# Patterns and rates of recent sedimentation and intertidal vegetation changes in the Kaipara Harbour

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# 1 Executive summary

The Auckland Council and Northland Regional Council commissioned NIWA to undertake a study to collect baseline information on historical sediment accumulation rates in the Kaipara Harbour. This follows a review of sediment data for the harbour (Reeve et al. 2009) that identified a lack of quantitative information on historical sediment accumulation rates (i.e., last 50–100 years) and bed-sediment composition (particularly in the northern Kaipara).

This study describes sedimentation in the harbour over the last 50–100 years based on detailed analysis of sediment cores collected from intertidal flats. This analysis is based on radioisotope profiles, x-ray images, and sediment particle size and bulk density data. Additional cores were collected from several sites and stored for possible future studies of historical changes in sediment sources and metal concentrations. The core sites were selected in consultation with the Auckland Council and Northland Regional Council and focused on un-vegetated depositional intertidal-flat environments that were most likely to preserve historical sedimentation records.

The specific objectives of the study are to:

- Determine sediment accumulation rates and mixing depths in harbour sediments based on analysis of lead-210 ($^{210}$Pb), casesium-137 ($^{137}$Cs) and berrylium-7 ($^{7}$Be) profiles and x-radiographs.
- Identify areas within the Kaipara Harbour that function as long-term sinks for fine sediments.
- Map and interpret changes in vegetated intertidal habitats that have occurred in the Kaipara Harbour over the last several decades based on analysis of aerial photography. The vegetated habitats of interest include mangrove forests and salt marsh, mixed mangrove/salt-marsh and sea grass beds.

**Kaipara Harbour – historical background**

The Kaipara Harbour is a complex drowned-valley/barrier-enclosed type estuary, which is located on the west coast of the Northland Peninsula. The harbour is one of the largest estuaries in the southern hemisphere, with a high-tide surface area of 947 km$^2$, of which about 43% is intertidal. The Kaipara Harbour contains a diverse range of estuarine environments, which include extensive wave-exposed intertidal flats, sand barriers, extensive mangrove and salt-marsh habitats and large tidal-creek systems. The harbour receives runoff from a 5,836 km$^2$ catchment. The Wairoa River accounts for 63% of the catchment area and discharges to the northern end of the harbour. Landcover is predominantly pastoral agriculture, with areas of production forestry, horticulture, native forest and scrub.

Land-use changes following the arrival of Polynesians about 700 years ago and in particular European settlers from the 1830s increased soil erosion from catchments. Kauri-gum extraction and timber harvesting preceded the conversion of native forests to pastoral agriculture. Catchment deforestation accelerated following European settlement and most of the land suitable for pastoral agriculture was cleared by the early 1900s. In recent decades, horticulture, urbanisation and other forms of land-use intensification have occurred. The effects of increased catchment sediment loads on receiving estuaries following deforestation has been documented for a number of North Island estuaries. In many cases there has been a shift from sand to mud-dominated systems due to increased loads of terrigenous fine silts and clays and an order of magnitude increase in sediment accumulation rates relative to pre-deforestation values. These changes in sediment composition and rate of delivery impact the ecological "health" of estuarine systems by reducing the abundance of fine-sediment sensitive species while favouring tolerant species (e.g., mangroves).

Large-scale environmental changes have also occurred in the Kaipara Harbour due to the reclamation of hundreds of hectares of intertidal flat, mangrove and salt-marsh habitat for agricultural land. Although much of this reclamation occurred prior to the early 1900s, analysis of aerial photography as part of the present study indicates that hundreds of hectares were also reclaimed sometime after the mid-1960s. These large reclamations of intertidal habitat would have led to local changes in tidal flows, wave fetch and sedimentation processes. The introduction of alien plant and animal species, including *Spartina* (cord grass), Pacific Oyster, and Asian date mussel is also likely to have locally altered estuarine hydrodynamics, sediment transport and bed composition as well as benthic community structure.

**Study methods**

Sediment cores were collected at 18 sites during 16–19 March and 15 April 2010 using a 10-cm diameter Gravity Corer deployed from the NIWA vessel Rangitahi III. Replicate cores up to 1.7-m long were collected using this method, with a third replicate core collected at some sites and frozen for possible future applications (e.g., sediment contaminants). In the laboratory, cores were imaged using a digital x-ray system, which provided information on the fine-scale sedimentary fabric of sediment deposits. The particle-size distributions (PSD) of sediment samples were determined using a time of transition (TOT) stream-scanning laser sizer, in the size ranges 0.1–300/10–2000 $\mu$m.

Sediment accumulation rates were estimated from their vertical concentration profiles of the radioisotopes lead-210 ($^{210}$Pb, ½ life 22.3 years) and caesium-137 ($^{137}$Cs, ½ life 30 years). $^{210}$Pb is a naturally occurring radioisotope that is deposited at the earth's surface from the upper atmosphere. Constant $^{210}$Pb deposition at annual–decadal time scales is a key assumption of the standard $^{210}$Pb dating model. Sediments labelled with $^{137}$Cs derived from atmospheric nuclear weapons tests indicate sediments deposited since the early 1950s. These methods can provide accurate "sediment clocks" because they decay exponentially at a known constant rate and using two or more independent methods offsets the limitations of any one approach. This is important when interpreting sediment profiles from estuaries because of the potential confounding effects of sediment mixing by physical and biological processes. The short-lived radioisotope berrylium-7 ($^{7}$Be, $t_{1/2}$ 53 days) provided information on the depth of the surface-mixed layer (SML).

Changes in the spatial extent of vegetated intertidal habitats since the mid-1960s/1970s were mapped from the GIS analysis of geo-referenced and rectified aerial photographs undertaken by the Auckland Council and Northland Regional Council. In the Auckland Region, this analysis included estimation of mangrove-forest % canopy cover. Geo-referenced aerial photographs and ARC-MAP shape files of the vegetated habitats were provided to NIWA for interpretation.

The good agreement between the $^{210}$Pb and $^{137}$Cs dating as well as the information provided by the x-radiographs, $^{7}$Be and sediment-composition data, indicates that we can have confidence in the recent geochronology reconstructed from these cores. The sediment accumulation rates estimated from the $^{210}$Pb concentration profiles preserved in individual cores varied from 1–30 mm yr$^{-1}$. We have also compared average $^{210}$Pb sediment accumulation rates in the Kaipara Harbour with average rates for other North Island estuaries, which enables recent sedimentation in the Kaipara Harbour to be considered in a wider context of human impacts on New Zealand estuaries over the last 50–100 years. The data set includes records from 85 cores collected and analysed using similar methods from intertidal and subtidal flats in estuaries and coastal embayments. These include: Auckland east-coast estuaries (i.e., Central Waitemata Harbour (CWH), Mahurangi, Puhoi, Okura and Te Matuku) and embayments (i.e., Karepiro, Whitford and Wairoa); Bay of Islands (BOI, i.e., Te Puna, Kerikeri, Kawakawa and Te Rawhiti Inlets and to the outer BOI to 100-m water depth and Pauatahanui Inlet (Porirua).

