath: a line or contour on a map or chart that connects points of equal water depth or seabed elevation relative to a fixed vertical datum.

LiDAR: Light Detection And Ranging is an optical remote sensing technology that measures properties of scattered light to find distance and/or other information of a distant target such as the earth's surface. The prevalent method to determine distance to an object or surface is to use laser pulses. The range to an object is determined by measuring the time delay between transmission of a laser pulse and detection of the reflected signal. LiDAR data have been used in the present study to construct DEM of intertidal flats areas in the estuaries.

LEL: Lower Elevation Limit defines the lowest elevation on intertidal flats that mangrove seedlings and trees occur. This is measured along survey transects in each of the study estuaries.

Mangroves: Mangroves are a taxonomically diverse group of halophytic (salt-tolerant) plants that, worldwide, include approximately 70 species. They are typically woody trees or shrubs taller than 0.5 m, and inhabit the intertidal areas of coastal and estuarine environments over a wide range of latitude. The New Zealand mangrove, or Manawa, is one of several taxa within the genus Avicennia. Avicennia are true mangroves in that their habitat is defined solely by the intertidal zone. They also possess specialised physiological and reproductive adaptations which allow them to grow there. Manawa is presently ranked as a sub-species (Avicennia marina (Forsk.) Vierh subsp. australasica (Walp.) J.Everett) within Avicennia marina (grey mangrove), a species occurring in both the northern and southern hemispheres of the globe.

MHWN: Mean High Water Neap tide, which occurs around the time of the moon's is in its first or last quarter.

MHWS: Mean High Water Spring tide, which occurs around the time of the full or new moon. Various definitions are used to define the average tide level of higher spring tides.

MHWPS: Mean High Water Perigean Spring tide. These tides occur every 7 months when new or full moon coincides with the moon's perigee, which is when it is closest to the earth during its 27.5 day elliptical orbit around the earth.

MSL: Mean Sea Level. Usually relates to the average sea level during a defined time period. The MSL can also be referred to in the context of a MSL fixed vertical datum, which is not equivalent to the actual sea level.

MLOS: Mean Level of the Sea. This term is used to avoid any confusion with the use of MSL and refers to the actual average sea level over a defined period (from months to several years).

MTL: Mean Tide Level. The arithmetic mean of the mean high water and mean low water level over a suitably long period (e.g., a month or a year). The MTL includes the effects of tidal amplification within an estuary (see definition), which can set up water levels by up to several cm above the MLOS measured at the estuary mouth.

MTL-2007: the Mean Tide Level during 2007.

Orthophoto: is an aerial photograph geometrically corrected, termed orthorectified, such that the horizontal scale is uniform across the image. Unlike an uncorrected aerial photograph, an orthophotograph can be used to measure true distances, because it is an accurate representation of the earth's surface, having been adjusted for topographic relief, lens distortion, and camera-tilt effects. Orthophotos are used in the present study to map historical and present-day distributions of mangrove habitat and to define areas of intertidal flat that are potential mangrove habitat.

^{210}Pb: lead 210 is a naturally occurring radioisotope (see definition) that is an intermediate decay product of uranium-238. Lead 210 forms naturally in sediments and rocks as well as in the atmosphere. It is this atmospheric lead 210 component that is the basis of sediment dating. Lead-210 has a half life of 22.3 years and can be used to date sediments up to about 150 years old. The method has been used in NZ estuaries & lakes to date sediments deposited since the late 1800s.

Projections: (as used by IPCC). Climate model can produce predictions of the future climate or ocean state, which is an attempt to produce the most-likely description of the actual evolution of climate and sea-level rise in the future. But these are dependent on assumptions or storylines of how the global community will respond in terms of projecting future emissions, socio-economic impacts and future population growth. Consequently, the synthesized results from IPCC assessments are usually presented in terms of projections, which cover the potential future evolution of the climate emphasising that they involve assumptions that may not be realised in time.

RTK-GPS: Real-Time Kinematic GPS is a technique used in land and hydrographic surveys where a single reference or base station provides real-time corrections of horizontal and vertical position of a point on the earth’s surface to centimetre accuracy.

SAR: Sediment accumulation rates are net time-averaged values that are usually expressed in units of millimetres per year (mm/yr). SAR are typically estimated from dated sediment cores, with layers in the cores dated using a variety of methods, which include radioisotopes and pollen profiles related to historical reconstructions of catchment vegetation changes. SAR derived from cores represent net values because they integrate the effects of all of the processes which have influenced sediment accumulation at a given location. These processes include sediments delivered by stormwater, tidal and wave driven currents as well as cycles of sediment entrainment and re-deposition.

SLR: Sea-Level Rise. There are two types: a) Eustatic SLR—the absolute rise in global or regional sea level from both thermal expansion (i.e., ocean volume expands due to increased water temperature) and discharges of water/ice mass from landmasses (i.e., ocean mass increases); b) Relative SLR—the relative rise in sea level relative to the local land mass, which takes into account the upwards or downwards movement of the landmass. Tide gauges measure relative SLR and is also the SLR that needs to be adapted to at the regional/local scale.

Radioisotopes: atoms of elements that have an unstable nucleus that undergo radioactive decay by emitting gamma rays and/or subatomic particles. Radioisotopes can occur naturally (e.g., lead-210) or can be artificially produced (e.g., caesium-137). These particular radioisotopes are widely used to date sediments deposited in marine, estuarine and lake environments as well as being used as sediment tracers in catchment erosion studies. Radioisotopes decay exponentially at characteristic rates often stated as a half-life. The half life is the time taken for the activity of a radioisotope to decay to exactly half its original value.

SPARROW: Spatially Referenced Regression on Watershed attributes (SPARROW) model developed by the United States Geological Survey. The model estimates annual average catchment sediment loads as a function of catchment characteristics, such as annual rainfall, surface slope, soil type and vegetation cover.

Subtidal: waters and seabed below the lowest astronomical tide or below the local Chart Datum.

T_A: Estuary Infill Time is the estimated time in years required to fill the intertidal volume of an estuary. This is taken as the tidal prism volume in m^3 (see definition) divided by the catchment mean annual sediment load (tonnes) converted to a volume assuming a typical wet-bulk density for estuarine sediments of 1.2 m^3/tonne. This parameter provides an index of the relative vulnerability of an estuary to sediment infilling. It assumes 100% sediment trapping efficiency whereas the proportion of the catchment sediment load that is actually trapped typically declines as an estuary infills.

Terrigenous: sediments that are eroded from the land surface.

Tidal amplification: An increase in the amplitude or range of the tide wave, particularly when propagating into and up an estuary or harbour until it starts to diminish towards the outlets of streams and rivers. Amplification is partly due to reflection from the effective end of an estuary and resonance within the estuary, but more generally caused by shoaling of the tidal wave in shallow waters and funneling (narrowing) of the estuary with distance upstream from the mouth.

Tidal Prism: the volume of water within an estuary at high tide between low and high tide elevations or the volume of water that flows into or out of an estuary during a flood or ebb tide.

Vertical Datum: a curved or level surface from which to determine elevations

Wave exposure: The degree of wave action on an open shore or intertidal bank, governed by the distance of open water over which the wind may blow to generate waves (the fetch) and the strength and incidence of the winds. Wave exposure may be measured by the fetch, wave height, work done or potential for sediment erosion. In the present study we adopt a definition of wave exposure based on the potential for entrainment of fine-sand particles found in Aucklands' east-coast estuaries.

Wave climate: temporal distribution of wave height, period and direction over a sufficiently long period to capture the general wave characteristics of the location.

3 Introduction

Mangrove-habitat expansion has occurred in many of Auckland's east coast estuaries over the last several decades (Roper et al. 1994; Morrisey et al. 1999). This increase in mangrove habitat has coincided with estuary infilling due to accumulation of sediments eroded from the land. Although sedimentation is a natural process, increased soil erosion due to catchment deforestation, conversion to pasture and rapid urban development over the last 50 years or so has accelerated sedimentation in Auckland's estuaries (e.g., Swales et al. 2002a). These eroded terrigenous sediments have built extensive intertidal flats that provide potential habitat for mangroves. Once established, mangroves enhance trapping of silts and clays by dampening tidal currents (Furukawa et al. 1997) and attenuating waves (Massel et al. 1999) such that sediment accumulation rates (SAR) are highest within the fringes of mangrove forests. In the process, mangroves accelerate estuary sedimentation and in doing so influence the large-scale geomorphic development of estuaries (Thom et al. 1975).

Mangroves also provide a number of ecosystem services in North Island estuaries. These include: trapping eroded fine-sediments and associated stormwater contaminants (Craggs et al. 2002; Swales et al. 2002b); carbon sinks (Lovelock & Swales, 2008); primary production supporting detrital food webs (Woodroffe 1985; Oñate-Pacalioga 2005); habitat for juvenile estuarine fish (e.g., parore, mullet and short-finned eel, Morrisey et al. 2007); roosting, feeding and breeding sites, although marginal habitats, for birds (Morrisey et al. 2007); and protection of low-lying shorelines from wave erosion (Swales et al. 2007a).

Community concern about mangrove-habitat expansion in North Island estuaries has led to the removal of juvenile and/or adult mangrove trees from intertidal flats. This action has often been taken due to a perceived loss of amenity, aesthetic values and other estuarine habitats due to mangrove-habitat expansion. Green (2003) provides a succinct overview of issues related to mangrove-habitat expansion and potential management options.

In response to the likely adverse effects of ongoing estuary sedimentation and resulting mangrove-habitat expansion, the Auckland Regional Council contracted NIWA to evaluate the potential for mangrove-habitat expansion in Auckland's east-coast estuaries over the next 100 years. The present study draws on existing information, recent advances in the understanding of processes driving mangrove-habitat expansion in NZ estuaries (Swales et al. 2007a), historical information and numerical modeling. These data are used to predict the potential extent of mangrove habitat in Auckland's east coast estuaries by 2050 and 2090.

3.1 Study objectives

The study objectives:

- Map the present-day distribution of mangroves in Auckland's east coast estuaries.

- Predict likely future changes in mangrove habitat extent and distribution in Auckland's east coast estuaries due to ongoing sedimentation and sea-level rise.
- Provide information to demonstrate the potential long-term consequences of current landuse practices on these estuarine systems.
- Provide objective information to support resource management and planning decision in Auckland's east-coast estuaries and their associated land catchments.
- Present predictions of potential future changes in mangrove-habitat for Auckland's east coast estuaries in a way that is readily understood.

3.2 Study estuaries

The study includes all major estuarine systems on Auckland's east coast, with the exception of Great Barrier Island (Fig. 3.1). The estuaries included in the study, from north to south, are:

- Whangateau (Omaha)
- Matakana
- Mahurangi
- North Cove and Bon Accord (Kawau Island)
- Puhoi
- Wairewa
- Orewa
- Weiti
- Okura
- Waitemata Harbour, including Shoal Bay and Hobson Bay
- Tamaki
- Whitford Embayment
- Wairoa
- Te Matuku, Awaawaroa Bay and Putiki Bay (Waiheke Island).

Figure 3.1:
Location of east-coast estuaries in the Auckland Region included in the study.

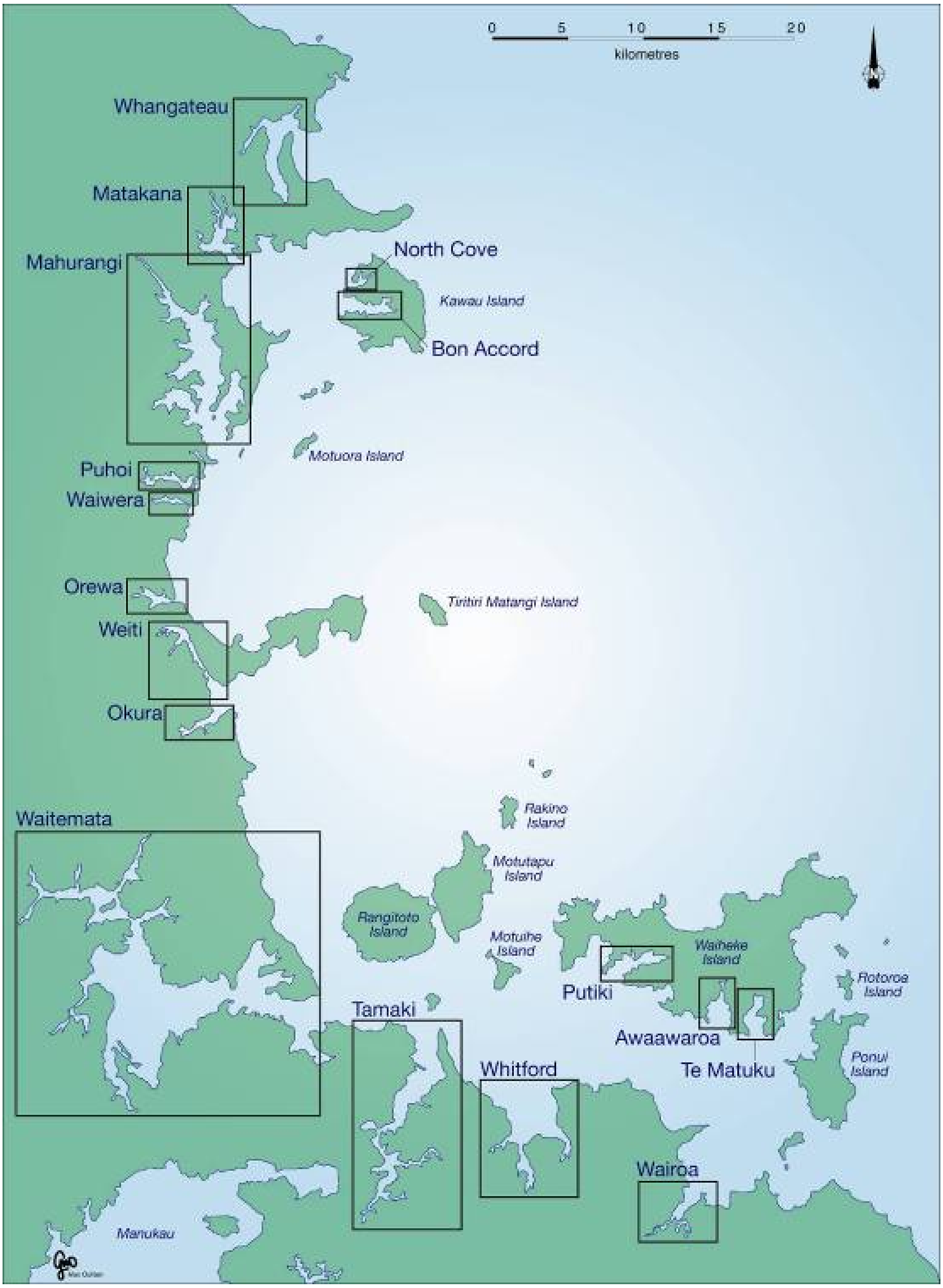


Table 3.1 summarises basic physical attributes of the study estuaries and their land catchments. Estuary size, defined as the high-tide surface area, varies from 1 to 66 km^2, with ~70% of the systems being less than 5 km^2. The two largest estuaries, the Mahurangi and Waitemata Harbours, have high tide surface areas greater than 20 km^2. Tidal prism volumes scale with the estuary size, with most of the systems being intertidal so that they have limited accommodation space for future catchment sediment inputs. Those systems with relatively large catchments, such as the Wairoa Estuary have almost entirely infilled with sediment, with extensive intertidal flats providing suitable mangrove habitat (section 3.3). Despite the metropolitan character of the Auckland Region, pasture remains a dominant catchment landcover class in the catchments of most of the study estuaries. Urban areas remain a minor landcover class, with the exception of the catchments discharging to the Waitemata Harbour and Tamaki Estuary.

Table 3.1:

Physical characteristics of Auckland's east-coast estuaries and land catchments. Notes: (1) area is estuary high-tide surface area; (2) Tidal prism is estimated from spring low and high tide volumes. Data source: NIWA Estuarine Environment Classification Database.

Estuary	Area[1] (km^2)	Tidal[2] Prism (10^6 m^3)	Catchment Area (km^2)	Urban (%)	Pasture (%)	Hort. (%)	Native Forest (%)	Planted Forest (%)	Scrub (%)
Whangateau	8.0	9.5	42.4	0.8	66	10	11	4	9
Matakana	4.4	2.8	50.2	0.6	68	0	12	8	12
Mahurangi	25.1	19.3	122	3	64	0.7	18	10	4
North Cove	0.6	0.9	12	0	0	0	3	0	97
Bon Accord	2.4	4.4	3.2	0	0	0	0.6	8	91
Puhoi	1.8	2.7	43	0	56	0	20	11	13
Waiwera	1	1.7	37.9	0.4	52	0	18	0.3	29
Orewa	1.2	1.8	28.2	9	76	0.2	5	0.3	10
Weiti	2.4	1.9	33.3	7	73	0	6	5	9
Okura	1.4	0.6	22.7	0.6	37	0	11	22	30
Waitemata	65.8	137.7	427	43	33	0	14	4	4
Tamaki	16.9	18.6	108.8	73	25	0	1	0.2	0.7
Whitford	11.3	21.5	61	5	70	0.2	9	9	6
Wairoa	2.9	5.8	311	0	63	0	19	11	7
Te Matuku	2.6	2.2	14.4	0	38	0	40	0	23
Awaawaroa	2.9	6.2	14.1	0	63	0	12	0	24
Putiki	3.4	5.6	13.3	3	53	0	6	0	37

3.3 Background

Globally, sediment loads delivered to estuaries and coasts have increased by as much as an order of magnitude or more due to human activities such as catchment deforestation, conversion to pasture and rapid urbanisation in recent decades (Syvitski et al. 2005). Increased inputs of fine terrigenous sediments due to human activities have had adverse effects on estuarine ecosystems due to increased turbidity and sedimentation and a shift from sand to mud habitats (Thrush et al. 2004). Estuaries age as a natural consequence of sedimentation although this occurs at different rates depending on relative catchment size, sediment yields, tidal-basin volume and geometry and sediment-trapping efficiency (Roy et al. 2001). Eroded terrigenous sediments have built extensive intertidal flats, which have been colonised by mangroves in temperate and tropical environments (Neil, 1998; Panapitukkul et al. 1998; Swales et al. 2007a).

In New Zealand, the grey mangrove or Manawa (*Avicennia marina* subsp *australasica*) occurs in North Island estuaries above 38°S latitude, which coincides with Kawhia and Ohiwa Harbours on the west and east coasts respectively. The southern latitudinal limit of mangrove in New Zealand is primarily related to physiological stress and plant damage associated with low overnight air temperatures and the frequency and severity of frosts (Morrisey et al. 2007). In the estuaries of southeastern Australia, *A. marina* seedlings colonise intertidal flats down to about the mean tide level (MTL, section 3.33), where seedlings are submerged for ≤ 6 hours per tide (Clarke & Myerscough, 1993). This is the maximum time period that *A. marina* seedlings can be continuously submerged (Hovenden et al. 1995). This limit reflects the physiological requirement of seedlings to maintain an adequate oxygen supply because they are submerged by the tide and typically grow in anaerobic substrates. Consequently, mangroves uptake oxygen while exposed to the air at low tide. In New Zealand estuaries, the semi-diurnal tide submerges intertidal areas twice each day. This tide has a 12.4 hour period so that intertidal flats above the mean sea level are submerged for less than *c*. six hours per tide.

The lower elevation limit (LEL) for *A. marina* establishment on tidal flats has not been systematically mapped in New Zealand estuaries but is likely to be similar to *A. marina* in Australian estuaries. The LEL for grey mangroves also appears to be influenced by wave-driven erosion of the substrate in which propagules and seedlings are rooted (Clarke & Myerscough, 1993; Swales et al. 2007a). In the southern Tauranga Harbour, mangrove trees extend down to about ~0.1 m below MTL (~0 m Moturiki Vertical Datum (MVD) 1953) at sheltered sites and ~0.2 m above MTL at wave-exposed sites (Park, 2004). Note that MTL at Tauranga is presently (i.e., 2004) 0.08 m above the fixed Moturiki Vertical Datum 1953. In the southern Firth of Thames, mangroves do not occur below +0.5 m MVD-53. Thus, wave exposure appears to be an important factor, in addition to tidal-flat elevation, controlling mangrove distribution in estuaries.

3.3.1 Sedimentation rates in Auckland estuaries

Previous studies in Auckland estuaries indicate that sediment accumulation rates (SAR) have increased during the last 150 years or so due to human activities in source catchments (Hume & McGlone 1986; Oldman and Swales, 1999; Craggs et al. 2001; Swales et al. 1997, 2002a, 2002b, 2007b; Hume et al. 2002). These activities include catchment deforestation and conversion to pasture since the mid-1800s and horticultural and rapid urban development during the last 50 years or so.

SAR measured in Auckland estuaries before catchment deforestation (1840–1900) were typically less than 1 mm yr^{-1} (Table 5.1, Swales et al. 2002a). The removal of native forest landcover and conversion to pasture increased soil erosion and catchment sediment loads such that SAR increased by as much as an order of magnitude during this period. This influx of eroded soil has accelerated estuary infilling. Tidal creeks close to catchment outlets have infilled most rapidly, with SAR averaging 20 mm yr^{-1} over the last 50 years. Many of these tidal creeks are now entirely intertidal so that they are completely exposed during low tides. In the main body of estuaries, sedimentation has built extensive intertidal flats, with SAR averaging less than 5 mm yr^{-1}.

Estuaries follow similar evolutionary paths over time as they infill with sediment: subtidal areas and average water depths decrease and as a result the hydrodynamic and sedimentological characteristics and biological communities change (Roy et al. 2001). SAR will decline as the available accommodation space for sediments is reduced and a larger proportion of the catchment sediment load is exported from the receiving estuary. Today, Auckland's east-coast estuaries are at various stages of infilling. Some estuaries have partially infilled and retain large subtidal habitats, such as the Waitemata and Mahurangi Harbours. Other estuaries, such as the Wairoa (Clevedon) is an example of one that has completely infilled with sediment to form tidal flats that have been colonised by mangroves (Fig. 3.2). This has occurred because the land catchment (311 km^2) is large in comparison to the estuary (high-tide area < 3 km^2). Evidence from sediment cores indicates that the Wairoa is exporting terrigenous fine sediments to the adjacent coastal environment (Swales et al. 2002a).

Estuary sedimentation has been partly offset by relative sea-level rise (SLR), which effectively slows down the pace of estuary "aging" due to infilling. The historical rate of relative sea-level rise recorded at Port of Auckland (Waitemata) averaged 1.30±0.09 mm yr^{-1} from 1899 to 1999 (Hannah, 2004). An update to 2007 for the Auckland record indicates that the long-term average rate since 1899 is now 1.4 mm yr^{-1}, due to higher mean sea levels since the Interdecadal Pacific Oscillation switched phases in 1999 (Rob Bell, NIWA, unpublished data). This SLR offset of estuary sedimentation is most effective in the main bodies of estuaries where average SARs over the last 50 years or so have been similar to SLR. This balancing process has been much less effective in tidal creeks, which have rapidly infilled seaward from their catchment outlets.

Figure 3.2:
Wairoa estuary (Clevedon). The Wairoa has infilled with sediment forming intertidal flats that have been colonised by mangrove over the last 50 years or so. (Photo: A. Swales).

3.3.2 Mangrove-habitat expansion

Mangrove-habitat expansion has occurred over recent decades in New Zealand's upper North Island estuaries (Burns & Ogden, 1985; Ellis et al. 2004; Morrisey et al. 2007). In the southern Firth of Thames, mangrove have colonised some 740 ha of tidal flat since the mid-1950s (Swales et al. 2007a). This example of large-scale mangrove habitat expansion has occurred as a result of rapid tidal-flat sedimentation (~20 mm yr^{-1}) since at least the late 1920s and followed deforestation (1850–1920) and resulting increases in catchment sediment loads. Major mangrove seedling recruitment events have occurred on average every ten years and are likely to coincide with rare, extended periods of calm weather during the summer when the tidal-flat is not eroded by wave action (Swales et al. 2007a).

In the Auckland Region, changes in mangrove distribution have been documented by several studies. Roper et al. (1994) mapped changes in mangrove habitat in the upper Waitemata Harbour during the period 1940–1991. They found some increase in the area of existing mangrove stands rather than colonisation of bare tidal flats. Morrisey et al. (1999) mapped mangrove-habitat expansion in six tidal creeks and estuaries. Rates of mangrove-habitat expansion varied widely between systems (5–160%) and in only two cases (i.e., Puhinui and Okura estuaries) did increases in mangrove habitat coincide with changes in catchment landuse. Observations in the Firth of Thames suggests that changes in tidal-flat elevation due to sedimentation are more direct precursors for mangrove-habitat expansion. Mangrove have also extended their distribution in Puhoi estuary (Kronen 2001), Whitford embayment and its tributary creeks (Ellis et al. 2004), Pakuranga Creek (Swales et al. 2002b), and the Pahurehue Inlet, Manukau Harbour (Kingett Mitchell 2005).

These previous studies indicate that rapid mangrove-habitat expansion in Auckland estuaries has occurred in tidal creeks and estuaries close to catchment outlets. This is related to the large increases in tidal-flat surface elevations in creeks due to rapid sedimentation. Furthermore, tidal creeks are sheltered from wave action due to their generally small size and convoluted channel network so that the potential for wave generation is quite limited. Consequently, tidal creeks fringing estuaries have provided suitable habitat for mangroves. Based on these observations, mangrove-habitat expansion in the main bodies of estuaries is likely to occur more gradually because: (1)

surface elevations for parts of the tidal flats remain below the LEL; and (2) seedling establishment is hampered due to more frequent substrate disturbance by waves.

3.3.3 Sea level and vertical datums

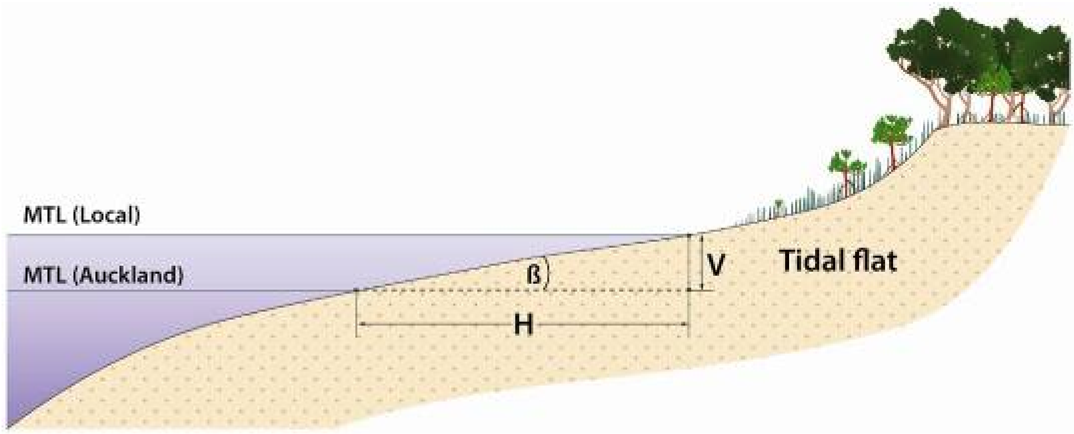
In New Zealand estuaries, the semi-diurnal tide submerges intertidal areas twice each lunar day. This tide has a 12.4 hour period so that intertidal flats above the mean tide level (MTL) are submerged for less than six hours per tide. The MTL elevation is considered the lower elevation limit (LEL) at which mangroves stands and forests can successfully establish on intertidal flats. Mangrove seedling may establish below this level but are unlikely to survive. The MTL in estuaries is primarily governed by the mean level of the sea (MLOS).

MLOS is the actual mean level of the sea averaged over at least one month, but mostly used in the context of an annual (calendar) mean or multi-year average. Consequently, MLOS is a varying level that includes the effects of long period (> 1 year) fluctuations in sea-level. These include the annual heating and cooling cycle, 2–4 year El Niño-Southern Oscillation (ENSO) cycle, the longer 20–30 year Inter-decadal Pacific Oscillation (IPO) effect plus long-term sea-level rise (SLR). The average rate of SLR at Auckland has averaged 1.4 mm yr^{-1} since 1900 and has increased to 1.6 mm yr^{-1} since 1950. While annual MLOS varies each year, it can be converted to a fixed reduced level, such as a local vertical datum after analysis of tide-gauge data. The fixed Auckland Vertical Datum 1946 (AVD-46) is employed in the present study.

The MTL varies spatially because of dynamic effects, which relate to friction as the tide (wave) propagates up an estuary. Typically, the tide is amplified as it travels up an estuary to a point where loss of momentum subsequently reduces the tidal range in the upper estuary. The magnitude of this effect depends on the geometry (i.e., shape and depth) of an estuary and is therefore not a fixed value. The tidal amplification effect is described in more detail in section 4.4.

The effect of the vertical variation (V) of MTL due to tidal amplification of MLOS at any particular location, on the horizontal offset (H) of the MTL position on the tidal flat depends on the tidal-flat slope (β) as $H = V/\tan\beta$. Thus, MTL = MLOS + V and the horizontal offset (H) due to V increases inversely with tidal-flat slope (Fig. 3.3). Quantifying the magnitude of the tidal amplification effect is also required to predict the future changes in MTL position due to changes in water depth associated with sedimentation and sea-level rise.

Figure 3:3:
Vertical variation of sea level due to the tidal amplification effect on the horizontal offset (H) or position of the Mean Tide Level (MTL) on a tidal flat. $H = V / \tan \beta$, where V is the vertical offset in water level between the Port of Auckland tide gauge and the local water level due to tidal amplification and β is the tidal-flat slope.

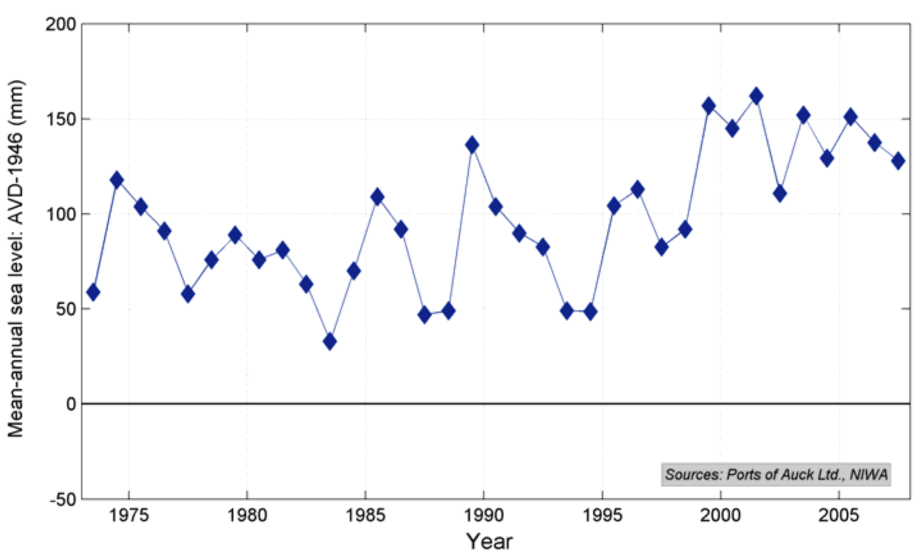


In the present study, the MTL contour was mapped for each estuary from aerial photographic surveys conducted by New Zealand Aerial Mapping in November 2007 and January 2008 (section 4.2).

The MTL (i.e., MLOS + *V*) is not to be confused with the mean sea level (MSL), which usually refers to a fixed vertical survey datum. In terms of the Auckland Vertical Datum 1946 (AVD-46), the datum is derived from MLOS measurements made during the 1920s–1940s. At the Port of Auckland, MLOS is presently ~0.13 m above the MSL datum (AVD-46) at Auckland (Fig 3.4). The present-day lower elevation limit (LEL) of mangroves in the study estuaries are related to AVD-46.

Long-term changes in MLOS are also a critical factor controlling the fate of fringing saltmarsh and mangrove systems (Allen, 1990; French, 1993). Previous work shows that these fringing habitats have kept pace with historical rates of sea-level rise by accumulating sediments. In Auckland estuaries, sedimentation rates during the last 100 years have out-paced sea-level rise (Swales et al. 2002a). However, the rate of sea-level rise is likely to accelerate due to climate warming.

Figure 3.4:
Record of the annual average mean level of the sea (MLOS, 1973–2007) relative to the Auckland Vertical Datum 1946 (AVD-46) measured at the Port of Auckland.



3.3.4 Sea-level rise projections

The Intergovernmental Panel for Climate Change (IPCC) released its Fourth Assessment Report (AR4) in April 2007. It found that "*Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global mean sea level*" (IPCC, 2007).

Increasing global sea levels are a well established consequence of global climate change. Measurements of sea-level changes over the last two centuries have primarily come from long-term data from tide gauges mounted on land, supplemented since the early 1990s by satellite measurements. The longest records suggest that the rate of rise of global sea levels began to increase from around the early to mid-1800s compared with a relatively stable sea level in the preceding century.

Over the 20th century, global sea levels have increased by on average 0.17 m ±0.05 m. In New Zealand, tide gauge records from our four main ports average out to a linear rise in relative mean sea level with respect to the land surface of 1.6 mm/yr (or 0.16 m per century) over the 20th century, (Hannah, 2004, and updated to 2006 by NIWA). Mean annual sea levels recorded at the Port of Auckland tide gauge since 1900 show a linear trend of 1.4 mm yr^{-1} during the period 1900 – 2007.

Sea levels will continue to rise over the next century and beyond primarily because of thermal expansion of ocean waters and loss of ice sheets and glaciers on land. The basic range of projected global sea-level rise estimated by the IPCC (2007) Fourth Assessment is for a rise of 0.18 m to 0.59 m by the decade 2090-2099 (2090s) relative to the average sea level over the period 1980 to 1999 (Fig. 3.5). This is based on projections from 17 Global Climate Models (GCMs) for six different future emission scenarios. The ranges for each emission scenario are 5 to 95% intervals characterising the spread of GCM results (bars on the right-hand side of Fig. 3.5). It is important to note that the range of uncertainty in future sea-level rise projections is largely related to different future scenarios of greenhouse gas emissions (based on scenarios of different future socio-economic profiles, energy use, population growth etc.) and the differences in projections from the various climate models used for each emission scenario.

The basic set of projections (light blue shading in Fig. 3.5) include sea-level contributions due to ice flow from Greenland and Antarctica at the rates observed between 1993 to 2003 but it is expected that these rates will increase in the future particularly if greenhouse gas emissions are not reduced. The IPCC (2007) concluded that an additional 0.1 to 0.2 m rise in the upper ranges of the emission scenario projections (dark blue shading) could be expected if these ice sheet contributions were to grow linearly with global temperature change. However, it also concluded that the possibility of faster ice melt and larger contribution to sea-level rise from Greenland and West Antarctica ice sheets could not be ruled out. Furthermore these projections do not include contributions to sea-level rise associated with carbon cycle feedbacks, nor the potential for there to be differences in sea-level rise in the New Zealand region compared to the global mean.

In their review of these various factors and the limited understanding currently of these processes, IPCC (2007) stated they would not provide a best estimate or an upper bound for sea-level rise to the 2090s. Recent papers published after the cut-off time for peer-reviewed papers considered by the IPCC (2007) such as Hansen (2007), Rahmstorf et al. (2007), Rignot et al. (2008) using various empirical approaches have suggested that sea-level rises of 1 m or more could be possible by 2100 A.D. if ice-sheet melt rates accelerate. Despite these studies it is likely to be some time before an upper limit of potential sea-level rise this century can be defined with some degree of confidence.

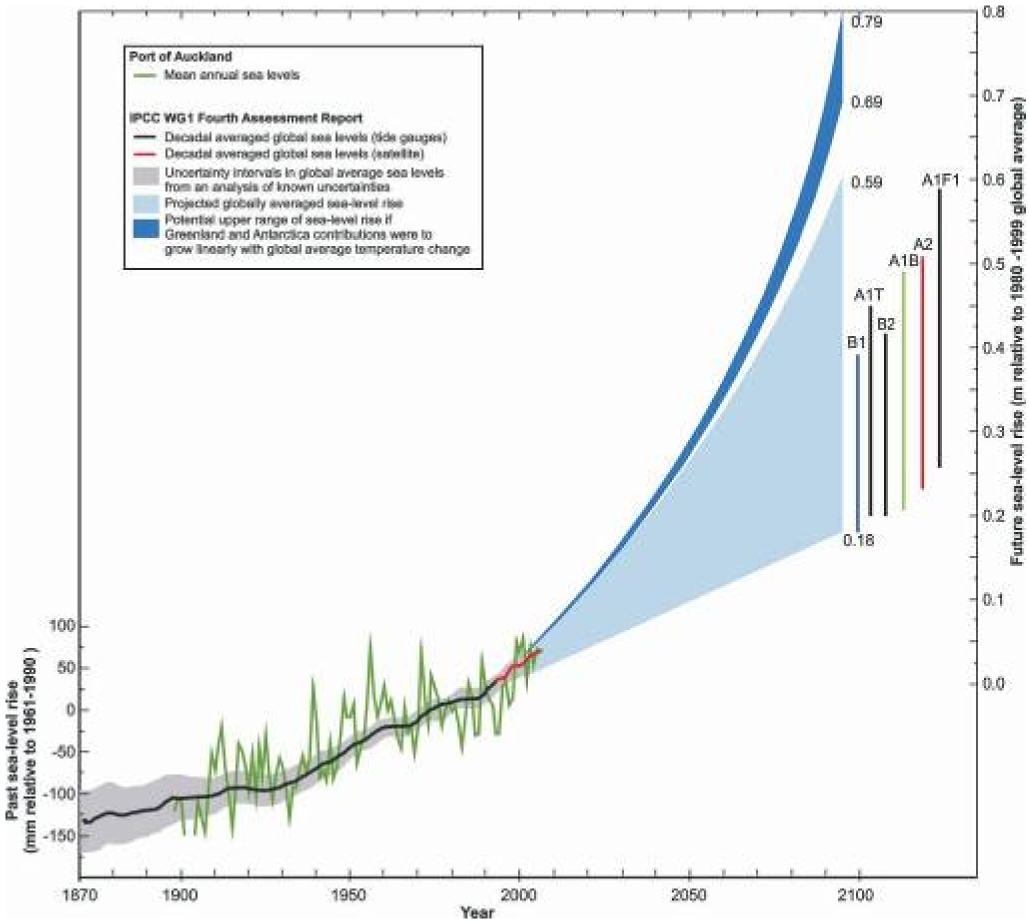
The climate-ocean modeling reviewed by IPCC (2007) also indicated a possibility of an additional 0.05+ m rise by 2080–2099 for the A1B emission scenario in the New Zealand region over and above the global mean projections. However, further research and downscaling of global model results is needed to verify the likely range of any regional variation for New Zealand waters.

Whilst there are uncertainties associated with the science around sea-level changes local government must continue to make decisions that either implicitly or explicitly make assumptions about what this rise will be over a planning timeframe. Guidance on the likely future changes in sea level around New Zealand over the next 100 years for planning purposes is provided by the Ministry for the Environment (MfE, 2008) Guidance Manual. This manual incorporates the findings of the most recent assessment of the Intergovernmental Panel on Climate Change (IPCC, 2007). For planning timeframes out to the 2090s, the MfE (2008) Guidance Manual recommends:

- a "base value sea-level rise of 0.5 m relative to the 1980–1999 average"; along with
- an "assessment of the potential consequences from a range of possible higher sea-level rises (particularly where impacts are likely to have high consequence or where additional future adaption options are limited)";

- "at the very least, all assessments should consider the consequences of a mean sea-level rise of at least 0.8 m" (by the 2090s) "relative to the 1980–1999 average."

Figure 3.5:
Global mean sea-level rise projections to the mid 2090s in the context of historical sea-level measurements back to 1870. The black line and grey shading on the left hand side show the decadal averaged global sea levels and associated uncertainty respectively, as measured by tide gauges throughout the world. The red line is the decadal averaged sea levels as measured by satellites since 1993. The green line is the mean annual relative sea level as measured at the Port of Auckland (Waitemata) since 1899. The light blue shading shows the range in projected mean sea level out to the 2090's. The dark blue line shows the potential additional contribution from Greenland and West Antarctica Ice Sheets if contributions to sea-level rise were to grow linearly with global average temperature change. The vertical colour lines on the right-hand side show the range in projections from the various GCM's for six emission scenarios.



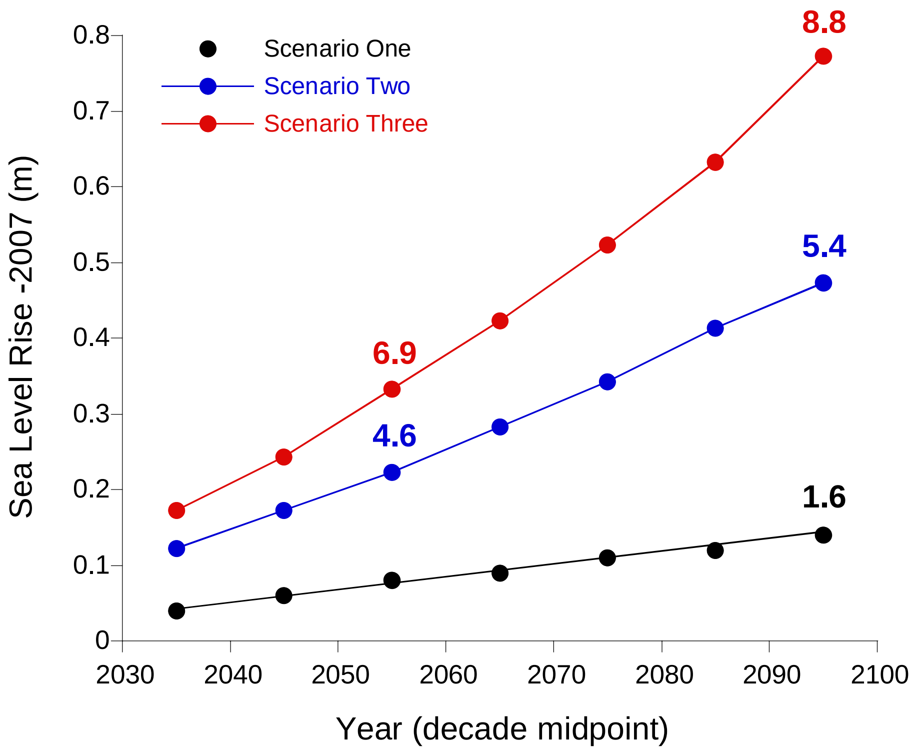
In the context of the present study of future mangrove habitat changes, predicted increases in sea level may result in a net reduction in mangrove habitat in some estuaries and in others have little effect because of spatial variations in the tidal-flat slope and SAR. The tidal-flat slope is a critical parameter because it determines the effect of vertical changes in surface elevation (due to sedimentation and sea-level rise) on the mean tide level and thus the area of intertidal flat suitable for mangrove colonisation.

In the present study, we consider the following scenarios for future sea-level rise projections from 2007 to the 2050s and 2090s based on historical trends in sea level observed at the Port of Auckland since 1950 and the recommendations of the MfE (2008) Guidance Manual. Average SLR rates in mm yr^{-1} take into account the observed increase in sea level of 2.7 cm between 1990 (mid-point IPCC reference timeframe) and 2007. The three SLR scenarios considered in the present study are:

- Scenario One: based on the historical trend in sea level observed at the Port of Auckland since 1950. Average SLR of 1.6 mm yr^{-1} resulting in an increase in sea-level of 0.08 m by the 2050s ($SLR_{0.08m}$) and 0.14 m by the 2090s ($SLR_{0.14m}$).
- Scenario Two: based on MfE (2008) guidance incorporating most recent IPCC (2007) projections. Average SLR of 4.6 mm yr^{-1} and increase in sea level of 0.22 m by the 2050s ($SLR_{0.22m}$) and 5.4 mm yr^{-1} (+0.47 m) by the 2090s ($SLR_{0.47m}$). Scenario Two represents a mid-range SLR projection.
- Scenario Three: based on MfE (2008) guidance incorporating most recent IPCC (2007) projections. Average SLR of 6.9 mm yr^{-1} and increase in sea level of 0.33 m by the 2050s ($SLR_{0.33m}$) and 8.8 mm yr^{-1} (+0.77 m) by the 2090s ($SLR_{0.77m}$). Scenario Three represents a possible upper-range SLR projection.

Figure 3.6 summarises these scenarios for Auckland's east-coast estuaries.

Figure 3.6:
Sea-level rise (SLR) projections based on historical (post -1950) and IPCC (2007) projections to the 2090s. The historical SLR is based on the average value observed at the Port of Auckland between 1947 and 2007. Average SLR rates (mm yr^{-1}) for the 2050s and 2090s are calculated for time periods after 2007 and take into account the observed increase in sea level of 2.7 cm between 1990 (mid-point IPCC reference timeframe) and 2007.



4 Methods

4.1 Overview

Predictions of future changes in mangrove-habitat in Auckland's east-coast estuaries presented in this study are based on several strands of information and analysis. As discussed, the distribution of adult mangrove stands and forest is limited to areas of intertidal flat above mean tide level (MTL) elevation. Thus, temporal changes in the size and location of suitable intertidal mangrove habitat are controlled by sediment accumulation rates (SAR) and sea-level rise (SLR), which reduces the effective rate of estuary infilling. Field observations indicate that wave exposure further limits the lower elevation at which mangroves are likely to successfully colonise tidal flats in the long term. Accordingly, data collection and analysis focus on the key factors influencing mangrove habitat expansion:

- The present-day spatial distribution of mangrove and mean tide level (MTL-2007) in the study estuaries are mapped based on an aerial photographic survey (section 4.2.1).
- The present-day LEL for seedlings and adult mangrove stands in each study estuary is determined. This information was collected by are surveying along shore-normal transects using a Real-Time Kinetic (RTK) GPS instrument (section 4.2.2). These data are also used to: (1) ground truth the LEL determined from the aerial photography and provide information on tidal-flat slopes in each estuary.
- A comprehensive database of SAR in Auckland's east-coast estuaries are provided by previous studies. Many of these studies have been commissioned by the Auckland Regional Council over the last decade or so (section 4.3). These data are used to predict areas of potential mangrove habitat in the study estuaries by the 2050s and 2090s.
- Rates of sea-level rise are based on the historical SLR measured at Auckland since the 1950s as well as IPCC (2007) projections up to the 2090s interpreted for local application by the MfE (2008) Guidance Manual (section 3.3.4).
- The effect of tidal amplification on the MLOS elevation and horizontal offset in estuaries is quantified. Amplification occurs as tides propagate and shoal in estuaries due to bed friction and basin geometry (i.e., shape) effects. Hydrodynamic models of the Mahurangi, Okura, Waitemata, Tamaki and Whitford estuaries are used to quantify the magnitude of the tidal amplification effect.
- The effect of wave exposure on the potential for mangrove seedling colonisation of tidal flats is determined. This effect relates to substrate stability and where bed sediment entrainment occurs frequently, mangrove seedling are less likely to establish. The lower elevation limit (LEL) of adult mangrove trees is also likely

to be greater than the MTL. This assessment is based on numerical modeling of waves using a regional wind climate as well as field observations. Wave statistics are estimated using simple empirical formulae, which incorporate fetch length and water depth. Critical thresholds for silt and sand mobilisation by waves are estimated using Komar and Miller's (1973) wave-orbital-speed theory. Empirical wave statistics are tested in the Waitemata Harbour using the SWAN wave model.

- Hindcast mangrove-habitat to 1950 AD at selected sites to test the methodology used to predict future changes in mangrove habitat in Auckland's east-coast estuaries.

4.2 Mapping the mean tide level (MTL) 2007

Task: Map the present-day MTL isobath (i.e., MLOS + *V*) and mangrove habitat in each study estuary. The MTL represents the most likely lower elevation limit (LEL) for mangrove habitat. This isobath will be subsequently referred to as **MTL-2007**.

4.2.1 Aerial Photographic Survey

The MTL-2007 isobath was mapped from aerial photographs of the waterline in each estuary using photogrammetric methods. These aerial photographs were taken at a time closely coinciding with the predicted time of MLOS at the Port of Auckland. This so called waterline method has been used to map the bathymetry of intertidal bays and estuaries (Mason et al. 1999; George et al. 2003). The use of the waterline method to map the MTL-2007 isobath for each estuary is preferred over other methods (e.g., LIDAR) because it integrates the dynamic effects of tidal amplification on the MTL position (section 4.5).

Aerial photographs were flown at 1:50,000 scale by NZ Aerial Mapping, with 60% forward overlap, allowing stereo coverage of the study areas. Orthophotos with a ground sample distance of one metre were also provided with this task as a backdrop to the vector information. The aerial photographic survey was considered the most cost effective method to map the position of the MTL-2007 isobath in the study estuaries. Ground control points (GCP) used to orient the photography in terms of New Zealand Transverse Mercator (NZTM) map projection, were surveyed at 24 sites in the study region using RTK GPS (Appendix 1).

To increase the accuracy of the MTL-2007 isobaths, stringent conditions were required for aerial photography capture:

- photography were to be acquired during daylight hours during the period 15 minutes before and 45 minutes after predicted MLOS at the Port of Auckland. This timeframe takes account of the time lag for the tide to propagate landward from the mouth of each estuary;
- no cloud cover over the estuaries;
- photographs were to be taken during neap tides (so the rate of change in tide level around MLOS was smaller);

- calm conditions – no wind set up of water level;
- water level not subject to storm-surge effects (within ± 5 cm).

Analysis of tide data from the Central Waitemata Harbour showed that changes in water level occur more slowly during neaps (~0.7 cm/minute) rather than during spring tides (~1 cm/minute). Thus, the timing of aerial photography was planned to coincide with neap tides when the measured position of the waters edge contour was mostly likely to coincide in time with the MTL-2007 isobath. There will be a small offset of the actual MTL-2007 in the upper reaches of estuaries due to a time lag from the time the water level passes through the MLOS at the Port and when the local MTL-2007 occurs. However, it was critical that the photography was timed to coincide with MLOS at the Port of Auckland, where actual tide measurements on the day were available.

Another constraint required the aerial photographs to be acquired during fine, calm weather so that complete coverage of the study estuaries was obtained while minimising variations in sea level due to wind and barometric pressure effects. NIWA's EcoConnect forecasting models were used to predict meteorological and storm-surge conditions on Auckland's east coast up to 72 hrs ahead of time to determine suitable tides for the aerial photographic surveys. Accordingly, aerial photographs of the Tamaki, Whitford, Wairoa at Clevedon, Waiheke and part of the Waitemata Harbour were acquired on 17th November 2007. Aerial photographs of the remaining study estuaries (Kawau Island and all estuaries north of the Waitemata) were photographed on 28 January 2008.

The photogrammetric process was undertaken using BAE's Socet Set Photogrammetry software. The software was used to mosaic, ortho-rectify and geo-reference the images at 1-m resolution, in terms of the NZ Transverse Mercator (NZTM) co-ordinate system.

The MTL-2007 isobath identified by the waterline was not immediately visible from initial inspection of the ortho-rectified photography. The MTL waters edge contour was subsequently identified by selecting stereo pairs that maximized the reflection of sunlight from the sea surface. The waters edge position was checked using the RTK GPS elevation data. Any areas of uncertainty were noted in the final mapping files. Contour data was supplied in Shapefile format, with date and time attributed for each line.

Figure 4.1 presents an example of the technique for the Whangateau Harbour (Omaha). In the left hand image, there is no reflection from the sea surface and the waters edge (~MLOS) is not visible. By selecting different combinations of images, the sun reflection was maximised and the waterline became clearly visible (right-hand image). Ortho-rectified images were prepared for the "clear-water" case where possible to maximise their information content. The presence of submerged channels, sandflats and seagrass beds are clearly visible in the clear water image.

Figure 4.1:
Whangateau Harbour at Omaha. Example of mapping the mean tide level (MTL-2007) contour by selecting stereo pairs that maximise sun reflection from the sea surface (right hand image), compared to an image where there is negligible sun reflection (left-hand image).

Table 4.1 presents the date(s) and timing of the aerial photography relative to the time of MLOS recorded at Ports of Auckland for each estuary. In cases where an estuary was covered by multiple photographs, photo times relate to the time the central photograph was taken. The Waitemata Harbour was surveyed on 17th November 2007 and 28 January 2008 so that three date/time combinations are provided for the mapping. Times recorded on the images relate to New Zealand Daylight Saving Time (DST). However, in this report we adopt the New Zealand Standard Time (NZST), which is one hour behind DST. Appendix 3 provides the photo date/time information as a series of maps. The aerial photography was planned based on predicted times of MLOS on a particular day. Differences between the actual and predicted time of MLOS result from the effects of wind set-up of water level along the coast and/or barometric effects as previously described. In the case of the 17 November 2007 survey the actual time of MLOS at 0848 NZST was 12 minutes before the predicted time (0900 NZST) at the Port of Auckland tide gauge. In the case of the 28 January 2008 survey the actual time of MLOS at 1438 NZST was 5 minutes after the predicted time (1433 NZST).

The vertical elevation offsets (V) for the waters-edge contour are based on the time difference between the actual time of MLOS on the day and the time that the photograph was taken. These vertical offsets indicate how closely the waters-edge elevation conforms to the target MTL-2007 (i.e., MLOS + V) elevation in each study estuary. The average rates of water-level change recorded at the Port of Auckland during the aerial-photo surveys were 0.8 cm min^{-1} (17 November 2007) and 1 cm min^{-1} (28 January 2008).

The vertical offsets indicated in Table 4.1 are combined with the tidal-flat slope data (RTK GPS surveys) to estimate average horizontal offsets from the actual MTL-2007 isobath for tidal flats in each estuary. Figures 4.2 and 4.3 show the timing of the aerial photographs relative to the actual time of MLOS recorded at the Port of Auckland.

Table 4.1:

Date and time (NZST) of aerial photography capture. For multiple photos, the time of the central image is given. MLOS at 0848 NZST (17 Nov. 2008) and 1438 NZST 28 Jan. 2008. Measured rates of sea-level change were 0.8 cm min^{-1} (17 Nov. 07) and 1 cm min^{-1} (28 Jan. 08). Horizontal corrections for true MLOS position (last column) based on actual time offset (col. 5) and measured tidal flat slope in each estuary.

Estuary	Date	Photo time (NZST)	Time ± predicted MLOS (min)	Time ± actual MLOS (min)	Elev. Offset ± actual MLOS (m)	MLOS Hz correctio n (m)
Whangateau	28 Jan. 08	1442	+9	+4	-0.04	+9
Matakana	28 Jan. 08	1458	+25	+20	-0.2	+19
Kawau	28 Jan. 08	1443	+10	+5	-0.05	+6
Mahurangi	28 Jan. 08	1459	+26	+21	-0.21	+9
Puhoi	28 Jan. 08	1500	+27	+22	-0.22	+56
Waiwera	28 Jan. 08	1500	+27	+22	-0.22	+53
Orewa	28 Jan. 08	1501	+28	+23	-0.23	+51
Weiti	28 Jan. 08	1502	+29	+24	-0.24	+14
Okura	28 Jan. 08	1502	+29	+24	-0.24	+34
Waitemata						
UWH + Henderson Ck	28 Jan. 08	1511	+38	+33	-0.33	+42
CWH	28 Jan. 08	1505	+32	+27	-0.27	+35
Shoal Bay	28 Jan. 08	1505 & 1522	+32 (west), +49 (east)	+27 (west) +44 (east)	-0.26 (west) -0.44 (east)	+38 +65
Orakei/Hobson	28 Jan. 08	1522	+39	+44	-0.44	+65
Tamaki	17 Nov. 07	0903 &0950	+50 (north) +3 (south)	+62 (north) +15(south)	+0.50 (north), +0.12 (south)	-35 -8
Whitford	17 Nov. 07	0917	+17	+31	+0.25	-107
Wairoa	17 Nov. 07	0915	+15	+27	+0.22	-61
Te Matuku	17 Nov. 07	0939	+39	+51	+0.41	-51
Awaawaroa	17 Nov. 07	0940	+40	+52	+0.42	-52
Putiki	28 Jan. 08	1530	+57	+52	-0.52	+64

Figure 4.2:
Timing of aerial photographs relative to the actual mean level of the sea (MLOS) on the survey day: (a) recorded and predicted tide for the Port of Auckland (17 November 2007). Water level relative to AVD-46; (b) Δ WL = record – predicted water level. Estuary codes: Tamaki north TK-N and south (TK-S), Wairoa at Clevedon (WR), Whitford (WH), Te Matuku and Awaawaroa (TMA).

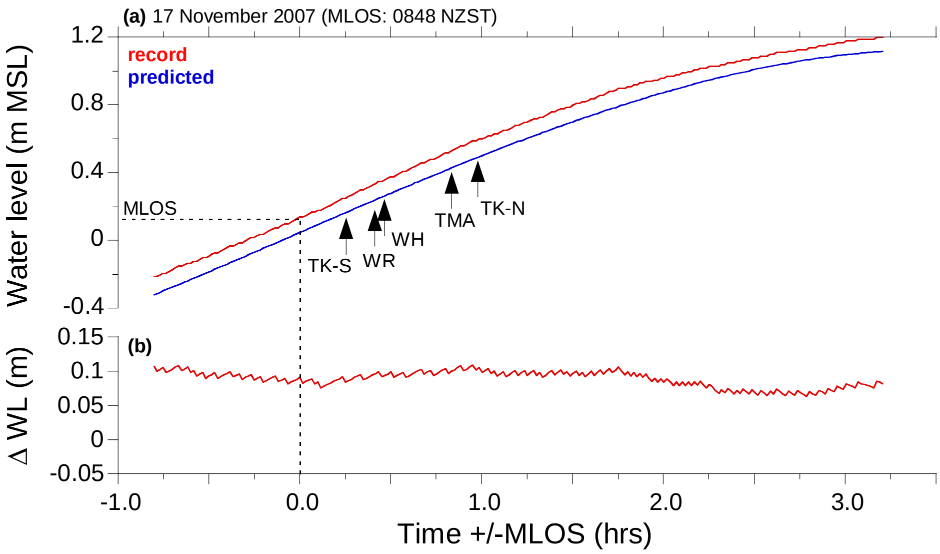
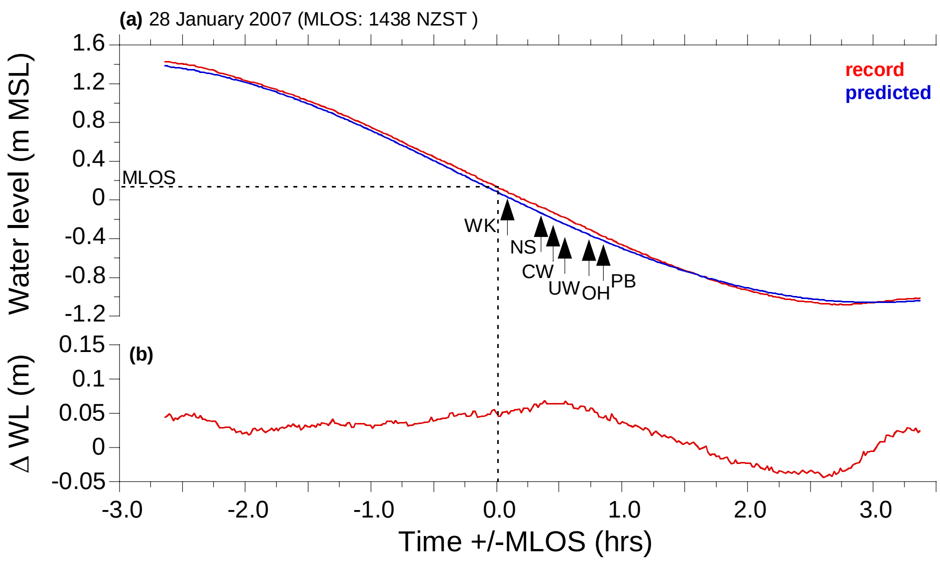


Figure 4.3:
Timing of aerial photographs relative to the actual mean level of the sea (MLOS) on the survey day: (a) recorded and predicted tide for the Port of Auckland (28 January 2008). Water level relative to AVD-46; (b) Δ WL = record – predicted water level. Estuary codes: Whangateau & Kawau (WK), Matakana, Mahurangi, Puhoi, Waiwera, Orewa, Weiti and Okura (NS), Upper Waitemata (UW), Central Waitemata & Shoal Bay (west) (CW), Orakei – Hobson & Shoal Bay (east) (OH) and Putiki Bay, Waiheke (PB).



4.2.2 Tidal-flat Elevation Surveys

Elevation profiles of the intertidal-flats were measured in the study estuaries (with the exception of Kawau Island) using a real-time kinetic (RTK) GPS system. The tidal-flat surveys were conducted on foot and from a boat during low – flood tides between November 2007 and May 2008. Typically, the profiles extended from the low-tide channels up the tidal flat into the mangrove stands above MTL-2007 elevation.

The objectives of the elevation surveys were to:

- provide ground control for the MTL-2007 isobath mapped from the aerial ortho-photos;
- provide information on the slopes of the intertidal flats;
- fix the lower elevation limit (LEL) of the present-day seaward fringe of mangrove stands and seedlings relative to the ocean MTL-2007 and fixed AVD-46 vertical datum;
- estimate changes in the horizontal position or offset of the MTL-2007 isobath due to tidal amplification effects and changes due to future sedimentation and sea-level rise.

In preparation for this work, elevation and slope measurements made using the RTK GPS system were compared with total station, dumpy level and emery pole surveys methods (Appendix 2). The comparisons showed that the accuracy of the RTK GPS data were comparable to the total station instrument, with the added advantage that the RTK GPS data can be directly reduced to a vertical survey datum and is not influenced by local meteorological conditions (e.g., heat haze).

Surveys were conducted as follows. In rural areas, a Trimble RTK 5700 base station was set up at a secure site with a line of sight to the tidal flat areas of interest in each estuary. A Trimble 'rover' RTK 5700 unit was then set up and calibrated by measuring the location of a known local LINZ geodetic survey mark. The horizontal position was calibrated relative to the New Zealand Geodetic Datum 2000 and the vertical elevation relative to AVD-46. This enabled any errors in the measured position to be corrected. With the instrument calibration completed, each transect was surveyed with the rover unit, and a point measurement of the bed elevation taken at approximately 10 m intervals (Figure 4.4). The position of the waters edge at the time of the survey, and locations of seedlings and juvenile mangroves and the seaward boundary of mature mangrove stands were also noted. The LINZ survey mark was re-surveyed at the end of each day to check for errors. The RTK GPS surveys enabled tidal-flat elevations to be measured to an accuracy of ± 2 cm (Appendix 1). Appendix 3 provides details of the RTK GPS surveys undertaken in each estuary.

Figure 4.4:
Low-tide RTK GPS survey of a tidal flat in Brownes Bay, Mahurangi Harbour (29 May 2008).

The slope (degrees) of the upper-tidal flats were calculated from the RTK-GPS profile data by linear regression analysis. The upper tidal flat was defined as the profile above -0.5 m AVD-46. Data below this fixed datum were included to increase the number of survey points used to estimate the tidal-flat slope. Several profile sections close to mangrove stands were excluded from the analysis due to the local enhancement of sedimentation by mangroves and the resulting increased profile slopes. Table 4.2 summarises the results of the regression analysis.

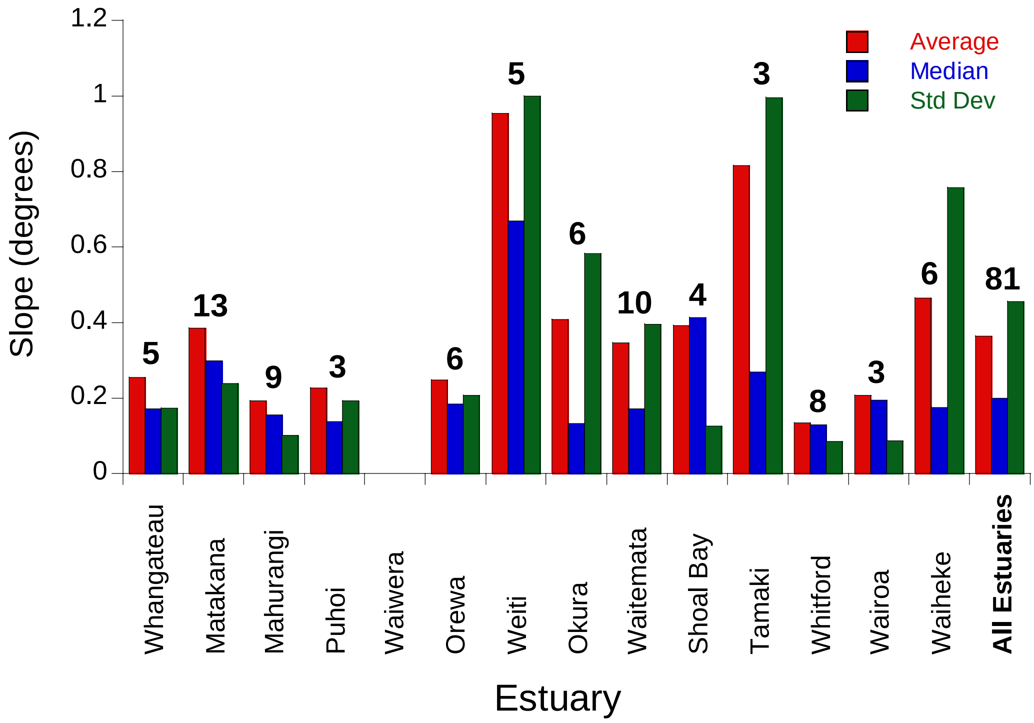
Table 4.2:

Summary of profile data analysed to determine the slope (degrees) of upper tidal flats in study estuaries. Linear regression co-efficient of determination (*r*) and sample size (*n*). Refer to Appendix 7 for location of transects in each estuary.

Estuary	Profile #	Slope (°)	r^2	n	Estuary	Profile #	Slope (°)	r^2	n
Whangateau	18	0.09	0.96	16	Henderson	1	1.27	0.96	7
	19	0.17	0.96	21		5	0.15	0.98	31
	20	0.34	0.97	6					
	21	0.52	0.98	7	Te Atatu	1	0.11	0.99	6
	22	0.16	0.97	22					
					Shoal Bay	3	0.33	0.99	15
Matakana	1	1.56	0.96	6		4	0.49	0.99	13
	2	0.62	0.98	5		2	0.50	0.99	5
	3	0.28	0.73	9		1	0.24	0.99	12
	5a	0.76	1.0	5					
	B1	0.81	0.99	8	Tamaki	56	1.96	0.97	5
	B3	0.18	0.98	13		51	0.27	0.96	9
	B6	0.58	0.98	5		50	0.21	0.96	11
Mahurangi	40	1.21	0.98	6	Whitford	TS-3	0.22	1.0	23
	41	2.34	0.98	6		TS-1	0.24	0.99	17
	42	1.24	0.98	4		TS-2	0.22	0.90	9
	44	0.42	0.8	5		B1	0.13	0.98	12
						B1	0.01	0.74	26
Puhoi	36	0.14	0.6	9		B2	0.07	0.98	44
	36b	0.09	0.89	6		B3	0.06	0.97	11
	34	0.45	0.84	5		B3	0.13	1.0	8
Orewa	27	0.09	0.86	5	Wairoa	1	0.20	0.72	4
	27A	0.57	0.94	5		4	0.29	0.59	4
	31	0.41	0.97	6		5	0.13	0.99	3
	30	0.27	0.91	6					
	29	0.09	0.88	6	Waiheke				
	28	0.06	0.91	8	Te Matuku	61	0.086	0.97	24
						60	0.189	0.97	24
Weiti	6	0.05	0.38	8		62	0.20	0.89	12
	5	0.67	0.98	5					
	4	0.48	0.98	8	Awaawaroa	63	2.01	0.91	37
	1	2.65	0.99	8					
					Putiki Bay	64	0.16	1.0	37
Okura	2-12	0.14	0.86	8		65	0.14	0.97	14
	2-13	0.03	0.70	9					
	2-14	0.12	0.97	8					
	2-15	1.51	0.92	4					
	1	0.61	1.0	8					
Waitemata									
Hellyers	2	0.87	0.96	7					
	1	0.17	0.84	22					

Figure 4.5 summarises the slope data for the upper tidal flat profiles measured during the RTK-GPS surveys. Average tidal-flat slopes in most of the study estuaries were less than the all-estuary average of 0.4°. Substantially higher tidal-flat slopes in the Weiti and Tamaki estuaries likely reflect the elongate shape of these drowned valley estuaries, with narrow tidal flats flanking the channels.

Figure 4.5:
Slopes of upper tidal flats derived from linear regression analysis of RTK-GPS profile data. The upper flats are defined as profile sections above Auckland Vertical Datum 1946. The number of profiles analysed per estuary is also indicated.



4.3 Recent estuary sedimentation

Task: Review available information on recent sedimentation accumulation rates (SAR) on intertidal flats. This assessment is based on radioisotope dating of sediment cores collected in the study estuaries during previous studies. Determine an average SAR for intertidal flats to adopt in the present study.

Predictions of past and future mangrove habitat in Auckland's east coast estuaries will depend on the magnitude of changes in tidal-flat surface elevation related to estuary sedimentation and sea-level rise (sections 3.3.1 – 3.3.3). We assume that sediment accumulation rates (SAR) are a reliable proxy for surface elevation changes on the intertidal flats. This is reasonable given that de-watering of sediments in the top 1 m of tidal-flat sediments is usually negligible, and is consistent with the uniform bulk-density profiles observed in sediment cores (Swales et al. 2002a, 2007a, 2007b).

Reliable SAR data for intertidal flats and tidal creeks were obtained from previous studies (Oldman & Swales, 1999; Swales et al. 2002a, 2002b, Swales et al. 2007b).

These studies provide robust estimates of time-averaged SAR over the last 50–100 years in Auckland estuaries based on lead-210 (^{210}Pb) and caesium-137 (^{137}Cs) dating of sediment cores. Importantly, these studies employed the same coring and dating methods so that SAR estimates are directly comparable.

^{210}Pb is a naturally occurring radioisotope that has been used to date sediments up to ~150 years old. ^{137}Cs is a product of atmospheric nuclear weapons tests since the 1940s and was first detected in NZ in 1953. Together these radioisotopes provide complimentary and independent SAR estimates. Swales et al. (2007b) provide a detailed description of these radioisotope-dating methods.

Table 4.3 summarises the available SAR data for sediment cores collected from open intertidal flats in Auckland estuaries. These SAR estimates are employed in the present study to:

- Determine changes in the available potential mangrove habitat by the 2050s and 2090s due to the net effect of sedimentation and sea-level rise on the position of the MTL-2007 isobath in each study estuary.
- Set up hydrodynamic models of the Mahurangi, Okura, Waitemata, Tamaki and Whitford estuaries to hindcast and forecast the combined effects of estuary sedimentation and sea-level rise on tidal amplification on the potential habitat available for mangroves above MTL-2007.

Table 4.3:

Sediment accumulation rates (SAR) on intertidal flats in Auckland estuaries derived from radioisotope dating of sediment cores.

Estuary	Core	Source	^{210}Pb SAR (mm yr^{-1})	^{210}Pb SAR fit (r)	^{137}Cs SAR (mm yr^{-1})	Comments
Mahurangi	MH-I2	TP221	4.4	0.83	5.4	
	MH-I3	"	4.2	0.99	4.6	
Puhoi	PU-I2	"	4.1	0.79	5.4	
Okura	OK-I1	"	3.5	0.91	3.0	
	OK-I2	"	6.3	0.65	> 6	
	OK-I3	"	2.4	0.67	3.0	
Waitemata	HN-I1	"	2.6	0.9	3.8	
	HN-I2	"	3.2	0.83	3.8	
	HN-I3	"	5.1	0.96	>6	
	HN-I1	Swales et al. (2007b)	3.2	0.86	2.6	Not same sites as sampled in TP221
	HN-I2	"	2.4	0.74	1.7	"
	TA-I1	"	2.4	0.93	2.6	
	TA-I2	"	4.9	0.79	4.7	
	WH-I1	"	2.2	0.55	2.3	
	WH-I2	"	0.7	0.77	0.6	
	WH-I3	"	1.5	0.67	4.2	
Te Matuku	TM-I1	TP221	4.2	0.96	4.6	
	TM-I2	"	6.7	0.83	5.4	
	TM-I3	"	8.7	0.85	4.6	
		Average	3.8		3.7	
		Median	3.5		3.8	
		s	1.9		1.4	

The ^{210}Pb data indicate that SAR on intertidal flats in Auckland's east-coast estuaries have averaged 3.8 mm yr^{-1} over the last ~50 years. This estimate is similar to the average ^{137}Cs SAR value of 3.7 mm yr^{-1}. By comparison, sedimentation rates in tidal creeks at catchment outlets have averaged 20+ mm yr^{-1} over the last 50 years (Oldman & Swales, 1999; Swales et al. 2002b). Tidal-creek systems have largely infilled with eroded catchment sediment, which form extensive intertidal flats colonised by mangroves (section 3.3.2). Historical records indicate that mangroves first colonised tidal creek habitats, which most likely provided sources of propagules for colonisation of the extensive intertidal flats in the main bodies of Auckland's estuaries.

The average ^{210}Pb SAR of 3.8 mm yr^{-1} for intertidal flats is used in section 4.8 to estimate changes in the extent of potential mangrove habitat for the future sea-level rise scenarios adopted in the present study.

4.4 Map historical changes in mangrove habitat

Task: Map historical changes in mangrove-habitat in selected estuaries since *c*. 1950. This analysis is used to: (1) validate hindcast predictions of mangrove habitat; and (2) provide a historical context for predicted changes in mangrove-habitat arising from ongoing sedimentation and sea-level rise over the next century.

Historical aerial photographs of a sub-set of the study estuaries were selected to test hindcast predictions of potential mangrove habitat in *c*. 1950. Comparison of the present-day distribution of mangroves relative to the MTL-2007 isobath (i.e., lower-elevation limit for mangrove habitat) shows variations between estuaries. At some sites, the present seaward boundary of mangrove stands closely coincides with the MTL-2007 isobath. At other sites adult mangrove are substantially above the MTL-2007 isobath. This difference may occur when: (1) a site has been recently colonised by mangrove, so that there has been insufficient time for mangrove to establish down to the MTL-2007 isobath; or (2) wave exposure and resulting bed instability prevents seedling establishment down to the MTL-2007 isobath.

Accordingly, historical ortho-photos of the Okura, Waitemata and Tamaki estuaries taken in 1959 were obtained from the ARC. Ortho-photos of Puhoi, Waiwera and Orewa (23 March 1951); Whitford and Wairoa (19 September 1950); and Te Matuku (March 1940) were obtained from NZ Aerial Mapping.