### Sediment accumulation in the Kaipara Harbour over the last 50–100 years

Most terrigenous mud is delivered to the Kaipara Harbour by episodic flood events. Surface plumes of silt-laden stormwater are discharged to the harbour and disperse fine sediment down the tidal channels and across the intertidal flats. Some of this fine sediment will be deposited on the intertidal flats as well as transported back into tidal creeks and rivers on subsequent incoming flood tides. Cores collected ~2km seaward of the Hoteo River mouth, contain the best examples of flood deposits, composed of pure mud layers up to 6-cm thick. Most of these flood deposits pre-date the 1950s. The excellent preservation of flood deposits reflects its close proximity to a large terrigenous sediment source and rapid post-event burial by sand.

Elsewhere in the Kaipara Harbour, long-term accumulation of fine sediments is patchy. The rapid pace of seaward expansion of the 335 ha Whakatu mangrove-forest and field observations indicate that mud is rapidly accumulating in this mangrove forest and also on the upper-intertidal mudflats. Wave resuspension and winnowing of fine sediments also most likely explains the absence of mud from intertidal flats at Omokoiti, Kaipara, Kakaraia and Tapora. Although terrigenous muds may be deposited on these intertidal areas after flood events, radioisotope data indicate that sediments are being reworked to tens of cm depth. Taken together with particle-size information, these radioisotope data indicate that mud has not accumulated on these large intertidal harbour flats for hundreds if not thousands of years. Thus, fine sediments are re-mobilised from these intertidal flats by waves and transported by currents to eventually accumulate in “low energy” mud sinks. Long-term accumulation of fine sediments has occurred on the harbour fringes in tidal rivers and creeks, vegetated intertidal habitats and on intertidal flats in areas with limited wave fetch. Major fine-sediment accumulation zones include the southern Kaipara Harbour, Kakaraia Flats in the vicinity of the Hoteo River mouth and the Arapaoa River. Other long-term mud sinks in similar environments, such as the Otamatea and Oruwharo Rivers are inferred. By contrast, muds have not accumulated on large intertidal flats in the northern and southern arms of the harbour, such as the Omokoiti, Kaipara and Wairoa-River Flats, where waves and/or tidal currents deeply rework sediment deposits.

### Fine-sediment fate

Important questions regarding sedimentation in the Kaipara Harbour are: (1) what is the fate of fine-sediments discharged by the Wairoa River (63% of the total catchment area); and (2) what is the degree of fine-sediment connectivity between the northern and southern arms of the harbour? For example, mud has rapidly accumulated in the southern Kaipara Harbour over the last 50–100 years or more. Mangrove forests in the southern Kaipara had colonised extensive tidal flat areas by the 1920's so that these mudflats must have developed decades earlier. How much of this mud was supplied by small local rivers such as the Kaukapakapa and Kaipara, and how much derived from more remote sources is unknown.

These questions about the fate of fine sediments in the harbour are currently being addressed by NIWA using stable-isotope signatures to track sediment sources and sediment-transport modelling. The initial results of a NIWA Capability Fund sediment-source study, which included three major river sources (Wairoa, Kaipara and Hoteo) are presented here. The stable-isotope data indicate that: (1) the Wairoa River is the major source of sediment deposited in the northern Kaipara Harbour, and into the Arapaoa, Otamatea and Oruawharo River systems; (2) sediment from the Wairoa River is also deposited in the southern Kaipara Harbour, particularly on the tidal flats flanking the western shore as far south as Shelly Beach; (3) sediments discharged by the Kaipara River are mainly deposited in the harbour close to their source, south of Shelly Beach; and (4) sediments discharged by the Hoteo are mainly deposited on the Kakaraia Flats, close to the river mouth, with deposition of Hoteo sediments being patchy on the lower-intertidal flats.

These initial results are indicative and are representative of conditions at the time of sampling. These data do not provide any information about the temporal variability of contemporary sediment sources over weeks–months nor changes in the relative contributions of major sediment sources over time (i.e., years–decades). Further work is also required to identify signatures for each of the land-use practices associated with each of these major river sources.

### Kaipara sediment accumulation rates compared to Auckland estuaries

The average $^{210}$Pb sediment accumulation rates estimated for the Kaipara Harbour is 6.7 mm yr$^{-1}$ (SE = 1.9 mm yr$^{-1}$), although excluding data from two outlier core sites reduces this to 4 mm yr$^{-1}$ (SE = 0.3 mm yr$^{-1}$). In either case these harbour-average sediment accumulation rates are not significantly different from the average $^{210}$Pb sediment accumulation rates for Auckland's east-coast estuaries (5.1 mm yr$^{-1}$, SE = 0.8). This estimate excludes the much larger CWH (3.3 mm yr$^{-1}$, SE = 0.3 mm yr$^{-1}$), where wave-driven winnowing of fine-sediment plays an important role in moderating the rate of infilling. Average $^{210}$Pb sediment accumulation rates are significantly lower in all other North Island estuaries and coastal embayments (range 1.9 –3.4 mm yr$^{-1}$) included in this comparison. The high average $^{210}$Pb sediment accumulation rates measured in Auckland east-coast estuaries in comparison to other estuaries reflects their close proximity to catchment outlets, degree of land-use intensification (e.g., urban development), the small size of receiving estuaries relative to their catchment as well as estuarine processes and basin shape which interact to influence sediment trapping. The average sediment accumulation rates in the Kaipara Harbour is intermediate between rates in Auckland's small, river-dominated, east-coast estuaries and larger estuaries, such as the Central Waitemata Harbour, where wave-driven winnowing of fine-sediment plays an important role in moderating the rate of infilling.

## Historical changes in mangrove and salt marsh habitats

Mangrove habitat accounts for a substantial proportion (19%) of the ~407 km$^2$ intertidal area of the Kaipara Harbour. The analysis of aerial photography indicates that the total area of mangrove habitat has increased by 11% from an estimated 6845 ha in 1966/1977 to 7615 ha in 2002/2007. This estimated net increase includes the effects of large-scale reclamation works that reduced the area of mangrove habitat in the Southern Kaipara. This entire net increase in mangrove habitat has occurred in the northern Kaipara, with the total area increasing by 41% (1977–2002). This estimate includes data from the Auckland Region of the Oruawharo River. The rate of mangrove-habitat expansion in the Kaipara Harbour at 0.2–2.1% yr$^{-1}$ is in the range observed in other North Island estuaries (0.2–20% yr$^{-1}$), although substantially less than the average rate of 4% yr$^{-1}$ since the 1940s. These data include studies of small mangrove stands as well as large forests ($10^0$–$10^3$ ha area) and all major estuary types, including drowned river valleys, barriers, embayments and coastal lagoons.