The historical and 2007 ortho-photos were analysed using ARC-GIS to map changes in the spatial extent of mangrove habitat over the last 50 years or so. Information was also available from previous studies. For example, Morrisey et al. (1999) mapped changes in estuarine vegetation in several Auckland estuaries based on analysis of historical aerial photography.

4.5 Effect of tidal amplification on the MTL-2007 isobath

Task 3: Quantify the magnitude of the tidal amplification effect on the horizontal position of the MTL-2007 isobath.

Due to the amplification or attenuation of tides as they propagate and shoal in the shallow estuaries, a horizontal sea surface at MLOS cannot be assumed, with MTL-2007 varying spatially within an estuary. For example, the MTL-2007 isobath could be several cm higher or lower than MLOS at the Port of Auckland.

In infilled estuaries with a large tidal range, the volume of water exchanged on each tide (i.e., tidal prism) is large in comparison to the low-tide volume. In this situation, estuary morphology and bed friction result in changes in the amplitude of the tide (wave) as it propagates up the estuary. Convergence of the estuary shoreline with distance from the mouth causes the tidal wave to be amplified, in the absence of bed friction. By contrast, in situations where bed friction dominates the tidal amplitude will be reduced. These mechanisms influence tides in Auckland's east-coast estuaries. Estuaries can be classified as one of three types depending on the relative importance of convergence and friction (Fig 4.6):

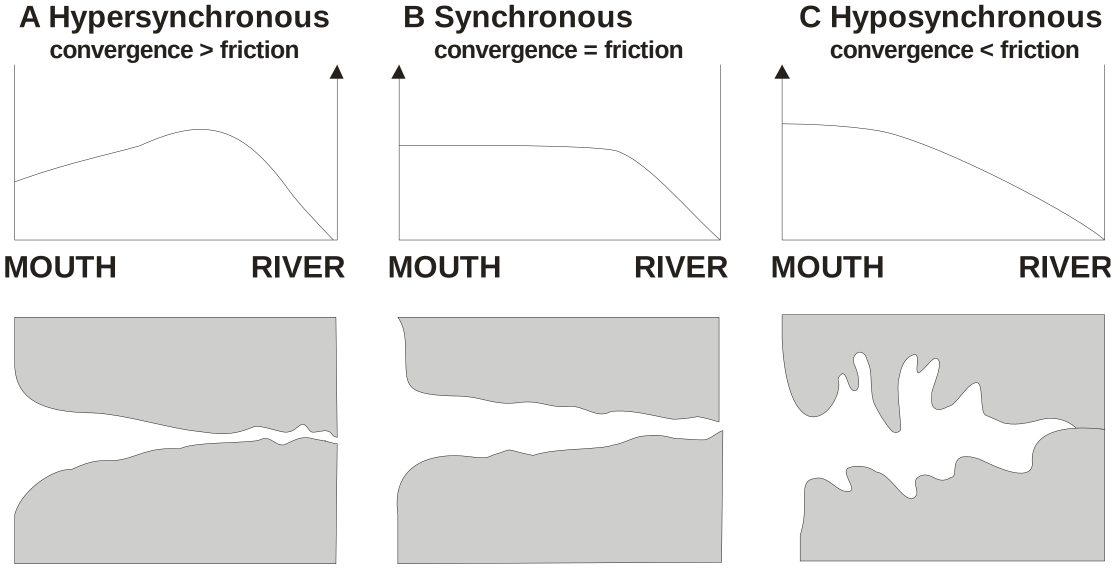
- Hypersynchronous: convergence > friction. Tidal amplitude increases towards the head of the estuary. Friction dominates in the upper estuary and tidal amplitude decreases. These types of estuaries are often funnel shaped. The Mahurangi Harbour and Tamaki Estuary are local examples of this morphology.

- Synchronous: convergence = friction. The friction and convergence effects are balanced and the tidal amplitude remains constant along the estuary until bed friction begins to dominate in the upper estuary.

- Hyposynchronous: convergence < friction. Convergence is less than bed friction and tidal amplitude declines with distance from the estuary mouth. These types of estuaries have restricted inlets with large basins with side arms. The Matakana Estuary is a local example of this morphology.

Tidal amplification can have important consequences for the area of intertidal flat above mean tide level available for mangrove colonisation. This is because of the small slopes of intertidal flats, which are typically less than one degree. These small vertical difference in water level due to tidal amplification may produce a large horizontal offset in MTL-2007 at a given location. This offset could be positive (hypersynchronous) in which case less tidal flat is available, or negative (hyposynchronous) in which case more tidal flat is available for mangrove colonisation. As Fig. 4.6 indicates, magnitude of the amplification effect and its distribution within an estuary may change over time as sedimentation occurs and estuaries infill. Tidal amplification or dissipation also affects the upper high tide limit.

Figure 4.6:
Amplification of tides in estuaries due to bed friction and estuary morphology. Adapted from Nichols and Biggs (1985, Fig. 2.23).



Hydrodynamic modelling of various tidal scenarios (e.g., highest astronomical tide, spring, average, neap tides) was undertaken for the Waitemata and Mahurangi Harbours. The Mahurangi Harbour is a funnel-shaped estuary, whereas the Waitemata Harbour is a basin with fringing tidal creeks. Models of the Tamaki, Okura Estuary and Whitford embayment were also developed from previous modelling studies. Modelling of all five estuaries was used to quantify the scale and the spatial pattern of the tidal-amplification effect in Auckland's east-coast estuaries. The DHI MIKE 21 hydrodynamic model was setup for each of the five estuaries and calibrated using historic water level records. The application of the same model in all cases ensured consistency of method for all the estuaries.

Details of the hydrodynamic modelling undertaken for each of the five estuaries for their present-day, past (1950) and future states based on estuary sedimentation and the sea-level rise scenarios are presented in the following sections.

4.5.1 Present-day estuaries: model set-up

The calibrated hydrodynamic models of the five east-coast estuaries provide good estimates of hydrodynamic conditions and tidal propagation. Appendix 5 includes plots of model bathymetry and calibration results for predicted and measured water levels. The models can therefore be used with some confidence to map the spatial distribution of tidal amplitudes and thus quantify amplification of water levels during the tidal cycle. In particular we focus on the amplification of the tide coinciding with the mean tide level. Details of the model set-up for the present-day estuaries is presented in this section.

4.5.1.1 Mahurangi

The Mahurangi model was based on the earlier work carried out for the ARC (Oldman and Black, 1997) and consisted of a 100 m grid resolution driven by offshore tides derived from tidal constituent data from an Aanderaa tide gauge moored near the entrance of the harbour. Water level data measured at Dawsons Creek (near the top of the harbour) was used for calibrating the model. Regression analysis indicates good model calibration, with predicted water levels in the upper Mahurangi Harbour close to observed values (b = 0.96, r^2 = 0.98).

4.5.1.2 Okura

The Okura model was derived from an earlier study for the ARC (Green and Oldman, 1999) and is based on a 20 m grid resolution. The model was driven by offshore tides derived from tidal constituents provided by an S4 tide gauge moored near the entrance to the Okura estuary. Regression analysis indicates a reasonable model calibration, with predicted water levels in the Okura estuary close to observed values (b = 1.02, r^2 = 0.78).

4.5.1.3 Whitford

A hydrodynamic model of Whitford Bay was set up based on the Whitford Bay study conducted for the ARC (Senior et al. 2003). This model was set up using a 20 m grid driven by tidal constituents derived from an S4 tide gauge water-level data. The S4 was located near the out boundary of Whitford Bay. The model was calibrated using field data from an S4 instrument moored near the entrance to the Mangemangeroa Creek. Regression analysis indicates good model calibration, with predicted water levels at the mouth of the Mangemangeroa Creek close to observed values (b = 0.99, r^2 = 0.97).

4.5.1.4 Waitemata

The hydrodynamic model used in the present study is based on that used in the Central Waitemata Harbour Contaminant Study and the Regional Harbour Model. The model was set up on a 100 m grid driven by tidal constituents derived from the analysis of a water-level record from Bean Rock. Field data from a DOBIE wave gauge moored to the west of the Harbour Bridge was used to calibrate the model. Regression analysis indicates good model calibration, with predicted water levels at the harbour bridge are close to observed values (b = 1.01, r^2 = 0.99).

4.5.1.5 Tamaki

A hydrodynamic model of the Tamaki Estuary was set up from the Regional Harbour Model (Oldman et al. 2004). The model consists of a 50 m grid driven by tidal constituents derived from a water level record measured near the Panmure Basin. Field data from an S4 current meter moored in the main channel south of the Otara Creek was used to calibrate the model. Regression analysis indicates good model calibration, with predicted water levels at the harbour bridge are close to observed values (b = 1.02, r^2 = 0.96).

4.5.2 Past and Future estuaries: model set-up

The potential magnitude of the tidal amplification effect in the study estuaries in 1950 and over the next century (2050s and 2090s) was quantified using the hydrodynamic models of the five estuaries. This assessment takes into account the effects of sedimentation on estuary bathymetry and changes in water levels due to sea-level rise.

The present-day bathymetry of each modelled estuary was modified using SAR and SLR estimates as follows. SAR data provided by previous studies was used to estimate changes in tidal-flat elevations over the last 50 years in tidal creeks and the main bodies of the estuaries (section 4.3). The SAR were interpolated across the model grids using a log fit to reflect the steep gradients in sedimentation rates that occur in the tidal creeks. In the main bodies of the estuaries, linear interpolation of observed SAR of 1–4 mm yr^{-1} was applied to map SAR onto the model grids. We assumed that sedimentation rates and patterns will remain the same during the next 100 years. These data were used to derive maps of sediment accumulation rates for each of the past and future SAR and SLR scenarios modeled in the five estuaries. Figures 4.7–4.11 show the spatial patterns of SAR in each of the five estuaries.

Figure 4.7:
Mahurangi Harbour. Spatial pattern of historical sediment accumulation rates (SAR) for the modelled past and future scenarios. SAR data sources: Swales et al. (1997, 2002a).

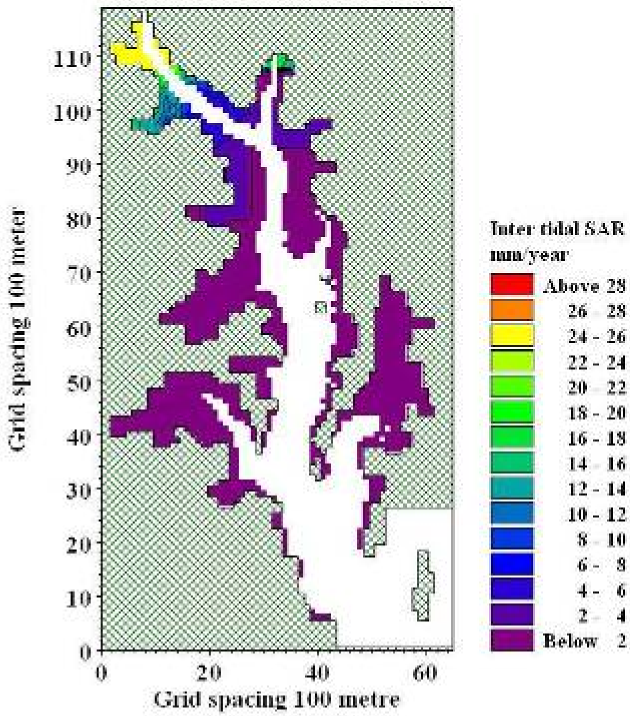


Figure 4.8:
Okura Estuary. Spatial pattern of historical sediment accumulation rates (SAR) for the modelled past and future scenarios. SAR data source: Swales et al. (2002a).

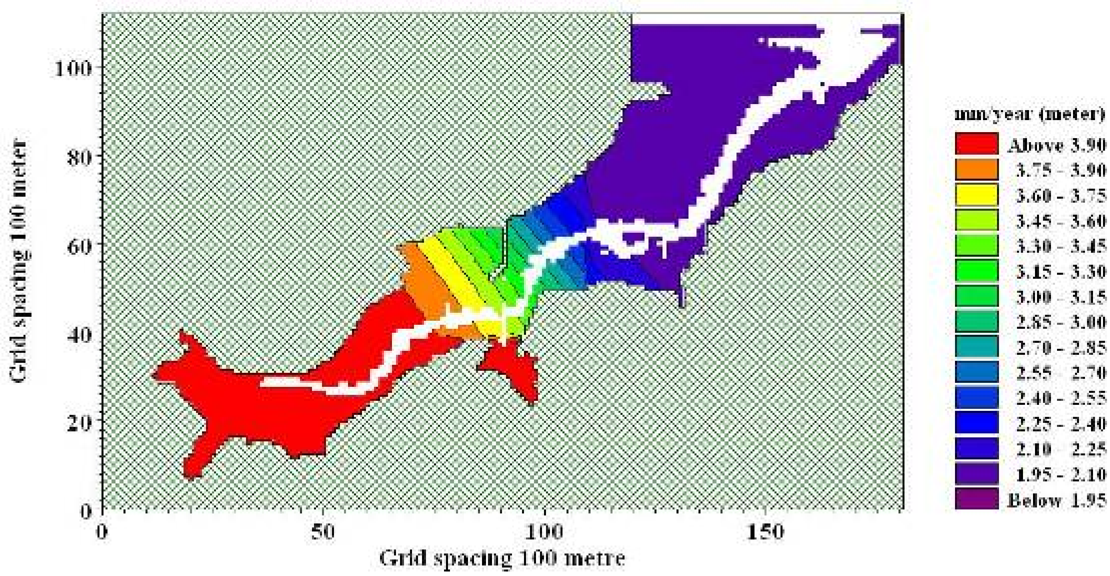


Figure 4.9:
Waitemata Harbour. Spatial pattern of historical sediment accumulation rates (SAR) for the modelled past and future scenarios. SAR data sources: Hume & McGlone (1986), Vant et al. (1993) Swales et al. (2002a, 2007b).

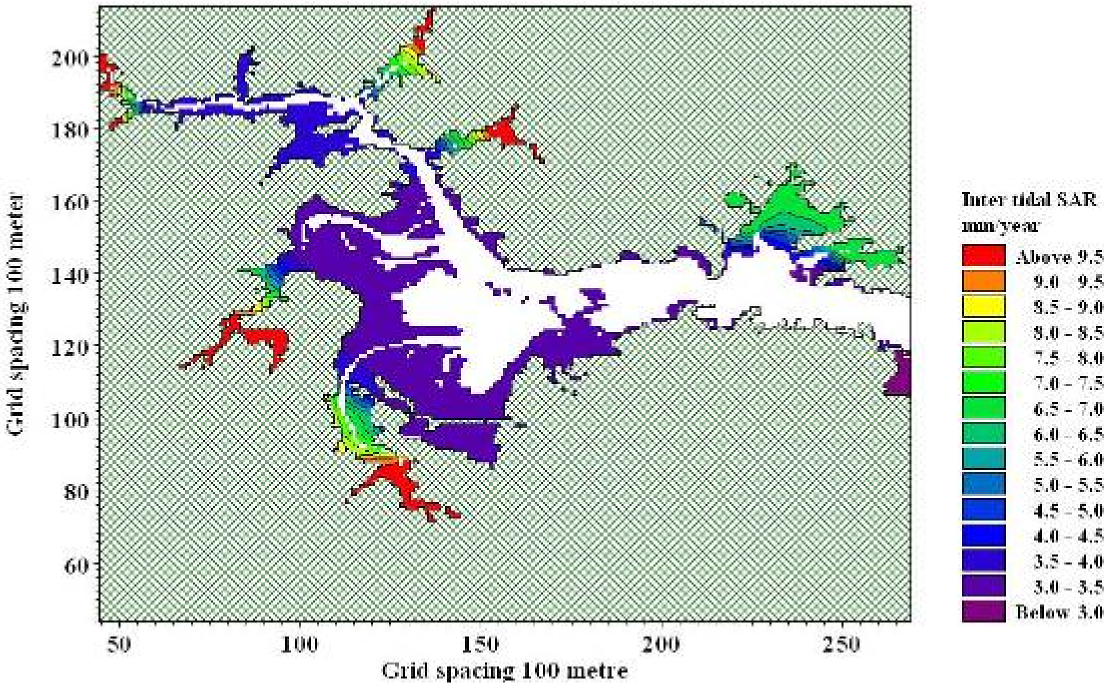


Figure 4.10:

Tamaki Estuary. Spatial pattern of historical sediment accumulation rates (SAR) for the modelled past and future scenarios. SAR data sources: Abrahim & Parker (2002), Swales et al. (2002a, 2002b).

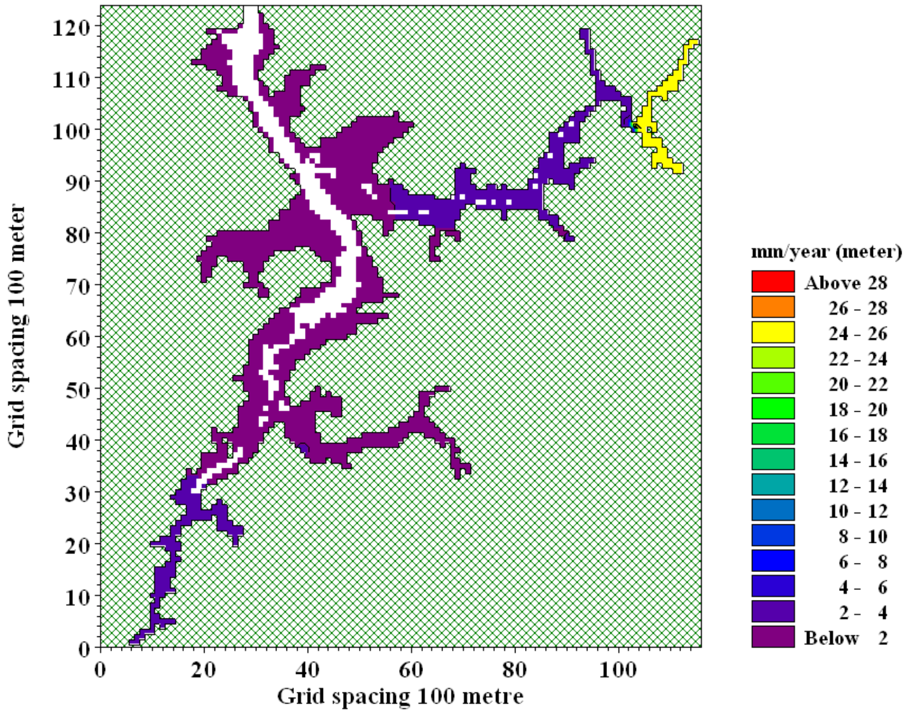
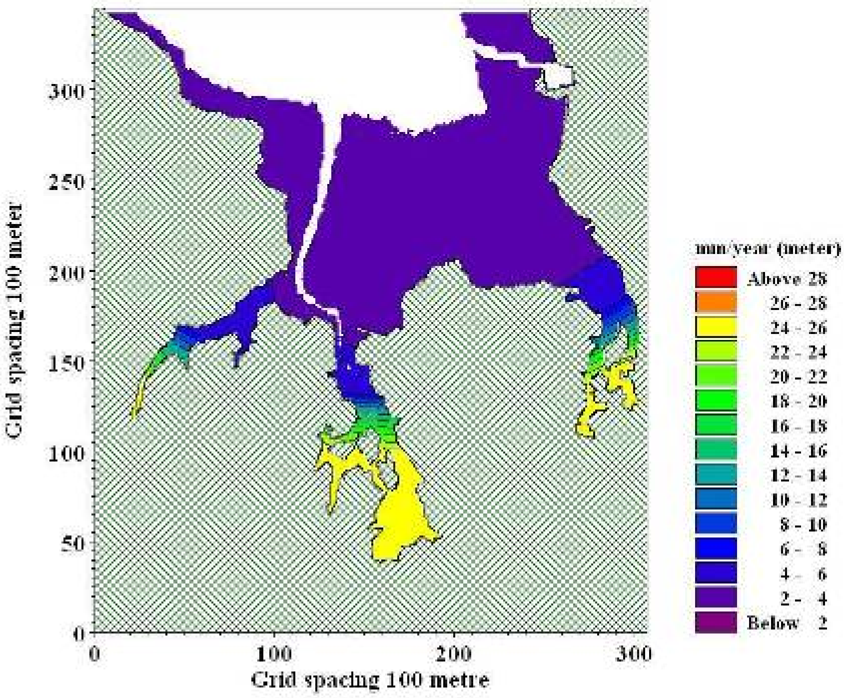


Figure 4.11:

Whitford Bay. Spatial pattern of historical sediment accumulation rates (SAR) for the modelled past and future scenarios. SAR data sources: Oldman and Swales (1999), Craggs et al. (2002), Swales et al. (2002a).



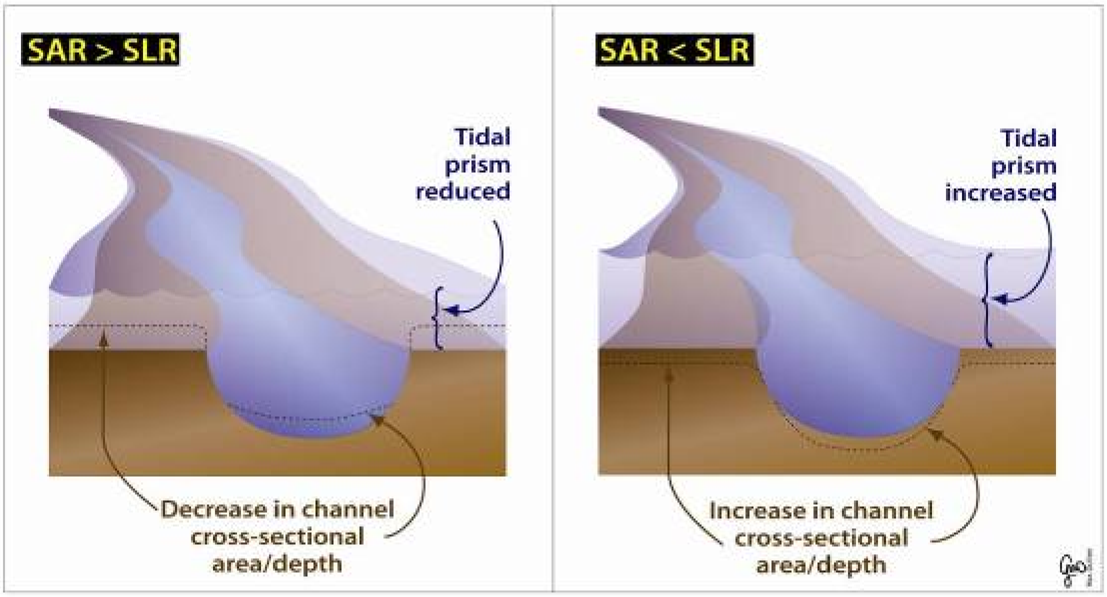
These data show that:

- SAR are highest in the tidal creeks fringing estuaries and decline exponentially in the creeks with distance from catchment outlets, from 20 to 3–4 mm/yr^{-1}.
- SAR are more uniform on tidal flats in the main body of estuaries and have averaged less than 4 mm/yr^{-1} over the last 50 years.

Sedimentation on the tidal flats will also result in changes in the cross-sectional area (i.e., depth) of the tidal channels. In turn, changes in channel geometry (i.e., size and morphology) will influence the propagation and amplification of tides up an estuary.

Empirical studies and field observations (O'Brien, 1931; Vincent & Corson, 1981) of tidal channels and inlets show that the cross-sectional area (A) of a channel varies in a linear proportion with the tidal prism volume (Ω). The Ω is the volume of water exchanged from an estuary during each tide, which is the volume between low and high tide levels. In the long-term, the Ω and thus A will change due to estuary sedimentation as well as sea-level rise effects. Fig. 4.12 illustrates these effects.

Figure 4.12:
Effect of changes in estuary tidal-prism volume on channel cross-sectional area and depth as quantified for Auckland estuaries (Hume, 1991). Tidal prism changes result from the combined effects of estuary sedimentation (SAR) and sea-level rise (SLR). When (a) SAR > SLR the tidal prism is reduced, resulting in a decrease in channel size (depth, area); (b) SAR < SLR, tidal prism increases with a consequent increase in channel size.



Hume (1991) describes a A–Ω relationship for Auckland estuaries based on field measurements that is adopted in the present study:

$$A = 4.37 \text{ x } 10^{-4}\,\Omega_s^{0.915} \qquad (1)$$

where Ω_s is the tidal prism measured during spring tides. This relationship is similar to that for North Island east-coast estuaries (Hume & Herdendorf, 1992) and gives a good fit to the available data (r^2 =0.98).

The Hume (1991) A–Ω relation was used to estimate changes in channel depth in the modeled estuary as follows. At key sites within each of the model grids the change in cross sectional area due to a change in tidal prism (driven by sedimentation and sea-level rise) was determined. Channels were defined as areas below Chart Datum (1.743 m below AVD-46). A rectangular channel cross-section was assumed. From these inputs the net change in channel depth (relative to the current mean level of the sea) was determined. The net rates of change in channel depth predicted at each of the cross-sections were applied in the immediate vicinity of the specified transects and linearly interpolated within the main channel for each of the modelled estuaries. Table 4.4 presents the results of this analysis for selected channel cross-sections in the modelled estuaries.

Table 4.4:

Estimated net annual changes in channel depth at selected cross-sections in the modelled estuaries based on historical sediment accumulation rates on tidal flats and sea-level rise since 1950.

Estuary	Net change in channel depth due to increasing tidal prism (mm yr^{-1})	Channel cross-section description	NZMG coordinates of channel cross-section
Waitemata	0.65	Entrance	2671860E, 6483280N
Waitemata	0.84	Central Waitemata	2662160E, 6484420N
Waitemata	0.94	Harbour Bridge	2666120E, 6484200N
Waitemata	1.05	Upper Waitemata	2660060E, 6488760N
Waitemata	1.11	Henderson Creek	2657580E, 6486160N
Waitemata	1.12	Whau Creek	2658940E, 6482220N
Mahurangi	0.51	Entrance	2665560E, 6519900N
Mahurangi	1.01	Grant Island	2664900E, 6525000N
Mahurangi	1.08	Hamilton landing	2663980E, 6528260N
Whitford	0.88	Waikopoa Creek	2687620E, 6475310N
Whitford	0.95	Turanga Creek	2685140E, 6474340N
Whitford	0.98	Mangemangeroa	2684410E, 6474850N
Whitford	0.98	Entrance	2684480E, 6478070N
Okura	0.96	Town basin	2664360E, 6501920N
Okura	1.01	Entrance	2665960E, 6503040N
Tamaki	1.11	Otahuhu	2676530E, 6473260N
Tamaki	1.11	Pakuranga	2677440E, 6473200N
Tamaki	1.12	Otara	2676260E, 6471250N
Tamaki	1.13	Entrance	2679120E, 6480440N

This

Analysis showed that the decrease in channel depths due to loss of tidal prism on the tidal flats related to sedimentation is of the order of 0.5 –1.1 mm yr^{-1} over the last 50 years (i.e., sedimentation rates have exceeded SLR). This analysis was also applied to the future sea-level rise scenarios. For the IPCC (2007) SLR scenarios increases in channel depth of the same order result from increases in tidal prism volume. This is because the IPCC SLR rates exceed the historical sedimentation rates, with exception of the tidal creeks. The resultant model bathymetries for 1950 and the 2050s and 2090s are presented in Appendix 6.

4.6 Wave-exposure effect on mangrove-habitat extent

Task: Determine the influence of wave exposure on the potential for mangrove seedling establishment and lower elevation limit of mangroves. Empirical wave formulae based on estuary characteristics (i.e., wave fetch, water depth) and wind climate (i.e., speed, direction and duration) are used to estimate wave heights, periods and bed orbital speeds. This work draws on information provided by the Estuarine Classification database developed by NIWA.

The methods employed as well as the full set of model outputs are reported by Gorman and Swales (2009) and are briefly reviewed here.

4.6.1 Empirical wave model

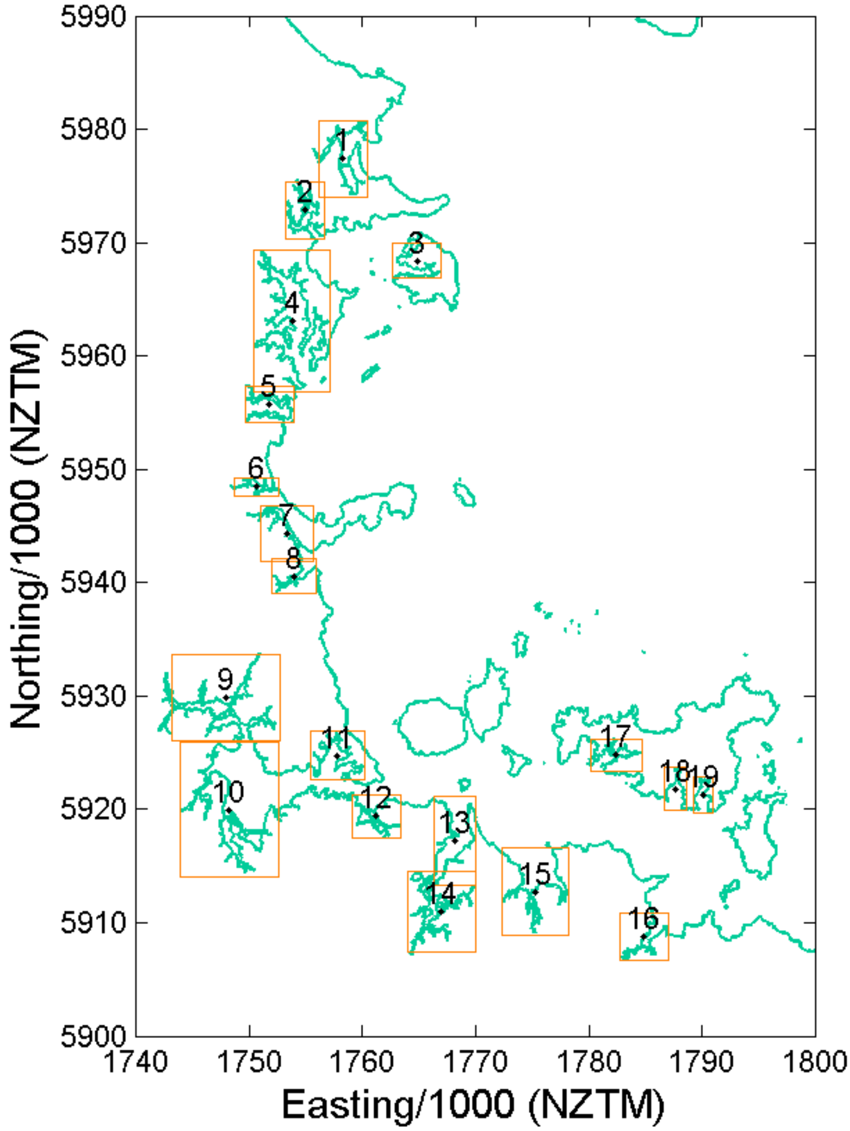
Empirical wave models were set-up to estimate wave statistics for the east-coast estuaries based on regional wind climate. Previous studies suggest that wind climate may influence the present-day spatial distribution of mangroves within estuaries that are sufficiently large for wave generation to occur (section 3). Work in the Firth of Thames shows that mangrove seedlings are excavated from the bed by wave action preventing establishment (Swales et al. 2007a). By mapping variations in wave exposure within and between estuaries areas were mangroves are unlikely to establish in the future were determined.

Wave exposure is defined in the present study as the potential for erosion of the seabed by waves, otherwise described as sediment entrainment. This exposure determines the likelihood of successful seedling establishment on any given intertidal flat above MTL-2007 elevation. Section 4.6.3 describes how the potential for sediment entrainment is evaluated.

Within an estuary, wave conditions are primarily determined by the action of local winds acting over short fetches within the estuary, assuming that waters within the estuary are largely sheltered from the influence of swell generated in distant waters by different weather conditions. This is a generally valid assumption for the shallow estuarine waters being considered here, which have exposure to waves entering from the surrounding waters of the Hauraki Gulf but generally very limited exposure to ocean swells entering the Gulf from the Pacific Ocean. Also, for estuaries of order a few kilometres or less in size, wave conditions will most often be fetch-limited rather than duration-limited, as the time scales for waves to propagate across the estuary will typically be less than the dominant time scales at which wind conditions vary (hours). In such cases, it is reasonable to estimate wave conditions from knowledge of the local wind speed and direction, the fetch (distance downwind from land) and the depth of the water.

The method used was based on empirical relationships developed by Young & Verhagen (1996), based on extensive measurements of wave growth in a shallow lake (Lake George, Australia). Empirical wave models were implemented and used to provide estimates of wave characteristics for each of the study estuaries (Fig. 4.13) based on long-term average wind climate. Full details of the empirical wave model development, verification and application to the present study are presented in the companion report by Gorman and Swales (2009).

Figure 4.13:
Model sub-grids used to provide empirical fetch-limited estimates of wave statistics in Auckland's east-coast estuaries.



4.6.2 Sediment entrainment by waves

Erosion of the tidal-flat by waves is a primary factor influencing mangrove-seedling establishment on an intertidal flat (Swales et al. 2007a). Studies in Auckland estuaries show that sediment entrainment on intertidal flats is driven by episodic wind-wave events. Typically, tidal currents alone are not sufficient to mobilise sediments on tidal flats (Green et al. 1997; Swales et al. 2004; Green & Coco, 2007).

Thresholds for sediment entrainment were estimated using the Komar and Miller (1973) wave-orbital speed theory, which has been found to reliably predict sediment entrainment thresholds under field conditions when waves are characterized by significant wave height ($H_{sig.}$) and mean spectral period (T_{mean}) (Green, 1999). The critical bed-orbital speed ($U_{crit.}$) for non-cohesive particles less than 500 μm (0.5 mm) diameter is given by:

$$U_{\text{crit.}} = \frac{(\rho_s - \rho) g D . a'' \left(\frac{A_b}{D} \right)^{0.5}}{\rho} \qquad (2)$$

Where ρ_s is the particle density (we assume quartz density, 2.65 g cm^{-3}), ρ is the fluid density, g is gravitational acceleration, D is the particle diameter, a'' is a constant (0.21, Komar and Miller, 1975) and A_b is the bed orbital radius. This relationship indicates that $U_{crit.}$ decreases with wave period for any given particle diameter.

Intertidal sediments in Auckland's estuaries are typically composed of mixtures of silt and sand particles. Non-cohesive silt particles (<63 μm diameter) have lower thresholds for entrainment by waves than do sand particles. In the main body of estuaries, such as the Central Waitemata Harbour, tidal flats are largely composed of fine sands with a secondary silt component. By comparison, silts are mainly deposited in sheltered tidal creeks and on the upper tidal flats.

Entrainment thresholds for both the silt and sand components were calculated for each estuary grid using the wave statistics estimated using the empirical wave model. Nominal diameters for silt and sand particles of 15 μm and 125 μm respectively were determined from sediment data collected in previous studies.

Having calculated whether sediment entrainment thresholds were exceeded at each location under each wind condition, the percentage of time entrainment conditions are expected to be exceeded in the long term were computed as an average weighted by the wind rose, as done for wave statistics. Gorman and Swales (2009) describe in detail the method used to calculate time-averaged measures of bed disturbance by waves that take into account the combined effects of wind climate and tidal variations in sea level.

4.6.3 Influence of wave-exposure on the lower elevation limit of mangroves

Task: Quantify the influence of long-term wave climate on the lower elevation limit (LEL) of mangrove stands and forests in the study estuaries. Previous work in the Firth of Thames and Tauranga Harbour indicates that the lower elevation limit for mangroves is related to the local wave exposure. Wave exposure is a function of wind climate, fetch length and water depth.

The empirical wave model was used to estimate long-term wave-climate characteristics for the mangrove LEL measurements made along the RTK-GPS transects (section 4.2.2). Based on the measured surface elevations, wave conditions at each point were calculated and averaged across the profile below the mangrove LEL. Transects were selected where mangroves have been present for several decades, so that the local mangrove LEL was more likely to reflect long-term conditions at the site.

The wave data were analysed to determine if any relationship existed between "wave exposure" as parameterised by the probability of bed disturbance by waves. Here, we calculated the probability of sand entrainment, P_E, for fine sand of uniform 125 μm diameter for the half-tide case using Komar and Miller's (1973) wave-orbital speed theory (sections 4.6.3 –4.6.4).

4.7 Predicting changes in potential mangrove habitat area and distribution

Historical and future changes in the extent and spatial distribution of mangrove habitat above mean tide level in the study estuaries were predicted using:

- Net changes in sea level relative to the tidal-flat surface elevation, based on the balance between SLR and estuary sedimentation (sections 3.3.4 & 4.3).
- Digital Elevation Models (DEM) of estuaries constructed using LiDAR data of tidal-flat elevations from a survey undertaken for a consortium of local authorities including the ARC. The DEM method was the preferred option for translating vertical changes in sea level into horizontal changes in MTL position because the DEM enables local changes in tidal-flat slope to be taken into account. DEM were available for the Whangateau, Mahurangi, Bon Accord, North Cove, Shoal Bay and Hobson Bay.
- Tidal-flat slopes derived from the RTK GPS surveys in each estuary along shore-normal transects where DEM were not available. The average tidal flat slope in estuaries without DEM were applied to calculate a constant horizontal offset for a given increase in sea level (section 4.7.2). The disadvantage of this method is that local variations in tidal-flat slope cannot be taken into account. For this reason, predicted changes in the MTL isobath position are limited to areas with wide tidal flats. Near channels, the surface slope will be substantially higher than on the tidal flats and will be variable (section 4.7.2).

4.7.1 GIS analysis and mapping

4.7.1.1 MTL-2007 Isobath

Historical and future changes in the extent and spatial distribution of mangrove habitat were analysed and mapped using ArcGIS software.

The first step in the analysis was to map the position of the mean tide level MTL-2007 isobath in each estuary. The raw waterline derived from the NZAM orthophotos was corrected for the actual time of the mean level of the sea (MLOS) measured at the Port of Auckland tide gauge (Table 4.1). The vertical offsets in water level to actual MLOS were applied to a two-metre resolution digital elevation model (DEM) of the intertidal areas of the estuaries using the ArcGIS Spatial Analyst Zonal Tool. The corrected waterline position is defined as the MTL-2007 isobath. No corrections were applied to the raw waterline for Whangateau, Bon Accord and North Cove because the timing of aerial photography was within five minutes of the actual MLOS.

The generated MTL-2007 isobath was checked for topological errors, such as gaps, and corrected if necessary. The MTL-2007 isobath was smoothed using the PAEK smoothing algorithm with a 30-m tolerance. This step was required to remove some of the fine detail generated by tidal-flat microtopography.

4.7.1.2 Hindcast and forecasts of MTL position

The net vertical changes in MTL due to sea-level rise (SLR) and sedimentation for observed historical trends (post-1950) and the IPCC (2007) projections were translated into horizontal changes in MTL position. Where a DEM was available, changes in MTL for each SLR scenario incorporate local-scale information on tidal-flat slope. Where no DEM was available, estuary-average slopes derived from RTK-GPS measurements where applied and a constant horizontal offset was calculated for each scenario. The MTL lines were checked for topological errors and corrected if necessary. To complete the generation of the past/future MTL contours, the Smooth line tool was applied using the PAEK smoothing algorithm and a smoothing tolerance of 30m.

4.7.1.3 Area measurements

Areas of tidal flat above MTL and mangrove habitat (digitised from the historical and 2007 orthophotos) were calculated using the ArcGIS Feature to Polygon tool.

4.7.2 Hindcast mangrove habitat in c. 1950 A.D.

Task: Hindcast historical mangrove-habitat expansion since *c*. 1950 to test the methodology used to predict future changes in mangrove habitat in Auckland's east-coast estuaries. The position of the MTL isobath in 1950 (MTL-1950) was hindcast from the MTL-2007 position based on the net change in sea level relative to the tidal-flat surface elevation and the local slope of the tidal flat.

The position of MTL-1950 was compared to the historical distribution of mangroves in the estuaries recorded by historical aerial photographs. Within each of the estuaries, sites were selected for comparison that:

- have extensive intertidal flats with no physical constraints on mangrove-habitat expansion;
- were colonised by mangroves before the 1970s so that there would have been sufficient time for mangroves to colonise a large proportion of the potential intertidal habitat above MTL.

The estuaries selected for analysis were Puhoi, Waiwera, Orewa, Okura, Central Waitemata, Shoal Bay, Orakei, Whitford, Wairoa and Te Matuku.

4.8 Potential for future changes in mangrove habitat

Task: Predict potential future changes in mangrove habitat to 2050 and 2090s.

The predictions take into account future changes in estuary bathymetry due to sedimentation and future rates of sea-level rise (SLR). This assessment does not take into account how future climate change may alter catchment sediment loads and estuary sedimentation rates. Under the IPCC (2007) SLR scenarios it is possible that increases in sea level in some estuaries will exceed sedimentation rates and vice versa. The hydrodynamic and wave models were used to quantify the effects of these relative changes in bathymetry on tidal amplification, wave exposure and ultimately the potential areas that would be available for future mangrove habitat expansion.

Field data and modelling were used to predict future changes in the extent of mangrove habitat at sheltered and wave-exposed sites. Surface elevation changes will be estimated from the present-day bathymetry, sediment accumulation rates (SAR) and sea-level rise (SLR) scenarios. We assume that SAR in Auckland east-coast estuaries over the next 100 years will be similar to those measured since the 1950s. Future SLR scenarios include:

- the historical trend of 1.6 mm yr^{-1} since 1950 resulting in a rise in sea level of 0.08 m by the 2050s and a 0.14 m rise in sea level by the 2090s;
- sea-level rise due to climate warming based on IPCC (2007) projections for the 2050s and 2090s AD. The projected SLR values for New Zealand are based on guidelines provided by the MfE (2008) Guidance Manual (section 3.3.4);
- the projected $SLR_{0.22}$ and $SLR_{0.33}$ scenarios for increases in sea level of 0.22 m and 0.33 m respectively by the 2050s (section 3.3.4);
- the projected $SLR_{0.47}$ and $SLR_{0.77}$ scenarios are for increases in sea level of 0.47 m and 0.77 m respectively by the 2090s (section 3.3.4).

The potential future changes in mangrove habitat in Auckland's estuaries will primarily depend on the relative magnitude of estuary SAR and SLR which determine the net change in tidal-flat habitat for mangrove colonisation. When:

- SAR = SLR then the area of tidal-flat habitat suitable for mangrove will not substantially change.
- SAR > SLR then the tidal-flat habitat suitable for mangrove will increase.
- SAR < SLR then the tidal-flat habitat suitable for mangrove will decrease.

Figure 4.17 presents a conceptual model of how SAR, SLR and tidal-flat slope interact to influence the area of tidal-flat above mean tide level (MTL) available as potential mangrove habitat. The net vertical offset or change in MTL (*V*) over time (*T*) due to SAR and SLR is calculated as V = (SAR – SLR)T. In turn, this translates into a horizontal offset or change in MTL (waters edge) position in an estuary given by

$H = V/\text{Tan } \beta$. The magnitude of this horizontal offset will depend on the local slope of the tidal flat and the net change in mean tide level.

Figure 4.17:
Future changes in potential mangrove habitat above mean tide level (MTL). Changes in tidal-flat area due to the net effect of sedimentation (SAR) and sea-level rise (SLR) on tidal-flat surface elevation (S). When SAR > SLR the tidal-flat surface elevation and area above mean tide level will increase (left). When SAR < SLR the tidal-flat surface elevation (S) and area above mean tide level will decrease (right). There is no net change in tidal-flat surface elevation and area when SAR = SLR. The vertical (V) and horizontal (H) offsets for each case are defined below.

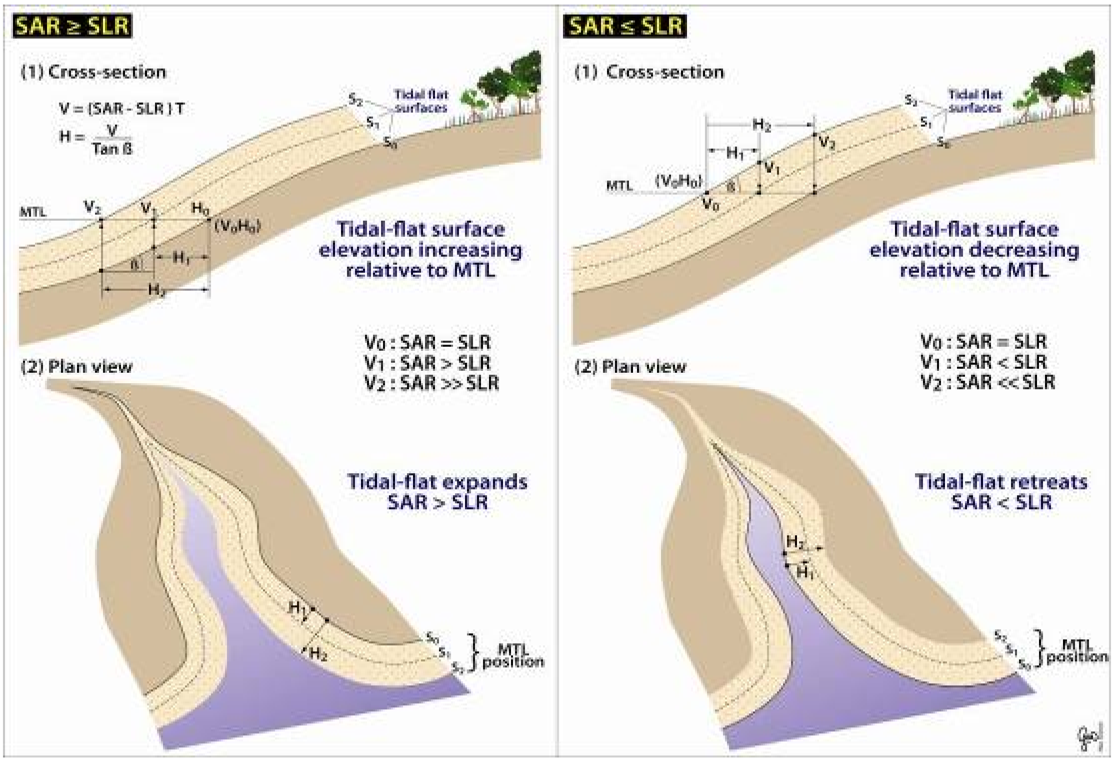
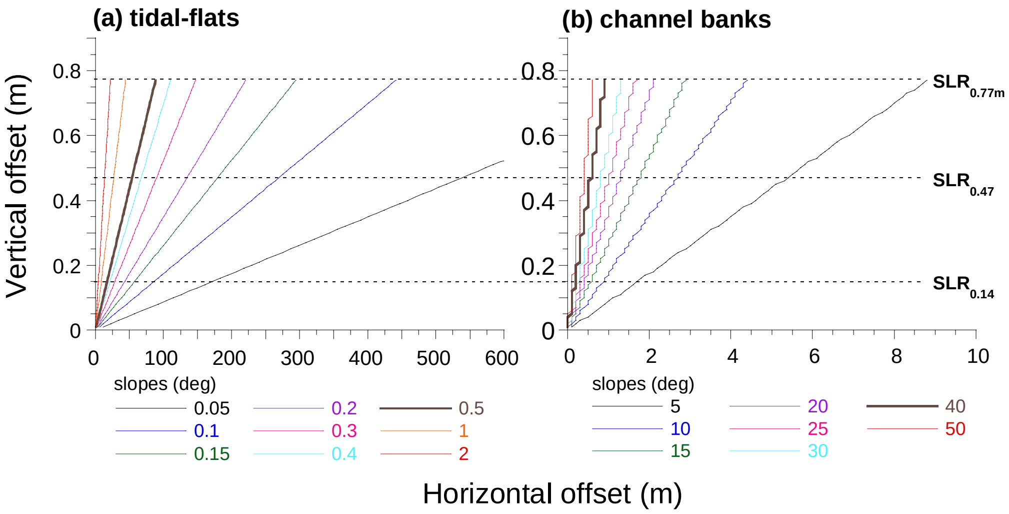


Figure 4.18 shows how these horizontal offsets or changes in MTL (waters edge) position in an estuary vary with the bed slope for the typical range of slopes observed on tidal flats and channel banks in the study estuaries. The net increase in MTL predicted by the 2090s for the three SLR scenarios considered (i.e., historical trend and acceleration due to climate warming) are indicated. These results show that:

- The habitat available to mangrove is most sensitive to changes in water level on gently-sloping tidal-flats. The predicted increases in sea level will result in changes in the MTL isobath position of 10s–100s of metres depending on the local tidal-flat slope (Fig. 4.18a).
- Along channel banks, changes in sea level result in relatively small horizontal offsets in MTL position of no more than a few metres. In tidal creeks, channel-bank slopes can exceed 45° and the resulting changes in MTL position are less than one metre even under the accelerated SLR scenario.

An additional factor in tidal creeks is that SAR are likely to keep pace with or exceed sea-level rise so that net changes in the MTL position and therefore the area of suitable mangrove habitat are unlikely to occur (Fig. 4.18b).

Figure 4.18:
Relationship between change in sea level, bed slopes and resultant horizontal offset on: (a) low-angle tidal flats and (b) high-angle channel banks in estuaries. Note: the average tidal-flat slope measured in the study estuaries is 0.36°. Sea-level rise (SLR) scenarios for the 2090s.



4.9 Sediment accommodation in mangrove habitats

Task: Estimate available sediment accommodation space (volume) within present-day and future mangrove habitat areas.

Previous studies show that there is a negative feedback between surface elevations in mangrove and sediment accumulation rates (SAR). This relates to the progressive reduction in the duration of tidal inundation. Mud accumulates in these fringing habitats, even at wave exposed sites, because of the shelter provided by the mangrove vegetation. In the southern Firth of Thames, surface elevations in the mangrove forest are now between Mean High Water Spring (MHWS) and Mean High Water Perigean Spring (MHWPS) levels and the forest is infrequently submerged by the tide. Swales and Bentley (2008) show that initially rapid sedimentation rates in the old-growth mangrove forests (i.e., pre-1960s) of the southern Firth eventually declined as surface elevations increased. This asymptotic behaviour reflects a progressive reduction in the frequency and duration of tidal inundation and sediment supply. Today, average surface elevations in the old-growth mangrove forests are close to the upper limit of the tide at MHWPS so that SAR are likely to be similar to the rate of sea-level rise.

The capacity of mangrove forests in Auckland's east-coast estuaries to accommodate future sedimentation is estimated based on:

- present-day surface elevations in the mangrove forests derived from digital elevation models (DEM) of each estuary;
- total area of mangrove derived from the 2007 ortho-photos;
- MHWS and MHWPS elevations of 1.43 m and 1.66 m above ADV-46 respectively.

4.9.1 Catchment sediment loads

A first-order estimate of the capacity of present-day mangrove stands to accommodate catchment sediment inputs were made by estimating the sediment loads delivered to each estuary. Sediment loads were estimated for sub-catchments using the USGS SPARROW model (Spatially Referenced Regression on Watershed attributes, Schwarz et al. 2006). SPARROW is a hybrid mechanistic-regression model that generates sediment loads as a function of sub-catchment parameters, such as land erosion rates. The model incorporates a mass-budgeting approach that accounts for source generation, stream routing and attenuation factors. Elliot et al. (2008) have adapted SPARROW to estimate mean annual sediment loads from New Zealand catchments. The model uses data from the NZ River Environment Classification, which includes more than 500,000 stream reaches and associated sub-catchments. The average sub-catchment size in the database is about 0.5 km^2. Elliot et al. (2008) calibrated the NZ SPARROW model using available data on mean annual suspended sediment loads from more than 200 sites around New Zealand measured over the last 50 years (Hicks et al. 2004). The NZ SPARROW model has a (log-log) regression fit (r^2) of 0.925 to the calibration data. It should be noted that few of these calibration data were from the Auckland Region. Thus it is unclear how SPARROW performs in the present study. However, the method provides a consistent and quantitative approach to estimate long-term mean-annual suspended sediment loads.

In the present study, the predicted annual suspended sediment loads at sub-catchment outlets were aggregated for each estuary catchment. Sediment loads were not available for some first-order catchments (i.e., smallest streams in catchment headwaters) and the aggregate catchment area was usually less than the total catchment area, which indicates some under-estimation of the catchment sediment load is likely.

5 Results

5.1 Catchment sediment loads

Catchment sediment erosion and delivery is a primary control on estuary infilling and the subsequent development of intertidal-flat habitats suitable for mangrove colonisation. Figure 5.1 presents the SPARROW model estimates of mean annual suspended sediment loads delivered to Auckland's east-coast estuaries. In total an estimated 115,000 tonnes of sediment are delivered each year. The two largest inputs, from the Wairoa (32,000 t) and Whitford (14,000 t) account for 40% of the total annual sediment load. Normalising the total loads by the catchment areas yields the specific loads, with the average specific load being 96 t km^{-2} yr^{-1} (range: 19 – 300 t km^{-2} yr^{-1}). The lowest specific load is delivered from the urbanised Central Waitemata Harbour Catchment. The analysis also indicates that the relatively large sediment input from the Wairoa system relates primarily to catchment size, with specific load of 104 t km^{-2} yr^{-1} being close to the average value.

The relative rate of estuary infilling due to catchment sediment inputs can be quantified by comparing the annual sediment loads to an estuary's volume or accommodation space to store sediment inputs. In Auckland's infilled estuaries, sedimentation occurs on tidal flats rather than in the channel, so that the tidal prism (volume between low and high tide) provides a suitable metric for this analysis. The estuary infill time (T_A, years) can thus be estimated as:

$$T_A = \Omega / S_V \tag{5}$$

where Ω is the tidal prism volume (m^3) and S_V is the mean annual sediment load (m^3) delivered to the estuary. The sediment load is converted to an equivalent volume using a typical wet bulk density for estuarine sediments of 1.2 t m^3. This simple analysis assumes that: (1) 100% of the sediment delivered to an estuary is trapped. In reality, the sediment trapping efficiency of an estuary declines as it infills and a larger proportion of the sediment input is exported from the estuary; (2) the estuary's catchment is the only sediment source; (3) present-day catchment sediment loads apply.

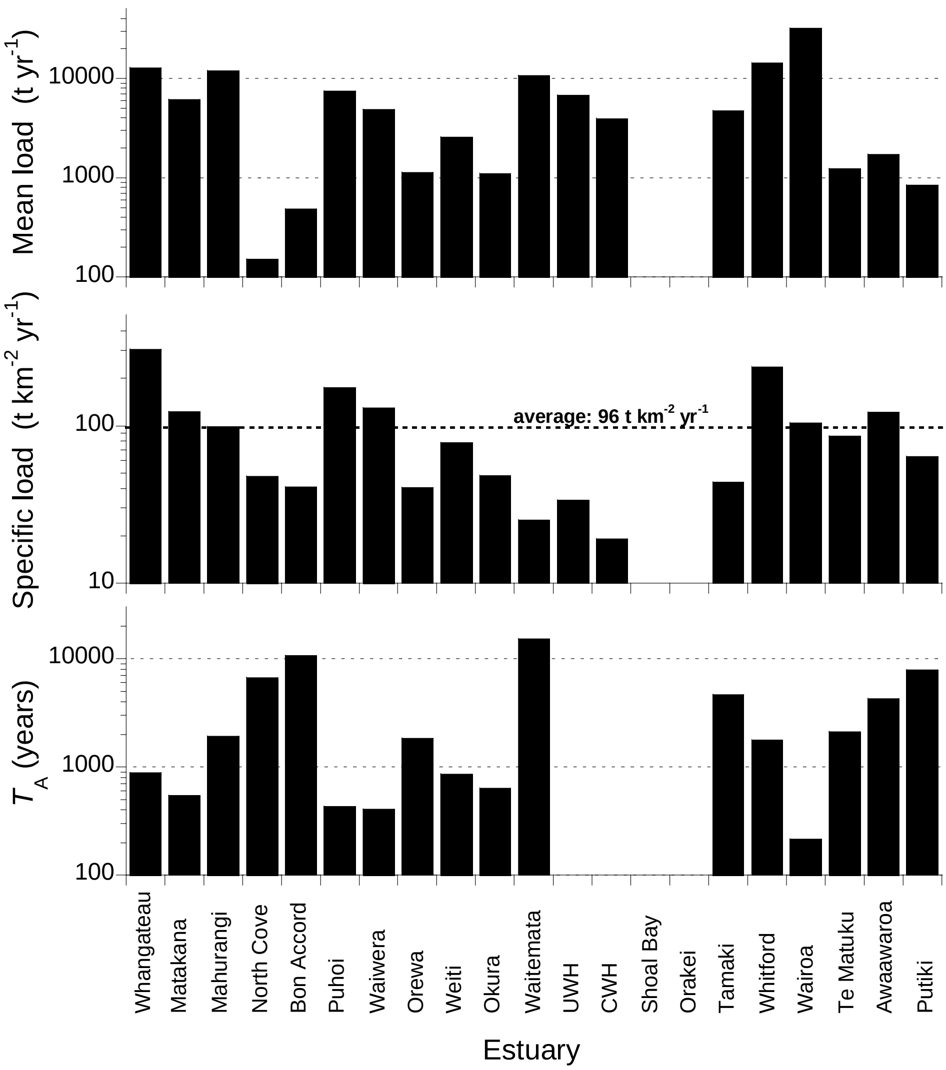
The T_A parameter provides a relative measure of an estuaries vulnerability to infilling resulting from catchment sediment inputs (Figure 5.1). This analysis shows that:

- T_A values vary from 200 to 15,000 years.
- The most vulnerable estuaries at risk of infilling, with $T_A \leq 500$ years are the Matakana, Puhoi, Waiwera and the Wairoa systems. These estuaries have already substantially infilled with sediment and have small tidal prisms and relatively high sediment inputs.

It should be noted that the sediment trapping efficiency of these largely intertidal estuaries will be substantially less than in the past so that a proportion of the catchment sediment input is exported to the open coast. On the other hand, mangroves will enhance sediment trapping on intertidal flats. In highly infilled estuaries, SAR will eventually approach the rate of SLR, which continually increases the accommodation space in estuaries.

- The least vulnerable estuaries, with $T_A \geq 5000$ years are the North Cove, Bon Accord (Kawau Island), Waitemata, Tamaki and Putiki (Waiheke Island). These estuaries have relatively large tidal prisms and/or low catchment sediment inputs.

Figure 5.1:
Catchment sediment loads delivered to Auckland's east-coast estuaries: (1) Mean annual suspended sediment loads estimated by the SPARROW model; (2) specific suspended sediment loads, normalised by catchment area; the estuary infill time (T_A) is the ratio of the tidal prism (m^3) to the annual sediment load (m^3). Note: log 10 scale on the y-axes.



5.2 Sediment accommodation space in existing mangrove habitats

Previous studies in North Island estuaries show that fine sediments preferentially accumulate in mangrove habitats (Craggs et al. 2001; Swales et al. 2007a). In the southern Firth of Thames the Mean High Water Perigean Spring (MHWPS) or "King" Tide appears to be an effective upper elevation limit for sedimentation (Swales et al. 2007a). This process is also documented in the southern Kaipara Harbour, where mangrove forests had infilled with sediment as early as the 1930s, such that the mangrove (tidal) flats were submerged only during high-spring tides (Ferrar, 1934).

Today, mangrove habitat covers some 27.1 km^2 of tidal flats in Auckland's east coast estuaries (Fig. 5.2a). Mangrove growing in the Waitemata Harbour accounts for 38% of the total mangrove-habitat area. Tidal-flat surface elevations in most of these mangrove areas have not yet reached MHWS tide level so that substantial accommodation space (V_M) remains for sediment infilling (Figure 5.2b). These storage volumes estimated using the estuary digital elevation models are:

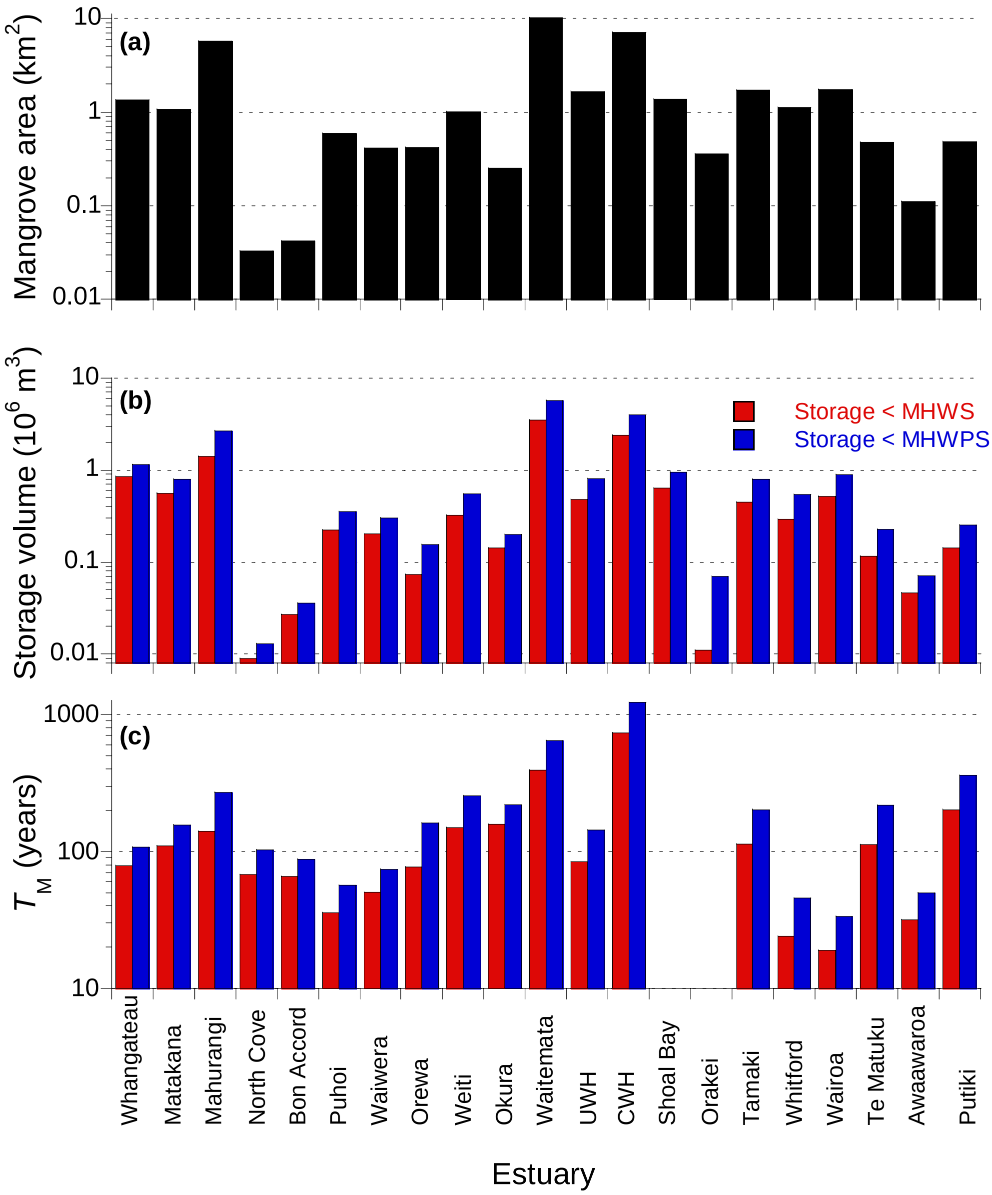
- 12.4 million m^3 below mean high water spring (MHWS) tide elevation at 1.43 m above AVD-46.
- 20.6 million m^3 below MHWPS tide elevation at 1.66 m above AVD-46.

The storage volumes available in existing mangrove habitats are largely proportional to the existing area of mangrove-habitat. The Waitemata Harbour accounts for 28% of the total sediment accommodation space in existing mangrove habitats. By comparison the five small northern estuaries of Puhoi, Waiwera, Orewa, Weiti and Okura together account for only 8% of the total available storage volume,

The relative sediment storage capacity of existing mangrove habitats in each estuary can be represented by the mangrove storage infill time (T_M, years). This is a similar parameter to the estuary infill time presented in section 5.1, substituting V_M for the tidal prism volume. The estimated mean annual sediment load delivered to the study estuaries represents about 100,000 m^3 of deposited sediment (section 5.1). This can envisaged as a 10-cm thick layer of sediment deposited over a 1 km^2 area of tidal flat. The T_M parameter indicates how long it would take to fill the present-day storage volume below MHWS and MHWPS tide level under the assumption that catchment sediment was trapped in the existing mangrove habitat (Fig. 5.2c). Not all of the catchment sediment delivered to estuaries is trapped. Additional storage volume is also added each year due to sea-level rise. Although SAR measured in mangrove forests exceed historical rates of SLR, this is likely to change in the future due to accelerated SLR associated with climate warming. Taking these factors into account, the T_M values presented here are likely to be under estimates of the time required to fill the available storage volumes. In many estuaries, the sediment storage capacity (below MHWPS) of existing mangrove habitats could be filled during the next 30 –100 years. By comparison, existing mangrove habitats in the Central Waitemata and Mahurangi Harbours have several hundred to 1,000 years of storage capacity respectively.

Figure 5.2:

Potential for sediment storage in existing mangrove habitats: (a) Area of mangrove habitat (km^2); (b) available sediment storage volume (millions m^3) below Mean High Water Spring Tide (MHWS, 1.43 m AVD-1946) and below Mean High Water Perigean Spring Tide (MHWPS, 1.66 m AVD-1946); (c) minimum mangrove storage infill time (T_M) in years based on SPARROW mean annual sediment loads delivered to estuaries. Note: log-scale on y-axes.



5.3 Estuary infilling as a function of system properties

Estuary size and catchment sediment loads appear to be key factors influencing sedimentation and the development of intertidal-flat habitats suitable for mangrove colonisation. Simple empirical relationships are presented here that can be used to predict the total area of intertidal habitat in an estuary that is potentially suitable for mangrove. This Habitat to Estuary Area (HEA) ratio is defined as HEA = MTL-2007/A_e, where MTL-2007 is the total area of intertidal flat above mean tide level and A_e is the high-tide surface area estimated from the aerial photographic survey. Two parameters appear to be useful as predictive variables:

- Estuary to Catchment Area (ECA) ratio. Estuaries with relatively large catchments will infill more rapidly and have a larger proportion of intertidal area.

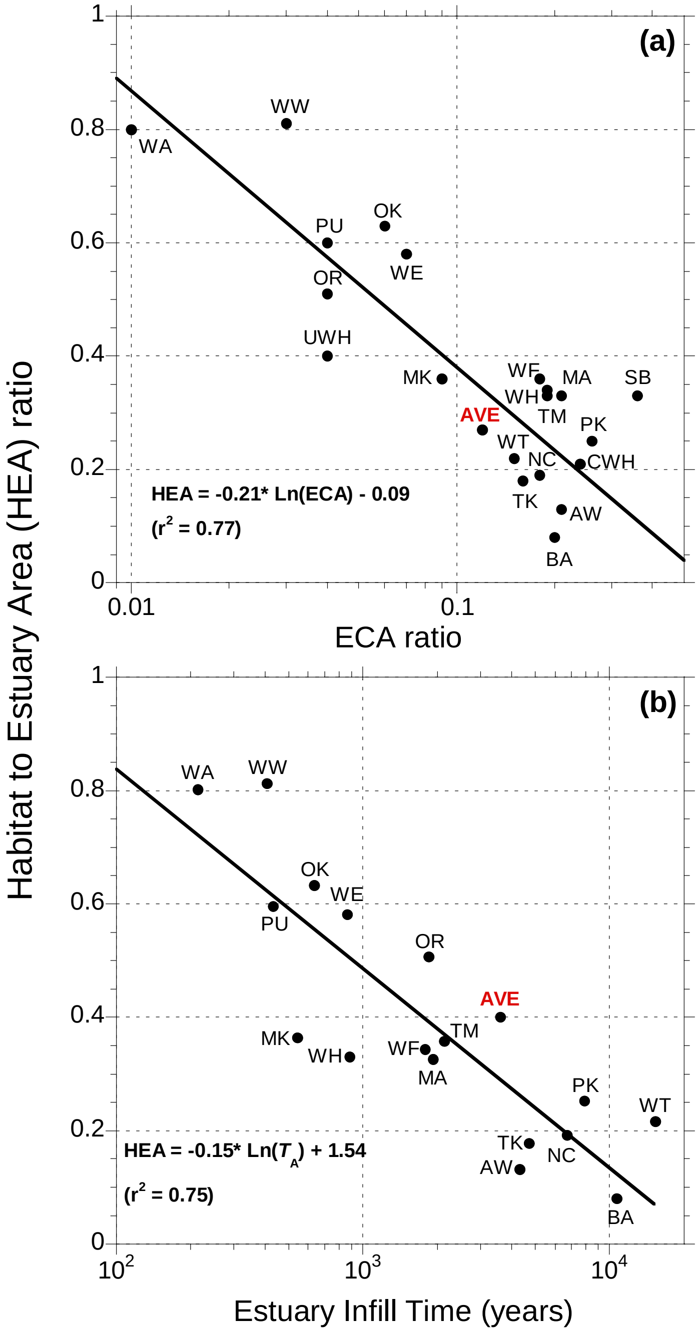
- Tidal Prism to Annual Load ratio (T_A, section 5.1). This parameter more directly relates the accommodation volume of an estuary and sediment inputs to the infill rate.

Figure 5.3a presents the results of this analysis and shows that the relationship between the relative estuary size (ECA ratio) and the proportion of an estuary's high-tide surface area that is above MTL-2007 (natural-log transformed HEA ratio) was significant ($r^2 = 0.77$, $P < 0.001$). Shoal Bay was not included in this regression analysis because this system accumulates sediments derived from sources other than its own catchment. These sources include the catchments of the Central Waitemata Harbour (CWH) and sediment resuspended from CWH tidal flats by waves and transported into Shoal Bay by ebb-tide currents (Swales et al. 2007b; Green et al. 2007). Thus, Shoal Bay has a substantially infilled with sediment and has a much larger area of tidal flat above MTL-2007 isobath than would be predicted and does not satisfy the assumptions of the empirical model.

The relationship between the HEA ratio and the estuary infill time (T_A) was also significant ($r^2 = 0.75$, $P < 0.001$) but did not explain any more of the variation in the data (Fig. 5.2b). Thus, the estuary/catchment area ratio is a useful predictor of the total intertidal area of an estuary above MTL that has the potential to be colonized by mangrove. The ECA ratio also has the advantage that it is readily estimated from topographic maps whereas the T_A requires tidal prism and sediment load data.

Figure 5.3:

Relationship between relative estuary size[1], catchment sediment inputs and the area of intertidal habitat above mean tide level 2007 (MTL-2007)[2] potentially suitable for mangrove colonisation, referred to as the **Habitat to Estuary Area (HEA) ratio**. The relative estuary size is defined as the Estuary to Catchment Area (ECA) ratio. Estuary codes: Whangateau (WH); Matakana (MK); North Cove, Kawau (NC); Bon Accord, Kawau (BA); Mahurangi (MA); Puhoi (PU); Waiwera (WW); Orewa (OR); Weiti (WE); Okura (OK); Waitemata (WT); Upper Waitemata (UWH); Central Waitemata (CWH); Shoal Bay (SB); Tamaki (TK); Whitford (WF); Wairoa (WA); Te Matuku (TM); Awaawaroa (AW); Putiki Bay (PK); Average – all estuaries (AVE). **Notes**: (1) Estuary size is the high-tide surface area (2) The MTL-2007 is based on the waterline survey.



5.4 Present-day mangrove habitat extent in estuaries

Appendix 7 presents ortho-rectified photos, which show the present-day distribution of mangrove habitat in each study estuary. Also shown are:

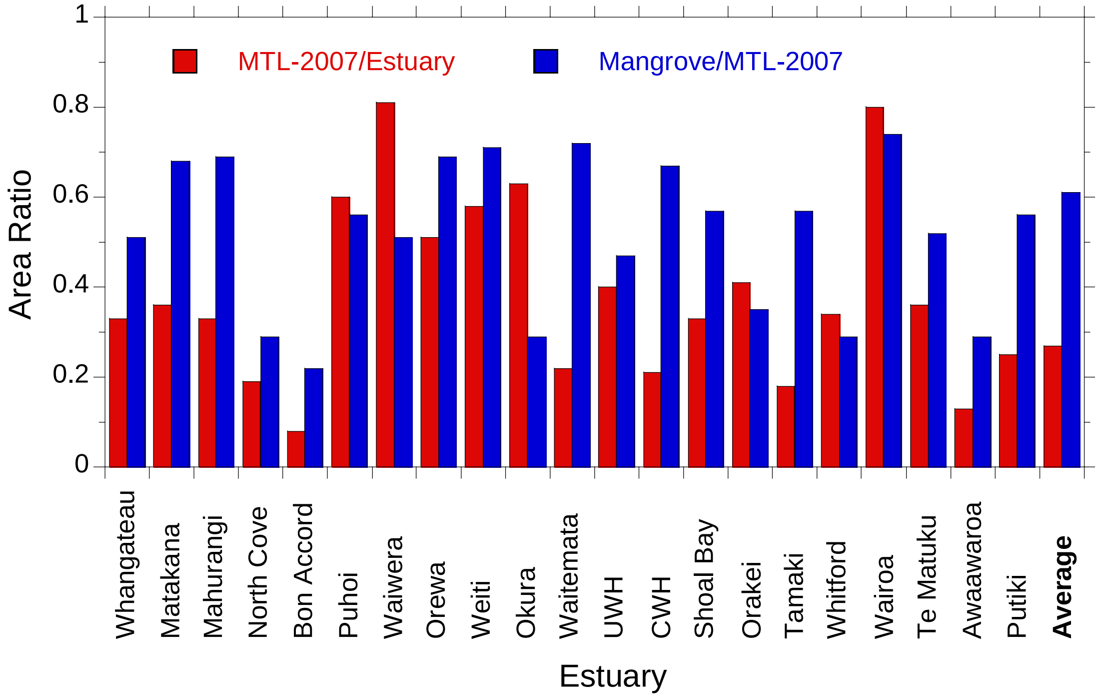
- raw mean tide level (MTL) indicated by the waters edge that was digitised from the ortho-photos using the method described in section 4.2. No attempt has been made to adjust the MTL waters edge position due to time differences between the time the photos were taken and the actual time of the mean level of the sea (MLOS) at the Port of Auckland;
- the fixed Auckland Vertical Datum 1946 (AVD-46) based on measurements of MLOS made during the 1920s–1940s. The MLOS during 2007 was 0.13 m above AVD-46;
- locations of the RTK-GPS elevation transects.

The raw MTL position corrected for the time difference between the aerial photography and the actual time of the Mean Level of the sea (MLOS) recorded at the Port of Auckland tide gauge is defined as the MTL-2007 isobath.

The aerial photography enables the present areas of potential mangrove habitat above the MTL 2007 (the HEA ratio) to be compared with the actual area presently occupied by mangrove. These data are expressed in Fig. 5.4 as ratios relative to each estuary's high-tide surface area and shows that the HEA ratio varies, by an order of magnitude, from 0.08 (Bon Accord) to 0.8 (Waiwera and Wairoa), with an average value of 0.4.

Figure 5.4 also shows that mangroves do not fully occupy their potential intertidal habitat above the MTL-2007 isobath. This proportion varies from 0.22 (Bon Accord) to 0.75 (Wairoa), with an average value of 0.52. There is no consistent pattern in the mangrove occupation data. Estuaries with less than 50% (i.e., ratio of 0.5) mangrove occupation include small estuaries with slow sediment infilling rates (Bon Accord and North Cove) and larger estuaries with relatively high infill rates (Whitford). Likewise, estuaries with mangrove occupation greater than 50% include small and large estuaries with variable infill rates. These patterns suggest that local factors, such as tidal-flat wave exposure (section 3.3) maybe influential.

Figure 5.4:
Proportion of tidal flat above mean tide level 2007 (MTL-2007) relative to high-tide estuary area and proportion of the tidal flat above the MTL-2007 isobath occupied by mangroves.



5.4.1 Lower elevation limit of mangroves in estuaries

The lower elevation limit (LEL) for mangrove seedlings and adult trees on the inter-tidal flats varied between estuaries. The LEL for seedlings and trees was determined from the (1) RTK-GPS surveys and (2) the elevation of the waterline derived from the ortho-photos taken at MLOS (-0.25 to +0.75 hours). Additional LEL data for mangrove trees is given where the waterline coincides with the edge of a mangrove stand.

Figure 5.5 summarises the mangrove LEL data provided by the RTK-GPS profile surveys. The lack of seedling data in some estuaries reflects the fact that some surveys were conducted during flood tides when observations could not be made and/or the absence of seedlings along the profiles. The average seedling LEL in the study estuaries varies between -0.28 m AVD-46 in the Mahurangi and 0.34 m AVD-46 in the Whangateau. Overall, the seedling LEL in the estuaries averaged -0.02 m AVD-46 (Fig. 5.1a). This estuary average value is ~0.15 m below the theoretical lower limit (0.13 m AVD-46) for grey mangrove habitat at mean tide level (section 3.3.3).

The LEL data for adult mangrove trees shows that the present-day distribution of mangrove habitat is substantially less than the potential habitat available above MTL-2007. The average LEL for mangrove trees varies between 0.08 m AVD-46 in the southern bays of Waiheke Island and 0.89 m AVD-46 in Whitford Bay (Fig. 5.5b). The equivalent elevation range in terms of MTL-2007 is -0.05 to +0.76 m). Overall, the LEL for adult trees in the study estuaries averaged 0.48 m above AVD-46 (Fig. 5.5b).

Figure 5.5:

Lower elevation limit (LEL) of mangrove seedlings (a) and trees (b) in Auckland's east-coast estuaries relative to Auckland Vertical Datum 1946. The number of RTK-GPS profiles for which mangrove data are available is also shown.

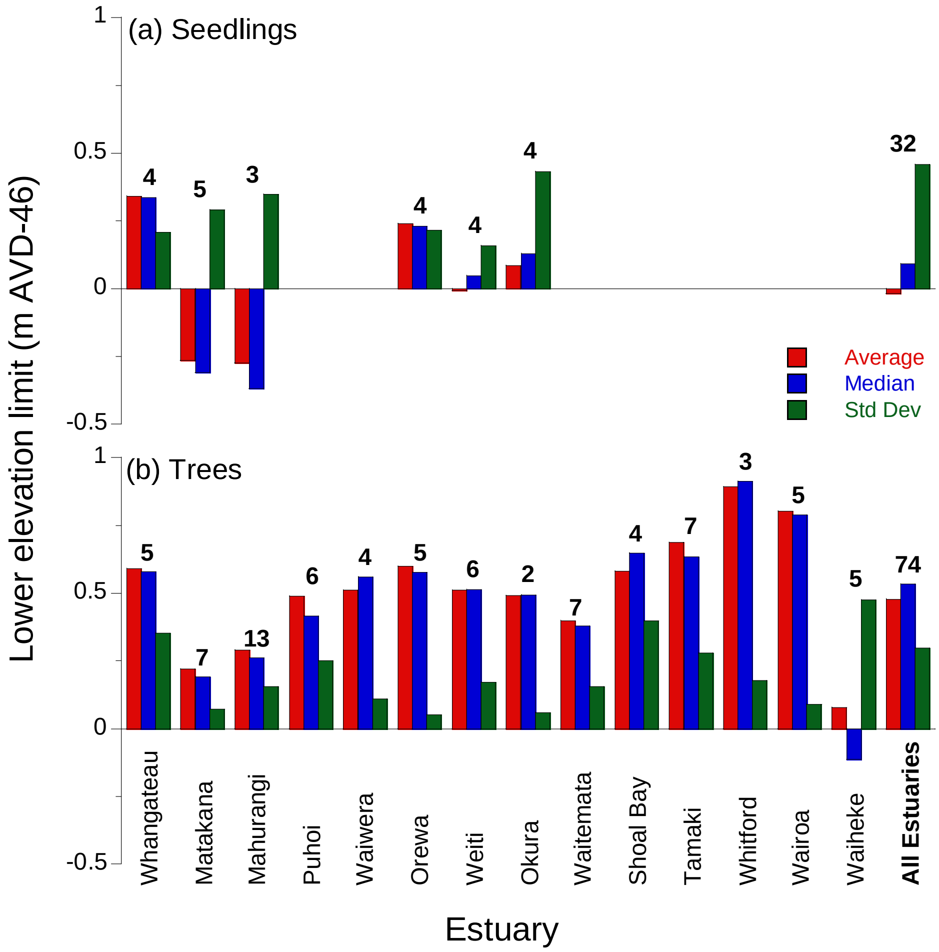


Table 5.1 summarises the information on the LEL for mangrove stands extracted from the waterline mapped in the ortho-photos. The waterline elevation was estimated from the measured tide at the Port of Auckland assuming a horizontal sea surface and minor tidal phase differences (section 4.2). Modelling indicates that the uncertainty in the waterline elevation due to the tidal amplification effect is of the order of ±1 cm (section 5.1).

The waterline measurements of mangrove stand LEL show that:

- mangrove stands have colonised intertidal flats down to 0.2 m below AVD-46 in the upper reaches of the Mahurangi Harbour and large areas of the smaller northern estuaries of Matakana, Mahurangi, Puhoi, Waiwera, Orewa and Weiti, tidal creeks of the Upper and Central Waitemata Harbour;

- mangroves have not colonised tidal flats down to AVD-46 in estuaries fringing the Tamaki Strait, such as Whitford, Wairoa, Te Matuku, Awaawaroa and Putiki Bay. These estuaries can be characterized as embayments with exposure to the relatively large wave fetch of the Tamaki Strait.

Table 5.1:

Lower elevation limit (LEL) of present-day mangrove stands coinciding with the waterline mapped from the aerial ortho-photos. Note: AVD-46 is ~0.1 m below MTL-2007.

Estuary	Waterline elev. (m AVD-46)	Area description	NZMG Easting	NZMG Northing
Whangateau	+0.07	Omaha River	2667690	6540415
Matakana	-0.09	Tidal creeks		
		Tongue Point branch	2665995	65346550
Mahurangi	-0.10	Cowans Bay north	2663580	6526795
		Landward of Hamiltons Landing		
		Dawsons Creek		
		upper Pukapuka Inlet	2661885	6522940
Puhoi	-0.11	upper Puhoi west of:	2661720	6518050
		Wenderholm	2663295	6517225
Waiwera	-0.11	mid-upper estuary west of:	2662380	6516475
Orewa	-0.11	Tidal creeks		
		Bay north of oxidation ponds	2660805	6510565
		Bay south-east of oxidation ponds	2661105	6509695
Weiti	-0.13	Estuary north of Stillwater	2664255	6505975
Upper Waitemata	-0.22	Tidal creeks		
Central Waitemata	-0.16	Areas of Whau & Waterview		
Wairoa	+0.33	Main channel bank		
		West of Pouto Point	2696385	6471310
Te Matuku	+0.52	Upper-estuary mangrove stands	2700315	6482995

The RTK-GPS and ortho-photo waterline elevation data indicate that:

- mangrove trees occupy most of their potential habitat down to MTL-2007 in sheltered environments, such as tidal creeks and on tidal flats in the smaller, fetch-limited estuaries;

- the spatial distribution of mangrove trees in relation to their LEL (Fig. 5.5) shows less variation within estuaries than between estuaries.

These between-estuary variations in the LEL for adult trees can reflect a number of factors:

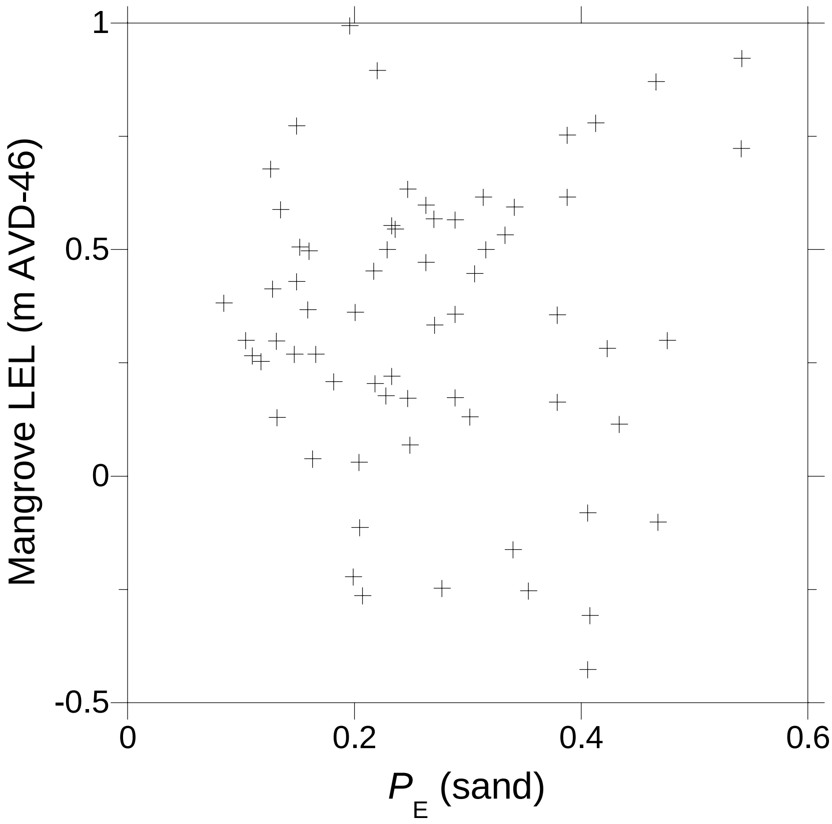
- Age of the mangrove stand. Young mangrove stands are less likely to fully occupy the entire area of intertidal flat suitable for colonization.

- Wave exposure. Seedling establishment on a tidal flat is influenced by wave exposure and in large, energetic estuaries major seedling recruitment events may not occur every year and/or be limited lower-energy zones on the upper tidal flat.

- Other factors, such as micro-climate effects (i.e., air temperature, frost frequency and severity).

The wave-climate analysis of the lower elevation limit (LEL) of mangrove trees at the RTK-GPS transects showed no relationship between bed disturbance and mangrove LEL (Fig. 5.6). Bed disturbance here is measured by the climate-average probability of fine-sand (125 μm) entrainment (P_E sand) by waves along each transect below the LEL at each site. This result does not mean that we can reject wave exposure as a primary physical mechanism controlling mangrove colonisation on tidal flats. Field studies in the Firth of Thames clearly show that waves control mangrove seedling recruitment (Swales et al. 2007a). However, the spatial distribution of adult mangroves on the tidal flats, as described by the LEL, may be influenced by other factors not considered here. Furthermore, the LEL dataset is limited to the RTK-GPS transects and is a far from comprehensive dataset. The empirical wave modeling also has limitations (section 4.6.2), which mainly relate to the simple representation of estuary bathymetry. Based on present understanding, our ability to predict the lower intertidal elevation of mangrove trees in Auckland's east-coast estuaries is limited.

Figure 5.6:
Relationship between the climate-average probability of sand entrainment (P_E) and the lower elevation limit for mangrove trees (LEL) at the RTK-GPS transects.



5.5 Hydrodynamic effects on mean tide level

The hydrodynamic modelling quantifies the magnitude of the tidal amplification effect on mean tide levels (MTL) in the Mahurangi, Okura, Waitemata, Tamaki and Whitford estuaries. Modelled scenarios are:

- Hindcast to 1950 A.D.
- Projections for the 2050s and 2090s.

The predicted changes in vertical and horizontal MTL positions were obtained from a 32-day model simulations which used the predicted tide curves (derived from tidal constituent data) for each of the estuaries. Model runs were carried out for 1950 sea level, current sea level, 2050s and 2090s for the three SLR scenarios adopted in this study. These scenarios include the historical SLR trend and two scenarios based on an MfE (2008) assessment of the IPCC (2007) SLR projections. (section 3.3.4).

Figures 5.7 – 5.16 present the results of the hydrodynamic modeling of tidal amplification in each of the five estuaries and show:

- the effect of tidal amplification on the mean tide level (MTL) relative to the MTL at the estuary mouth;

- change in the horizontal position of the MTL due to tidal amplification. This is estimated from the average tidal-flat slope measured in each estuary;
- the pattern of tidal amplification in each estuary is not altered by sedimentation or sea level changes that have occurred over the last 50 years or may occur over the next century.

Based on the classification system discussed in section 4.6 the Okura and Whitford estuaries are hyposynchronous, with the tidal amplitude decreasing with distance from the estuary mouth. Up-estuary variations in the MTL (vertical) position are very small in both cases being less than 5 mm and result in changes in the horizontal position of the MTL of less than one metre (Figs. 5.7 – 5.10). The Mahurangi Harbour behaves synchronously, with the tidal amplitude remaining nearly constant up estuary. Variations in the horizontal position of the MTL up-estuary are less than half a metre (Figs. 5.11 – 5.12). By contrast, the Waitemata Harbour and Tamaki Estuary are hypersyncronous, with tidal amplitude increasing with distance from the estuary mouth (Figs. 5.11 – 5.12). In the Waitemata, the effect of tidal amplification on the MTL is relatively minor, being less than 50 mm in the vertical and three metres in the horizontal position. The effect of tidal amplification in the Tamaki Estuary is more pronounced and is typical of funnel-shaped estuaries. Figure 5.16 shows that of all the estuaries modelled, the magnitude of the tidal amplification in the Tamaki is the most sensitive to sea-level changes. Variations in the horizontal position of the MTL up-estuary are as much as five metres under the future sea-level rise scenarios considered in this study.

The main conclusion to be drawn from the numerical modeling of tidal amplification is that this dynamic process is likely to have a minor effect on the MTL position in comparison to the effect of future sea level changes.

Figure 5.7:
Okura Estuary: spatial pattern of tidal amplification relative to the mean tide level (MTL) at the estuary mouth (units: mm). Predicted up-estuary variations in MTL for: (1) the 1950 and 2007 sea levels; and (2) future sea levels in the 2050s and 2090s for the base IPCC (2007) base SLR scenario. The cross symbols show the location of data used to construct the up-estuary longitudinal profiles of tidal amplification of the MTL.

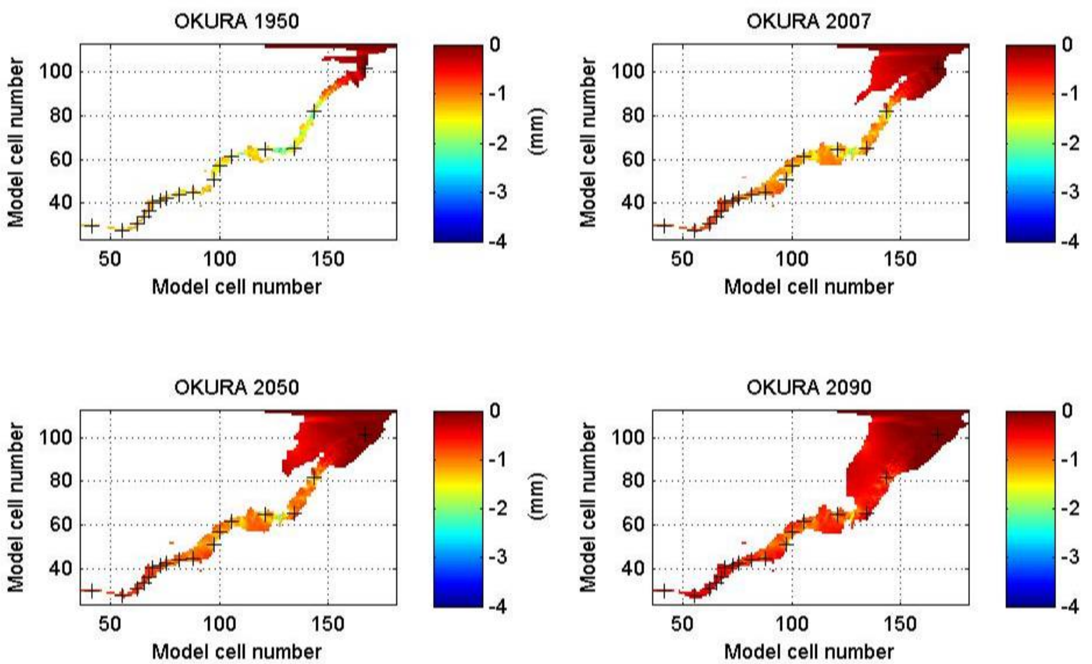


Figure 5.8:

Okura Estuary: longitudinal (up-estuary) pattern of tidal amplification relative to the mean tide level (MTL) at the estuary mouth. The vertical change in MTL are shown in the left-hand plots (units: mm) and the resulting change in the horizontal MTL position (units: m) are shown in the right hand plots. Predicted up-estuary variations in MTL for: (1) the 1950 and 2007 sea levels; and (2) future sea levels in the 2050s and 2090s for the three modelled scenarios. Note: black curve is scenario one (historical trend, $SLR_{0.14m,\ 2090s}$); blue curve is scenario two ($SLR_{0.47m,\ 2090s}$); red curve is scenario three ($SLR_{0.77m,\ 2090s}$).

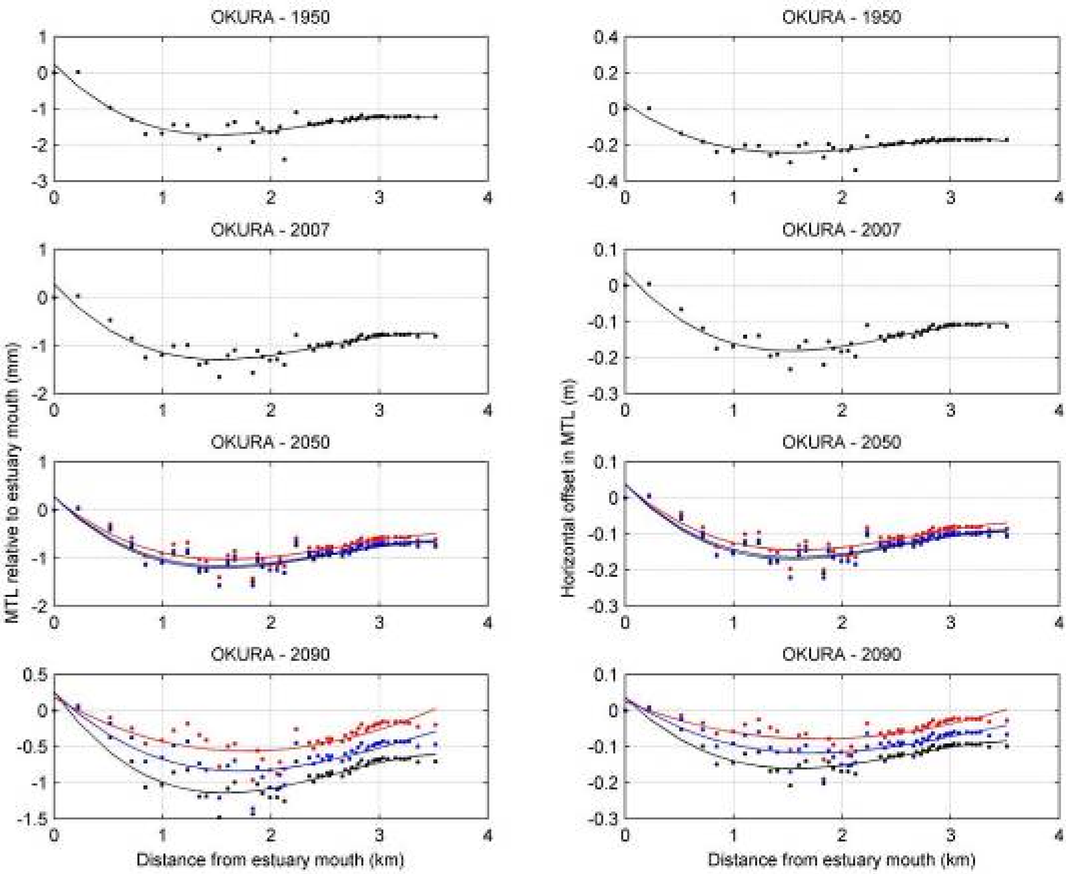


Figure 5.9:

Whitford Bay: spatial pattern of tidal amplification relative to the mean tide level (MTL) at the estuary mouth (units: mm). Predicted up-estuary variations in MTL for: (1) the 1950 and 2007 sea levels; and (2) future sea levels in the 2050s and 2090s for the base IPCC (2007) base SLR scenario. The cross symbols show the location of data used to construct the up-estuary longitudinal profiles of tidal amplification of the MTL.

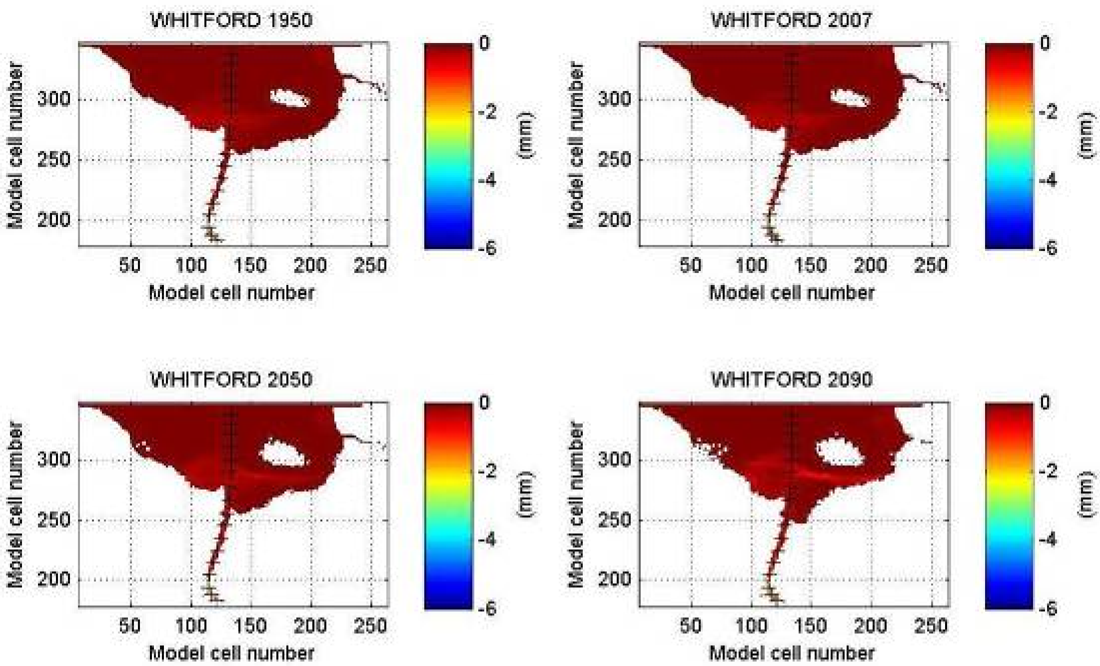


Figure 5.10:

Whitford Bay: longitudinal (up-estuary) pattern of tidal amplification relative to the mean tide level (MTL) at the estuary mouth. The vertical change in MTL are shown in the left-hand plots (units: mm) and the resulting change in the horizontal MTL position (units: m) are shown in the right hand plots. Predicted up-estuary variations in MTL for: (1) the 1950 and 2007 sea levels; and (2) future sea levels in the 2050s and 2090s for the three modelled scenarios. Note: black curve is scenario one (historical trend, $SLR_{0.14m,\ 2090s}$); blue curve is scenario two ($SLR_{0.47m,\ 2090s}$); red curve is scenario three ($SLR_{0.77m,\ 2090s}$).

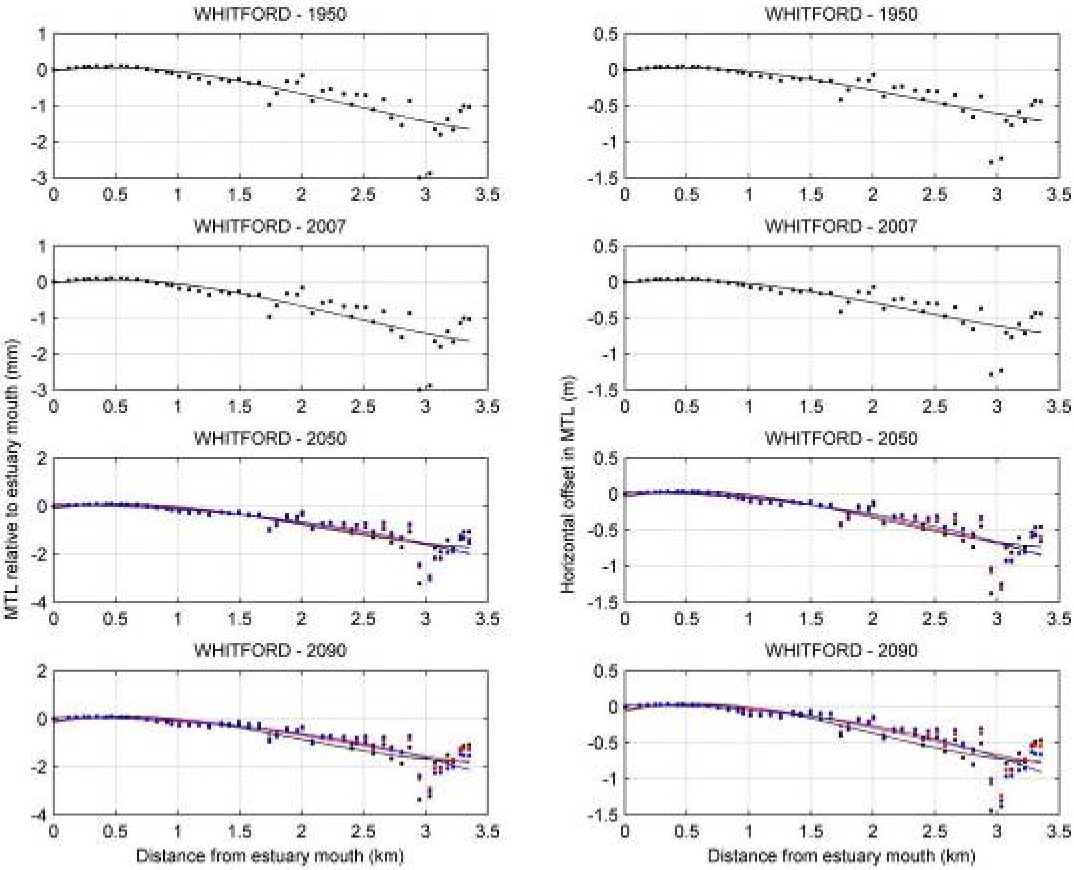


Figure 5.11:

Mahurangi Harbour: spatial pattern of tidal amplification relative to the mean tide level (MTL) at the estuary mouth (units: mm). Predicted up-estuary variations in MTL for: (1) the 1950 and 2007 sea levels; and (2) future sea levels in the 2050s and 2090s for the base IPCC (2007) base SLR scenario. The cross symbols show the location of data used to construct the up-estuary longitudinal profiles of tidal amplification of the MTL.

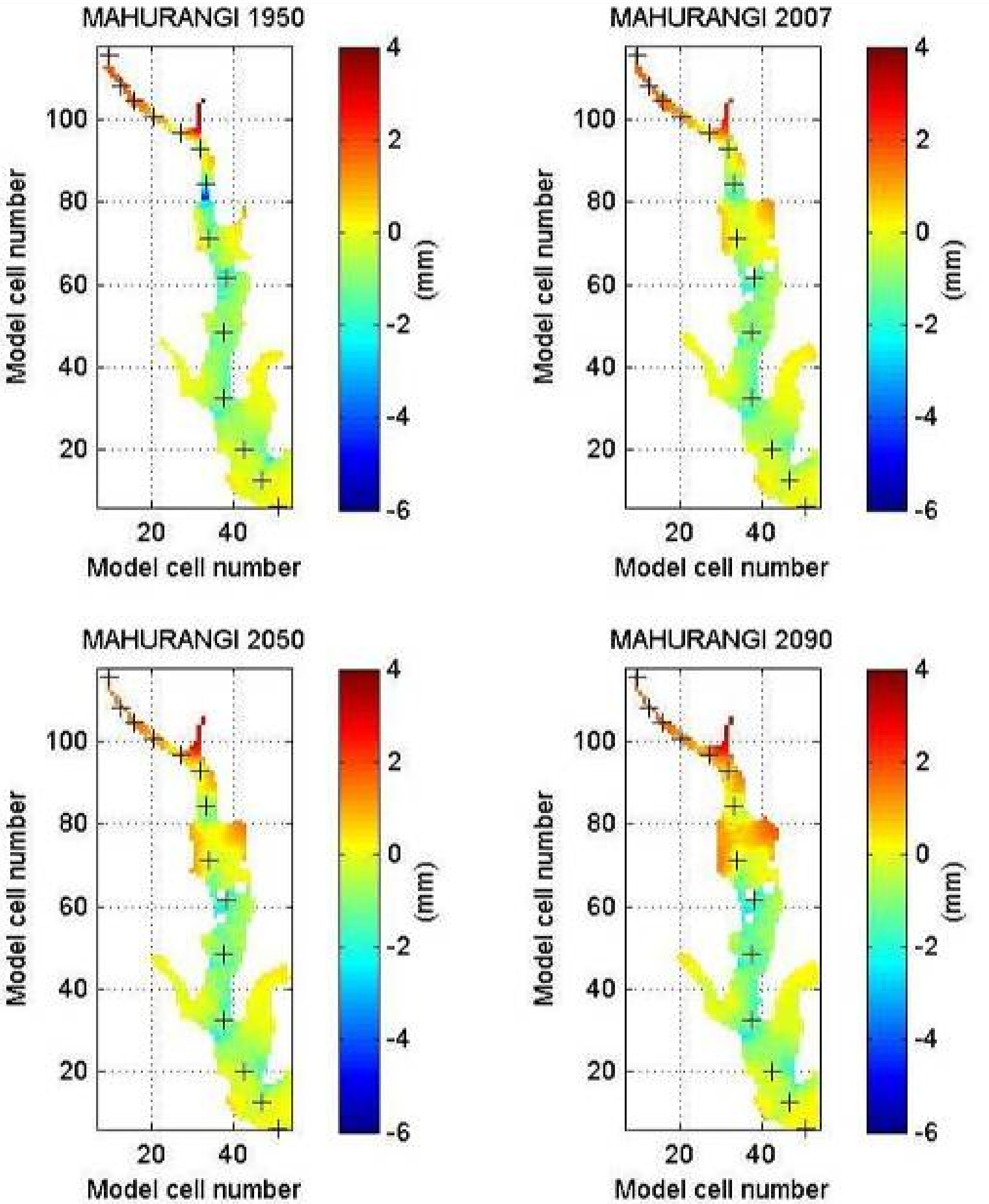


Figure 5.12:

Mahurangi Harbour: longitudinal (up-estuary) pattern of tidal amplification relative to the mean tide level (MTL) at the estuary mouth. The vertical change in MTL are shown in the left-hand plots (units: mm) and the resulting change in the horizontal MTL position (units: m) are shown in the right hand plots. Predicted up-estuary variations in MTL for: (1) the 1950 and 2007 sea levels; and (2) future sea levels in the 2050s and 2090s for the three modelled scenarios. Note: black curve is scenario one (historical trend, $SLR_{0.14m,\ 2090s}$); blue curve is scenario two ($SLR_{0.47m,\ 2090s}$); red curve is scenario three ($SLR_{0.77m,\ 2090s}$).

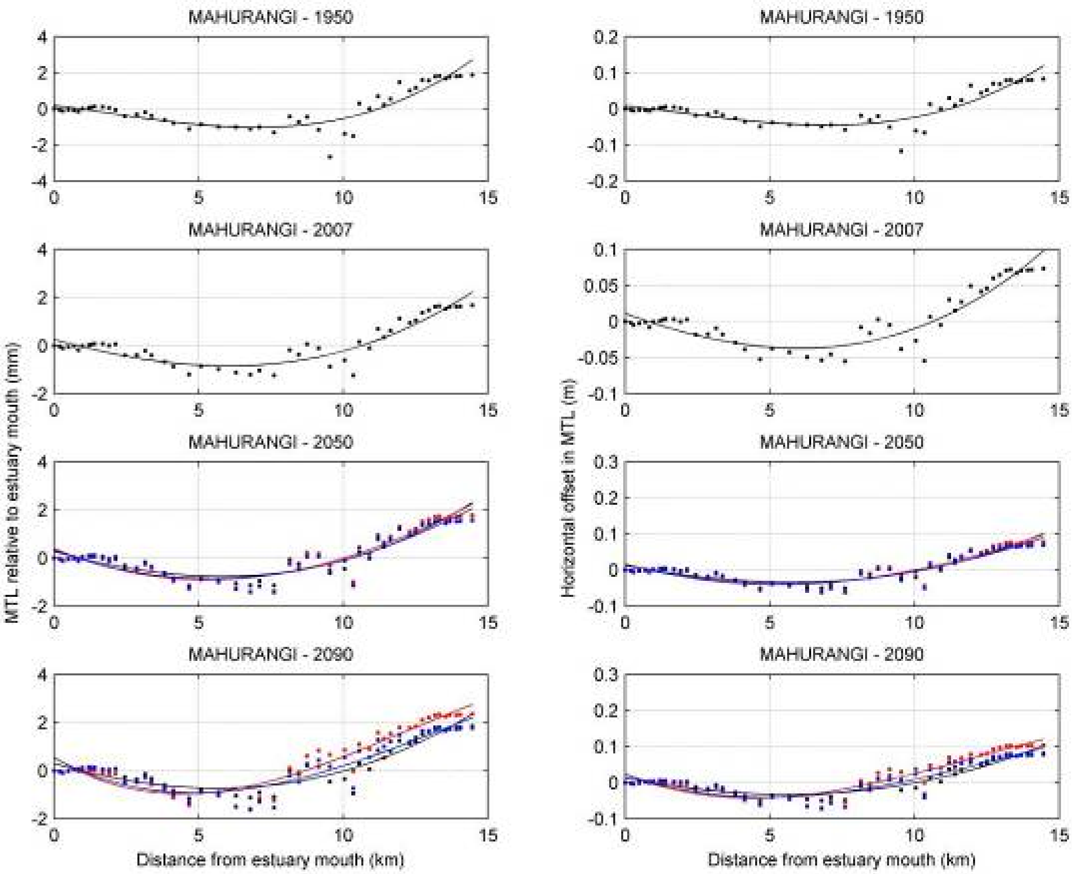


Figure 5.13:

Waitemata Harbour: spatial pattern of tidal amplification relative to the mean tide level (MTL) at the estuary mouth (units: mm). Predicted up-estuary variations in MTL for: (1) the 1950 and 2007 sea levels; and (2) future sea levels in the 2050s and 2090s for the base IPCC (2007) base SLR scenario. The cross symbols show the location of data used to construct the up-estuary longitudinal profiles of tidal amplification of the MTL.

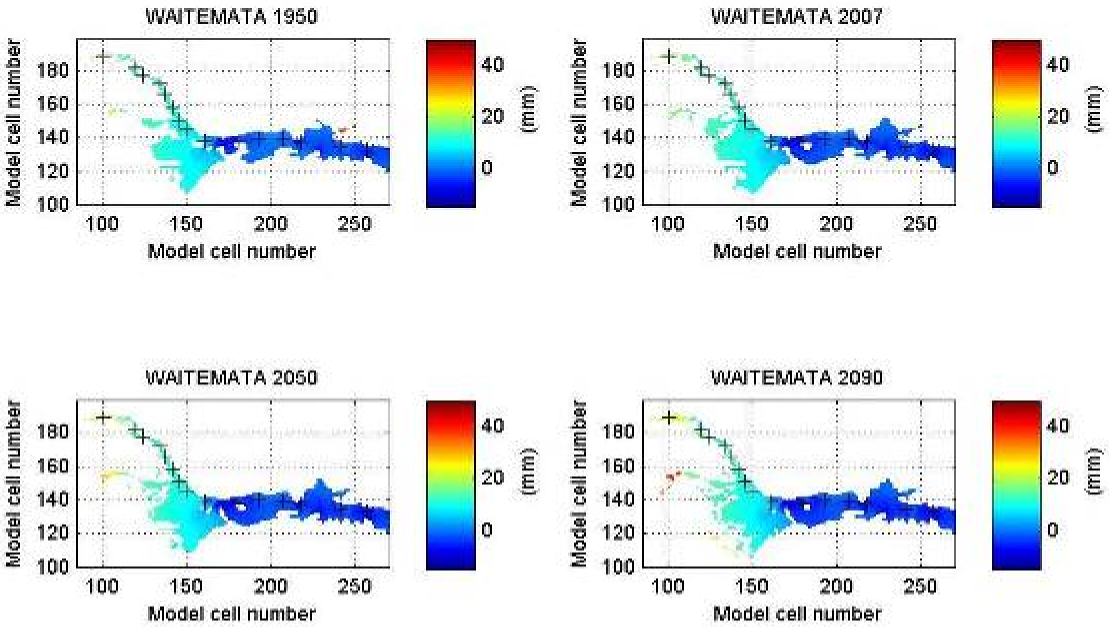


Figure 5.14:

Waitemata Harbour: longitudinal (up-estuary) pattern of tidal amplification relative to the mean tide level (MTL) at the estuary mouth. The vertical change in MTL are shown in the left-hand plots (units: mm) and the resulting change in the horizontal MTL position (units: m) are shown in the right hand plots. Predicted up-estuary variations in MTL for: (1) the 1950 and 2007 sea levels; and (2) future sea levels in the 2050s and 2090s for the three modelled scenarios. Note: black curve is scenario one (historical trend, $SLR_{0.14m,\ 2090s}$); blue curve is scenario two ($SLR_{0.47m,\ 2090s}$); red curve is scenario three ($SLR_{0.77m,\ 2090s}$).

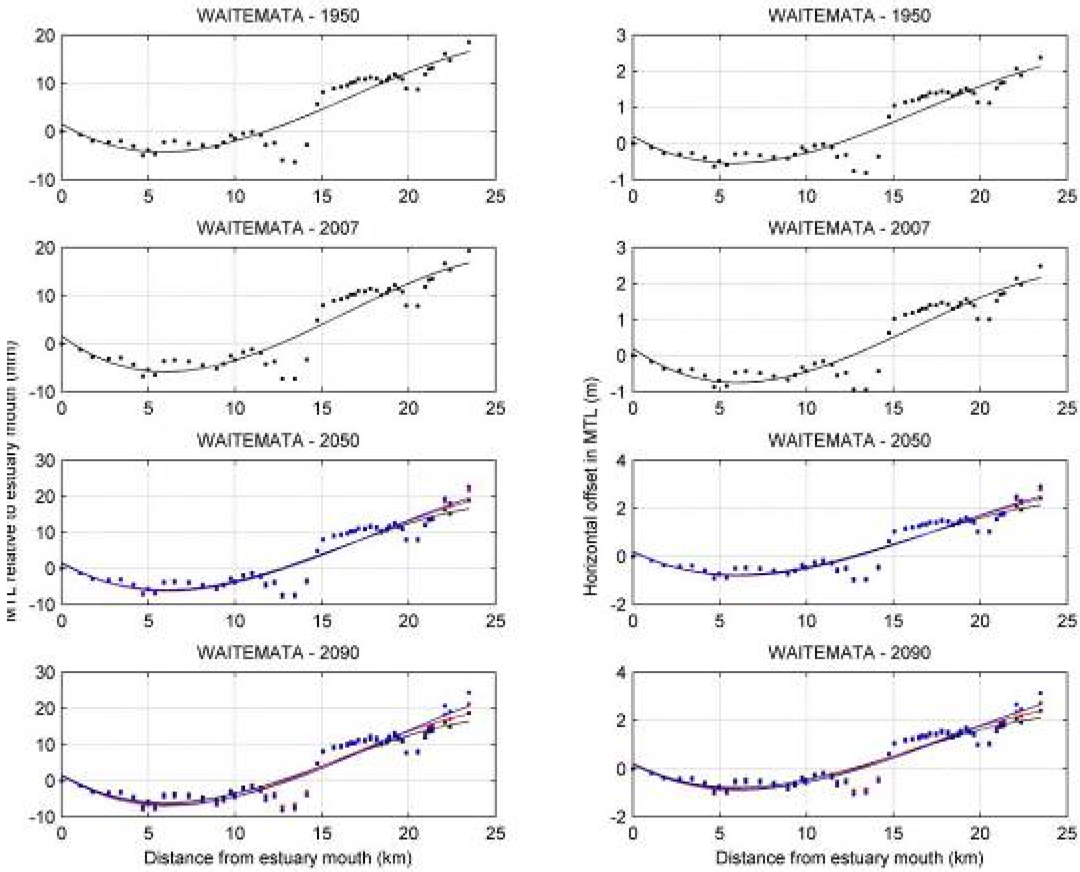


Figure 5.15:

Tamaki Estuary: spatial pattern of tidal amplification relative to the mean tide level (MTL) at the estuary mouth (units: mm). Predicted up-estuary variations in MTL for: (1) the 1950 and 2007 sea levels; and (2) future sea levels in the 2050s and 2090s for the base IPCC (2007) base SLR scenario. The cross symbols show the location of data used to construct the up-estuary longitudinal profiles of tidal amplification of the MTL.

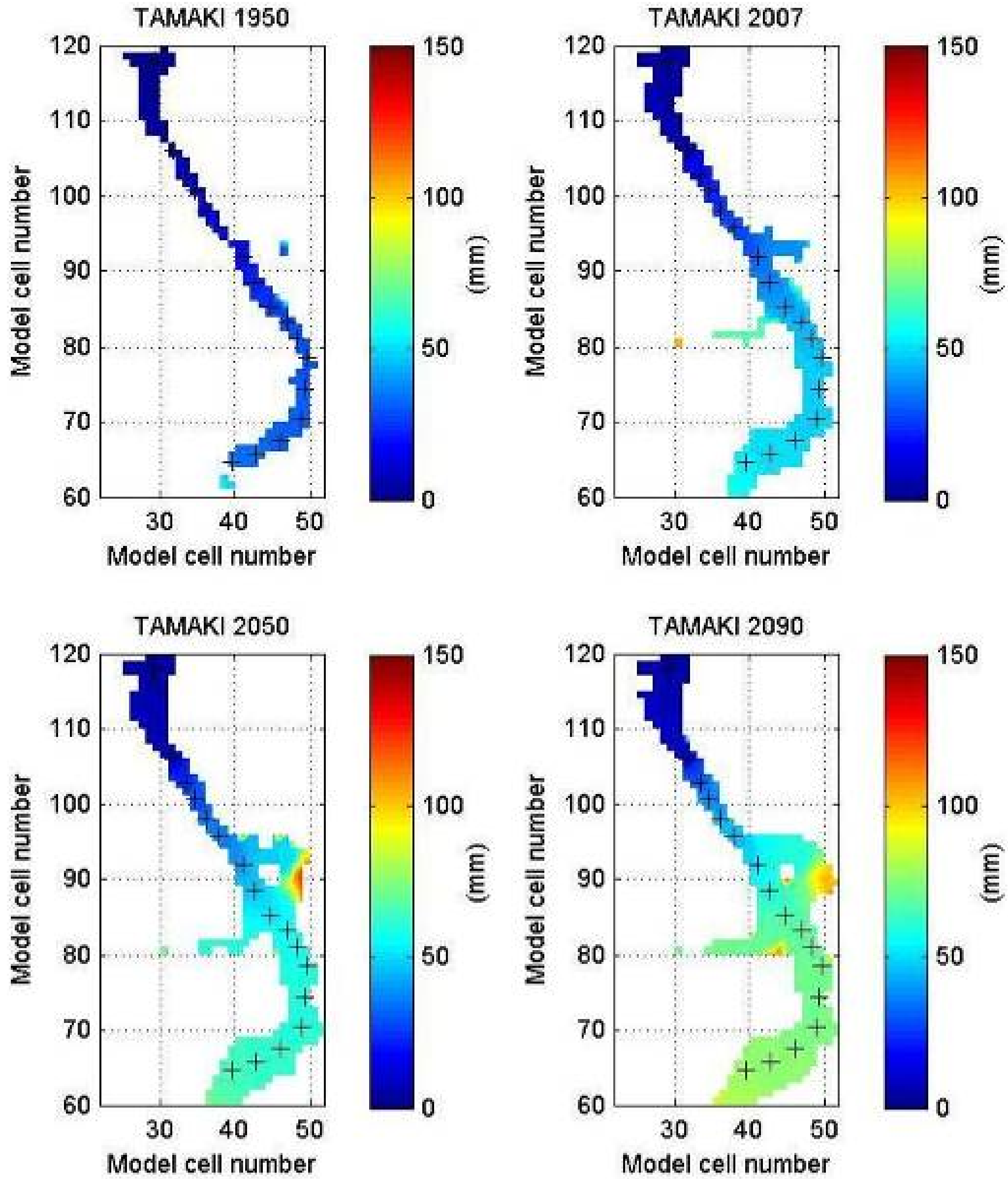
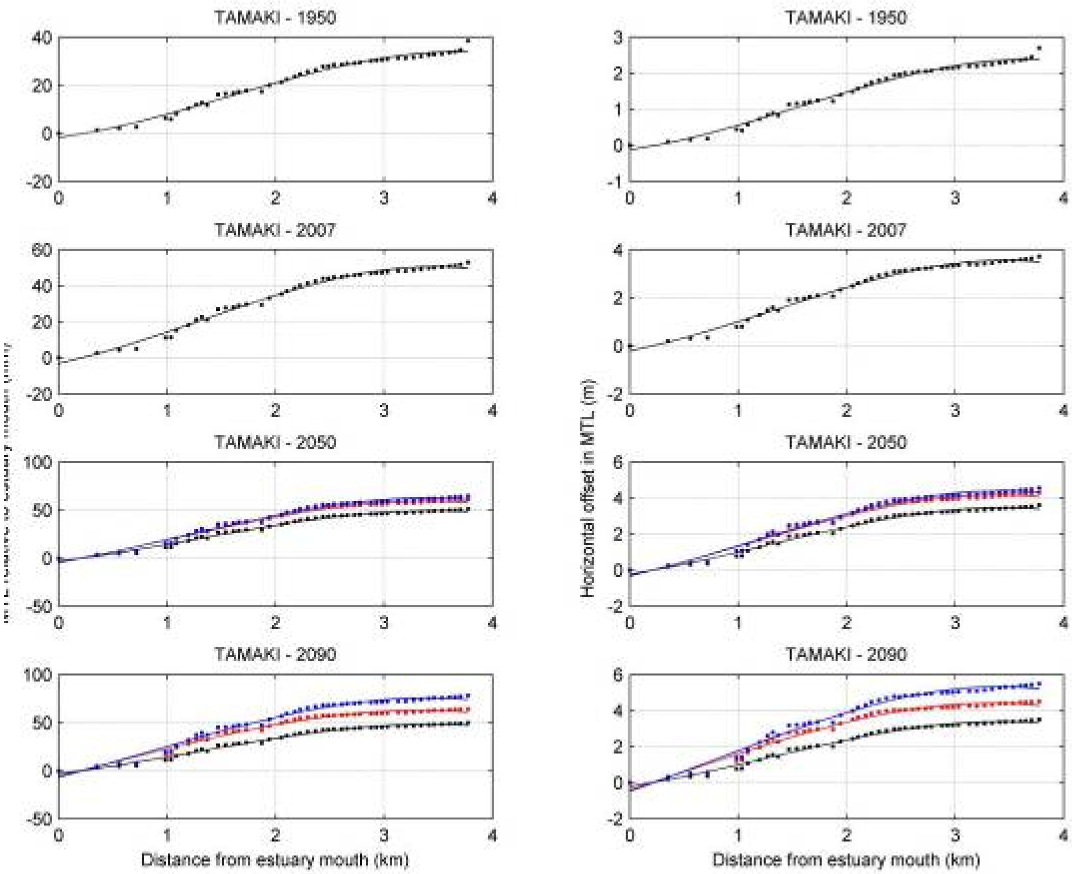


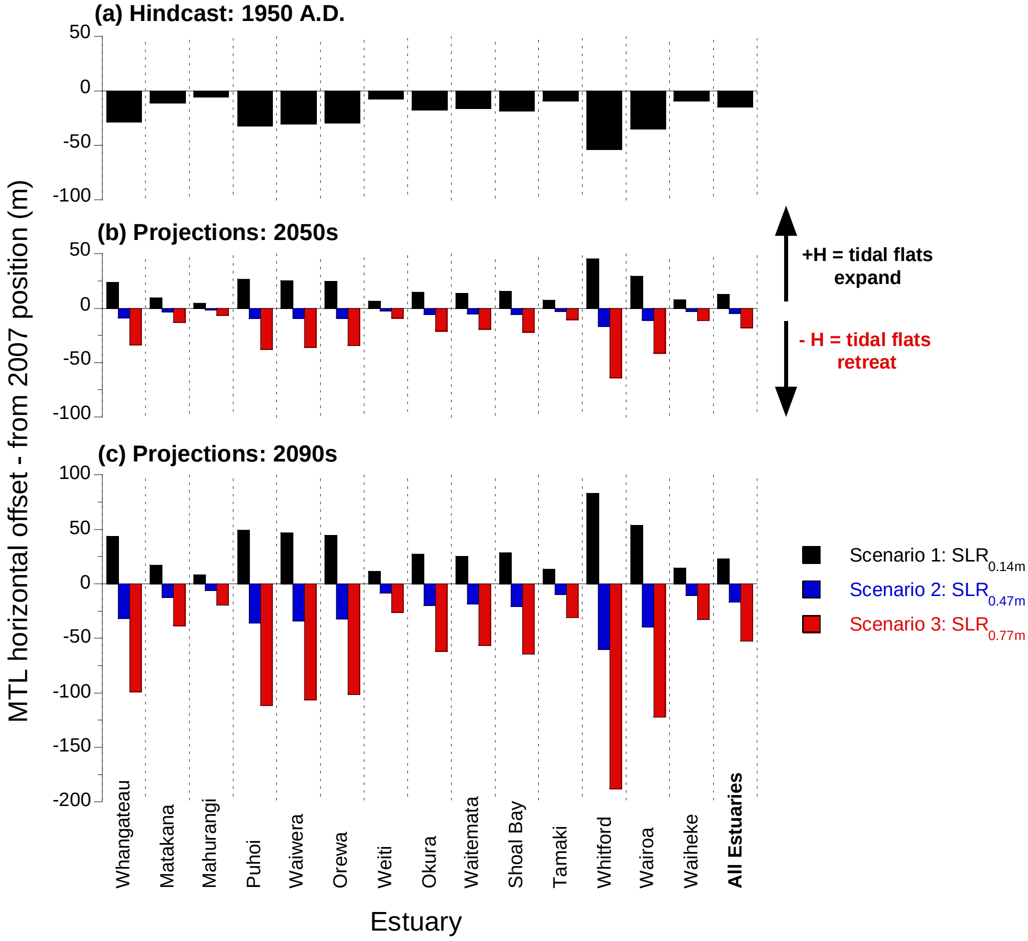
Figure 5.16:
Tamaki Estuary: longitudinal (up-estuary) pattern of tidal amplification relative to the mean tide level (MTL) at the estuary mouth. The vertical change in MTL are shown in the left-hand plots (units: mm) and the resulting change in the horizontal MTL position (units: m) are shown in the right hand plots. Predicted up-estuary variations in MTL for: (1) the 1950 and 2007 sea levels; and (2) future sea levels in the 2050s and 2090s for the three modelled scenarios. Note: black curve is scenario one (historical trend, $SLR_{0.14m,\ 2090s}$); blue curve is scenario two ($SLR_{0.47m,\ 2090s}$); red curve is scenario three ($SLR_{0.77m,\ 2090s}$).



5.6 Hindcast & projected future changes in tidal-flat habitat

Figure 5.17 shows how past and future changes in sea level, including the effect of sedimentation, translate into horizontal changes in MTL position. These estimates are based on the average tidal-flat in each study estuary. Local variations in tidal-flat slope will have a substantial effect on MTL position and this is accounted for by using digital terrain models (DEM) for estuaries where they are available.

Figure 5.17:
Examples of horizontal changes in the position of the MTL-2007 isobath based on average tidal-flat slopes measured in the study estuaries for the hindcast and future SLR scenarios. Note: for the SLR scenarios projected increases in sea level by the 2090s are indicated.



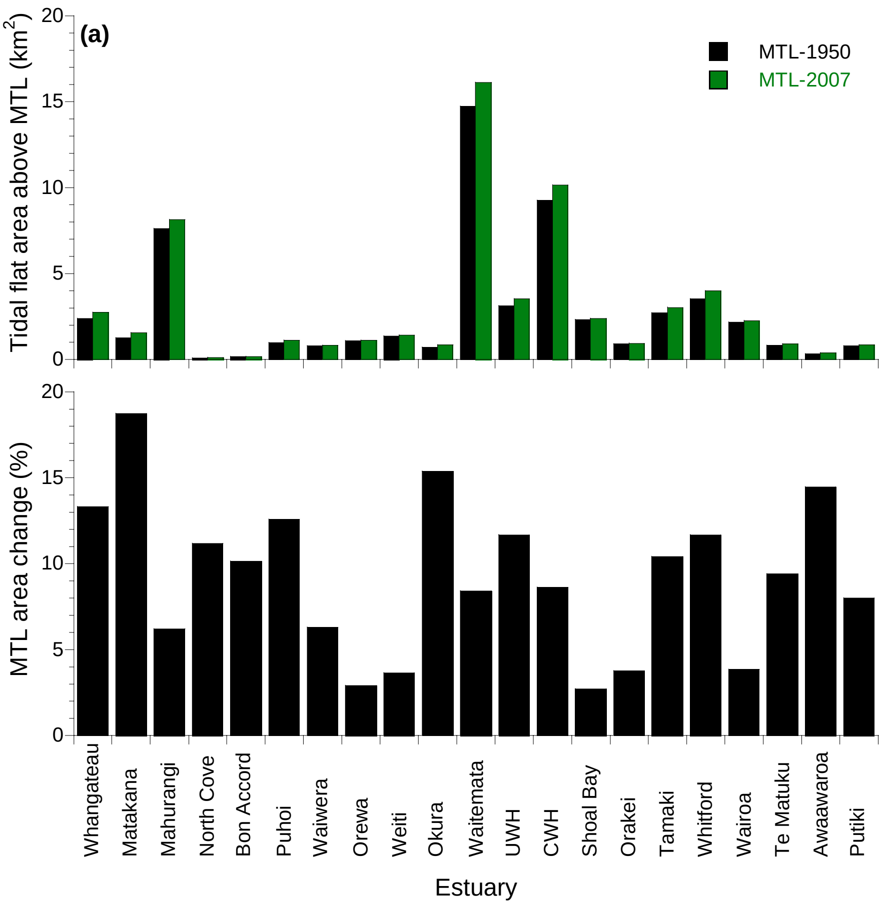
5.7 Historical changes in mangrove habitat

In this section we present data on the historical changes in mangrove habitat in a selection of the study estuaries over the last 50–70 years. We distinguish between mangrove habitat, which are areas that are occupied by mangrove stands and potential mangrove habitat, which is the available tidal-flat area above MTL.

5.7.1 Hindcast changes in potential mangrove habitat

The area of tidal flat above MTL in 1950 has been hindcast from the MTL-2007 isobath based on the net change in sea level since 1950 and tidal-flat slope data provided by DEMs or RTK-GPS measurements. Figure 5.18 summarises the results of this analysis for each estuary. In Auckland's east-coast estuaries, the tidal-flat area above MTL has increased on average by 9% (range: 3–19%) since 1950 due to sedimentation. These hindcasts suggest that mangrove-habitat expansion should have occurred in Auckland's east-coast estuaries since the 1950s due to an increase in the area of potential habitat. The next section reviews the actual changes in mangrove habitat that have occurred over the last 50–70 years.

Figure 5.18:
Hindcast predictions of potential mangrove habitat above mean tide level in 1950 based on the MTL-2007 isobath, historical rate of sea-level rise and sedimentation in estuaries: (a) tidal-flat area above MTL in 1950 and 2007; and (b) percentage change between 1950 and 2007. Note: digital terrain models were not available for Whangatau, Mahurangi, Kawau Island, Shoal Bay and Orakei/Hobson Bay.



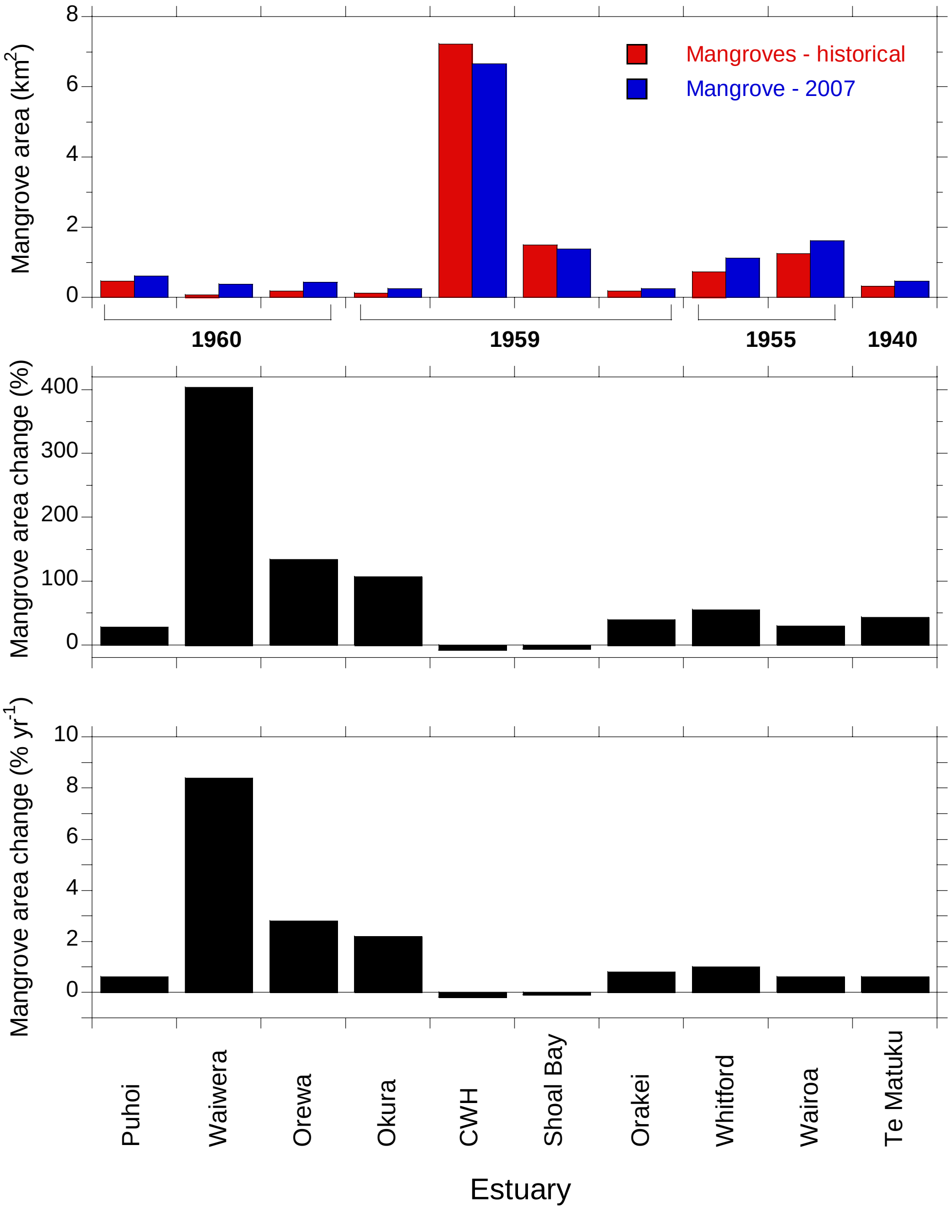
5.7.2 Observed changes in mangrove habitat

Mapping of mangrove habitat from historical and 2007 ortho-photos enables changes in the area of mangrove habitat to be quantified. Figure 5.19 summarises the historical changes in mangrove-habitat area that have occurred in a selection of the study estuaries over the last ~70 years. The age of the historical aerial photographs spans the period between 1940 and 1960. In most of the estuaries the area of mangrove habitat has increased by 28 – 404%, which translates to increases of between 0.6 and 8.4 % per annum relative to the historical baseline values. These increases in mangrove habitat substantially exceed the increases in potential mangrove habitat above the MTL isobath since 1950 (section 5.6.1).

The largest observed increases in mangrove habitat, of >100%, have occurred in the smallest estuaries, with high-tide areas less than 1.5 km^2. These include the Okura (107%), Orewa (134%) and Waiwera (404%) estuaries. Figure 5.4 shows that these systems have some of the smallest ECA ratios (i.e., small estuary relative to catchment area) of all the study estuaries. The largest increase in mangrove habitat has occurred in the Waiwera estuary, which along with the Wairoa estuary, has the largest proportion of its high-tide area potentially available for mangrove colonisation. Some 80% of the Waiwera estuary is above MTL-2007 elevation (i.e., HEA ratio).

Figure 5.19:

Historical changes in mangrove habitat area in selected east-coast estuaries between 1940/1955/1959/1960 and 2007: (1) comparison of mangrove-habitat areas (km^2); (2) total percentage change; (3) percentage change per year.



The Waiwera is also vulnerable to sediment infilling as indicated by its relatively short estuary infill time (T_A) of less than 500 years (Fig. 5.2). It is also notable that the 28% increase in mangrove habitat in the adjacent Puhoi estuary (1960 – 2007) is substantially lower than in the Waiwera. This is despite the fact that the Puhoi estuary has similar characteristics (i.e., ECA, HEA, T_A) to the Waiwera.

In contrast to most of the study estuaries, the area of mangrove habitat in the Waitemata Harbour, which is the largest estuarine system, has reduced over the last 50 years. In the Central Waitemata Harbour (CWH) and Shoal Bay the areas of mangrove in 2007 are respectively 8% and 6.7% less than in 1959 (Fig. 5.2).

Figures 5.20 – 5.34 compare the historical and 2007 orthophotos and show how the distribution and extent of mangrove habitat have changed in the estuaries over the last 50–70 years. Contact prints of several other estuaries also provide qualitative historical information on mangrove distribution.

In the Whangateau Harbour, historical aerial photographs indicate that mangroves had begun to colonise the Omaha River, a large tidal-creek arm of the harbour, before 1953 (Fig. 5.20).

Figure 5.20:
Omaha River (Whangateau Harbour, 1953). Mangrove stands on intertidal flats (arrows).

In the Matakana Estuary and the Mahurangi Harbour, mangrove had by 1960 colonised most of the tidal flat areas where we see them today (Figs. 5.21–5.23). Based on the area and extent of mangrove habitat it is likely that mangroves first colonised these two northern estuaries at least several decades before 1960.

Figure 5.21:
Matakana Estuary (1960). Mangrove stands on intertidal flats (arrows).

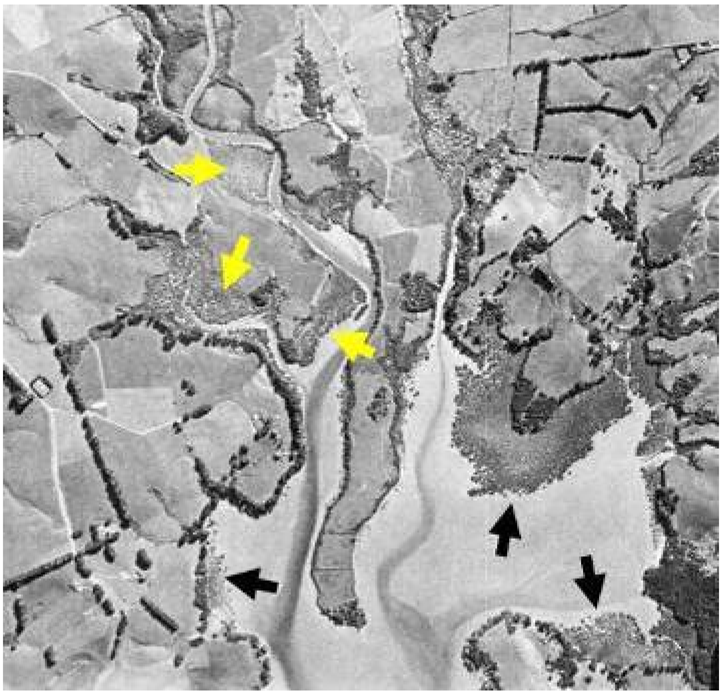


Figure 5.22:
Mahurangi Harbour at Hamilton's Landing (1960). Mangrove stands on intertidal flats (arrows).

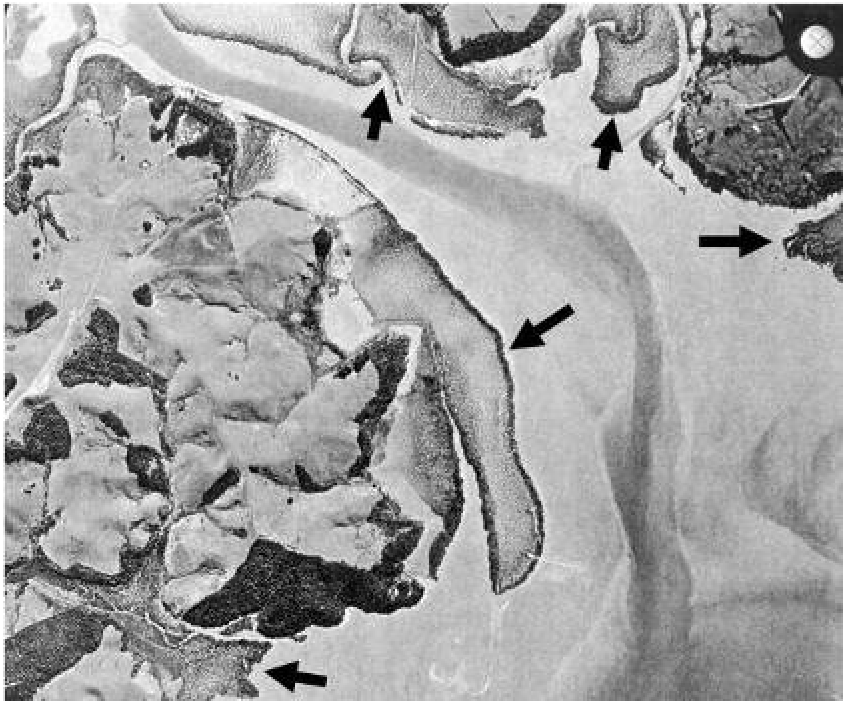
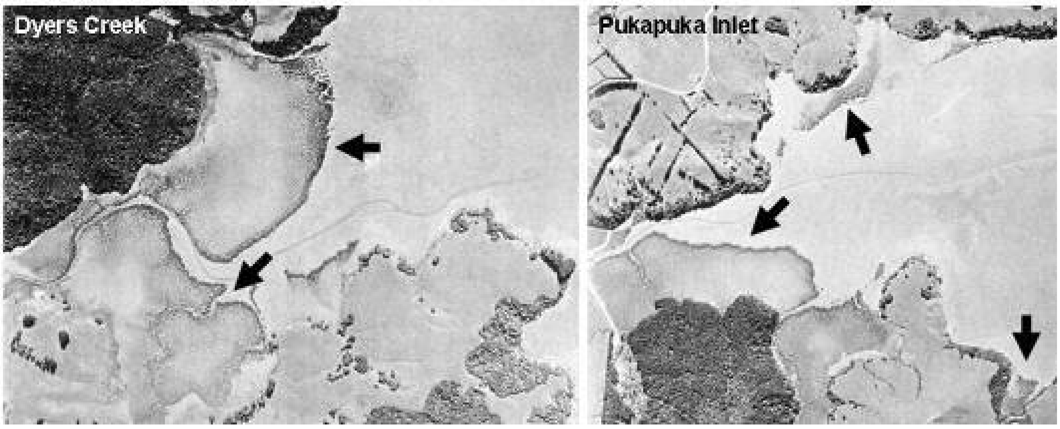
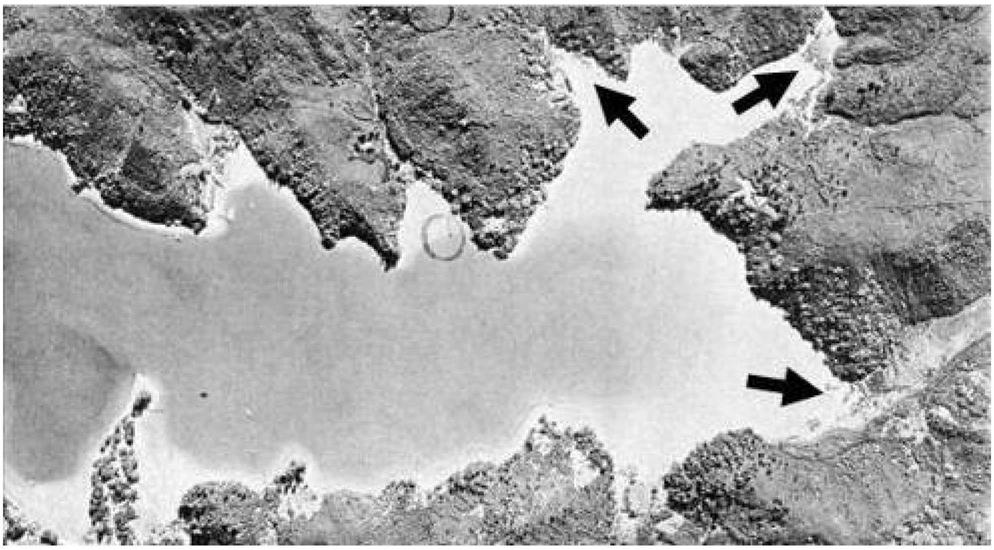


Figure 5.23:
Mahurangi Harbour at Dyer's Creek and Pukapuka Inlet (1960). Mangrove stands on intertidal flats (arrows).



At Bon Accord, mangrove had colonised several small tidal creeks in the upper estuary by 1960 (Fig. 5.24) and have not substantially increased there distribution since that time.

Figure 5.24 :
Bon Accord Harbour, Kawau Island (1960). Mangrove stands in the tidal creeks (arrows).



Historical orthophotos of the Puhoi, Waiwera and Orewa show that mangroves were also present in the upper reaches of all three estuaries by 1960. In the upper Puhoi estuary, the photographs indicate an increase in the size and/or density of mangrove trees rather than an increase in areal coverage. The largest increase in mangrove area has occurred in the lower estuary in a bay adjoining the Wenderholm sand spit (Fig. 5.25). Large areas of tidal flat above MTL-2007 have not been colonized by mangroves. By comparison, in the adjacent Waiwera estuary, there has been a substantial increase in the area of mangrove forest since 1960. Most of the tidal flat above MTL in the middle reaches of the estuary has been colonised by mangrove (Fig. 5.26). Despite these timing differences, the area of tidal flat above MTL-2007 colonised by mangrove is similar in both the Puhoi (56%) and Waiwera (52%) estuaries (Fig. 5.3).

At Orewa, the pattern of mangrove colonization is similar to Puhoi, with mangroves having first colonised tidal-flats at sub-catchment outlets (Fig. 5.27). At most sites the size and/or density of mangrove trees have increased more than the areal extent of the mangrove stands. Mangrove have extended their distribution at all sites and have colonized upper tidal flats along the northern shore of the estuary. The construction of sewage treatment ponds after 1960 has reclaimed ~11 ha of tidal flat above the MTL isobath. Figure 5.27 shows that large areas of potential mangrove habitat, above MTL, in the middle estuary have not yet been colonized by mangrove.

Figure 5.25:

Puhoi estuary. Historical (1960) and recent (2007) orthophotos of the estuary showing changes in mangrove forest areas and position of MTL-2007 and MTL-1950 isobaths.