The total area of salt-marsh habitat in the Kaipara Harbour has reduced by an estimated -3.6%, from 684 ha (1966/1977) to 660 ha in 2002/2007, with all of this net decrease occurring in the Auckland region (-31%) primarily due to reclamation. By contrast, the area of salt-marsh habitat in the Northland region has increased by 48% since the mid-1970s and now accounts for ~ 53% of the total. With the exception of the Arapaoa River, where the area of salt marsh has been static, increases in salt-marsh habitat have averaged 0.2–4.5% yr$^{-1}$ in comparison to losses in the southern Kaipara (0 to -0.3% yr$^{-1}$) related to reclamation works sometime after the mid-1960s. Data for mixed mangrove and salt-marsh habitat (Auckland region only) also shows a substantial reduction from 417 ha (1966/1977) to 212 ha in 2007, with most of this habitat loss occurring also due to reclamation on the South Kaipara and Omokoiti Flats. It should be noted that the area of salt-marsh habitat mapped from the earlier (1966, 1977) black and white aerial photography is likely to be underestimated.

The analysis of historical aerial-photography does not encompass the environmental changes, including mangrove-habitat expansion that occurred in many New Zealand estuaries prior to the 1940s. In the Kaipara Harbour, McShane (2005) complied the historical accounts and photographs of settlers, some of which date back to the 1860s. These records show that white-sand beaches fringed the shoreline and mangroves were not widespread in the large tidal rivers of the northern Kaipara. Although we cannot quantify the extent of these earlier environmental changes, these historical records show that in some locations major phases of mangrove-habitat expansion occurred prior to the 1940s (e.g., Ferrar 1934, McShane 2005).

# 2 Background

The Auckland Council (AC) and Northland Regional Council (NRC) commissioned NIWA to undertake a study to collect baseline information on historical sediment accumulation rates (SAR) in the Kaipara Harbour system. The present study has been partly motivated by the absence of quantitative information on sedimentation in the Kaipara Harbour. This information gap was identified during a review of sediment data for the harbour (Reeve et al. 2009). That review specifically identified that there is:

- no quantitative data on historical SAR in the Kaipara Harbour, over the last 150 years, during the period following large-scale catchment deforestation
- negligible data on contaminant accumulation in harbour sediments associated with human activities
- limited information on bed-sediment composition, particularly in the northern Kaipara Harbour.

The present study primarily addresses the lack of information on sedimentation rates and patterns in the harbour. Although not reported here, sediment cores from two of the sites have been selected for analysis of historical changes in terrigenous sediment sources. This sediment-source tracing work, based on the Compound-Specific Stable Isotope (CSSI) method (Gibbs 2008), is funded as part of a 2010/11 NIWA Capability Fund research project.

The present study provides quantitative information on sedimentation and changes in sediment composition over the last 100 years or so based on detailed analysis of sediment cores. This information is derived from radioisotope profiles, x-ray images, and sediment particle size and bulk density data. Additional cores were collected from several sites and stored for possible future studies of historical changes in sediment sources and metal concentrations.

Selection of core sites has focused on un-vegetated depositional environments in areas that are most likely to preserve historical sedimentation records. Potential sedimentary sub-environments for preservation of sediment records include intertidal and subtidal flats and tidal creeks.

## 2.1 Study objectives

The specific objectives of the present study are:

- determine sediment accumulation rates and mixing depths in harbour sediments based on analysis of radioisotope profiles (i.e., $^{210}$Pb, $^{137}$Cs and $^{7}$Be) and x-radiographs
- identify areas within the harbour that function as long-term sinks for fine sediments
- collect and store additional sediment cores from selected sites for possible future analyses of historical changes in sediment sources (i.e., CSSI method) and metal concentrations

- map and interpret the historical changes in vegetated intertidal habitats that have occurred in the Kaipara Harbour over the last several decades based on analysis of geo-referenced aerial photography. The vegetated habitats of interest include native mangrove forests and salt marsh and introduced *Spartina* (cord grass) saltmarsh. Geo-referenced aerial photographs and ARC-MAP shape files of the vegetated habitats were provided by AC and NRC. Classification of mangrove forest density (i.e., canopy cover) was also undertaken by the AC using the method of Wilton and Saintilan (2000).

## 2.2 Estuary sedimentation

Sediments deposited in estuaries and coastal marine areas can provide detailed information about how these receiving environments have changed over time, which include the effects of human activities on the land. In New Zealand, major changes have occurred in estuaries and coastal ecosystems over the last several hundred years due to large-scale removal of native forests. This deforestation began shortly after initial colonisation by Polynesians in ~1300 A.D. (McGlone 1983, Wilmshurst et al. 2008) and accelerated following the arrival of European settlers in the early–mid 1800s. Forest clearance associated with slash and burn agriculture by early Maori, and subsequent timber extraction, mining and land conversion to pastoral agriculture by European settlers triggered large increases in fine-sediment loads from catchments. During the peak period of deforestation in the mid-1800s to early 1900s), sediment loads typically increased by a factor of ten or more.

In many New Zealand estuaries, this influx of fine sediment resulted in a shift from sandy to more shallow, turbid and muddy environments and large increases in sediment accumulation rates (SAR). Studies mainly in North Island estuaries indicate that in pre-Polynesian times (i.e., before 1300 A.D.) SAR estimated from radiocarbon dating averaged 0.1–1 millimetres per year (mm $yr^{-1}$). In comparison the rates have increased to 2–5 mm $yr^{-1}$ in these same systems today. Sedimentation rates in tidal creeks, mangrove forests and in tidal creeks and estuaries near large catchment outlets are even higher and typically in the range of 10–30 mm/yr (e.g., Hume and McGlone, 1986; Sheffield et al. 1995; Swales et al. 1997; 2002a, 2002b).

The eroded catchment soils and marine sediments that have accumulated in estuaries form the tidal flats that we see today. These sediment deposits can be sampled by coring and dated using a variety of techniques to determine sediment accumulation rates (SAR). Radioisotope dating has been successfully applied to quantify SAR in a number of Auckland and upper North Island estuaries (e.g., Goff et al. 1998, Oldman and Swales 1999, Swales et al. 1997, 2002a, 2002b, 2005, 2007a, 2007b, 2008a, Swales and Bentley 2008). This work includes a regional study of sedimentation in Auckland's east-coast estuaries over the last 50 years (Swales et al. 2002b). The use of radioisotopes for dating estuarine sediments is described in sections 3.5 and 8.2 (appendices).