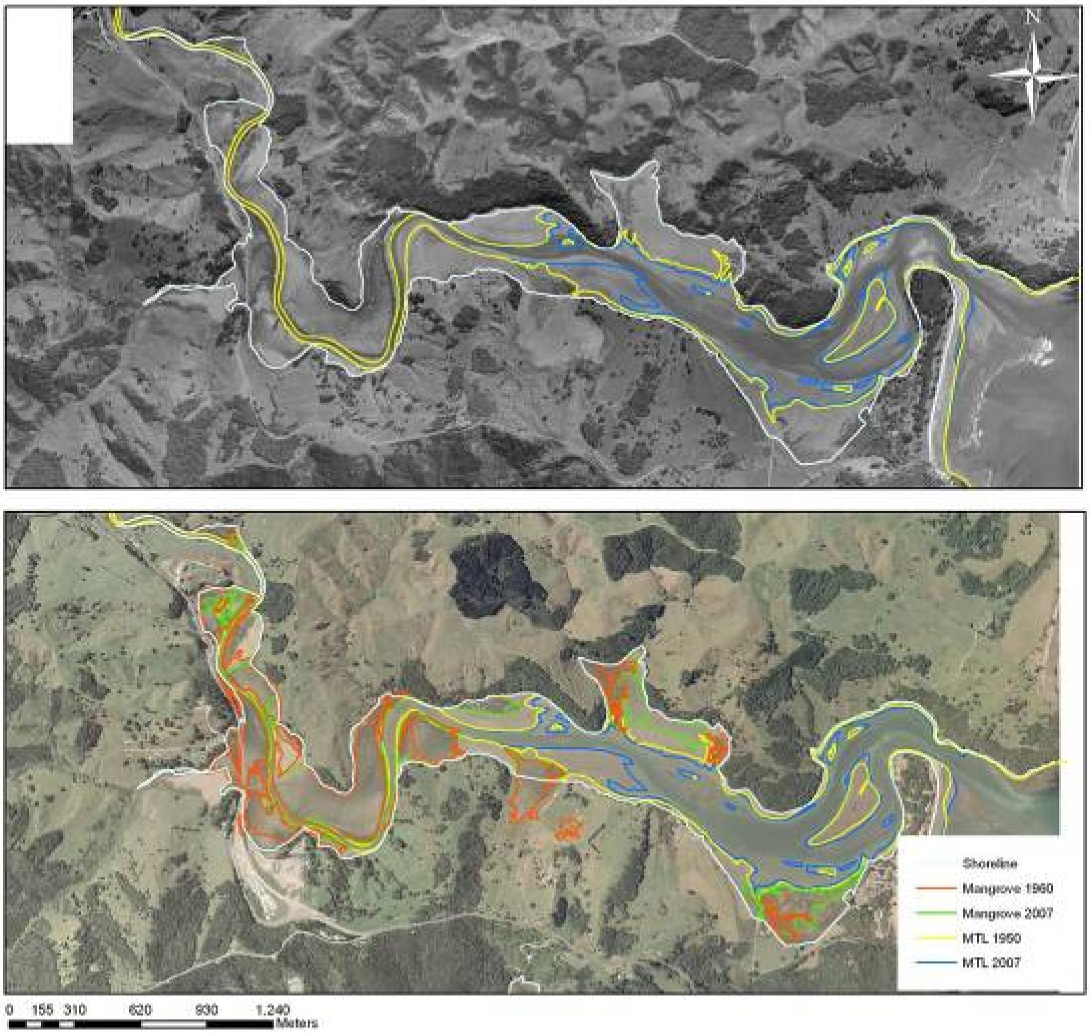


Figure 5.26:

Waiwera estuary. Historical (1960) and recent (2007) orthophotos of the estuary showing changes in mangrove forest areas and position of MTL-2007 and MTL-1950 isobaths.

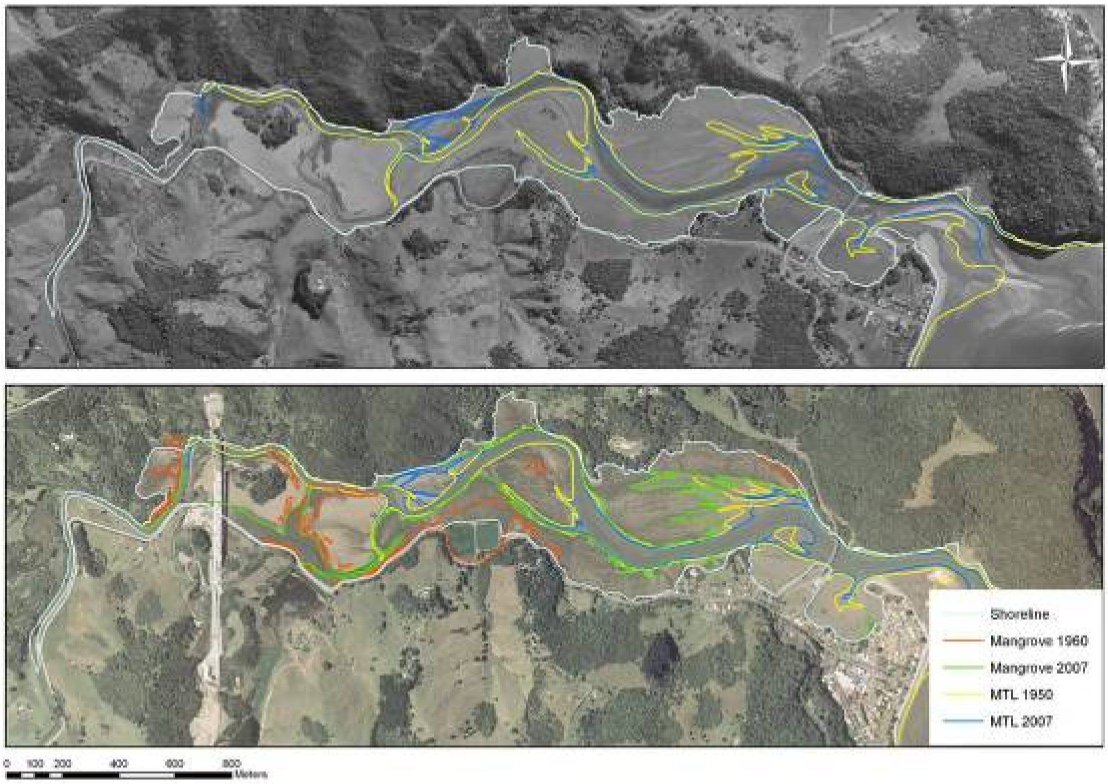
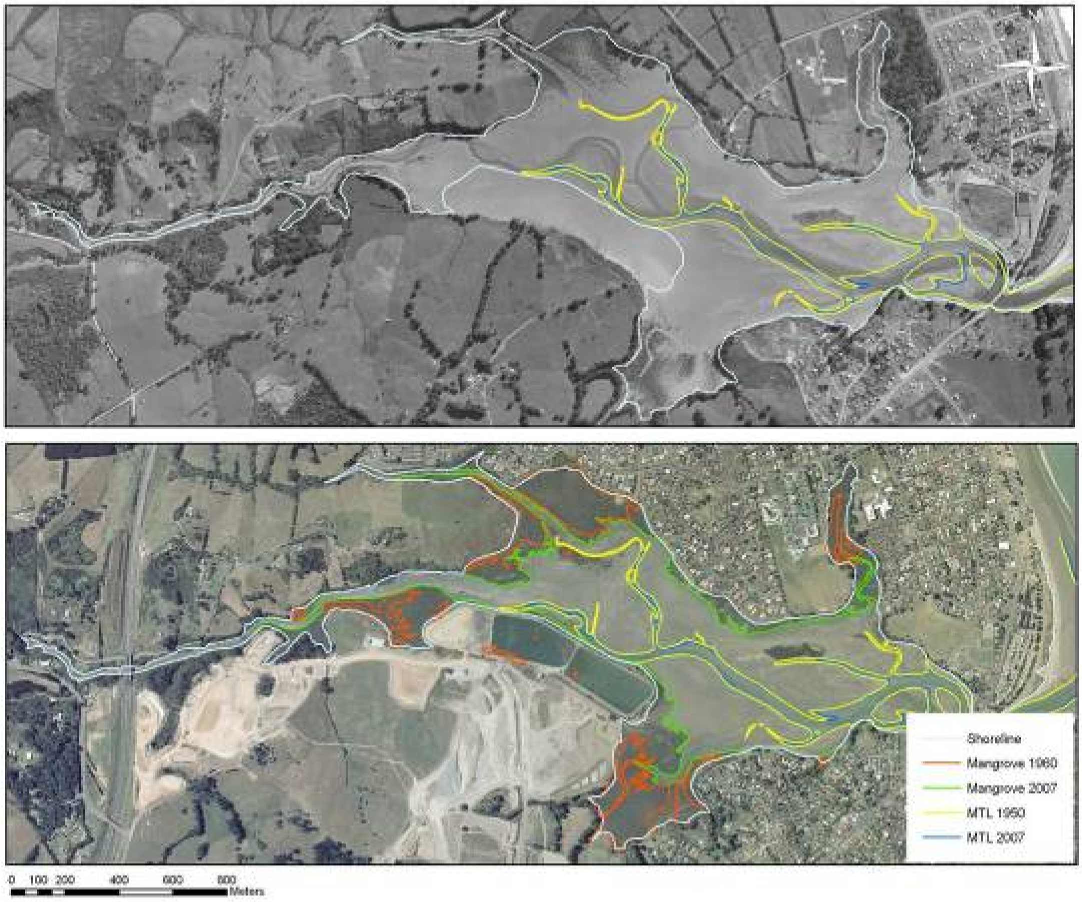


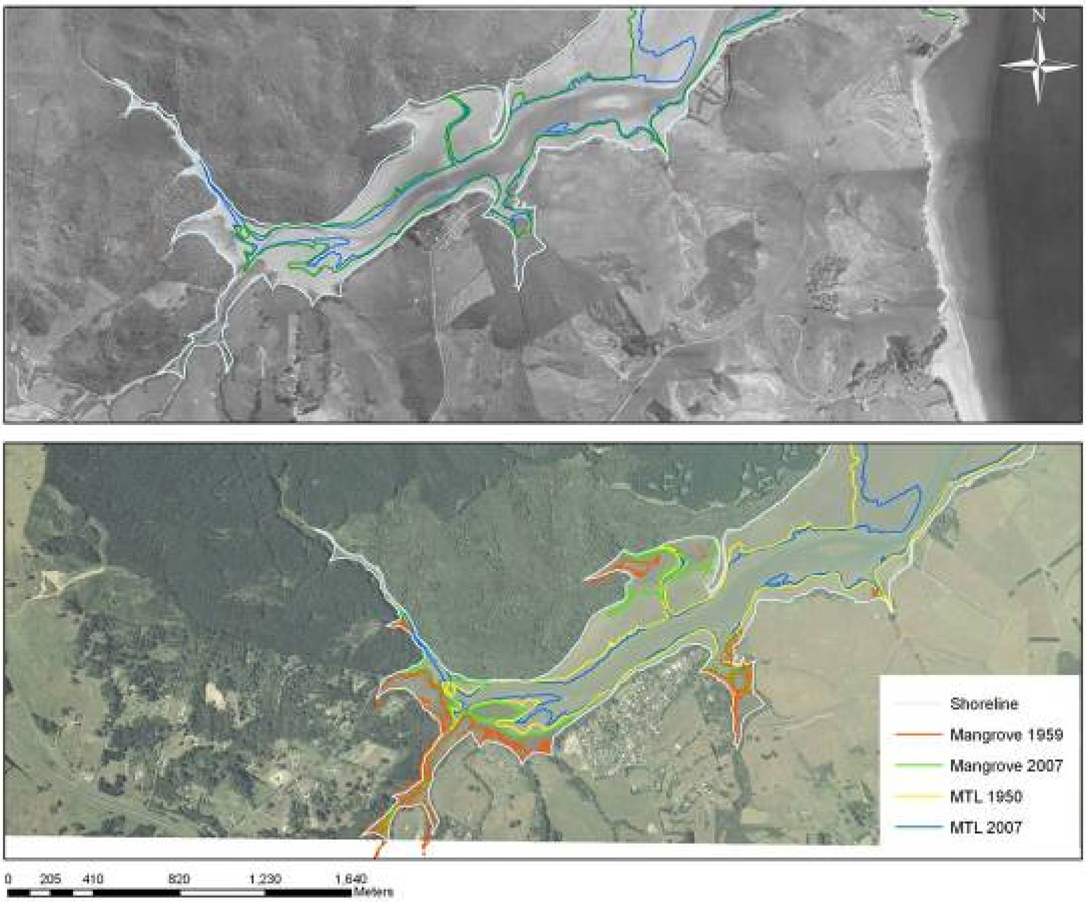
Figure 5.27:

Orewa estuary. Historical (1960) and recent (2007) orthophotos of the estuary showing changes in mangrove forest areas and position of MTL-2007 and MTL-1950 isobaths.



The pattern of mangrove colonisation of the Okura Estuary is similar to Puhoi and Orewa. The 1959 aerial photographs show that mangroves initially colonised tidal-flats at sub-catchment outlets and in the tidal creeks (Fig. 5.28). Over the last 50 years, mangrove stands at these sites have increased in size rather than new sites being established. The main sites of mangrove forest expansion have been in the upper estuary at the Awanohi Stream outlet and in the bay immediately landward of the shell bank in the middle estuary. To date, mangroves have not established on the extensive intertidal flats seaward of the of shell bank.

Figure 5.28:
Okura estuary. Historical (1960) and recent (2007) orthophotos of the estuary showing changes in mangrove forest areas and position of MTL-2007 and MTL-1950 isobaths.



Today, mangrove habitat in the Waitemata Harbour accounts for 32% of the total in Auckland's east coast estuaries. Most of the mangrove habitat in the region's largest east-coast estuary is located in the CWH (67%) west of the Te Tokaroa Reef (Point Chevalier. Mangroves first established in the tributary creeks that fringe the CWH, such as the Henderson Creek, Whau River, Pollen Island and Waterview Inlet (Fig. 5.29). The orthophotos show that mangrove have not substantially increased their distribution in the CWH since the late 1950s. This pattern is clearly seen in the large mangrove stands at the northern tip of the Te Atatu Peninsula, Whau River and Waterview Inlet. There has also been relatively little change in the position of the MTL isobath since 1950 so that the potential area for mangrove habitat expansion has also not increased. Thus, these mangrove stands today occupy almost all their potential habitat down to MTL.

Figure 5.29 :
Central Waitemata Harbour. Historical (1960) and recent (2007) orthophotos of the estuary showing changes in mangrove forest areas and position of MTL-2007 and MTL-1950 isobaths.

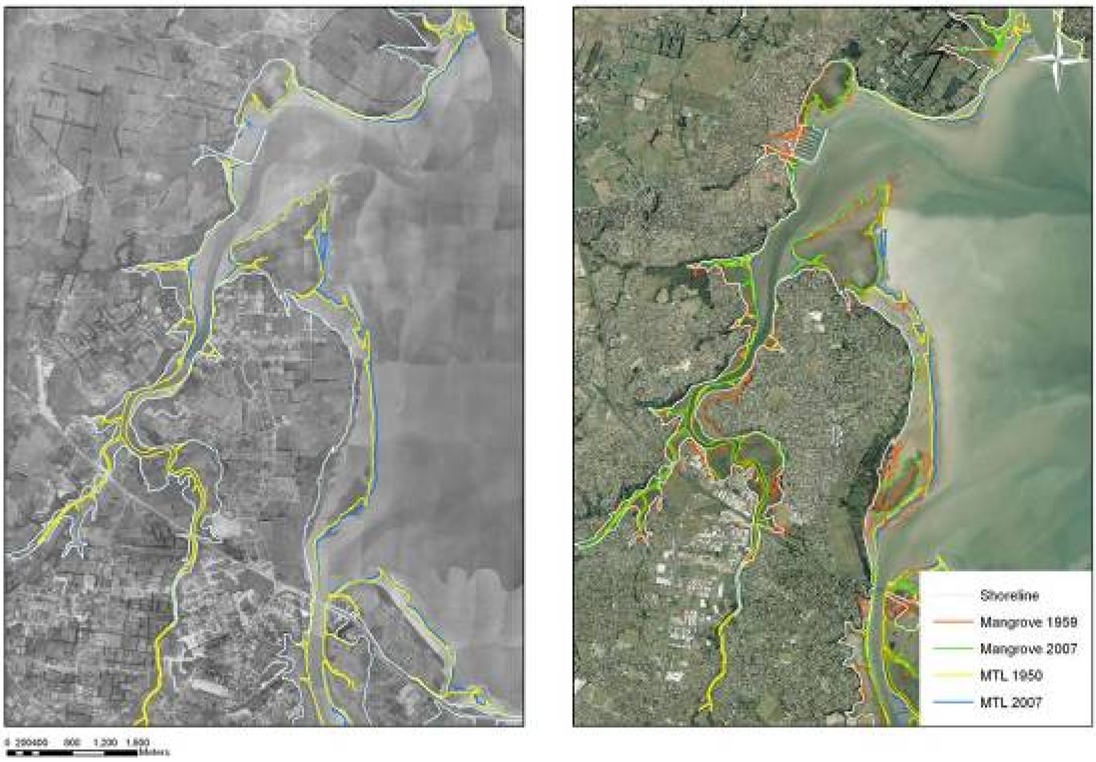
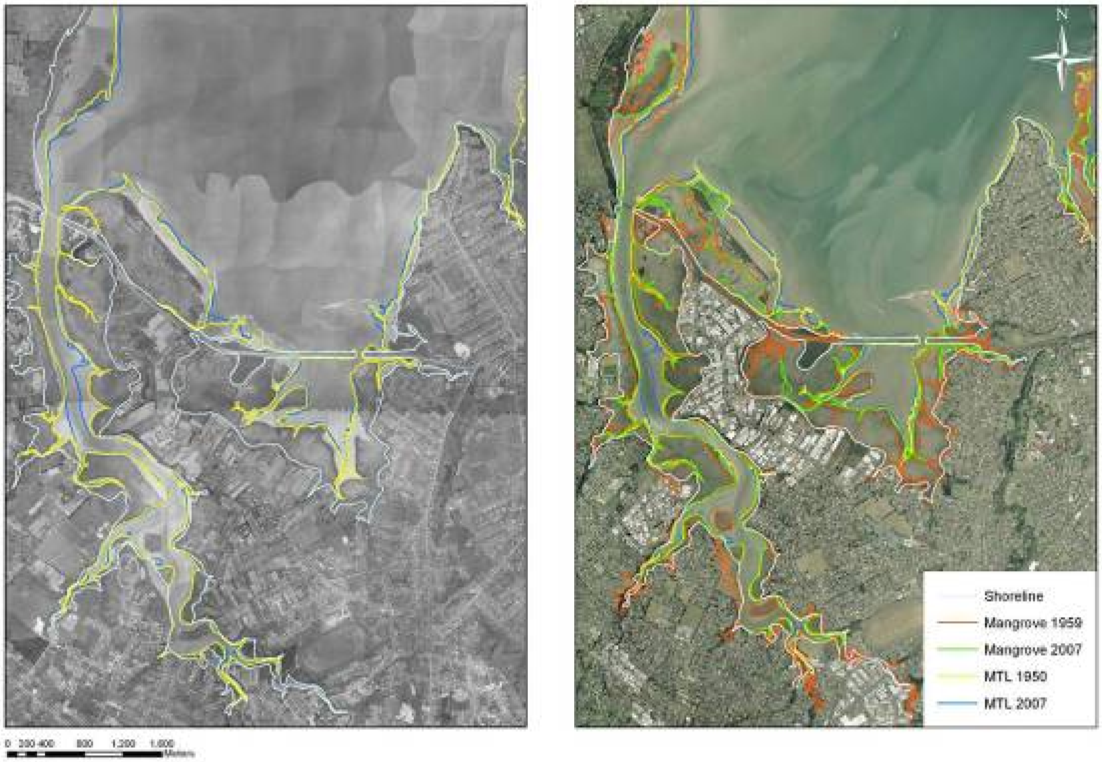


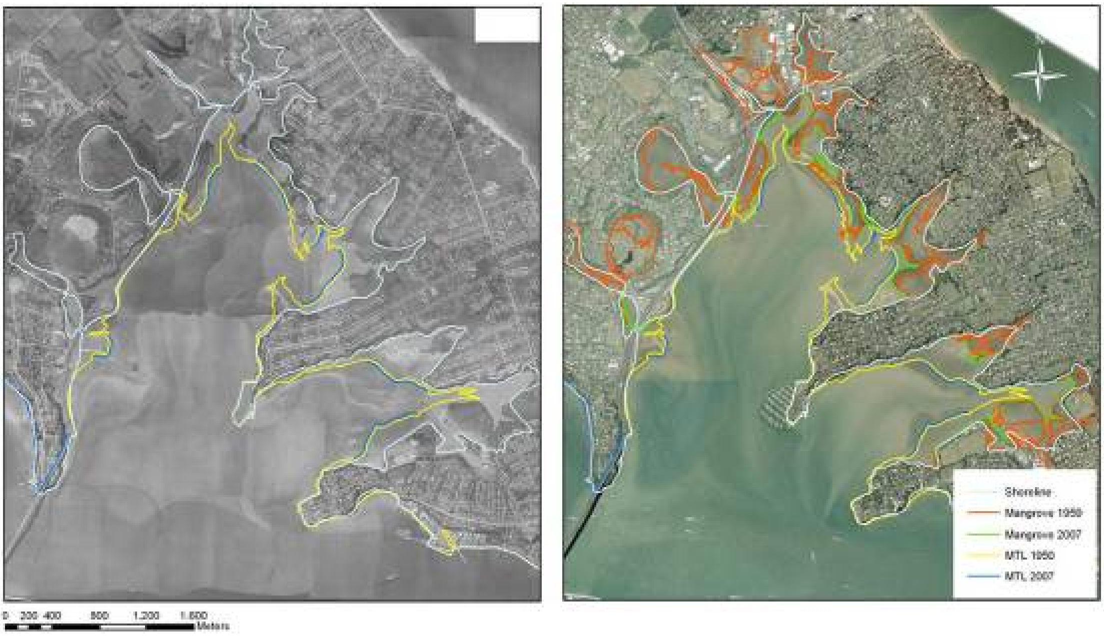
Figure 5.29b:

Central Waitemata Harbour. Historical (1960) and recent (2007) orthophotos of the estuary showing changes in mangrove forest areas and position of MTL-2007 and MTL-1950 isobaths.



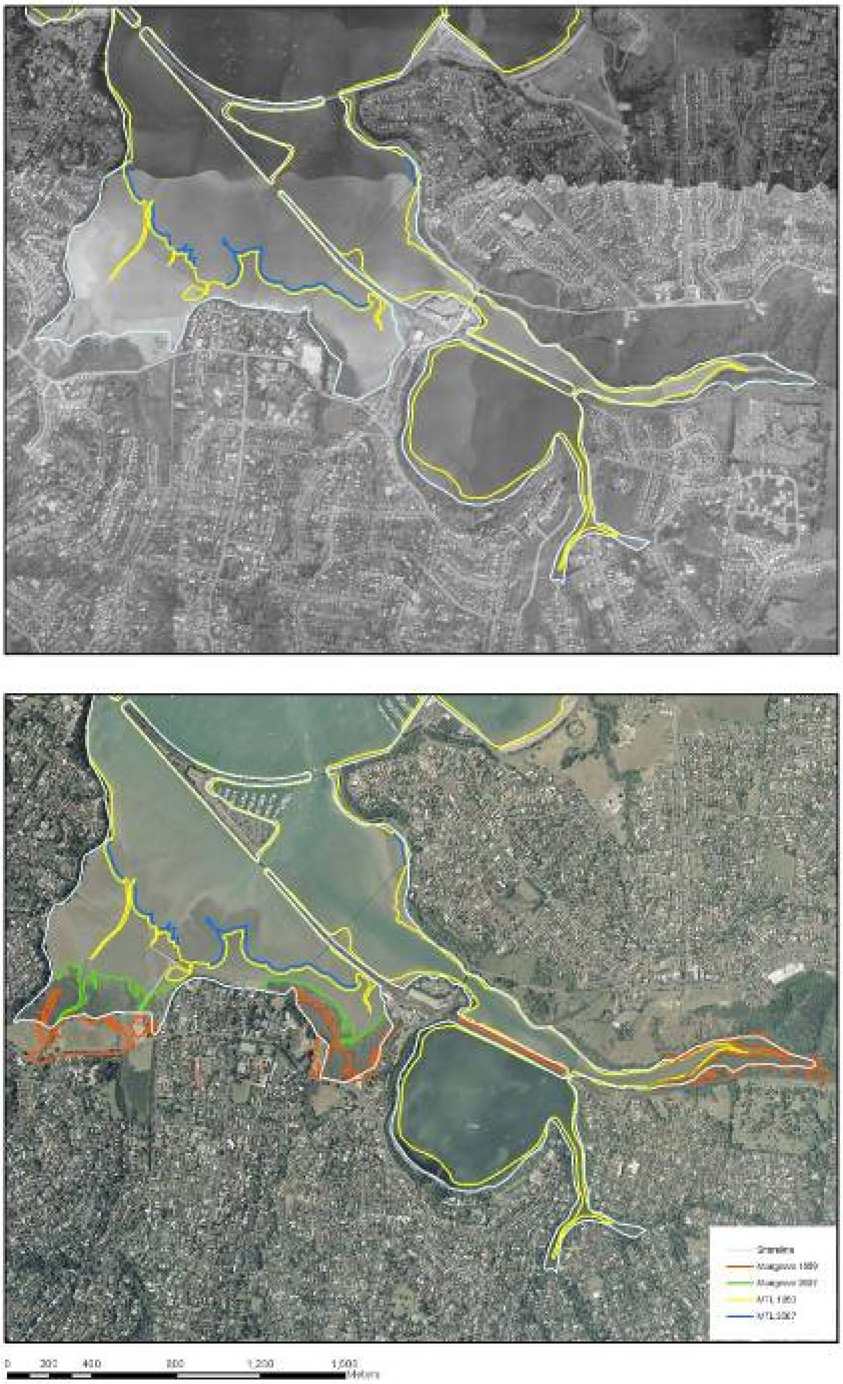
In Shoal Bay, substantial mangrove habitat loss (-6.7%) since the late 1950s can be attributed to reclamation of former mangrove habitat at the Onepoto Basin and former Barrys Point Road Refuse Facility (Fig. 5.30). Like many of the study estuaries, the orthophotos show that: (1) mangroves initially colonised tidal creeks fringing Shoal Bay; and (2) there have been negligible increases in mangrove-habitat extent since the late 1950s.

Figure 5.30:
Shoal Bay. Historical (1960) and recent (2007) orthophotos of the estuary showing changes in mangrove forest areas and position of MTL-2007 and MTL-1950 isobaths.



In Hobson Bay, mangrove-habitat loss has also occurred due to reclamation (Fig. 4.31). Although mangrove have colonized tidal flat seaward of the reclamation, most of their potential habitat above the MTL isobath has not been exploited.

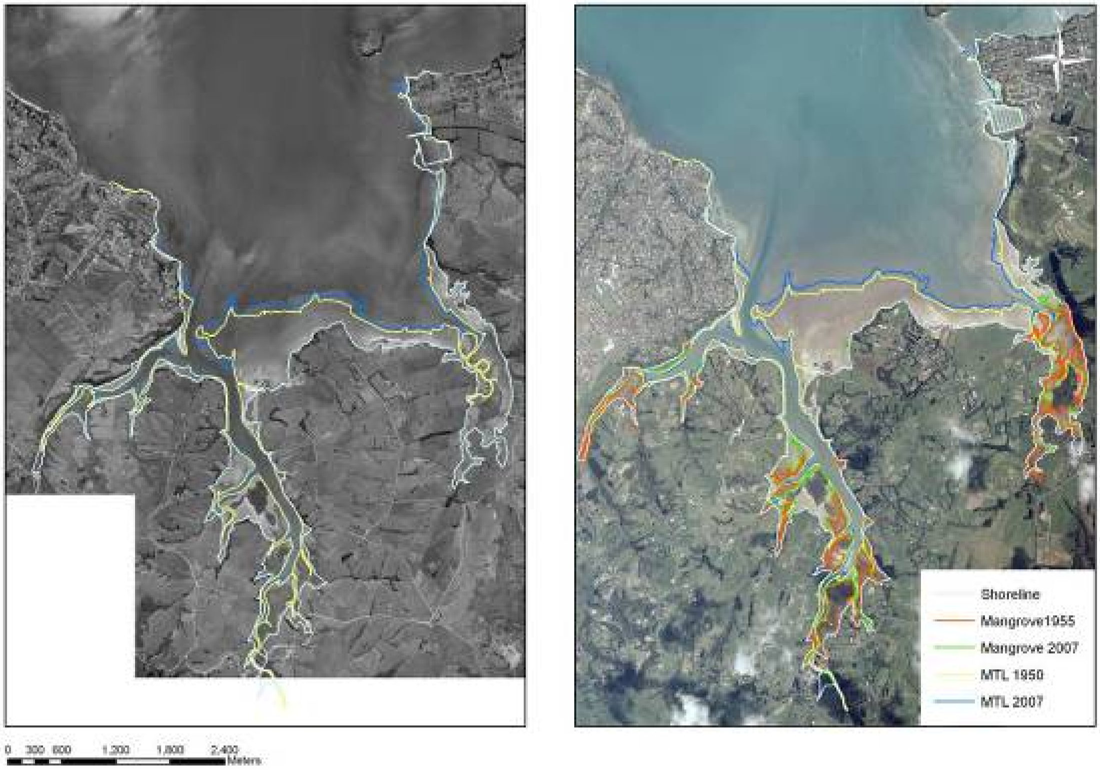
Figure 5.31:
Hobson Bay. Historical (1960) and recent (2007) orthophotos of the estuary showing changes in mangrove forest areas and position of MTL-2007 and MTL-1950 isobaths.



At Whitford, mangroves had extensively colonised the Mangemangeroa, Turanga and Waikopua Creeks by 1955 (Fig. 4.32). The ~50% increases in mangrove forest area in Whitford Bay since 1955 has occurred in these tidal creeks, with mangroves virtually absent from the extensive tidal flat that fringe the southern shore of the bay.

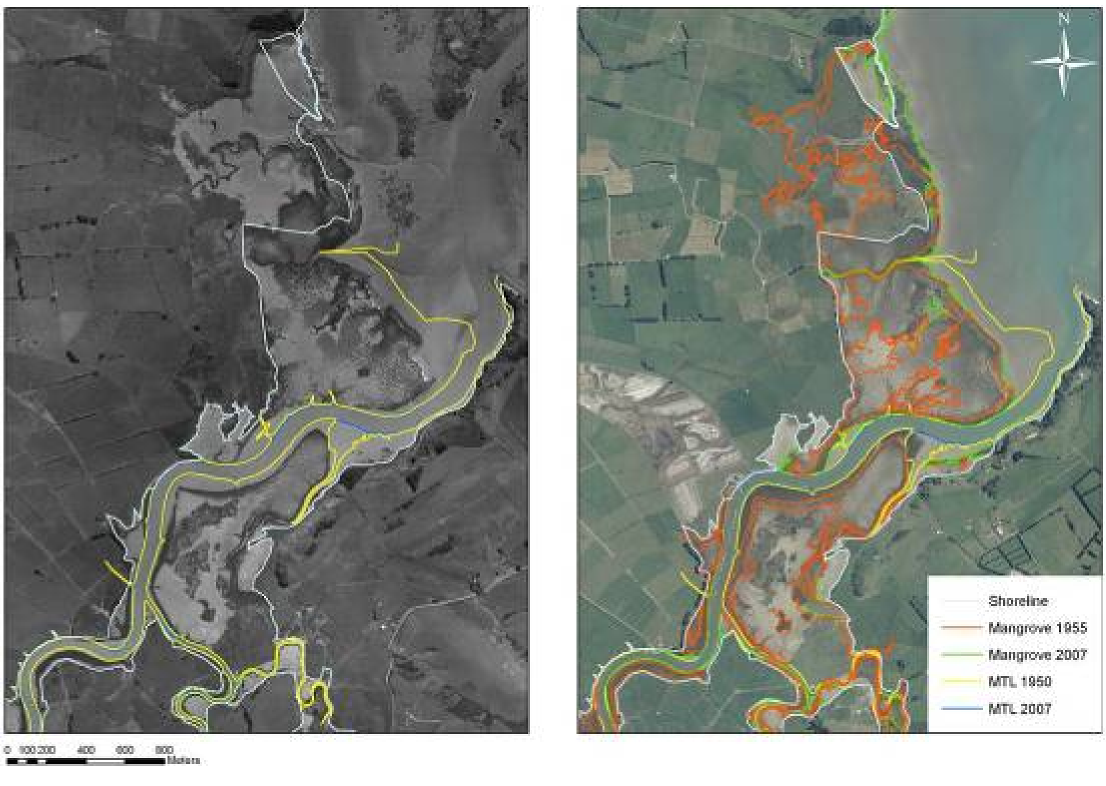
Figure 5.32:

Whitford Bay. Historical (1955) and recent (2007) orthophotos of the estuary showing changes in mangrove forest areas and position of MTL-2007 and MTL-1950 isobaths.



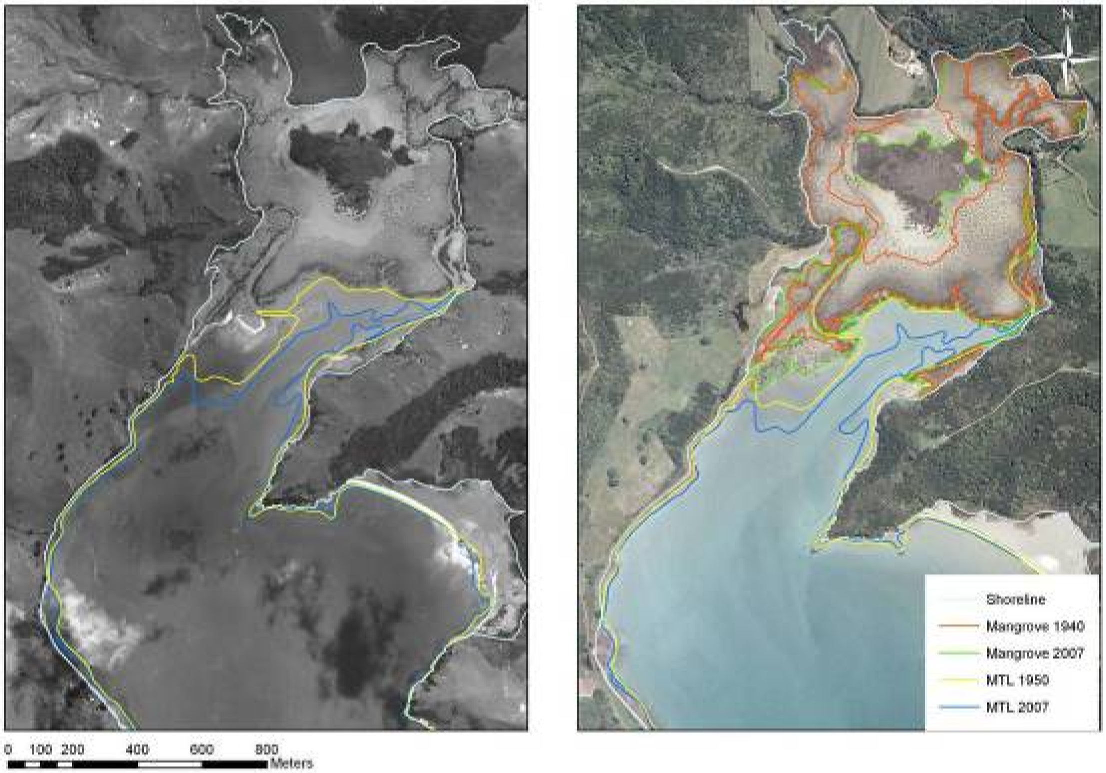
In the Wairoa Estuary, mangrove had almost entirely colonised the tidal flats by 1955 (Fig. 5.33). The mangrove cover is broken, with areas of low density and or dwarf mangrove landward of the largest mangrove trees on the seaward fringe of the forest. Comparison the aerial photographs show that seaward expansion of the mangrove forest has been negligible since 1955. The photos also indicate extensive loss of mangrove on tidal flats immediately north of estuary mouth the due to reclamation for farm land. In addition, large areas of estuarine plants that were present on the lower tidal flats north of Pouto Point in 1955 are absent in 2007. These plants are likely to be former seagrass (*Zostera* spp.) beds because of their elevation in the lower intertidal/shallow subtidal zone. The other potential candidate plant is the invasive cordgrass *Spartina anglica*, which was introduced to New Zealand in the early 1900s (Lee and Partridge, 1983). *S. anglica* occupies a wide zone in the intertidal, which extends below the elevation of native saltmarsh species and forms characteristic circular patches which grow in size through seasonal radial extension or rhizomes. Seagrass also displays a radial growth form so that we cannot conclusively identify the plant species from the small-scale black and white 1955 orthophoto.

Figure 5.33:
Wairoa Estuary. Historical (1955) and recent (2007) orthophotos of the estuary showing changes in mangrove forest areas and position of MTL-2007 and MTL-1950 isobaths.



At Te Matuku Bay (Waiheke Island), mangrove had also colonised tidal flats near the catchment outlets and occupied most of the area above MTL by 1940 (Fig. 5.34). As observed in other Auckland estuaries, the density and/or size of mangrove trees has increased since 1940. Mangroves have also colonized areas of bare tidal flat landward of the tallest trees on the seaward fringe of the forest. However, the seaward extent of the mangrove forest has not substantially increased since 1940, despite intertidal sedimentation rates of 4.2 – 8.7 mm yr^{-1} that exceed the regional average value (Swales et al. 2002a). This rapid sedimentation has extended the MTL-2007 isobath up to 150 m seaward of its 1950 position, although none of this additional new habitat has been colonised by mangroves.

Figure 5.34:
Te Matuku Bay. Historical (1955) and recent (2007) orthophotos of the estuary showing changes in mangrove forest areas and position of MTL-2007 and MTL-1950 isobaths.



5.7.3 Validation of the hindcast MTL-1950 isobath

Comparison of the MTL-1950 isobath with the actual distribution of mangroves recorded by the historical orthophotos can be used to assess how well the hindcast predicted the lower elevation limit of mangrove trees at that time. The analysis presented in section 5.7.2 showed that substantial areas of intertidal habitat above MTL have not been colonised over the last 50 years or so. This was explained in terms of wave exposure effects as observed in previous studies, although our ability to predict, at a local scale, intertidal areas that will be colonised by mangrove is limited (section 5.4.1). However, we would not expect to see mangroves growing below the

MTL-1950 isobath if our hindcast of the estuary bathymetry at that time is reasonably accurate so that our validation of the methodology is based on this basic test (i.e., no mangroves below MTL-1950).

How accurately the hindcast MTL-1950 isobath matches the actual bathymetry of the estuaries at that time depends on several factors: (1) the vertical change in tidal-flat elevation is a function of sedimentation and sea-level rise; (2) how well the digital elevation models describes the"present-day" intertidal surface; (3) the assumption that the past bathymetry mirrors the present-day bathymetry so that changes over time are due mainly to spatially uniform changes in surface elevation. This is a reasonable assumption for uniform, gently-sloping intertidal flats whereas surface slopes change rapidly close to tidal channels. Although SAR on intertidal flats vary spatially, the average value of 3.8 mm yr^{-1} adopted in this study is robust and represents the best available dataset for Auckland's east-coast estuaries (section 4.3). Hydrodynamic modeling also shows that tidal amplification has a minor influence on the position of the MTL isobath in comparison to SLR (section 5.5) so that this hydrodynamic factor can largely be ignored. Together these primary factors influence the local change in the MTL position between 1950 and 2007.

The validation is also complicated by the fact that the actual dates of the historical photos span the time period 1940–1960, rather than tightly constrained to the baseline 1950 hindcast.

Despite these limitations, the historical orthophotos of the selected estuaries (Figs 5.25–5.34) show that mangrove stands do not extend below the hindcast MTL-1950 isobath. In some cases the actual seaward boundary of mangrove forests closely coincides with the MTL-1950, such as in the Puhoi, Wairoa and Te Matuku Estuaries and Waitemata Harbour. Where mangrove forests fringe tidal creeks, the horizontal position of the MTL isobath is less sensitive to vertical changes in surface elevation due to the steeply sloping creek banks (section 4.8). The most severe test of the MTL hindcast is on gently sloping intertidal flats because cm-scale changes in surface elevation can translate into tens of metres of horizontal change in the MTL isobath position. In all of the estuaries where historical orthophotos were obtained, mangrove stands do not occur below the hindcast MTL-1950 isobath. This indicates that we can have some confidence in the methodology as applied to predictions of future changes in the MTL isobath under Scenarios 1–3 (while still acknowledging the assumptions and limitations of the method). The MTL isobaths predicted under these scenarios therefore represent our best estimate of the maximum potential extent of mangrove habitat in the future.

5.8 Future changes in potential mangrove habitat

Predictions of potential future changes in mangrove habitat by the 2050s and 2090s due to sea-level rise (SLR) and estuary sedimentation indicate:

- increases in potential mangrove habitat given that the historical SLR trend observed at Port of Auckland continues over the next century (Scenario One, section 3.3.4);

- reductions in potential mangrove habitat under scenarios two and three (section 3.3.4), which are based on IPCC (2007) projections (Scenarios Two and Three).

These projections indicate rates of sea-level rise over the next century that are several times higher than the historical trend.

The primary reason for these different predicted outcomes is that under scenarios two and three the rate of sea-level rise in the future will exceed sedimentation rates in Auckland's east coast estuaries (section 4.8). The main exception to this pattern is that higher sediment accumulation rates in tidal creeks are likely to more than compensate for any future increases in SLR rates. The implications of this scenario for future changes in mangrove habitat distribution are discussed in section 6.

Figures 5.35–5.36 summarise the predicted changes in tidal-flat areas above MTL for the 2050s and 2090s for each of the three SLR scenarios. Predicted changes in tidal-flat areas above MTL by the 2050s are:

- Scenario One (historical trend, $SLR_{0.14m}$ by 2090s): increase in potential mangrove habitat averaging 8% (range 0 to 26%).
- Scenario Two ($SLR_{0.47m}$ by 2090s): decrease in potential mangrove habitat averaging -3.7% (range -0.8 to -8.5%).
- Scenario Three ($SLR_{0.77m}$ by 2090s): decrease in potential mangrove habitat averaging -10.6% (range -3.2 to -20.6%).

Predicted changes in tidal-flat areas above MTL by the 2090s are:

- Scenario One: increase in potential mangrove habitat averaging 14.4% (range 0.2 to 46%).
- Scenario Two: decrease in potential mangrove habitat averaging -10.2% (range -3 to -20%).
- Scenario Three: decrease in potential mangrove habitat averaging -27% (range -8 to -55%).

An assessment of the likelihood of large-scale mangrove-habitat expansion in each estuary is also provided. This is based on the long-term historical wave climate, probabilities of sand entrainment (P_E, sand) and availability of suitable intertidal habitat above MTL. Full details of the wave modeling are presented by Gorman & Swales (2009).

Although large decreases in potential mangrove habitat are predicted to occur by the 2090s under Scenario Three, these reduced intertidal habitats above MTL will still exceed the present-day (2007) area of mangrove in most estuaries. In particular, the MTL 2090s areas in each estuary represent 89% to 330% (average 167%) of intertidal flat occupied by mangroves in 2007. Only in the Matakana Estuary is the intertidal area above MTL likely to be less than the present area of mangrove forest. However, under Scenarios Two and Three, mangrove loss is likely to occur locally. This is because sea-level rise will out-pace sedimentation and mangroves presently occupying tidal flat down to MTL-2007 will be progressively lost as the MTL isobath retreats up the tidal flat.

Figure 5.35:
Predicted changes in potential mangrove habitat area above mean tide level (MTL) by the 2050s for the historical trend and IPCC sea-level rise scenarios with an average sediment accumulation rate of 3.8 mm yr^{-1}: (a) tidal flat area above MTL-2007 and (b) change in area above MTL expressed as a percentage of the MTL-2007 area. Note: Scenario One is the historical trend ($SLR_{0.14m}$ by 2090s). Scenarios Two ($SLR_{0.47m}$ by 2090s) and Three ($SLR_{0.77m}$ by 2090s) are based on IPCC (2007) SLR projections.

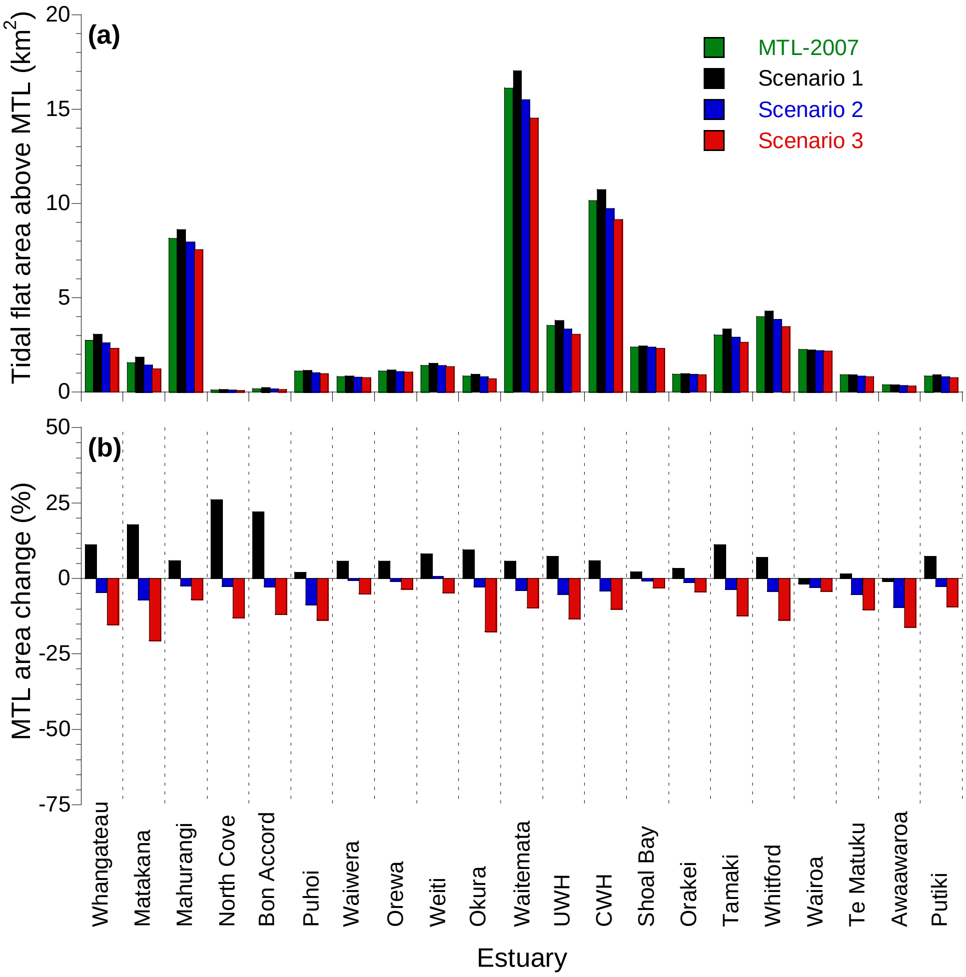
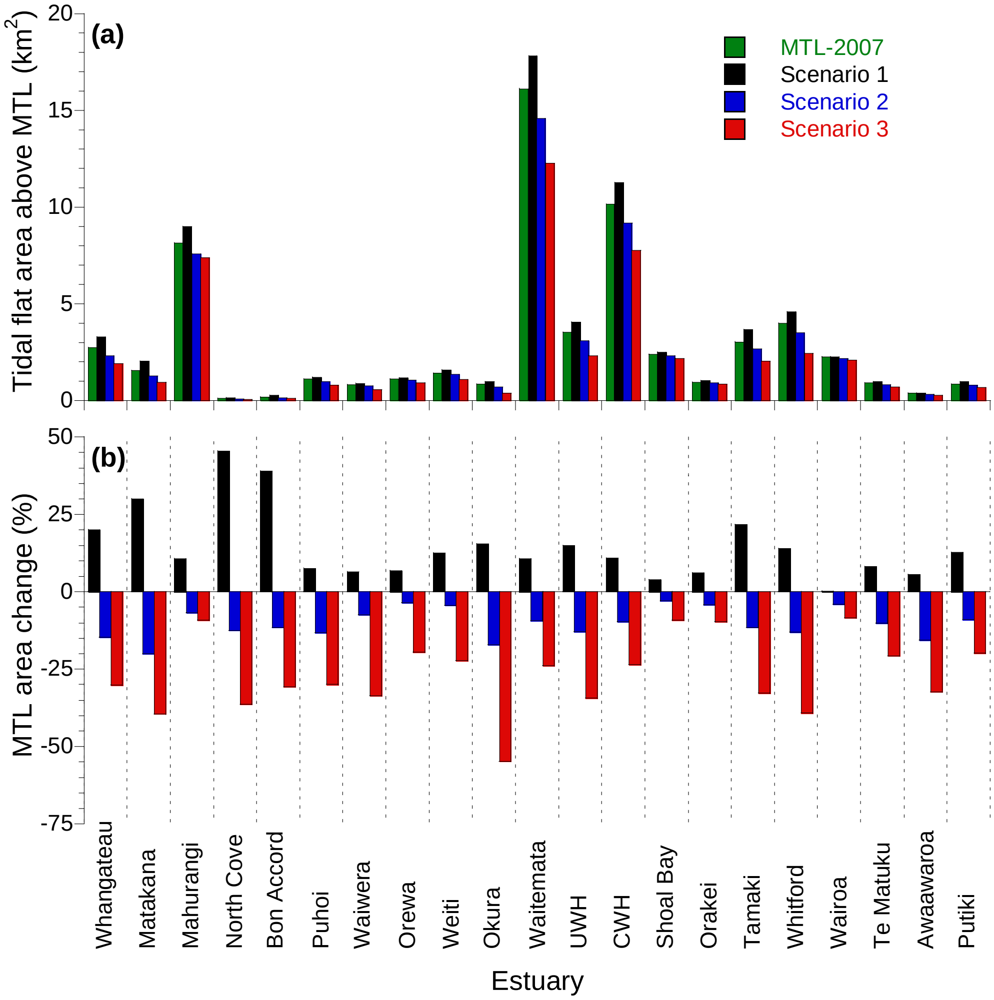


Figure 5.36:
Predicted changes in potential mangrove habitat area above mean tide level (MTL) by the **2090s** for the historical trend and IPCC sea-level rise scenarios with an average sediment accumulation rate of 3.8 mm yr^{-1}: (a) tidal flat area above MTL and (b) change in area above MTL expressed as a percentage of the MTL-2007 area. Note: Scenario One is the historical trend ($SLR_{0.14m}$ by 2090s). Scenarios Two ($SLR_{0.47m}$ by 2090s) and Three ($SLR_{0.77m}$ by 2090s) are based on IPCC (2007) SLR projections.



Figures 5.37 – 5.81 show the changes in potential mangrove habitat above MTL in each study estuary that are predicted to occur by the 2050s and 2090s for the SLR scenarios considered:

- blue line: present-day position of the mean tide level, MTL-2007;
- yellow line: MTL position for historical trend scenario one ($SLR_{0.14}$ by 2090s);
- orange line: MTL position for scenario two ($SLR_{0.47}$ by 2090s);
- red line: MTL position for scenario three ($SLR_{0.77}$ by 2090s).

In the following sections, we make assessments of the likelihood of future mangrove habitat expansion in each of the study estuaries based on:

- the relative likelihood of mangrove seedling establishment on intertidal flats fringing present-day mangrove stands. This assessment is based on the probability of fine sand entrainment (P_E) under the existing wave climate (Gorman and Swales, 2009). A conservative approach is adopted to estimate the likelihood of seedling establishment as follows:

  High likelihood: P_E (sand) ≤ 10%;

  Medium likelihood: P_E (sand) 10–25%;

  Low likelihood: P_E (sand) ≥ 25%;

- changes in the position of the MTL isobath due to the net effect of estuary sedimentation and projected increases in sea level under Scenarios 1–3. Note that in some estuaries, future changes in the MTL isobath position may encroach on present-day (i.e., 2007) mangrove stands so that mangrove-habitat loss will occur;

5.8.1 Whangateau Estuary (Omaha)

Figures 5.37 and 5.38 map changes in potential and existing mangrove habitat in the Whangateau Estuary that are predicted to occur over the next century under SLR Scenarios 1–3. It should be noted that:

- a DEM was not available for the Whangateau Estuary. Changes in MTL position are calculated as constant horizontal offsets based on average tidal flat slope measured in the main body of the estuary. Surface slopes in the tidal creeks will be more spatially variable and higher than on the open tidal flats, so these sub-environments are excluded from the analysis;
- we have no quantitative SAR data for the estuary so that we cannot determine to what extent the predictions may differ from the estuary-average SAR of 3.8 mm yr^{-1}.

The results of the assessment for Whangateau Estuary indicate:

- mangroves presently occupy 51% of their potential habitat above MTL-2007 in the Whangateau Estuary. The estuary has a medium level of vulnerability to sediment infilling, with an estuary infill time (T_A) of ~900 years (section 5.1);
- mangrove occupy most of the tidal flat above MTL-2007 in the Omaha River, so are potentially vulnerable to future changes in MTL position. This maybe mitigated by rapid sedimentation, as observed in tidal creeks elsewhere in the region (i.e., 20 mm yr^{-1} over last 50 years). In this case future sedimentation would more than compensate for accelerated sea-level rise under the scenarios considered in this study. Also, steep channel-bank slopes in tidal creeks result in relatively minor changes in MTL position, of the order of metres. By comparison, MTL positions will shift by 10s–100s of metres on the gently sloping tidal flats in the estuary;

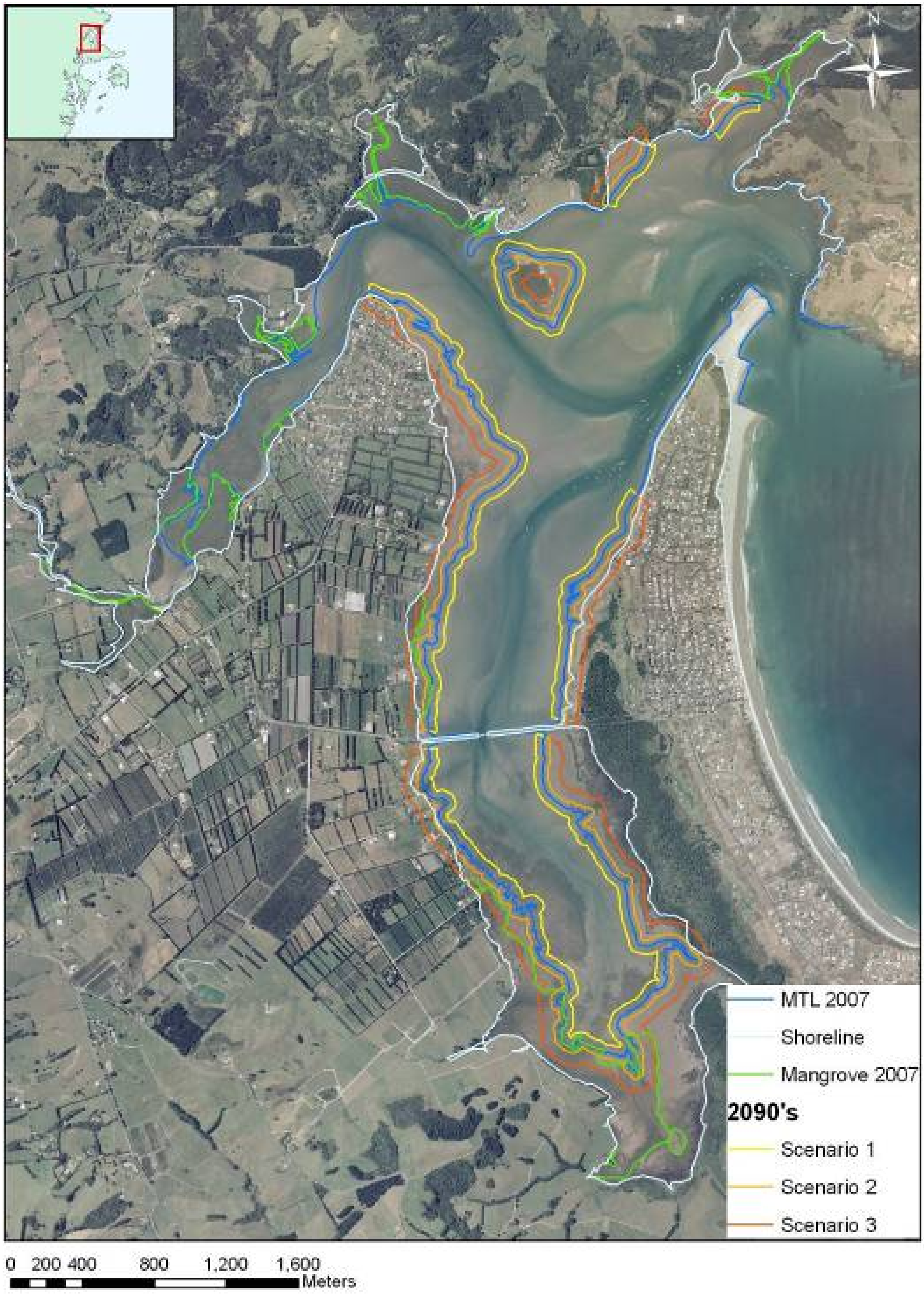
- a medium to low likelihood of mangrove seedling establishment in the Whangateau Estuary under the existing wave climate;
- changes in the MTL isobath position under Scenarios Two ($SLR_{0.47m}$) and Three ($SLR_{0.77m}$) would result in loss of existing mangrove habitat along the west and southern shores of the estuary. In particular, existing mangrove stands south of the causeway that extend down to the MTL-2007 isobath are vulnerable. Large-scale loss of mangrove stands in the Whangateau is not likely to occur until after the 2050s;
- a medium to low likelihood of large-scale mangrove-habitat expansion in the Whangateau Estuary during the next century based on: the existing wave climate; availability of suitable intertidal habitat; and future SLR scenarios.

Figure 5.37:

Whangateau Estuary - 2050s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2050s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).

Figure 5.38:

Whangateau Estuary - 2090s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2090s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).



5.8.2 Matakana Estuary

Figures 5.39 and 5.40 map changes in potential and existing mangrove habitat in the Matakana Estuary that are predicted to occur over the next century. A DEM was used to predict changes in the MTL position under SLR Scenarios 1–3. In many parts of the Matakana estuary, mangroves occur down to the MTL-2007 isobath so that they are vulnerable to the effects of rising sea level.

The results of the assessment for Matakana Estuary indicate:

- mangroves presently occupy 68% of their potential habitat above MTL-2007 in the Whangateau Estuary. The estuary has a high level of vulnerability to sediment infilling, with an estuary infill time (T_A) of ~500 years (section 5.1);
- a medium to low likelihood of mangrove seedling establishment in the Matakana Estuary under the existing wave climate;
- large increases in potential mangrove habitat are predicted to occur under Scenario One ($SLR_{0.14m}$) in the shallow eastern arm of the estuary. Reductions in tidal-flat area above MTL under Scenarios Two ($SLR_{0.47m}$) and Three ($SLR_{0.77m}$) will result in large-scale loss of existing mangrove stands in the estuary. This is unlikely to occur until sometime after the 2050s. Changes in mangrove habitat areas in the tidal creeks are negligible;
- a medium to low likelihood of large-scale mangrove-habitat expansion in the Matakana Estuary during the next century based on: the existing wave climate; availability of suitable intertidal habitat; and future SLR scenarios.

Figure 5.39:

Matakana Estuary - 2050s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2050s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (Section 3.3.4).

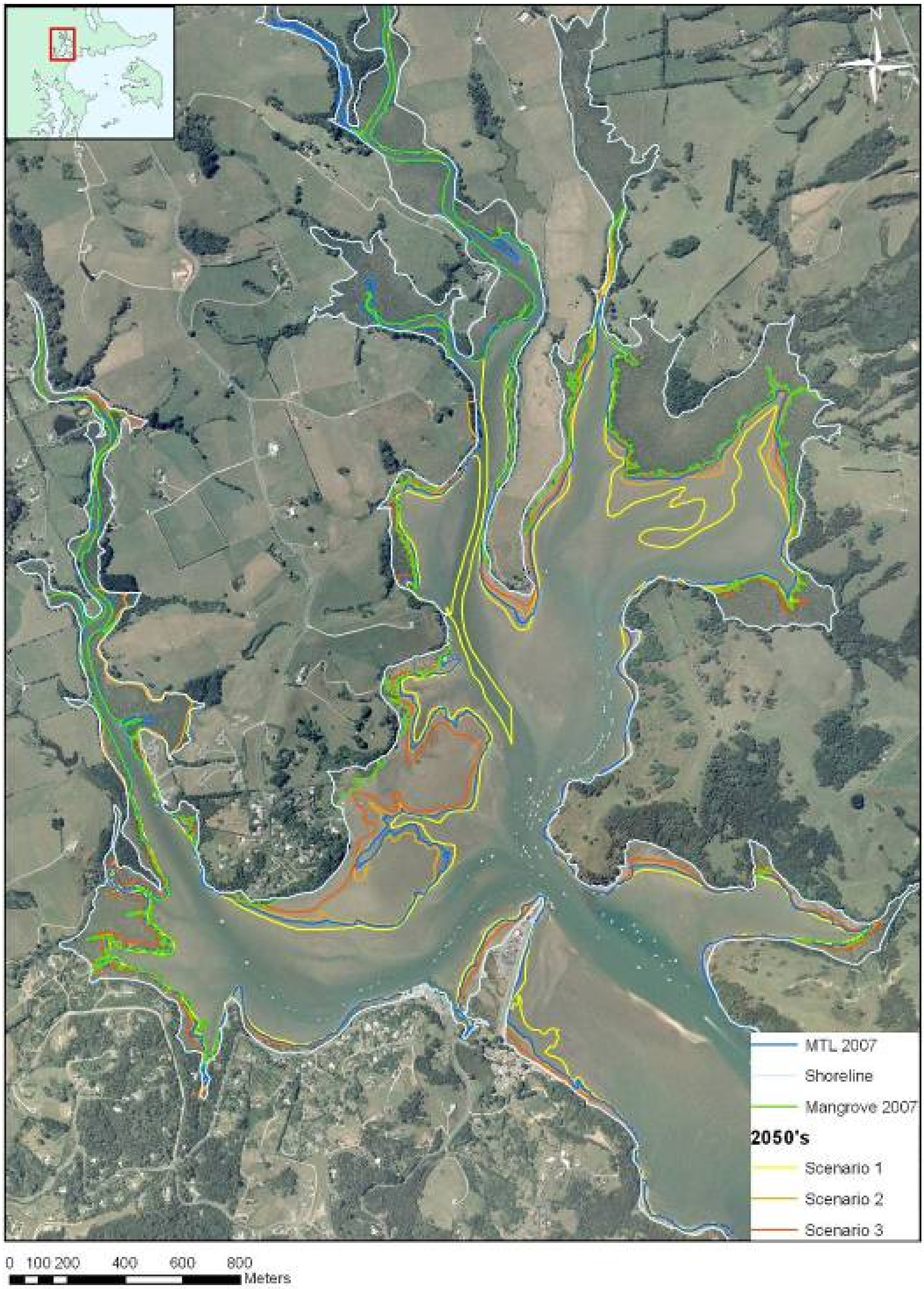
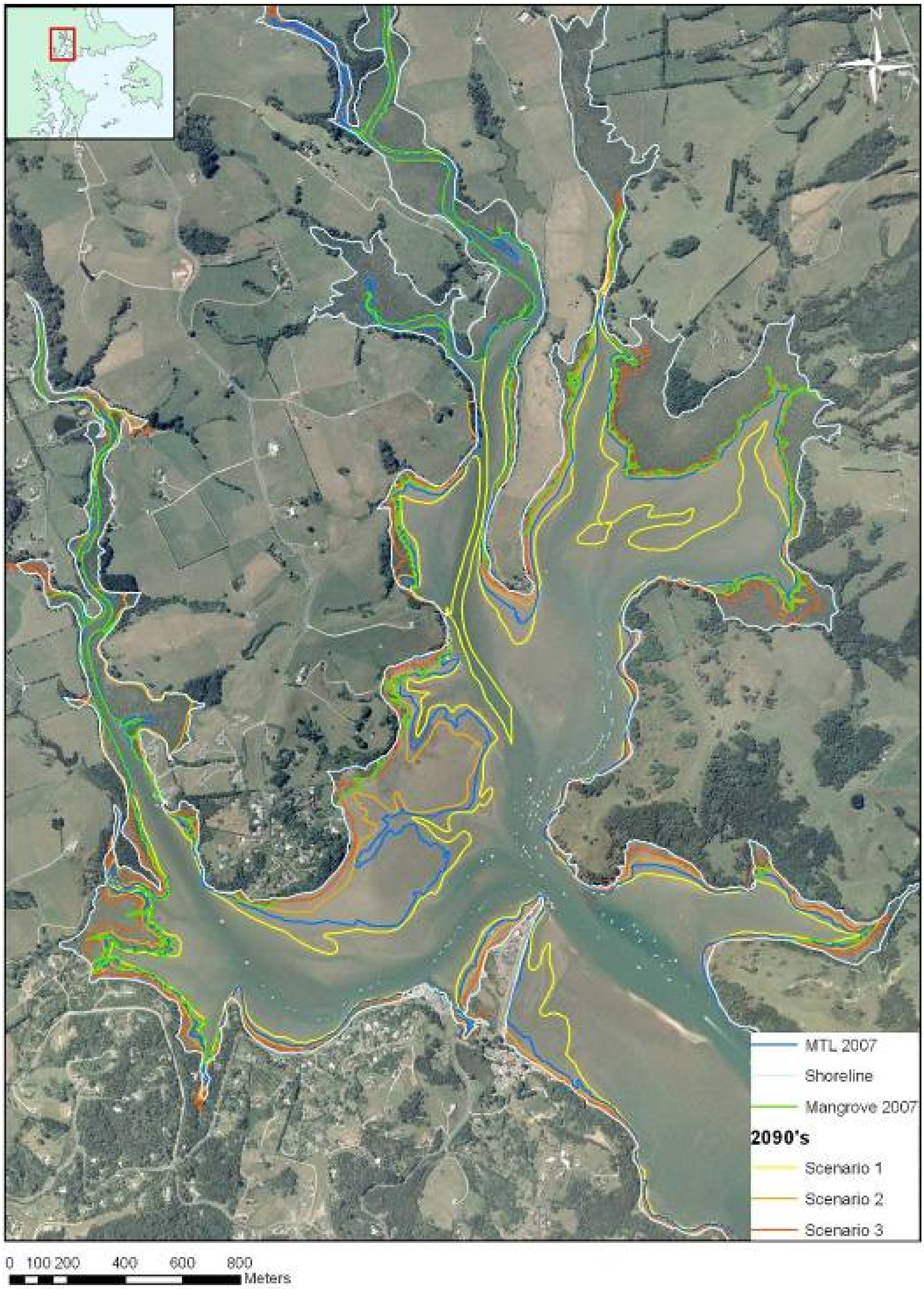


Figure 5.40:

Matakana Estuary - 2090s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2090s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).



5.8.3 North Cove and Bon Accord (Kawau Island)

Figures 5.41 and 5.42 map changes in potential and existing mangrove habitat in the North Cove and Bon Accord Estuaries, which are predicted to occur over the next century under SLR Scenarios 1–3. Mangroves occupy delta deposits at the heads of these mainly subtidal estuaries. Both systems have low potential for sediment infilling due to relatively low sediment loads from mainly native bush/scrub catchments (section 5.1) and isolation from mainland sediment sources.

The results of the assessment for North Cove and Bon Accord Estuaries indicate:

- mangroves presently occupy 29% and 22% of their potential habitat above MTL-2007 in North Cove and the Bon Accord Harbour respectively. These estuaries have a low level of vulnerability to sediment infilling, with an estuary infill time (T_A) of ~6,700 (NC) and ~10,700 (BA) years (section 5.1);
- because of the limited intertidal area available above MTL, there is limited potential for future mangrove-habitat expansion under SLR Scenario One ($SLR_{0.14m}$). Loss of existing mangrove stands are unlikely to occur until after the 2050s;
- a low likelihood of mangrove seedling establishment in the North Cove and the Bon Accord Estuaries under the existing wave climate;
- there is a low likelihood of large-scale mangrove-habitat expansion in the North Cove and the Bon Accord Estuaries during the next century based on existing wave climate; availability of suitable intertidal habitat and future SLR scenarios.

Figure 5.41:

North Cove and Bon Accord, Kawau Island - 2050s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2050s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).

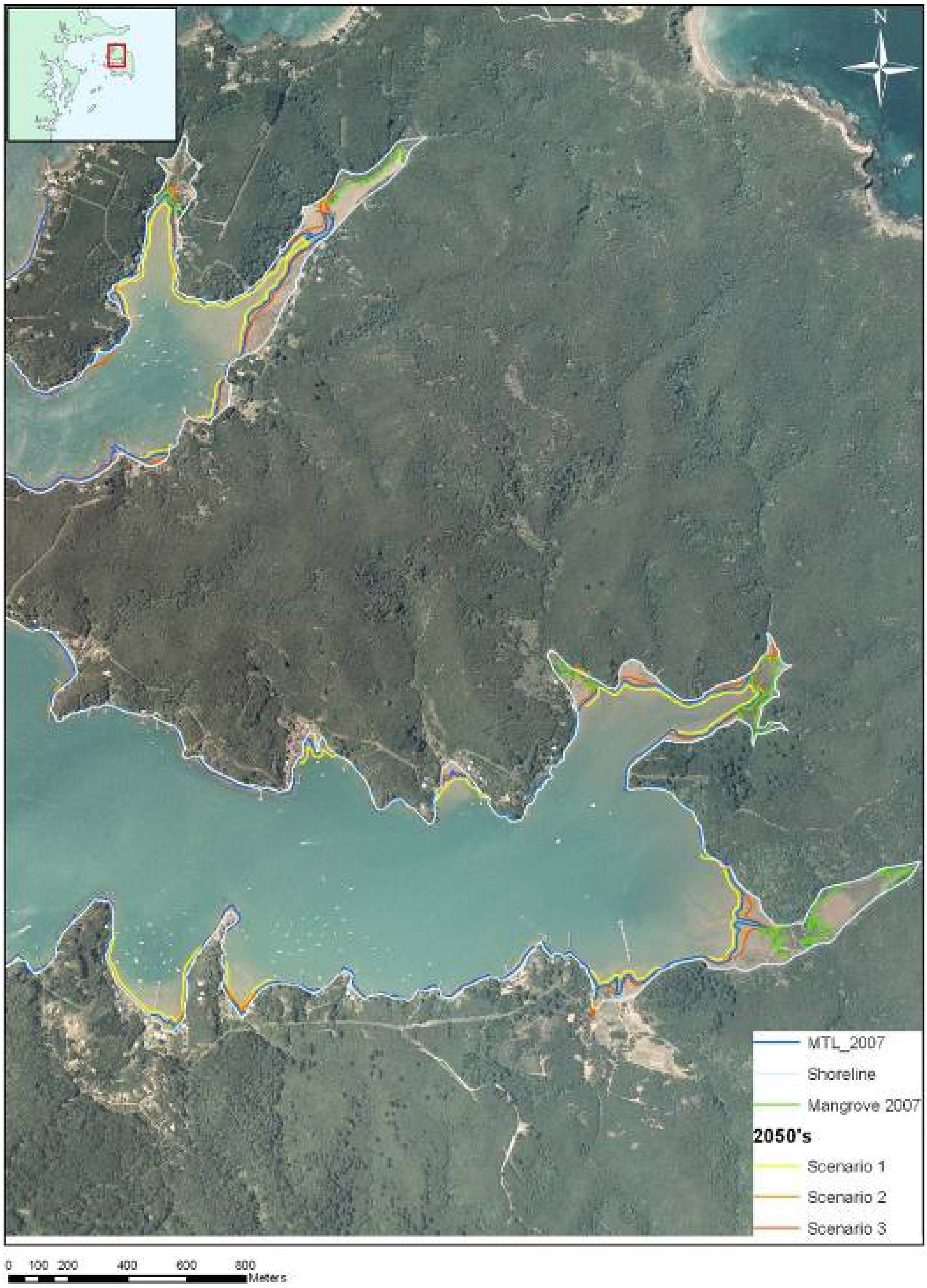
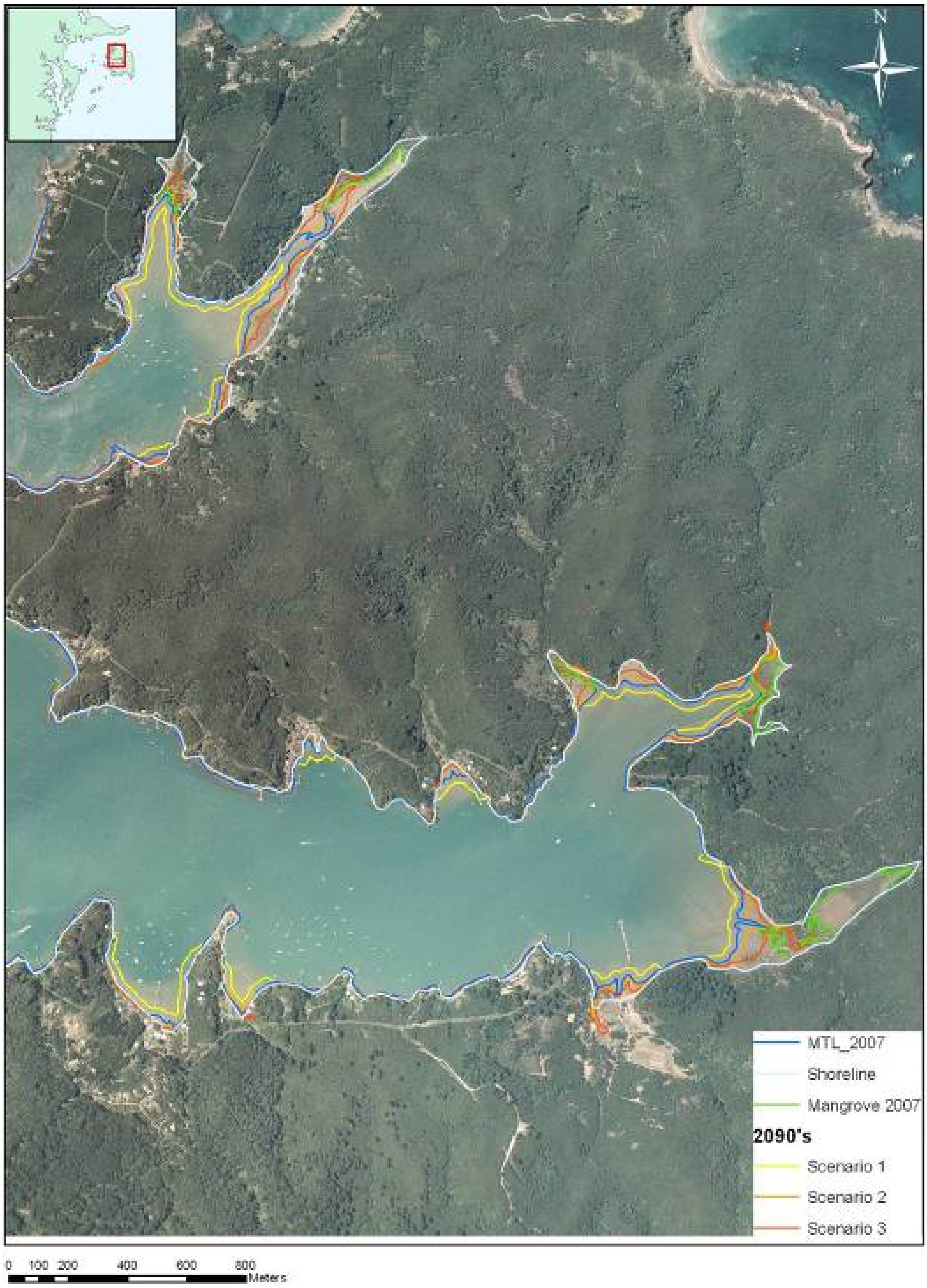


Figure 5.42:

North Cove and Bon Accord, Kawau Island - 2090s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2090s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).