## 2.3 Study area

The Kaipara Harbour is a complex drowned-valley/barrier-enclosed type estuary, which is located on the west coast of the Northland Peninsula (Figure 2.1). The Kaipara Harbour is also one of the largest estuaries in the southern hemisphere, with a high-tide surface area of ~947 $km^2$, of which 43% is intertidal (Heath 1975). Although most of the harbour is composed of intertidal flat and shallow subtidal habitats, the entrance channel is up to 50 m deep.  The sand barriers that form the North and South Heads are composed of late Pliocene and Quaternary dune sand and swamp deposits, as well as the more recent Holocene deposits that form the tidal deltas, beach and dune systems today.  The ebb-tide delta alone (to 30 m water depth) contains an estimated 12.3 billion cubic metres of sand (NZ Geological Survey 1972, Hicks and Hume 1996, Hume et al. 2003).  These vast deposits are composed of marine sands that were transported onshore as sea level rose at the end of the last ice age, which was at its peak 16–18,000 years ago.  At this time, sea level was 120 m lower than today and the ancestral Kaipara Harbour was most likely a branching system of river valleys that discharged over the present-day continental shelf to an open coast, some ~25 km west of its present position (Hume et al. 2003).  The harbour that we see today was formed ~6,500 years ago when the sea reached its present level.  Subsequently, the ancestral river valleys began to infill with marine and terrigenous sediments, which form the present-day sand banks and tidal flats of the inner harbour.

The Kaipara Harbour contains a diverse range of estuarine environments, which include extensive wave-exposed intertidal flats (Fig 2.2) and sand barriers (Fig. 2.3), extensive mangrove (Fig. 2.4) and salt-marsh habitats (Fig 2.5) and large tidal-creek systems (Fig. 2.6).

Figure 2-1: Location map of the Kaipara Harbour showing catchment boundary and major sub-habitat types.

Source: NZ Hydrographic Chart NZ24, 2001

**Figure 2-2: Extensive intertidal flats flank the tidal channels.** View of the Kaipara River looking south towards Helensville, March 2009 (Photo: A. Swales, NIWA).

**Figure 2-3: View of the Kaipara Harbour entrance.** Marine sands transported onshore since the last ice-age have built the large sand barriers and tidal flats that characterise the central harbour. View looking west across Tapora Island, August 2009 (Photo: A. Swales, NIWA).

**Figure 2-4: Mangrove forests occur at several locations in the Kaipara Harbour, such as this one flanking the Puharakeke Creek, south Kaipara Harbour, March 2009.** (Photo: A. Swales, NIWA).

**Figure 2-5: Mixed mangrove stand salt-marsh complexes are a common feature of the upper-intertidal flats, March 2009.** (Photo: A. Swales, NIWA).

**Figure 2-6: Numerous tidal creeks indent the Kaipara Harbour shoreline.** These environments are characterised by sinuous channels flanked by mud flats and mangrove stands. Very large tidal creeks, extending 10 km or more from the upper reaches to their outlets, occur in the northern Kaipara. View of the upper Oruawharo River, November 2010 (Photo: A. Swales, NIWA).

The harbour receives runoff from a 5,836 km$^2$ land catchment. The Wairoa River accounts for 63% of the total catchment area, and discharges to the northern end of the harbour (Figure 2.1). Catchment geology is largely composed of a Cretaceous–Miocene age basement of inter-bedded sandstones and siltstones (NZ Geological Survey, 1972). Land use is predominantly pastoral agriculture, with production forestry, horticulture and native forest and scrub (Reeve et al. 2009).

As documented elsewhere, land-use changes following the arrival of Polynesians about 700 years ago and European settlers from the 1830s increased soil erosion from catchments. Kauri gum extraction and timber harvesting preceded the conversion of native forests to pastoral agriculture. Catchment deforestation would have accelerated following the first hydrographic survey of the harbour by H.M.S. Pandora in 1852 and most of the land suitable for pastoral agriculture was cleared by the early 1900s (Ferrar 1934, Bryne 1986, Ryburn 1999). In recent decades, horticulture, urbanisation and other forms of land-use intensification have occurred.

The effects of increased catchment sediment loads on receiving estuaries following deforestation has been documented for a number of North Island systems. In many cases there has been a shift from sand to mud-dominated systems due to increased loads of terrigenous fine silts and clays and an order of magnitude increase in SAR relative to pre-deforestation values (e.g., Oldman & Swales 1999, Swales et al. 1997, 2002a, 2002b, 2005, 2007a). These sediment changes (i.e., SAR and sediment composition) impact the ecological “health” of estuarine systems by reducing the abundance of fine-sediment sensitive species while favouring tolerant species (e.g., mangroves) (Hewitt and Funnell 2005, Thrush et al. 2004). The relative paucity of data on sedimentation in the Kaipara

Harbour system means there is a risk that degradation in environmental quality will not be detected in time for an effective management response to be developed and implemented.

In large estuaries with extensive wave fetch, such as the Kaipara Harbour, fine-sediments are not typically uniformly distributed. Instead they accumulate in “low-energy” sedimentary environments such as tidal creeks, mangrove forests, salt marshes, sub-tidal flats and the upper reaches of intertidal flats where the potential for wave-driven re-suspension is low (e.g., Green et al. 1997, Swales et al. 2004, Swales and Bentley 2008). Relatively detailed information on surficial-sediment composition exists for the southern Kaipara Harbour, which was extensively sampled as part of a benthic-habitat mapping study undertaken for the ARC (Hewitt and Funnell 2005). Figure 2.7 shows the spatial distribution of mud (i.e., particles < 62.5 μm dia.) in the southern Kaipara Harbour. The mud content of bed sediments varies from less than 2% on the lower-middle intertidal flats (e.g., Kaipara Flats, Omokoiti Flats and flats flanking Tapora Island) and greater than 50% on the upper intertidal flats south of Shelly Beach and the Tauhoa Creek and Oruawharo River. Although surficial sediments in mangrove and salt-marsh habitats were not sampled in the southern Kaipara, these habitats are primary sinks for terrigenous muds (e.g., Swales et al. 2002, 2007). Field observations in the Whakatu mangrove forest conservation area (northern Kaipara) by NIWA indicate this is also the case in the Kaipara Harbour (Fig. 2.10).