5.8.4 Mahurangi Harbour

Figures 5.43 and 5.44 map changes in potential and existing mangrove habitat in the Mahurangi Harbour that are predicted to occur over the next century under SLR Scenarios 1–3. A DEM was not available for the Mahurangi so that predicted changes in MTL position are based on the average tidal-flat slope from RTK-GPS measurements. Surface slopes in the tidal creeks will be more spatially variable and higher than on the open tidal flats, so that these sub-environments are excluded from the analysis.

The Mahurangi is on of the most extensively studied estuarine systems in the Auckland Region. Over the last 100 years, SAR have averaged ~20 mm yr^{-1} in the upper-harbour (north of Hamiltons Landing) and 2–4 mm yr^{-1} in the main body of the harbour (Swales et al. 1997; 2002a).

The results of the assessment for the Mahurangi Harbour indicate:

- mangroves presently occupy 69% of their potential habitat above MTL-2007 in the Mahurangi Harbour. The estuary have a medium level of vulnerability to sediment infilling, with an estuary infill time (T_A) of ~1,900 years (section 5.1);
- in the upper estuary, Dawsons Creek, Cowans Bay, Dyers Creek and Pukapuka Inlet mangrove occur down to the MTL isobath so that future changes in sea level are likely to have immediate effects on the distribution of mangrove. In Te Kapa Inlet, mangrove occur on the upper flat above +0.35 m MTL-2007 so that the effects of future increases in SLR will be delayed. Large-scale loss of existing mangrove stands growing in the main body of the harbour is unlikely to occur until late this century;
- sedimentation in the tidal creeks will more than likely compensate for accelerated sea-level rise over the next century and will provide refuges for mangrove;
- a low likelihood of mangrove seedling establishment in the Mahurangi Harbour under the existing wave climate. However, there is a high likelihood of seedling establishment in the sheltered bays and creeks fringing the harbour;
- there is a low likelihood of large-scale mangrove-habitat expansion in the estuary during the next century based on: the existing wave climate; availability of suitable habitat; and future SLR scenarios.

Figure 5.43:

Mahurangi Harbour - 2050s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2050s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).

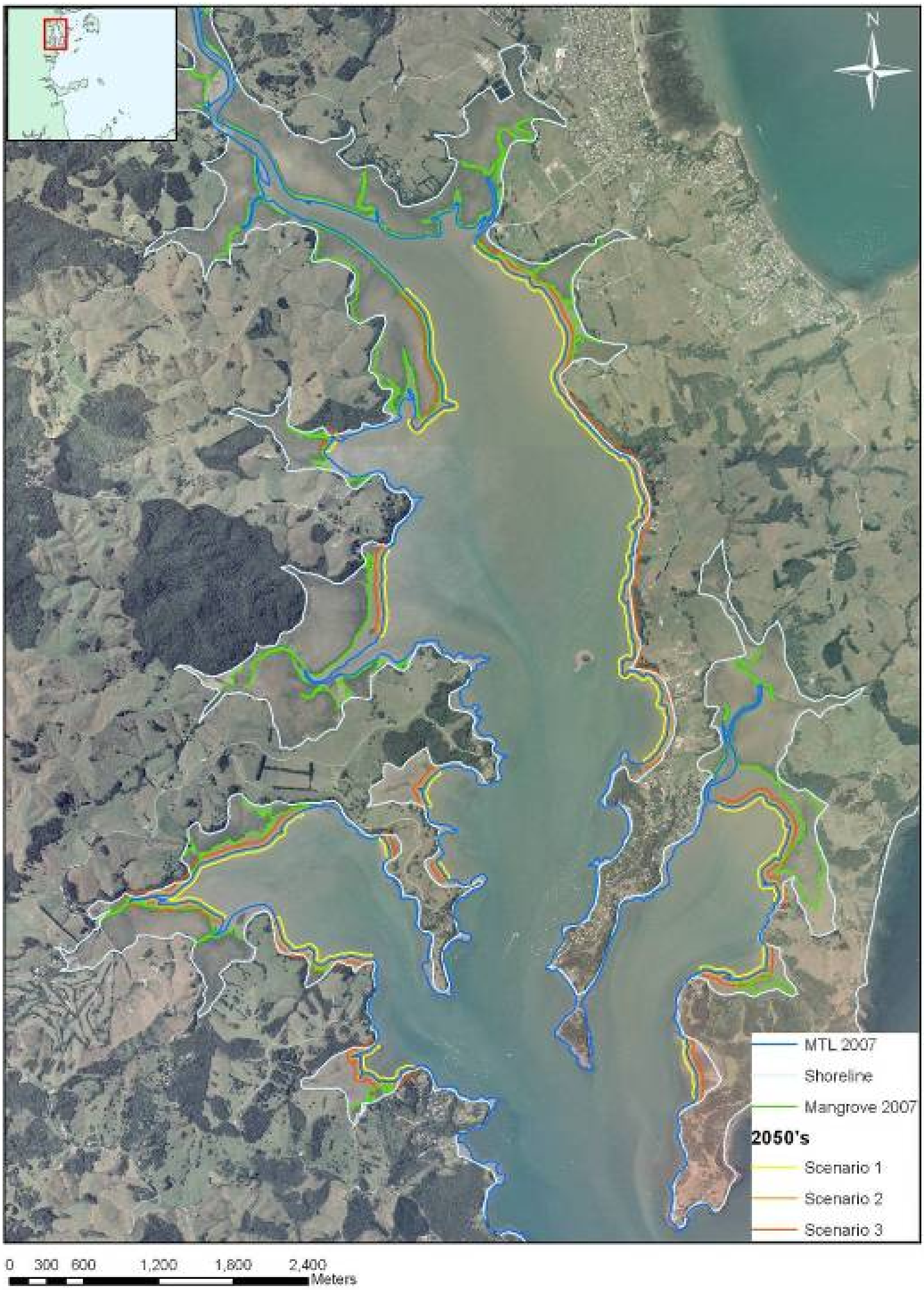
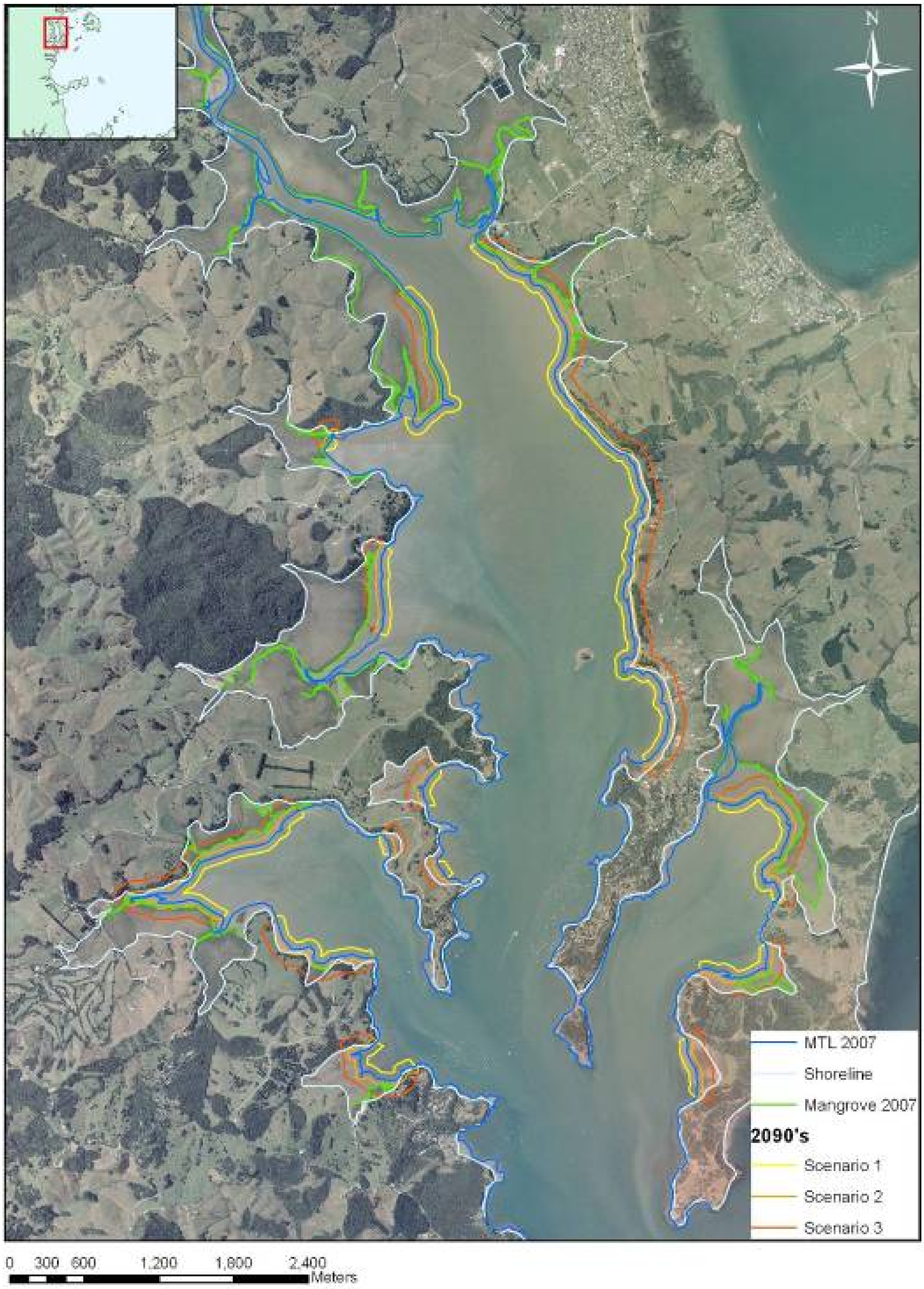


Figure 5.44:

Mahurangi Harbour - 2090s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2090s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).



5.8.5 Puhoi Estuary

Figures 5.45 and 5.46 map changes in potential and existing mangrove habitat in the Puhoi Estuary that are predicted to occur over the next century under SLR Scenarios 1–3.

The results of the assessment for the Puhoi Estuary indicate:

- mangroves presently occupy 56% of their potential habitat above MTL-2007 in the Puhoi Estuary. The estuary have a high level of vulnerability to sediment infilling, with an estuary infill time (T_A) of ~400 years (section 5.1);
- mangroves presently occur down to MTL-2007 in the upper estuary, on the flanks of the main channel. Future changes in MTL position in the upper estuary are likely to be minor because of the steeply sloping channel banks. Increases in tidal-flat elevation due to sedimentation (Swales et al. 2002a) over the last ~50 years have also exceeded the accelerated rates of sea-level rise predicted to occur over the next century. Thus changes in MTL in the upper estuary are likely to be minor;
- under SLR Scenario One, relatively minor increases in potential mangrove habitat will occur in the middle-lower reaches of the estuary over the next century due to the extension of existing intertidal flats. Under Scenarios Two and Three, the impacts of accelerated sea-level rise on existing mangrove stands in the lower-middle estuary will be delay until after the 2050s;
- a medium likelihood of mangrove seedling establishment in the Puhoi Estuary under the existing wave climate;
- there is a medium likelihood of large-scale mangrove-habitat expansion in the Puhoi Estuary during the next century based on existing wave climate; availability of suitable intertidal habitat and future SLR scenarios.

Figure 5.46:

Puhoi Estuary - 2050s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2050s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).

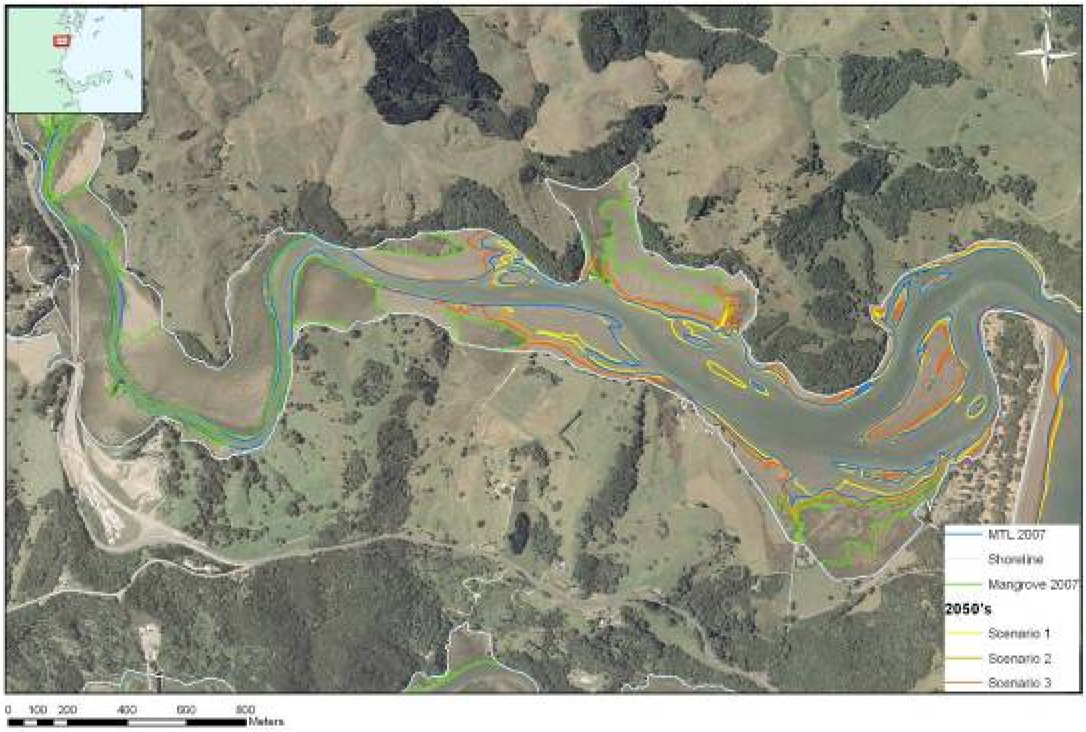
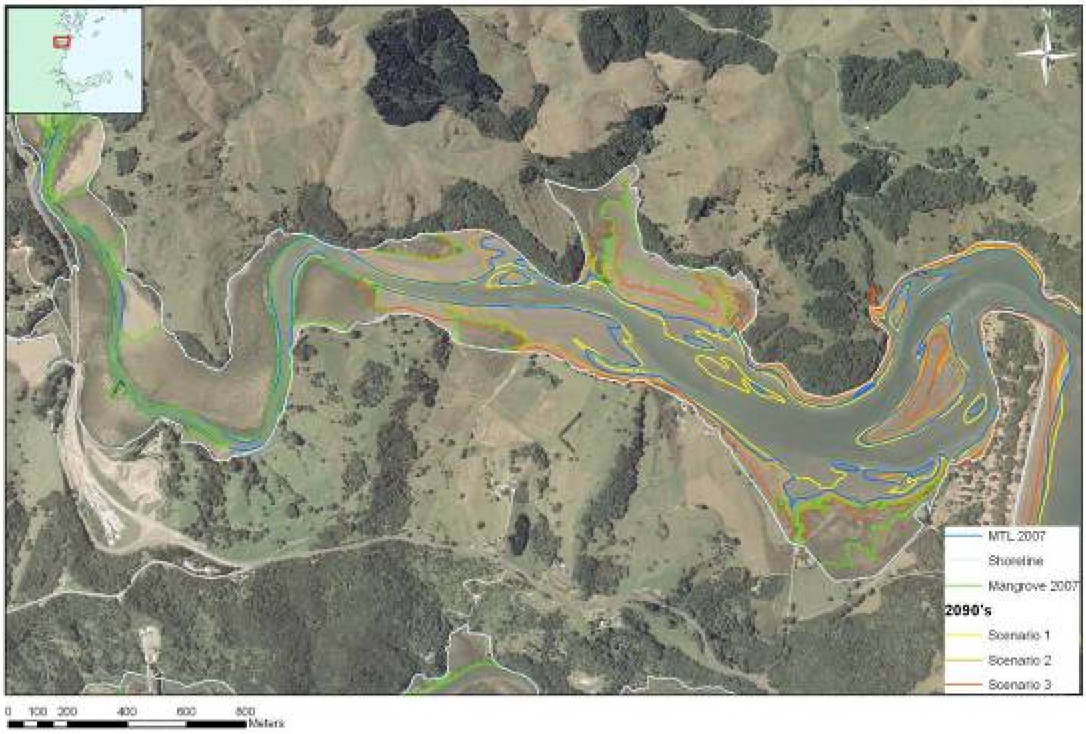


Figure 5.47:

Puhoi Estuary - 2090s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2090s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).



5.8.6 Waiwera Estuary

Figures 5.48 and 5.49 map changes in potential and existing mangrove habitat in the Waiwera Estuary that are predicted to occur over the next century under the SLR Scenarios 1–3.

As discussed in section 5.1, the Waiwera Estuary has substantially infilled with sediment so that today ~80% of its high-tide surface area is above MTL-2007. Mangroves have also colonised a large proportion of the tidal flat above MTL-2007, which follows the main tidal channel. Thus, future changes in potential or existing mangrove habitat will be mitigated by the steeply sloping channel banks.

The results of the assessment for Waiwera Estuary indicate:

- mangroves presently occupy 51% of their potential habitat above MTL-2007 in the Waiwera Estuary. The estuary has a high level of vulnerability to sediment infilling, with estuary infill times (T_A) of ~400 years (section 5.1);
- mapping of changes in MTL position by the 2050s and 2090s indicate minor increases in habitat under SLR Scenario One ($SLR_{0.14m}$). Future loss of existing mangrove habitat in the middle estuary is unlikely to occur until after the 2050s if at all, under SLR Scenario Three;

- estuary sedimentation rates are likely to exceed the average SAR of 3.8 mm yr^{-1} adopted in this study. This is supported by the vulnerability of the estuary to infilling (sections 5.1–5.2) and the fact that mangrove enhance sediment trapping and accelerate sedimentation (Craggs et al. 2001; Swales et al. 2007). Thus, under SLR Scenarios Two ($SLR_{0.47m}$) and Three ($SLR_{0.77m}$), future losses of potential and existing mangrove habitat are likely to be less than predicted here;

- a high likelihood of mangrove seedling establishment in the Waiwera Estuary under the existing wave climate;

- there is a high likelihood of large-scale mangrove-habitat expansion in the Waiwera Estuary during the next century based on: the existing wave climate; availability of suitable intertidal habitat; and future SLR scenarios.

Figure 5.48:
Waiwera Estuary - 2050s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2050s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).

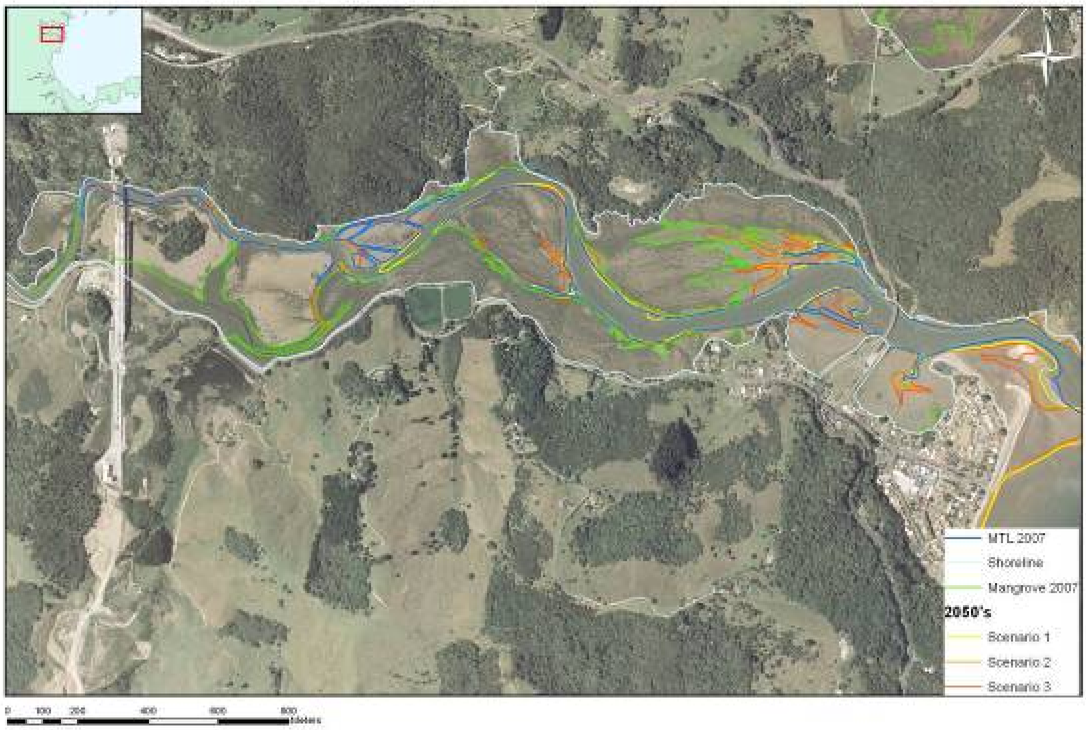
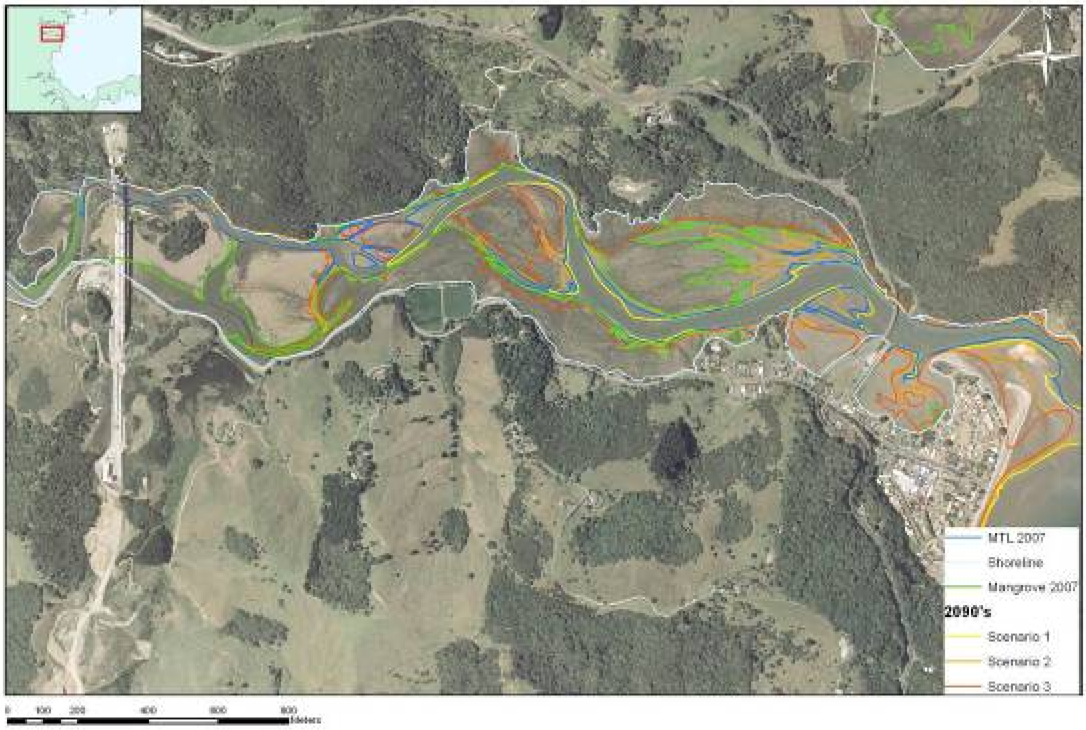


Figure 5.49:

Waiwera Estuary - 2090s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2090s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).



5.8.7 Orewa Estuary

Figures 5.50 and 5.51 map changes in potential and existing mangrove habitat in the Orewa Estuary that are predicted to occur over the next century under SLR Scenarios 1–3. Although a DEM was used to predict changes in the MTL position under the future SLR scenarios, the morphology of the estuary is complex so that applying the DEM to the MTL-2007 isobath (waterline) resulted in nonsensical results. As an alternative, the AVD-1946 isobath, was adopted for the mapping of future mangrove habitat changes.

Like Puhoi and Waiwera, the Orewa Estuary has substantially infilled with sediment so that at low tide only the subtidal channel remains submerged. At mean tide level (i.e., MTL-2007) numerous exposed flats and banks are separated by shallow submerged areas of tidal flat (Appendix 7).

The results of the assessment for Orewa Estuary indicate:

- mangroves presently occupy 69% of their potential habitat above MTL-2007 in the Orewa Estuary. The estuaries have a medium level of vulnerability to sediment infilling, with an estuary infill time (T_A) of ~1,900 years (section 5.1);

- mapping of changes in MTL position by the 2050s and 2090s indicate that increases in potential mangrove habitat under SLR Scenario One ($SLR_{0.14m}$) will be minor and result from partially infilling of the tidal channel. Future loss of existing mangrove habitat in the middle estuary is unlikely to occur until after the 2090s, under SLR Scenario Three ($SLR_{0.77m}$);
- a medium to low likelihood of mangrove-seedling establishment in the Whangateau Estuary under the existing wave climate;
- there is a medium to low likelihood of large-scale mangrove-habitat expansion in the Orewa Estuary during the next century based on: the existing wave climate; availability of suitable intertidal habitat; and future SLR scenarios.

Figure 5.50:
Orewa Estuary - 2050s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2050s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).

Figure 5.51:

Orewa Estuary - 2090s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2090s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).

5.8.8 Weiti Estuary

Figures 5.52 and 5.53 map changes in potential and existing mangrove habitat in the Weiti Estuary that are predicted to occur over the next century under SLR Scenarios 1–3.

The Weiti is similar to many of the small north-east coast estuaries in the Auckland Region that have substantially infilled with sediment, that form intertidal flats flanking a narrow subtidal channel. The morphology associated with this mature-stage estuary type means that future changes in mangrove habitat are limited. Extensive mangrove stands occur in the upper estuary and have completely colonised tidal flats above MTL-2007.

The results of the assessment for Weiti Estuary indicate:

- mangroves presently occupy 71% of their potential habitat above MTL-2007 in the Weiti Estuary. The estuary has a medium level of vulnerability to sediment infilling, with an estuary infill time (T_A) of ~900 years (section 5.1);
- increases in potential mangrove habitat will be minor under SLR Scenario One ($SLR_{0.14m}$) and will result from sedimentation on the channel banks and lower intertidal flat. Mapping of changes in MTL position by the 2050s and 2090s;

- loss of existing mangrove habitat is unlikely to occur until after the 2090s, under SLR Scenario Three ($SLR_{0.77m}$);
- a low likelihood of mangrove-seedling establishment in the Weiti Estuary under the existing wave climate;
- there is a low likelihood of large-scale mangrove-habitat expansion in the Weiti Estuary during the next century based on: the existing wave climate; availability of suitable intertidal habitat; and future SLR scenarios.

Figure 5.52:
Weiti Estuary - 2050s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2050s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).

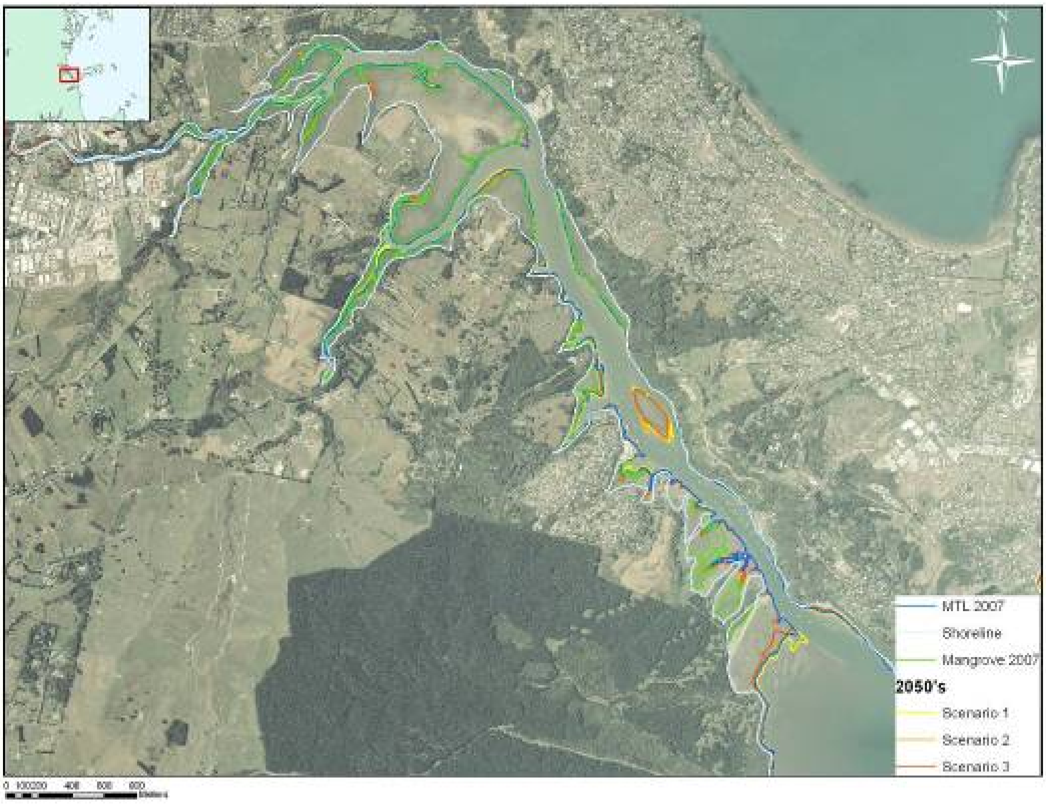
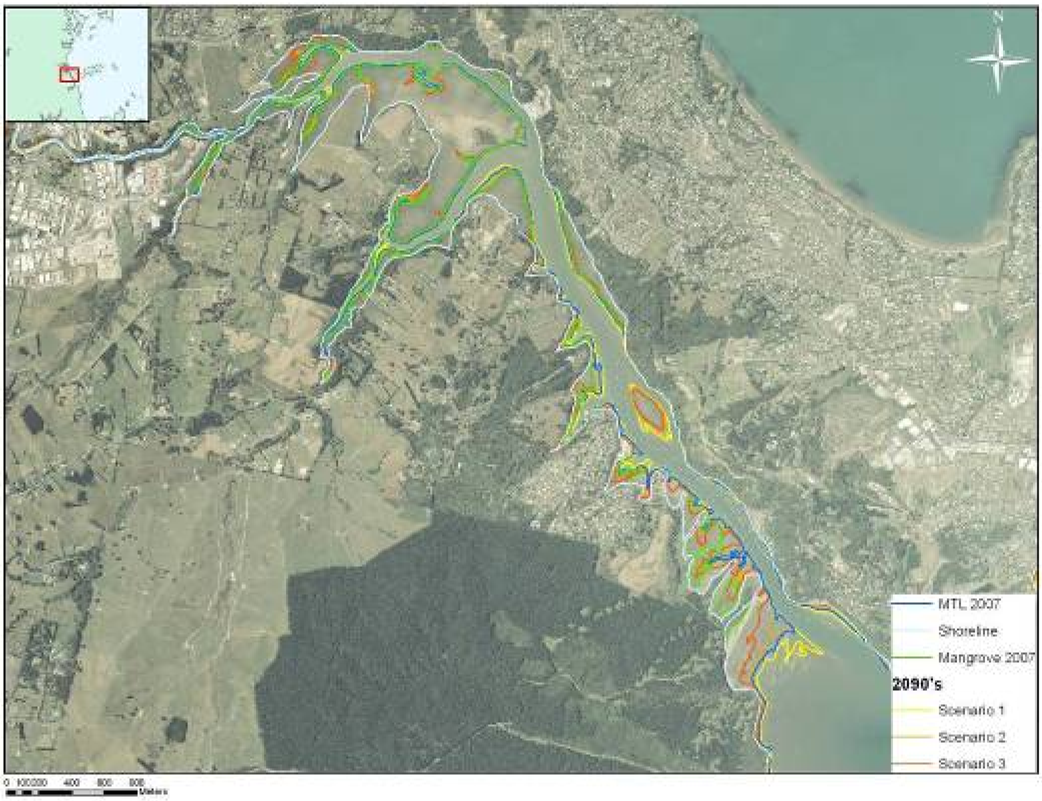


Figure 5.53:

Weiti Estuary - 2090s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2090s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).



5.8.9 Okura Estuary

Figures 5.54 and 5.55 map changes in potential and existing mangrove habitat in the Okura Estuary that are predicted to occur over the next century under the historical trend and IPCC SLR scenarios.

Mangrove presently occur in the upper reaches of the Okura estuary near sub-catchment outlets and in the lee of a large shell bank that shelters tidal flats to the west of this natural barrier from waves generated by easterly winds. ^{210}Pb dating of sediment cores show sediments have accumulated on tidal flats in the upper estuary, averaging 4mm yr^{-1} (range: 2.4 – 6.3 mm yr^{-1}) since the 1950s (Swales et al. 2002a). In the lower estuary, the extensive tidal flats above MTL-2007 are exposed to waves and radioisotope analysis indicates that sediments are rapidly reworked and mixed to depths of ~5-cm (Swales et al. 2008b). Mangrove seedlings are unlikely to establish and survive in this environment.

The results of the assessment for Okura Estuary indicate:

- mangroves presently occupy 29% of their potential habitat above MTL-2007 in the Okura Estuary. The estuaries have a medium level of vulnerability to sediment infilling, with an estuary infill time (T_A) of ~600 years (section 5.1);
- increases in potential mangrove habitat will be limited under the SLR Scenario One ($SLR_{0.14m}$) and result from sedimentation on the channel banks and lower intertidal flat. Mapping of changes in MTL position by the 2050s and 2090s indicate that loss of existing mangrove habitat is unlikely to occur until after the 2050s, under SLR Scenario Three ($SLR_{0.77m}$);
- a low likelihood of mangrove seedling establishment in the lower estuary (seaward of the shell bank) and a low – medium likelihood in the upper estuary under existing wave conditions;
- there is a low likelihood of large-scale mangrove-habitat expansion in the lower estuary and a low – medium likelihood of large-scale mangrove-habitat expansion in the upper estuary during the next century based on: existing wave climate; availability of suitable intertidal habitat; and future SLR scenarios.

Figure 5.54:
Okura Estuary - 2050s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2050s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).

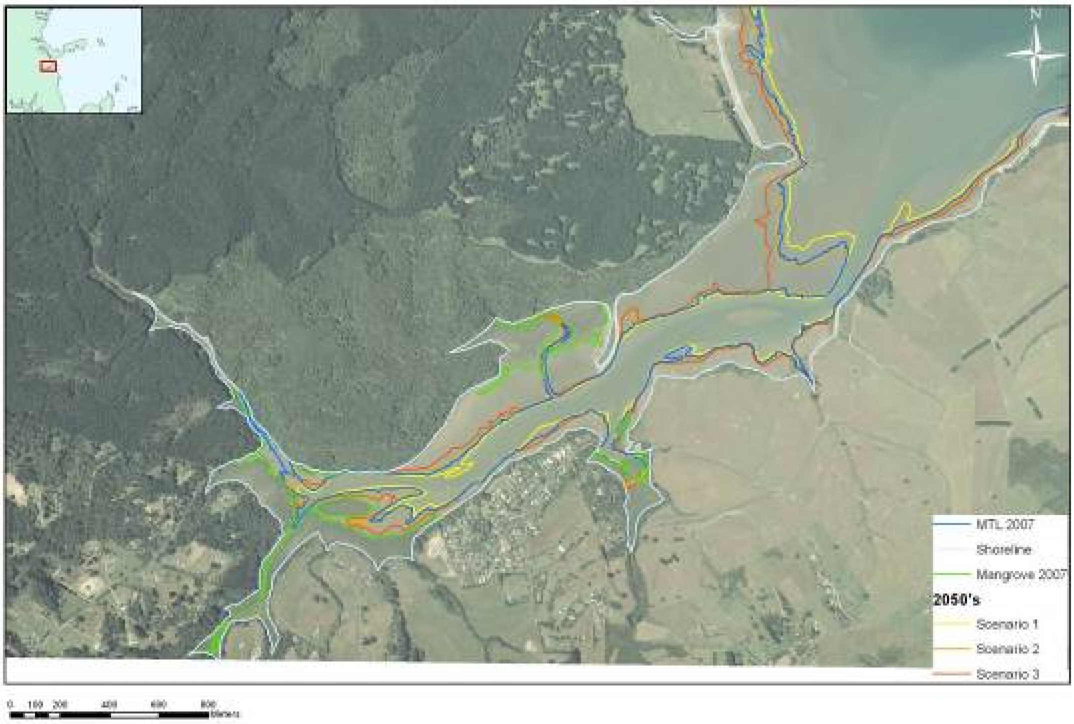
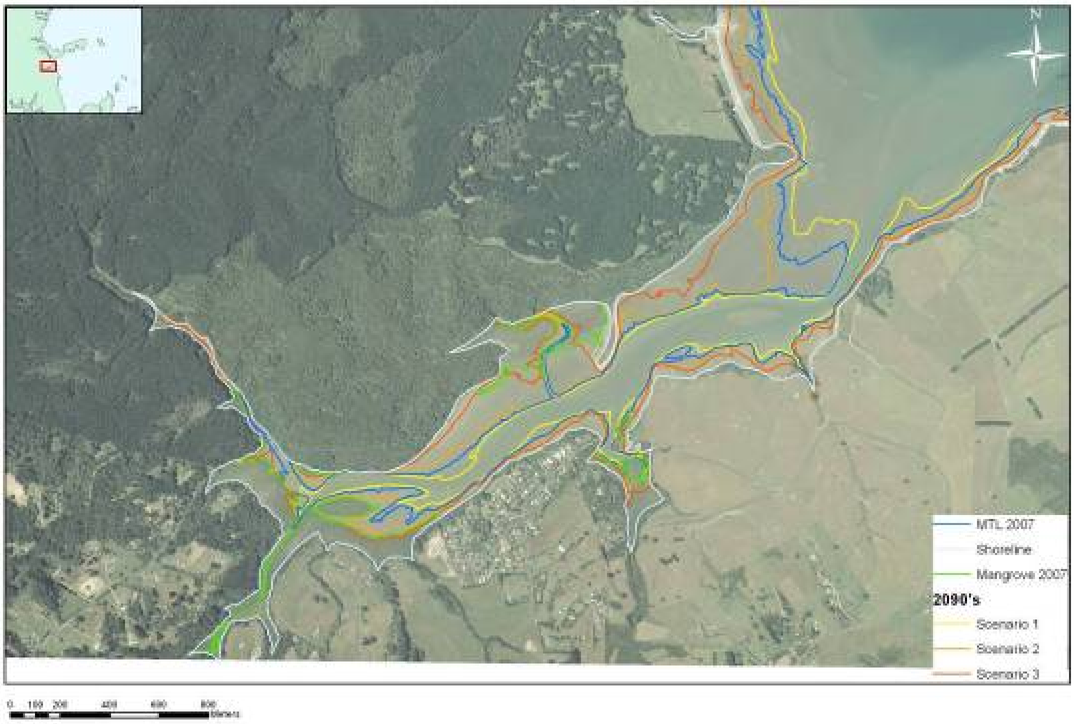


Figure 5.55:

Okura Estuary - 2090s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2090s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).



5.8.10 Upper Waitemata Harbour

Figures 5.56 and 5.57 map changes in potential and existing mangrove habitat in the Upper Waitemata Habour (UWH) that are predicted to occur over the next century under SLR Scenarios 1–3.

The UWH is a system of seven tidal creeks which receive runoff from a mixture of urban and rural sub-catchments. These tidal creeks are, from west to east: Rangitopuni; Brighams; Rawararu; Paremoremo; Waiarohia; Lucas and Hellyers Creeks. Lucas Creek is typical of the UWH creeks, with mangrove stands occupying most of the present-day tidal flat above MTL-2007. In Lucas Creek, this potential mangrove habitat represents only 30% of the high-tide surface area. The historical rate mangrove-habitat expansion has also been modest, increasing by 6% since 1950 (Morrisey et al. 1999).

The results of the assessment for the UWH indicate:

- increases in potential mangrove habitat will be limited under SLR Scenario One ($SLR_{0.14m}$) and will result from sedimentation on the channel banks and lower intertidal flat. Mapping of changes in MTL position by the 2050s and 2090s indicate loss of existing mangrove habitat in the middle estuary is unlikely to occur until after the 2090s under SLR Scenarios Two and Three. Higher sedimentation rates in the tidal creeks are also likely to offset the effects of accelerated se-level rise;

- a low likelihood of large-scale mangrove-habitat expansion in the UWH under existing wave climate;
- mangroves presently occupy 47% of their potential habitat above MTL-2007 in the UWH. Based primarily on the limited availability of suitable intertidal habitat (outside the tidal creeks), there is a low likelihood of large-scale mangrove-habitat expansion in the UWH during the next century.

Figure 5.56:
Upper Waitemata Harbour - 2050s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2050s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).

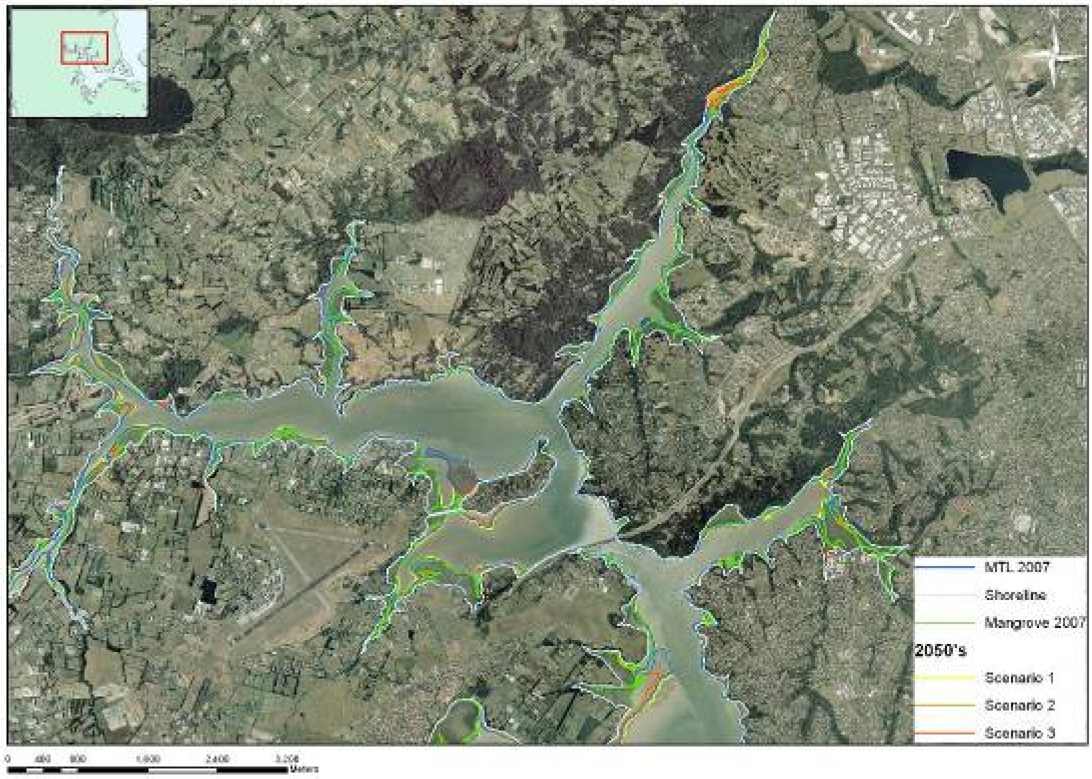
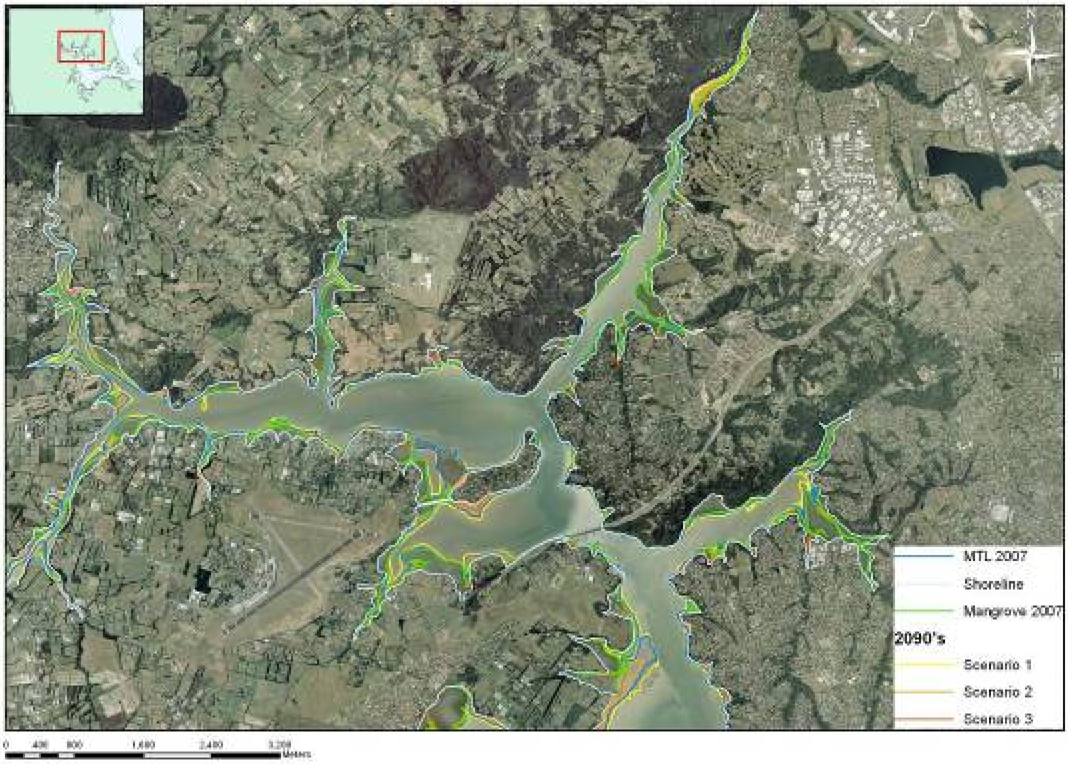


Figure 5.57:
Upper Waitemata Harbour - 2090s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2090s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).



5.8.11 Central Waitemata Harbour

Figures 5.58 and 5.59 map changes in potential and existing mangrove habitat in the Central Waitemata Habour (CWH) that are predicted to occur over the next century under SLR Scenarios 1–3. The CWH includes the harbour area between the Auckland Harbour Bridge and Hobsonville.

Mangrove habitat in the CWH is concentrated in the Henderson Creek and Whau River, Pollen Island Marine Reserve and Waterview Inlet, Meloa and Motions Creeks and Coxs Bay. The main tidal channel is close to the northern shore of the CWH and flanked by a narrow tidal flat and rocky coast exposed to the prevailing south-west winds. Isolated mangrove stands are restricted to small inlets and bays such as Soldiers Bay (Beach Haven) and Chelsea Bay. Sediment accumulation rates on the intertidal flats flanking the south-west shore of the CWH have averaged 3.2 mm yr^{-1} over the last 50 years and less than the regional average value of 3.8 mm yr^{-1}. Radioisotope data also show that the top ~5 cm of tidal-flat sediments are rapidly reworked and mixed due to sediment resuspension by waves (Swales et al. 2007b). Mangrove seedlings are unlikely to establish and survive in this environment.

The results of the assessment for the CWH indicate:

- mangroves presently occupy 67% of their potential habitat above MTL-2007 in the CWH. The Waitemata Harbour has a low level of vulnerability to sediment infilling, with an estuary infill time (T_A) of 15,000 years (Swales et al. 2008, section 5.1);
- there is a low likelihood of mangrove-seedling establishment under the existing wave climate;
- increases in potential mangrove habitat occur under SLR Scenario One ($SLR_{0.14m}$) due to accretion of the tidal flats, although these changes are modest. Under the SLR Scenarios Two and Three, retreat of the tidal flats occurs in the main body of the harbour but is limited in the tidal creeks due to steep channel-bank slopes. Loss of the potential mangrove habitat above MTL will also be mitigated by higher in the tidal creeks. Predicted changes in the MTL isobath indicate that loss of existing mangrove habitat along the Te Atatu – Waterview shore is unlikely to occur until after the 2090s;
- there is a low likelihood of large-scale mangrove-habitat expansion in the CWH during the next century based on: existing wave climate; availability of suitable habitat; and future SLR Scenarios.

Figure 5.60:
Central Waitemata Harbour - 2050s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2050s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).

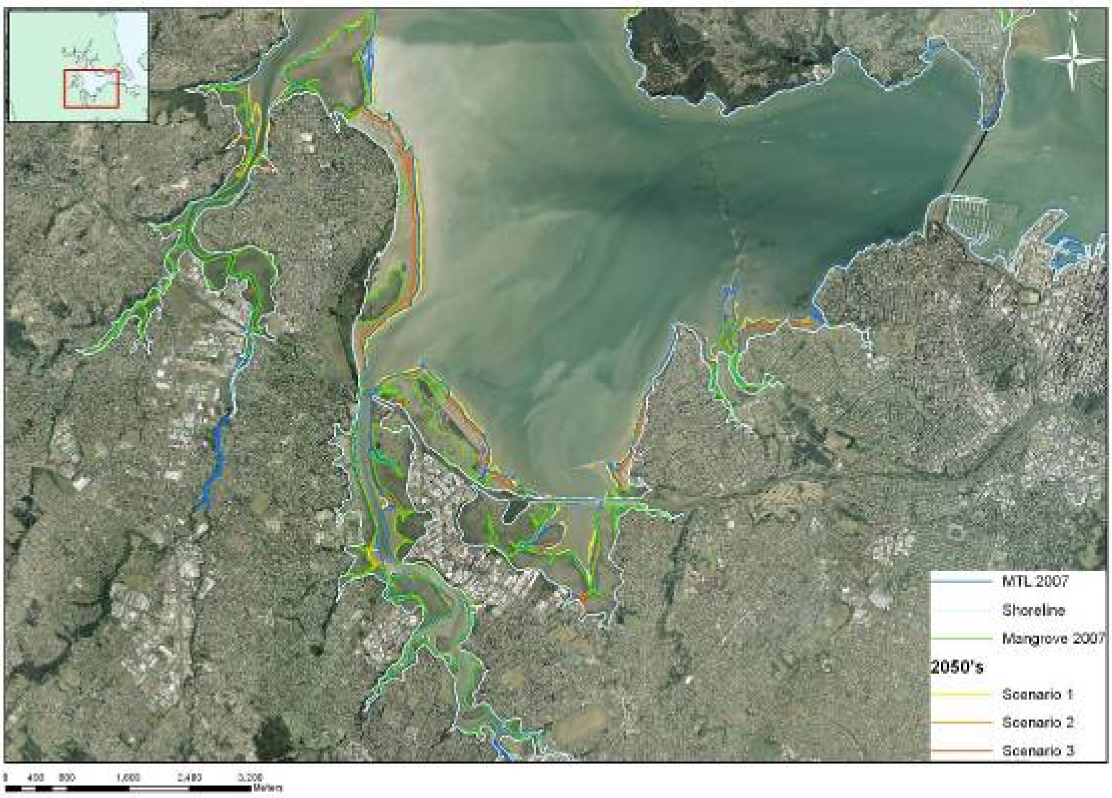


Figure 5.61:

Central Waitemata Harbour - 2090s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2090s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).

5.8.12 Shoal Bay

Figures 5.62 and 5.63 map changes in potential and existing mangrove habitat in Shoal Bay that are predicted to occur over the next century under the SLR Scenarios 1–3. A DEM of Shoal Bay was not available so that predicted changes in MTL position are based on the average tidal-flat slope from RTK-GPS measurements. Surface slopes in the tidal creeks fringing the Bay will be more spatially variable and higher than on the open tidal flats, so that these sub-environments are excluded from the analysis.

The orthophotos show that the lower elevation limit of existing mangrove stands fringing the bay show are substantially above MTL-2007, so that there is a large are of potential habitat that has not been colonised by mangroves.

The results of the assessment for Shoal Bay indicate:

- mangroves presently occupy 57% of their potential habitat above MTL-2007 in Shoal Bay. Although the Bay has a relatively small land catchment, it represents a long-term sink for sediments from the CWH;

- a low likelihood of mangrove-seedling establishment in Shoal Bay under the existing wave climate;
- increases in potential mangrove habitat occur under SLR Scenario One ($SLR_{0.14m}$) due to tidal-flat sedimentation. Retreat of the tidal flats occurs along the eastern shore of the bay under SLR Scenario Two ($SLR_{0.47m}$) and Scenario Three ($SLR_{0.77m}$). A large section of the western shore of Shoal Bay is protected by reclamations associated with the northern motorway. Extensive mangrove stands occur within the tuff crater, which receives sediment inputs entirely from Shoal Bay. Shoal Bay is a major sink for fine-sediments derived from catchments draining to the CWH, and sediment eroded from tidal flats in the CWH (section 5.2). These sediments are rapidly accumulating in Shoal Bay. At one site in the upper reaches of the bay SAR has averaged 6.8 mm yr^{-1} over the last 50 years. However, there is intense physical mixing of sediments by waves to ~5-cm depth (Swales et al. 2007b);
- under SLR Scenarios Two and Three, loss of the existing mangrove habitat is likely to be mitigated by high SAR in the bay and any losses are unlikely to occur until after the 2090s;
- there is a low likelihood of large-scale mangrove-habitat expansion in Shoal Bay during the next century primarily due to the existing wave climate.

Figure 5.64:

Shoal Bay - 2050s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2050s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).

Figure 5.65:

Shoal Bay - 2090s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2090s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).

5.8.13 Hobson Bay

Figures 5.66 and 5.67 map changes in potential and existing mangrove habitat in Hobson Bay that are predicted to occur over the next century under SLR Scenarios 1–3.

A DEM of Shoal Bay was not available so that predicted changes in MTL position are based on the average tidal-flat slope from RTK-GPS measurements in the CWH and Shoal Bay. Surface slopes in the tidal creeks fringing the Bay will be more spatially variable and higher than on the open tidal flats, so that these sub-environments are excluded from the analysis.

Existing mangrove stands are located on the upper intertidal flats and well above the MTL-2007 isobath. This is despite the fact that mangroves occupied a substantial area of the upper tidal flat by the early 1920s. Wave exposure is a likely mechanism limiting seedling recruitment in Hobson Bay. Erosion of the tidal-flat by waves exposing the root systems of mangrove trees has been documented by Chapman & Ronaldson (1958). Extensive mangrove stands also occurred in the adjacent Orakei Basin but were removed soon after the installation of tide gates by the City Council in 1929 (Chapman & Ronaldson, 1958).

The results of the assessment for Hobson Bay indicate:

- mangroves presently occupy 35% of their potential habitat above MTL-2007 in Hobson Bay. Given the relatively sheltered environment within Hobson Bay and large area of potentially suitable tidal-flat habitat it is unclear why mangroves do not occupy a larger area;
- there is a low – medium likelihood of mangrove-seedling establishment in Hobson Bay under the existing wave climate;
- increases in potential mangrove habitat under SLR Scenario One ($SLR_{0.14m}$), occur due to tidal-flat sedimentation. Loss of existing mangrove habitat under SLR Scenarios Two and Three is unlikely to occur until after the 2090s;
- there is a low – medium likelihood of large-scale mangrove-habitat expansion in Hobson Bay during the next century based on the existing wave climate and future SLR scenarios.

Figure 5.66:
Hobson Bay - 2050s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2050s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).

Figure 5.67:

Hobson Bay - 2090s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2090s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).

5.8.14 Tamaki Estuary

Figures 5.68 – 5.71 map changes in potential and existing mangrove habitat in the Tamaki Estuary that are predicted to occur over the next century under the SLR Scenarios 1–3.

Existing mangrove stands are largely restricted to the tidal creeks that fringe the upper estuary: Pakuranga, Otahuhu, Otara Creeks, where mangrove occupy most of the tidal flat above MTL-2007. Large-scale mangrove colonisation of the Pakuranga Creek from the early 1960s coincided with the onset of rapid catchment urbanisation and increased sediment loads (Swales, 1989; Swales et al. 2002b).

The results of the assessment for the Tamaki Estuary indicate:

- mangroves presently occupy 57% of their potential habitat above MTL-2007 in the Tamaki Estuary. The estuary has a low level of vulnerability to sediment infilling, with an estuary infill time (T_A) of ~4,700 years (section 5.1);
- a low likelihood of mangrove seedling establishment under the existing wave climate;

- increases in potential mangrove habitat under SLR Scenario One occur due to tidal flat sedimentation although these gains are limited by the tidal-flat slope. Loss of existing mangrove habitat under SLR Scenarios two and Three is unlikely to occur until after the 2090s;
- sediment accumulation rates in tidal creeks, such as the upper Pakuranga Creek have averaged 25 mm yr^{-1} since the 1950s (Swales et al. 2002b). Consequently, mangroves are likely to be maintained in these high-sedimentation environments even under the accelerated SLR Scenarios Two and Three based on IPCC (2007) projections;
- a low likelihood of large-scale mangrove-habitat expansion in the Tamaki Estuary during the next century. The primary limiting factor is the relatively small area of suitable habitat above MTL-2007.

Figure 5.68:

Tamaki Estuary (North) - 2050s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2050s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).

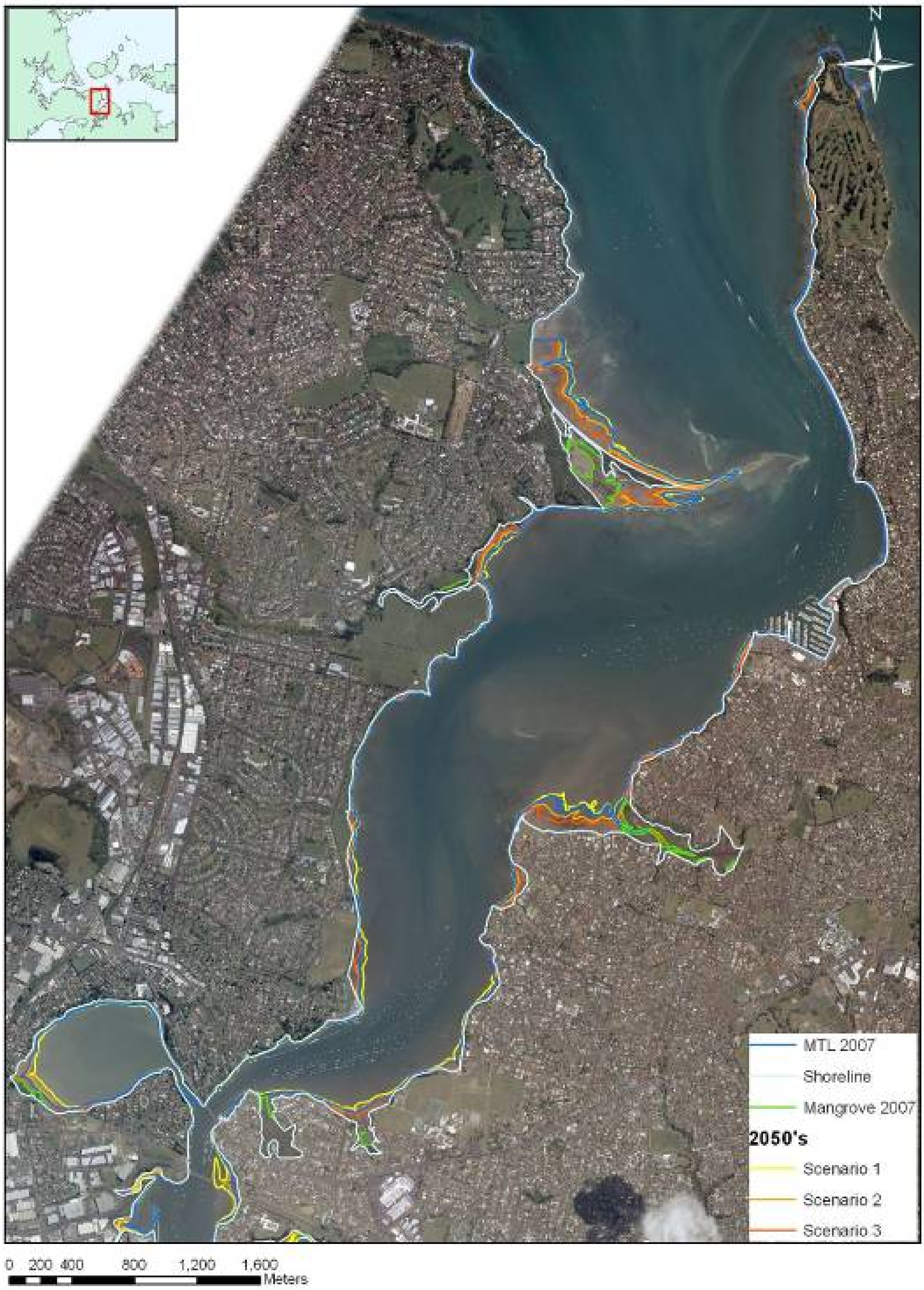


Figure 5.69:

Tamaki Estuary (South) - 2050s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2050s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).

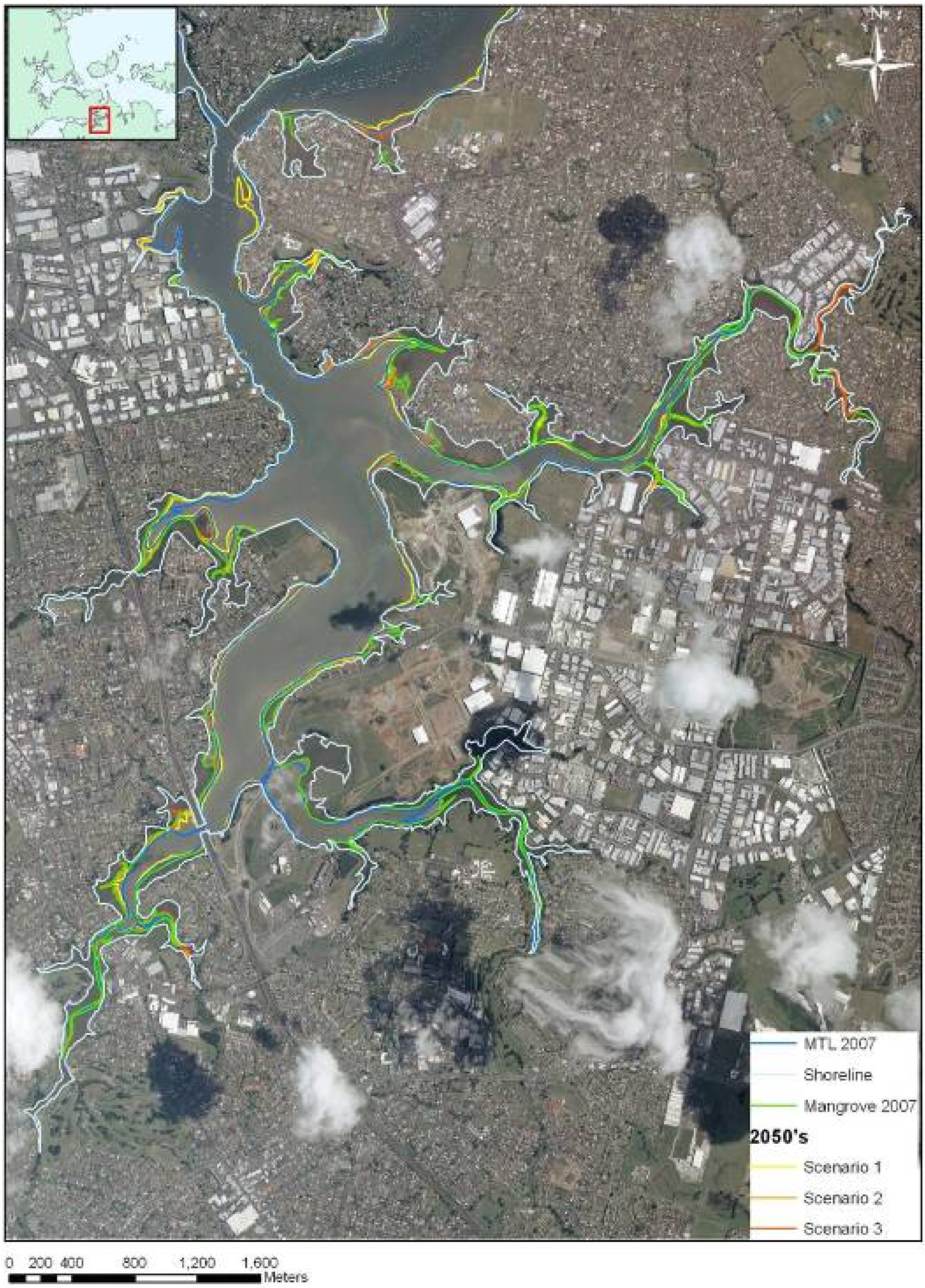


Figure 5.70:

Tamaki Estuary (North) - 2090s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2090s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).

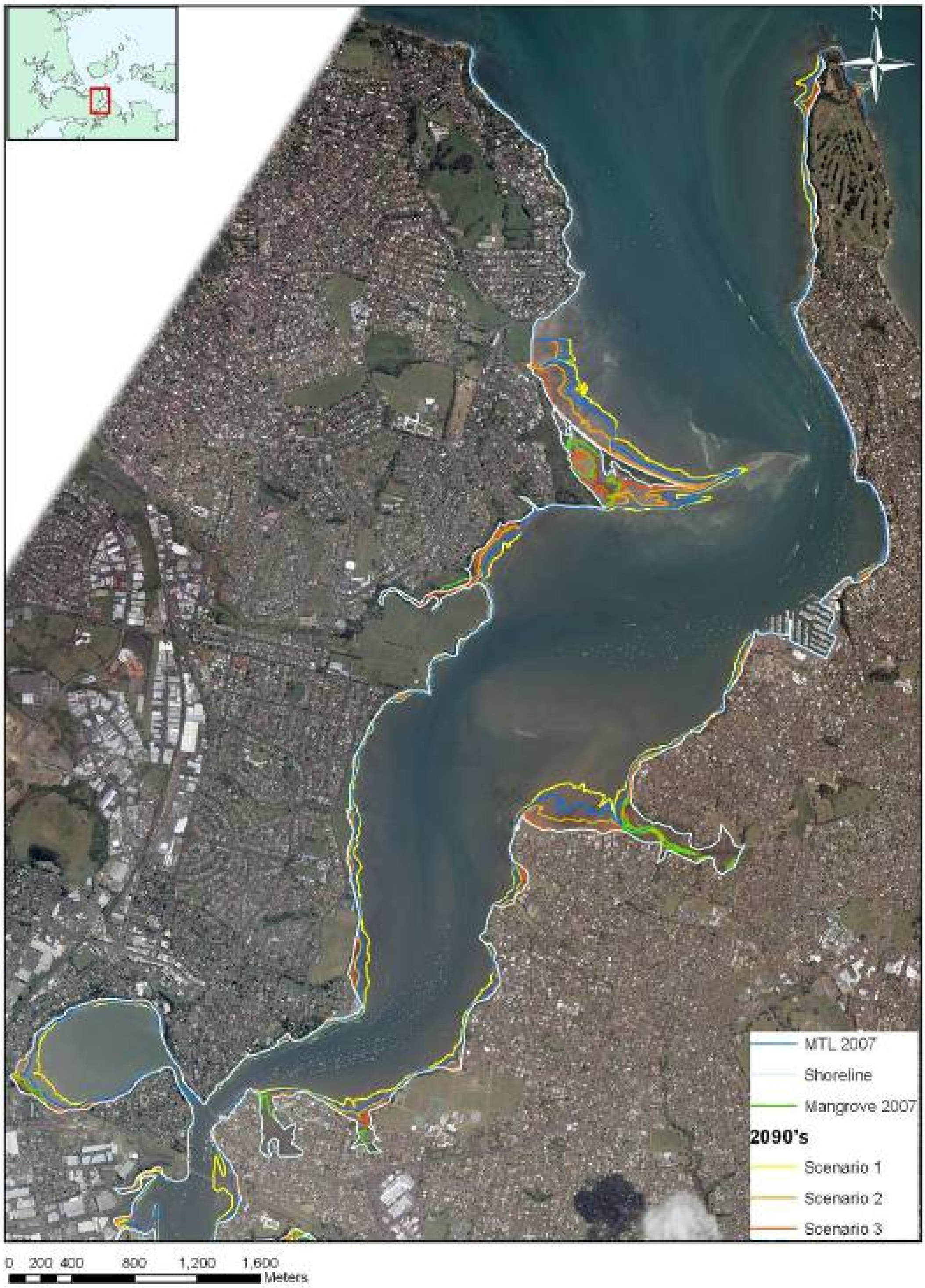
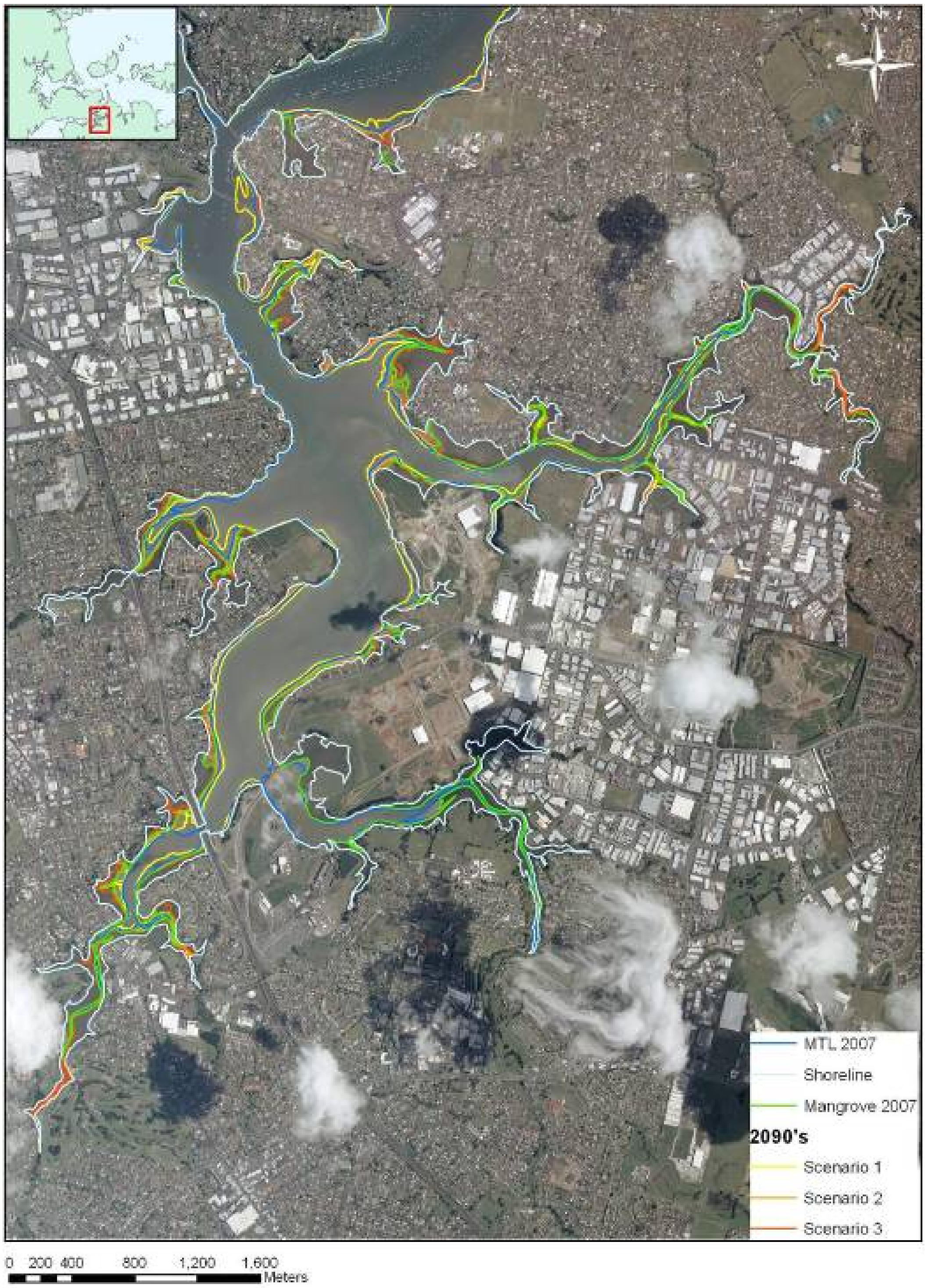


Figure 5.71:

Tamaki Estuary (South) - 2090s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2090s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).



5.8.15 Whitford Bay

Figures 5.72 and 5.73 map changes in potential and existing mangrove habitat in Whitford Bay that are predicted to occur over the next century under SLR Scenarios 1–3.

Mangrove stands occur in the Mangemangeroa, Turanga and Waikopua Creeks, with mangroves virtually absent from the extensive tidal flat that fringe the southern shore of the bay. Mangrove are gradually colonising the tidal flats at the mouth of Waikopua Creek (Morrisey et al. 1999; Craggs et al. 2001).

The results of the assessment for Whitford Bay indicate:

- mangroves presently occupy only 29% of their potential habitat above MTL-2007 in Whitford Bay. Most of this existing mangrove occurs in the sheltered tidal creeks. The estuary has a medium level of vulnerability to sediment infilling, with an estuary infill time (T_A) of ~1,800 years (section 5.1);
- there is a low likelihood of mangrove-seedling establishment in Whitford Bay under the existing wave climate;
- increases in potential mangrove habitat under the SLR Scenario One occur due to tidal flat sedimentation. Extensive loss of potential mangrove habitat along the southern shore of the bay is likely to occur under the SLR Scenarios two and Three;
- loss of existing mangrove habitat in the tidal creeks is unlikely to occur due to sedimentation rates (Oldman & Swales, 1999) well in excess of SLR projections for the next 100 years;
- there is a low likelihood of large-scale mangrove-habitat expansion in Whitford Bay during the next century based on: the existing wave climate, availability of suitable intertidal habitat and future SLR scenarios.

Figure 5.72:

Whitford Bay - 2050s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2050s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).

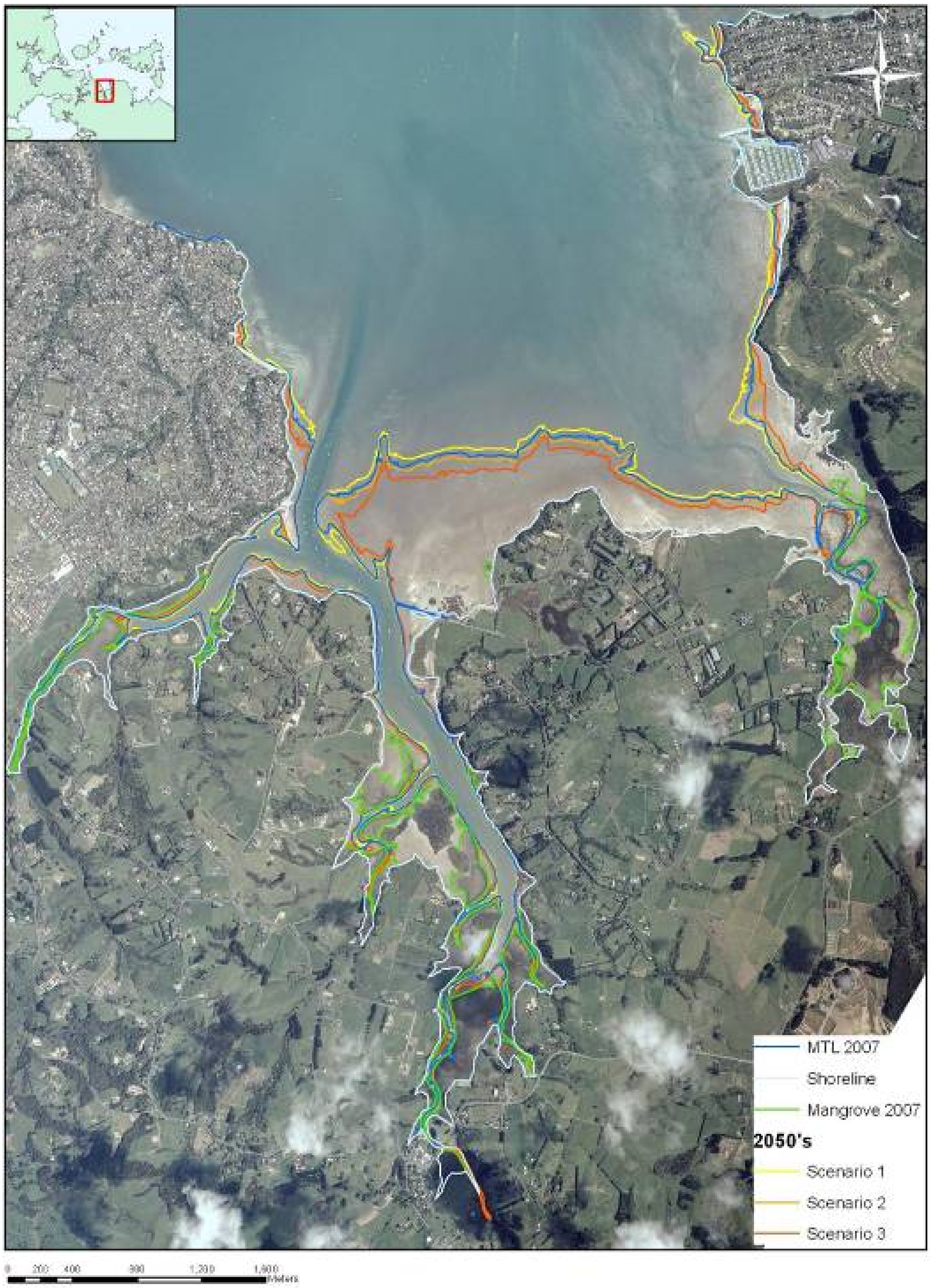
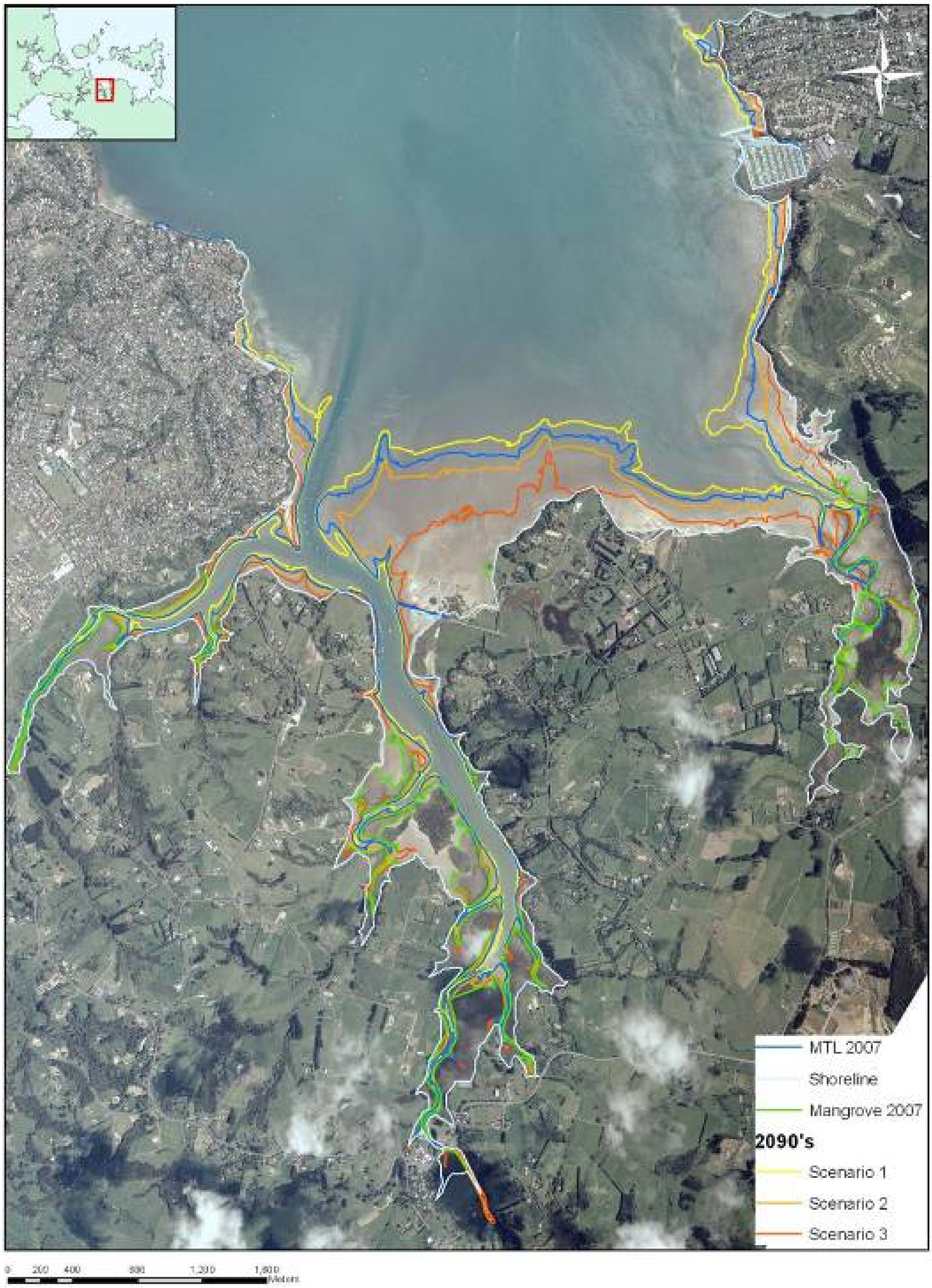


Figure 5.73:

Whitford Bay - 2090s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2090s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).



5.8.16 Wairoa Estuary (Clevedon)

Figures 5.74 and 5.75 map changes in potential and existing mangrove habitat in the Wairoa Estuary that are predicted to occur over the next century under the SLR Scenarios 1–3.

The Wairoa Estuary represents a high-sedimentation end member of Auckland's east coast estuaries. The estuary is vulnerable to infilling due to its relatively large land catchment (sections 5.1–5.2).

The results of the assessment for Wairoa Estuary indicate:

- mangroves presently occupy 74% of their potential habitat above MTL-2007 in the Wairoa Estuary. The estuary has a high level of vulnerability to sediment infilling, with an estuary infill time (T_A) of ~200 years (section 5.1);
- a low likelihood of mangrove-seedling establishment on the intertidal flats at the estuary mouth under the existing wave climate;
- increases in potential mangrove habitat occur under SLR Scenario One due to tidal-flat sedimentation. This is limited within the estuary because of the steeply sloping channel banks. Loss of existing mangrove habitat is unlikely to occur under SLR Scenarios Two and Three until after the 2090s;
- rapid sedimentation in the estuary and adjacent bay over the last 50 years (Swales et al. 2002a) suggests that existing mangrove habitat will be maintained in the estuary. Most of this infilling has already occurred and the Wairoa represents an extreme infilled end-member of Auckland's east-coast estuaries;
- there is a low likelihood of large-scale mangrove-habitat expansion on the intertidal flats at the estuary mouth during the next century based on: the existing wave climate; limited availability of suitable intertidal habitat and future SLR scenarios.

Figure 5.74:

Wairoa Estuary - 2050s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2050s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).

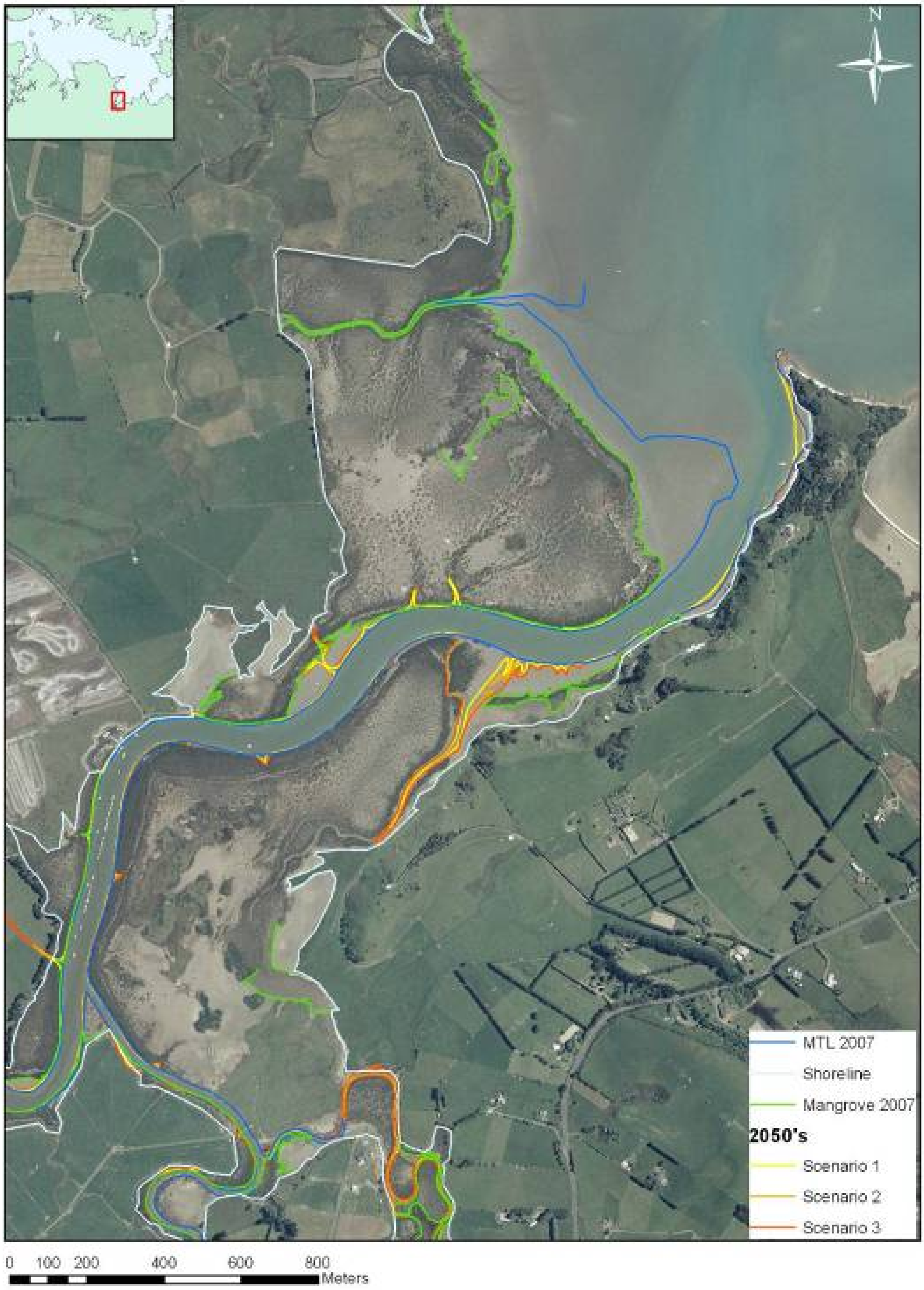
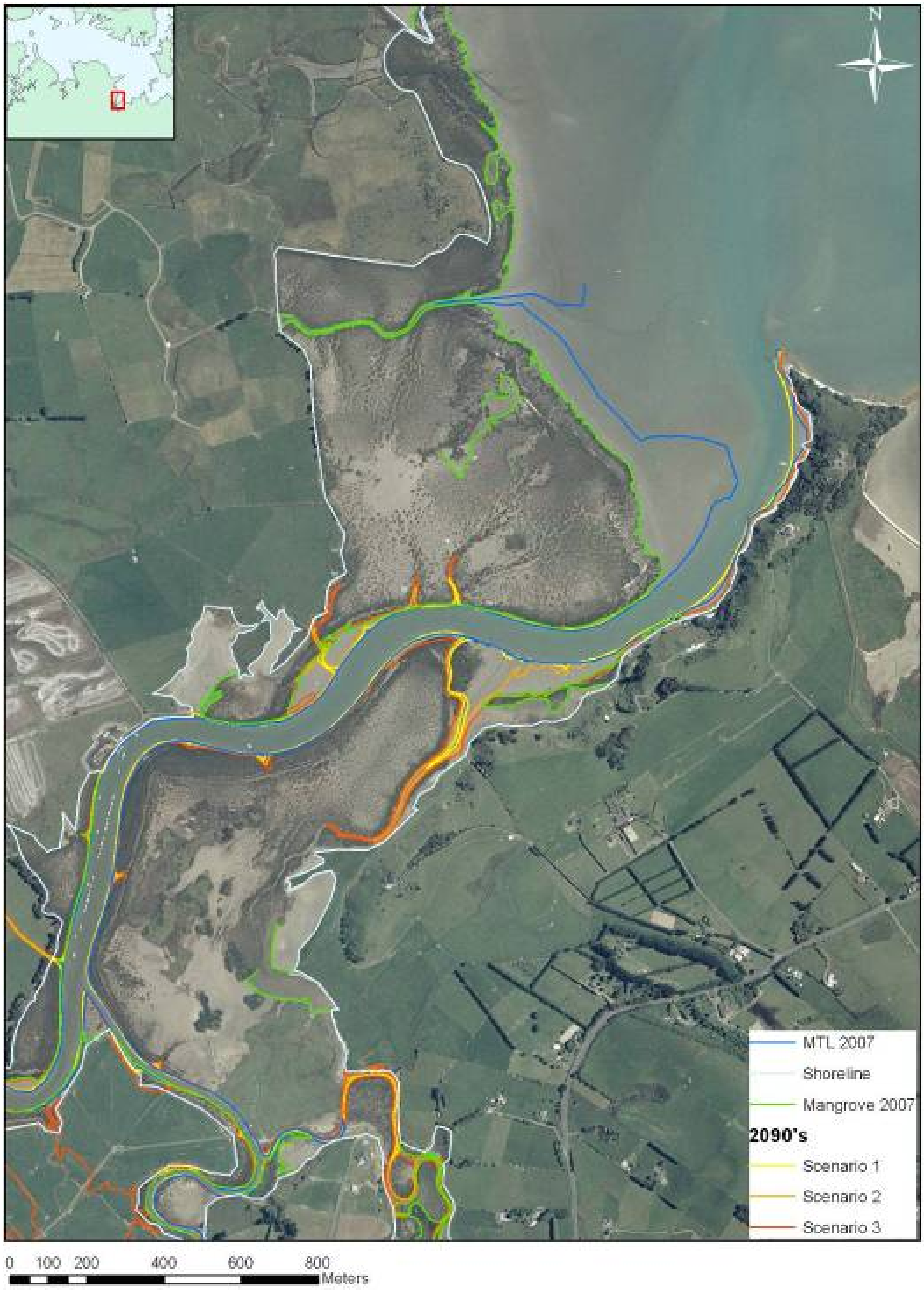


Figure 5.75:

Wairoa Estuary - 2090s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2090s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).



5.8.17 Te Matuku Bay (Waiheke)

Figures 5.76 and 5.77 map changes in potential and existing mangrove habitat in the Te Matuku Bay that are predicted to occur over the next century under the SLR Scenarios 1–3.

^{210}Pb dating of sediment cores indicate that SAR have averaged 6.5 mm yr^{-1} since the early 1950s (range: 4.2 – 8.7 mm yr^{-1}) on the upper intertidal flats immediately seaward of the mangrove forest (Swales et al. 2002a). Thus, tidal-flat elevation has increased more rapidly than the estuary-average SAR of 3.8 mm yr^{-1} adopted in the future SLR scenarios.

The results of the assessment for Te Matuku Bay indicate:

- mangroves presently occupy 52% of their potential habitat above MTL-2007 in Te Matuku Bay. Based on the relative catchment size, the estuary has a low level of vulnerability to sediment infilling, with an estuary infill time (T_A) of ~4,300 years (section 5.1). However, it is possible that sediment exported from the Wairoa Estuary is elevating sedimentation rates in Te Matuku Estuary;
- a low –medium likelihood of mangrove-seedling establishment on the intertidal flats at the estuary mouth under the existing wave climate;
- in the upper bay, the MTL-2007 isobath fringes a tidal channel draining the mangrove forest and the tidal-flat here slopes steeply into the channel. As a result, the predicted increases in tidal-flat area above MTL for SLR Scenario One over the next century are negligible. Loss of existing mangrove habitat in the upper bay is unlikely to occur until after the 2090s under SLR Scenarios Two and Three. Rapid sedimentation in the upper bay over the last 50 years (Swales et al. 2002a) suggests that existing mangrove habitat will be maintained in the long term;
- there is a low –medium likelihood of large-scale mangrove-habitat expansion in Te Matuku Bay during the next century based on: existing wave climate; availability of suitable habitat and future SLR scenarios.

Figure 5.76:

Te Matuku Bay - 2050s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2050s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (Section 3.3.4).

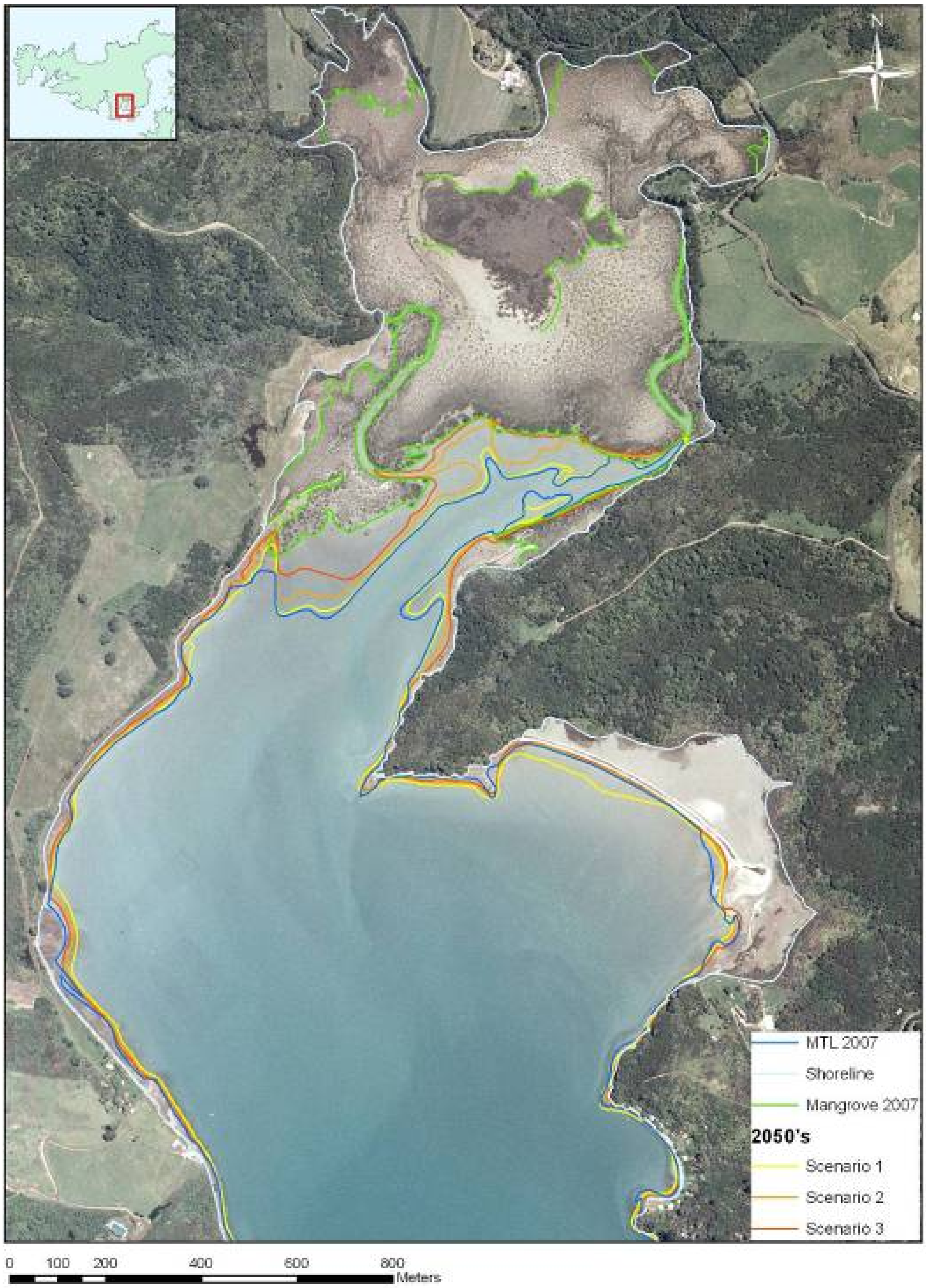
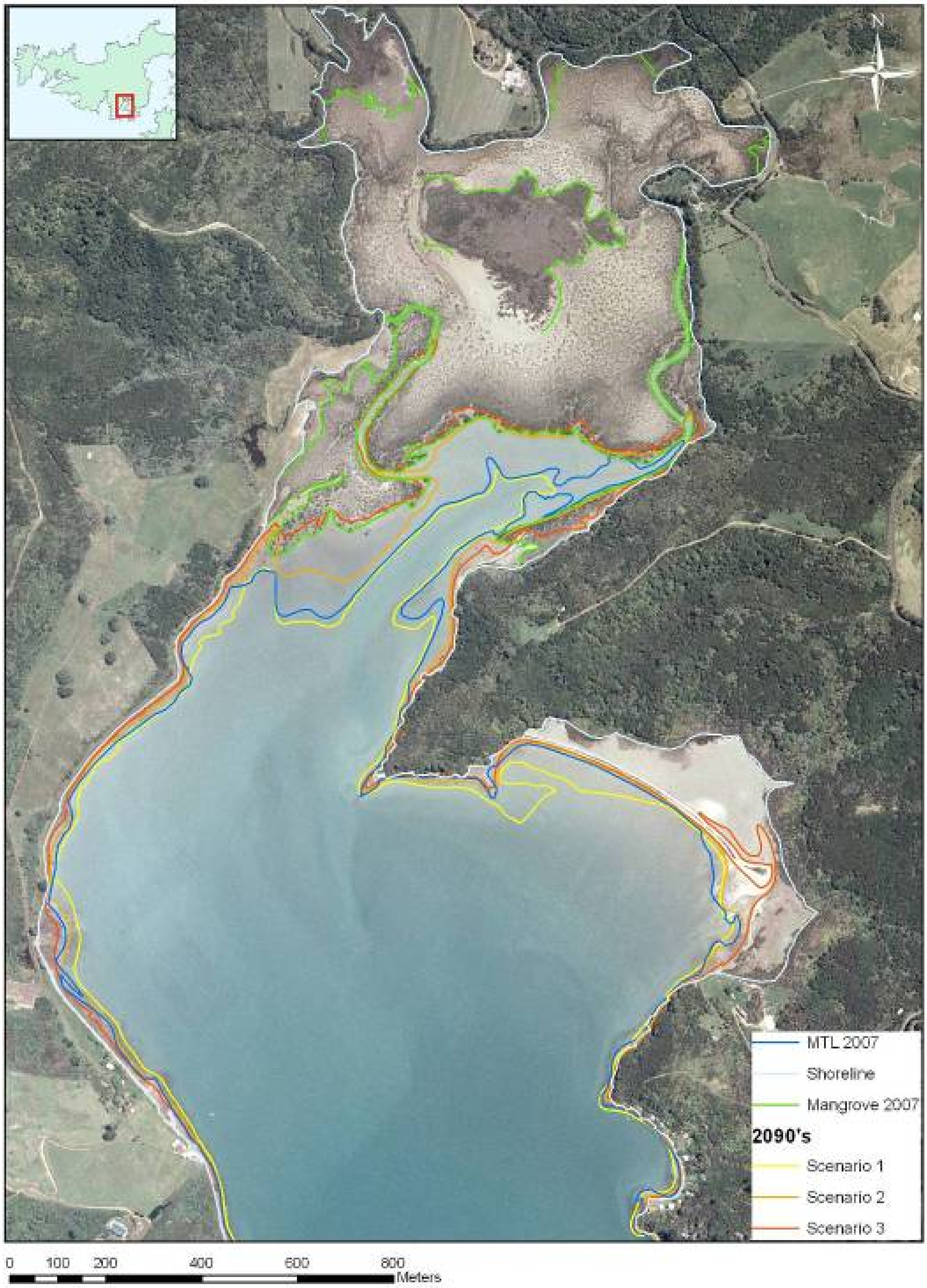


Figure 5.77:

Te Matuku Bay - 2090s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2090s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).



5.8.18 Awaawaroa Bay (Waiheke)

Figures 5.78 and 5.79 map changes in potential and existing mangrove habitat in the Awaawaroa Bay that are predicted to occur over the next century under SLR Scenarios 1–3.

The Awaawaroa Bay remains substantially subtidal and mangroves are limited to the tidal creek at the catchment outlet. A substantial area of tidal flat above MTL-2007 facing the bay has not been colonised by mangroves. Within the creek itself, the steeply sloping channel-banks mean that changes in MTL position due to future sea-level rise will be much less than occurs on the gently-sloping tidal flats.

The results of the assessment for Awaawaroa Bay indicate:

- mangroves presently occupy 29% of their potential habitat above MTL-2007 in Awaawaroa Bay. The estuary has a low level of vulnerability to sediment infilling, with an estuary infill time (T_A) of ~4,300 years (section 5.1);
- a low likelihood of mangrove-seedling establishment on the intertidal flats at the estuary mouth under the existing wave climate;
- minor increases in potential mangrove habitat occur under SLR Scenario One due to tidal-flat sedimentation. Loss of existing mangrove habitat is unlikely to occur under SLR Scenarios Two and Three until after the 2090s. Rapid sedimentation observed in tidal creeks in recent decades suggests that tidal-flat surface elevation will keep pace with the accelerated SLR Scenarios Two and Three, so that the existing mangrove habitat at the head of the bay will be maintained;
- there is a low likelihood of large-scale mangrove-habitat expansion in Awaawaroa Bay during the next century based on: existing wave climate; availability of suitable intertidal habitat; and future SLR scenarios.

Figure 5.78:

Awaawaroa Bay - 2050s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2050s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).

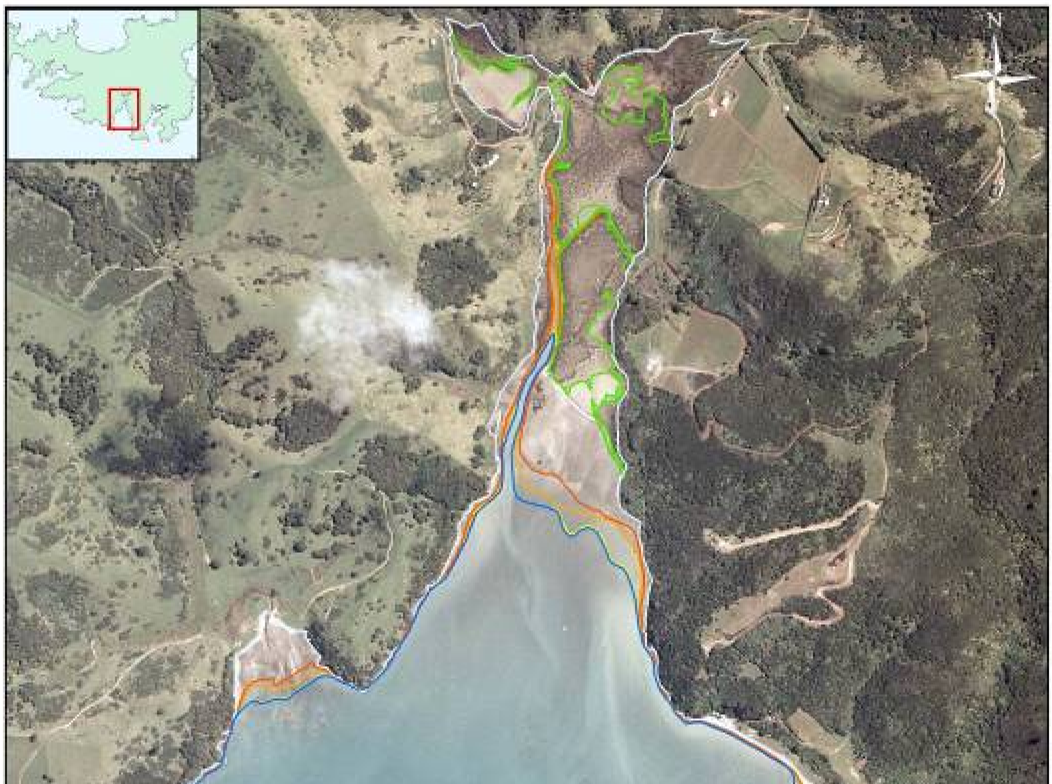
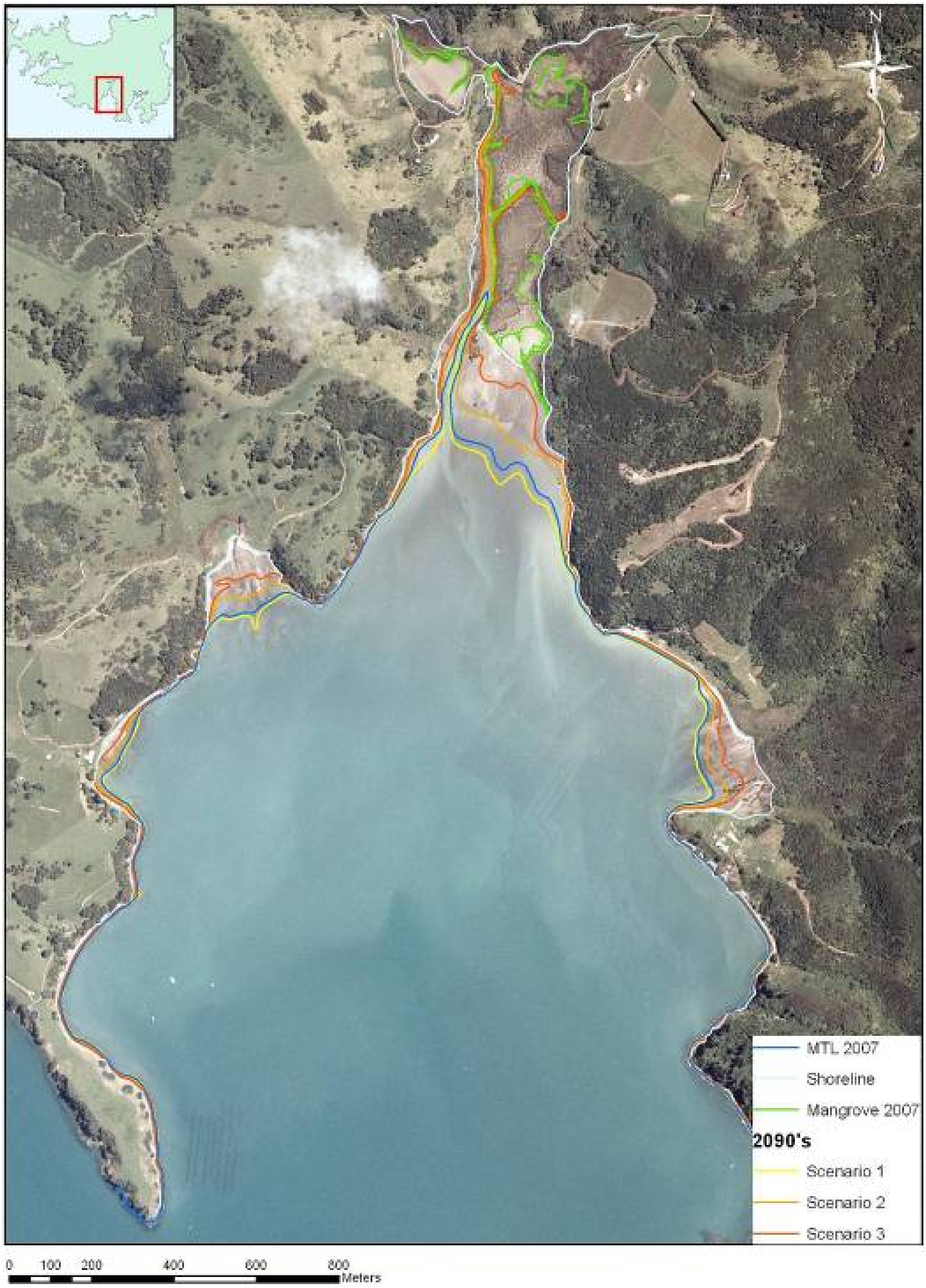


Figure 5.79:

Awaawaroa Bay - 2090s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2090s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).



5.8.19 Putiki Bay (Waiheke)

Figures 5.80 and 5.81 map changes in potential and existing mangrove habitat in the Putiki Bay that are predicted to occur over the next century under SLR Scenarios 1–3.

Like Awaawaroa, Putiki Bay remains substantially subtidal and mangroves are limited to tidal flats in the upper bay and in tidal creeks at sub-catchment outlets. A substantial area of tidal flat above MTL-2007, exposed to the south-west winds, has not been colonised by mangroves.

The results of the assessment for Putiki Bay indicate:

- mangroves presently occupy 56% of their potential habitat above MTL-2007 in Putiki Bay. The estuary has a low level of vulnerability to sediment infilling, with an estuary infill time (T_A) of ~7,900 years (Swales et al. 2008, section 5.1);
- a low likelihood of mangrove-seedling establishment on the intertidal flats at the estuary mouth during the next century under the existing wave climate;
- increases in potential mangrove habitat occur under the SLR Scenario One due to sedimentation in tidal-creeks and on the tidal flats. Loss of existing mangrove habitat is unlikely to occur until after the 2090s under SLR Scenarios Two and Three;
- there is a low likelihood of large-scale mangrove-habitat expansion in Pukiti Bay during the next century based on: existing wave climate; availability of suitable intertidal habitat; and future SLR scenarios.

Figure 5.80:

Putiki Bay - 2050s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2050s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).

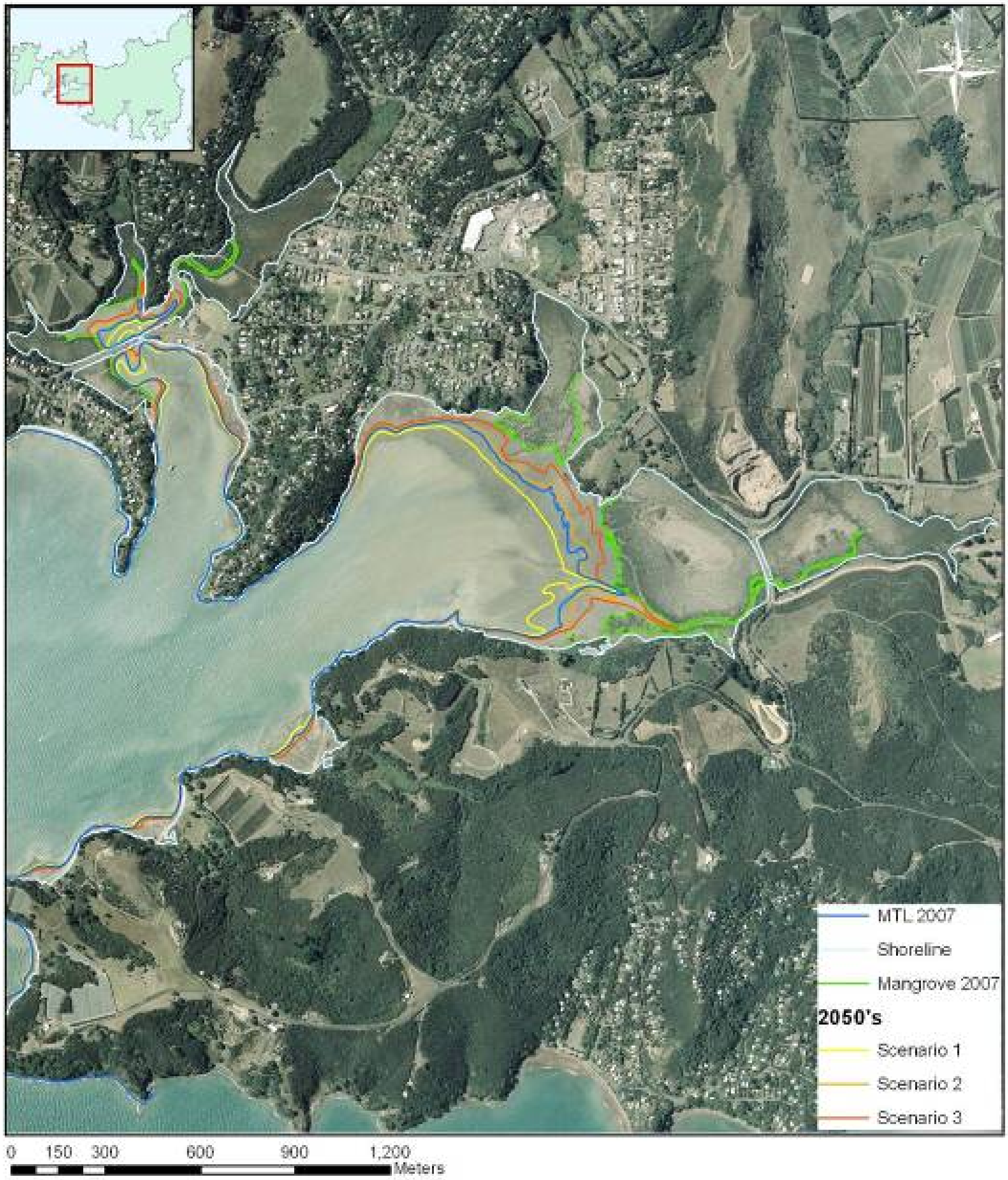
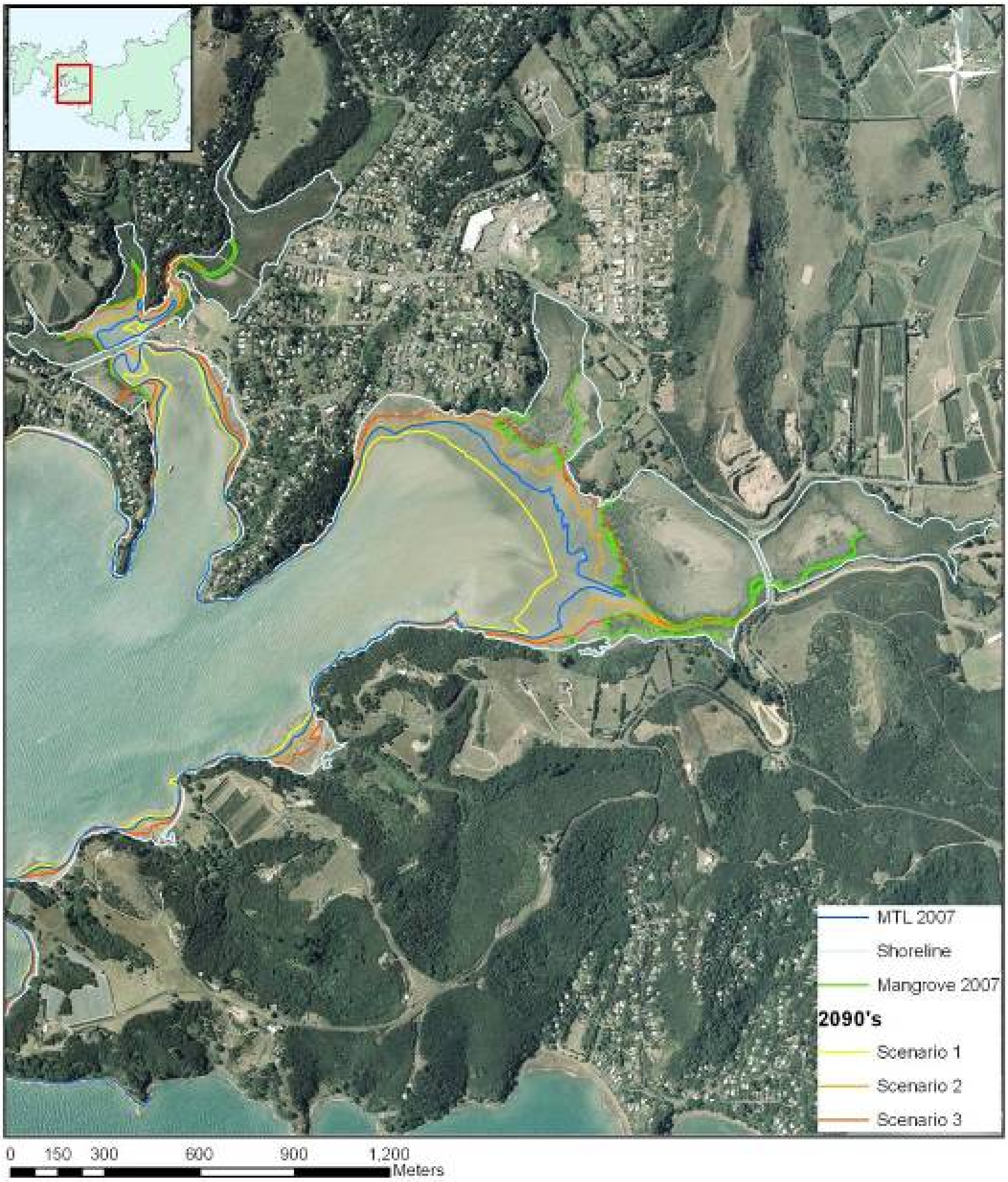


Figure 5.81:

Putiki Bay - 2090s. Predicted changes in potential mangrove habitat above the mean tide level (MTL) isobath by the 2090s due to estuary sedimentation and sea-level rise (SLR). Scenario 1 is based on the historical SLR trend since 1950. Scenarios 2–3 incorporate IPCC (2007) projections of accelerated SLR (section 3.3.4).



6 Synthesis

6.1 Influence of estuary infilling on mangrove-habitat expansion

Estuaries follow similar evolutionary paths over time as they infill with sediment: subtidal areas and average water depths decrease and as a result the hydrodynamic and sedimentological characteristics and biological communities change (Roy et al. 2001). In this context, the grey mangrove (*Avicennia marina* subsp *australasica*) that occurs in New Zealand may colonise intertidal flats down to mean tide level (MTL), as observed in southeast Australia (Clarke & Myerscough, 1993). This lower elevation limit reflects the physiological limitations of mangrove seedling survival due to oxygen supply (Hovenden et al. 1995). The ability of *A. marina* seedlings to colonise their potential habitat above MTL is also significantly influenced by bed-sediment reworking by waves (Clarke & Myerscough, 1993; Swales et al. 2007a). The role of waves in controlling seedling recruitment and resulting mangrove-habitat expansion in Auckland's east-coast estuaries is discussed in section 6.2.

The estuary infill time (T_A), adopted here provides a relative measure of the time in years to fill the tidal prism with catchment sediment (section 5.1). Using this metric we identified the Matakana, Puhoi, Waiwera and Wairoa estuaries as being most vulnerable to sediment infilling, with T_A < 500 years. Thus, those estuaries with relatively low infill times should have reached a more advanced stage of infilling with a proportionally larger intertidal area. An empirical analysis shows that this is indeed the case. Estuaries with relatively large catchments (ECA ratio) have a larger proportion of intertidal flat above MTL-2007 (Habitat to Estuary Area, HEA ratio). This can be described as:

$$\text{HEA} = -0.21\ (\text{LN(ECA)}\ -0.1\ (r^2 = 0.77,\ P < 0.001)$$

where LN denotes a natural-log transformation. The relationship between the HEA ratio and the estuary infill time (T_A) was also significant ($r^2 = 0.75$, $P < 0.001$) but did not explain any more of the variation in the data (Fig. 5.2b). Thus, the estuary/catchment area ratio is a useful predictor of the total intertidal area of an estuary above MTL that has the potential to be colonised by mangrove. The ECA ratio also has the advantage that it is readily estimated whereas the T_A requires tidal prism and sediment load data.

This analysis showed that the Wairoa and Waiwera estuaries have the highest HEA ratios (0.8) of all the study estuaries. Large areas of the tidal-flat areas above MTL-2007 in the Waiwera (50%) and Wairoa (75%) have been colonised by mangroves (section 5.4). Mangroves have also colonised a large fraction of their potential habitat in the Matakana (70%) and Puhoi (55%) estuaries.

6.2 Controls on mangrove-habitat expansion

Seedling recruitment is the precursor to mangrove habitat expansion in estuaries. Physical factors have a strong influence on mangrove colonisation of tidal flats, with biological factors appear to be of lesser importance. Key factors controlling mangrove colonisation of estuaries include:

- Propagule dispersal. Previous work indicates that *Avicennia* propagules are unlikely to survive long-distance dispersal by ocean currents and have a limited period of viability (i.e., several days), which is influenced by temperature and salinity. Initial propagule establishment is more likely to occur in close proximity to the parent plant (de Lange & de Lange, 1994).

- Tidal-flat surface elevation. Mangrove seedlings will not indefinitely survive submersion for more than six hours per tidal cycle, so that mangrove trees are not likely to be found below mean tide level.

- Wave climate. The frequency and intensity of bed sediment reworking by waves influences the stability of the substrate in which mangrove propagules must root. In estuaries with sufficient fetch, wave climate is an important factor controlling seedling recruitment.

These factors are each considered in the following section.

6.2.1 Propagule dispersal

Propagule dispersal by tidal currents and wind-induced drift is likely to be most effective within estuaries. This is mainly because of the limited period of propagule viability once dropped from the parent plant (de Lange & de Lange, 1994). The initial colonisation of Auckland's east-coast estuaries by propagules depended on the coincidence of suitable tide and wind conditions, which transported propagules from other estuaries. Mangroves have existed in NZ for millions of years (Morrisey et al. 2007) and are likely to have colonised present-day estuaries sometime after the sea reached its present level ~6,500 years ago and sediments eroded from the land gradually built suitable intertidal habitats. For example, Captain James Cook visited the Firth of Thames in 1769 and noted the presence mangroves along the lower Waihou River (Beaglehole, 1968) almost 100 years before large-scale catchment deforestation began. Sediment cores collected from the northern Firth of Thames, 35 m below present-day sea level, indicate that mangroves were present along the former coast 12,000 to 14,000 years ago (Pocknall et al. 1989).

Once adult mangrove plants become established in an estuary, these individuals became the most likely source of propagules. This local-source concept is consistent with the observed expansion of existing mangrove stands in Auckland estuaries (Roper et al. 1994; Morrisey et al. 1999; Swales et al. 2007c). Colonisation of tidal flats isolated from existing mangrove stands is less common and wind-drift is likely to be more important at dispersing propagules across the tidal-flats where currents are weak. Chapman & Ronaldson (1958) recognised that the prevailing westerly wind would be an important factor controlling propagule dispersal in Auckland's estuaries.

6.2.2 Tidal-flat elevation

The importance of tidal-flat elevation as a control on mangrove colonisation of tidal flats underpins the present study. The mean-tide level (MTL) is considered the lower-elevation limit (LEL) for grey mangroves, based on laboratory and field studies in Australia (Clarke & Hannon, 1970; Bird, 1971; Clarke & Myerscough, 1993; Hovenden et al. 1995). In New Zealand, the LEL has not previously been examined in detail. Based on observations in Auckland's estuaries, Chapman & Ronaldson (1958) concluded that mangrove swamps develop where "*there is active accretion by mud deposition ultimately bringing the sea bed sufficiently high for mangrove plants to colonise*." In the southern Firth of Thames, mangrove did not colonise the tidal flats until the early 1950s when they had accreted to 0.4 m above present-day MTL. In this case, the high wave exposure of the tidal flats has prevented seedling establishment below this elevation (Swales et al. 2007c).

In the present study, field surveys in late summer (February – April) 2008 showed that mangrove seedlings occurred on the tidal flats, on average, down to -0.2 m MTL (-0.09 m AVD-46, section 5.4.1). However, seedlings growing below MTL are unlikely to survive based on the physiological limitations previously discussed. The present-day distribution of mature mangrove trees in Auckland's east-coast estuaries is restricted to tidal flats, on average, above 0.25 m MTL (range: -0.1 to +0.73 m MTL). Field observations and wave modeling indicate that wave exposure is also a factor controlling mangrove distribution in Auckland's east-coast estuaries.

6.2.3 Wave climate

Our understanding of how wave climate influences mangrove habitat expansion in NZ estuaries has been advanced by recent research in the southern Firth of Thames (Swales et al. 2007a, 2007c). Sediment accumulation rates in the southern Firth are at the upper end of values measured in North Island estuaries, with SAR averaging ~20 mm yr^{-1} on the intertidal flats since the 1920s. This is similar to SAR measured in Auckland's tidal creeks and five times higher than average rates in their parent estuaries.

Wave climate strongly influences the frequency of seedling recruitment in the southern Firth. Major seedling recruitment events have occurred on average once per decade since the early 1950s. Bed sediments are frequently reworked by waves to ~5cm depth. During a typical summer, waves erode and detach the seedling's root system from this surface layer and they subsequently die. Consequently, major mangrove-habitat expansion occurs during rare periods of extended calm weather (i.e., up to several weeks) during the summer when propagules are released. Despite these adverse conditions, mangrove have colonised some 750 ha of tidal flat in the southern Firth since the early 1950s.

6.3 Historical trends in mangrove-habitat expansion

Presently, mangroves occupy 58% (27.1 km^2) of the 46.5 km^2 of their potential tidal-flat habitat above MTL-2007 in Auckland's east-coast estuaries. The aerial photographic record shows that the area of tidal flat in estuaries occupied by mangroves has increased by 28–400% since the 1950s (section 5.7). During the same period, the area of tidal flat above MTL is estimated to have increased by only 3 –19%, due to sedimentation. This disproportionately larger increase in mangrove distribution over the last 50 years suggests that:

- large areas of potentially suitable tidal flat habitat (above MTL) had not been colonised by mangrove before 1950;
- mangrove have colonised substantial areas of these pre-existing potential tidal-flat habitats since 1950;
- there has been a substantial time lag, of the order of decades, between tidal-flat development and subsequent mangrove-habitat expansion.

The colonisation time-lag observed in Auckland's mangroves is also a feature of cordgrass (*Spartina*) growth in estuaries, where rapid expansion of its distribution can occur after decades of gradual extension or stability. This lag phase maybe related to gradual acclimatisation to less than optimal environments or gradual tidal-flat accretion to an elevation suitable for Spartina colonisation (Gray and Raybould, 1997), in a similar way to mangroves.

Mangrove-habitat expansion has occurred most rapidly in the smallest estuaries, with high-tide areas less than 3 km^2. These estuaries are effectively fetch limited so that wave-driven reworking of bed sediments is a less influential factor controlling seedling recruitment in these small estuarine systems. Sediment accumulation rates in many of these small estuaries are also higher than the estuary average 3.8 mm yr^{-1} because of their close proximity to catchment sources and their small size. This means that the area potentially suitable for mangrove to colonise has increased more rapidly.

By comparison, mangroves have not substantially increased their distribution in the largest estuarine systems, such as the Mahurangi and Central Waitemata Harbour (CWH). In fact the area of mangroves in the CWH reduced by 8% between 1959 and 2007. Unlike Shoal Bay and Hobson Bay, mangrove loss due to reclamation and engineering works does not appear to be a major factor. In these largest estuaries, their fetches are large enough to drive frequent wave reworking of bed sediments. Chapman & Ronaldson (1958, p19) identified the instability of the substrate on the Te Atatu sand flats (CWH) as the key factor preventing mangrove seedlings from colonising the tidal flat. Recent work in the CWH shows that intertidal-flat sediments are rapidly mixed to ~5-cm depth, as observed in the southern Firth, due to frequent cycles of sediment resuspension by waves (Oldman et al. 2007; Swales et al. 2007b). Because of these conditions, SAR are lower on the intertidal flats and fine sediments preferentially accumulate in subtidal habitats where wave resuspension is less pronounced.

6.4 Potential for future mangrove habitat expansion

The potential for future expansion of present-day mangrove stands has been assessed based on:

- proportion of potential habitat (i.e., above MTL-2007) presently occupied by mangrove trees;
- vulnerability to sediment infilling;
- analysis of the long-term wave climate based on wave modelling for present-day and future sea-level rise (SLR) scenarios. The wave-modelling methodology and results are described in detail by Gorman and Swales (2009);
- probability of sand entrainment on the intertidal flats;
- mapping of future changes in the area of intertidal flat above MTL-2007 isobath based on estuary SAR over the last 50 years and SLR Scenarios 1–3 (section 3.3.4).

To assist with the interpretation of results: Table 6.1 presents key attributes of the study estuaries; and Figs. 6.1–6.3 plot the likelihood of seedling establishment versus the percentage change in estuary area above MTL for each of the three sea-level rise scenarios (section 3.3.4).

The analysis indicates that, there is a low likelihood of large-scale mangrove-habitat expansion in most of Auckland's east-coast estuaries. The Puhoi and Waiwera Estuaries respectively are identified as having medium and high likelihoods of large-scale mangrove habitat expansion.

The Wairoa Estuary (Clevedon) also has all of the key attributes that make it vulnerable to mangrove colonisation, which include a high vulnerability to sediment infilling, large proportion of tidal flat above MTL-2007 and low wave-energy environment. However, the estuary infilled with sediment and was largely colonised by mangroves before the 1950s. The Wairoa provides an example of the fate of estuaries subject to accelerated sedimentation.

Table 6.1:

Summary of estuary physical characteristics, vulnerability to sediment infilling and likelihood of large-scale mangrove habitat expansion based on long-term historical wave climate and availability of suitable intertidal habitat above MTL-2007. Notes: (1) present-day mangrove habitat as a % of the intertidal area above MTL-2007; (2) sediment infill time (T_A) based on tidal-prism volume and estimated mean annual catchment sediment loads. Vulnerability to sediment infilling: High (T_A < 500 yrs); Medium (T_A = 500 – 5,000 yrs); Low (T_A > 5,000 yrs).

Estuary	Area (km^2)	MTL-2007 Area (km^2)	MTL-2007 Area (%)	Mangrove Area (%)[1]	T_A (years)[2]	Likelihood of mangrove habitat expansion
Whangateau	8.0	2.66	33	51	900	Medium – Low
Matakana	4.4	1.58	36	68	500	Low – Medium
Mahurangi	25.1	8.16	33	69	1,900	Low
North Cove	0.6	0.11	18	29	6,700	Low
Bon Accord	2.4	0.19	8	22	10,700	Low
Puhoi	1.8	1.05	58	56	400	Medium
Waiwera	1.0	0.81	81	51	400	High
Orewa	1.2	0.61	51	69	1,900	Low – Medium
Weiti	2.4	1.42	59	71	900	Low
Okura	1.4	0.85	61	29	600	Low – Medium
Waitemata	65.8	14.21	22		15,000	
UWH		3.55		47		Low
CWH		10.66		67		Low
Shoal Bay		2.42		57		Low
Hobson Bay		1.04		35		Low – Medium
Tamaki	16.9	3.02	18	57	4,700	Low
Whitford	11.3	3.89	34	29	1,800	Low
Wairoa	2.9	2.33	80	74	200	Low
Te Matuku	2.6	0.91	35	52	4,300	Low – Medium
Awaawaroa	2.9	0.38	13	29	4,300	Low
Putiki	3.4	0.87	26	56	7,900	Low

Figure 6.1:

Scenario One (2090s) sea-level rise: assessment of potential for future mangrove-habitat expansion in Auckland's east coast estuaries for SLR of 0.14 m by the 2090s and an average annual sedimentation rate of 3.8 mm yr^{-1}. The graph plots the likelihood of seedling establishments under the existing wave climate versus the percentage change in potential mangrove habitat above mean tide level. Estuary codes: Whangateau (WH); Matakana (MK); North Cove, Kawau (NC); Bon Accord, Kawau (BA); Mahurangi (MA); Puhoi (PU); Waiwera (WW); Orewa (OR); Weiti (WE); Okura (OK); Waitemata (WT); Upper Waitemata (UWH); Central Waitemata (CWH); Shoal Bay (SB); Tamaki (TK); Whitford (WF); Wairoa (WA); Te Matuku (TM); Awaawaroa (AW); Putiki Bay (PK).

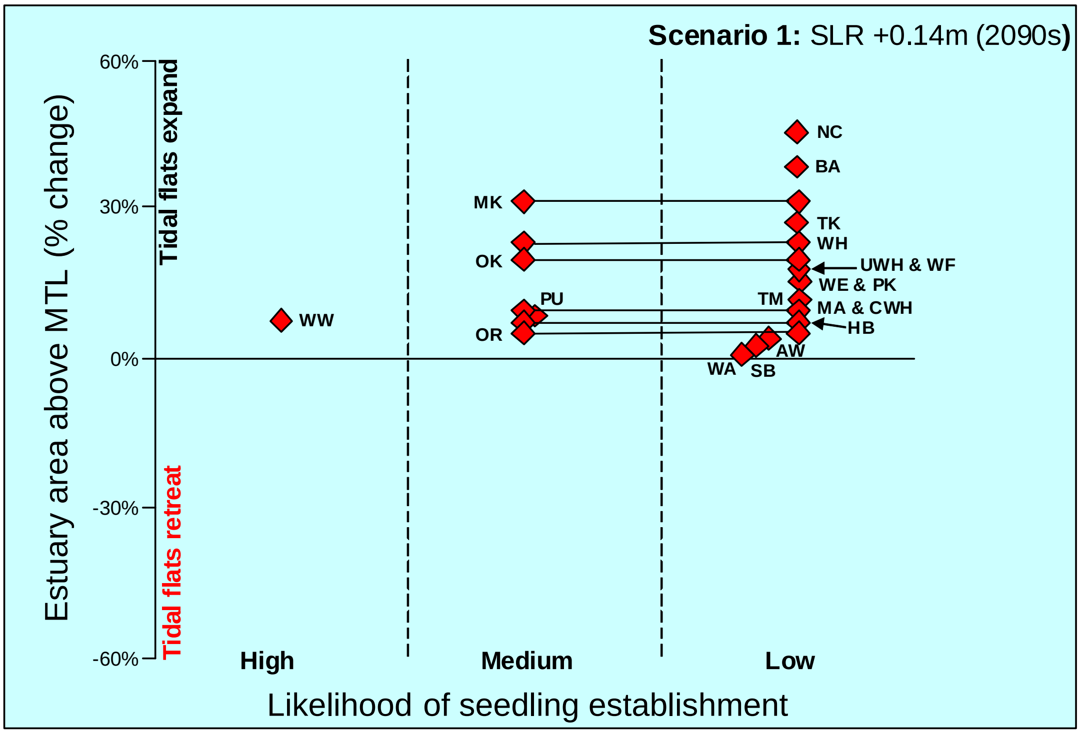


Figure 6.2:

Scenario Two (2090s) sea-level rise: assessment of potential for future mangrove-habitat expansion in Auckland's east coast estuaries for SLR of 0.47 m by the 2090s and an average annual sedimentation rate of 3.8 mm yr^{-1}. The graph plots the likelihood of seedling establishments under the existing wave climate versus the percentage change in potential mangrove habitat above mean tide level. Estuary codes: Whangateau (WH); Matakana (MK); North Cove, Kawau (NC); Bon Accord, Kawau (BA); Mahurangi (MA); Puhoi (PU); Waiwera (WW); Orewa (OR); Weiti (WE); Okura (OK); Waitemata (WT); Upper Waitemata (UWH); Central Waitemata (CWH); Shoal Bay (SB); Tamaki (TK); Whitford (WF); Wairoa (WA); Te Matuku (TM); Awaawaroa (AW); Putiki Bay (PK).

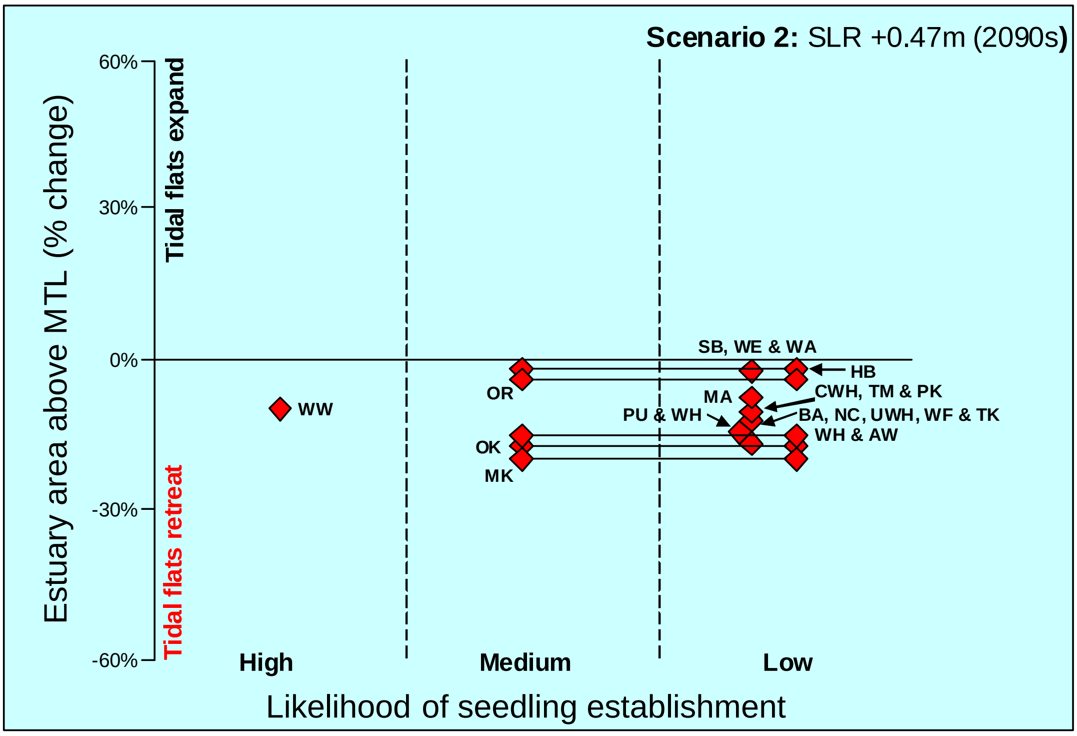
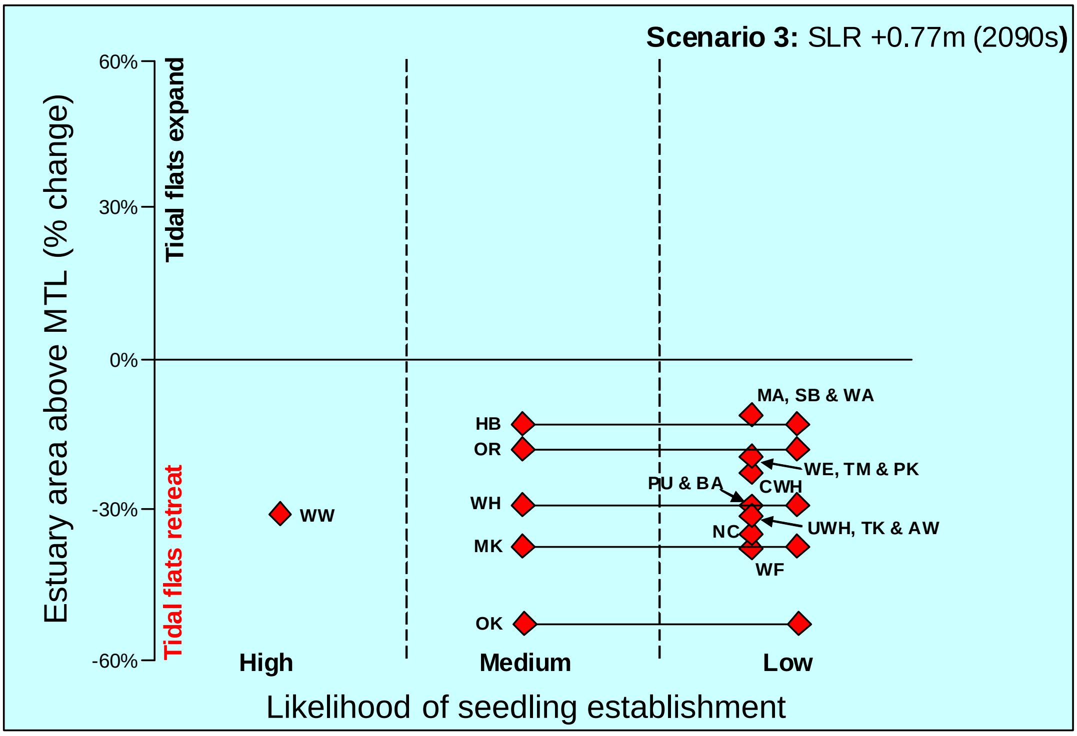


Figure 6.3:

Scenario Three (2090s) sea-level rise: assessment of potential for future mangrove-habitat expansion in Auckland's east coast estuaries for SLR of 0.77 m by the 2090s and an average annual sedimentation rate of 3.8 mm yr^{-1}. The graph plots the likelihood of seedling establishments under the existing wave climate versus the percentage change in potential mangrove habitat above mean tide level. Estuary codes: Whangateau (WH); Matakana (MK); North Cove, Kawau (NC); Bon Accord, Kawau (BA); Mahurangi (MA); Puhoi (PU); Waiwera (WW); Orewa (OR); Weiti (WE); Okura (OK); Waitemata (WT); Upper Waitemata (UWH); Central Waitemata (CWH); Shoal Bay (SB); Tamaki (TK); Whitford (WF); Wairoa (WA); Te Matuku (TM); Awaawaroa (AW); Putiki Bay (PK).



The pace of future sea-level rise relative to sedimentation rates will ultimately determine the long-term fate of the mangrove stands and forests that already exist in Auckland's east–coast estuaries. Predictions of potential future changes in mangrove habitat by the 2050s and 2090s due to sea-level rise (SLR) and estuary sedimentation indicate:

- increases in potential mangrove habitat above MTL under SLR Scenario One;
- reductions in potential mangrove habitat above MTL under SLR Scenarios Two and Three.

The main reason for this major difference in the predicted outcomes is that under the SLR scenarios based on IPCC (2007) projections the rate of sea-level rise will exceed average sediment accumulation rates in Auckland's east coast estuaries (3.8 mm yr^{-1}, section 4.8), This is not the case for Scenario One, which is based on the historical trend in sea-level observed at the Port of Auckland. The main exception to this general pattern is that higher SAR in several tidal creeks are likely to more than compensate for any future acceleration in the rate of sea-level rise.

Under the historical-trend assumption, increases in potential mangrove habitat (i.e., tidal flat area above MTL) will average 8% by the 2050s and 14% by the 2090s (section 5.8). Thus, future estuary sedimentation will potentially add a further 3 km^2 of potential mangrove habitat by the 2050s and 5.8 km^2 by the 2090s. These rates are in line with values over the last 50 years. However, as we have seen, there is already 19.4 km^2 of tidal flat above the MTL-2007 isobath potentially available for mangrove-habitat expansion.

Under SLR Scenarios Two and Three, the area of potential mangrove habitat is predicted to shrink by -4.5 km^2 (Scenario Two) and -11 km^2 (Scenario Three) by the 2090s. Mangroves may respond to rising sea-level by retreating landward or by increasing tidal-flat surface elevations at a rate equal to or exceeding sea-level rise.

In many of Auckland's estuaries engineering structures, such as stopbanks, motorway reclamations and seawalls will prevent landward retreat of mangrove stands. The effect of this relative increase in sea level will be increased water depths, landward retreat of the MTL isobath and increasing exposure of existing mangrove stands and forests to direct wave attack. The effects of this accelerated SLR will be most severe in the largest and therefore least fetch-limited estuaries (i.e., CWH, Shoal Bay and Mahurangi) and estuaries directly exposed to the coast (e.g., Okura, Whitford, Wairoa, Waiheke and Kawau Island estuaries).

Alternatively, tidal-flat surface elevations will keep pace with future sea-level rise. However this would require substantial increases in catchment sediment loads and/or substantial sediment redistribution within estuaries (e.g., tidal flat erosion). For example, long-term average intertidal SAR of 3.8 mm yr^{-1} (1950 – present) would have to more than double to keep pace with the average 8.8 mm yr^{-1} SLR predicted under Scenario Three (section 3.3.4). The doubling of sediment loads implied by this scenario is unlikely to occur unless there is a major shift in rainfall patterns and/or landuse that enhance soil erosion. Sedimentation is enhanced in mangrove stands fringing tidal creeks (Craggs et al. 2001; Swales et al. 2002b) and tidal flats (Swales et al. 2007a) so that locally mangrove forests may keep pace with future sea-level rise. However, this is not the case for the mature mangrove stands on the upper intertidal flat where SAR are likely to track closely with historical SLR (Swales et al. 2008). In these mature forest stands sediment supply is limited by the low frequency and duration of tidal inundation. Although future accelerated SLR would increase tidal inundation and potential for sediment delivery to the mangrove forest, it is uncertain if sediment surface elevation could keep pace with increases in sea level. As identified above, this would require a doubling or more in sediment supply.

Mapping the future retreat of the MTL isobath under SLR Scenarios Two and Three indicates that in most estuaries loss of existing mangrove stands is unlikely to occur until after the 2090s. Tidal creeks will provide refuge for mangroves, assuming that the rapid sedimentation (~20 mm yr^{-1}) observed in these environments over the last 50 years occurs in the future. Thus, over time mangrove stands would be displaced from intertidal flats in the main body of Auckland's east coast estuaries but retained in the tidal creeks where they appear to have first colonised these systems.

6.4.1 Oceanographic and hydrodynamic effects

The predictions of future changes in mangrove habitat in Auckland's east-coast estuaries under the accelerated SLR Scenarios Two and Three indicate that we are unlikely to see any large-scale loss of mangroves during the next century. Recent studies published after the IPCC (2007) report indicate that rates of sea-level rise over the next century are likely to equal or exceed Scenario Three (section 3.3.4), which projects a 0.77 m increase in sea level at the Port of Auckland by the 2090s. Thus, the historical trend in sea level observed over the last century is considered an unlikely future scenario.

Long-period fluctuations in sea level may also influence how quickly the effects of accelerated sea-level rise will be seen in estuaries. These longer period effects include the:

- inter-annual 2–4 year El Nino-Southern Oscillation (ENSO) cycles, which result in fluctuations in sea level of ±0.12 m on the east and west coasts of the upper North Island;
- inter-decadal 20–30 year Interdecadal Pacific Oscillation (IPO) cycles, which results in fluctuations of ±0.05. The rate of sea-level rise tends to increase during negative phases of the IPO and to slow rates of SLR during positive phases. The IPO began a negative phase in 1999, which appears to have resulted in a higher mean level of the sea over the last several years.

In concert, the ENSO and IPO can result in periods of decreased or more stable or more rapid increases in sea level relative to long-term average values. This year to year variability in mean sea level partly reflects these long-period fluctuations (Fig. 3.5). The implications for future reductions in mangrove habitat are that changes could occur rapidly after a period of relative stability in sea levels, depending on the timing of the IPO in particular. The potential effects of the IPO will become an important factor after the 2050s when rising sea levels begin to inundate tidal flats in Auckland's estuaries.

Ultimately, mangrove habitat loss is likely to occur because sea level will continue to rise for several centuries beyond 2100 AD in response to historical emissions of greenhouse gases. This is due to the long time lags for the ocean to respond to climate warming. This lag response is known as present future commitment to sea-level rise. For example, global climate models predict that sea level will rise by 0.6 – 2 m over the next several hundred years due to thermal expansion alone.

The analysis undertaken in the present study has also considered dynamic effects on sea levels in estuaries, by modelling the influence of tidal amplification in estuaries due to morphology and bed-friction effects on tidal-wave propagation (sections 4.5). On gently-sloping tidal flats, amplification of the tide may locally increase or decrease sea level and therefore the area available to mangroves. However, numerical modelling of several estuaries under present-day and future sea level scenarios showed that tidal amplification will have a minor effect on MTL position in comparison to the effect of sea-level rise itself. The effect of tidal amplification is most pronounced in the Tamaki Estuary, due to its funnel-shaped morphology. Even in this case, changes in MTL horizontal position under the SLR scenarios considered are of order of several metres.

6.5 Sources of uncertainty

Predictions of future mangrove-habitat changes in Auckland's east-coast estuaries are based on several key assumptions. We discuss these assumptions as well as sources of uncertainty.