Large-scale environmental changes have also occurred in the Kaipara Harbour due to the reclamation of tidal flat, mangrove and salt-marsh habitat for agricultural land and associated drainage works. It appears that large areas of former tidal flat had been reclaimed by the early 1900s. Rowan (1917) describes the reclamation process, with the construction of stopbanks, drainage canal and flood gates at the seaward boundary of the reclamation area. The estuarine sediments impounded behind stopbanks consolidate and salt is flushed out by rainfall. Typically weeds (e.g., thistle) would establish after 12 months or so, with mixed grasses and clover sown within five years of stopbank construction. Reclamation of hundreds of hectares of estuarine habitat in the Kaipara harbour has occurred in this manner, although the total area reclaimed is unknown. Reclamation of vegetated intertidal habitat would have led to local changes in tidal flows, wave fetch and sedimentation processes.

The introduction of alien plant and animal species has also likely to have resulted in environmental changes in the harbour. The smooth cord-grass, *Spartina alterniflora* Loisel, was introduced to the Kaipara Harbour and other North Island estuaries in the 1950s (Shaw and Gosling 1997) (Fig 2.8). As occurred elsewhere, *Spartina* spp. were introduced to New Zealand estuaries to promote reclamation of tidal flats for agriculture, protect low-lying shorelines from wave erosion and to provide areas for stock grazing (Swales et al. 2005). The sediment budgets of tidal flats are substantially altered by *Spartina* marshes by promoting rapid mud deposition. Sediment accumulation rates in *Spartina* marshes of tens of mm per year have been documented (Swales et al. 2004). Furthermore, like the native mangrove, *Avicennia marina*, *Spartina* spp. can colonise intertidal flats down to mean tide level so that large areas of tidal flat can potentially be colonised. Colonisation of bare tidal flats may also occur more rapidly than for mangroves because the growth of *Spartina* marshes can also occur asexually through the radial extension of rhizomes. In New Zealand, concerns about the environmental effects of *Spartina* spp. on estuarine environments initiated eradication programs by the Department of Conservation and regional councils since the mid-1990s.

**Figure 2-7: Mud content (%) of surficial sediments (top 2-cm) in the southern Kaipara Harbour.** Mud content is calculated as the percentage of the total sample weight (source: Hewitt and Funnell 2005).

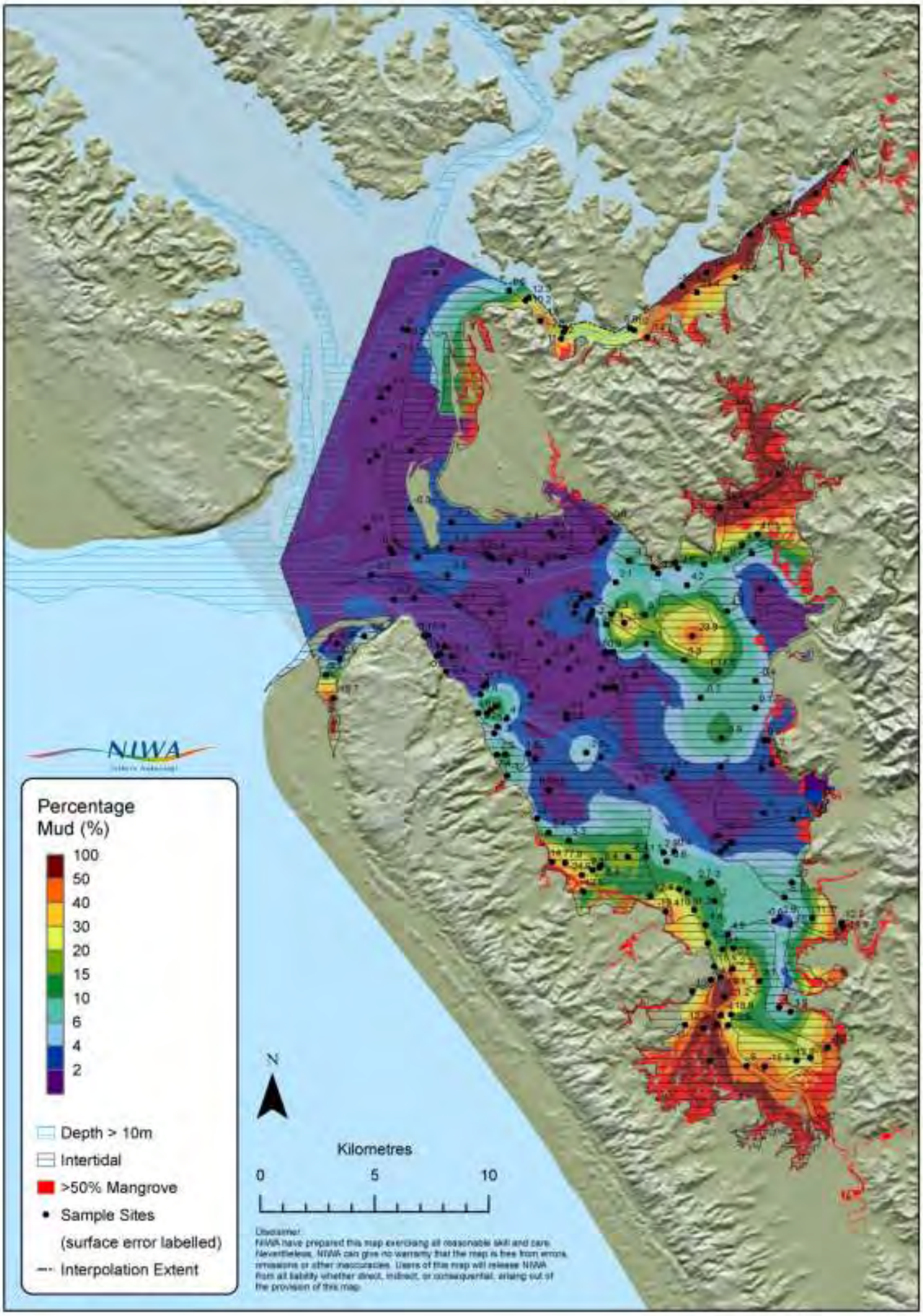

**Figure 2-8: Cord-grass (Spartina spp.) colonising an upper-intertidal flat immediately seaward of a mangrove stand, south Kaipara Harbour, March 2009.** (Photo: A. Swales, NIWA).

Invasive shellfish species also occur in the Kaipara harbour. These include the Pacific Oyster (*Crassostrea gigas*), Asian date mussel (*Musculista senhousia*) and the small bivalve *Theora lubrica*. (Hewitt and Funnell, 2005). Both *Crassostrea* and *Musculista* have the potential to locally alter hydrodynamic conditions and sediment transport. For example, living *Crassostrea* and their shell material can form extensive oyster/mud reefs or mounds on intertidal flats that alter wave exposure and sedimentation processes. These oyster/mud reefs often persist for decades with living shellfish growing on the remains of a previous cohort. Large numbers of such oyster reefs occur in the northern Kaipara on the mid-intertidal flats immediately seaward of the Whakatu mangrove forest (Figure 2.9). The growth of oyster reefs can also trigger mangrove seedling establishment due to increased surface elevation and/or reduced wave exposure (Chapman and Ronaldson, 1958). Such oyster reefs may subsequently be buried by rapidly accumulating mud as mangrove forests develop (e.g., southern Firth of Thames, Swales et al. 2007b).

**Figure 2-9: Oyster reefs up to one metre elevation above the adjacent intertidal flat occupy much of the mid-intertidal.** Seaward of the Whakatu mangrove forest (northern Kaipara). Source: A. Swales (NIWA, March 2009).

The Asian date mussel, which was first observed in the Waitemata Harbour during the 1970's (Hayward et al. 2008), now occurs in a number of Auckland/Northland estuaries, including the Kaipara Harbour. Beds of these mussels typically occur in estuaries on lower intertidal and shallow subtidal flats (water depths $\leq$ 10 m) and form high-density mats (up to 1200 $m^{-2}$) which trap and bind fine sediments with their byssal threads. Where sediment supply is not limiting, these beds may build raised mud banks several deci-metres high and cover several hectares. However, unlike oyster reefs, date mussels beds break up when individual shellfish die (i.e., lifespan $\leq$ 2 years) and releasing the mud deposits. Mussel beds may subsequently re-establish at the same location (Hayward et al. 2008).

Thus the colonisation of tidal flats by invasive plants and animals, such as *Spartina* spp., mangroves, Pacific Oyster and Asian date mussel can significantly alter estuarine hydrodynamics, sediment processes, bed-sediment composition and benthic community structure (Swales et al. 2004, Hewitt and Funnell 2005, Hayward et al. 2008).

**Figure 2-10: View of: (a) the Whakatu mangrove forest conservation area (northern Kaipara), looking north west toward the Wairoa river mouth.** Extensive oyster reefs on the mid intertidal flats separate lower-intertidal sand flats from thick mud deposits on the upper intertidal flats; (b) mud accumulating in the mangrove forest. Source: A. Swales (NIWA, March 2009).

# 3 Methods

## 3.1 Sediment-core sampling

Sediment core sites on intertidal and subtidal flats were selected in consultation with AC and NRC, as well as being informed by existing information. For example, Haggitt et al. (2008) identified areas of the Kaipara Harbour that are likely to be vulnerable to fine-sediment accumulation by mapping peak-tidal current velocities estimated using a hydrodynamic model. Although not included in this assessment, it was acknowledged that wave-driven re-suspension would also influence where fine-sediments ultimately accumulate. Using this approach, areas with peak tidal currents less than 0.1 m $s^{-1}$ were identified as being at risk of fine-sediment accumulation. These accumulation zones included: (1) upper reaches of the Arapaoa, Otamatea, Oruawharo and Whakaki Rivers, coastal margin of the Wairoa River, Tapora Bank, Tauhoa River, Kakaraia (Hoteo) and Kaipara Flats and intertidal flats south of Shelly Beach.

Information on surface bed-sediment composition from the benthic-habitat mapping study of Hewitt and Funnell 2005 (Figure 2.7) was also used to inform core-site selection in the central–southern Kaipara Harbour (although sediment composition can vary with depth). In particular, the mud map was used to select sites with surface sediments containing sufficient mud for radioisotope dating. From experience, sediments containing as little as 2-3% mud by volume can be dated using $^{210}$Pb and $^{137}$Cs, so that in practice only pure-sand deposits are unlikely to yield sedimentation information.

A total of 27 potential core sites were identified in the southern Kaipara, Omokoiti and Kaipara Flats, Hoteo River mouth, Tauhoa Creek, Oruawharo and Arapaoa Rivers and northern Kaipara seaward of the Whakatu mangrove forest. Of these potential sites, high-quality cores were collected from 18 sites. As it eventuated, the high sand content (~100%) of bed sediments on the Kaipara Flats and seaward of the Whakatu mangrove forest prevented cores being collected in those areas. Two lower-priority sites in the Oruawharo River were also not sampled as the weather deteriorated at the end of the field work. The locations of the 18 core sites that were sampled are shown in Figure 3.1 and listed in Table 8.1(appendices).

Sediment cores were collected during 16–19 March and 15 April 2010 using a Gravity Corer deployed from the NIWA research vessel Rangitahi III (Figure 3.2). Replicate cores up to 1.7-m long and with a10-cm internal diameter were collected using this method. Gravity corers provide a simple but effective way to collect long cores in muddy sediments. The corer, loaded with up to 140 kg of lead weight, was slowly lowered to within ~ 2 m of the seabed and then released in free fall to penetrate the sediment column. The gravity corer was extracted from the seabed using an electric winch and davit system. Sediments are retained in a PVC pipe as the corer was winched back up to the boat by using a one-way valve at the top of the corer to provide suction as well as a core catcher attached to the bottom end of the core pipe.

**Figure 3-1: Location of core sites in the Kaipara Harbour, 2010.**

On the boat the PVC barrel containing the sediment was separated from the corer, sealed at both ends, labelled and stowed in racks ready for shipment to NIWA Hamilton. Typically two replicate cores were collected at each site; one was used for radioisotope dating, particle size and bulk density analysis, while the second core was prepared for x-ray imaging. At some sites a third replicate core was collected and frozen on return to the laboratory. These cores provide the option for future studies, for example to examine historical changes in sediment sources and contaminant concentrations.

**Figure 3-2: Retrieving the Gravity Corer used to collect long cores in the Kaipara Harbour, R.V. Rangitahi III, Kaipara Harbour.** March 2010 (photo: Rod Budd, NIWA Hamilton).

## 3.2 Sediment bulk density

The dry-bulk densities (DBD) of sediments were determined for each of the 1-cm thick slices sampled from the cores for radioisotope analysis. The sample volume of 78 $cm^3$ was taken from the cross-section area of the core (10 cm ID) minus the ~0.5 $cm^3$ sub-sample taken for particle-size analysis. Each wet sample was weighed on a chemical balance to the nearest 0.01 g, dried at 70°C for 24 hours and reweighed to obtain the dry-sample weight. Sediment DBD expressed as grams per cubic centimetres (g $cm^3$) were calculated from the dry sample weight and sample volume.