1. **Physical processes are the key factors controlling mangrove distribution and habitat expansion in Auckland's east-coast estuaries.**

Morrisey et al. (2007) have reviewed the current state of knowledge regarding the New Zealand mangrove. Their literature review, as well as data presented in the present study, supports the hypothesis that tidal-flat elevation is the primary control on mangrove distribution. This lower elevation limit is close to mean tide level and appears to be modified by wave exposure, although we where not able to confirm this from the wave modelling. However, Swales et al. (2007a) have shown that wave climate is an important factor controlling mangrove-seedling recruitment that relates to the frequency and intensity of bed erosion by waves.

Other factors, such as increased nutrient loads to estuaries and increasing atmospheric CO_2 concentrations may enhance mangrove growth. However there is no conclusive evidence that these factors have accelerated mangrove spread in North Island estuaries (Morrisey et al. 2007). Given the physiological intolerance of grey-mangrove seedlings to continuous submersion (section 3.3), tidal-flat elevation must be the primary controlling factor.

2. **Sediment accumulation rates (SAR) over the next century will be similar to SAR measured in Auckland's estuaries over the last 50 –100 years.**

Catchment sediment loads and the estuary sediment trapping efficiency are key parameters influencing SAR. Changes in rainfall patterns and catchment landcover will determine long-term catchment sediment loads. In particular the frequency and intensity of storms will affect sediment delivery to estuaries. Whilst it is expected that the intensity of severe storms may increase, there is still much uncertainty associated with how future climate change will influence the frequency, intensity and tracking of tropical cyclones (in the Pacific tropics), ex-tropical cyclones, which track down to the temperate regions such as New Zealand), extra tropical cyclones, mid- and low-latitude storms (MfE, 2008).

The proportion of the annual catchment sediment load that is trapped in an estuary typically declines as the estuary infills with sediment. As the estuary becomes intertidal, stormwater is discharged from the estuary to the coast and there is less storage volume to accommodate sediments. Waves also become more effective at resuspending tidal-flat sediments as water depths decrease (Swales et al. 2004; Green & Coco, 2007) which can be transported from the estuary by tidal currents.

Mangroves substantially enhance sediment trapping in estuaries and SAR in the fringes of mangrove forests are typically several times higher than on bare intertidal flats. However, sediment trapping becomes less effective as surface elevation increases because of the reduced frequency and duration of inundation by the tide (section 6.4).

There has been little progress, both globally and in New Zealand since the IPCC Third Assessment Report in 2001 in understanding the effects climate change is having, and will have on coastal processes, such as tides, storms, waves, swell and coastal sediment supply (MfE, 2008). In the context of the present study, changes in rainfall and wind climate have the potential to effect catchment sediment loads to estuaries and sediment transport and deposition within estuaries.

3. Future changes in wind climate that will influence the likelihood of mangrove seedling recruitment in estuaries.

Whilst it is expected that the intensity of severe storms may increase, there is still much uncertainty associated with how future climate change will influence the frequency, intensity and tracking of ex-tropical cyclones, which track down to the temperate regions such as New Zealand), extra tropical cyclones and mid- and low-latitude storms. There is a reasonable level of confidence that an increase in the mean westerly-wind component will occur by the 2090s. Although there is likely to be a shift in bias to more westerly winds, overall wind speeds in all directions may not change significantly. For the consideration of wind-climate effects, the MfE Guidance Manual (MfE, 2008) recommends:

- a 10% increase in the frequency of occurrence of the westerly wind component for both 2050s and 2080s;
- a 10% increase in the intensity of the most extreme events for the Hauraki Gulf coast, reflecting potential increases in intensity of ex-tropical cyclones systems.

These scenarios indicate that the pattern of prevailing westerly winds are likely to be reinforced by future climate change. The implications of such changes for mangrove-habitat expansion is that seedling recruitment will be less likely to occur on the down-wind lee shores of estuaries. Wave modelling also indicates substantial increases in the probability of sand entrainment on the tidal flats by the 2090s under the SLR Scenarios Two and Three (Gorman & Swales, 2009). Thus, the information that is presently available suggests that conditions for mangrove-seedling recruitment will be even less favourable in the future.

4. Future projections of mangrove-habitat changes are inherently uncertain.

Projections of future changes in mangrove-habitat extent in Auckland's east-coast estuaries are based on an average annual sediment accumulation rate of 3.8 mm yr^{-1} (section 4.3) and three different scenarios of future sea level rise. Scenario One is based on the historical trend in sea level of 1.6 mm yr^{-1} observed at Auckland since 1950. Scenarios Two and Three are based on MfE (2008) guidance regarding accelerated sea-level rise associated with climate warming. Under these two scenarios rates of sea-level rise will exceed SAR. Thus, under Scenario One an increase in the intertidal-flat area above MTL and therefore potential mangrove habitat is expected. By comparison, under Scenarios Two and Three: (1) intertidal areas will shrink as a result of accelerated sea-level rise; and (2) loss of existing mangrove stands due to increased sea levels and/or wave exposure is unlikely to occur until after the 2090s in most estuaries.

Dormann (2007) has highlighted the potential limitations of predicting future changes in species distributions. Many of these issues are relevant to the prediction of mangrove-habitat changes in Auckland's east-coast estuaries:

- uncertainty attached to future climate and land-use change scenarios;

The uncertainty in future climate-change scenarios has been addressed by considering a range of sea-level rise scenarios, which include the observed historical trend in sea level as well as base and accelerated SLR scenarios for New Zealand as recommended by the Ministry for the Environment in its recent Guidance Manual (MfE, 2008). More recent studies, not included in MfE assessment indicate that even the accelerated IPCC (2007) scenario of +0.8 m SLR by the 2090s maybe conservative.

- environmental-change scenarios are spatially uncertain;

In the present study we have adopted an estuary-average SAR of 3.8 mm yr^{-1}, which offset the effects of future SLR in estuaries. This value is based on robust estimates derived from sediment cores collected at 19 sites in several of the study estuaries (section 4.3). The advantage of adopting a constant SAR value is that predicted changes in the spatial extent of potential mangrove habitat (due to SLR) is only a function of local tidal-flat slope. This enables direct comparisons of the effects of SLR scenarios to be made between estuaries. Furthermore, the tidal-slope data, in most cases, is derived from high-resolution LiDAR measurements. By comparison SAR measurements are available for a relatively small number of sites.

Sediment accumulation rates will vary within and between estuaries so that the local SAR may be more or less than the estuary-average value. This will result in local differences from predicted changes in potential mangrove habitat.

- causal drivers are rarely quantifiable;

In comparison to many plants, the potential distribution of grey mangroves within estuaries is largely determined by relatively few, mainly, physical factors. Tidal-flat elevation appears to be the single most important factor. Mangrove recruitment is also strongly influenced by wave exposure. The importance of these physical controls also relates to the fact that mangroves extend below the elevation ranges of most estuarine plants, so that biotic factors such as inter-species competition is less important. This is not necessarily the case near their upper elevation limit near high tide where mangroves may compete with saltmarsh species (Morrisey et al. 2007). Cord-grass (*Spartina*) shares many similarities with grey mangroves in that physical processes also largely control its distribution on intertidal flats (Swales et al. 2004).

- species distribution may not be in equilibrium with its environment;

The present distribution of mangroves within an estuary may not be in equilibrium with sea level and tidal flat elevation due to lag effects and catastrophic events. For example, in estuaries with sufficient fetch, mangrove-seedling recruitment can be highly infrequent due to wave-exposure effects. In the Firth of Thames large-scale recruitment only occurs once per decade on average. Storm-wave erosion of tidal flats may also result in loss of adult mangrove stands (Swales et al. 2007a,c). Severe, infrequent frosts may also kill large areas of mangroves. In the Waitemata Harbour, severe frosts in 1951 killed mangrove trees in the Henderson Creek (Chapman and Ronaldson (1958). Dwarf forms that grow behind the tallest trees that fringe tidal flats and creeks are particularly vulnerable to frost effects. This may in some cases explain the bare tidal-flat areas within mangrove stands that are observed in many of the study estuaries. Climate-change projections for New Zealand indicate that mean air temperatures will increase and the frequency of frosts will decrease over the next century (Ministry for the Environment, 2008b). Thus, the frequency of mangrove mortality associated with extreme cold temperatures and frosts will also decrease.

- predicted species distributions are potential distributions contingent on the assumption that limiting factors remain limiting factors.

The future fate of mangrove forests primarily depends on sediment-surface elevation increasing at a rate equal to or exceeding sea-level rise. Sediment-core studies suggest that mangroves may not be able to survive accelerated SLR, particularly in sediment-starved systems. McKee et al. (2007) reconstructed a Holocene (i.e., last 10,000 years) sea-level record for Caribbean mangrove forests from dated cores. These mangrove forests were able to accommodate SLR rates of up to 4 mm yr^{-1}, mainly due to peat deposition. At higher rates of SLR, mangroves were absent. In New Zealand, it is highly likely that elevated catchment sediment loads will enable mangroves to keep pace with future sea-level rise. Studies such as McKee et al. (2007) demonstrate: (1) the importance of physical processes in determining the long-term fate of mangroves; and (2) that these factors, in particular sea-level changes and sedimentation processes, have also been key drivers in the past.

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9 Appendices

9.1 Appendix 1: Ground control points for aerial photography

Ground control points (GCP) were surveyed by Geomatics Survey Ltd of Rotorua (contact: Mr Kevin Sewell, job ref: 20761) during March 2008. The horizontal positions of the GCP were surveyed using a Leica dual frequency RTK GPS system. The GCP were surveyed in terms of the GD2000 PositioNZ permanent GPS base stations in Auckland, Hamilton and the Coromandel. Results are reported in terms of the NZ transverse Mercator (NZTM) co-ordinate system and Mean Sea Level Auckland Vertical Datum 1946 (AVD-46). The positional accuracy was to within ± 0.1 m (horizontal) and ± 0.35 m (vertical). Table 8.1 provides details of each GCP.

Table 8.1:

Ground control points (GCP) surveyed for aerial photography control. Elevation is relative to the Auckland Vertical Datum 1946 (AVD-46).

GCP #	Location	NZTM (East)	NZTM (North)	Elevation (m AVD-46)	Site Description
1	Waiheke Island	1785908.5	5926609.87	5.56	Fence intersection. RL at GL roadside.
2	Waiheke Island	1781382.08	5927857.69	4.41	Intersection of projected driveway edge with seal edge.
3	Waiheke Island	1780265.29	5924089.19	40.77	Corner of concrete Footpath and low rail fence. RL on footpath.
4	Waiheke Island	1783580.03	5923200.99	10.69	Centre of circular traffic island. Flag pole in centre. RL beside pole and 0.45m above sealed road.
5	Waiheke Island	1791622.17	5920203.62	2.64	Corner of Orapiu Wharf. RL on deck level.
6	Waiheke Island	1792495.79	5923430.96	90.01	Intersection of white painted concrete walls. RL at GL beside gate post.
7		1790604.04	5909055.53	29.03	Gate post
8		1783012.30	5905482.27	11.20	Gate post
9		1777877.99	5916630.85	16.79	Corner of concrete pad.
10		1763724.86	5913642.68	25.67	Corner of concrete traffic island in shop carpark. RL at seal level. Concrete 0.1m above RL.
11		1758758.94	5908436.01	16.11	Corner of concrete drive at grass level at kerb. Channel 0.15m below RL.
12		1767179.42	5904205.26	28.08	Corner of concrete island in car park. RL at seal level. Concrete 0.1m above RL.

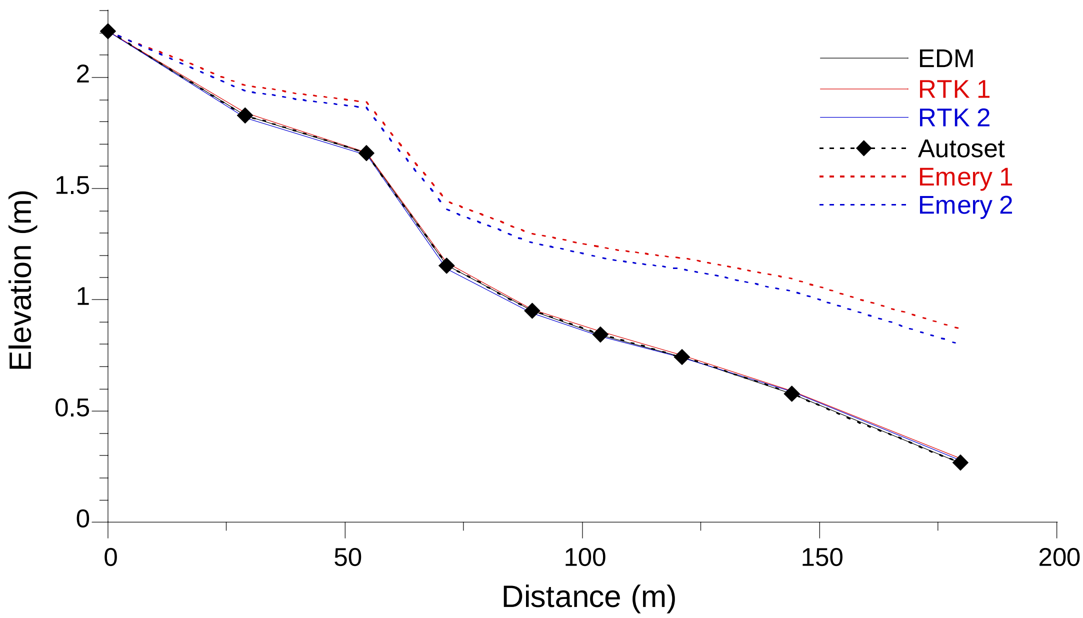
GCP #	Location	NZTM (East)	NZTM (North)	Elevation (m AVD-46)	Site Description
13		1755300.69	5917700.53	35.60	Intersection of light coloured concrete paving with edge of asphalt seal 1.3 metres off fence angle
14		1742294.95	5931104.30	11.45	Corner of concrete drive.
15		1740636.67	5914406.43	63.20	End of white wooden fence and corner of cattle stop.
16		1749248.21	5912743.96	42.77	Intersection of edge of light .coloured seal with face of kerb.
16A		1749248.32	5912743.75	42.80	Corner of Light coloured seal.
17		1748896.05	5935039.32	120.96	Fence Intersection.
18		1756232.63	5935182.31	4.02	Corner of concrete edge with grass of gravel petanque court.
19		1748345.71	5953723.37	9.86	Gate Post.
19A		1748739.59	5953589.47	5.67	Fence Corner.
20		1757012.22	5962369.61	66.67	Intersection of fence/gate alignment with edge of white metalled track.
21		1757645.72	5982322.69	300.59	Corner of concrete drive.
22		1749799.03	5982831.51	73.66	Fence Intersection.
24		1763951.16	5973377.23	2.19	Strainer post at fence angle gate intersection.

9.2 Appendix 2: Comparison of elevation survey methods

The accuracy of elevation measurements using the Trimble RTK GPS system was tested by comparison with a Geodimeter 464 Total station, an auto-set level and Emery poles. The latter are used by NIWA, ARC and Environment Waikato for beach-profile surveys where a sea horizon is used to provide a fixed level. The field comparison was undertaken on a tidal flat in the Raglan Harbour on 19 September 2007. Figure 9.1 compares the tidal-flat profiles measured using each survey method. The accuracy of the Emery method was poor due to the short horizon within the estuary (i.e., < 1km). The error increased with distance from the observer. From experience, the Emery method is only useful when the horizon is ≥ 3 km from the observation point. The total station provided consistently accurate results, as did the auto-set level after being adjusted for a systematic error of +9 mm elevation per 80 m distance. The RTK GPS was within +/-2 cm of the total station instrument, which is within the industry guidelines for this instrument. The reduced distances for the total station and RTK GPS were within 1 cm of each other.

This inter-comparison of survey instruments demonstrated that the RTK GPS would provide accurate elevation profiles of tidal flats in the study estuaries.

Figure 9.1:
Tidal-flat elevation survey. Comparison of Total station (EDM), Autoset level and repeat RTK-GPS and Emery-pole elevation surveys of a tidal flat in Raglan Harbour (19 September 2007). Elevation is relative to an assumed vertical datum.



9.3 Appendix 3: Details of RTK-GPS surveys in the study estuaries

For estuaries, within the Auckland urban area, a Trimble iBase system was used to communicate with a permanently established base station operated by Geo-Systems Ltd) via a mobile-phone link. The base station which is based in Albany has a range of approximately 30 km. This method overcame the problem of radio interference caused by other RTK GPS operators using VHF base stations.

RTK GPS survey dates and number of tidal-flat profiles surveyed in each study estuary (Table 8.2).

Table 8.2:

Details of RTK GPS elevation surveys in the study estuaries.

Estuary	Survey date(s)	No. of transects
Whangateau	26 February 2008	6
Matakana	26 February & 15 May 2008	5
Kawau	–	–
Mahurangi	26 February & 29 May 2008	14
Puhoi	15 January 2008	9
Waiwera	16 January 2008	5
Orewa	28 February 2008	6
Weiti	22 May 2008	6
Okura	29 February & 5 March 2008	5
Waitemata	7–8 February 2008	9
Shoal Bay	4 & 7 February 2008	4
Orakei & Hobson	–	–
Tamaki	5 March 2008	7
Whitford	28 May 2008	6
Wairoa	9–10 January 2008	5
Te Matuku	26 March 2008	3
Awaawaroa	27 March 2008	1
Putiki	27 March 2008	3

9.4 Appendix 4: Aerial photographic survey – dates and times

Figures 9.2–9.4 map the date and time (DST) of theaerial-photographic surveys of the study estuaries acquired on 17 November 2007 and 28 January 2008 by NZ Aerial Mapping Ltd. Where multiple photos were taken, the time given is for the central photo for each estuary.

Figure 9.2:
Time (Daylight Saving Time) of aerial photographs taken in the Whangateau, Kawau Island, Matakana, Mahurangi, Puhoi and Waiwera estuaries on 28 January 2008.

Figure 9.3:
Time (Daylight Saving Time) of aerial photographs taken in the Orewa, Weiti, Okura estuaries and Waitemata Harbour on 28 January 2008.

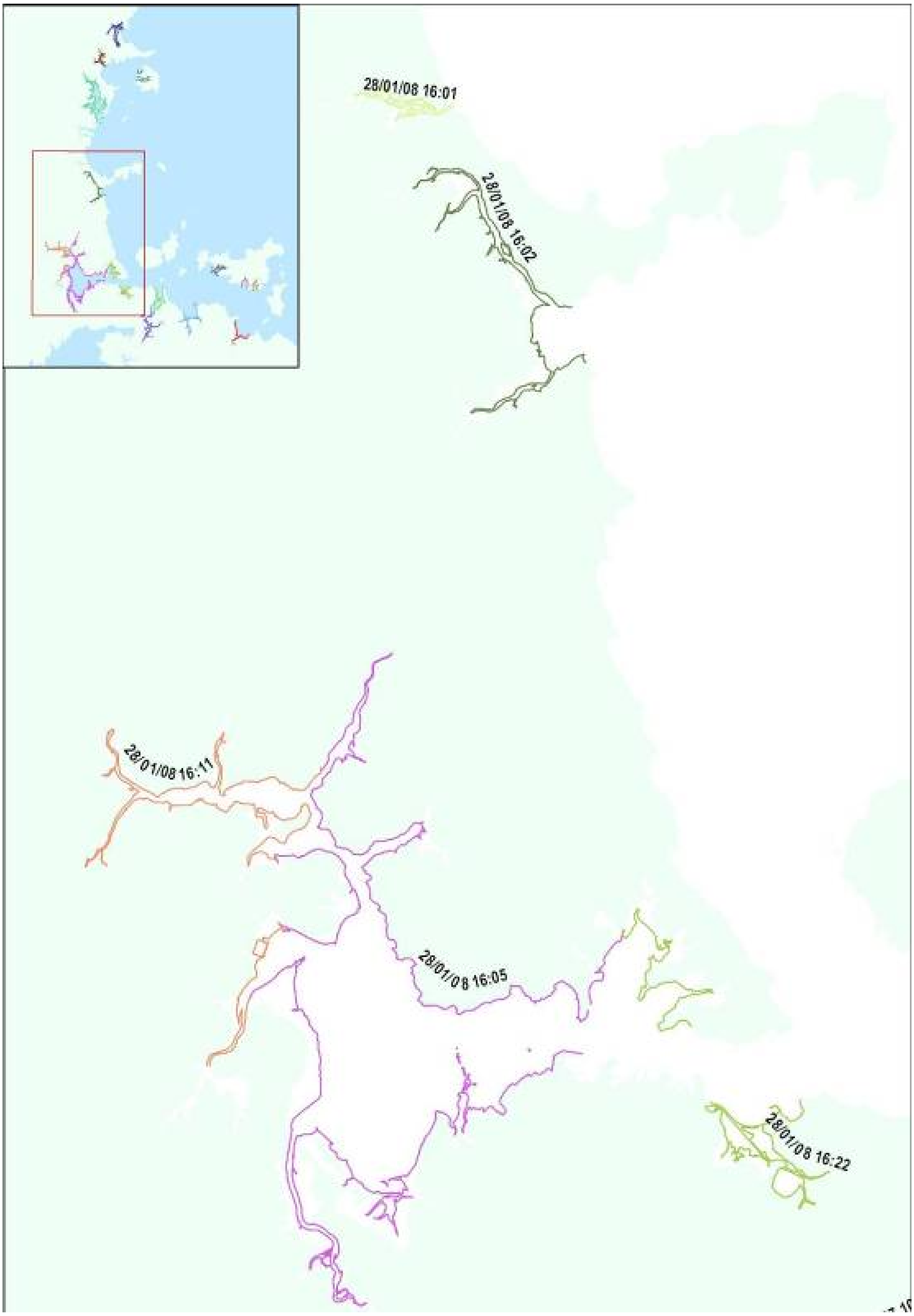
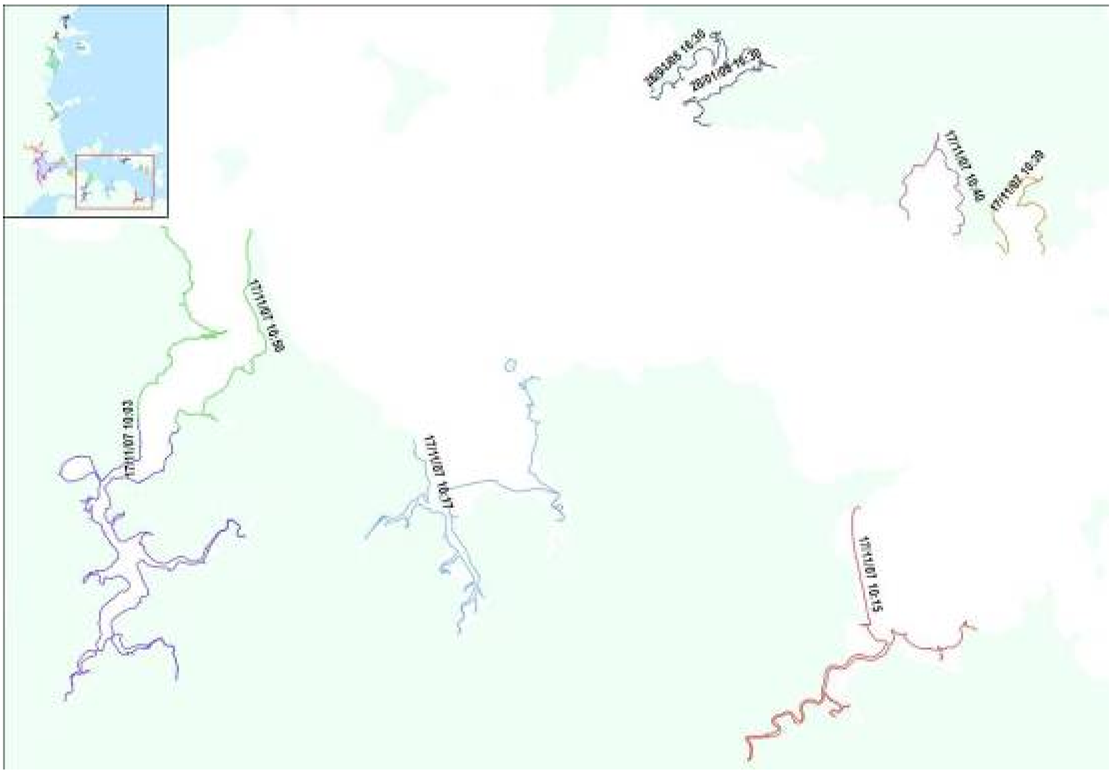


Figure 9.4:

Time (Daylight Saving Time) of aerial photographs taken in the Tamaki, Whitford, Wairoa and Waiheke-Island estuaries on 17 November 2007 and 28 January 2008.



9.5 Appendix 5: Present-day estuaries – calibration of hydrodynamic models

Figure 9.5:
Present-day hydrodynamic-model bathymetry for the Mahurangi Estuary.

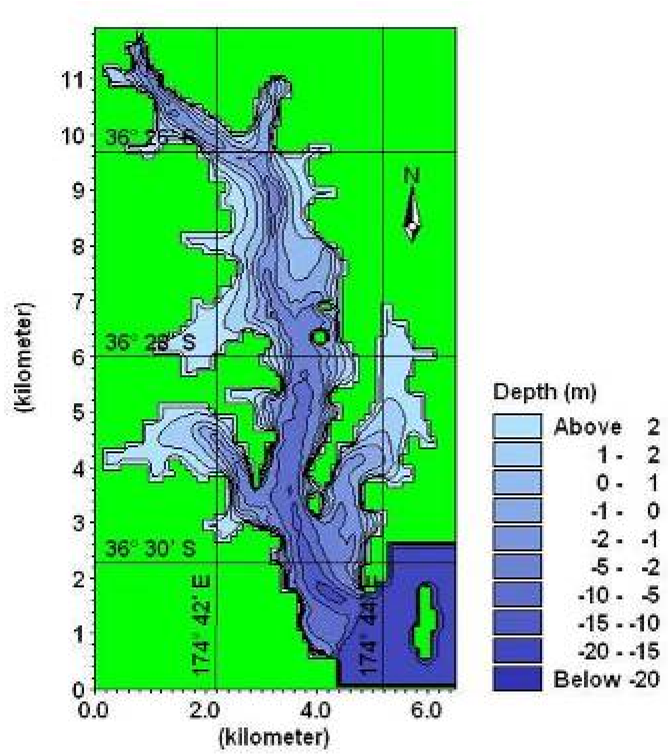


Figure 9.6:

Mahurangi Harbour: time series of predicted (blue line) and measured (black line) tidal water levels in the Mahurangi Estuary at Dawsons Creek (Town Basin). Date and time on the x axis.

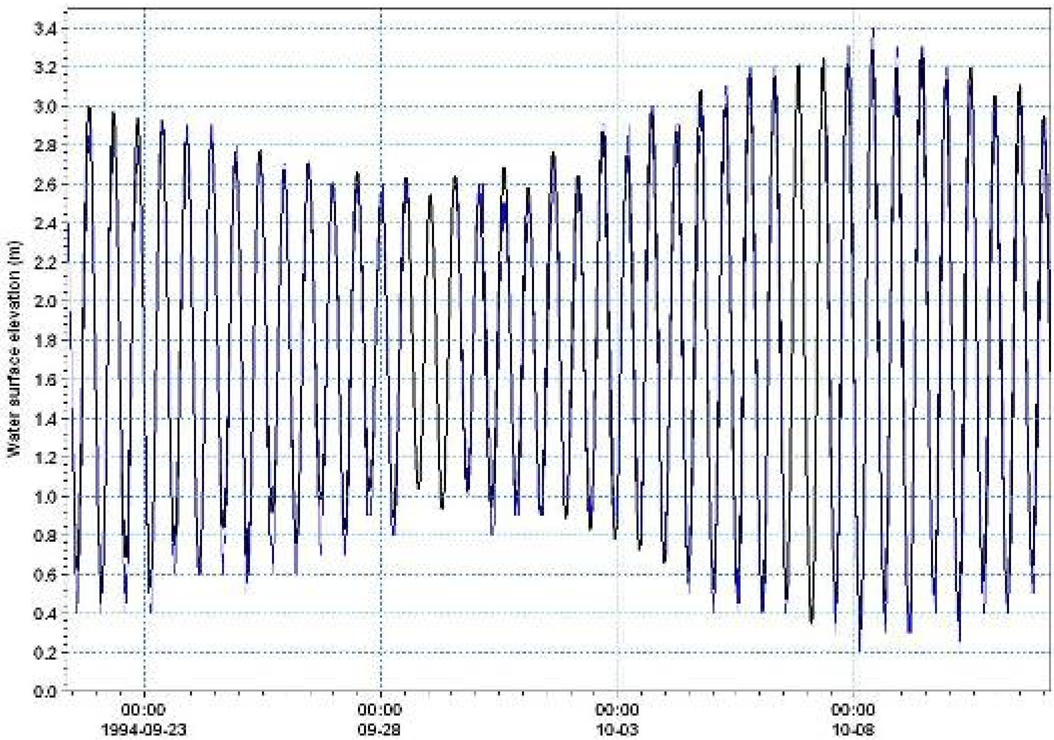


Figure 9.7:
Mahurangi Harbour: relationship between measured and predicted water surface elevations (WSE) at Dawsons Creek (Town Basin). Linear regression results are also shown.

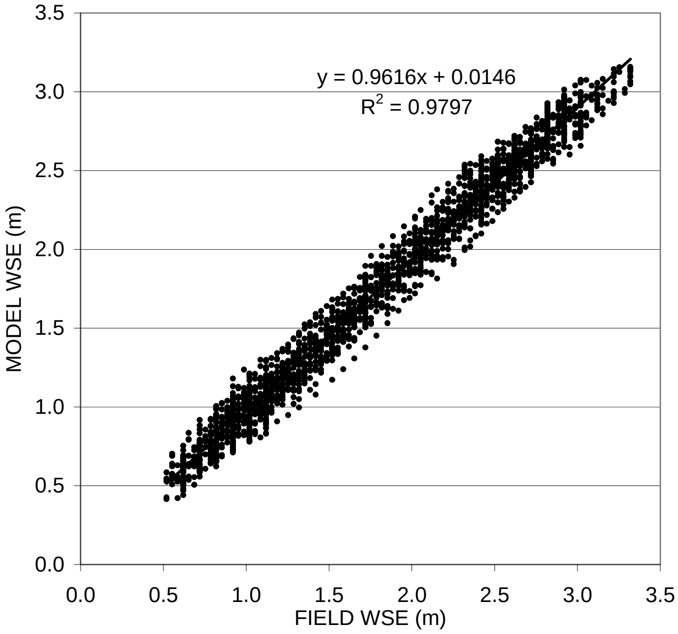


Figure 9.8:
Present-day hydrodynamic-model bathymetry for the Okura Estuary.

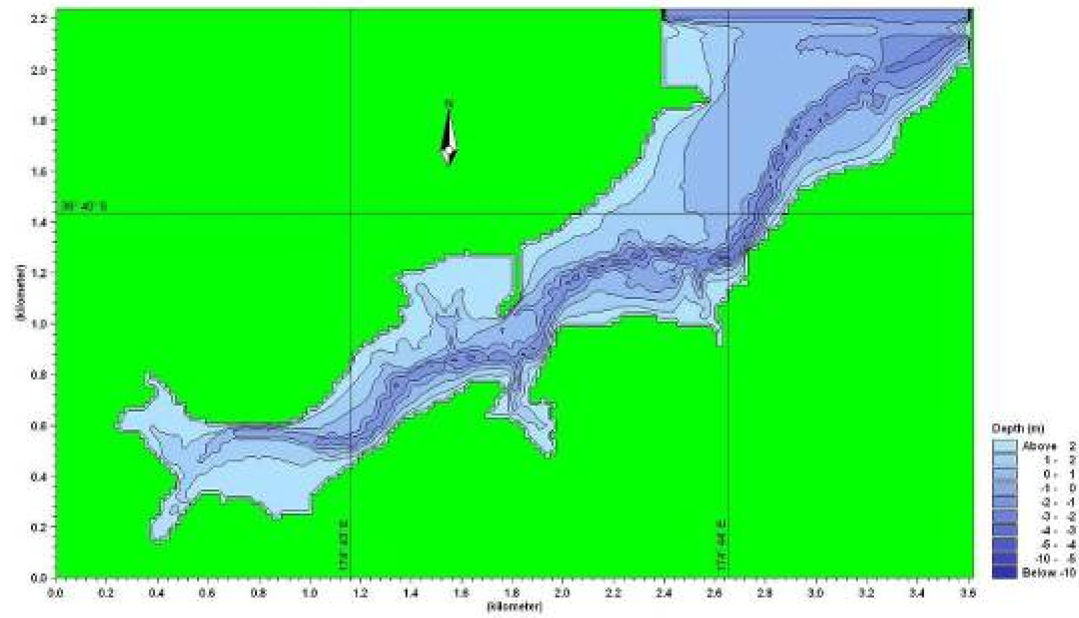


Figure 9.9:
Okura Estuary: time series of predicted (blue line) and measured (black line) tidal water levels in the Okura Estuary. Date and time on the x axis.

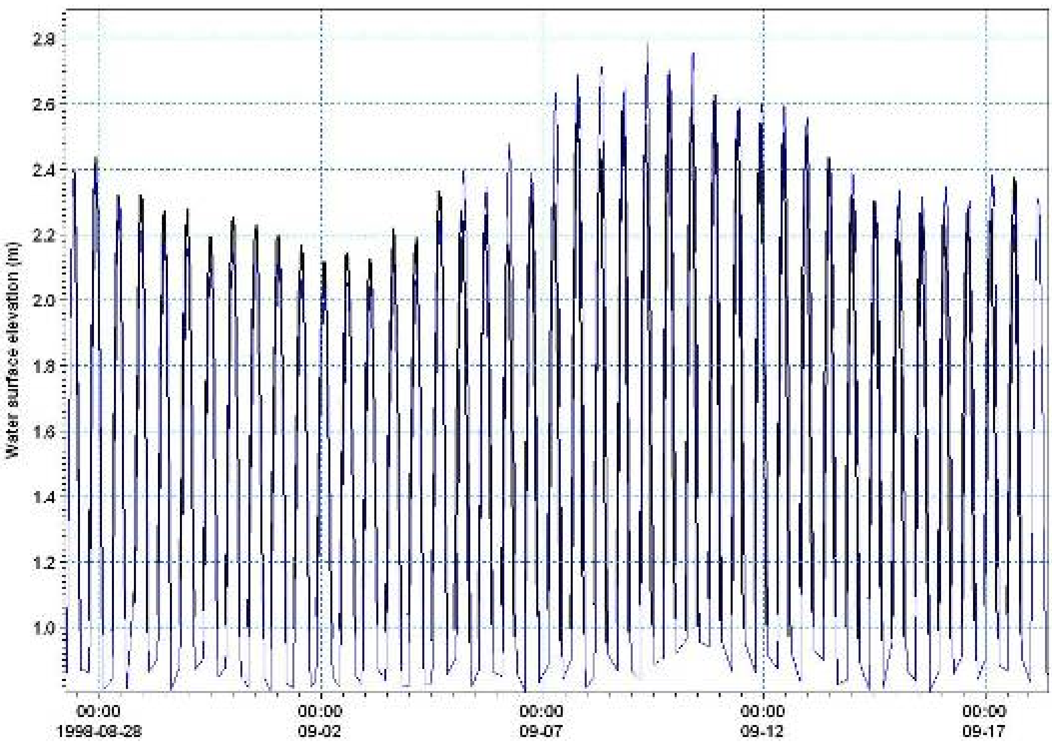


Figure 9.10:

Okura Estuary: Relationship between measured and predicted water surface elevations (WSE) at the estuary mouth. Linear regression results are also shown.

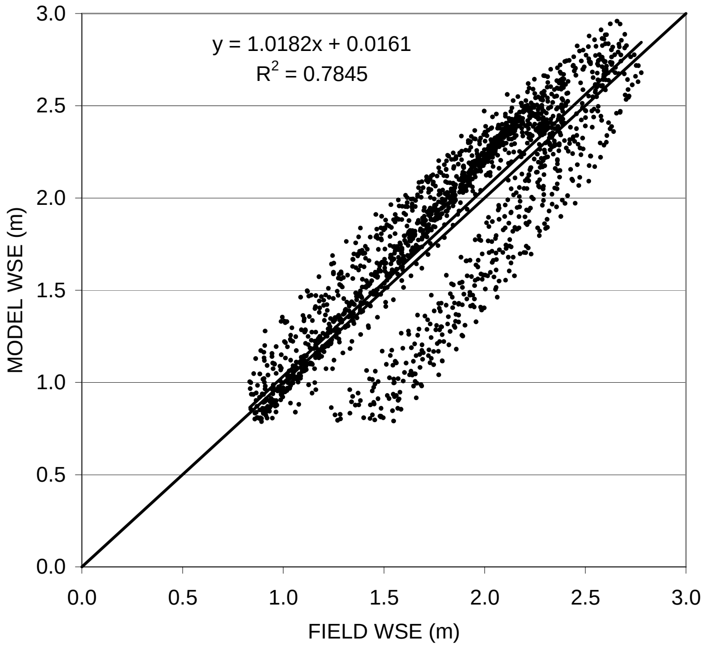


Figure 9.11:

Present-day hydrodynamic-model bathymetry for Whitford Bay and tributary creeks.

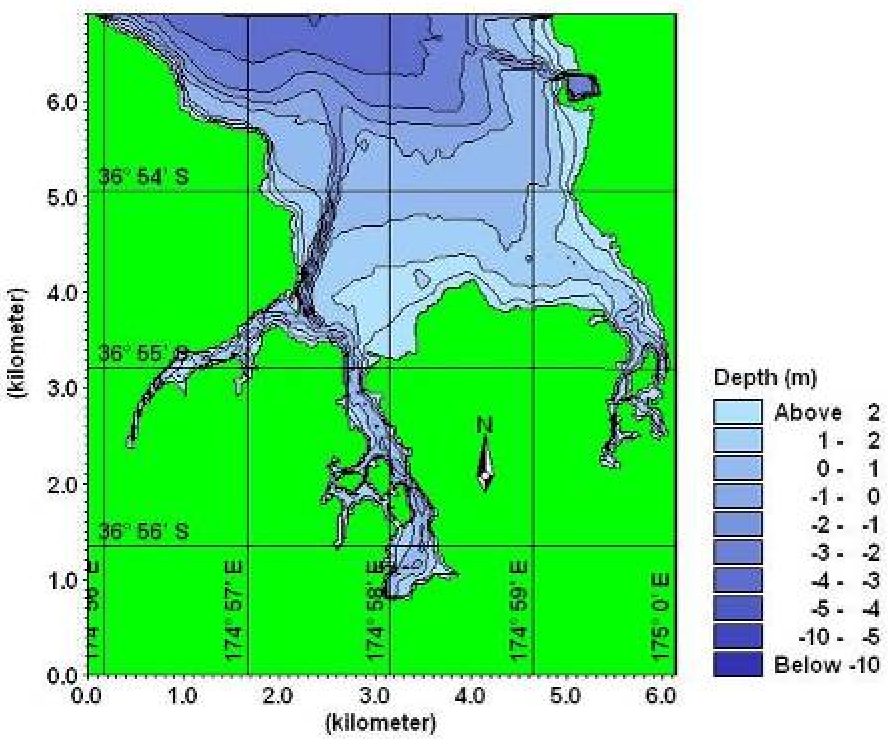


Figure 9.12:

Time series of predicted (blue line) and measured (black line) tidal water levels in Whitford Bay at the mouth of the Mangemangeroa Creek. Date and time on the x axis.

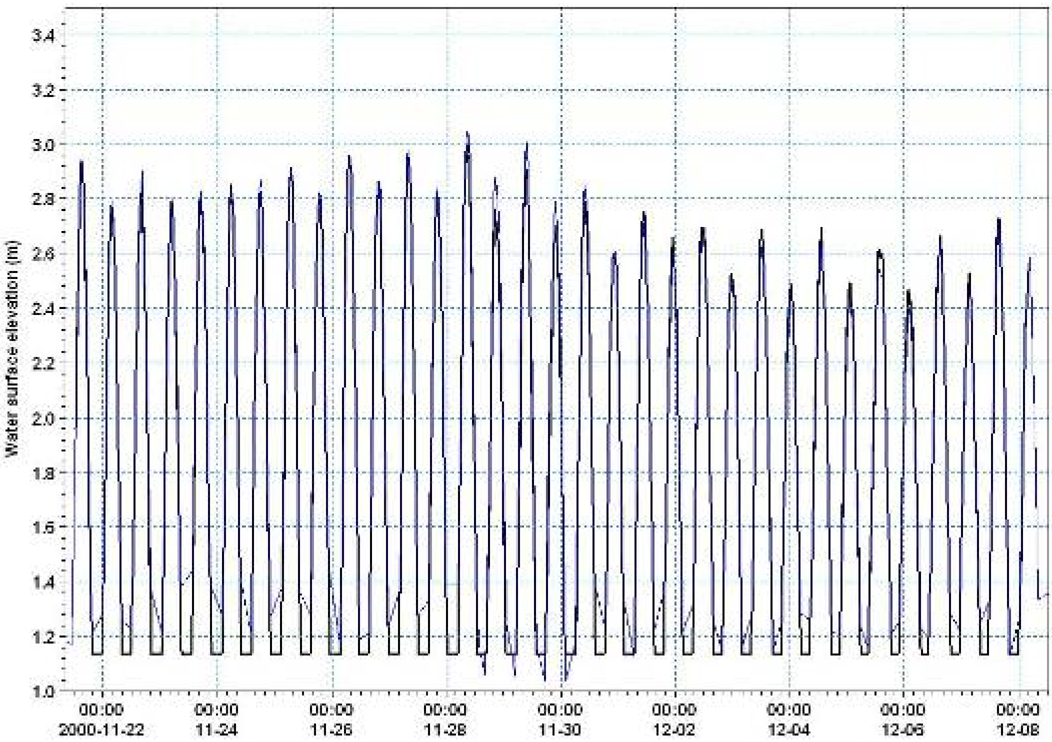


Figure 9.13:
Relationship between measured and predicted water surface elevations (WSE) for Whitford Bay at the mouth of the Mangemangeroa Creek. Linear regression results are also shown.

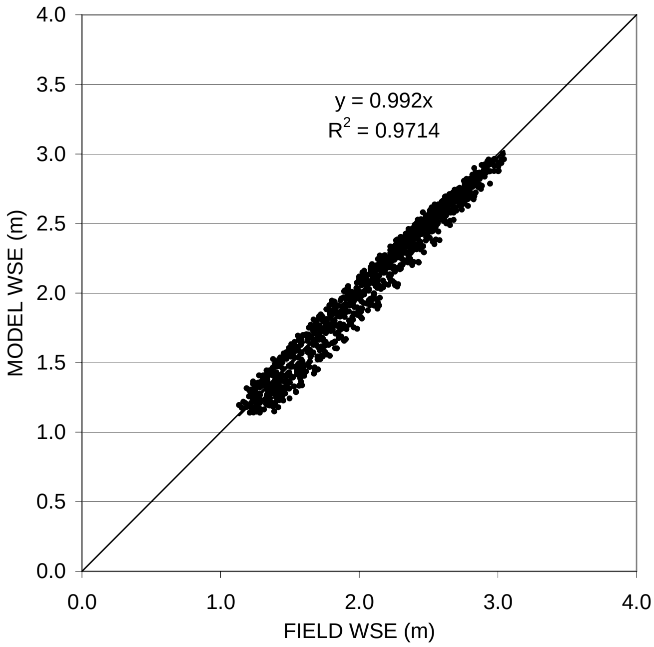


Figure 9.14:
Present-day hydrodynamic-model bathymetry for the Waitemata Harbour.

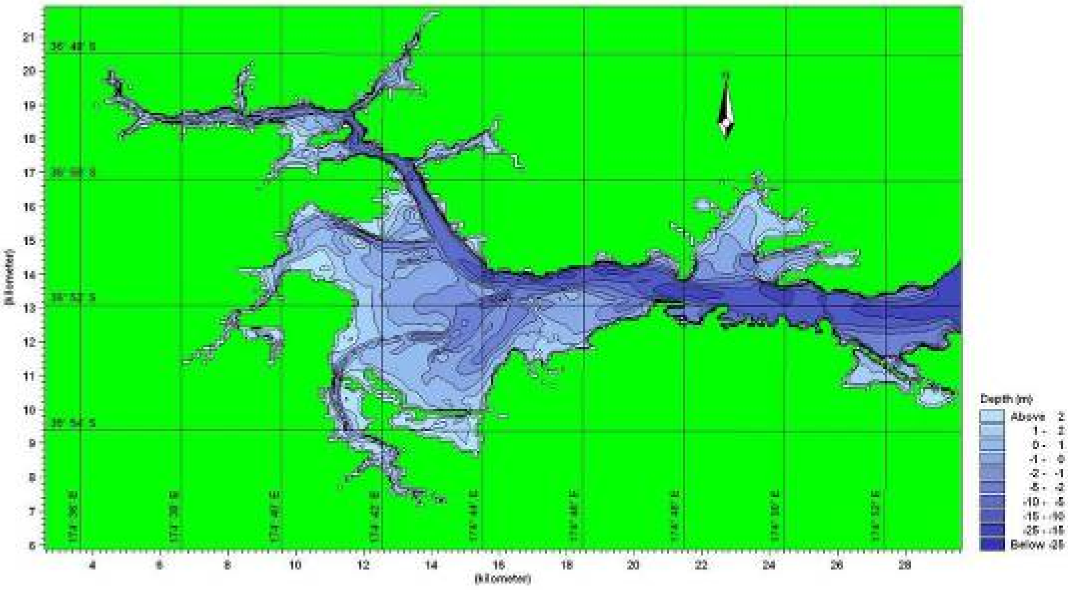


Figure 8.15:
Time series of predicted (blue line) and measured (black line) tidal water levels in the Waitemata Harbour at the Harbour Bridge. Date and time on the x axis.

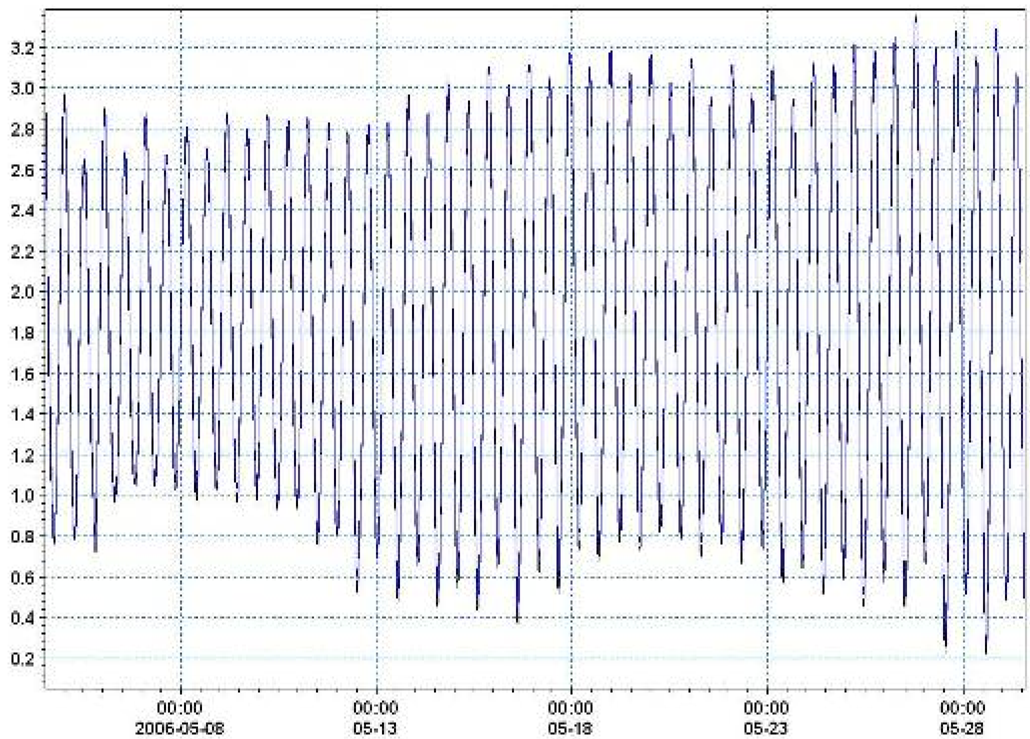


Figure 9.16:

Relationship between measured and predicted water surface elevations (WSE) for the Waitemata Harbour at the harbour bridge. Linear regression results are also shown.

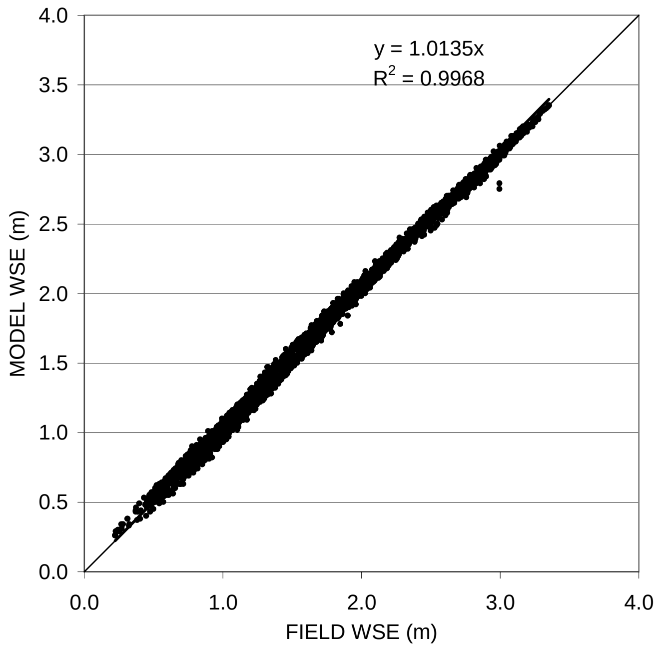


Figure 9.17:

Present-day hydrodynamic-model bathymetry for the Tamaki Estuary.

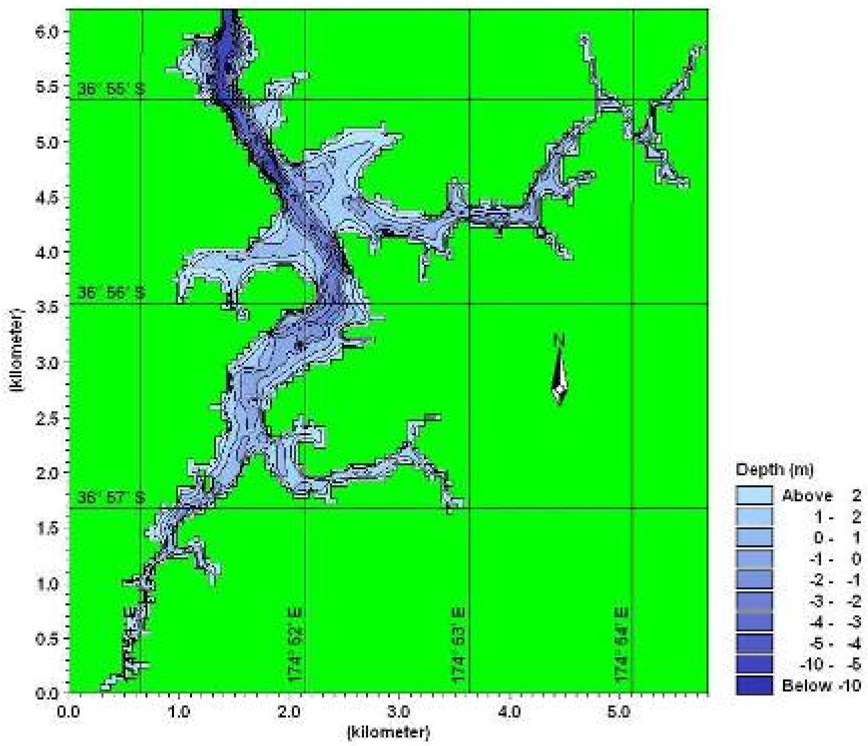


Figure 9.18:
Time series of predicted (blue line) and measured (black line) tidal water levels in the Tamaki Estuary at Otahuhu. Date and time on the x axis.

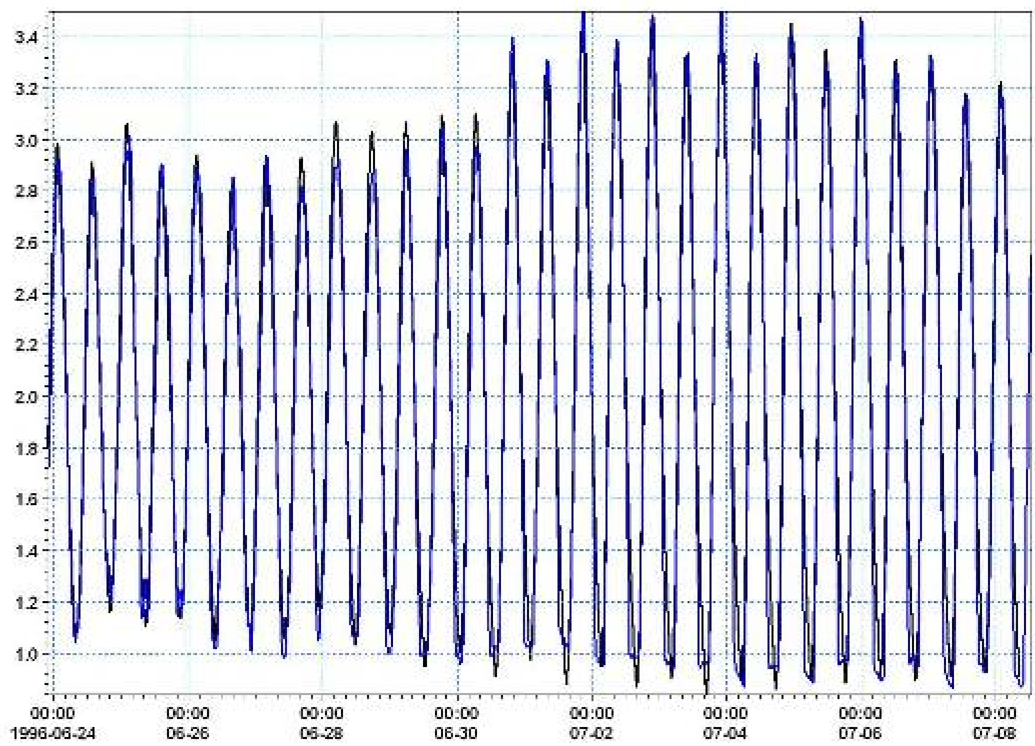
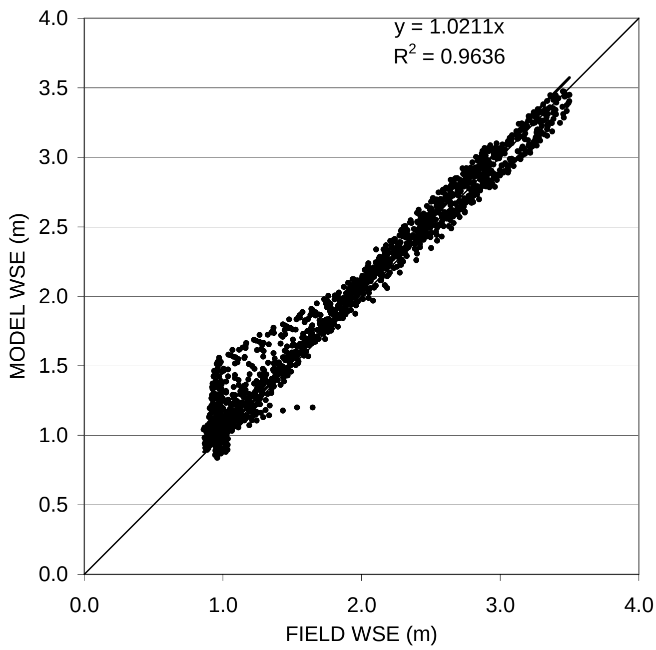


Figure 9.19:
Relationship between measured and predicted water surface elevations (WSE) for the Tamaki Estuary at Otahuhu. Linear regression results are also shown.



9.6 Appendix 6: Past and future bathymetry for modeled estuaries

9.6.1 Mahurangi Estuary bathymetry hindcasts and forecasts

Figure 9.20:
Mahurangi Harbour, bathymetry hindcast to 1950.

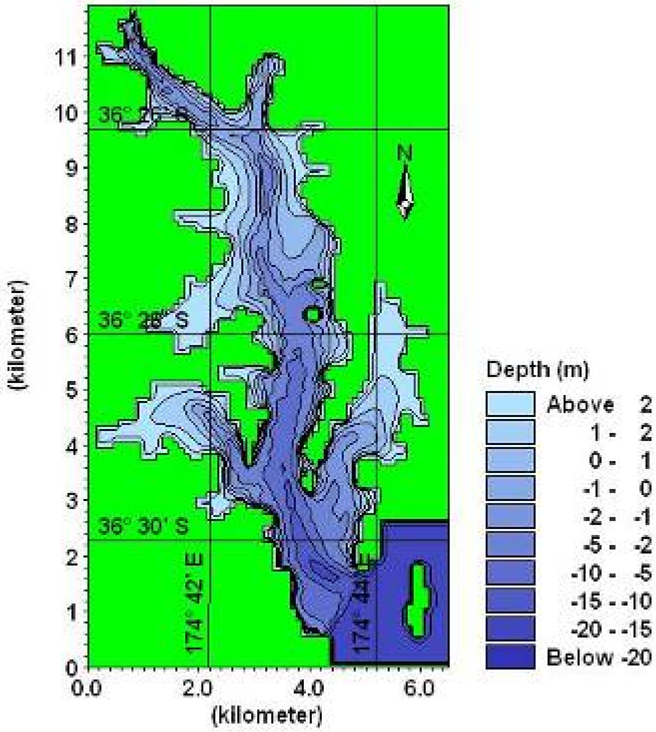


Figure 9.21:
Mahurangi Harbour, predicted bathymetry predicted for 2050.

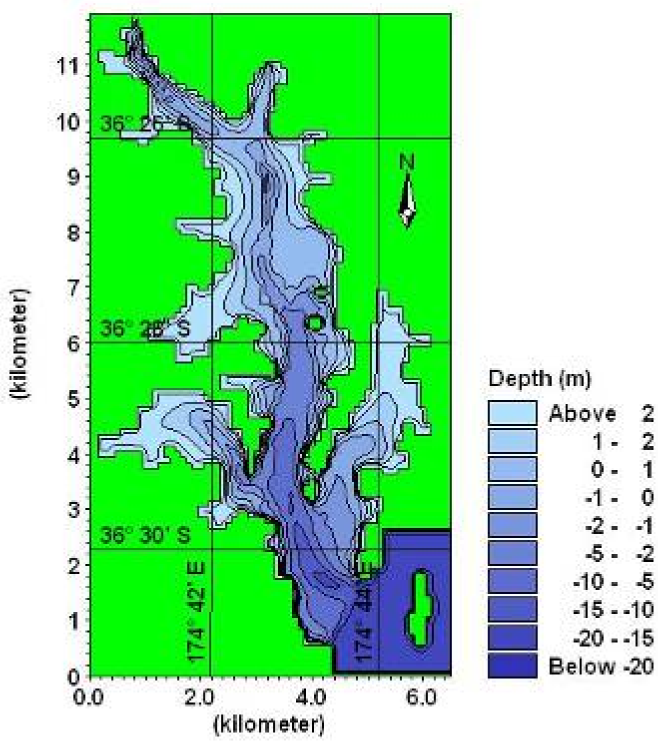
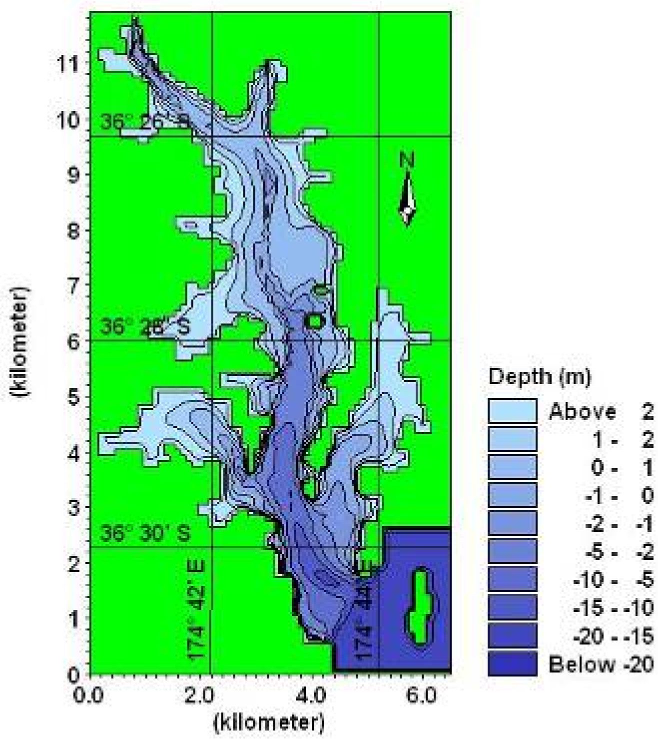


Figure 9.22:
Mahurangi Harbour, predicted bathymetry predicted for 2090.



9.6.2 Okura Estuary bathymetry hindcasts and forecasts

Figure 9.23:
Okura Estuary, bathymetry hindcast to 1950.

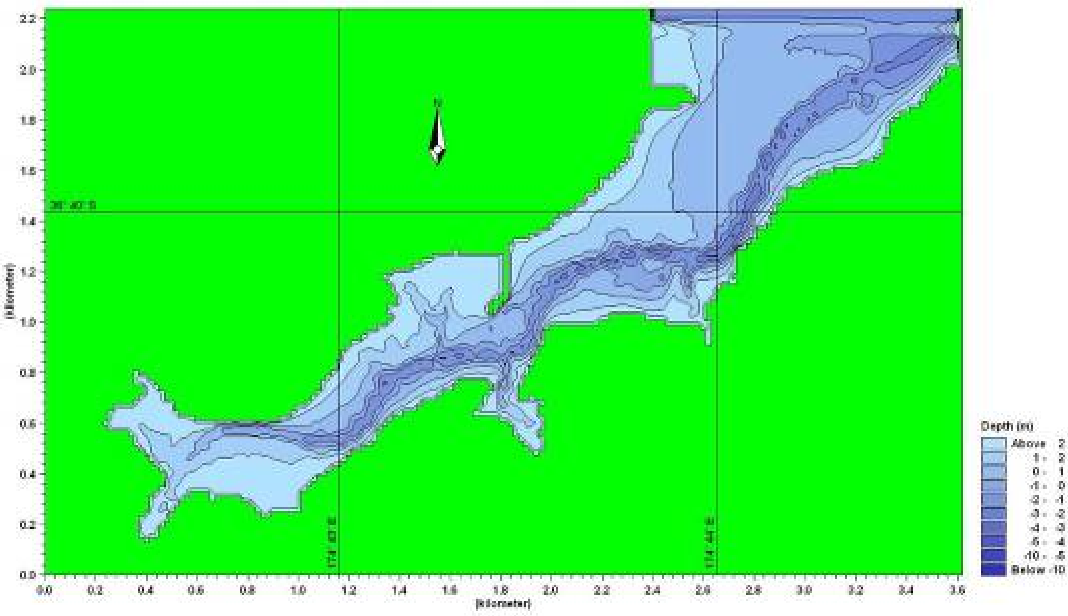


Figure 9.24:
Okura Estuary, predicted bathymetry predicted for 2050.

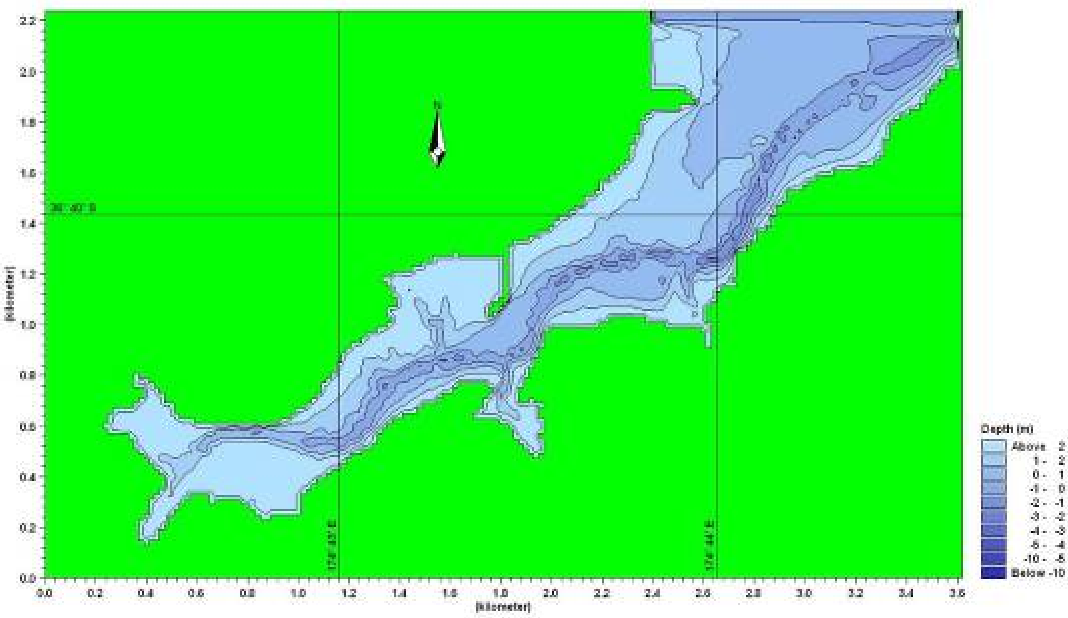
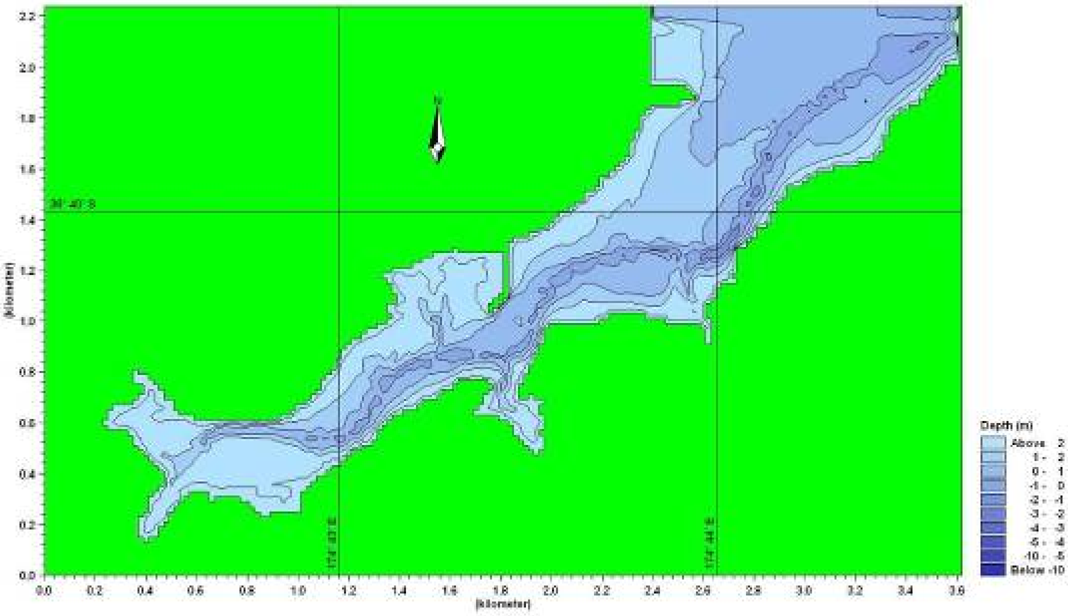


Figure 9.25:
Okura Estuary, predicted bathymetry predicted for 2090.



9.6.3 Waitemata Harbour bathymetry hindcasts and forecasts

Figure 9.26:
Waitemata Harbour, bathymetry hindcast to 1950.

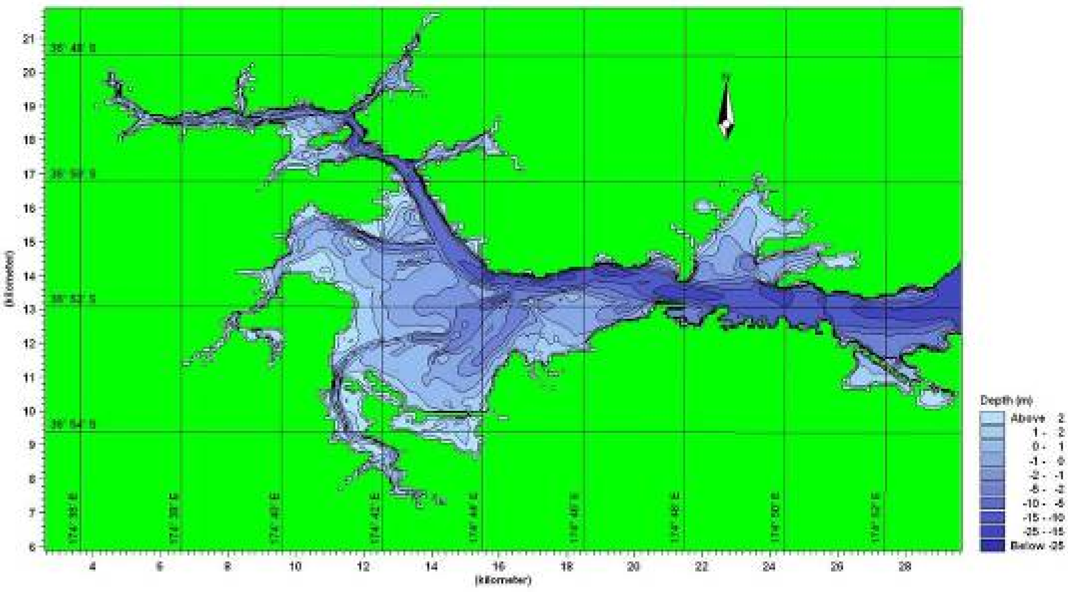


Figure 9.27:
Waitemata Harbour, predicted bathymetry predicted for 2050.

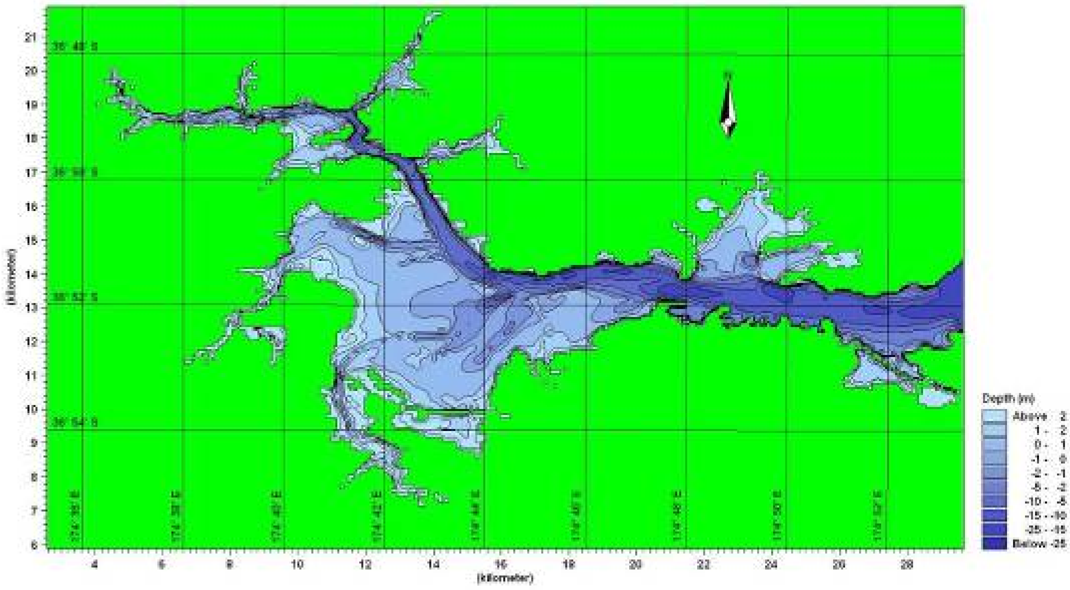
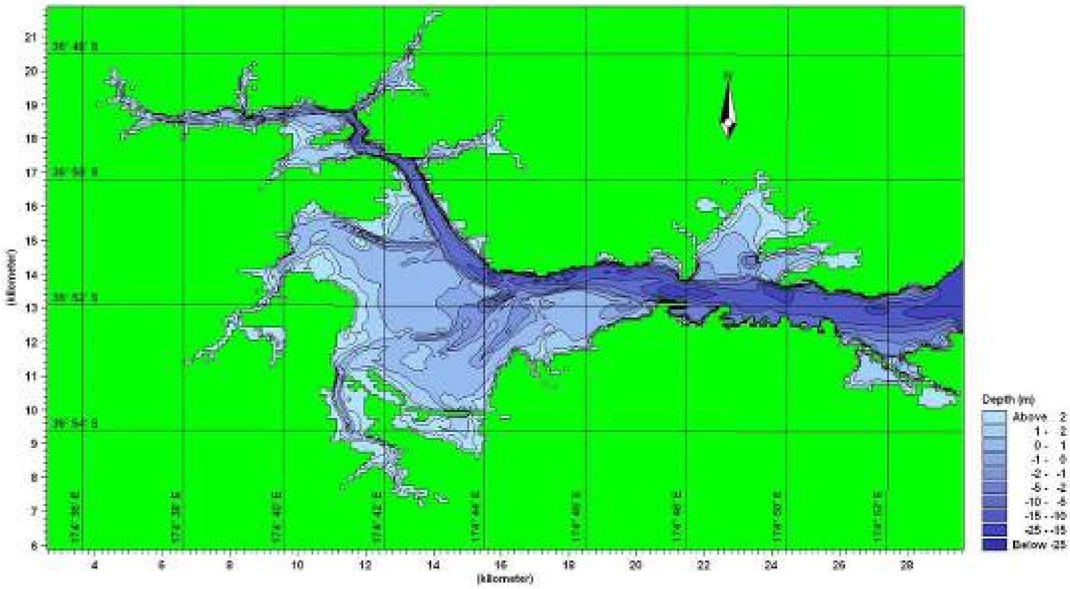


Figure 9.28:
Waitemata Harbour, predicted bathymetry predicted for 2090.



9.6.4 Tamaki Estuary bathymetry hindcasts and forecasts

Figure 9.29:
Tamaki Estuary, bathymetry hindcast to 1950.

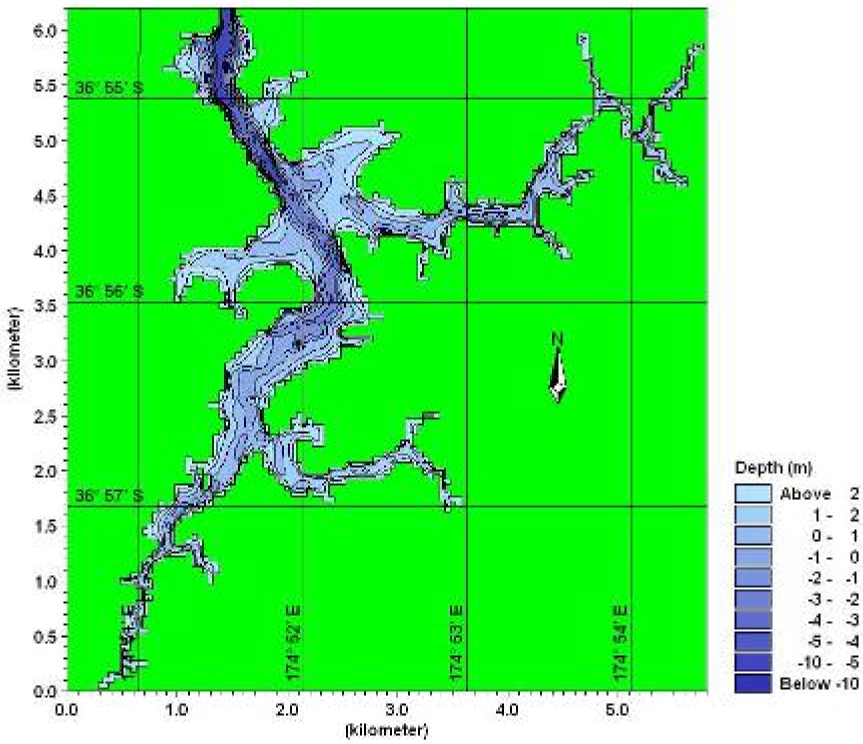


Figure 9.30:

Tamaki Estuary, predicted bathymetry predicted for 2050.

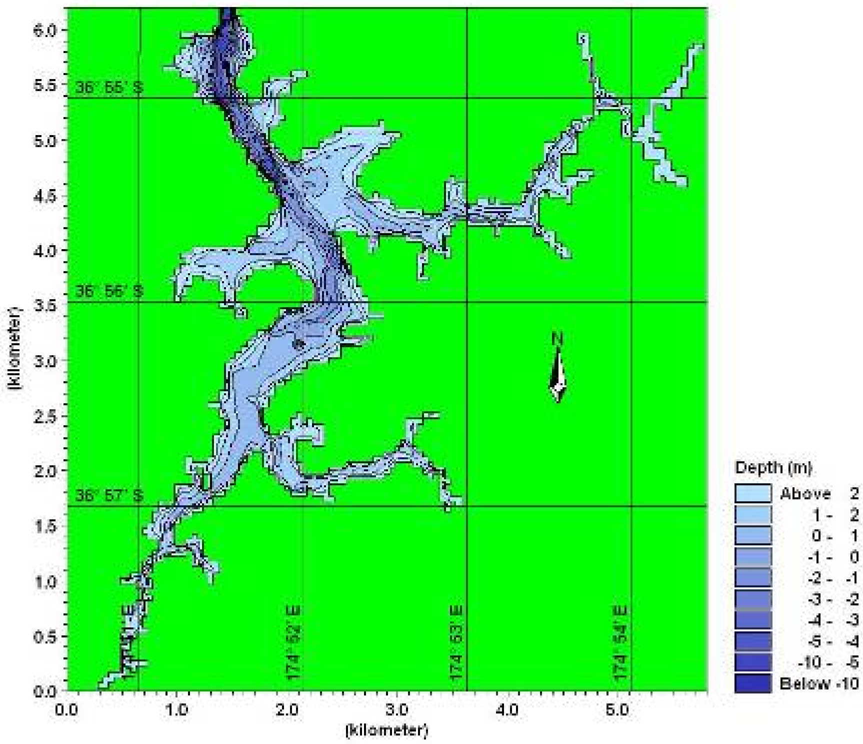
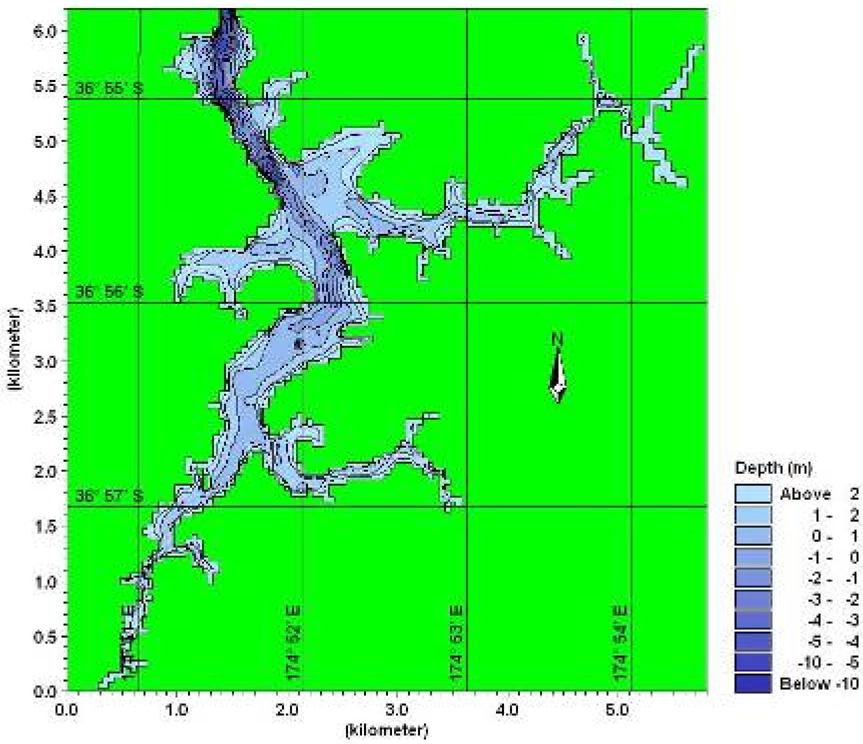


Figure 9.31:

Tamaki Estuary, predicted bathymetry predicted for 2090.



9.6.5 Whitford Bay bathymetry hindcasts and forecasts

Figure 9.32:
Whitford Bay, bathymetry hindcast to 1950.

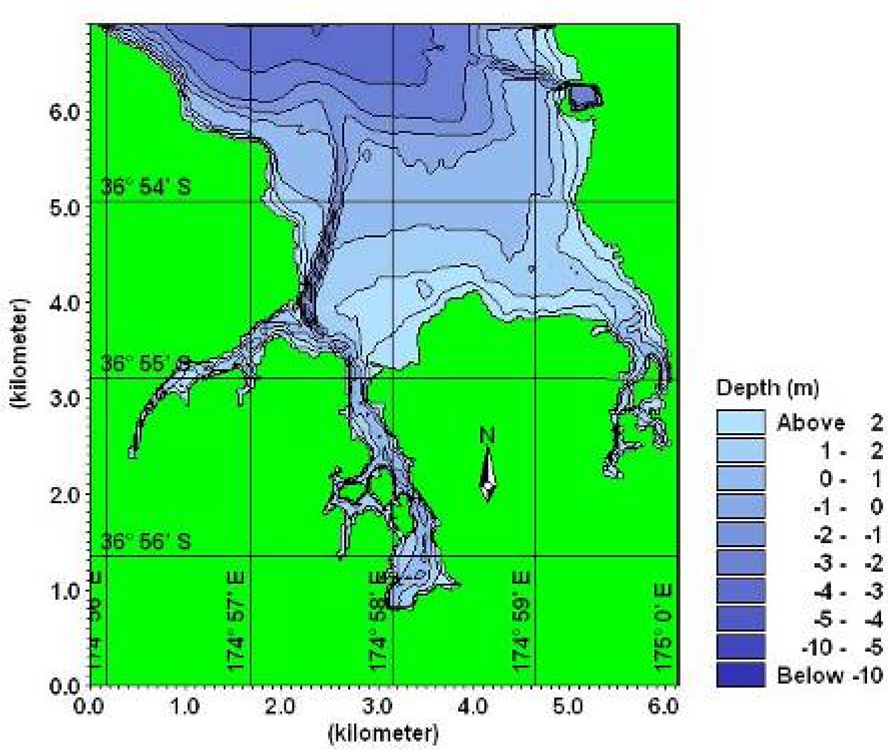


Figure 9.33:
Whitford Bay, predicted bathymetry predicted for 2050.

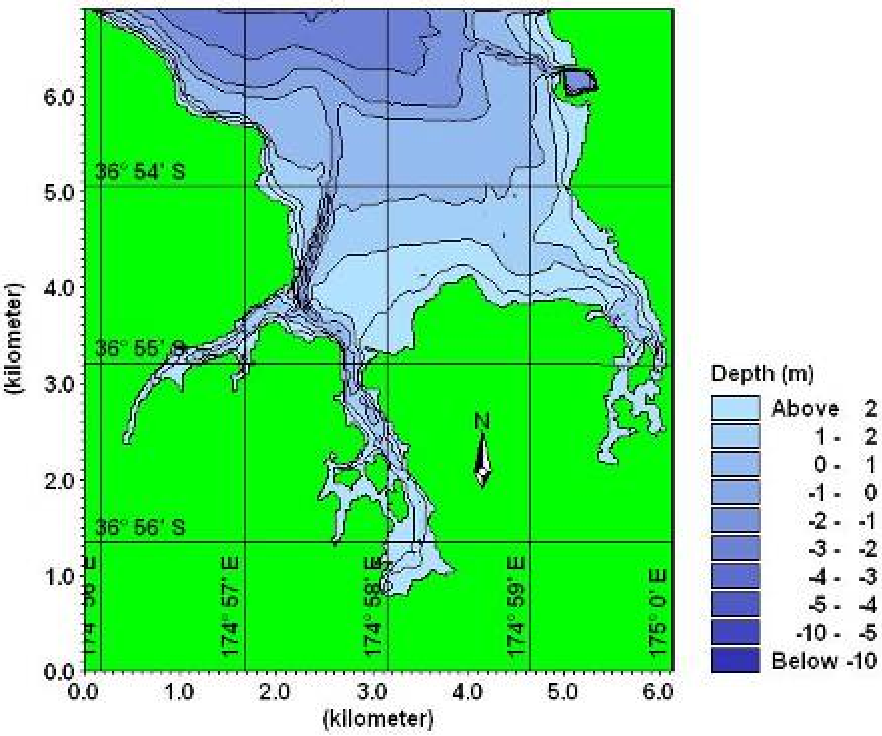
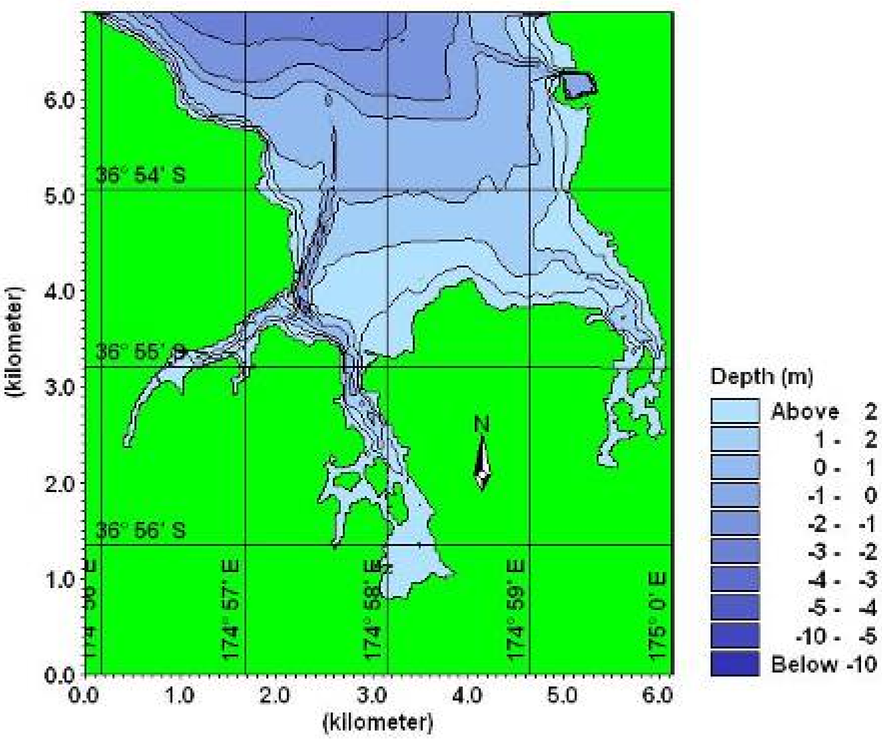


Figure 9.34:
Whitford Bay, predicted bathymetry predicted for 2090.



9.6.6 Appendix 7: Present-day mangrove-habitat extent and mean tide level

Figures 9.35 – 9.52 map the present-day distribution of mangrove habitat in the study estuaries. Also shown:

- Raw mean tide level (MTL) indicated by the waters edge that was digitised from the ortho-photos using the method described in section 4.2. No attempt has been made to adjust the MTL waters edge position due to time differences between the time the photo(s) was taken and the actual time of the mean level of the sea (MLOS) at the Port of Auckland.
- The fixed Auckland Vertical Datum 1946 (AVD-46) based on measurements of MLOS made during the 1920s–1940s. The MLOS during 2007 was ~0.13 m above AVD-46.

Figure 9.35:

Whangateau Harbour (28 January 2008): mangrove habitat; waters-edge contour at 1442 NZST (MLOS + 6 minutes); fixed elevations relative to Auckland Vertical Datum 1946 (AVD-46); and RTK GPS transects, with colour coded elevations relative to AVD-46. MLOS is the mean level of the sea recorded at the Port of Auckland on the day of the aerial photography.

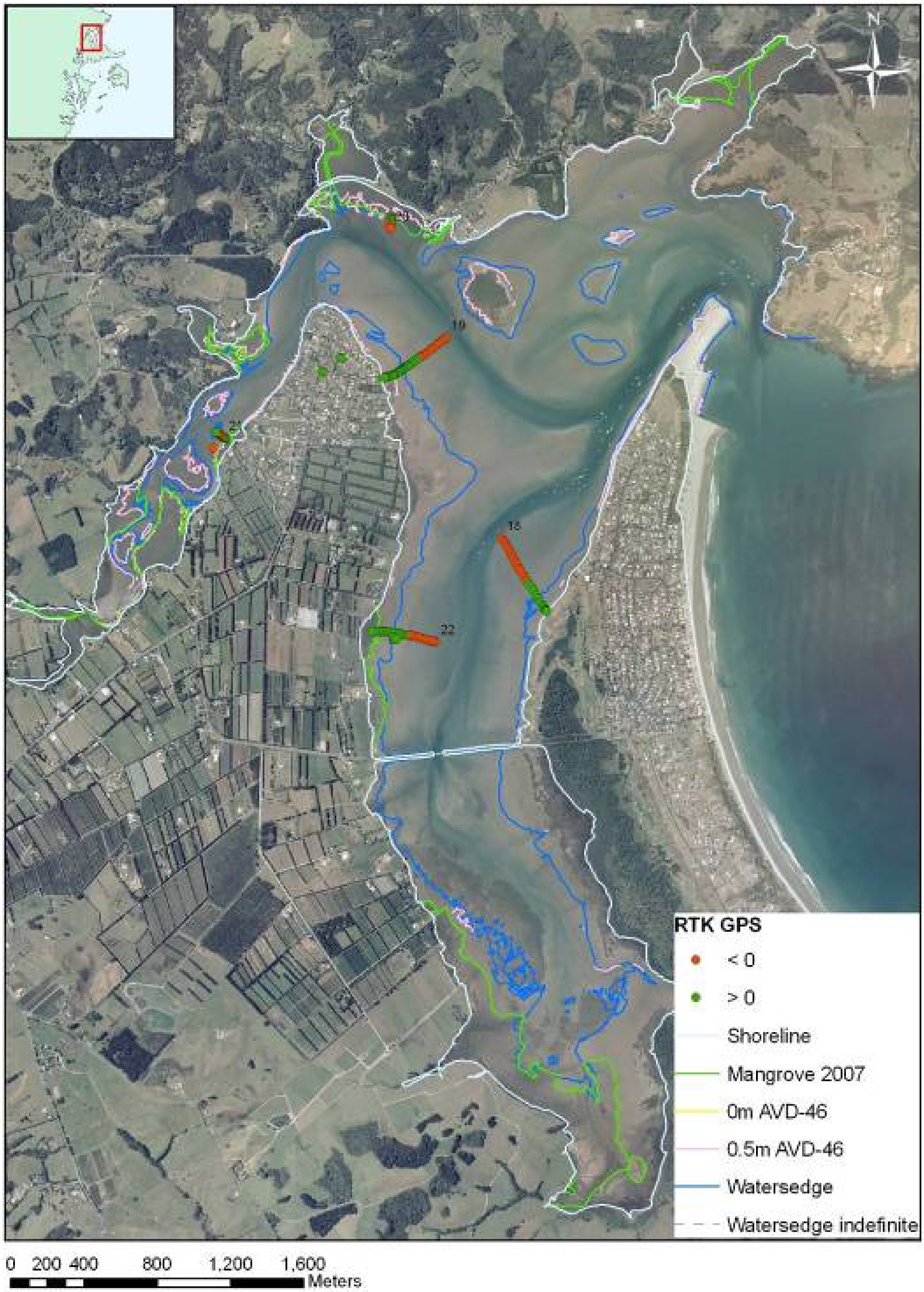


Figure 9.36:

Matakana Estuary (28 January 2008): mangrove habitat; waters-edge contour at 1458 NZST (MLOS + 20 minutes); fixed elevations relative to Auckland Vertical Datum 1946 (AVD-46); and RTK GPS transects, with colour coded elevations relative to AVD-46. MLOS is the mean level of the sea recorded at the Port of Auckland on the day of the aerial photography.

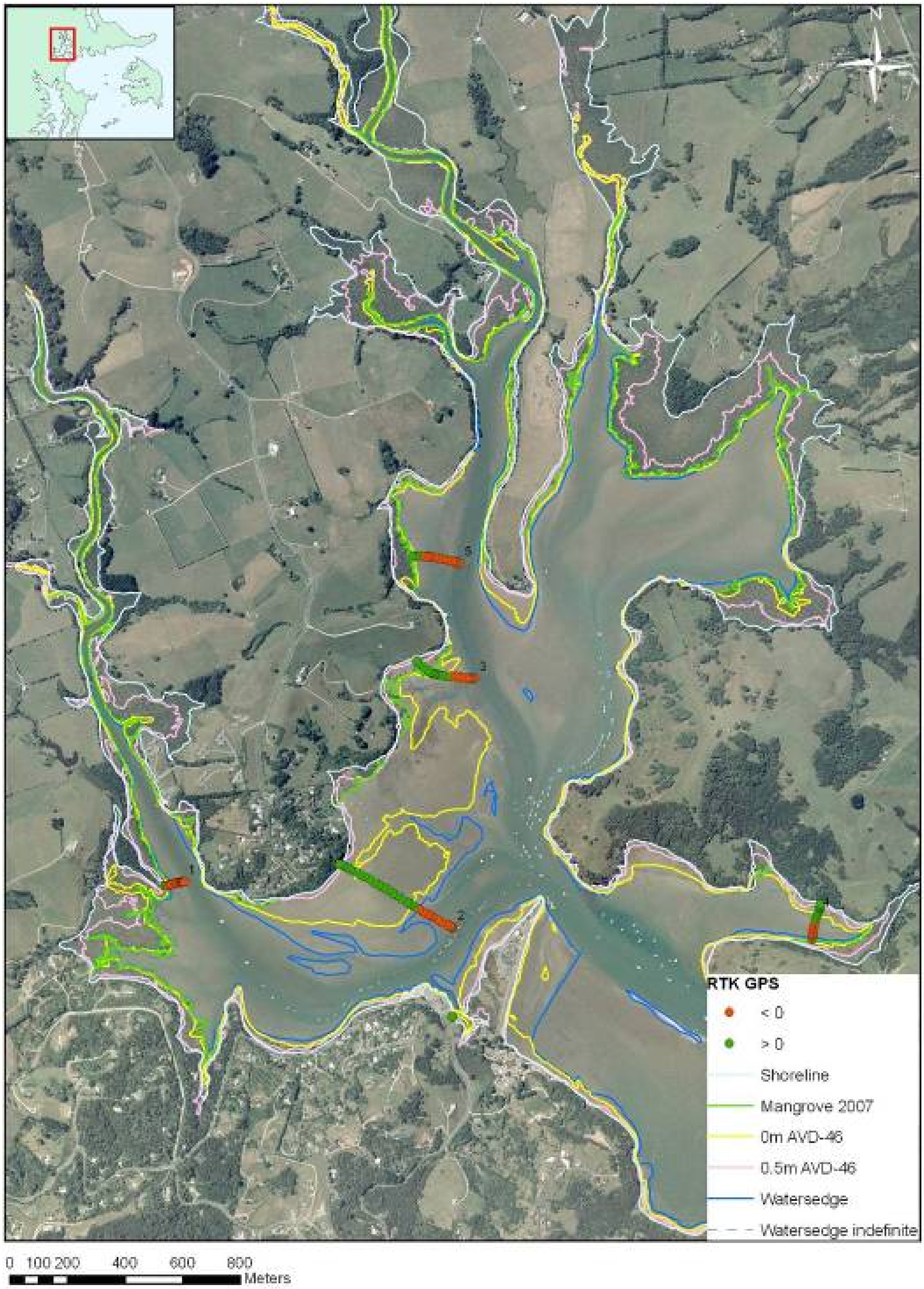


Figure 9.37:
North Cove and Bon Accord Harbour, Kawau Island (28 January 2008): mangrove habitat; watersedge contour at 1443 NZST (MLOS + 5 minutes); fixed elevations relative to Auckland Vertical Datum 1946 (AVD-46); and RTK GPS transects, with colour coded elevations relative to AVD-46. MLOS is the mean level of the sea recorded at the Port of Auckland on the day of the aerial photography.

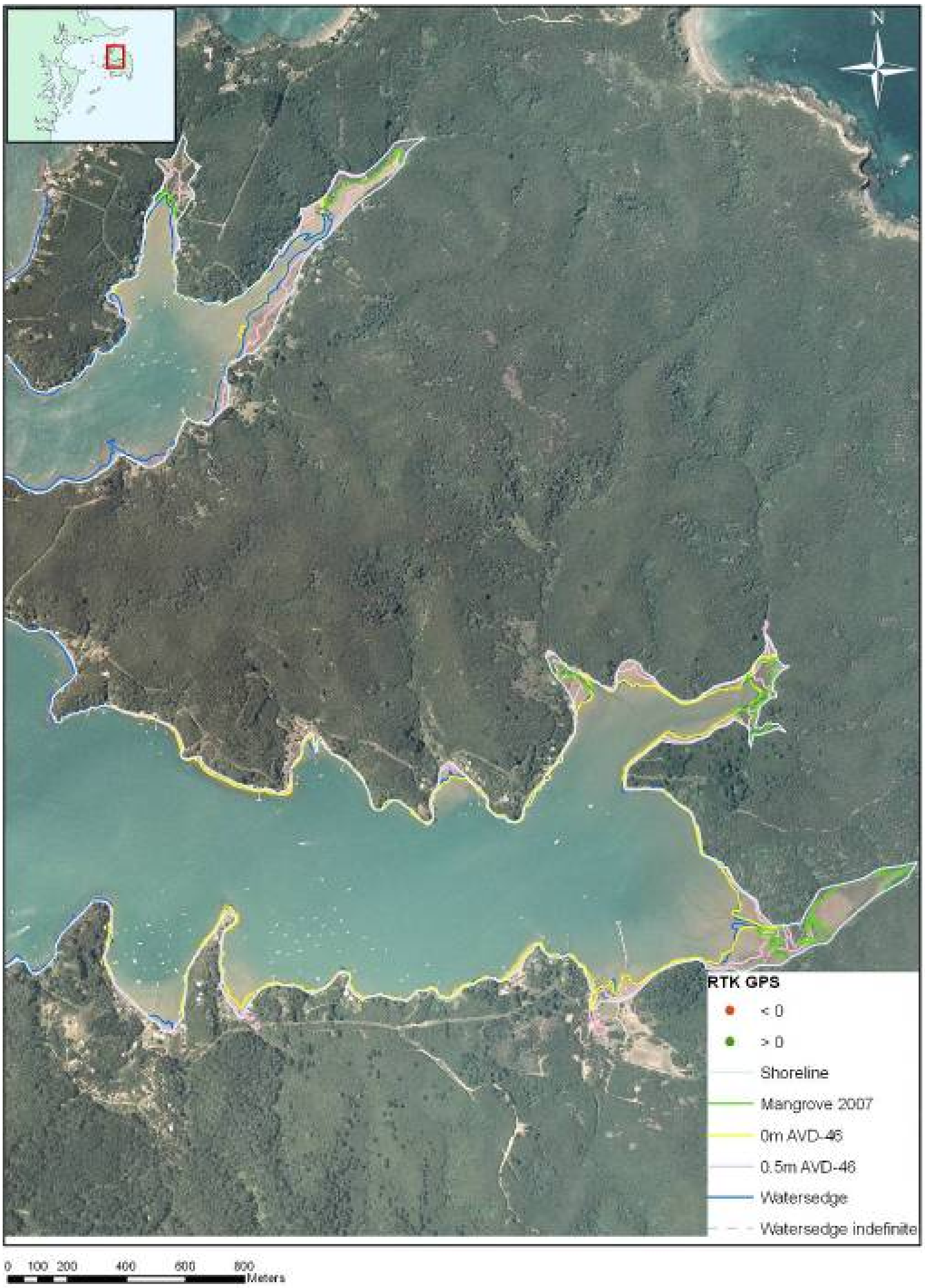


Figure 9.38:

Mahurangi Harbour (28 January 2008): mangrove habitat; waters-edge contour at 1449 NZST (MLOS + 21 minutes); fixed elevations relative to Auckland Vertical Datum 1946 (AVD-46); and RTK GPS transects, with colour coded elevations relative to AVD-46. MLOS is the mean level of the sea recorded at the Port of Auckland on the day of the aerial photography.

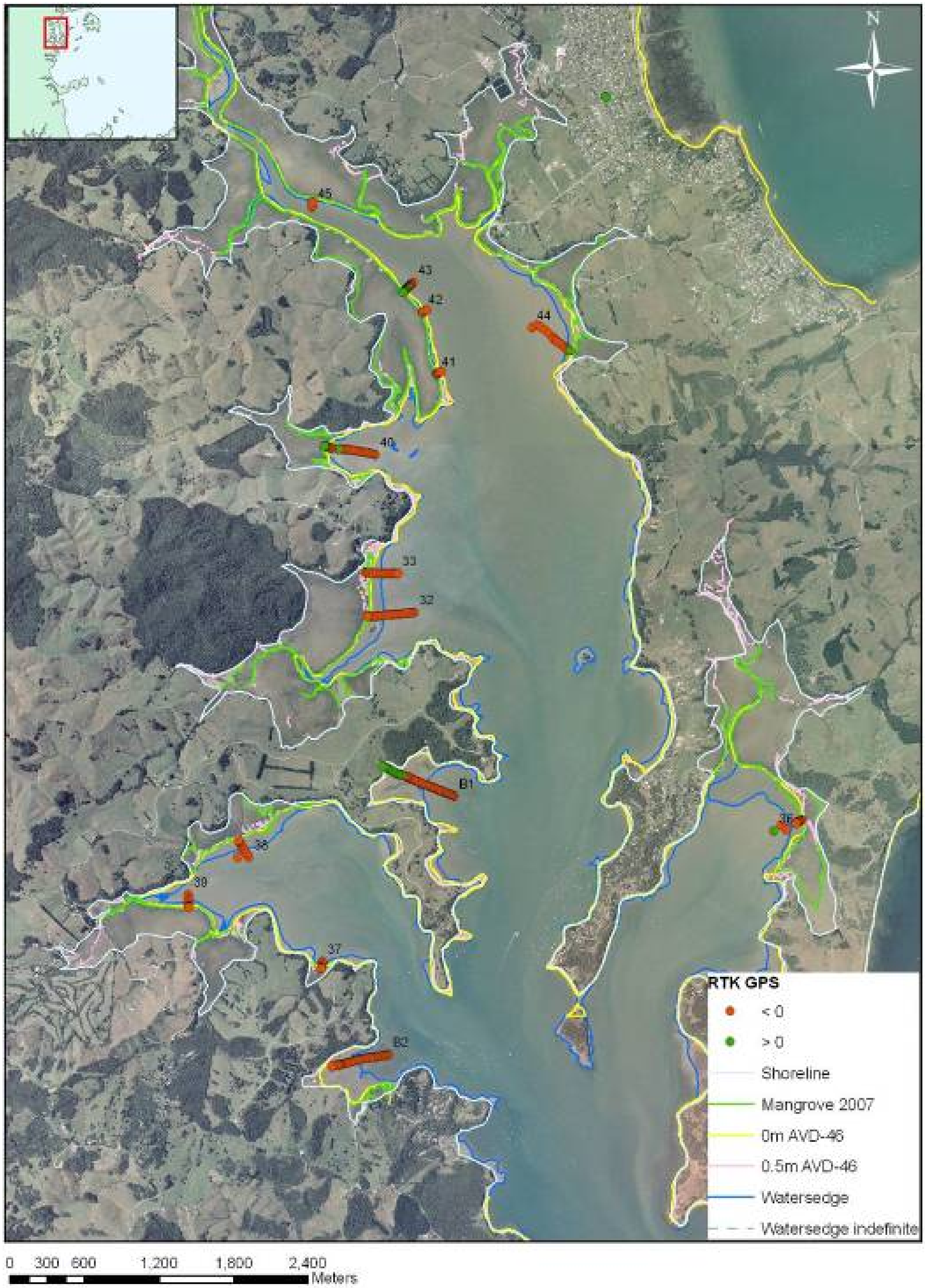


Figure 9.39:

Puhoi & Waiwera (28 January 2008): mangrove habitat, waters-edge contour at 1500 NZST (MLOS + 22 minutes), fixed mean sea level contour (Auckland Vertical Datum 1946); fixed elevations relative to Auckland Vertical Datum 1946 (AVD-46); and RTK GPS transects, with colour coded elevations relative to AVD-46. MLOS is the mean level of the sea recorded at the Port of Auckland on the day of the aerial photography.

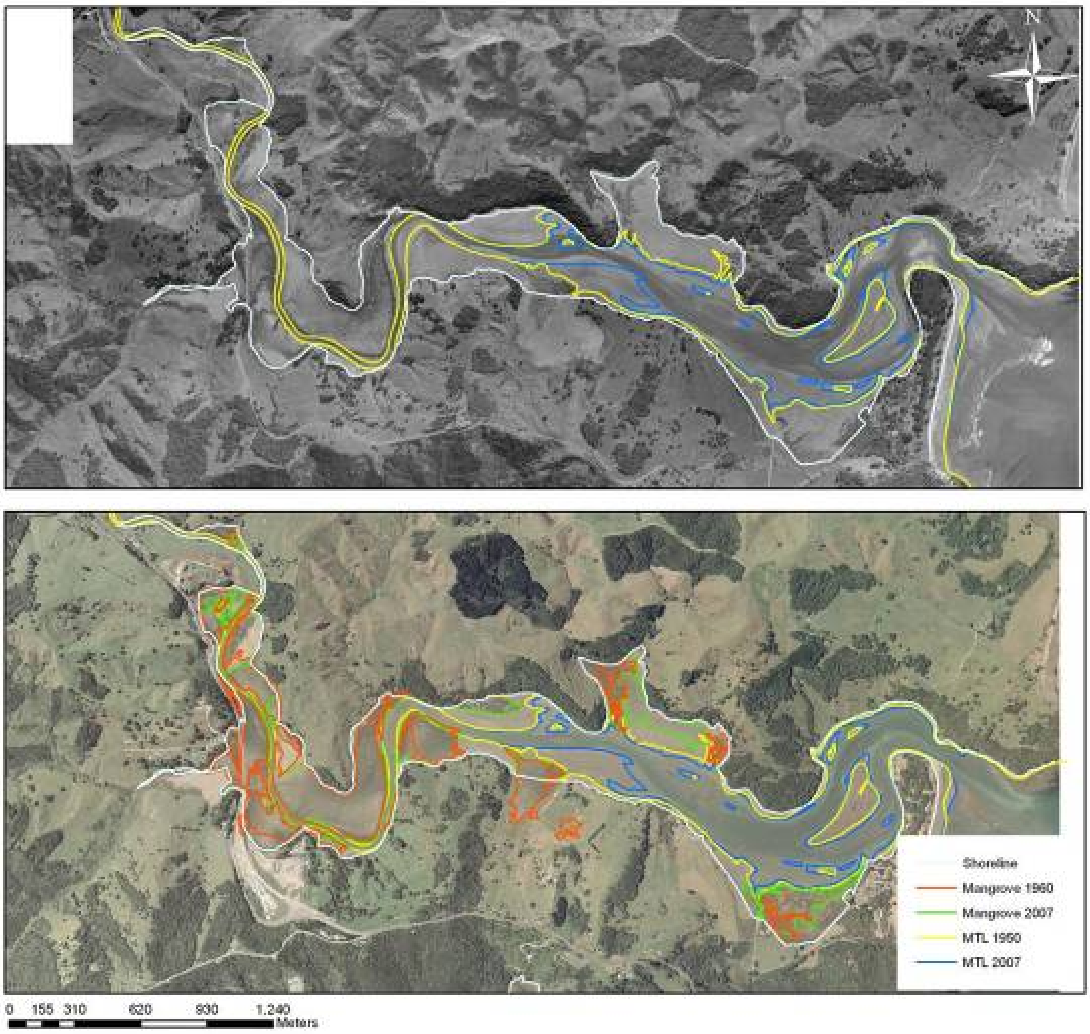


Figure 9.40:
Orewa Estuary (28 January 2008): mangrove habitat; waters-edge contour at 1501 NZST (MLOS + 23 minutes); fixed elevations relative to Auckland Vertical Datum 1946 (AVD-46); and RTK GPS transects, with colour coded elevations relative to AVD-46. MLOS is the mean level of the sea recorded at the Port of Auckland on the day of the aerial photography.

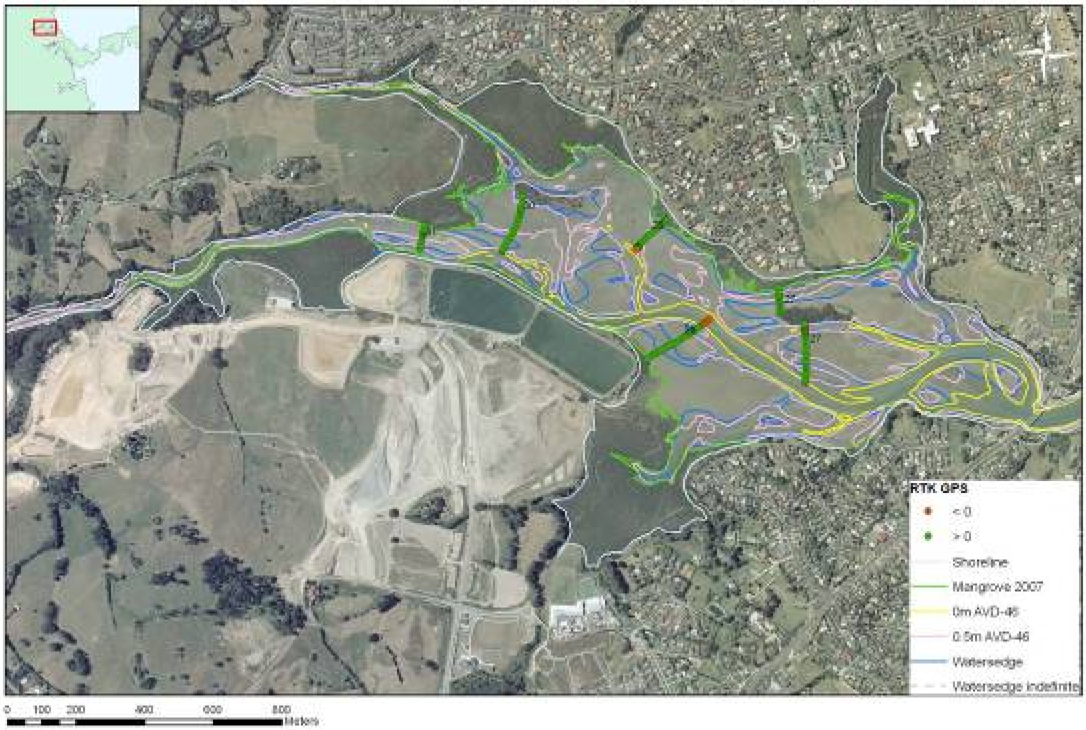


Figure 9.41:

Weiti Estuary (28 January 2008): mangrove habitat; waters-edge contour at 1502 NZST (MLOS + 24 minutes); fixed elevations relative to Auckland Vertical Datum 1946 (AVD-46); and RTK GPS transects, with colour coded elevations relative to AVD-46. MLOS is the mean level of the sea recorded at the Port of Auckland on the day of the aerial photography.

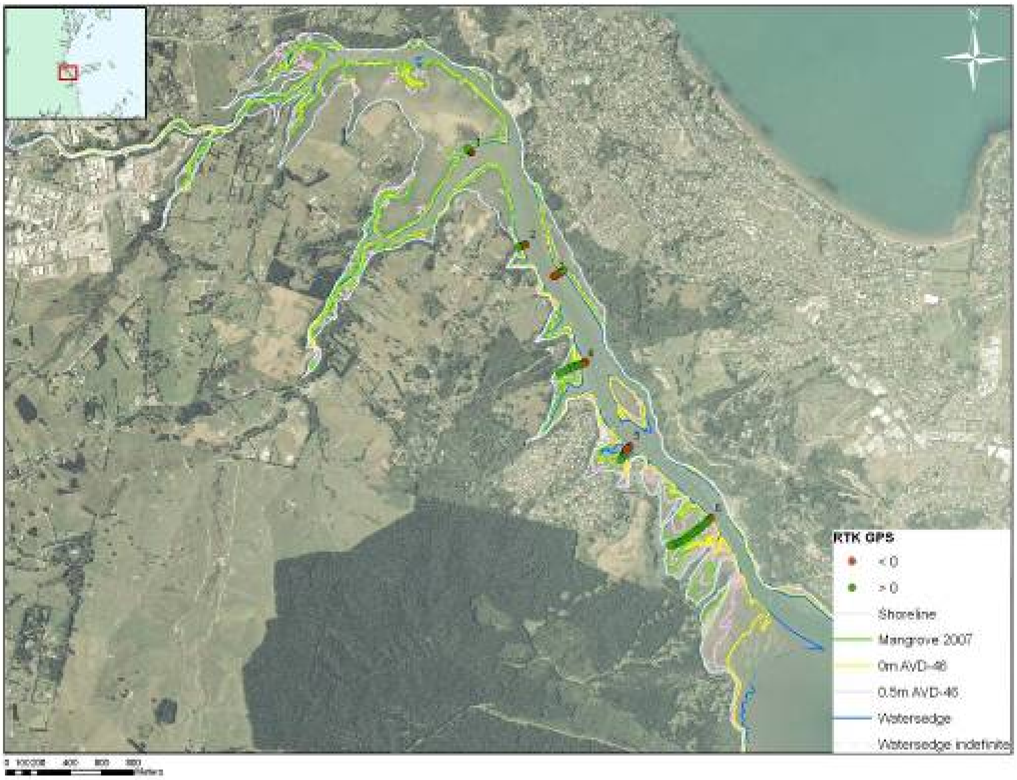


Figure 9.42:

Okura Estuary (28 January 2008): mangrove habitat; waters-edge contour at 1502 NZST (MLOS + 24 minutes); fixed elevations relative to Auckland Vertical Datum 1946 (AVD-46); and RTK GPS transects, with colour coded elevations relative to AVD-46. MLOS is the mean level of the sea recorded at the Port of Auckland on the day of the aerial photography.

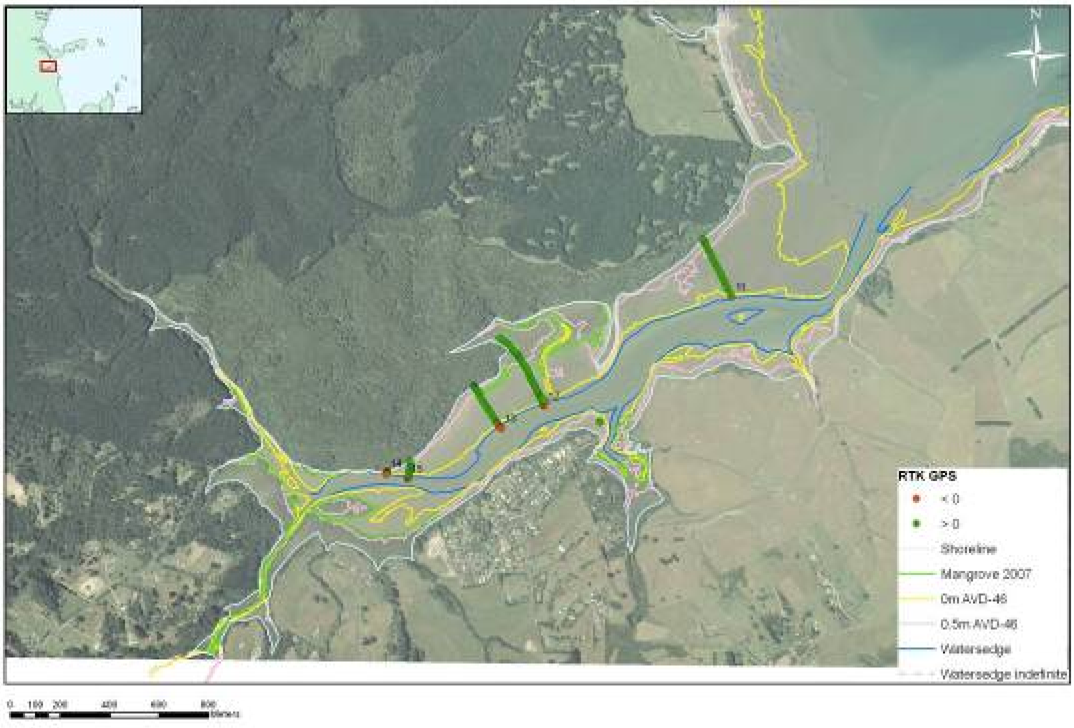


Figure 9.43:

Upper Waitemata Harbour (28 January 2008): mangrove habitat; waters-edge contour at 1511 NZST (MLOS + 33 minutes); fixed elevations relative to Auckland Vertical Datum 1946 (AVD-46); and RTK GPS transects, with colour coded elevations relative to AVD-46. MLOS is the mean level of the sea recorded at the Port of Auckland on the day of the aerial photography.

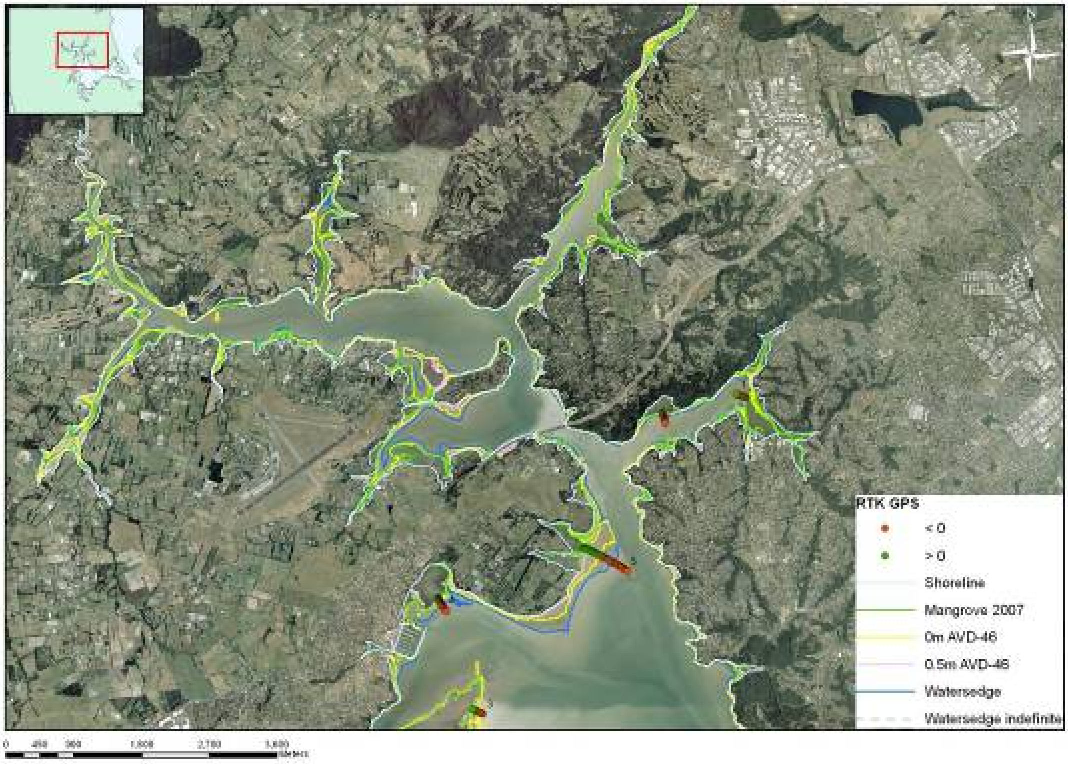


Figure 9.44:

Central Waitemata Harbour (28 January 2008): mangrove habitat; waters-edge contour at 1505 NZST (MLOS + 27 minutes); fixed elevations relative to Auckland Vertical Datum 1946 (AVD-46); and RTK GPS transects, with colour coded elevations relative to AVD-46. MLOS is the mean level of the sea recorded at the Port of Auckland on the day of the aerial photography.

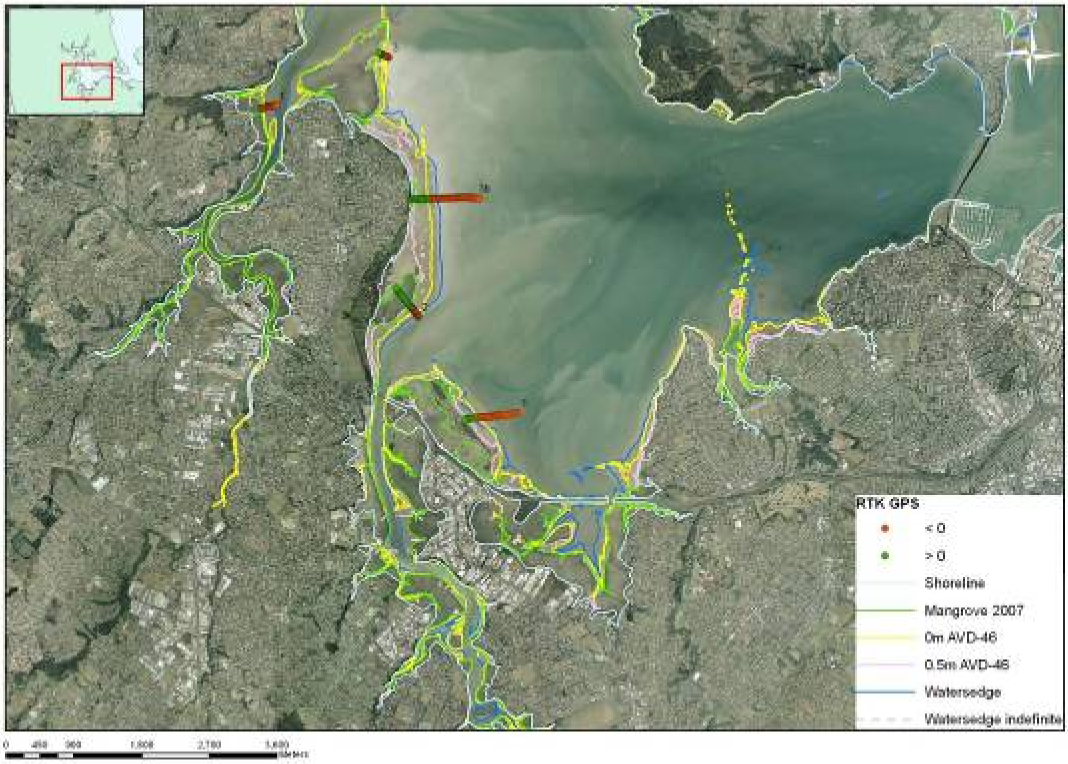
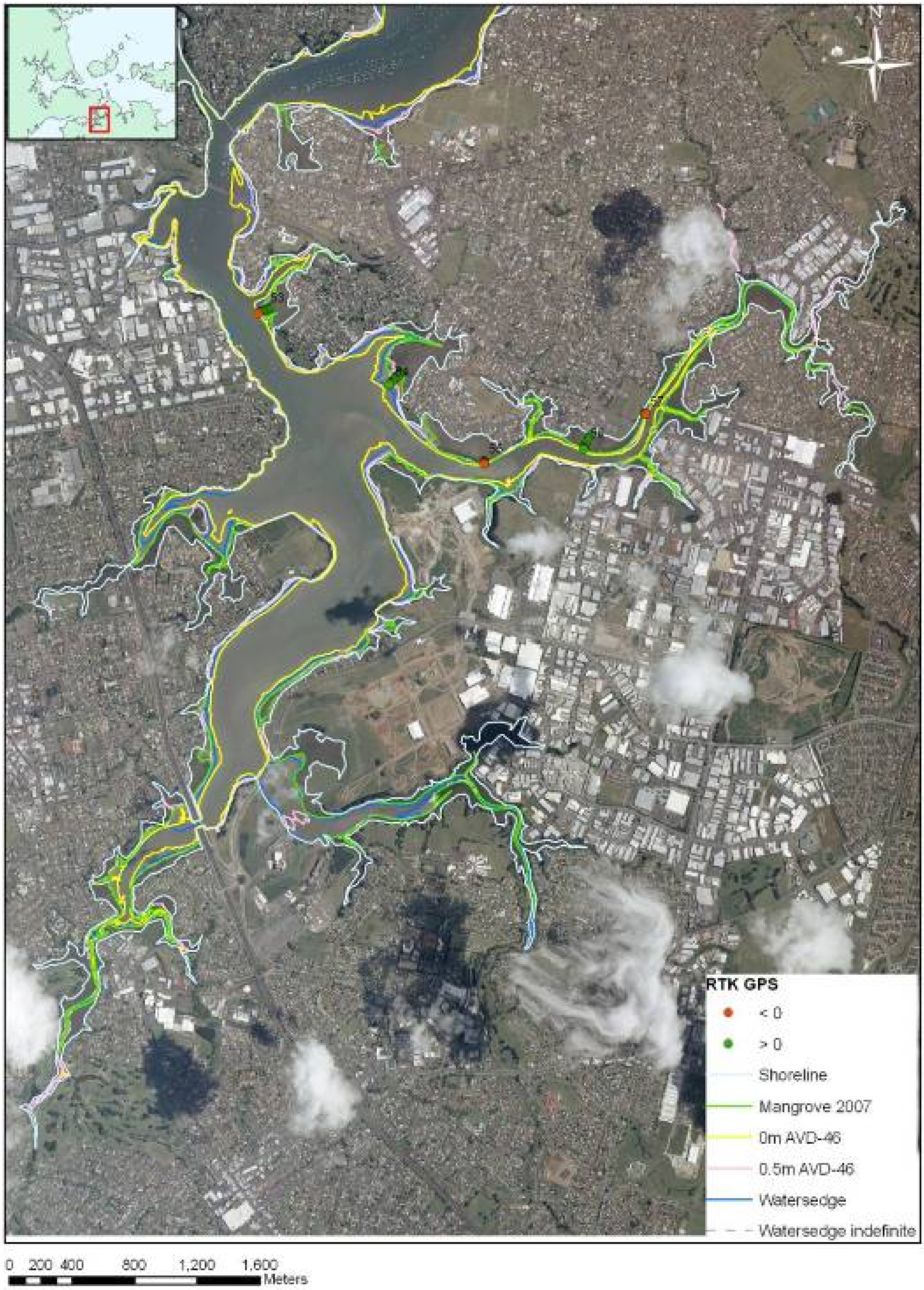


Figure 9.45:
Shoal Bay (28 January 2008): mangrove habitat; waters-edge contour at 1505 &1522 NZST (MLOS +27 (west) & + 44 minutes (east); fixed elevations relative to Auckland Vertical Datum 1946 (AVD-46); and RTK GPS transects, with colour coded elevations relative to AVD-46. MLOS is the mean level of the sea recorded at the Port of Auckland on the day of the aerial photography.

Figure 9.46:

Orakei Basin & Hobson Bay (28 January 2008): mangrove habitat, waters-edge contour at 1522 NZST (MLOS + 44 minutes); fixed elevations relative to Auckland Vertical Datum 1946 (AVD-46); and RTK GPS transects, with colour coded elevations relative to AVD-46. MLOS is the mean level of the sea recorded at the Port of Auckland on the day of the aerial photography.

Figure 9.47:
Tamaki Estuary (17 November 2007): mangrove habitat, waters-edge contour at 0903 & 0950 NZST (MLOS +15 (south) & +58 (north) minutes); fixed elevations relative to Auckland Vertical Datum 1946 (AVD-46); and RTK GPS transects, with colour coded elevations relative to AVD-46. MLOS is the mean level of the sea recorded at the Port of Auckland on the day of the aerial photography.



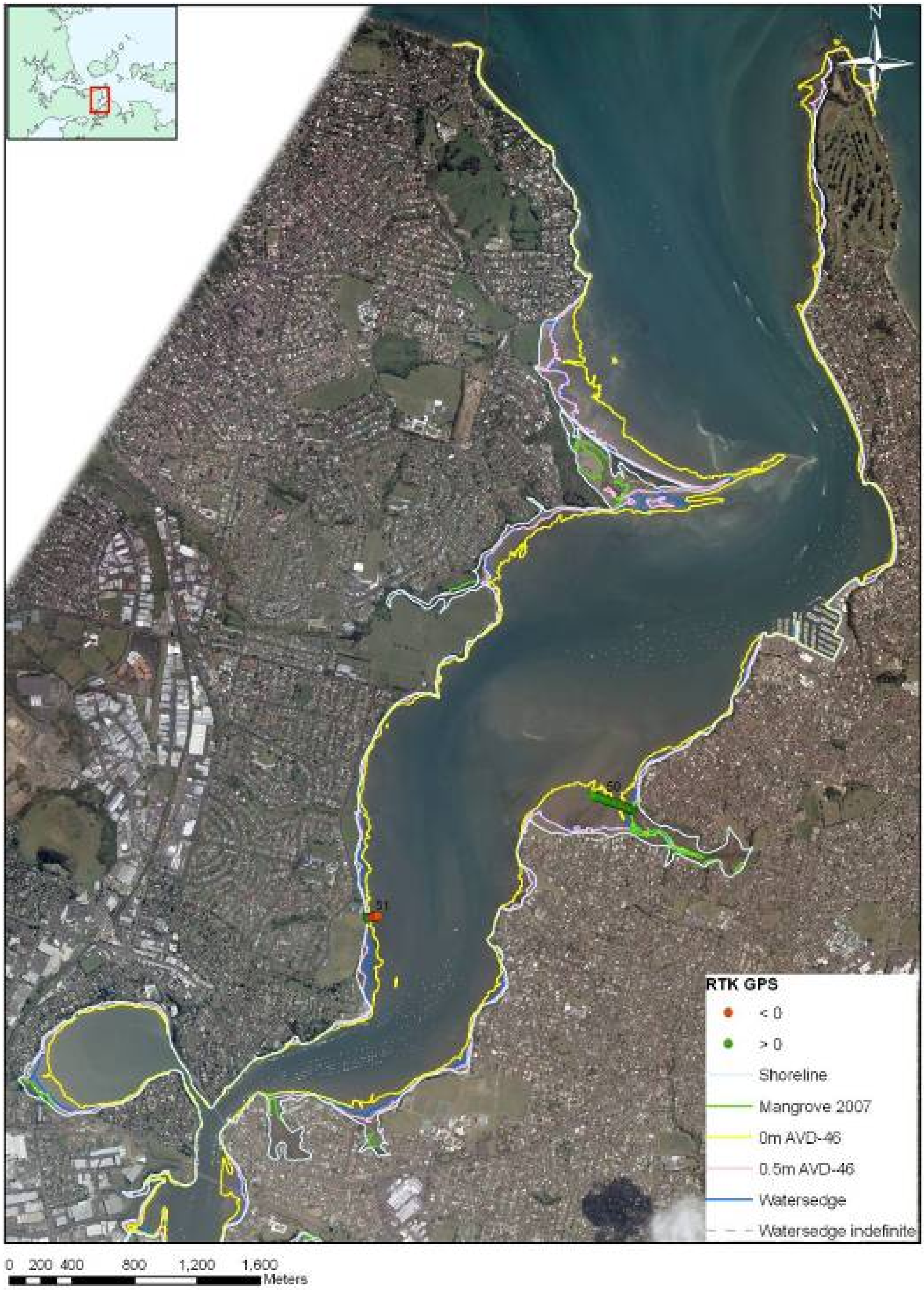

N
51
50
RTK GPS
< 0
> 0
Shoreline
Mangrove 2007
0m AVD-46
0.5m AVD-46
Watersedge
Watersedge indefinite
0 200 400 800 1,200 1,600
Meters

Figure 9.48:
Whitford Bay (17 November 2007): mangrove habitat, waters-edge contour at 0917 NZST (MLOS +29 minutes); fixed elevations relative to Auckland Vertical Datum 1946 (AVD-46); and RTK GPS transects, with colour coded elevations relative to AVD-46. MLOS is the mean level of the sea recorded at the Port of Auckland on the day of the aerial photography.

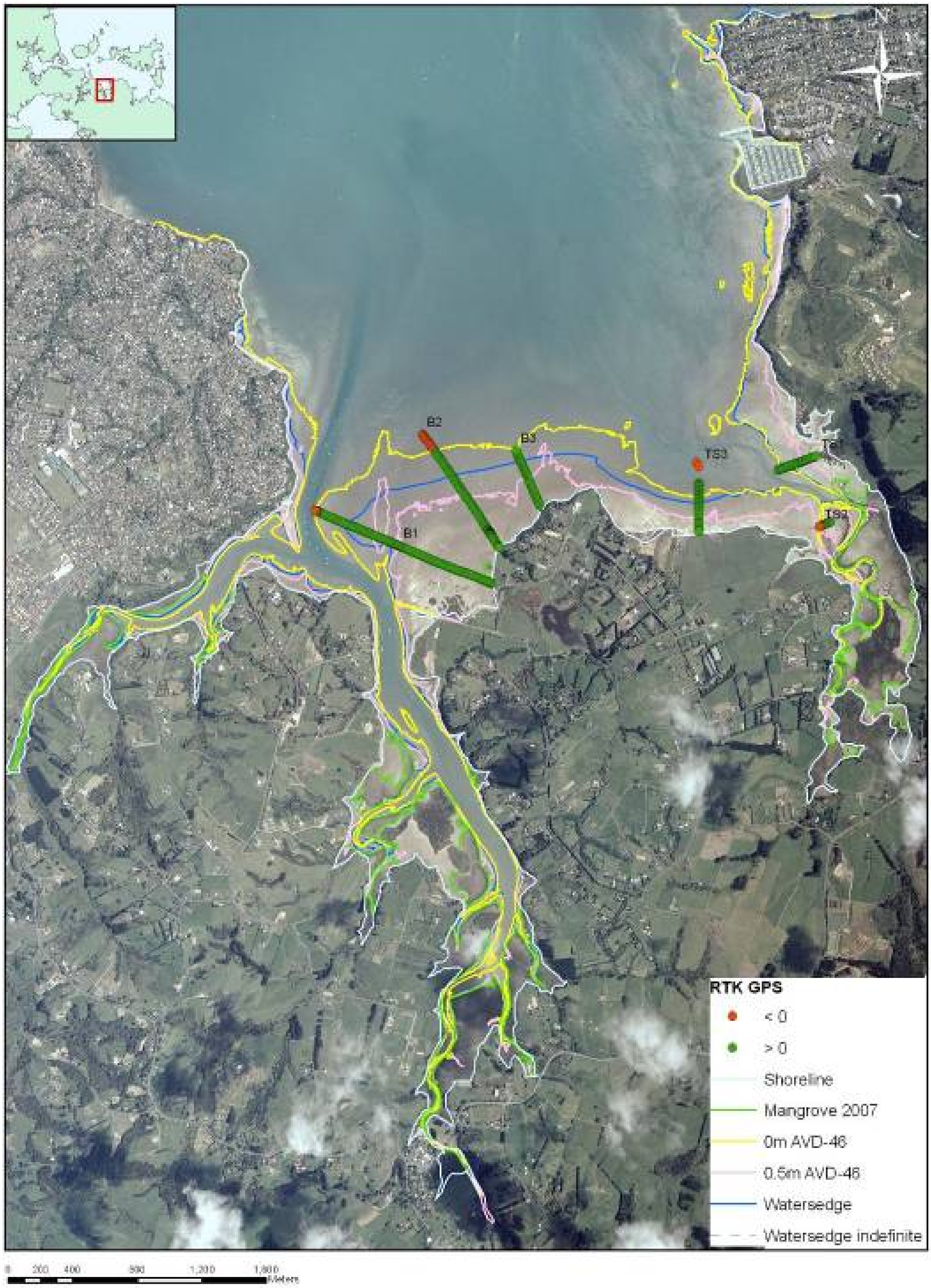


Figure 9.49:
Wairoa Estuary (17 November 2007): mangrove habitat, waters-edge contour at 0915 NZST (MLOS +27 minutes); fixed elevations relative to Auckland Vertical Datum 1946 (AVD-46); and RTK GPS transects, with colour coded elevations relative to AVD-46. MLOS is the mean level of the sea recorded at the Port of Auckland on the day of the aerial photography.

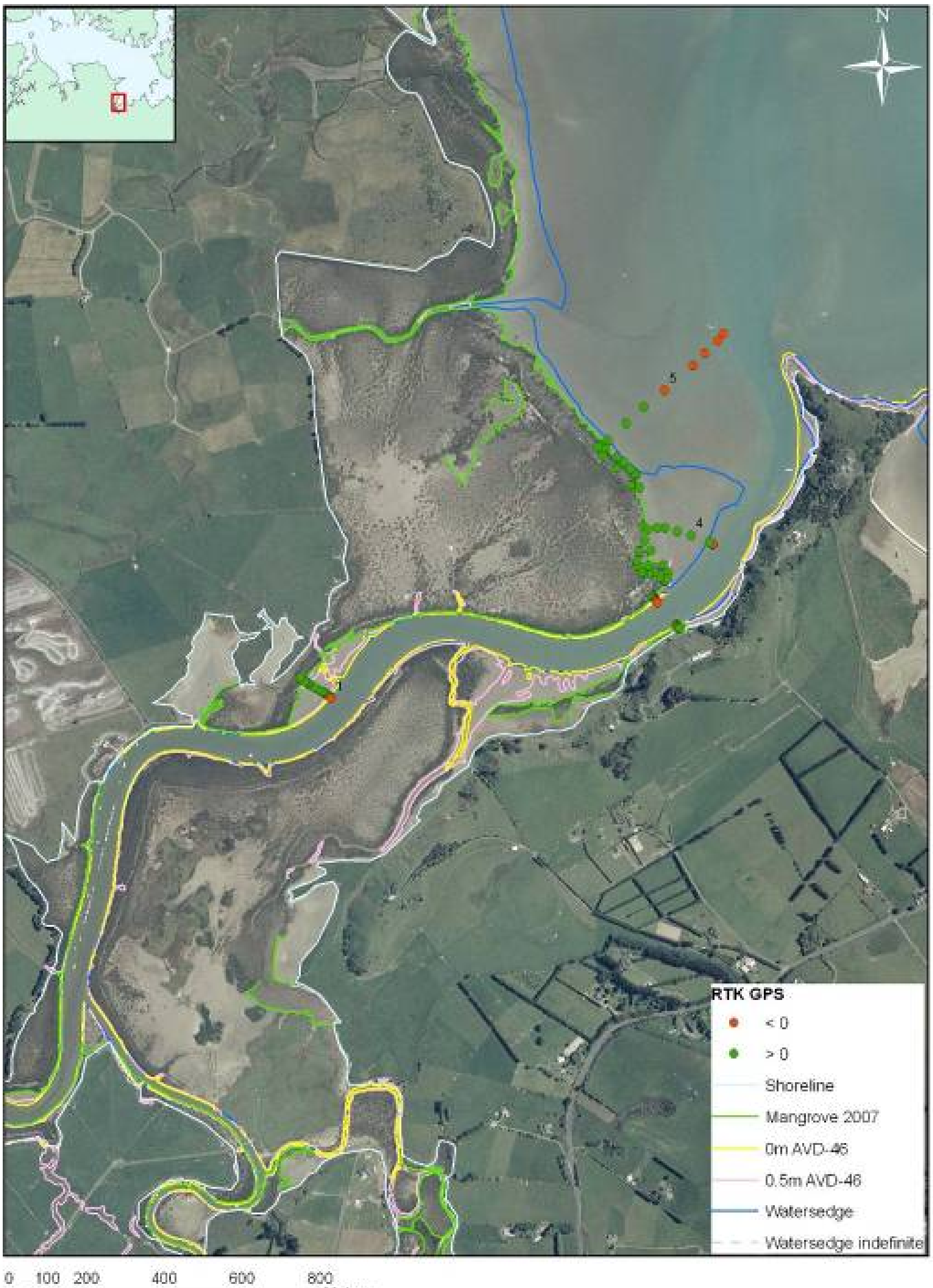


Figure 9.50:

Te Matuku, Waiheke (17 November 2007): mangrove habitat, waters-edge contour at 0939 NZST (MLOS +51 minutes); fixed elevations relative to Auckland Vertical Datum 1946 (AVD-46); and RTK GPS transects, with colour coded elevations relative to AVD-46. MLOS is the mean level of the sea recorded at the Port of Auckland on the day of the aerial photography.

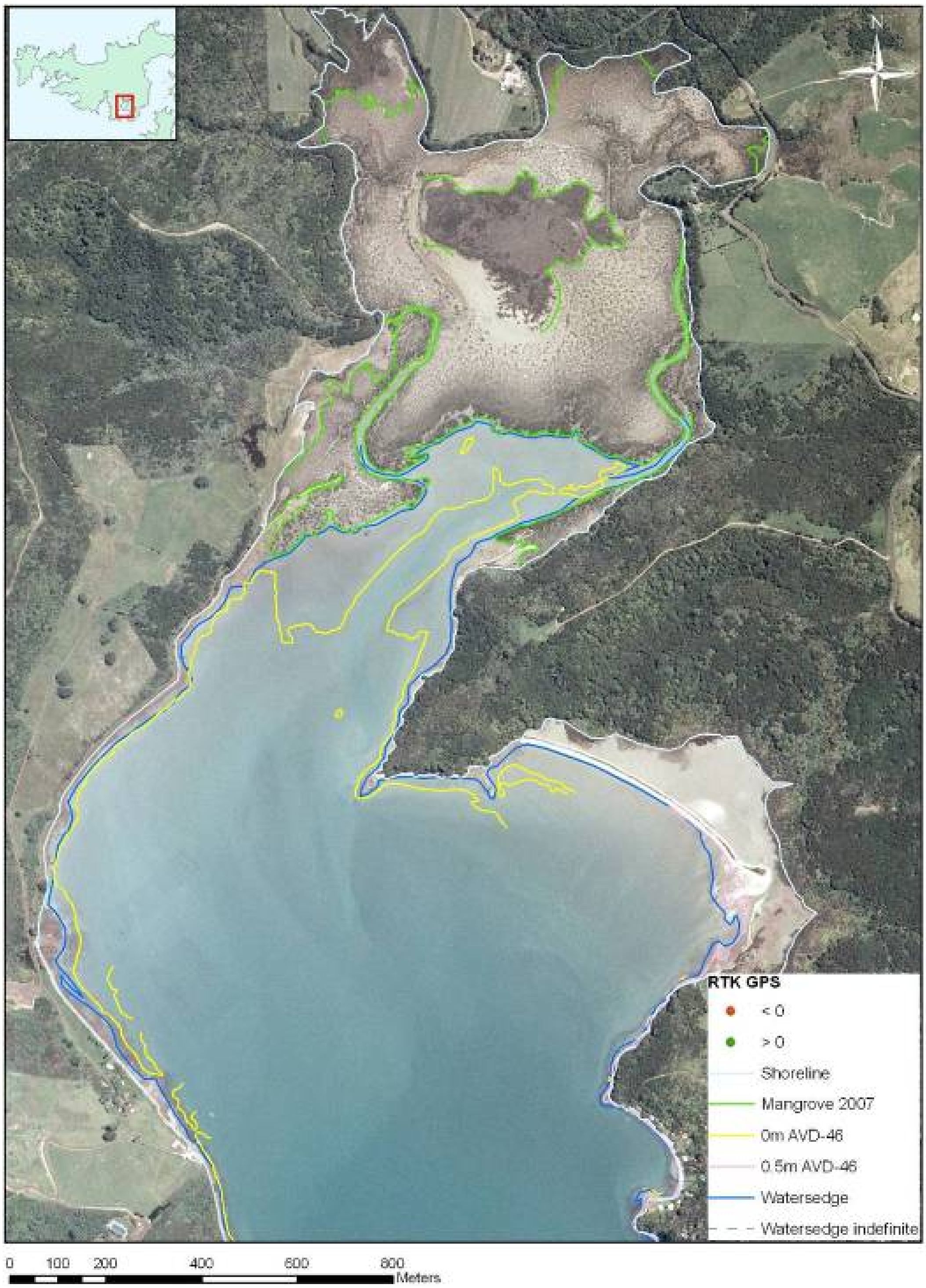


Figure 9.51:

Awaawaroa, Waiheke (17 November 2007): mangrove habitat, waters-edge contour at 0940 NZST (MLOS +52 minutes) ; fixed elevations relative to Auckland Vertical Datum 1946 (AVD-46); and RTK GPS transects, with colour coded elevations relative to AVD-46. MLOS is the mean level of the sea recorded at the Port of Auckland on the day of the aerial photography.

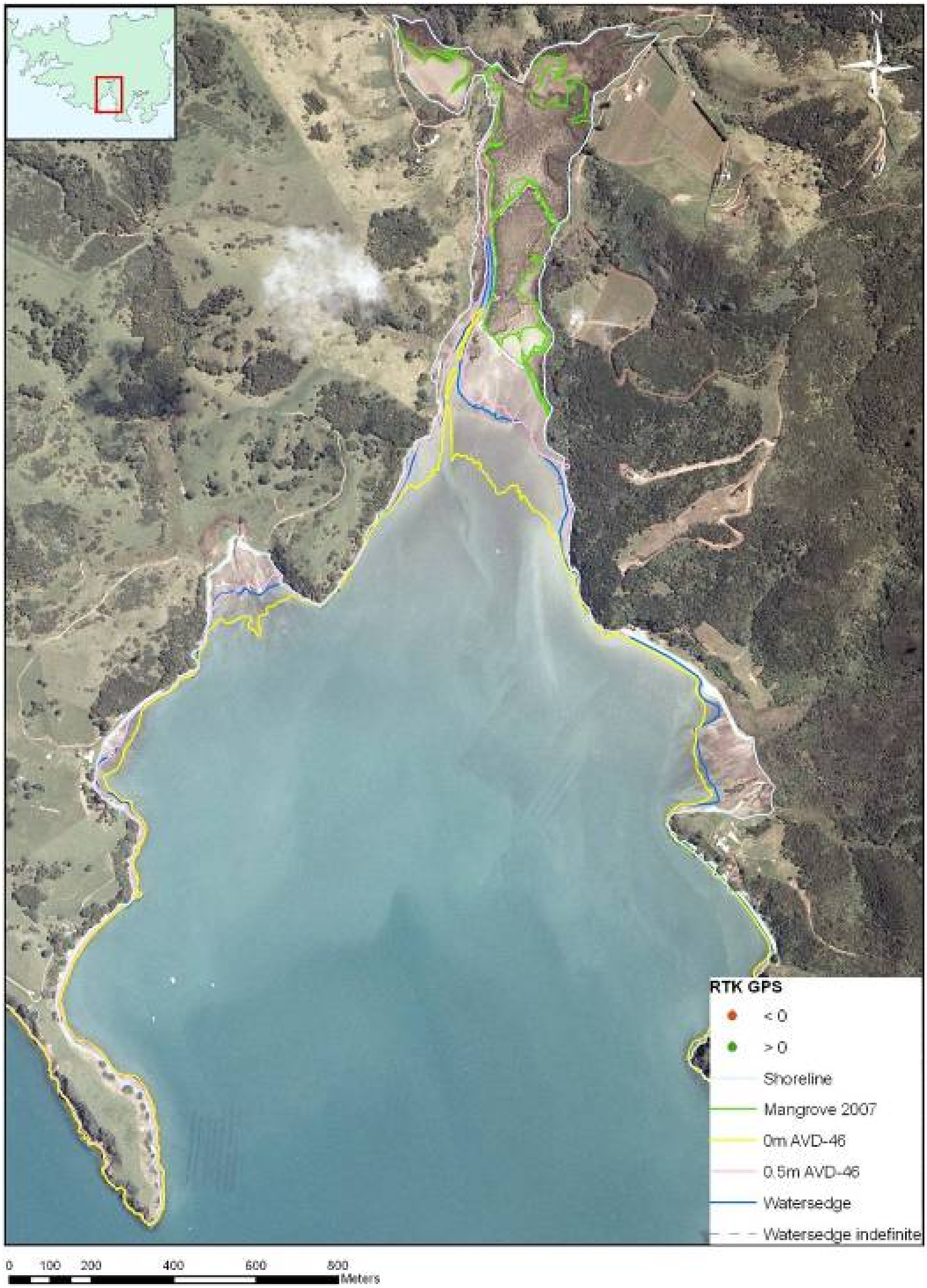


Figure 9.52:
Putiki Bay, Waiheke (28 January 2008): mangrove habitat, waters-edge contour at 1530 NZST (MLOS +52 minutes); fixed elevations relative to Auckland Vertical Datum 1946 (AVD-46); and RTK GPS transects, with colour coded elevations relative to AVD-46. MLOS is the mean level of the sea recorded at the Port of Auckland on the day of the aerial photography.