## 3.3 X-radiographs

Sediment cores were cut in half length-ways and a 2-cm thick longitudinal slab prepared for x-ray imaging. X-radiographs of sediment cores provide information on the fine-scale sedimentary fabric of deposits. For example, x-radiographs highlight subtle and/or fine-scale density differences, such as those between thin laminae of silt and sand or animal borrows infilled with mud that may not be visible to the naked eye. The sediment slabs were imaged using an Ultra EPX-F2800 portable x-ray source with a Varian PaxScan 4030E (40 x 29 cm) amorphous silicon digital detector panel. The resolution of the detector panel, with a pixel size of 127 microns is more than adequate to identify very fine scale sedimentary features such as mm-scale laminae and animal burrows.

The x-ray source was mounted 95 cm vertically above the detector panel, with 37-cm core sections imaged in turn from the top to the base of each core. Initial tests indicated a suitable exposure of 25 mAs (milli-Amp seconds) at 50–62 kV. Each core section was imaged at several different x-ray voltages to optimise the exposure to a mid-range grey-scale value. The optimal exposure primarily depended on sediment composition and degree of homogeneity. The 16-bit x-ray images were processed using the ImageJ ver. 1.40g software. Images were converted to 8-bit format and cropped to the sediment slab area. The raw grey-scale pixel values were inverted to follow the usual convention that high-density materials (e.g., carbonate shells and quartz sands) appear white and lower-density materials (e.g., fluid mud, organic material) appear black in processed images. The images were also adjusted to optimise the contrast between sediment of varying density, due to water content, particle size and composition, by constraining the full-range grey-scale to the range for each sediment slab (i.e., grey-scale window and level). Images were output as 8-bit TIF format files.

## 3.4 Particle size

The particle-size distributions (PSD) of sediment samples were determined using an Ankersmid Eyetech time of transition (TOT) stream-scanning laser sizer. This system is an upgrade of the Galai CIS-100 instrument used by NIWA since 1998 but essentially uses the same principle to measure particle size (e.g., Jantschik et al. 1992, http://www.ankersmid.com). Sediment samples of ~ 0.5 $cm^3$ were first wet-sieved to remove vegetation and shell fragments greater than 2 mm diameter (i.e., 2000 microns, $\mu$m). With few exceptions most of the sediments analysed were composed of clay and silt particles < 63 $\mu$m and fine sand particles < 250 $\mu$m diameter. A representative sub-sample was taken from a homogenised one-litre suspension. Samples were disaggregated by ultra-sonic dispersion for 4 minutes before analysis and then continuously re-circulated through the measurement cell by a peristaltic pump. Particle diameters were individually measured in the ranges 0.1–300 $\mu$m and 10–2000 $\mu$m, as required, until their mean size and standard deviation became constant for at least 100 seconds. The spherical volume of each particle was estimated from the measured particle diameter and these were used in turn to construct a volume-based PSD for each sediment sample.

## 3.5 Radioisotope dating

Sediment accumulation rates (SAR) were estimated from radioisotope activities measured in each core. Radioisotopes are strongly attracted to the surfaces of clays and silt particles and this makes them particularly useful as "mud meters" (Sommerfield et al. 1999).

The sediment cores collected from the Kaipara Harbour were dated using the radioisotopes caesium-137 ($^{137}$Cs, ½ life 30 years) and lead-210 ($^{210}$Pb, ½ life 22.3 years). Sediment accumulation rates were calculated from the vertical concentration-activity profiles of $^{210}$Pb and $^{137}$Cs. Concentrations of the cosmogenic radioisotope berrylium-7 ($^{7}$Be, $t_{1/2}$ 53 days) were also measured in the core samples. $^{7}$Be is particle reactive and tends to be concentrated in aquatic systems, making it a useful sediment tracer in fluvial-marine systems at seasonal timescales (Sommerfield et al. 1999). In the present study, $^{7}$Be is used to provide information on the depth and intensity of sediment mixing in the surface-mixed layer (SML).

Sediment dating using two or more independent methods offsets the limitations of any one approach. This is important when interpreting sediment profiles from estuaries because of the potential confounding effects of sediment mixing by physical and biological processes (Smith, 2000). Sediment mixing by physical and biological processes in the surface mixed layer (SML) results in uniform radioisotope concentrations. Because of differences in $^{7}$Be and $^{210}$Pb decay rates, these radioisotopes provide quantitative information about the depth and rate of sediment mixing. This is important when considering the fate of fine-sediments in estuaries. The radioisotope-dating techniques used in the present study are described in detail in section 8.2.

Radioisotope activity concentrations expressed in S.I. units of Becquerel (disintegration $s^{-1}$) per kilogram (Bq $kg^{-1}$) were determined by gamma-spectrometry. For simplicity, we will refer to the activity concentrations of $^{137}$Cs and $^{210}$Pb as concentrations. Dry samples (~50 g) were counted for 23 hrs using a Canberra Model BE5030 hyper-pure germanium detector. The unsupported or excess $^{210}$Pb concentration ($^{210}Pb_{ex}$) was determined from the $^{226}$Ra ($t_{1/2}$ 1622 yr) assay after a 30-day ingrowth period for $^{222}$Rn ($t_{1/2}$ 3.8 days) gas in samples embedded in epoxy resin. Gamma spectra of $^{226}$Ra, $^{210}$Pb and $^{137}$Cs were analysed using Genie2000 software.

The uncertainty ($U_{2\sigma}$) of the $^{210}Pb_{us}$ concentrations was calculated as:

$$U_{2\sigma} = \sqrt{(^{210}\mathrm{Pb}_{2\sigma})^2 + (^{226}\mathrm{Ra}_{2\sigma})^2} \qquad (1)$$

where $^{210}Pb_{2\sigma}$ and $^{226}Ra_{2\sigma}$ are the two standard deviation uncertainties in the total $^{210}$Pb and $^{226}$Ra concentrations at the 95% confidence level. The main source of uncertainty in the measurement of radioisotope concentrations relates to the counting statistics (i.e., variability in the rate of radioactive decay). This source of uncertainty is reduced by increasing the sample size. The $U_{2\sigma}$ values are presented in section 4 with the radioisotope concentration data.

The $^{210}Pb_{ex}$ profiles in cores are used to determine the time-averaged SAR from regression analysis of natural log-transformed data and validated using independent SAR estimates derived from $^{137}$Cs profiles. The $^{137}$Cs SAR was based on the maximum depth of $^{137}$Cs in each core and included a correction for sediment mixing in the surface layer based on the maximum depth of the $^{7}$Be profiles. In NZ, $^{137}$Cs deposition from the atmosphere was first detected in 1953 (Matthews, 1989).

### 3.5.1 Sediment accumulation rates (SAR)

Time-averaged SAR were estimated from the unsupported $^{210}$Pb ($^{210}Pb_{ex}$) concentration profiles preserved in cores. The rate of $^{210}Pb_{ex}$ concentration decrease with depth can be used to calculate a net sediment accumulation rate. The $^{210}Pb_{ex}$ concentration at time zero ($C_0$, Bq $kg^{-2}$), declines exponentially with age ($t$):

$$C_t = C_0 e^{-kt} \qquad (2)$$

Assuming that within a finite time period, sedimentation ($S$) or SAR is constant then $t = z / S$ can be substituted into Eq. 2 and by re-arrangement:

$$\frac{\ln\left[\frac{C_t}{C_0}\right]}{z} = -k / S \qquad (3)$$

Because $^{210}Pb_{ex}$ concentration decays exponentially and assuming that sediment age increases with depth, a vertical profile of natural log($C$) should yield a straight line of slope $b = -k / S$. We fitted a linear regression model to natural-log transformed $^{210}$Pb concentration data to calculate $b$. The SAR over the depth of the fitted data is given by:

$$S = -(k) / b \qquad (4)$$

An advantage of the $^{210}$Pb-dating method is that the SAR is based on the entire $^{210}$Pb$_{ex}$ profile rather than a single layer, as is the case for $^{137}$Cs. Furthermore, if the $^{137}$Cs tracer is present at the bottom of the core then the estimated SAR represents a minimum value.

The $^{137}$Cs profiles were also used to estimate time-averaged SAR based on the maximum depth of $^{137}$Cs in the sediment column, corrected for surface mixing. The $^{137}$Cs SAR is calculated as:

$$S = (M - L)/T - T_0 \qquad (5)$$

where S is the $^{137}$Cs SAR, M is the maximum depth of the $^{137}$Cs profile, L is the depth of the surface mixed layer (SML) indicated by the $^{7}$Be profile and/or x-ray images, $T$ is the year cores were collected and $T_0$ is the year (1953) $^{137}$Cs deposition was first detected in New Zealand.

### 3.5.2 Surface mixed layer - sediment residence time

The SAR found by the $^{210}$Pb method can also be used to estimate the residence time ($R$) of sediment particles in the surface mixed layer (SML) before they are removed by burial. For example, given an SML ($L$) depth of 40 mm and SAR of 2 mm yr$^{-1}$ then $R = L$ /SAR = 20 years. Although this greatly simplifies the process (i.e., the likelihood of particle mixing reduces with depth in the SML), this approach provides a useful measure of the relative effect of sediment mixing between cores, sub-environments and estuaries.

## 3.6 Recent changes in the spatial extent of vegetated intertidal habitats

Changes in the spatial extent of vegetated intertidal habitats since the mid-1960s/1970s were mapped from the analysis of geo-referenced and rectified aerial photographs.

In the Northland Region, mangrove and salt-marsh habitats were mapped using aerial photography for 1977 (SN 5027, black and white, scale 1:12,500) and 2002 (SN 12734a, colour digital images, scale 1:10,000). In the Auckland Region, mangrove and salt-marsh habitats were mapped using aerial photography for 1966 ( south Kaipara/Helensville area, SN 1875, black and white, scale 1:66,000), 1976/1977 (SN 5015, black and white, scale 1:12,500) and 2007 (source: Auckland Council), colour digital images, scale 1:5,000). Additional information on intertidal vegetated habitats in the southern Kaipara was derived from an earlier mapping exercise by the ARC, based on colour aerial photographs taken in 1999. This earlier analysis included mapping of sea-grass beds; mangroves; introduced (i.e., *Spartina*) and native salt marsh. This earlier analysis is described by Hewitt and Funnell (2005) as part of mapping benthic marine habitats in the southern Kaipara. In the present study, checking that the “present-day” vegetated habitat maps (i.e., 2002 and 2007 orthophotos) were qualitatively assessed based on the local knowledge of AC and NRC staff.

As far as practicable the habitat mapping followed the protocols for mapping estuarine vegetation described by Wilton and Saintilan (2000). In the Auckland Region, this analysis included estimation of mangrove-forest density (i.e., canopy cover). Geo-referenced aerial photographs and ARC-MAP shape files of the vegetated habitats were provided to NIWA by AC and NRC for interpretation.

### 3.6.1 Analysis of aerial photographs

The aerial photographs were analysed as follows. The 1976/1977 aerial photographs were scanned/digitised at 600 dots per inch (dpi) and each frame was geo-rectified using a minimum of six ground control points (GCP). The 1966, 2002 and 2007 aerial photography were supplied to NIWA as digital ortho-images. To ensure the accuracy of the estuarine vegetation mapping, the final images were analysed at a larger scale (e.g., 1:2,000), with each discrete area (i.e., polygons) of vegetation digitised by hand.

Several protocols were also adopted to standardise the vegetation mapping:

- the smallest vegetation units to be digitised had a long-axis dimension of at least 10 m. This avoided the possibility that vegetation units, with a long-axis dimension of ≥10 m, would be excluded based on a short or intermediate axes < 10 m
- where the boundary between mangrove and salt marsh was difficult to distinguish, other data sources (i.e., contours, topographical maps, coastal boundary and the NZ landcover data base) where used to assist identification. This issue primarily related to the older black and white photography. A mixed zone on the mangrove/salt marsh boundary also occurred at some sites. In these situations, decisions were based on expert judgement
- where the landward boundary of a vegetation habitat was obscured by shadow cast by the shoreline (e.g., cliffs) or clouds, the landward extent of the vegetation was taken to be at the shadow boundary
- where mangrove stands or salt marsh are dissected by small but obvious features (e.g., tidal channels and/or < 10 m separation), then the vegetation area is digitised as two or more individual polygons
- single mangrove tree separated from stands by even small distances (e.g., ≤10 m) were excluded from the mapped area. Including these outlying individual trees substantially increased the apparent size of a stand.

In the Auckland Region of the harbour, mangrove-forest/stand density (i.e., canopy cover) was determined for four classes: 0–25%, 25–50%, 50–75% and >75% (Wilton and Saintilan, 2000) using ARC-MAP.

It should also be noted that the data for salt-marsh habitat is likely to be less accurate than for mangrove due to the difficulty in some cases of identifying salt-marsh in the earlier (1966, 1977) black and white aerial photography. As a result the area of salt-marsh habitat mapped from these early photographs is likely to be underestimated.

The outputs from this GIS analysis of intertidal vegetation habitat were a series of maps and tables for discrete compartments of the Kaipara harbour (Figure 3.3).

**Figure 3-3: Kaipara Harbour: definition of compartments used to map changes in intertidal vegetated habitats.** Based on analysis of aerial photographs for the Northland (1977 and 2002) and Auckland Regions (1977 and 2007).